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Influence of Temperature on the Viscoelastic Behavior and Durability of Flexible Pavements

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Abstract

This study meticulously examines the impact of temperature variations on the viscoelastic characteristics of flexible pavements composed of mineral aggregates and bituminous binders. The primary objective is to understand how temperature fluctuations affect the structure and durability of these pavements, designed to withstand traffic loads while absorbing stresses induced by weather conditions. The methodology involves a thorough analysis of a range of temperatures from T1 to T4, assessing their effects on road rutting and the longevity of pavement infrastructure. Through a detailed analytical approach, the research investigates the viscoelastic behavior of bituminous mixes, which display viscous and elastic properties that change with temperature. The findings reveal significant correlations between temperature variations and the performance of flexible pavements, offering insights into their structural resilience and durability under different climatic conditions. This research introduces a novel approach to managing flexible pavement infrastructure by enhancing our understanding of the temperature-induced viscoelastic response. The improvement lies in the precise quantification of temperature impacts, which can inform better maintenance and design strategies for flexible pavements. Ultimately, this leads to more resilient and long-lasting road surfaces, addressing the critical need for durable infrastructure in changing weather patterns.

Keywords: Flexible Pavements; Temperature Variations; Road Rutting; Viscoelastic Behavior; Durable Infrastructure.

1. Introduction

The durability of flexible pavements is essential for maintaining road infrastructure's long-term functionality and reliability. Temperature is a critical factor affecting pavement durability, primarily due to its significant influence on asphalt, a material susceptible to temperature changes. Extreme temperatures, whether excessively high or low, can induce various types of pavement distress, such as rutting, cracking, and premature aging. Combined stresses from vehicular traffic and environmental thermal conditions worsen these challenges, highlighting the need for a comprehensive understanding of their intricate interplay and subsequent impact on pavement performance [1, 2]. Over time, these interactions can lead to fatigue, structural cracking, and overall deterioration, underscoring the importance of resilient pavement systems that effectively manage both mechanical loads from traffic and thermal stresses from external environments [3, 4]. Asphalt mixtures, often used in flexible pavements, possess inherent flexibility, durability, and resilience. These attributes make asphalt an excellent choice for road construction because it can endure the stresses and strains caused by different traffic loads and patterns. The flexibility of asphalt allows it to absorb and distribute the weight of heavy vehicles, reducing the likelihood of cracks and other structural damages. Its durability ensures a longer lifespan for the pavement, minimizing the need for frequent repairs and maintenance. Additionally, asphalt's resilience enables it to adapt to environmental variables such as temperature fluctuations, precipitation, and freeze-thaw cycles, which can otherwise compromise the integrity of the pavement [5, 6].

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Numerous studies have investigated the influence of temperature on the performance of flexible pavements. Ayasrah et al. (2023) [7] concentrated on creating a temperature prediction model tailored to local conditions, improving its relevance and applicability. They conducted comprehensive data collection using temperature data loggers at various depths, providing a detailed dataset for model validation. The model underwent validation using field data to confirm its reliability and utilizes sophisticated MATLAB software for precise temperature profile generation, achieving a relative error of around 7%. Moreover, it incorporates external heat transfer modes such as radiation and thermal convection to simulate real-world conditions. However, the research study focuses solely on temperature prediction without considering other factors such as traffic load and moisture. The model necessitates continuous adjustments and calibration, and the complexity of MATLAB may restrict its accessibility for some practitioners. Furthermore, the short-term validation period may not capture the long-term effects of temperature on pavement performance.

Additionally, Xu et al. (2022) [8] employed a discrete-element model (DEM) to analyze asphalt pavement responses to seasonal temperature changes, providing valuable insights into the effects of temperature on interlayer bonding and mechanical behavior. Their study focused on the impact of temperature variations on the physical and structural properties of asphalt layers across different seasons. By employing DEM, they simulated and observed detailed interactions within pavement materials, revealing that lower temperatures enhance layer continuity and reduce compressive stress. On the other hand, higher temperatures weaken bonds and increase tensile and shear stresses. This detailed analysis bears significant implications for enhancing pavement design and maintenance strategies by addressing seasonal performance variations in asphalt pavements. However, while innovative, their reliance on DEM involves assumptions that may oversimplify the complex behavior of asphalt materials and their interactions in real-world scenarios. The model's accuracy heavily depends on the quality and appropriateness of these assumptions, potentially limiting the generalizability of findings to different pavement types and environmental conditions. In addition, the study's focus on short-term seasonal analysis does not fully capture the long-term effects of temperature fluctuations on pavement durability. Long-term studies are crucial for comprehending the cumulative impact of temperature changes and ensuring pavements withstand these stresses throughout their service life. Continuous validation and calibration of the model with field data from diverse regions and conditions are necessary to enhance its applicability and reliability for broader use in pavement engineering.

Pham et al. (2023) [9] innovatively incorporated rubber aggregates into cement-stabilized bases to mitigate temperature fluctuations in semi-rigid pavements. Their research aimed to explore how adding rubber aggregates could enhance the thermal stability of pavement materials, potentially reducing temperature-induced distress such as cracking and shrinkage. The researchers performed thorough tests on thermal properties, investigating parameters such as thermal conductivity, thermal diffusivity, and specific heat capacity of the rubberized cement-stabilized mixtures. The results demonstrated that incorporating rubber aggregates reduces temperature fluctuations within the pavement structure, a significant advantage for maintaining pavement integrity under varying thermal conditions. The study indicates that incorporating rubberized bases could improve pavement resilience, allowing them to endure temperature extremes without significant degradation.

However, despite these promising findings, the study also revealed some limitations. The focus was primarily on specific aggregate sizes and short-term thermal effects, which may not fully represent the performance of these materials in a broader context. The study used rubber aggregates within a narrow size range and did not explore the effects of using different sizes or blends of aggregates. This limited focus restricts the generalization of the results to other types of rubber aggregates or different mix designs. Furthermore, the study primarily concentrated on short-term thermal performance and did not extensively investigate long-term durability. Despite the evident thermal benefits, concerns remain regarding the long-term structural integrity of pavements due to potential reductions in mechanical properties such as compressive strength and tensile strength. The study did not thoroughly explore how these mechanical reductions might affect pavement performance over an extended period under real-world traffic and environmental conditions. To fully understand the capabilities of rubberized cement-stabilized bases, additional investigations are needed to evaluate long-term durability, mechanical resilience, and performance under various conditions. The study should include different aggregate sizes, varying rubber contents, and extensive field trials to assess the practical application of this innovative approach across diverse regions and climates.

Our study aims to evaluate asphalt mixtures' viscoelastic characteristics across varying temperatures (T1 to T4) to predict pavement rutting as an indicator of fatigue-induced deterioration. By integrating these temperature influences, we aim to increase the longevity of flexible pavements. The article offers a structured analysis of pavement behavior and management strategies, beginning with a literature review on road pavement design and methods essential for longevity, stability, and safety. The experimental case study on Berrechid's pavement structure highlights its significance amid urban and industrial growth, detailing local climatic conditions essential for understanding year-round thermal stresses on pavements. Structural design considerations optimize pavement performance under diverse environmental conditions. Results and discussion sections present findings from specific pavement structure analyses, including viscoelastic modeling of stress, strain, and displacement responses to varying temperatures (T1-T4). This comprehensive approach integrates data collection, climatic insights, structural design, and advanced modeling to inform future pavement management effectively.

1.1. Literature Review on Road Pavement Design

Designing road pavements is a crucial task that impacts road durability, stability, and safety. This complex process involves selecting materials, predicting performance, and ensuring that the pavement can withstand various loads and environmental conditions for a prolonged duration. It relies on several principles and methodologies, typically grouped into three main categories.

The first type, commonly used in pavement design, treats the pavement as a series of linear, homogeneous, and isotropic elastic layers. The methodology referred to as the layered elastic theory simplifies the complex analysis of the pavement's mechanical properties by breaking down the pavement structure into distinct layers. Each layer is assumed to have uniform properties throughout, making it easier to model and predict how the pavement will respond to various loads. These layers exhibit specific elastic traits, including stiffness, which measures how much a material deforms under stress, and resistance to deformation, which indicates how well the material can return to its original shape after being subjected to forces [10]. For a layer composed of these materials subjected to tensile stress by bending, the allowable strain $\varepsilon_{t,adm}$ is determined using Equation 1.

$$\varepsilon_{t,adm} = \varepsilon_6 \times A_1 \times (\frac{NE}{10^6})^b \times K_c \times K_f \times K_s \quad (1)$$

where ε_6 is represents, the deformation leading to a specified lifespan, a parameter of the fatigue law of the bituminous material. NE is the number of passes of the reference axle. b is the slope of the fatigue law of the bituminous material. A_1, K_c, K_f and K_s are adjustment coefficients.

This method helps understand how stresses are distributed across the pavement, enabling predictions of how it will deform and handle the strains caused by traffic over time. By modeling the pavement as a series of linear, homogeneous, and isotropic elastic layers, we can calculate the distribution of stresses and strains throughout the pavement structure when subjected to different loads. Despite its utility in calculating mechanical responses, this approach has significant limitations because it does not fully consider the viscoelastic properties of the asphalt used in the top layer of the pavement. Asphalt exhibits viscous and elastic behavior, meaning its stress response is time-dependent and temperature-sensitive. The layered elastic theory suggests that materials primarily behave elastically, simplifying computations but not accurately representing the real-world behavior of asphalt. This constraint leads to less accurate forecasts of pavement performance, particularly under fluctuating temperature conditions and prolonged loading, where the asphalt may exhibit significant deformation and time-dependent recovery. Therefore, while the layered elastic method provides valuable insights and a foundation for pavement design, it requires additional considerations and models that account for the complex viscoelastic nature of asphalt to ensure a more comprehensive and accurate assessment of pavement durability and performance.

The second type of pavement design employs an empirical approach, which relies on extensive analysis of historical data to derive relationships and patterns concerning road performance. This empirical method delves into vast datasets accumulated over time to discern correlations between various environmental factors and the structural requirements of pavements. By scrutinizing data related to traffic patterns, geological conditions, topographical features, and climate variables, we can extract valuable insights. These insights aid in understanding how different environmental conditions and road characteristics affect pavement behavior and durability. Through this method, we can develop practical guidelines and predictive models to inform pavement design decisions, ensuring that road infrastructure is resilient and optimized for its specific environmental context [11]. The relative damage that the pavement sustains each season is determined using Equation 2.

$$U_f = \frac{N}{N_{adm}} \quad (2)$$

where U_f is Relative damage, N is the total number of cycles endured by the pavement, N_{adm} is the allowable number of cycles for the pavement.

However, these empirical models are typically specific to particular regions or road types, as they are developed based on data collected from localized conditions and circumstances. Considering the diverse range of factors such as climate, traffic volume, soil composition, and terrain characteristics across various regions, applying these models universally without modifications can result in inaccuracies in pavement design or predictions. It's crucial to recognize the unique aspects of each location and adapt empirical models accordingly, incorporating local data and considerations to ensure the reliability and effectiveness of the design outcomes. Failure to account for these variations may compromise the performance and longevity of the pavement, underscoring the importance of context-specific adjustments in empirical modeling approaches.

The third type is the Mechanistic-Empirical (ME) Method, which skillfully blends theoretical modeling with empirical data. This methodology seeks to integrate the precision of these models, which simulate physical forces and deformations within the pavement, with the specific conditions of each site. The permissible rut depth limit is 25 mm

[12, 13]. The theoretical criterion involves determining the number of single-axle load repetitions needed to reach the rut depth. The study allows obtaining the following criterion using Equation 3.

$$\varepsilon_z = 0.0058.\mathrm{N}^{-0.171} \quad (3)$$

where ε_z is represents the vertical deformation on the pavement induced by a wheel pass, N is denotes the number of repetitions of loads leading to the 25 mm rut.

Mechanistic components of this method might encompass intricate calculations aimed at comprehensively assessing the stress distribution and structural response induced by traffic loads. Such an analysis involves considering various factors, including the properties of individual pavement layers, the condition of the underlying soil, and the dynamic interactions between these elements. By employing sophisticated modeling techniques, we can gain deeper insights into how different materials and configurations will perform under real-world conditions, enabling more precise and reliable pavement designs. However, while the Mechanistic-Empirical (ME) Method provides a robust framework for pavement design, such an analysis involves considering various factors, including the properties of individual pavement layers, the condition of the underlying soil, and the dynamic interactions between these elements. By employing sophisticated modeling techniques, we can gain deeper insights into how different materials and configurations will perform under real-world conditions, enabling more precise and reliable pavement designs. However, while the Mechanistic-Empirical (ME) Method provides a robust framework for pavement design, such an analysis involves considering various factors, including the properties of individual pavement layers, the condition of the underlying soil, and the dynamic interactions between these elements. By employing sophisticated modeling techniques, we can gain deeper insights into how different materials and configurations will perform under real-world conditions, enabling more precise and reliable pavement designs. However, while the Mechanistic-Empirical (ME) Method provides a robust framework for pavement design, it can be inherently complex and resource-intensive. Executing this method necessitates the availability of comprehensive datasets, sophisticated computational tools, and substantial technical proficiency [14, 15].

The methods mentioned earlier have certain limitations. This article proposes a new approach that integrates the influence of temperature on the viscoelastic behavior of flexible pavements at different temperatures ranging from T1 to T4. The main objective is to predict pavement rutting caused by fatigue to establish the pavement's lifespan.

2. Material and Methods

The methodology employed in this research comprises several steps focused on analyzing the viscoelastic behavior of pavements and identifying the necessary actions for their proper design. The process starts with data collection, covering various factors influencing pavement performance. Concurrently, we assess the thickness of different layers, and appropriate materials are selected, followed by dynamic viscoelastic modeling of the pavement structure.

The initial phase involves collecting extensive data on multiple aspects, including studying and documenting traffic patterns to comprehend vehicular movement dynamics. Additionally, a detailed analysis of local climatic conditions takes place to assess environmental influences on pavement durability and performance. Furthermore, we conducted thorough geotechnical studies to determine the composition and properties of the underlying soil to design resilient and stable road surfaces [16].

The subsequent step entails meticulously selecting suitable structures for implementation and identifying requisite pavement rehabilitation actions. This pivotal phase stands at the core of the study, functioning as a preliminary diagnosis that profoundly influences the decision-making process. A precise determination of the thickness for each layer holds paramount importance, as it directly affects the overall structural integrity of the roadway. This thorough evaluation process guarantees that each layer is appropriately sized, taking into meticulous consideration anticipated traffic loads, soil characteristics, and the unique climatic conditions prevailing in the area. By meticulously aligning the thickness of each layer with these crucial factors, the project team ensures the resilience and durability of the pavement infrastructure, mitigating potential risks and enhancing overall performance and longevity.

Following this, we conduct dynamic viscoelastic modeling over a temperature range from T1 to T4. This modeling process aims to clarify several critical parameters essential for evaluating pavement performance. These parameters encompass the vertical stress σ_z exerted on the pavement, the corresponding vertical deformation ε_z experienced by the pavement layers, and the precise determination of vertical displacement Uz, which captures the extent of vertical movement within the roadway structure. By meticulously analyzing these parameters across different temperature scenarios, we can gain profound insights into the pavement's response to thermal variations, facilitating robust maintenance strategies and infrastructure enhancements designed to ensure long-term durability and optimal serviceability. The objective of this modeling is to gain a comprehensive understanding of how the roadway structure reacts under the influence of varying temperatures. Evaluating vertical extension deformation ε_z is another essential aspect, quantifying how the roadway deforms under the influence of applied loads and offering valuable insights into its resilience to repeated traffic stresses [17].

Moreover, the determination of vertical displacement U_z offers a holistic perspective on the dynamic behavior of the roadway. Delving into how the roadway responds vertically to varying temperatures enables a comprehensive evaluation of its structural integrity and capacity to sustain an optimal level of service for users. By grasping the extent of vertical movement, we can assess the pavement's resilience against temperature-induced stresses and its overall performance under real-world conditions, facilitating informed decisions regarding maintenance and infrastructure improvements.

The organizational chart presented below (Figure 1) offers a thorough and detailed outline of the various stages that constitute the methodology adopted for this project.

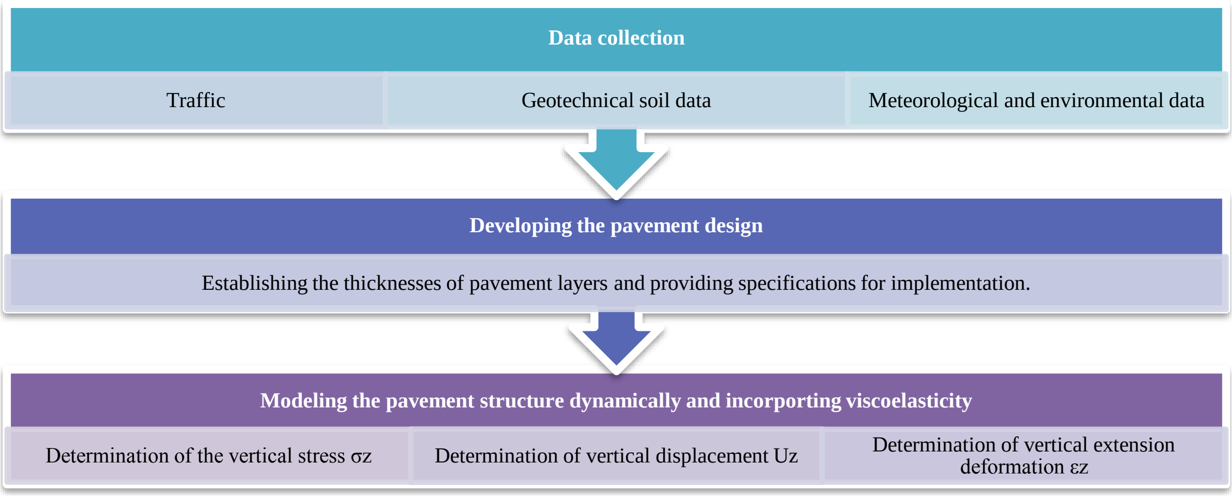

Figure 1. The flowchart illustrates the employed methodology

2.1. Experimental Case Study

The pavement structure under study is located in the province of Berrechid, within the administrative region of Casablanca-Settat in Morocco, as shown in Figure 2. Berrechid is a significant locality known for its rapidly developing infrastructure and strategic location as a hub for transportation and logistics within the region. This area has been experiencing substantial urban and industrial growth, making it a critical point of focus for road network assessments and enhancements. Located approximately 30 kilometers southeast of Casablanca, Berrechid is a vital link between major cities and industrial zones. The region's climate, characterized by a semi-arid to Mediterranean climate, poses unique challenges for pavement performance, necessitating thorough investigation and tailored engineering solutions. The choice of Berrechid for this study is particularly relevant due to its diverse traffic patterns, which include heavy commercial vehicles, commuter traffic, and agricultural transport, all contributing to varying stress levels on the pavement structure.

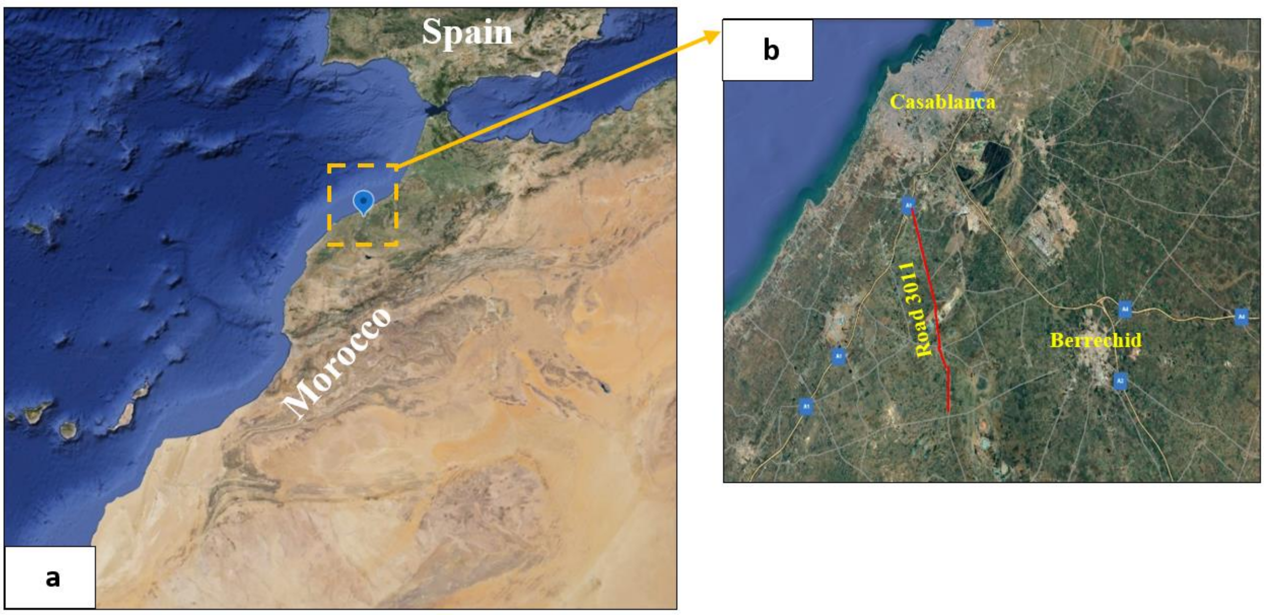

Figure 2. The geographical location of the study area

The research conducted in Berrechid aims to address these multifaceted challenges by employing advanced methodologies, such as dynamic viscoelastic modeling, to evaluate the pavement's response to various stressors. This approach involves a comprehensive analysis of the pavement's behavior under different loading conditions and environmental factors, providing a detailed understanding of how the material properties change over time and under varying temperatures [18].

To support our proposed methodology, we plan to implement a comprehensive strategy that involves various investigative measures. This methodology will encompass extensive field investigations, detailed laboratory testing, and rigorous analysis [19]. Then, we will conduct field investigations, collecting representative road material samples for precise testing. Additionally, we will perform geotechnical studies to gather detailed information about subsurface characteristics and measure the road's structural response to understand its behavior under various conditions. Concurrently, the laboratory-testing phase will be thorough, focusing on evaluating the diverse properties of road materials, including soil and aggregates [20]. This detailed assessment aims to determine the suitability of these materials for the proposed reinforcement techniques. Combining field investigations and laboratory testing is essential for a comprehensive understanding of the pavement's current condition and the intrinsic properties of the materials used (refer to Table 1).

Table 1. The classification of pavement structures

Layer	Material type	Young's modulus (E)	Poisson's ratio (ν)
Surface Layer	Asphaltic concrete (BB)	1270 to 9120 MPa	0.35
Base Layer	Bituminous concrete gravel (GBB)	1880 to 11000 MPa	0.35
Sub-base Layer	Untreated gravel (GNF1)	200 to 600 MPa	0.35
Capping Layer	Untreated gravel (GNF1)	200 to 600 MPa	0.35
Subsoil	supporting subsoil	20 to 200 MPa	0.35

2.2. The Climatic Environment

The outcomes of the climate analysis conducted in the study area reveal an average annual precipitation of 429 mm and a temperature range fluctuating from a minimum of 6°C in winter to a maximum of 31°C in summer. These climatic factors are vital for comprehending the thermal stresses endured by pavements throughout the year. During winter, the lower temperatures can render pavement materials brittle, elevating the risk of cracks. Conversely, the elevated summer temperatures may cause asphalt to soften, resulting in rutting and deformation under heavy traffic. Such conditions play a pivotal role in shaping the viscoelastic behavior of pavement materials, thereby influencing their performance, longevity, and maintenance demands [21].

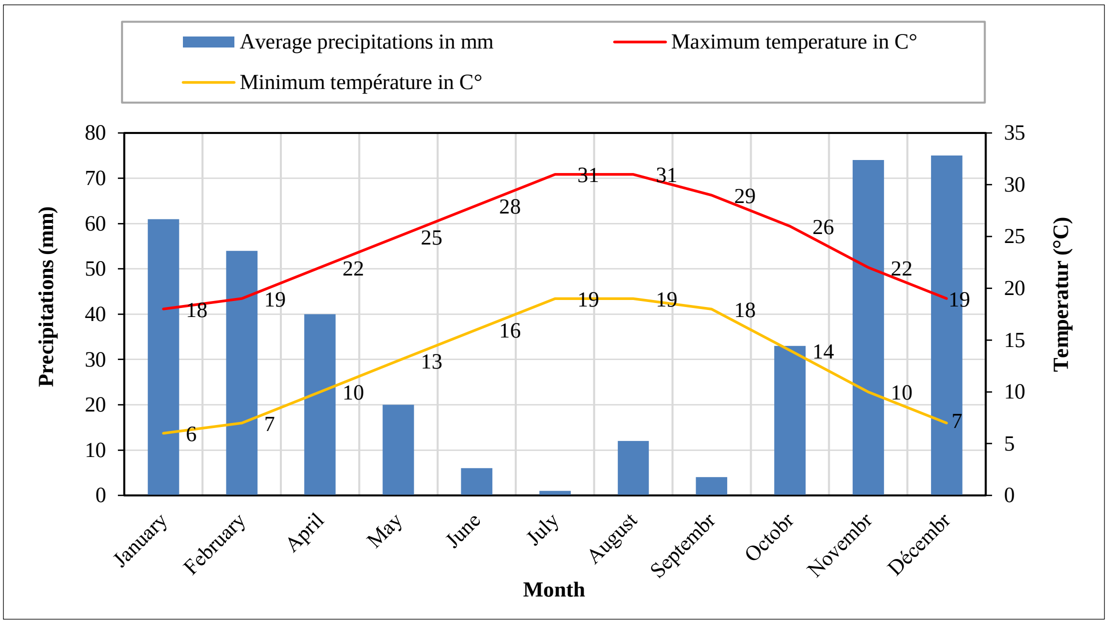

Figure 3. The average annual precipitation and the monthly minimum and maximum temperatures of the province of Berrechid

2.3. The Structural Design of the Pavement

Designing pavement structures is crucial for developing road infrastructure that is resilient, safe, and performs effectively under diverse conditions. Designing a pavement that is both durable and environmentally friendly requires in-depth consideration of numerous factors. Critical influences on pavement design include traffic loads, weather conditions, subgrade properties, and viscoelastic properties. Understanding and carefully evaluating these critical aspects are vital for optimizing pavement performance and ensuring long-term utility [22]. To analyze heavy vehicle traffic, we will use Equation 4, as shown below.

$$N13t = A1 \times A2 \times A3 \times A4 \times M4 \times M2 \times T1 \tag{4}$$

where A1 represents the width coefficient, a crucial parameter in characterizing pavement structures. This coefficient, denoted by A1, directly influences width considerations in road surface design and construction, A2 represents the average aggressiveness coefficient, capturing the overall intensity and harshness of external factors affecting the pavement, A3 is the number of heavy vehicles, A4 symbolizes the growth in heavy vehicles within the traffic mix. This symbolic representation, identified as A4, highlights the specific factor of increased heavy vehicle presence, contributing to the overall load dynamics experienced by the pavement, M4 represents cumulative traffic. This cumulative measure, indicated by M4, is instrumental in comprehensively evaluating the overall stress on the pavement structure, M2 signifies adjusted traffic specifically attributed to heavy vehicles exceeding 8 tons. This designation, expressed as M2, allows for a targeted assessment of the substantial loads borne by the pavement from heavier vehicles, aiding in the formulation of tailored reinforcement strategies, T1 is the coefficient dedicated to traffic distribution, providing insights into the dispersion patterns of different vehicle types on the road network.

3. Results and Discussion

3.1. The Results of the Studied Pavement Structure

This study meticulously executed the dimensioning process, adhering closely to established methodological guidelines. We plan and execute each stage of the process to ensure the accuracy and reliability of the pavement structure. This comprehensive methodology aimed to establish a solid foundation for subsequent analysis. Figure 4 details the results of the dimensioning process for the selected pavement structure. This visual representation illustrates the essential parameters, configurations, and specifications derived from the dimensioning efforts. It encapsulates critical data points crucial for a comprehensive understanding of the structural attributes and pavement design.

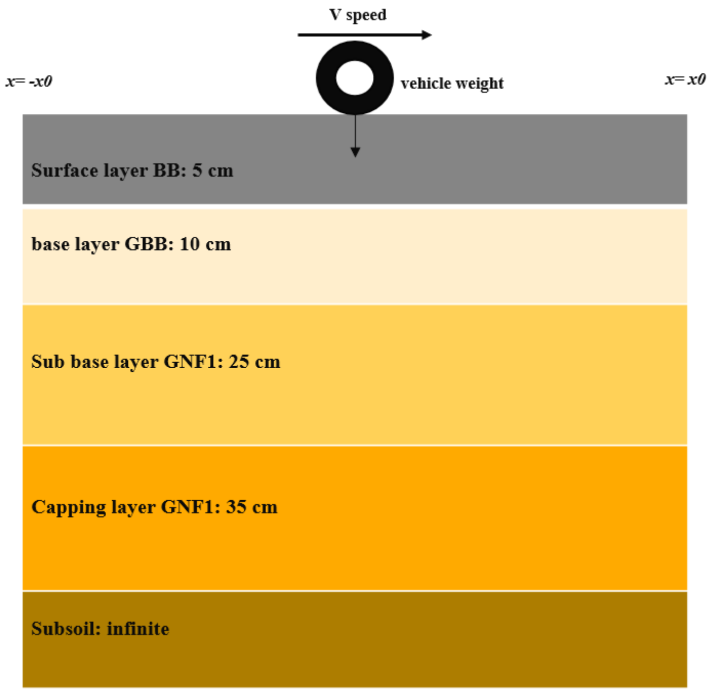

Figure 4. The adopted pavement structures

The designated pavement structure for this project includes layers specified as 5BB+10GBB+25GNF1+35GNF1, as shown in Table 2. This alphanumeric representation outlines the sequence of materials incorporated into the pavement, with each layer serving a distinct purpose to ensure optimal performance.

Table 2. The characteristics of the pavement structure materials as a function of temperature

Layer	Material Type	Young's modulus (E) at T1=6°C (MPa)	Young's modulus (E) at T2=16°C (MPa)	Young's modulus (E) at T3=20°C (MPa)	Young's modulus (E) at T4=31°C (MPa)
Surface layer	Asphaltic concrete (BB)	9120	5040	3600	1270
Base layer	Bituminous concrete gravel (GBB)	11000	6600	5000	1880
Sub-base layer	Untreated gravel (GNF1)	200	200	200	200
Capping layer	Untreated gravel (GNF1)	200	200	200	200
Subsoil	Supporting subsoil	50	50	50	50

BB stands for Asphalt Concrete 0/10. This layer, denoted by BB, comprises asphalt concrete with a particle size distribution ranging from 0 to 10 mm.

GBB corresponds to Grave Bituminous Concrete 0/14, indicating that this layer comprises grave bituminous concrete with particles ranging from 0 to 14 mm in size.

GNF1 designates Untreated Gravel 0/40. The layer identified as GNF1 consists of untreated gravel with a particle size distribution from 0 to 40 mm.

The detailed examination of the characteristics and features of the materials comprising the pavement structure, as documented and delineated in Table 2, provides essential insights into the composition and behavior of the construction materials employed in road infrastructure. This thorough examination encompasses various facets, including the composition of asphalt blends, the properties of aggregates, and other pertinent material specifications. Examining these diverse elements allows us to grasp the individual contributions of each material to the overall performance, durability, and lifespan of the pavement structure.

3.2. The Viscoelastic Creep Compliance

Viscoelastic creep compliance, denoted as $D(t)$, is a property of materials used in pavements, especially asphalt or bituminous materials. It describes the material's response over time when exposed to a consistent load or stress. Viscoelastic creep compliance measures how a material deforms over time under sustained loading. This property is essential for understanding the performance of asphalt or bituminous layers in a pavement structure, especially under repeated traffic loads.

The function $D(t)$ delineates the correlation between the imposed stress or load and the consequent strain or deformation during a specified duration. It captures the viscoelastic nature of the material, which includes both elastic (recoverable) and viscous (non-recoverable) components of deformation. The function $D(t)$ illustrates the connection between the applied stress and the resulting strain over a defined period. This function encapsulates the viscoelastic properties of the material, encompassing both elastic, which refers to the recoverable component of deformation, and viscous, representing the non-recoverable aspect. Integrating these components provides a thorough insight into how the material reacts to external forces across time, encompassing immediate elastic response and gradual viscous relaxation [23], as detailed in Equation 5.

$$D(t) = D_\infty + \frac{D_0 - D_\infty}{1+(\frac{t}{T_0})^{N_D}} \tag{5}$$

where $D(t)$ represents the viscoelastic creep compliance in MPA^{-1}, D_0 signifies the viscoelastic creep compliance when t=0, D_∞ denotes the viscoelastic creep compliance when $t = \infty$, T_0 and N_D are shape parameters.

3.3. The Results of the Viscoelastic Modeling of the Road Pavement Structure

In this section, we undertake an extensive series of examinations meticulously designed to validate the proposed pavement structure. These evaluations rigorously analyze the impacts of applied stress, deformation, and displacements along the Z-axis, aiming to uncover a detailed understanding of how the pavement behaves under a spectrum of load conditions. Our main aim is to evaluate the pavement's structural integrity and performance capabilities, ensuring its ability to withstand the challenging demands of vehicular traffic and various environmental factors. By conducting these meticulous assessments, our study aims to substantiate the reliability and resilience of the proposed pavement structure across a broad array of operational scenarios. This thorough approach provides significant practical insights into pavement engineering and design. The findings from these examinations are pivotal in refining current practices and advancing the knowledge base, ultimately contributing to the optimization and sustainability of infrastructure systems.

Furthermore, our evaluation encompasses a comprehensive range of temperatures, from 6 to 31°C. This wide temperature range allows us to assess the pavement's performance under various thermal conditions. We aim to gain profound insights into its resilience against climate fluctuations and varying loads through this rigorous testing. Through this systematic examination of varied scenarios, our validation process aims to establish the resilience and efficiency of the pavement structure under a spectrum of real-world operational conditions. This approach not only ensures robustness in design but also provides crucial data for enhancing the longevity and performance of pavements in practical applications. The insights garnered from these assessments are essential for refining engineering strategies and advancing our understanding of pavement behavior under dynamic environmental influences.

The viscoelastic response of the surface layer to applied load stress represents a complex interaction influenced by the inherent mechanical properties of the material and the external forces exerted upon it. This intricate response encompasses the material's capacity to undergo deformation and demonstrate a combination of elastic and viscous behaviors when subjected to applied load stress. Temperature plays a pivotal role in modulating this viscoelastic behavior, especially in the context of flexible pavements. Temperature variations can induce significant changes in the material properties of the pavement, thereby affecting its overall performance. For instance, as temperatures fluctuate, the stiffness and viscosity of the pavement material can vary, altering its ability to absorb and dissipate stress from vehicular traffic and environmental conditions. This temperature sensitivity is crucial in pavement engineering, given its impact on rutting resistance, fatigue life, and overall durability. By thoroughly studying these temperature-dependent effects, we can optimize pavement designs to improve longevity and resilience under diverse climatic conditions and traffic loads. Thus, understanding the dynamic interplay of viscoelasticity and temperature provides essential insights for advancing the field of pavement materials and engineering practices.

As shown in Table 3 and Figure 5, the results indicate a clear trend where the viscoelastic stress response increases with rising temperature. This correlation is evident across a temperature spectrum that ranges from a low of 6°C (T1min) to a high of 31°C (T4max). As the temperature rises, the pavement material becomes softer and more pliable, which enhances its viscous behavior. At a low temperature of 6°C, the pavement's flexibility causes deformation under traffic load, resulting in elevated stress levels. The pavement material's stiffness and brittleness suggest it experiences less deformation under equivalent loads. However, as temperatures approach the higher end of the range (31°C), the materials increased softness results in a higher viscoelastic response.

Table 3. Calculation results for the viscoelastic stress response as a function of temperatures T1, T2, T3, and T4

Location of applied load (m)	Time (s)	The viscoelastic Stress response in Pa for T1=6 °C	The viscoelastic Stress response in Pa for T2=16 °C	The viscoelastic Stress response in Pa for T3=20 °C	The viscoelastic Stress response in Pa for T4=31 °C
-2	0	3.06	3.18	3.21	3.22
-1.5	0.09	0.55	0.91	1.07	1.46
-1	0.18	-0.81	-1.75	-1.77	-0.55
-0.5	0.27	52.27	42.14	34.14	2.32
0	0.36	82.81	597.79	904.73	2214.74
0.1	0.378	-186.40	-166.46	-109.47	458.35
0.5	0.45	-14.96	-52.61	-75.11	-185.00
1	0.54	-28.88	-38.80	-43.31	-71.61
1.5	0.63	-14.22	-20.59	-23.71	-41.74
2	0.72	-8.51	-13.41	-15.66	-27.80

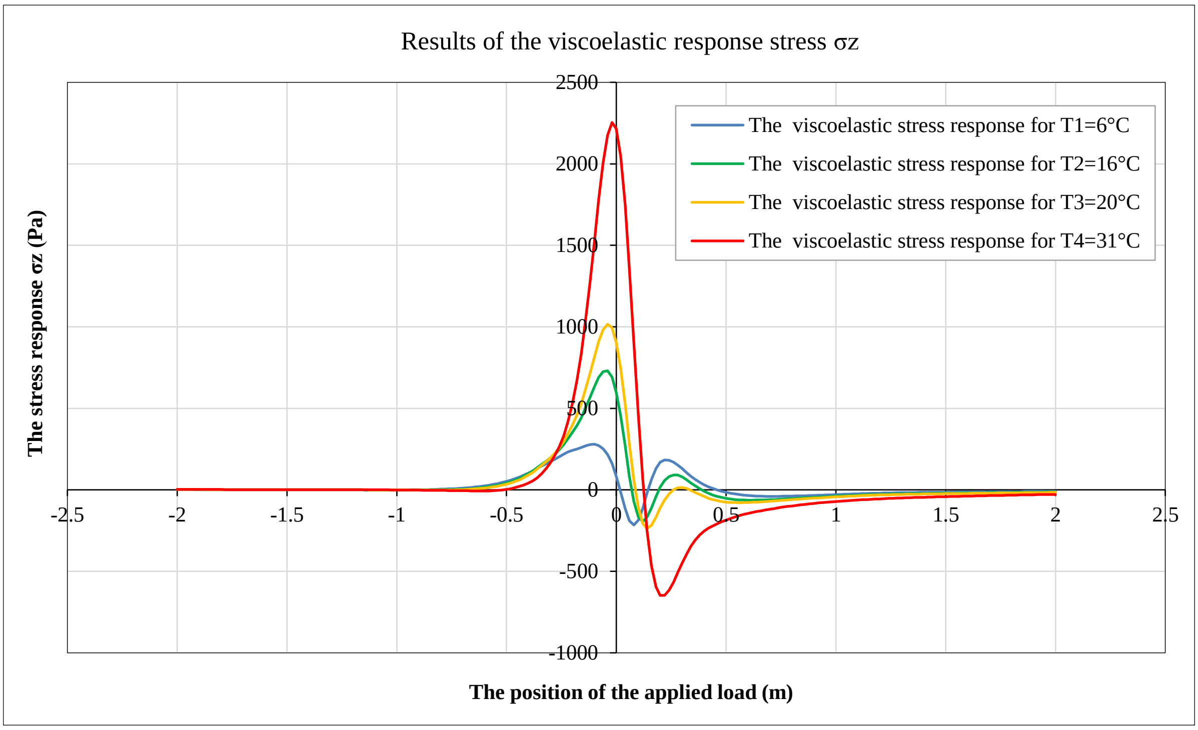

Figure 5. The calculation results of the viscoelastic stress response as a function of temperature

The result of the viscoelastic strain response along the Z-axis, εz, offers valuable insights into the material's behavior when subjected to vertical forces. Understanding εz is pivotal in predicting how the material will deform under sustained loads, such as gravitational forces or dynamic loads like seismic activity. This understanding becomes especially crucial in structural scenarios where Z-axis deformation significantly affects the overall stability and performance of the structure. Analyzing εz provides a comprehensive understanding of the material's viscoelastic characteristics, including how it responds to varying rates of loading and environmental conditions. Such insights are indispensable for designing structures that must endure long-term stresses, ensuring they maintain integrity and functionality over their operational lifespan. Moreover, by incorporating εz data into structural design and assessment processes, engineers can optimize material selection, construction methodologies, and maintenance schedules. This holistic approach enables the development of innovative solutions tailored to specific environmental and loading conditions.

The material's viscoelastic strain response includes its initial strain, denoted as ε0, and its strain under infinite time conditions, denoted as ε∞. This relationship illustrates the dynamic evolution of strain deformation over time, revealing how the material responds to applied loads. Initially, ε0 represents the immediate deformation under the influence of loading, while ε∞ signifies the long-term deformation as the material reaches a stabilized or infinite condition. Understanding this dependency on both initial and infinite strain is crucial for comprehensively defining the viscoelastic behavior of the material. It offers invaluable insights applicable to structural analysis, guiding material design methodologies, and accurately predicting long-term deformation patterns. Equation 6 exemplifies these insights as a foundational tool for quantifying and modeling the material's viscoelastic response across various loading conditions and environmental factors.

$$\varepsilon(t) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1+(\frac{t}{T_0})^{N_D}} \quad (6)$$

Where $\varepsilon(t)$ represents the strain in micrometers, ε_0 signifies the viscoelastic strain when $t = 0$, ε_∞ denotes the viscoelastic strain when $t = \infty$, T_0 and N_D are shape parameters.

As shown in Table 4 and Figure 6, the results indicate a clear trend where the viscoelastic strain response εz increases with rising temperature. This correlation is evident across a temperature spectrum that ranges from a low of 6°C (T1min) to a high of 31°C (T4max). The data suggest a pronounced impact of temperature on the material's viscoelastic properties. With rising temperatures, the material demonstrates heightened strain under consistent loading conditions, highlighting increased viscoelastic deformation. This behavior suggests higher compliance and reduced rigidity at elevated temperatures, promoting greater molecular mobility within the material's structure. Understanding these dynamics is essential for anticipating the material's behavior across different thermal settings and optimizing its application in environments with varying temperature ranges.

Table 4. Calculation results for the viscoelastic strain response as a function of temperatures T1, T2, T3, and T4

Location of applied load (m)	Time (s)	The viscoelastic Strain response in µm for T1=6 °C	The viscoelastic Strain response in µm for T2=16 °C	The viscoelastic Strain response in µm for T3=20 °C	The viscoelastic Strain response in µm for T4=31 °C
-2	0	-0.35	-0.40	-0.44	-0.51
-1.5	0.09	-1.20	-1.48	-1.80	-2.52
-1	0.18	-2.54	-3.19	-3.95	-5.82
-0.5	0.27	-5.10	-6.14	-7.63	-12.10
0	0.36	-30.56	-31.52	-32.18	-33.43
0.1	0.378	-29.62	-31.12	-32.54	-36.40
0.5	0.45	-7.24	-8.56	-10.49	-17.01
1	0.54	-3.46	-4.41	-5.66	-9.55
1.5	0.63	-1.90	-2.39	-3.05	-5.20
2	0.72	-0.98	-1.24	-1.59	-2.79

The detailed analysis presented in Table 4 provides precise measurements of the strain response across different temperature intervals, offering quantitative insights. Figure 6 complements these findings by visually depicting the observed trends, enhancing understanding with a clear graphical representation. This temperature-dependent behavior of the viscoelastic strain response holds significant importance for applications involving materials exposed to diverse thermal conditions. It directly influences the performance and longevity of pavements, maintenance, and material selection to ensure optimal durability and functionality over time. Understanding this relationship is essential for predicting material behavior and optimizing performance in real-world applications.

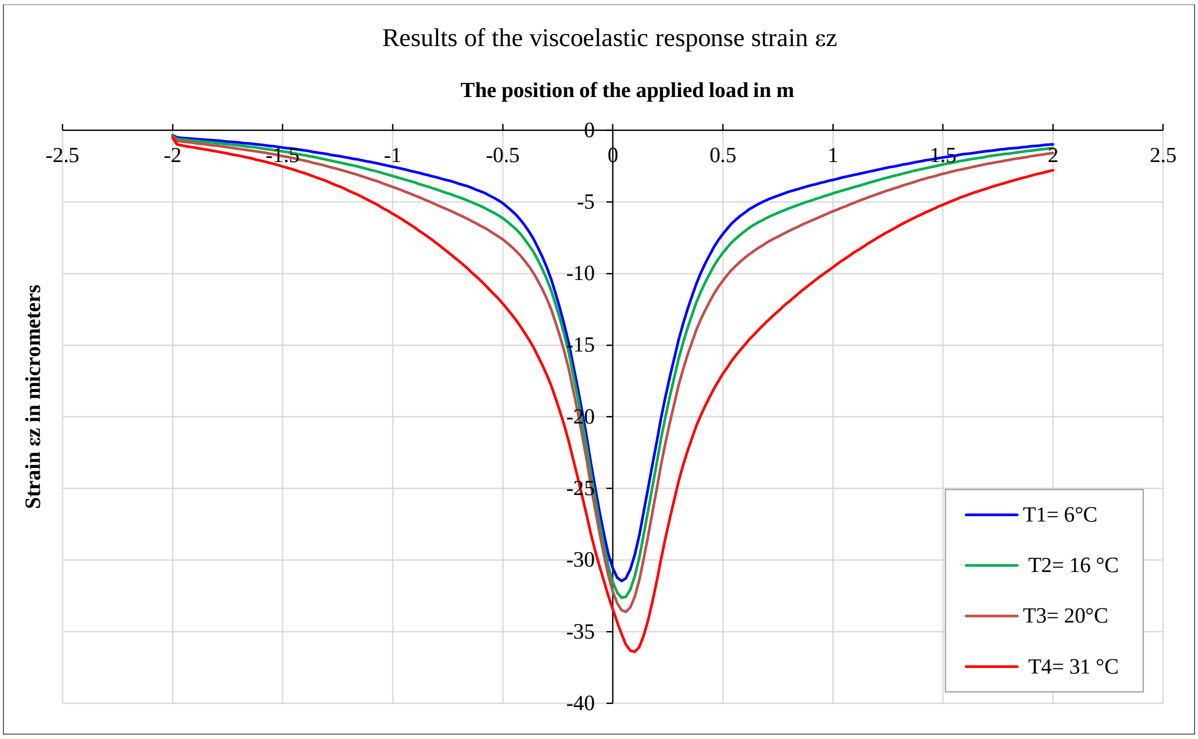

Figure 6. The outcomes of calculating the viscoelastic strain response relative to temperature variations

The result of the viscoelastic response of displacements along the Z-axis, denoted as Uz, offers valuable insights into how the material undergoes deformation and movement in the vertical direction. This information is essential for understanding how pavement materials structurally respond to applied forces along the Z-axis, especially concerning temperature fluctuations. As temperature changes, the viscoelastic properties of pavement materials, such as asphalt, are significantly affected. The data obtained from the analysis of Uz under different temperature conditions contributes to a comprehensive characterization of the pavement's viscoelastic properties. This understanding is crucial for designing and evaluating pavement structures that experience diverse loading conditions, especially where vertical displacement is critical.

As shown by the data provided in Table 5 and depicted in Figure 7, a significant pattern becomes apparent: the viscoelastic displacement response Uz consistently increases as temperatures rise, spanning from a minimum of T1 = 6°C to a maximum of T4 = 31°C. This observation underscores the pivotal role that temperature plays in shaping the viscoelastic properties of the material. It underscores how temperature variations directly affect the material's ability to deform and recover under load, thereby emphasizing the critical importance of temperature management in understanding and optimizing the performance of pavement materials

Table 5. Calculation results for the viscoelastic displacement Uz response as a function of temperatures T1, T2, T3, and T4

Location of applied load (m)	Time (s)	The viscoelastic Displacement response in µm for T1=6 °C	The viscoelastic Displacement response in µm for T2=16 °C	The viscoelastic Displacement response in µm for T3=20 °C	The viscoelastic Displacement response in µm for T4=31 °C
-2	0	102.48	102.53	102.56	102.60
-1.5	0.09	126.85	127.91	129.15	132.05
-1	0.18	155.40	156.98	158.84	163.49
-0.5	0.27	195.56	197.66	200.03	205.95
0	0.36	246.78	252.23	257.93	272.00
0.1	0.378	243.93	248.91	253.97	265.77
0.5	0.45	199.45	201.75	204.31	210.76
1	0.54	157.87	159.95	162.51	169.35
1.5	0.63	128.89	130.50	132.49	137.82
2	0.72	106.42	107.56	108.97	112.79

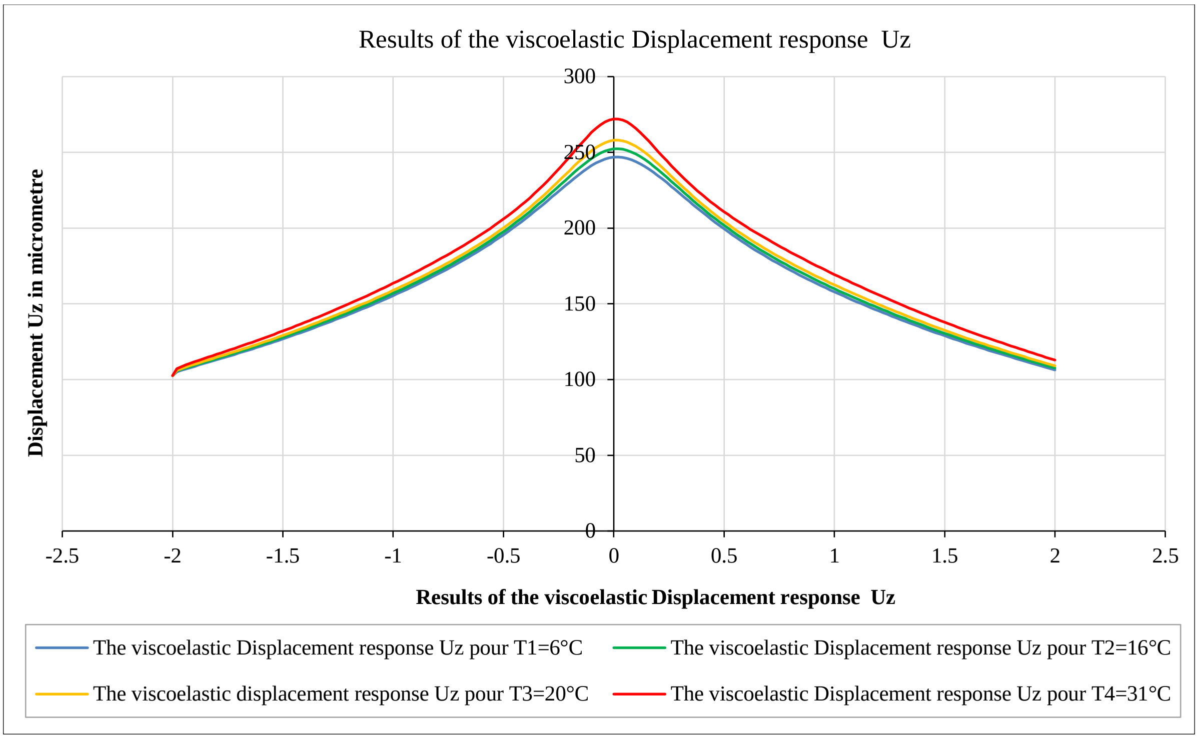

Figure 7. The calculation results of the viscoelastic displacement response as a function of temperature

3.4. Comparison of the present study with Previous Studies and Analysis of Results

The current study thoroughly investigates the viscoelastic behavior of pavement materials, focusing on the impacts of applied stress, deformation, and displacements along the Z-axis under varying temperature conditions. This comprehensive analysis includes examining viscoelastic stress, strain, and displacement responses, highlighting the significant influence of temperature on these properties. The findings reveal a consistent trend: as temperatures rise, there is a marked increase in viscoelastic responses. At lower temperatures, the behavior of pavement materials undergoes distinct changes that impact their structural integrity and performance. The pavement remains stiffer, resulting in reduced deformation under load, whereas, at higher temperatures at 31°C, the pavement becomes noticeably softer and more pliable, leading to higher stress levels due to increased deformation under identical loading conditions.

These observations align closely with research by García Mainieri et al (2023) [24], and Zhang et al. (2021) [25], showing that flexible pavement materials exhibit heightened viscoelastic responses at elevated temperatures due to asphalt binder softening. Zhang and Sun conducted extensive laboratory tests and field studies analyzing asphalt mixtures under varying temperature conditions, finding that as temperature increased, the asphalt binder became more pliable and less resistant to deformation, resulting in increased viscoelastic stress responses under load. Similarly, Mainieri and Singhvi explored the temperature-dependent properties of asphalt pavements through experimental procedures and modeling approaches, confirming that higher temperatures lead to increased molecular mobility within the asphalt binder, significantly softening the material and thereby increasing viscoelastic strain and stress responses under applied loads.

Additionally, the study highlights that higher temperatures result in elevated strain under identical loading conditions, a phenomenon attributed to increased molecular mobility within the material. As temperatures rise, the asphalt binder molecules gain energy and move more freely, resulting in a softer and more pliable material that deforms more readily under stress. This finding is consistent with the results reported by Sukhija and Saboo (2021) [26], and Luo, et al. (2023) [27], all of whom observed similar temperature-dependent behaviors in their studies. Sukhija's experiments on asphalt mixtures have highlighted that elevated temperatures significantly affect the material's stiffness, leading to increased deformation under constant loading conditions. Understanding this phenomenon is crucial for the effective design of pavements and the formulation of maintenance strategies tailored to varying climatic conditions. Luo, Yao, et al. demonstrated through their experiments that viscoelastic strain in asphalt pavements increases with temperature, indicating reduced resistance to deformation at higher temperatures.

Moreover, the study indicates that the viscoelastic displacement response also increases with rising temperatures, confirming the findings of Ren et al. (2024) [28] and Gong et al. (2022) [29]. Ren et al. investigated the displacement behavior of asphalt pavement under various thermal conditions, finding that higher temperatures increase vertical deformation due to the greater flexibility of the asphalt binder. This increase in displacement is due to increased molecular mobility within the binder, which makes the material more compliant and less capable of maintaining structural integrity under applied stresses. Gong et al. further emphasized the significant influence of temperature on the deformation and recovery behavior of asphalt materials, indicating that elevated temperatures reduce the binder's ability to recover from deformation, resulting in increased and more persistent displacements. The consistency of these findings across multiple studies validates the methodology and models used in the current research, providing a comprehensive understanding of the temperature-dependent nature of viscoelastic stress, strain, and displacement responses in pavement materials. This alignment with previous research reinforces the robustness and reliability of the current study's conclusions, confirming that the observed trends are not isolated phenomena but part of a well-documented behavior pattern in asphalt pavements. This enhanced understanding is crucial for pavement engineering and design, facilitating accurate prediction and optimization of pavement structure performance under varying thermal and loading conditions.

This study is especially pertinent in the context of climate change, where extreme temperature variations are becoming increasingly common. It significantly contributes to advancing the development of pavement structures that are both robust and resilient, enabling them to effectively address a wide range of environmental challenges and maintain long-term performance and durability. Furthermore, the findings from this research support the identification of suitable materials and design parameters to enhance pavement durability and performance. Predicting the response of pavement materials to various temperatures and loads can lead to substantial savings in maintenance and repair expenditures. In summary, confirming the methodology and models used in this study with consistent results across various research efforts provides essential insights to advance pavement engineering and design. These advancements are crucial for meeting the requirements of modern transportation systems.

4. Conclusion

This study has provided valuable insights into the complex interplay between viscoelastic response, temperature, and displacements in pavement materials. Through meticulous analysis, we have observed a clear correlation between temperature variations and the viscoelastic properties of the material, as evidenced by the increase in strain ε_z, stress σ_z, and displacements U_z with rising temperatures. The viscoelastic modeling of road pavement structure has yielded valuable insights into its behavior under diverse operational conditions.

The validation process, which includes assessments across a wide range of temperatures, ranging from T1 = 6°C to T4 = 31°C, has highlighted the resilience and efficiency of the proposed pavement structure. Moreover, the viscoelastic response of strain, particularly along the Z-axis, has proven instrumental in elucidating the material's deformation characteristics under applied forces. This understanding, coupled with insights into initial and infinite strain behaviors, has provided a robust framework for characterizing the viscoelastic properties of the material. Furthermore, our analysis has revealed a significant influence of temperature on the viscoelastic properties of the material, with a clear trend of increasing strain response as temperature rises. The importance of this temperature-sensitive behavior underscores the need to consider thermal conditions in efforts to design and optimize pavements.

This study highlights the necessity of incorporating thermal conditions into the analysis and design of flexible pavement structures. The sensitivity of the material to temperature variations highlights the need for comprehensive assessment and strategic planning to ensure the longevity and performance of pavement systems under diverse environmental conditions. This research lays a foundation for further development and enhancement of pavement design methodologies, focusing on integrating temperature considerations into predictive models and engineering practices. Overall, these findings contribute to the advancement of pavement engineering and design, offering valuable insights for enhancing the performance and durability of road infrastructure under real-world operational conditions.

5. Declarations

5.1. Author Contributions

Conceptualization, O.B.; methodology, O.B.; software, O.B.; validation, K.B.; formal analysis, O.B.; investigation, O.B.; resources, O.B. and K.B.; data curation, O.B.; writing—original draft preparation, O.B.; writing—review and editing, O.B. and K.B.; 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.

5.2. Data Availability Statement

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

5.3. Funding

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

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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