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Assessing the Effects of Freeze-Thaw Cycles and Traffic Load on Pavement Resilience

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Abstract

This study examines the impact of freeze-thaw cycles on the performance of flexible pavements, focusing on a specific road in Morocco. The primary objectives are assessing pavement resilience under varying climatic conditions and investigating the combined effects of freeze-thaw cycles, traffic speed (ranging from V1 to V4), and temperature fluctuations (from T1 min to T2 max) on pavement durability and structural integrity. The methodology involves comprehensive data collection on traffic loads, local climate conditions, and soil characteristics. These data inform the pavement design process, helping determine the optimal thickness and selection of materials to withstand environmental stresses. The study also examines the effects of freeze-thaw cycles, assessing frost-resistant materials and comparing frost indices to enhance durability. Advanced modeling techniques simulate pavement performance under real-world conditions, optimizing resilience. The methodology investigates the interaction between traffic speed and pavement behavior, focusing on strain (ε_z), displacement (U_z), and stress (σ_z). The findings reveal a significant correlation between freeze-thaw cycles and pavement deterioration, with strain and displacement increasing as traffic speed decreases while stress intensifies with higher traffic speeds. This research provides valuable insights into the effects of traffic speed on flexible pavements, contributing to more effective maintenance strategies and design solutions for durable, weather-resilient roadways.

Keywords: Freeze-Thaw Cycles; Flexible Pavement; Traffic Speed; Temperature Fluctuations; Pavement Durability.

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1. Introduction

Maintaining the resilience of flexible pavements is crucial for the efficient and reliable operation of transportation networks. Freeze-thaw cycles pose a significant challenge to pavement durability, notably by accelerating the degradation of temperature-sensitive asphalt. Both extreme heat and cold can lead to various forms of pavement distress, including rutting, cracking, and accelerated aging [1-3]. This phenomenon occurs when water present in the lower layers of the pavement freezes and then thaws successively, causing volume changes that affect the structure of road materials [4, 5]. Freeze-thaw cycles can lead to cracks, potholes, depressions, and other pavement degradation, reducing driving quality and increasing maintenance and repair costs. These degradations compromise not only the durability of the pavement but also the safety of road users, exposing the infrastructure to increased risks of long-term damage [6, 7]. Flexible pavements, typically composed of granular material layers with a bituminous surface, are particularly susceptible to these phenomena. Due to their more flexible structure than rigid pavements, they better absorb initial stresses but may deform more quickly under the repeated effects of freezing and thawing cycles. This increased susceptibility is due to the nature of the materials used, which are more sensitive to temperature variations and water

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infiltration [8, 9]. Therefore, understanding the interaction mechanisms between freeze-thaw cycles and flexible pavements is crucial for enhancing the maintenance and longevity of transportation infrastructure in harsh climatic environments.

Several studies have explored the impact of freeze-thaw conditions on road infrastructure, particularly analyzing how asphalt and concrete pavements perform in cold climates. Luo et al. (2022) [10] highlight that these cycles represent a significant risk to pavement durability by inducing stress through hydrostatic pressure, osmotic forces, and salt crystallization pressure. In bituminous pavements, moisture infiltration and phase changes contribute to structural degradation, with the critical saturation degree marking the threshold for severe damage. In addition, freeze-thaw deterioration mechanisms are not yet fully understood, with factors like pore solution salinity and external loading further accelerating damage progression. Deicing salts interact with pavement materials, leading to internal pore formation and crystalline expansion pressure, while higher stress levels further exacerbate deterioration.

However, one of the key weaknesses of this study is its failure to address the impact and consequences of freezing and thawing cycles on the condition of flexible pavements under varying traffic speeds and temperatures. While previous research has extensively focused on the general impacts of freezing and thawing cycles, particularly on bituminous and concrete pavements, it has not sufficiently explored how the interaction between traffic loads and temperature variations during freezing and thawing events can influence pavement durability. Traffic speeds and load frequencies are critical factors that could amplify or mitigate the damage caused by freezing and thawing, especially in regions where pavement conditions fluctuate dramatically with seasonal changes. Moreover, the study overlooks how varying temperatures ranging from extreme cold to thawing conditions interact with traffic-induced stress, potentially leading to more rapid or localized deterioration of flexible pavements. This gap in understanding limits the comprehensive assessment of pavement performance under real-world conditions, where environmental and operational factors play crucial roles in pavement degradation.

In addition, Zhang et al. (2024) [11] conducted a study on semi-flexible pavements (SFP), examining their performance under freezing and thawing cycles and their impact on durability in cold climates. Their research provides valuable insights into the failure mechanisms of SFP, emphasizing the role of interfacial transitions and material degradation in structural deterioration. Using a combination of mechanical and microstructural analysis techniques—including indirect tensile tests (IDT), three-point bending tests, scanning electron microscopy (SEM), and computed tomography (CT)—the study systematically investigates the strength characteristics and microstructural evolution of SFP. The findings indicate that freezing and thawing cycles significantly weaken the tensile strength of SFP, leading to crack formation at the asphalt-cement interfacial transition zone (ITZ), degradation of the cement matrix, and loss of adhesion between asphalt and Sulphoaluminate cement (JGM301). Moreover, the expansion of cement gel exacerbates internal stresses, accelerating material failure. These findings provide a theoretical foundation for optimizing SFP material properties by enhancing bonding at the ITZ and developing more resilient cementitious components, ultimately improving pavement durability in cold climates. One significant limitation of the present research is its failure to consider the impact of freezing and thawing cycles on the condition of flexible pavements under varying traffic speeds and extreme temperatures. Freeze-thaw cycles are widely recognized as a major contributor to pavement deterioration, as they induce structural damage, reduce material cohesion, and accelerate crack propagation, ultimately compromising the long-term performance of road surfaces. The repeated expansion and contraction of water within pavement layers during freezing and thawing phases can weaken the subgrade, increase surface roughness, and heighten the likelihood of pothole formation. While Zhang et al. (2024) [11] conducted an in-depth analysis of semi-flexible pavements (SFPs) under such conditions, their findings cannot be readily applied to fully flexible pavements, as these exhibit distinct mechanical behaviors and material compositions. Unlike SFPs, which combine rigid and flexible properties to enhance durability, fully flexible pavements rely solely on bituminous materials, making them more susceptible to moisture infiltration and thermally induced stresses. Consequently, the absence of these critical environmental factors in the current study limits its applicability, particularly in regions experiencing severe seasonal temperature variations where freeze-thaw cycles are frequent and intense. A more comprehensive investigation that integrates the effects of freeze-thaw cycles, traffic-induced loads, and extreme temperature fluctuations would provide a clearer understanding of pavement performance under real-world conditions.

Furthermore, WU et al. (2023) [12] propose an innovative reliability model to assess asphalt pavement performance by incorporating four key factors: weather conditions, traffic impact, pavement composition and structure, and human actions. Applied to the Qinghai-Tibet Plateau, which faces extreme climatic challenges, including very low temperatures, thermal variations, and frequent freeze-thaw cycles, this model addresses the significant vulnerabilities of road infrastructure in such harsh environments. The study highlights the direct relationship between the frequency and intensity of freezing and thawing cycles and the progressive deterioration of pavement structures. In particular, the researchers show that these cycles accelerate pavement degradation, reduce structural durability, and increase the need for maintenance and rehabilitation. This study further explores the role of various variables in the pavement's lifecycle, focusing on five random variables—SN, ΔPSI, Mr, ESAL0, and r—each contributing to the uncertainties that influence performance. Notably, the researchers observe that as freeze-thaw cycles increase, the durability of the pavement decreases linearly, with SNF-T being particularly sensitive to these changes. The sensitivity analysis reveals that the variable ESAL0 plays a crucial role in influencing the load equation, and SNF-T emerges as a dominant factor in evaluating pavement structural performance.

A notable weakness of the research lies in its limited focus on the impact and consequences of freezing and thawing cycles on the condition of flexible pavements at various traffic speeds. While the study effectively establishes a correlation between freeze-thaw cycles and pavement degradation, it does not adequately explore how different traffic speeds interact with these climatic factors to exacerbate or mitigate the deterioration process. Traffic speed plays a crucial role in influencing the intensity and frequency of loads and stresses imposed on the pavement, which, in turn, can significantly affect its structural integrity, durability, and lifespan. Higher speeds can lead to increased dynamic loading, amplifying the stress on the pavement surface, while lower speeds might result in more localized damage over time. By not incorporating traffic speed as a variable in the model, the research overlooks an essential aspect of real-world pavement performance, particularly in regions where extreme climatic conditions and fluctuating traffic patterns coexist. This omission could significantly limit the model's applicability and accuracy, especially in predicting pavement behavior under diverse operational conditions. Moreover, a more comprehensive approach that integrates traffic speed and freeze-thaw cycles would provide a more realistic representation of pavement degradation, enhancing the model's predictive power and utility for infrastructure planning and maintenance.

The susceptibility of asphalt pavements in regions experiencing seasonal freeze-thaw cycles to accelerated deterioration is a critical concern in infrastructure maintenance. While composite fiber incorporation is a common strategy to enhance pavement durability, recent research, notably by Xu et al. (2025) [13], reveals that repeated freeze-thaw events significantly undermine these enhancements, resulting in a notable decline in mechanical properties. Employing a microscopic analysis through a two-dimensional discrete element method (DEM) simulation, the study elucidated that the primary mechanism behind this degradation is the progressive expansion of pores during freeze-thaw cycles. This pore expansion reduces the number and strength of effective contacts within the asphalt mixture, disrupting the crucial force chains that maintain compressive and tensile strength. Consequently, this disruption fosters the development of microcracks, impairs stress transmission throughout the pavement structure, and ultimately diminishes the overall load-bearing capacity, highlighting the need for innovative materials and design strategies to mitigate these freeze-thaw-induced damages.

A significant limitation of the study lies in its failure to account for the impact and consequences of freezing and thawing cycles on the condition of flexible pavements at various traffic speeds. While the study focuses on the deterioration of asphalt pavements due to temperature fluctuations and the incorporation of composite fibers, it does not explore how different traffic speeds may influence the extent of damage caused by freezing and thawing cycles. Traffic speed is a critical factor affecting the stress distribution and loading conditions on pavements, which could potentially exacerbate or mitigate the effects of freezing and thawing cycles on the material properties of the asphalt. Furthermore, varying traffic speeds may alter the rate of damage progression, with higher speeds leading to more dynamic loading and increased potential for pavement wear. The omission of this factor represents a gap in understanding the full spectrum of conditions that could affect the durability and performance of flexible pavements in regions prone to freezing temperatures.

Our research investigates the complex interplay between freezing and thawing cycles, traffic speed, and pavement rutting in flexible pavements. By systematically varying traffic speeds from V1 to V4 and temperatures from T1 (minimum) to T2 (maximum), we aim to quantify the impact of these environmental and operational stressors on pavement integrity. Specifically, we will develop predictive models for rutting, a critical indicator of fatigue-related damage, to understand how these factors contribute to pavement deterioration. This analysis will provide valuable insights for optimizing pavement design and maintenance strategies, ultimately enhancing road quality, safety, and longevity under diverse traffic and climatic conditions.

The article outlines a systematic evaluation of pavement performance and management strategies, starting with a detailed explanation of the methodology used. This methodology encompasses experimental and theoretical approaches, allowing for a comprehensive understanding of how freeze-thaw cycles interact with pavement materials under different loading conditions. Subsequently, we conduct an experimental case study on the pavement structure in Ifrane, Morocco, a location of particular significance due to its rapid urban and industrial growth, which increases the demand for robust and durable road infrastructure. The study also emphasizes regional climate factors essential for understanding the temperature fluctuations that pavements endure throughout the year. These conditions, including temperature variations and precipitation patterns, contribute to the freeze-thaw cycles that impact pavement performance. Furthermore, the article examines structural design factors to enhance pavement functionality across diverse environmental conditions. The results and discussion sections offer in-depth analyses of pavement structures, incorporating advanced modeling techniques to assess stress, strain, and displacement responses at varying traffic speeds (V1–V4) and temperatures ranging from T1min to T2max.

2. Material and Methods

This study employs a comprehensive, multi-stage methodology to evaluate the impact of freezing and thawing cycles on flexible pavements. This research meticulously analyzes the intricate interplay between environmental conditions and freeze-thaw cycles and their cumulative effect on pavement performance. By employing a combination of experimental testing, numerical modeling, and field observations, the approach aims to thoroughly understand how these cycles affect pavement performance, informing the development of more durable pavement structures.

The initial stage focuses on systematic data collection, encompassing several essential components. These include detailed traffic data analysis to capture loading conditions and comprehensive climatic data gathering, focusing on temperature fluctuations, precipitation trends, and historical freeze-thaw events. Simultaneously, a geotechnical investigation assesses the supporting soil's properties, evaluating critical factors such as moisture content, density, and frost susceptibility. These soil properties are fundamental for understanding the pavement's response to freeze-thaw cycles and its overall structural stability. Following data collection, the study proceeds to the structural design phase, a crucial step ensuring the pavement can withstand expected loads and environmental stressors. This phase begins with determining optimal layer thicknesses within the pavement structure. Thickness decisions are based on analyzing the collected data, considering parameters like traffic volume, load distribution, and insights from similar pavements' historical performance. The process balances durability and cost-effectiveness by adhering to established design standards and guidelines [14]. Material selection is crucial in this phase. Each material used in the pavement must meet specific mechanical and thermal requirements to ensure its ability to endure the environmental and load conditions it will encounter over time. Materials are analyzed based on their strength, flexibility, and resistance to temperature fluctuations and moisture.

The next critical component of the methodology is freeze-thaw cycle analysis, which is crucial for understanding the impact of these cycles on pavement durability. This analysis involves assessing the permissible frost quantity (QS) that frost-susceptible soils can withstand without negatively affecting the pavement structure. This assessment helps determine whether the pavement design can endure varied climatic conditions.

Additionally, the methodology thoroughly examines the role of frost-resistant materials in the pavement and base layers (Z) to determine how these components enhance the structure's resistance to frost-related damage. The research evaluates the effectiveness of these materials in mitigating the impact of freeze-thaw cycles, which significantly contribute to pavement deterioration in cold climates. The study highlights how these materials strengthen durability by reducing the likelihood of cracking, heaving, and moisture infiltration in pavement layers during freezing and thawing. To better understand pavement performance under such conditions, we compare the standard frost index (IR) and the allowable frost index (IA). This analysis reveals critical insights into the pavement's ability to withstand freeze-thaw cycles without losing structural integrity. Recognizing the discrepancies between IR and IA, the study identifies key opportunities to optimize material properties and improve design strategies for enhanced resilience.

In the final phase of the study, advanced dynamic and viscoelastic modeling techniques simulate the behavior of flexible pavement under real-world conditions [15]. This stage is crucial for understanding how the pavement responds to cyclic loading and the impact of temperature fluctuations, especially in areas subject to freeze-thaw cycles. Key metrics analyzed in this modeling phase include axial strain (ϵ_z), compressive stress (σ_z), and axial displacement (U_z). Axial strain (ϵ_z) represents the extent to which the pavement compresses or stretches under applied loads, indicating its structural flexibility and load-distribution capability. Measuring and modeling ϵz allows the study to assess the pavement's resilience to repeated loadings, such as those imposed by traffic over time. If the pavement layers cannot adequately distribute these stresses, it can result in wear, fracturing, or lasting distortion, compromising the pavement's performance. Compressive stress (σ_z) measures the intensity of internal forces within the pavement layers when subjected to external loading, offering insight into how stress propagates through the pavement structure. This metric is crucial for understanding the potential for stress concentrations that could lead to localized failures, especially in the subgrade soil.

Analyzing σ_z allows the study to identify specific areas within the pavement structure requiring reinforcement to mitigate stress-induced damage. Axial displacement (U_z) quantifies the pavement structure's movement in response to external loads. This metric provides crucial data regarding the overall stability of the pavement system, highlighting areas where excessive displacement could jeopardize structural integrity. Analysis of U_z aids in pinpointing weaknesses within the pavement's foundation or base layers, thereby informing design modifications to improve stability.

Figure 1 clearly and comprehensively illustrates the various stages of the research approach for this project. By depicting each phase building upon the previous one, the chart ensures a logical and organized progression of the methodology.

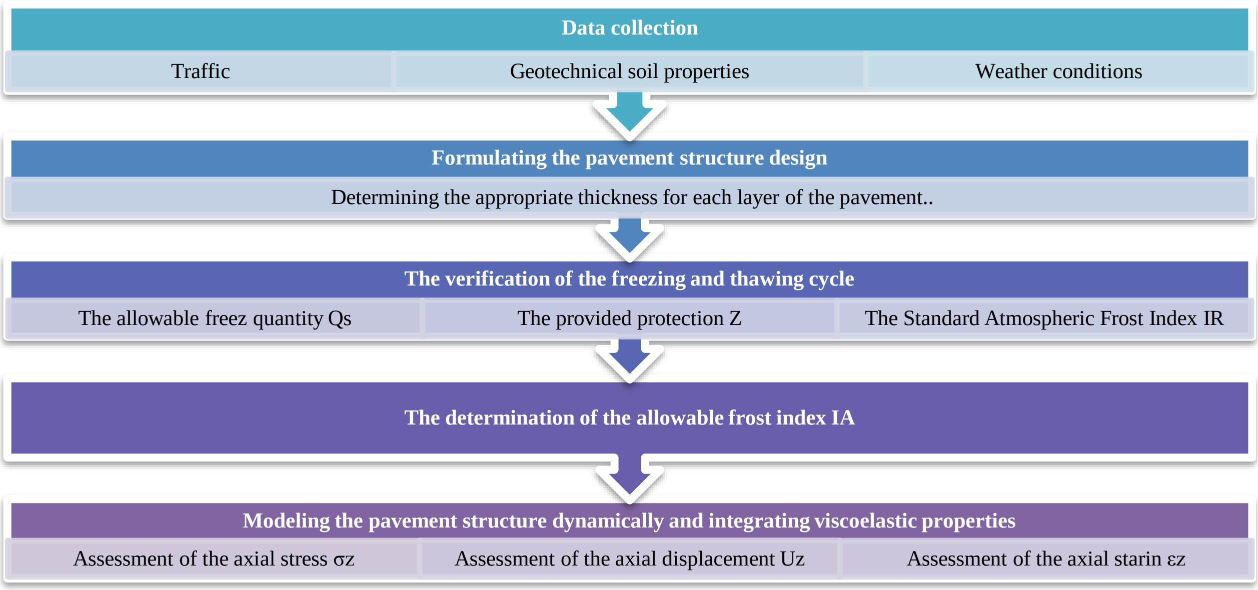

Figure 1. The flowchart outlines the methodology implemented in the research

2.1. Experimental Case Study

The pavement structure under analysis sits in the Ifrane province, which belongs to the Fes-Meknes administrative region in Morocco, as illustrated in Figure 2. Ifrane is a junction between regional destinations, fostering connectivity and economic activity. Situated approximately 70 km south of the historical city of Fes, Ifrane serves as a vital junction between various regional destinations, promoting connectivity and economic growth. The area has seen a rise in tourism and local development, requiring a comprehensive evaluation of the road infrastructure to accommodate increasing traffic volumes. The region's climate, with its cold winters and mild summers, poses specific challenges for pavement durability. As a result, an assessment of material resistance to climatic variations is indispensable. The pavement structure experiences changing stress levels due to Ifrane's diverse vehicular flow, including tourism-related traffic and heavy vehicles.

This study focuses on Ifrane due to its diverse traffic conditions, encompassing various vehicle categories. The province experiences a mix of local commuter traffic, tourism-related vehicles, and agricultural transport, creating a unique dynamic that impacts pavement performance. The research conducted in Ifrane province aims to address these complex issues by analyzing the effects and consequences of freeze-thaw cycles on pavement longevity across a range of traffic speeds, designated V1 to V4. This approach involves an in-depth analysis of pavement performance under varying load conditions and environmental influences, offering valuable insights into the evolution of material properties over time and their response to traffic speed variations [11, 16]. We plan to implement a comprehensive approach incorporating various investigative methods. This strategy will include detailed field surveys, extensive laboratory testing, and meticulous data analysis. The fieldwork will involve collecting representative road material samples for accurate testing [17, 18]. Geotechnical assessments will provide insights into the physical and structural properties of soils such as density, moisture content, and shear strength, which are critical for understanding pavement performance. These evaluations will also examine pavement responses to stressors like traffic loads, temperature fluctuations, and freeze-thaw cycles, offering valuable resilience data. Experimental analyses will assess road material characteristics, including soils and aggregates, focusing on gradation, compaction properties, and stress durability [19, 20]. Laboratory testing will involve sieve analysis, Proctor compaction, and unconfined compression tests to determine material suitability for flexible pavements. By integrating field assessments with controlled laboratory investigations, this study bridges the gap between in-situ conditions and theoretical predictions (see Table 1).

Table 1. Mechanical characteristics of different pavement layer materials

Layer	Nature of the Material	Young's Elastic Modulus (E)	Poisson's Coefficient (ν)
Top layer	High Modulus Bituminous (BBME)	2170 to 22235 MPa	0.35
Structural Base Layer	Bituminous Gravel Concrete	2000 to 16000 MPa	0.35
Sub-base Layer	Unbound Gravel	200 to 600 MPa	0.35
Protective layer	Chosen Natural Gravel	20 to 200 MPa	0.35
Underlying soil	Underlying soil	20 to 200 MPa	0.35

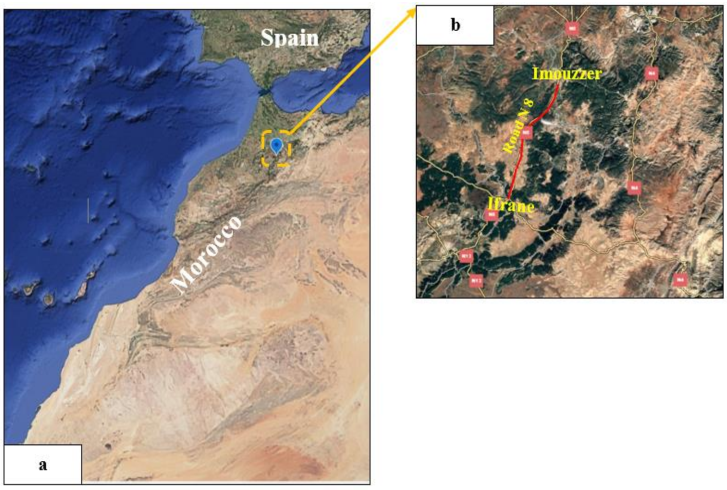

Figure 1. The geographic location of the study area

2.2. Weather Conditions

Figure 3 illustrates the average monthly precipitation, maximum temperature, and minimum temperature in Ifrane Province, revealing a distinct seasonal pattern**.** The highest precipitation occurs in April (~70 mm) and December (~60 mm), while the lowest levels are recorded in July and August (~10 mm each). Maximum temperatures peak in July (30°C), whereas minimum temperatures reach their lowest in January (-5°C). Winter months—especially January and February—are characterized by cold conditions, often dropping below freezing. In contrast, summer months, especially July and August, are marked by warm temperatures and minimal rainfall, reflecting a dry summer climate. These seasonal variations suggest a Mediterranean-like climate in Ifrane, characterized by wet winters and dry summers. In colder conditions, materials become stiffer and more prone to fracture. Conversely, warmer temperatures enhance flexibility but can cause permanent deformations, such as rutting. The viscoelastic properties of materials, which define their capacity to resist stress and strain, exhibit a high sensitivity to thermal fluctuations. Consequently, pavements must be designed with these climatic factors in mind to ensure durability and optimal performance under varying weather conditions [21, 22]. Although higher temperatures increase the flexibility of asphalt pavements, reducing the likelihood of low-temperature cracking, they also introduce significant challenges. Elevated temperatures soften the asphalt binder, making the pavement more susceptible to permanent deformations, such as rutting—a common distress characterized by depressions in the wheel paths due to repeated traffic loading. Over time, excessive rutting can compromise ride quality, reduce skid resistance, and lead to water pooling, increasing the risk of hydroplaning and further pavement deterioration. As a result, pavements must be designed with these climatic factors in mind to ensure long-term durability under varying weather conditions.

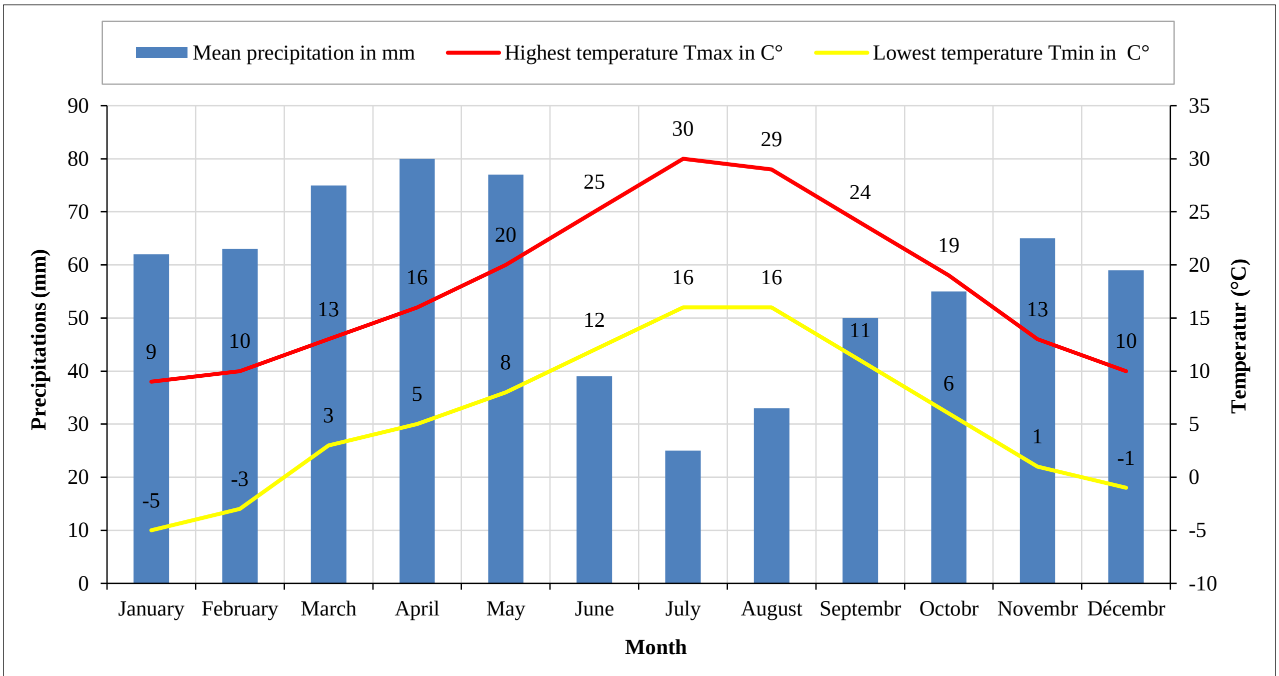

Figure 2. The average monthly rainfall and temperature extremes (minimum and maximum) for the province of Ifrane

2.3. Traffic

Traffic analysis is vital in pavement design because it directly affects the structural durability of the pavement. Traffic data—including vehicle volume, types, weights, and distribution patterns—provides essential insights for designing a pavement structure capable of withstanding expected loads throughout its service life. Heavier vehicles, such as trucks, exert significantly greater stress on pavement layers than lighter vehicles, necessitating robust materials and structural configurations to prevent premature failure [23, 24]. Accurate traffic analysis ensures that the pavement is neither under-designed (which could lead to costly repairs) nor overdesigned (which would result in unnecessary expenses).

Table 2 and Figure 4 depict the truck traffic volume and growth rate in the study area between 2013 and 2023, revealing a consistent upward trend. Over this period, truck traffic volume rose significantly from 864 PL in 2013 to 1,263 PL in 2023. While the growth rate exhibited minor fluctuations, it remained positive throughout, varying between a low of 1.82% in 2014 and a peak of 4.35% in 2023.

Table 2. The truck traffic volume and growth rate in the study area

Year	Truck Traffic Volume PL per day	Growth Rate in %
2013	864	-
2014	880	1,82
2015	913	3,61
2016	938	2,67
2017	968	3,10
2018	1012	4,35
2019	1058	4,35
2020	1106	4,34
2021	1156	4,33
2022	1208	4,30
2023	1263	4,35

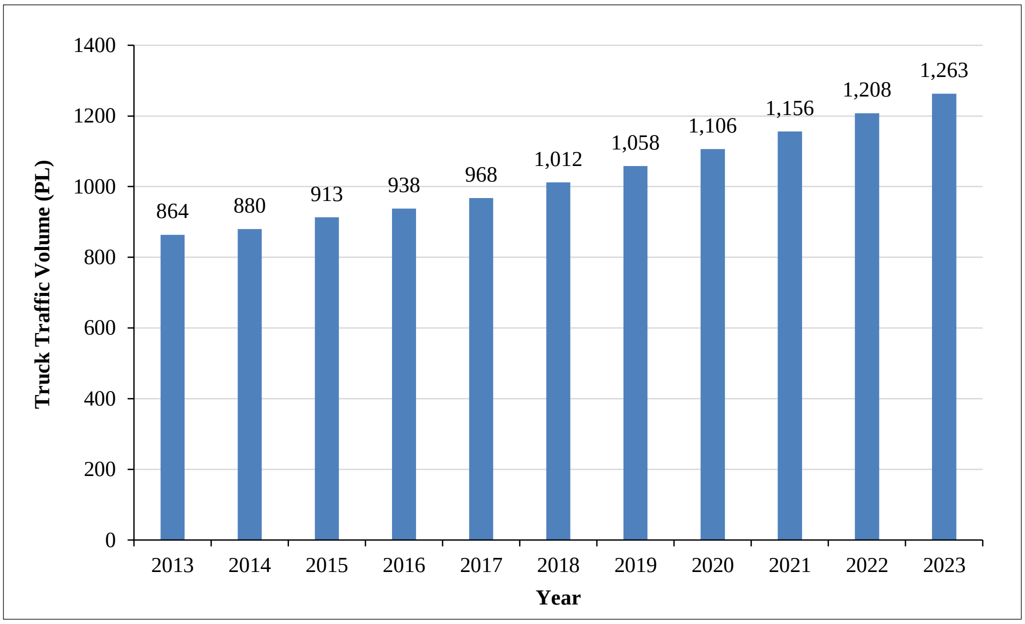

Figure 4. Yearly Truck Traffic Volume in the study area

3. The Verification of the Freeze-Thaw Cycle

We analyzed freeze-thaw cycles using a methodological approach to assess the permissible frost quantity (Qs) and the role of frost-resistant materials in pavement durability. Rather than relying solely on real-world temperature variations, the study evaluated pavement resistance to freeze-thaw effects through key indicators, such as the standard frost index (IR) and the permissible frost index (IA). This comparison provided insights into the pavement's ability to withstand freeze-thaw cycles without structural compromise. Although the methodology does not explicitly include accelerated laboratory testing, it emphasizes a detailed assessment of material properties and design strategies to enhance resilience against frost-related damage. Freeze-thaw verification of pavement structures requires three key parameters.

First, the permissible frost quantity Qs of the natural frost-susceptible soil must be determined to assess its ability to endure freezing conditions. Secondly, it is necessary to quantify the protective role of frost-resistant materials in the pavement and base layers (Z), given that these materials significantly reduce the impact of freezing on structural integrity. Finally, the standard frost index (IR), representing regional frost severity, must be compared to the permissible frost index (IA), which defines the maximum frost level the pavement can safely endure [25, 26]. This comparison is critical for determining whether the pavement design offers sufficient resistance to freeze-thaw cycles. Ensuring this resistance minimizes the risk of premature degradation caused by frost-related stresses.

3.1. The Permissible Frost Heave Quantity (QS) of Frost-Susceptible Natural Soil

The permissible frost heave quantity (QS) is calculated based on the values provided in the attached Table 3. These values serve as a reference for evaluating the soil's response to freezing conditions and its potential to undergo frost heave.

Table 3. The permissible frost heave quantity (QS)

QS	Soil Characteristics	Soil Type
2.5	Slightly frost-susceptible soil (SPG)	A4, B1, B2, B3, B4
0	Highly frost-susceptible soil (STG)	A1, A2, A3, B5, B6

The subgrade and underlying soil materials are classified as F1 gravel, highly resistant to water-induced degradation. This property ensures structural integrity even under wet conditions. Additionally, their non-frost-susceptible (SPG) nature prevents frost heave, making them suitable for regions prone to freeze-thaw cycles. With a bearing capacity coefficient of QS = 2.5, these materials demonstrate strong load-bearing performance, meeting the standards for stable and durable foundation layers in construction and infrastructure projects.

3.2. The Protection Offered by Frost-Resistant Materials in the Pavement and Base Layers (Z)

The protection offered by frost-resistant materials in the pavement surface, foundational layers, and subgrade material. (Z) is calculated using the Equation 1:

$$Z = Z_F + Z_C + Z_M \tag{1}$$

Where: Z_F: Measure the thermal protection of the subgrade layer in centimeters (cm); Z_C: Measure the thermal protection of the pavement structure materials in centimeters (cm); Z_M: Express the coefficient corresponding to the mechanical resistance of the pavement structure in centimeters (cm).

The Equation 2 calculates the thermal protection of the subgrade layer (Z_F):

$$Z_F = 0.14H_F - 0.6 \tag{2}$$

Where: H_F denotes the subgrade layer thickness in centimeters (cm); We calculate the heat resistance of pavement structure materials (Z_C) using Equation 3:

$$Z_C = \sum_{i=1}^{n} A\, H_i \tag{3}$$

Where: A represents a calculation coefficient: 0.06 for bituminous materials and 0.1 for concrete or untreated aggregates (GNT); H_i denotes the thickness of each pavement layer in centimeters (cm).

Equation 4 calculates the coefficient corresponding to the mechanical resistance of the pavement structure:

$$Z_M = \begin{cases} 0 & H_M \leq 13\ cm \\ 0.1HM - 1.3 & H_M \geq 13\ cm \end{cases} \tag{4}$$

Z_M equals zero when H_M is less than 13 cm.

H_M represents the total thickness (in cm) of treated materials, untreated materials, and modular materials, as given in Equation 5:

$$H_M = H_{MT} + H_{MNT} + H_{MD} \tag{5}$$

H_{MT}: Thickness of treated materials (cm); H_{MNT}: Thickness of untreated materials (cm); H_{MD}: Thickness of modular materials (cm).

3.3. The Allowable Frost Index (IA)

The allowable frost index IA of the pavement structure is determined using Figure 5. This index represents the maximum frost level the pavement can endure without losing structural integrity or functionality [27]. The chart correlates IA with key variables, such as frost penetration depth (Z) and roadbed-specific parameters like the frost heave susceptibility factor Qs. By analyzing this relationship, we can select appropriate design measures to maintain pavement stability under frost conditions, reducing risks such as cracking, heaving, and long-term damage from freeze-thaw cycles.

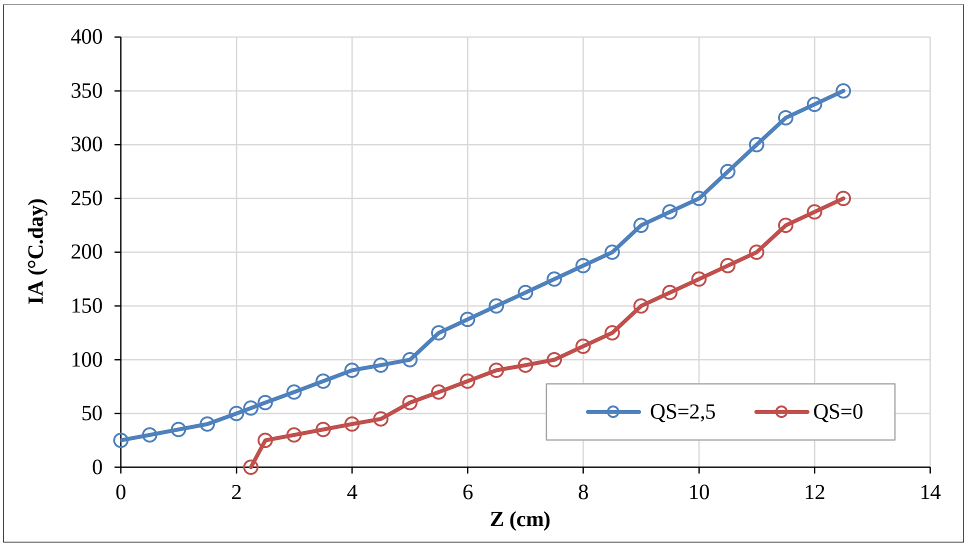

Figure 5. The allowable frost index IA as a function of Z

3.4. The Standard Atmospheric Frost Index (IR)

The standard atmospheric frost index (IR) for pavement verification is the severe winter index recorded from 1990 to 2023, calculated using Equation 6:

$$IR = \left|\sum_{i=1}^{n} Ti\right| \tag{6}$$

With: T_i: average daily negative temperature (°C) for a severe winter.

As shown in Figure 6, the most severe frost index for freeze-thaw cycle verification occurred in 2012, with an IR value of 111.4°C·days. This value reflects the extreme frost conditions recorded that year, making it a critical benchmark for evaluating pavement structural integrity and durability under freeze-thaw cycles. The reference frost index (IR) for 2012 provides a benchmark for designing pavement structures to withstand seasonal temperature fluctuations, thus reducing the risk of damage such as cracking or heaving caused by repeated freeze-thaw cycles.

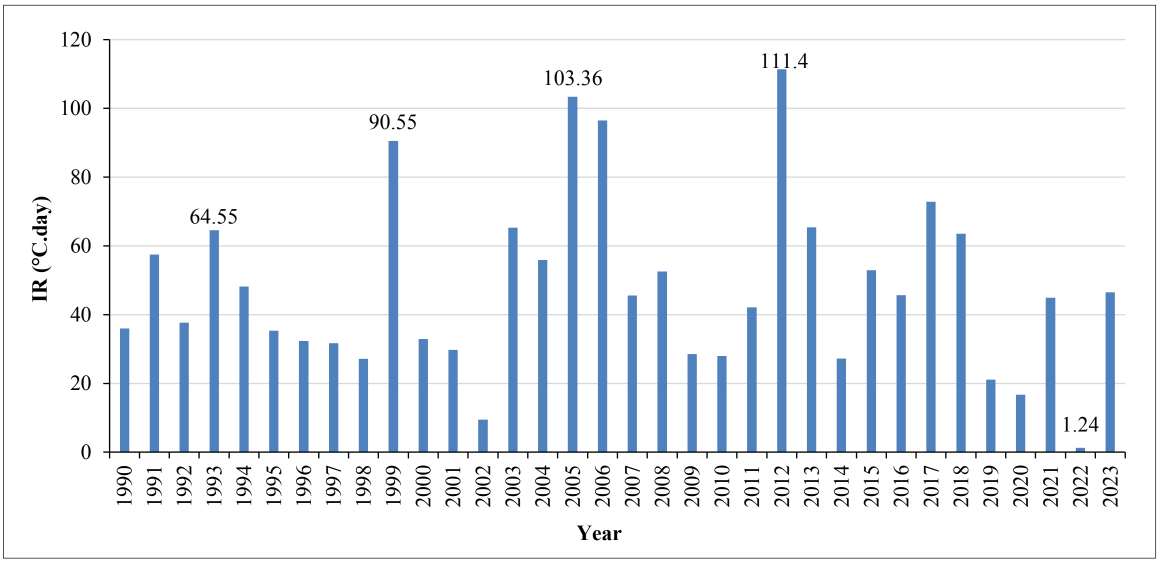

Figure 6. Yearly reference frost index IR in the study area

4. Results

4.1. The Assessment Outcomes of the Pavement Structure

This study used a structural design methodology to ensure accuracy and reliability, systematically planning and executing each step to dimension a robust pavement structure. The adopted pavement structure, illustrated in Figure 7, consists of a five-layer system to support vehicular traffic. The topmost layer, the BBME surface layer (5 cm), comprises High-Performance Bituminous Material 0/20, providing a smooth and durable driving surface. Beneath this, the 10 cm thick GBB layer (Granular Bituminous Base 0/14) efficiently distributes loads to the underlying layers. The 15 cm sub-base layer (GNF1), made of Unbound Natural Filler 0/40, offers additional structural support and acts as a transition between the base and lower layers. Below this lies the 40 cm capping layer (F1), constructed from Natural Gravel 0/80, which further distributes loads and protects the subsoil. The subsoil, assumed to be infinite in depth, provides the ultimate foundation for the pavement structure. This layered system effectively manages vehicular weight and speed, ensuring optimal load transfer and dynamic stress distribution. Carefully selected materials and layer thicknesses (BBME, GBB, GNF1, and F1) are critical to enhancing the pavement's resilience and long-term performance.

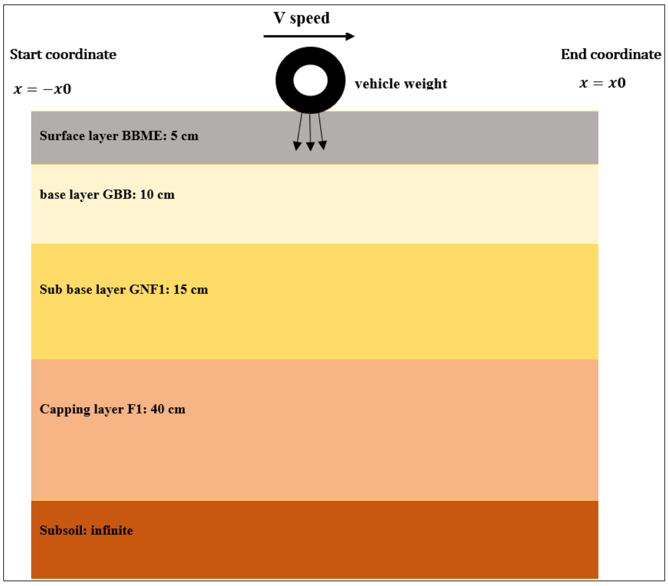

Figure 7. The adopted pavement structures

4.2. The Deformation Compliance in Viscoelastic Materials

Deformation compliance, denoted by $D1(t)$, is a key characteristic of materials used in pavement construction, especially for asphalt and bituminous mixtures. It describes how a material deforms under sustained loading or stress over time [28]. $D1(t)$ characterizes the time-dependent response of deformation to applied load/stress. It captures the material's viscoelastic properties, encompassing both the recoverable elastic strain and the permanent viscous deformation. This function offers an in-depth understanding of the material's response to external forces, including its instantaneous elastic reaction and the gradual, time-dependent viscous adjustment, as expressed in Equation 7 [29, 30].

$$\mathrm{D1(t)} = \mathrm{D}_{\infty} + \frac{\mathrm{D}_{01} - \mathrm{D}_{\infty}}{1 + (\frac{\mathrm{t}}{\mathrm{T}_0})^{\mathrm{N_D}}} \tag{7}$$

This equation $D1(t)$ denotes the viscoelastic creep compliance in 1/Mpa, D_{01} corresponds to the initial viscoelastic creep compliance, $D\infty$ signifies the creep compliance value as (t) approaches infinity, and T_0 and N_D are parameters that define the form of the compliance curve. The viscoelastic model used to analyze pavement material behavior employs linear viscoelastic theory. This framework examines the interactions of stresses, strains, and displacements in a layered viscoelastic half-space under a uniformly distributed, moving circular load. The model assumes that the pavement layers are homogeneous and isotropic, meaning that the material properties are consistent throughout the thickness of the layers and the same in all directions. This simplification enables the analysis to use constant material properties, which remain uniform across position and direction within the layers. Furthermore, the model considers the material's time-dependent response, accounting for elastic and viscous behavior during load movement.

4.3. The Results of the Road Pavement System

In this part of the study, we conduct tests to evaluate the selected pavement design. These tests focus on examining the impact of applied compressive stresses (σz), axial strains (εz), and axial displacements (Uz). The primary objective is to evaluate the structural soundness and functional pavement efficiency. It involves analyzing its capacity to endure the demands of vehicular traffic and environmental factors. This in-depth analysis offers valuable perspectives on the principles of pavement design. The results are key to enhancing current methodologies, advancing knowledge, and boosting the optimization and durability of the road network over time. Additionally, the study examines a range of traffic speeds, from 20 to 80 km/h, enabling an assessment of roadway performance under different traffic conditions. At higher speeds, the reduced duration of load application limits viscous deformation, thereby increasing the apparent rigidity of the material. Conversely, lower speeds prolong loading, enabling greater viscous flow and potentially leading to deformation and stress accumulation within pavement layers. Over time, these differences significantly affect wear rates, rutting susceptibility, and overall pavement performance. The impact of speed on viscoelastic behavior is especially pronounced in pavements subjected to frequent heavy traffic. High-speed, heavy vehicles produce rapid cyclic loading, straining the material's recovery capacity and contributing to micro-damage and fatigue. In contrast, slower traffic induces more deformation per cycle, promoting creep and permanent deformation over time. These scenarios underscore the importance of accounting for traffic speed, load frequency, and material viscoelasticity in pavement design.

Data analysis (Table 4, Figure 8) reveals a strong positive correlation between traffic speed and the viscoelastic stress response, particularly within the 20 km/h (Vmin) to 80 km/h (Vmax) range. As speed increases, vehicle loads become more dynamic, altering stress distribution within the pavement material.

Table 4. Axial viscoelastic stress at various speed and load application positions for Tmin = -5 °C

The Point of Load Application (m)	The axial compressive stress σz, expressed in (Pa) for V1=20 km/h	The axial compressive stress σz, expressed in (Pa) for V2=40 km/h	The axial compressive stress σz, expressed in (Pa) for V1=60 km/h	The axial compressive stress σz, expressed in (Pa) for V4=80 km/h
-2	23.94	23.94	23.94	23.94
-1.5	0.53	0.77	0.93	1.05
-1	42.49	47.36	50.25	52.29
-0.5	518.24	549.52	567.22	579.46
-0.02	8771.23	10012.89	10741.53	11255.41
0	8298.97	9637.62	10423.43	10977.71
0.5	-310.61	-359.10	-386.27	-403.72
1	-360.85	-393.13	-411.93	-424.86
1.5	-241.24	-267.23	-282.74	-293.66
2	-140.10	-159.78	-171.80	-180.42

At lower speeds (20 km/h), static loads cause more gradual deformation, allowing the material to dissipate stress. For instance, at -0.02 m, the stress response reaches 8771.23 Pa for V1. However, at higher speeds, such as 80 km/h (V4max), dynamic effects significantly amplify the stress, resulting in a higher response of 11255.41 Pa at the same point. The pavement material's behavior explains this phenomenon: as speed increases, the load application duration decreases, causing heightened stress concentrations within particular regions of the pavement structure. Evidence of this is the gradual increase in stress values throughout the speed range, with significant peaks recorded at critical locations, specifically -0.02 m and adjacent to the surface layer. Such variations highlight the importance of accounting for traffic speed in pavement design and performance evaluation.

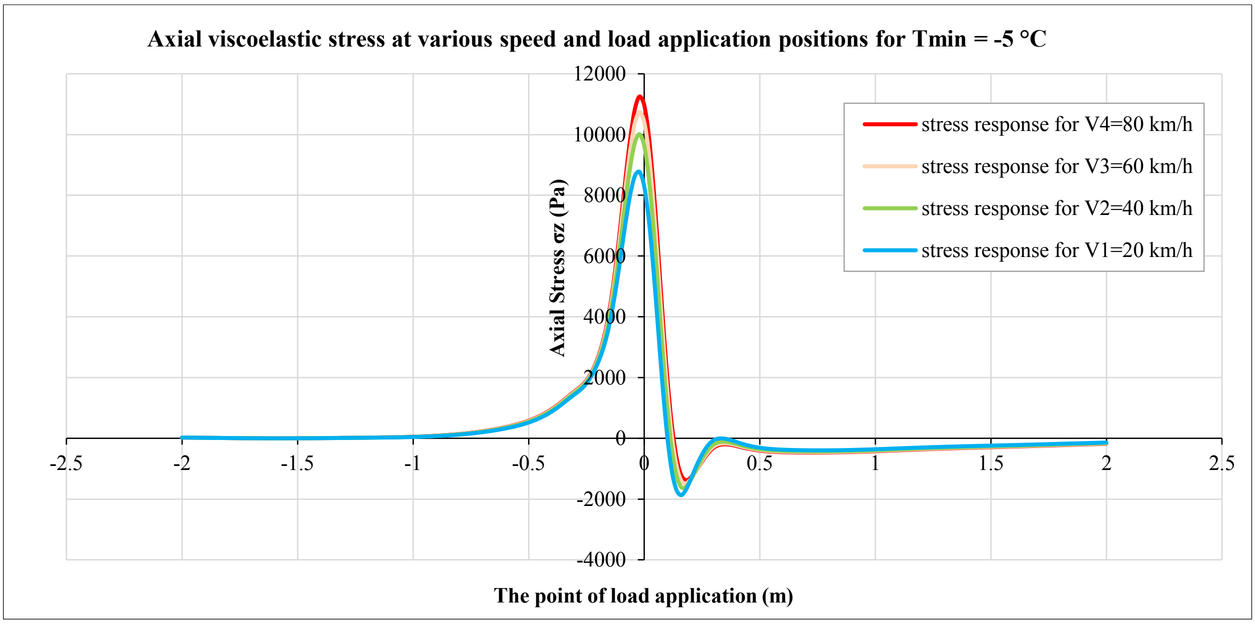

Figure 8. The viscoelastic stress results for Tmin= -5 °C

The axial viscoelastic strain behavior in the Z-direction, denoted as εz, offers critical insights into how pavements respond to axial forces. This parameter is vital for predicting material deformation under long-term loading, enabling the design of durable structures that maintain performance and reliability under sustained stress. Incorporating ε_z into design and assessment processes facilitates informed decision-making regarding material selection, construction techniques, and maintenance strategies, ultimately supporting tailored solutions for specific environmental and operational challenges. Viscoelastic strain behavior, characterized by initial strain (ε_{01}) and long-term strain (ε∞), reflects the material's time-dependent response to forces. Here, $\boldsymbol{\varepsilon_{01}}$ represents the immediate deformation upon loading, while **ε**∞ reflects the long-term deformation at equilibrium. Equation 8 models this viscoelastic behavior, accounting for diverse loading conditions and environmental factors, and quantifies the strain evolution over time.

$$\varepsilon 1(t) = \varepsilon_\infty + \frac{\varepsilon_{01} - \varepsilon_\infty}{1 + (\frac{t}{T_0})^{N_D}} \tag{8}$$

In this context, $\varepsilon(t)$ denotes the strain in micrometers, ε_{01} represents the initial strain, ε_∞ refers to the strain as (t) approaches infinity, and T_0 and N_D are parameters describing the material's behavior.

As illustrated in Table 5 and Figure 9, the findings demonstrate a distinct trend where the axial strain, ε_z, exhibits an increasing magnitude as the speed diminishes. This correlation is evident over a speed range spanning 20 km/h (V1min) up to 80 km/h (V4max).

Table 5. Axial Viscoelastic Strain ε_z at Various Speed and Load Application Positions for Tmin = -5 °C

The Point of Load Application (m)	The axial Strain in µm for V1=20 km/h	The axial Strain in µm for V2=40 km/h	The axial Strain in µm for V3=60 km/h	The axial Strain in µm for V4=80 km/h
-2	-0,03	-0,03	-0,03	-0,03
-1,5	0,20	0,18	0,16	0,15
-1	0,51	0,42	0,37	0,33
-0,5	-2,49	-2,51	-2,51	-2,50
0	-33,20	-30,00	-28,28	-27,13
0,04	-34,28	-30,90	-29,08	-27,87
0,5	-8,91	-8,52	-8,24	-8,01
1	-1,68	-1,82	-1,87	-1,88
1,5	-1,01	-1,08	-1,11	-1,12
2	-0,91	-0,94	-0,95	-0,95

The data underscore the substantial effect of traffic speed on the viscoelastic behavior of the material. Under consistent loading, the material exhibits a rise in viscoelastic strain, suggesting higher compliance and lower stiffness at reduced speeds. This behavior is likely due to increased molecular mobility within the material's structure. For instance, at the center of the applied load (0 m), the strain response is recorded as −33.20 µm for V1 = 20 km/h but decreases to −27.13 µm for V4 = 80 km/h. Similarly, at a location slightly off-center (0.5 m), the strain response decreases from −8.91 µm at V1 to −8.01 µm at V4. These values highlight how the viscoelastic response diminishes as traffic speed increases, indicating that slower speeds allow more time for the material to deform.

The in-depth analysis in Table 5 offers accurate measurements of the strain response at different traffic speeds, providing valuable quantitative information. Figure 9 provides a visual representation of these findings, graphically illustrating the observed trends and facilitating a clearer understanding. This relationship is critical for evaluating road pavement performance and longevity. It also guides maintenance strategies and material selection, enhancing resistance and durability. A thorough understanding of this interaction is essential to accurately predict material behavior under varying traffic conditions and optimize performance in real-world applications. Such analysis supports the development of tailored solutions for road infrastructure challenges, ensuring both efficiency and long-term durability.

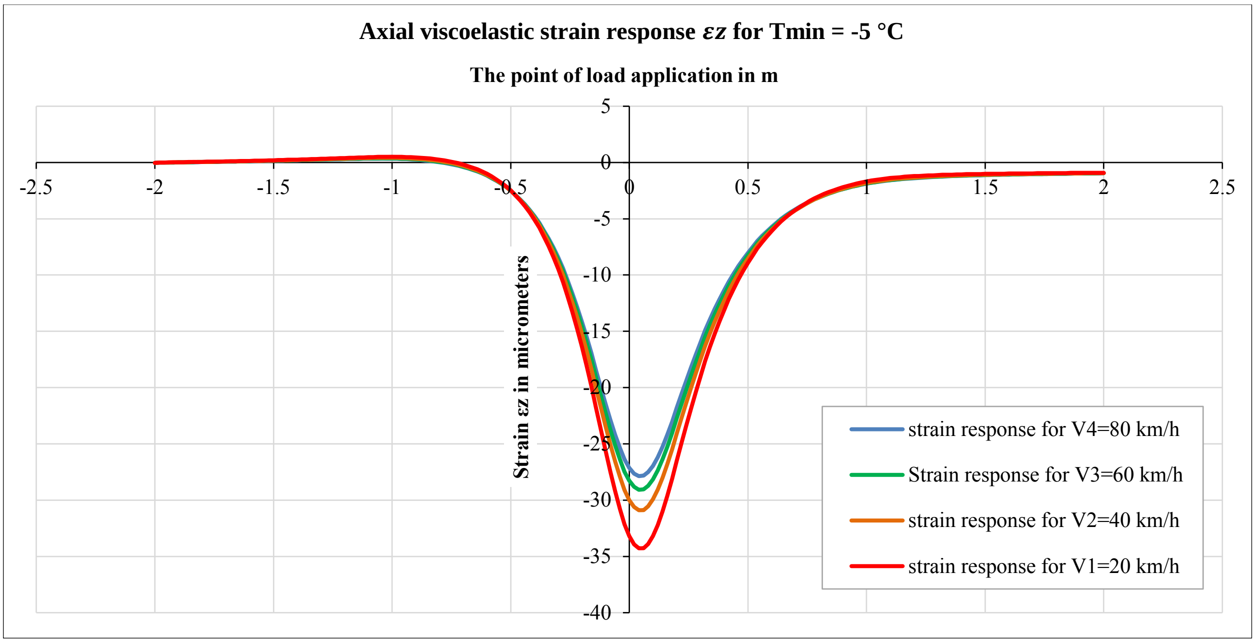

Figure 9. The viscoelastic strain results relative to speed variations for Tmin= -5°C

As illustrated in Figure 10, the viscoelastic displacement (Uz) increases significantly as traffic speed decreases, ranging from a minimum at V4 (80 km/h) to a maximum at V1 (20 km/h). This trend underscores the critical role of loading duration in pavement deformation. At lower speeds, vehicles exert forces for extended durations on a specific section of the pavement, resulting in increased displacement and deformation along the Z-axis. Conversely, higher speeds reduce loading duration, resulting in less vertical displacement. This observation aligns with the fundamental principles of viscoelasticity, where a material's response is time-dependent and influenced by the duration of applied forces. The analysis highlights the importance of considering traffic speed variations in pavement design and performance evaluation.

By incorporating speed-dependent Uz data into the design process, we can develop more accurate models of pavement behavior under real-world conditions. This approach enables the creation of roadways better suited to withstand variable traffic speeds without compromising structural performance or service life. Furthermore, these findings highlight the importance of adopting effective maintenance strategies and selecting materials that accommodate variations in traffic speeds and loading durations—key steps toward enhancing the resilience and sustainability of pavement infrastructure.

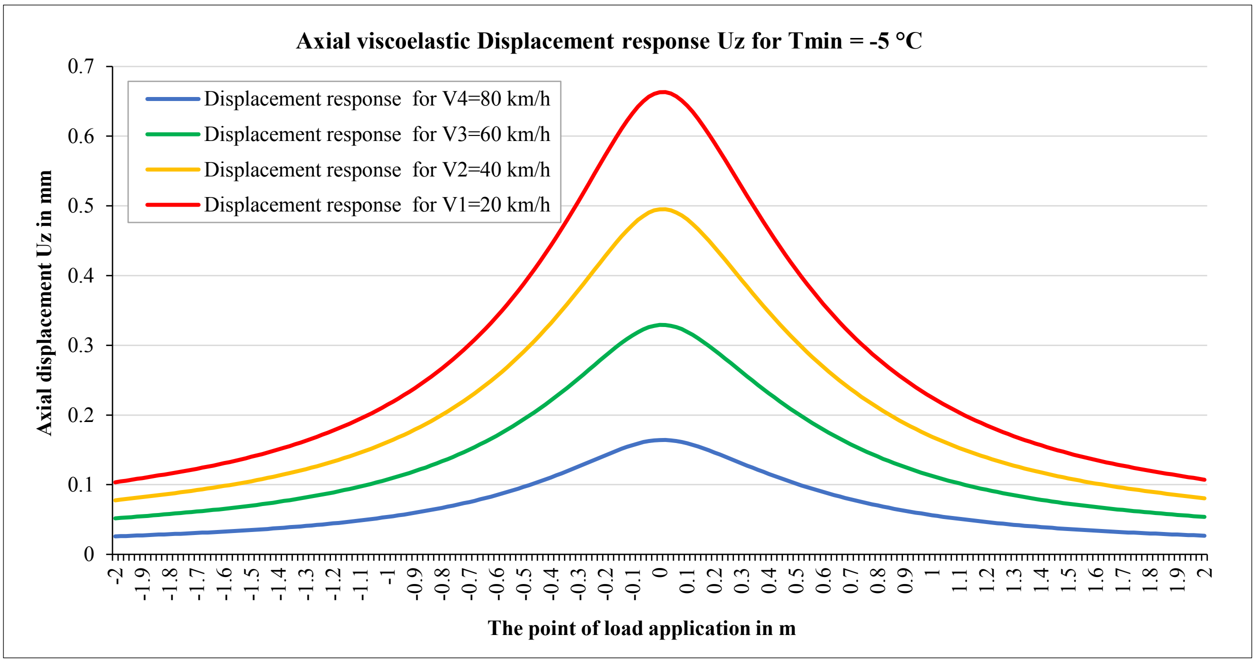

Figure 10. The axial viscoelastic displacement Uz for Tmin= -5°C

Figure 11 illustrates the axial viscoelastic stress (σz) response of the material under varying vehicle speeds and load application points at a maximum temperature of Tmax = 30 °C. The graph presents four curves corresponding to different speeds: V1 = 20 km/h (green), V2 = 40 km/h (blue), V3 = 60 km/h (yellow), and V4 = 80 km/h (red). The axial stress peaks sharply at the center position (0 m), where the load is applied, with the magnitude decreasing symmetrically as the distance from the center increases. Higher vehicle speeds result in greater stress magnitudes, as evidenced by the red curve (V4 = 80 km/h), which exhibits the highest stress, while the green curve (V1 = 20 km/h) shows the lowest. This behavior highlights the material's sensitivity to speed and dynamic loading, providing valuable insights into its performance under high-temperature and variable-speed conditions.

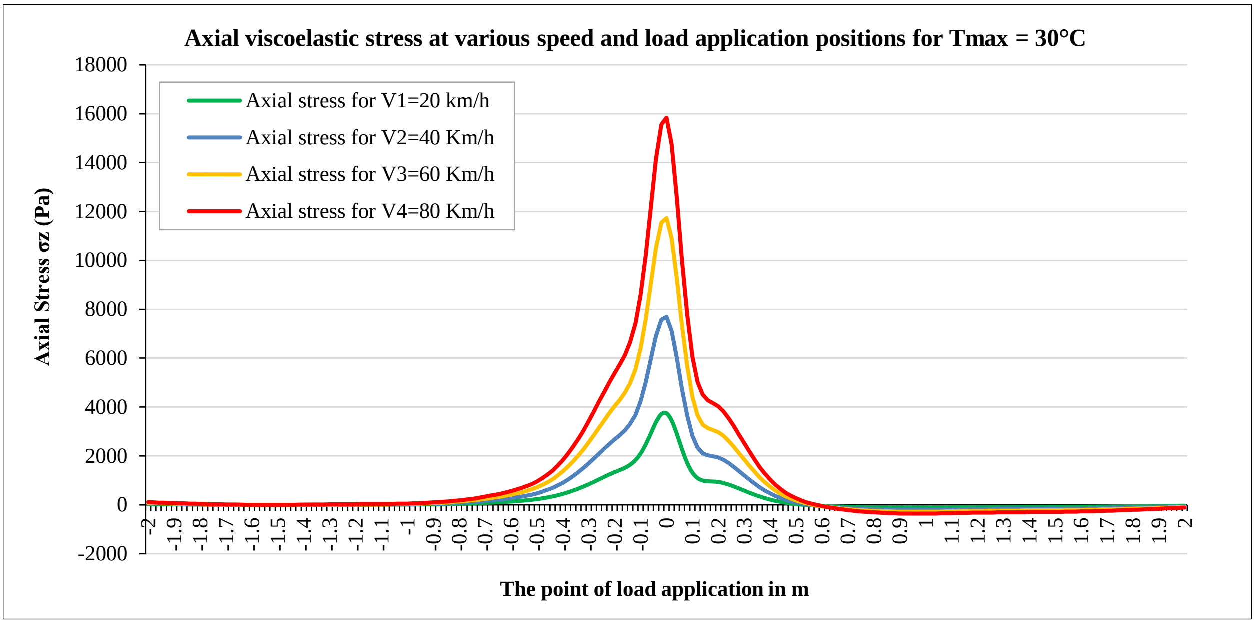

Figure 11. The viscoelastic stress results for Tmax = 30 °C

Figure 12 depicts the viscoelastic strain (ε_z) responses under varying vehicle speeds and load application positions at Tmax = 30 °C. The graph shows four curves representing different speeds: V1 = 20 km/h (red), V2 = 40 km/h (yellow), V3 = 60 km/h (blue), and V4 = 80 km/h (green). The strain is most negative (compressive) at the center position (0 m), where the load is applied, with values decreasing symmetrically as the distance from the center increases. The strain magnitude is highest at lower speeds, particularly for V1=20 km/h, and decreases progressively with increasing speeds, reaching the lowest strain at V4= 80 km/h. This trend suggests that higher vehicle speeds result in lower strain magnitudes, likely due to shorter load durations. The symmetrical strain distribution indicates even load application, and the results underscore the dynamic interaction between speed, load duration, and the material's viscoelastic properties.

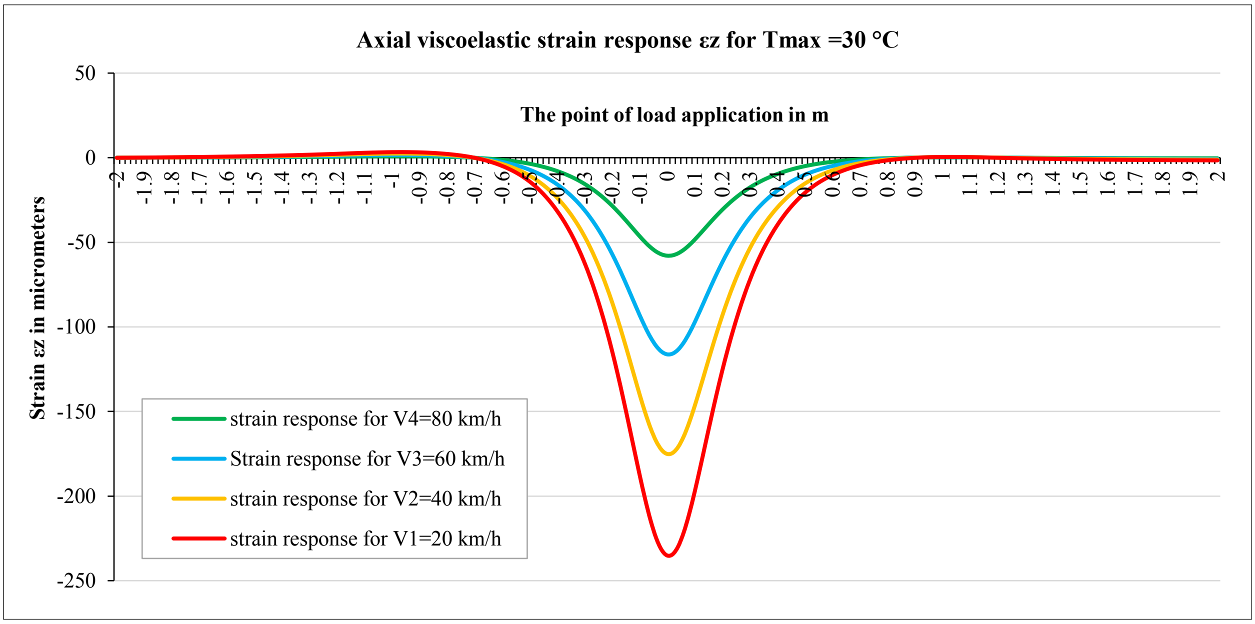

Figure 12. The viscoelastic strain results relative to speed variations for Tmax= 30°C

Figure 13 illustrates the axial viscoelastic displacement (Uz) response at different vehicle speeds under the maximum temperature (Tmax = 30 °C). The graph displays four distinct curves, each corresponding to a specific speed: V1 = 20 km/h (red), V2 = 40 km/h (yellow), V3 = 60 km/h (blue), and V4 = 80 km/h (green). The axial displacement peaks at the load application point (0 m) and gradually decreases with increasing distance from it.

Lower vehicle speeds result in higher displacement peaks due to the prolonged load duration. The red curve (V1 = 20 km/h) shows the highest displacement (~0.8 mm), while the green curve (V4 = 80 km/h) exhibits the lowest (~0.3 mm). The symmetric displacement patterns across all speeds demonstrate the material's uniform viscoelastic behavior under the given conditions. At Tmax = 30 °C, the displacement magnitude remains sensitive to vehicle speed, confirming the inverse relationship between speed and displacement.

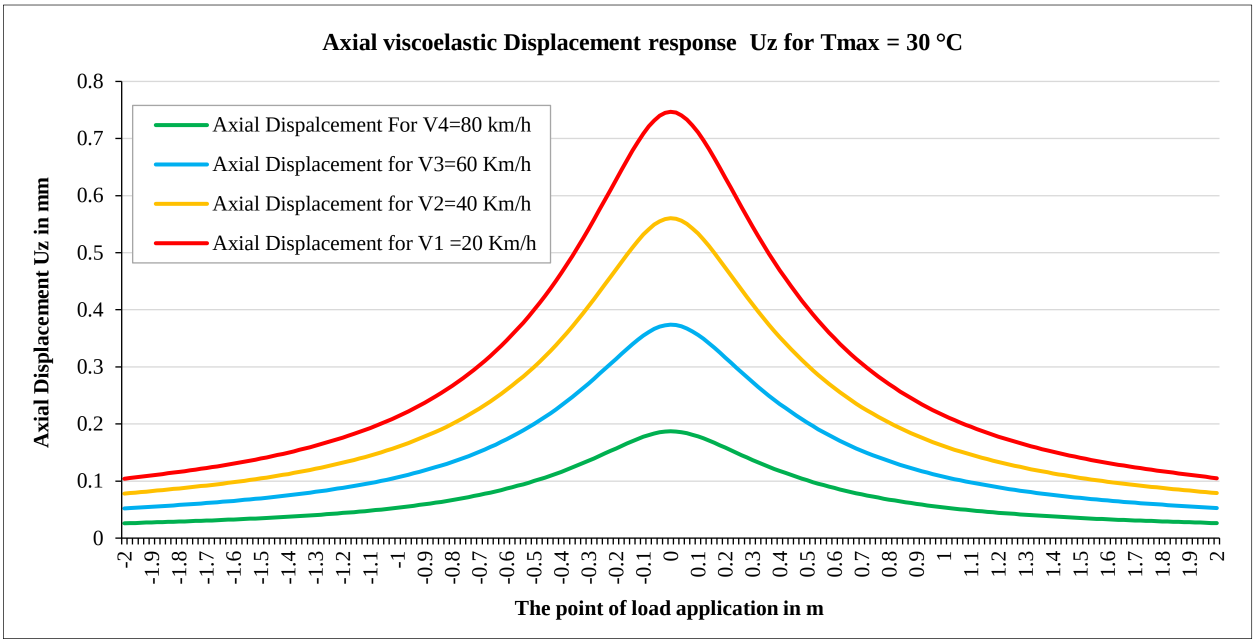

Figure 13. The axial viscoelastic displacement Uz for Tmax= 30°C

This study, conducted in the challenging climatic region of Ifrane Province, Morocco, meticulously examined the effects of freeze-thaw cycles on a specifically constructed flexible pavement section utilizing High-Performance Bituminous Material (0/20). Rather than comparing diverse asphalt or base materials, this research prioritized a detailed investigation of the pre-selected bituminous material under realistic operational conditions. By replicating the region's extreme freeze-thaw cycles, this study rigorously simulated Ifrane's dynamic climate by applying a range of traffic speeds (V1 to V4) and temperature fluctuations (T1min to T2max) to the pavement. The primary goal was to isolate and quantify the effects of these environmental stressors on the selected bituminous material, with a specific focus on its structural integrity and long-term performance. By concentrating solely on this material, rather than conducting a comparative analysis of alternatives, the study yielded more in-depth insights into its behavior under Ifrane's unique environmental pressures.

To accurately assess pavement durability and structural integrity, the research incorporated the influence of moisture variations and water infiltration, crucial factors in freeze-thaw damage. Although direct moisture measurements were not explicitly detailed, the study used local climate data, including temperature fluctuations, to model moisture dynamics within the pavement structure. Additionally, the evaluation of frost-resistant materials and frost indices inherently accounted for water infiltration and moisture-related stresses. Advanced modeling techniques were employed to simulate real-world conditions, providing an indirect but comprehensive analysis of moisture's impact on pavement performance.

The findings revealed a significant inverse relationship between traffic speed and pavement stress/strain, demonstrating that higher speeds correlate with reduced pavement deterioration. Specifically, as vehicle speed increases, the strain exerted on the pavement progressively diminishes, reaching a minimum of approximately 80 km/h. Elevated speeds facilitate a uniform distribution of vehicle forces across the road surface. Thereby minimizing localized stress concentrations and contributing to reduced deterioration. Consequently, the optimal speed range for minimizing pavement deterioration appears to center around this higher speed, with 80 km/h identified as a critical threshold for achieving the lowest observed strain. This study provides valuable insights into the performance of flexible pavements under freezing and thawing conditions, emphasizing the importance of considering both environmental factors and traffic dynamics in pavement design and maintenance, particularly for regions with harsh climates like Ifrane, where freezing and thawing cycles exacerbate pavement stress and necessitate optimized speed management strategies.

4.4. Discussion

This research provides significant insights into the complex interplay between viscoelastic responses, traffic speed, freeze-thaw cycles, and material displacements in pavement structures. The analysis confirms a clear relationship between traffic speed and the viscoelastic properties of pavement materials. Specifically, strain (ε_z) and displacements (Uz) increase as traffic speed decreases, whereas stress (σ_z) rises with higher traffic speeds. By employing viscoelastic-modeling approaches, this study enhances the understanding of pavement performance under varying environmental and operational conditions.

The verification process involved tests at traffic speeds ranging from V1 = 20 to V4 = 80 km/h, demonstrating the proposed design's robustness and efficacy. This investigation into viscoelastic responses—particularly vertical strains—played a key role in uncovering material deformation behavior under applied loads. The findings on immediate and long-term deformation patterns provide a comprehensive framework for characterizing the viscoelastic properties of pavement materials, with practical implications for improving durability and design. Other studies align closely with these findings, further validating the significant relationship between environmental/operational factors and pavement performance. For instance, Wang et al. (2020) [31] conducted an in-depth analysis of the effects of vehicle dynamics, axle configurations, and pavement surface roughness on strain responses. Their results showed a decrease in strain responses at higher traffic speeds, reinforcing the inverse relationship between speed and viscoelastic deformation observed in this study.

Similarly, Liu et al. (2022) [32] investigated the effects of loading speeds, axle weights, and temperature on strain and stress distributions in asphalt pavements using full-scale accelerated pavement testing and finite element simulations. Their findings revealed that higher speeds and axle weights significantly increase longitudinal strain and shear stress, aligning with this study's conclusions regarding dynamic pavement responses. This consistency highlights the need to account for speed variations and load conditions in pavement performance evaluations. Fan et al. (2020) [33] examined the impact of freeze-thaw cycles on the fatigue life of asphalt mixtures, demonstrating that increased cycles and saturation levels exacerbate material degradation. Their results justify the inclusion of freeze-thaw cycles as a critical variable in this study's analysis of material deformation. Furthermore, Fan et al.'s fatigue-freeze-thaw equation provides a quantitative basis for assessing these effects, reinforcing the research's comprehensive approach to evaluating environmental influences on viscoelastic behavior.

Furthermore, Sanfilippo et al. (2022) [34] investigated the effects of freezing-thawing cycles on void topology and asphalt's structural properties. Using X-ray imaging, they tracked changes in void structure before and after these cycles, identifying significant correlations between void topology and material degradation. Their findings align with this study's comprehensive assessment of how freeze-thaw cycles interact with viscoelastic material properties to influence pavement performance under varying conditions. These parallel results from independent studies reinforce the robustness of this research and significantly highlight its unique contributions to pavement engineering. While prior work has separately examined factors such as traffic speed, freeze-thaw cycles, or material deformation, this study distinguishes itself by integrating these elements into a unified framework through advanced viscoelastic modeling.

This comprehensive approach provides a deeper understanding of the complex relationships between environmental conditions, operational variables, and material behavior, addressing challenges that previous studies have only partially explored. This study addresses significant gaps in the literature by integrating the effects of traffic speed variations and freeze-thaw cycles with a detailed analysis of viscoelastic responses**.** Moving beyond traditional evaluations, this analysis reveals how these factors collectively influence pavement performance, both immediately after loading and over the long term. The findings offer valuable insights for optimizing pavement designs, particularly in regions with harsh climates and variable traffic demands. In addition, the study's innovative methodology—including a rigorous validation process across a wide range of traffic speeds—distinguishes it from prior work. This robust approach ensures the reliability of the proposed design framework and enhances its real-world applicability. Ultimately, this research provides actionable recommendations for improving pavement durability and resilience, establishing a foundation for future advancements in sustainable, high-performance pavement systems.

5. Conclusion

This study provides an essential insight into the intricate interactions between viscoelastic behavior, traffic speed, freeze-thaw cycles, and material displacements in pavement systems. The detailed analysis reveals a strong correlation between traffic speed and the viscoelastic characteristics of pavement materials. Notably, strain (ε_z) and displacements (U_z) increase as traffic speed decreases, while stress (σ_z) intensifies at higher speeds. Viscoelastic modeling in pavement structures has significantly advanced our understanding of their performance under diverse environmental and operational conditions. The verification process, which involved evaluating the pavement structure across traffic speeds ranging from V1 = 20 km/h (minimum) to V4 = 80 km/h (maximum) and temperatures from T1 (minimum) to T2 (maximum), demonstrates the durability and effectiveness of the proposed design. Our study also highlighted the significant impact of traffic speed and freeze-thaw cycles on the material's viscoelastic properties. A clear trend emerged, with the strain response increasing as traffic speed decreased. Similarly, freeze-thaw cycles accelerated material degradation, further altering its viscoelastic behavior. These findings underscore the need to account for traffic speed variations and freeze-thaw effects in pavement design and optimization. This study emphasizes the necessity of a comprehensive approach to pavement analysis and design. Accounting for the material's sensitivity to traffic speed and freeze-thaw cycles is critical for ensuring pavement durability and performance under diverse operational and environmental conditions. These research insights establish a foundation for advanced pavement design methodologies that integrate traffic dynamics and climatic factors, resulting in more resilient and efficient road infrastructure.

6. Declarations

6.1. Author Contributions

Conceptualization, O.B.; methodology, O.B.; software, O.B.; validation, K.B. and L.O.; formal analysis, O.B.; investigation, O.B.; resources, O.B., K.B., and L.O.; data curation, O.B.; writing—original draft preparation, O.B.; writing—review and editing, O.B., K.B., and L.O.; visualization, K.B.; supervision, K.B.; project administration, O.B and K.B; funding acquisition, O.B. and K.B. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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