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Original Research Article

Multivariate Analysis of Mechanical Response and Rutting Performance in Asphalt Pavements Using 3D-Move Analysis

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Abstract: This study investigates the mechanical response and rutting performance of asphalt pavements using 3D-Move Analysis software based on the three-dimensional continuous finite layer method. A multivariate orthogonal experimental design was employed to simulate two pavement structures with different surface layer combinations (SBS-modified asphalt and SMA) under coupled thermal-mechanical loading. Key parameters including vehicle speed (35‑77 km/h), temperature (0‑40° C), and traffic volume (15,000‑45,000 vehicles/day) were systematically analyzed. Results demonstrate that temperature significantly influences the viscoelastic behavior of asphalt mixtures, and optimal material selection effectively enhances long-term pavement performance. This research provides practical guidance for pavement structural design and material optimization.

Keywords: Finite Element, Asphalt Pavement, Rutting, Mechanical Response Analysis, 3D-Move Analysis.

1. Introduction

During service, pavement structures are subjected to complex mechanical and environmental loads, including cyclic vehicle loading and temperature-induced variations in material properties. The coupling of these factors significantly affects the mechanical performance, durability, and service life of pavements. Traditional analytical approaches generally fall into two categories: firstly, conducting long-term physical loading tests with periodic measurements to capture deformation data of the pavement structure; secondly, applying simplified assumptions to predict long-term in-service performance. However, these methods exhibit notable limitations. Physical testing demands substantial temporal and economic resources, while simplified predictive models often fail to accurately represent the complex multi-physics coupling involved[1], [2]. In contrast, the Finite Element Method (FEM), with its robust numerical computation capability and flexibility, has emerged as an effective tool for investigating the structural response of pavements.

Zhang et al. employed finite element modeling to investigate the drainage performance and driving safety of drainage asphalt pavement. Through finite element simulation results, they determined the influence of longitudinal slope on drainage capacity, providing parametric support for pavement design[3]. Woo et al. utilized a three-dimensional finite element approach to establish a response model for asphalt pavement sections with underground voids. They analyzed the structural behavior of asphalt pavement containing subsurface cavities and evaluated the risk level of road collapse. Comparative analyses of different pavement combinations were conducted to identify the most sensitive characteristics, thereby establishing a benchmark for data-driven decision support[4]. Khiavi et al. investigated the effects of rubber modifiers on flexible pavement performance to optimize the material's rutting resistance. They developed models using finite element software and examined the impact of varying material dosages on performance outcomes, subsequently providing recommendations for pavement material optimization[5]. Dong et al. considered that airport asphalt pavement damage results from multiple contributing factors, while also accounting for challenges encountered in real-world data collection. They established an airport pavement model using finite element software to simulate the service conditions of airport pavements[6].

To address the limitations of idealized boundary conditions in traditional numerical simulations, which often fail to capture real-world engineering scenarios, this study employs a multivariate orthogonal experimental design approach[7], [8]. By systematically and controllably adjusting key parameters associated with coupled fields, the mechanical states of pavements under varying combinations of environmental conditions and traffic loads are simulated. The comprehensive dataset acquired enables an in-depth analysis of the influence of thermal fields and traffic loading on the mechanical behavior of pavement surface layers under dynamic excitation, thereby revealing the dynamic response characteristics and damage mechanisms of pavement structures under multi-factor coupled effects[9], [10].

The accuracy of finite element modeling critically depends on the appropriate description of material behavior, precise application of boundary conditions, and accurate simulation of multi-field coupling[11], [12]. Specifically, the following aspects must be considered: Loading Cycles: Repetitive loading induces cumulative material damage, necessitating the integration of fatigue models to evaluate long-term performance. Loading Rate: The frequency and amplitude of dynamic loads affect the viscoelastic response of materials, requiring analysis methods in either the time or frequency domain. Temperature: Temperature variations influence material properties such as stiffness and ductility[13], [14].

2. 3D-Move Analysis

Based on the pavement structural design, the 3D-Move Analysis software was employed to simulate structural responses under long-term dynamic loading. Realistic environmental factors were incorporated as influential characteristics to enhance simulation fidelity and facilitate evaluation of pavement service performance under coupled multi-factor effects.

The 3D-Move software, developed by the Siddharthan research group at the University of Nevada, Reno, utilizes the three-dimensional continuous finite layer method (3D-CFLM) grounded in pavement mechanical response analysis principles. Within this computational framework, each pavement layer is treated as a continuous entity. By inputting essential structural parameters and employing Fourier transform (FT) techniques, the software enables precise simulation of pavement mechanical behavior, calculating stress, strain, and displacement responses under applied loading. Compared with conventional finite element analysis (FEA) tools, 3D-CFLM offers significant advantages including high computational efficiency, minimal mesh generation requirements, and robust result reliability. Furthermore, the software accurately characterizes the viscoelastic behavior of asphalt materials and simulates mechanical response variations under different temperature conditions through temperature parameter adjustments, thereby authentically reflecting pavement performance evolution in actual service environments.

In light of these advantages, this study adopts 3D-Move to conduct numerical simulations of the designed pavement structure, with the objective of assessing mechanical behavior and long-term service performance under complex environmental and loading conditions.

2.1 Finite Element Analysis Flowchart

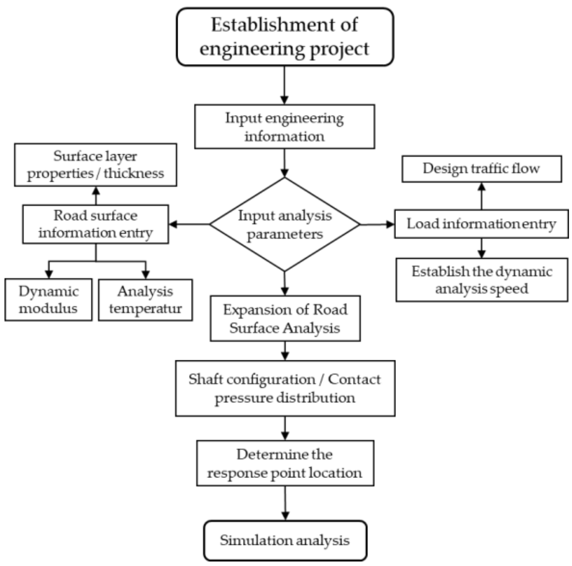


Figure 1. Finite element analysis flowchart.

2.2 Basic assumption

The analysis of pavement structures using the three-dimensional continuous finite layer method is based on the following fundamental assumptions:

First, each pavement structural layer is assumed to be a continuous, homogeneous medium with uniform thickness. Each layer can be assigned distinct material properties according to the specific materials being analyzed, and all layers are treated as single-phase systems.

Second, the asphalt mixture layer is modeled as a viscoelastic material that does not change over time or space, and its temperature is assumed to remain constant throughout the analysis. The structural layers are considered finite in the horizontal direction, and the pavement system is assumed to rest on a rigid, impermeable base layer.

Finally, when the pavement is subjected to vehicle axle loads, it is assumed that the vehicle travels at a constant speed. The stresses and strains in the pavement are assumed to approach infinitesimally small values at infinite distances both horizontally and vertically.

2.3 Principle of Load Action

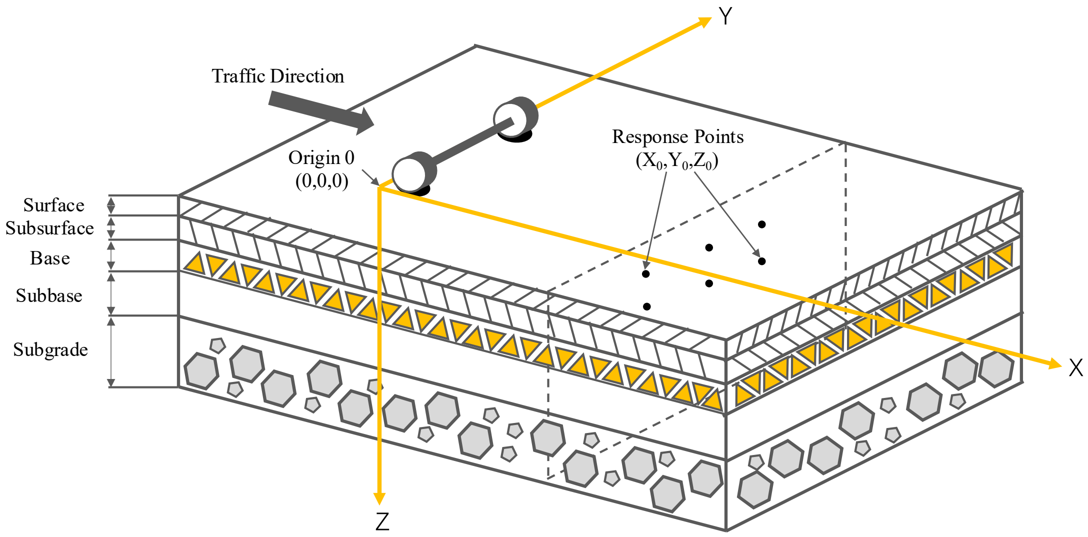


Figure 2. Finite element modeling schematic diagram

The 3D-Move Analysis software utilizes discrete Fourier transform (DFT) technology to discretize pavement loads and decomposes them into a series of harmonic waves via Fourier transform. Through the superposition of multiple harmonic components, the software simulates a uniformly moving load.

3 Determination of pavement structure model parameters

The pavement structure primarily relies on the surface course to resist deformation induced by long-term loading conditions. Consequently, two distinct pavement structural configurations were adopted for subsequent finite element simulations to investigate the influence of different material combinations on the long-term service performance of pavements. This comparative approach enables a comprehensive evaluation of how varying material properties and layer compositions affect the structural response, durability, and functional performance of pavement systems under sustained traffic loading and environmental exposure over extended service periods.

3.1 Analyze vehicle speed

To better simulate and analyze the performance of asphalt pavements under varying vehicle speed conditions, different speed values were selected. For instance, a lower speed (35 km/h) may correspond to urban roads or congested sections, whereas a higher speed (77 km/h) may represent highways or expressways.

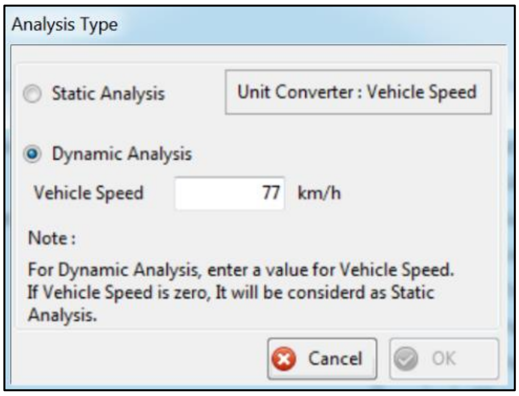


Figure 3. Analysis of vehicle speed design page

On the interface shown in Figure 3, the vehicle speed is input and modified to determine the average velocity of traffic for long-term pavement loading analysis.

3.2 Analysis temperature

Environmental temperature serves as a critical factor governing the viscoelastic mechanical characteristics of pavement materials, particularly asphalt mixtures. During the model parameter configuration phase, temperature parameters can be set and adjusted through the interface illustrated in Figure. 4 [15], [16]. Given the subtropical monsoon climate (STC) characteristics of the region featuring hot and rainy summers, mild and dry winters, and significant diurnal temperature variations pavement temperatures exhibit substantial fluctuations across different seasons. To accurately simulate actual service conditions, appropriate temperature parameter selection is paramount.

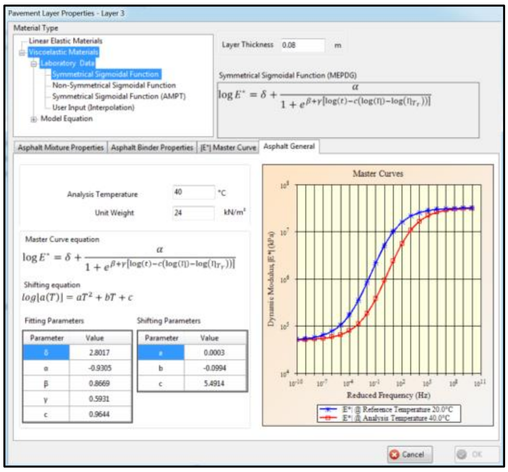


Figure 4. Analysis temperature adjustment page

The figure above presents the initial master curve constructed at a reference temperature of 20°C (indicated by the blue solid line) through the input of material dynamic modulus parameters and asphalt property parameters. Subsequently, shifting and fitting operations were performed based on transformation equations to derive material master curves at various target temperatures, thereby authentically reflecting the dynamic response characteristics of pavement materials under actual service temperatures. As exemplified in the figure, the red curve specifically illustrates the shifting pattern and performance variation of the material master curve when the analysis temperature is set to 40°C.

3.3 Number of vehicles in operation

Based on pavement structural mechanics and cumulative damage theory, traffic load applications serve as a core parameter characterizing pavement performance deterioration. This study employs daily traffic volume of design axle loads as the fundamental input, which directly determines stress-strain cycling levels and consequently influences cumulative fatigue cracking and permanent deformation rates[14], [17].

Two typical traffic levels were selected: 15,000 and 45,000 vehicles/day, representing light and heavy traffic conditions on arterial highways. To conservatively assess long-term durability considering operational uncertainties such as overloading and seasonal fluctuations, a modification coefficient of 0.9 was applied, with 90% of design traffic volume adopted for analysis[18], [19].

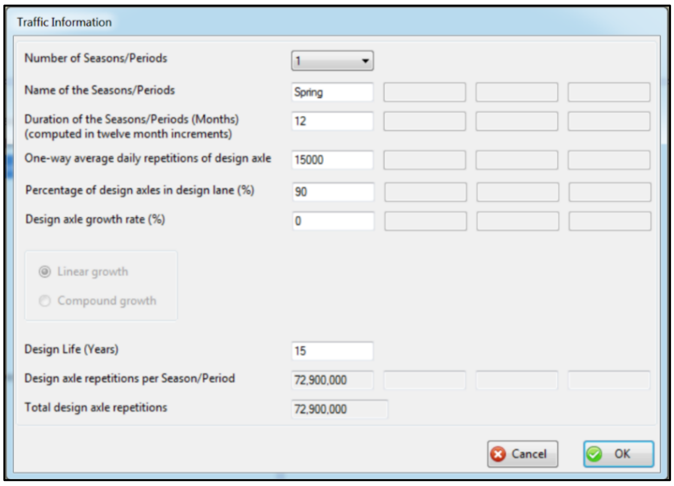


Figure 5. Vehicle count adjustment page

Traffic loading constitutes a core input parameter for pavement structural design. Within the traffic volume configuration module of the software, not only can the base traffic volume be specified, but customization of traffic volume variability across different seasons and months is also supported according to actual engineering conditions. However, considering the primary research focus of this study and the principle of variable control, seasonal fluctuations in traffic flow induced by environmental alterations are temporarily excluded; instead, a constant traffic volume for a single season is extracted for in-depth analysis.

3.4 Axle load type

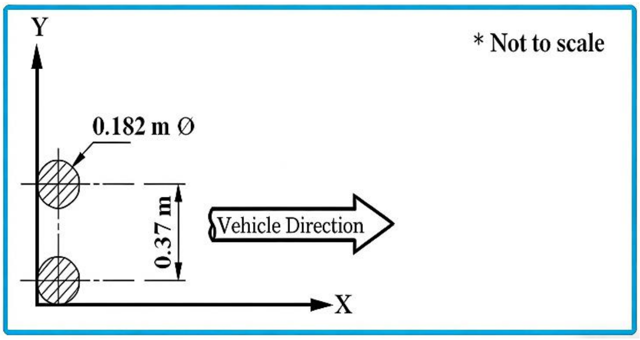


Figure 6. Axle load type diagram

This study employs a typical dual-tire single-axle load configuration inherent to the software, comprising four circular contact areas corresponding to two tire contact patches. A uniform contact pressure of 862 kPa is assumed within each circular area, with a total load of 45 kN applied to one side of the axle (22.5 kN per tire). This load level conforms to standard axle load parameters in pavement design, providing quantifiable mechanical boundary conditions for subsequent dynamic modulus analysis and structural response calculations.

3.4 Response points

Mechanical response analysis typically employs three critical points (A, B, and C), with maximum response values serving as design parameters. Point A denotes the center of the contact circle between dual tires; Point B represents the tire contact edge; and Point C indicates the center of the gap between dual tires, as illustrated in the figure below[20], [21].

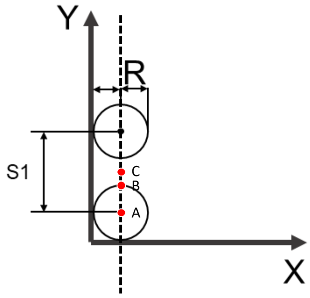


Figure 7. Diagram of response points

To accurately capture the mechanical response characteristics within the pavement structure, this study systematically arranged monitoring points for stress observation across various structural layers based on the wheel-axle load position in the software (the specific spatial distribution is detailed in the figure below).

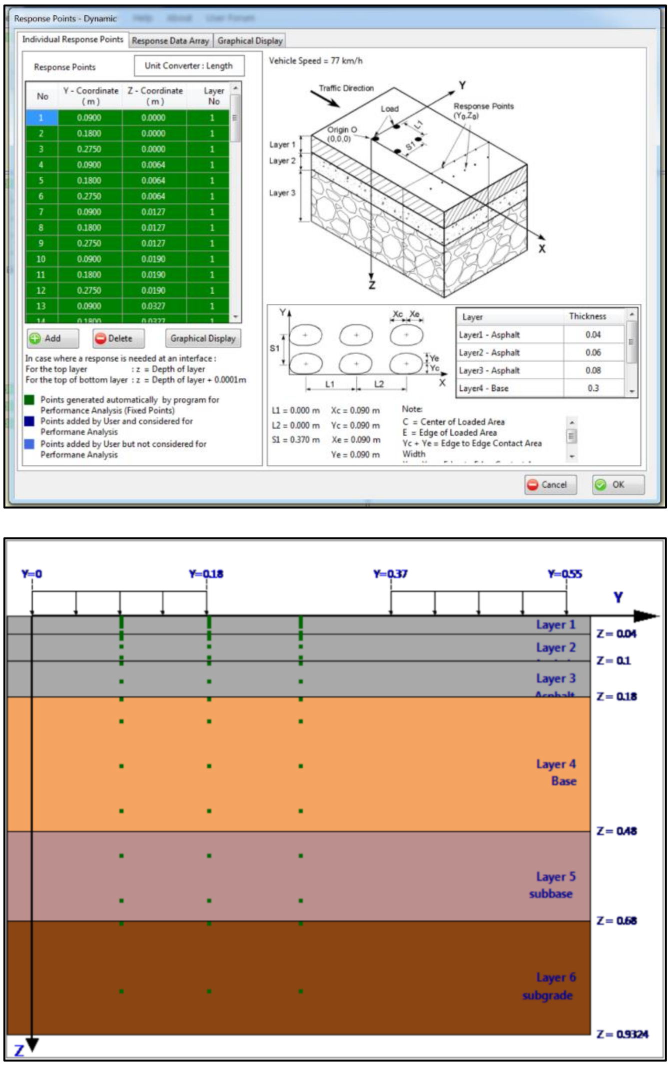


Figure 7. Diagram of response points

The nodal arrangement covers critical depths and load-bearing layers. Upon simulation completion, the system extracts 3D displacement and strain data at all nodes, enabling reconstruction and visualization of plastic deformation (e.g., rutting) evolution and settlement distribution under long-term service conditions[22], [23].

3.5 Structural layer parameters

Two pavement structures with different surface layer combinations were selected as the primary analysis variables to investigate the influence of material properties on long-term loading performance, while other structural components remained fixed to minimize confounding factors [23], [24]. The pavement system comprised a cement-stabilized macadam base and subbase, with SBS-modified asphalt and SMA serving as the two alternative surface layers. For mechanical response analysis using 3D-Move, asphalt surface layers were modeled as both ideal linear elastic and viscoelastic materials, whereas base, subbase, and subgrade layers were treated as ideal linear elastic materials. Layer thicknesses followed construction specifications, with subgrade modeled as an infinite half-space (0 mm thickness).

Key material parameters included Poisson's ratio (μ) and elastic modulus (E). Poisson's ratio, critical for evaluating transverse deformation of asphalt mixtures, was determined according to the Highway Asphalt Pavement Design Specifications (JTG D50-2017) based on material type. Surface layer elastic moduli were obtained through dynamic modulus (|E*|) testing of gyratory-compacted specimens at six temperatures (0–40°C) and six frequencies (0.1–25 Hz), with experimental values directly incorporated into the model for validation against field measurements.

Table 1. Pavement material parameters

Structure	Material type	Layer thickness [cm]	Elastic Modulus [Mpa]	Poisson's ratio [μ]	Damping ratio [%]	Density [kN/m3]
Base	Cement-stabilized crushed stone	30	1500	0.2	3	22
Subbase	Cement-stabilized crushed stone	20	200	0.25	3	21
Subgrade	Silt-bearing soil	-	70	0.4	3	18

To investigate the influence of different input characteristics on the long-term service performance of pavement structures using 3D-Move Analysis software, two distinct surface layer structures were adopted. The dynamic modulus data for the specific surface mixtures are presented in the table below.

Table 2. Surface material parameters (kPa)

Structure One						
AC13-70-SBS						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	11775250	15282250	16814000	20346250	21728500	23439000
10°C	4943500	7814500	9193000	12862500	14486750	16584250
20°C	1640000	3013500	3846500	6551500	7951250	9817000
30°C	772150	1345250	1748500	3361000	4342000	5863750
40°C	386800	592700	735200	1404000	1892250	2813000
AC-20-SBS						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	14040500	18065750	19874750	24018750	25682000	27768000
10°C	6061000	9315000	10894750	15148750	17018500	19535000
20°C	2149250	3973500	5064750	8486250	10113000	12179500
30°C	803175	1438750	1897500	3776500	4926500	6726000
40°C	466775	714600	896150	1766500	2407750	3517250
AC-25-sbs						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	13917000	17593000	19177250	22917750	24445250	26173750
10°C	6570250	9790750	11264500	15235250	16953000	19188750
20°C	2155250	3999250	5017250	8196000	9697500	11746500

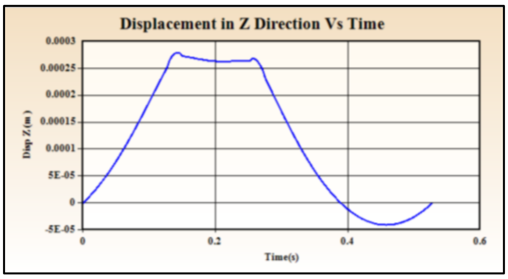
30°C	827200	1576000	2074750	4050750	5195500	6888500
40°C	396300	702450	909850	1852250	2529000	3726500
Structure Two						
SMA13						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	10519750	13522250	14805750	17833750	19047750	20485750
10°C	4611000	7055250	8221000	11374000	12751750	14535250
20°C	1582750	2835250	3558500	5930750	7106750	8720250
30°C	710375	1259250	1637750	3156750	4081250	5532000
40°C	308450	500700	635150	1248500	1679000	2452750
AC-20-SBS						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	14040500	18065750	19874750	24018750	25682000	27768000
10°C	6061000	9315000	10894750	15148750	17018500	19535000
20°C	2149250	3973500	5064750	8486250	10113000	12179500
30°C	803175	1438750	1897500	3776500	4926500	6726000
40°C	466775	714600	896150	1766500	2407750	3517250
AC-25-sbs						
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
0°C	13917000	17593000	19177250	22917750	24445250	26173750
10°C	6570250	9790750	11264500	15235250	16953000	19188750
20°C	2155250	3999250	5017250	8196000	9697500	11746500
30°C	827200	1576000	2074750	4050750	5195500	6888500
40°C	396300	702450	909850	1852250	2529000	3726500

4. Analysis of Mechanical Response Results of Asphalt Pavement

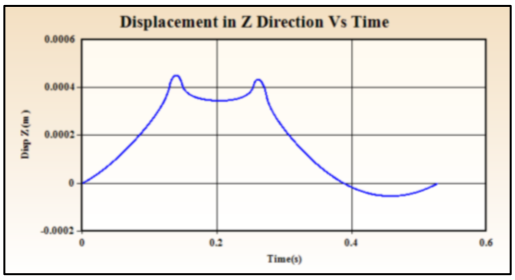
The software enables intuitive visualization of finite element simulation results at selected monitoring points. Through graphical displays and comparative charts, users can readily examine the mechanical responses across different locations. By systematically varying input parameters and analyzing the resulting output diagrams, the influence of each parameter on simulation outcomes can be quantitatively assessed, thereby providing practical guidance for engineering applications.

4.1 Comparison of displacement values

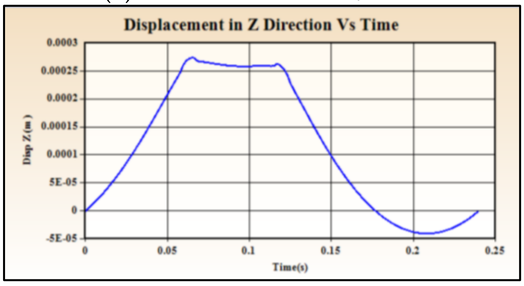
Among the three monitoring points established in the simulation, the maximum deflection occurred at Point A (the center of the wheel load contact area). Consequently, Point A was selected as the primary research focus for subsequent analysis. Comparative results under varying parameters are presented in the figures below.



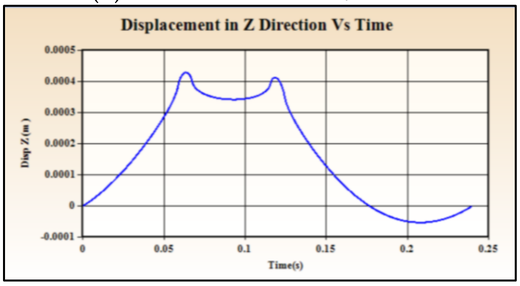
(a) Structure 1 35 km/h 0°C



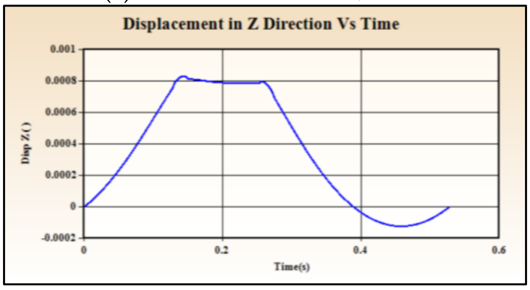
(b) Structure 1 35 km/h 40°C



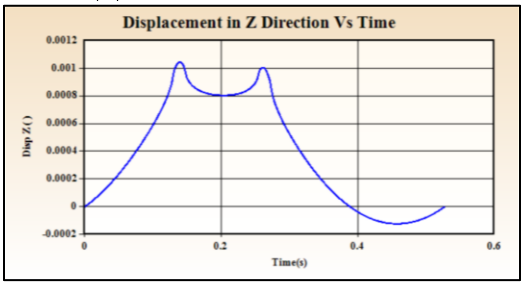
(c) Structure 1 77 km/h 0°C



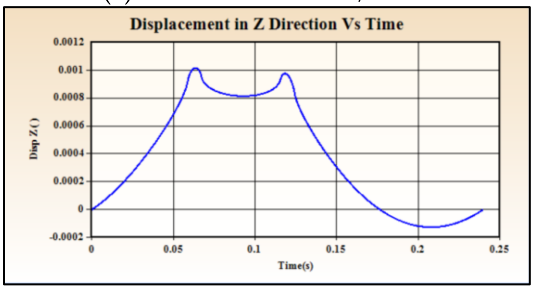
(d) Structure 1 77 km/h 40°C



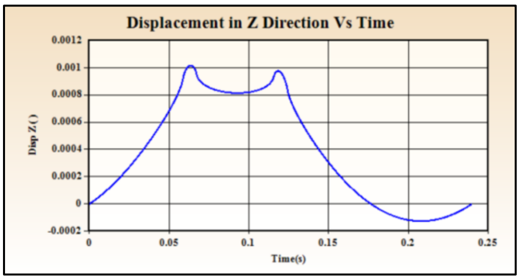
(e) Structure 2 35 km/h 0°C



(f) Structure 2 35 km/h 40°C



(g) Structure 2 77 km/h 0°C



(h) Structure 2 77 km/h 40°C

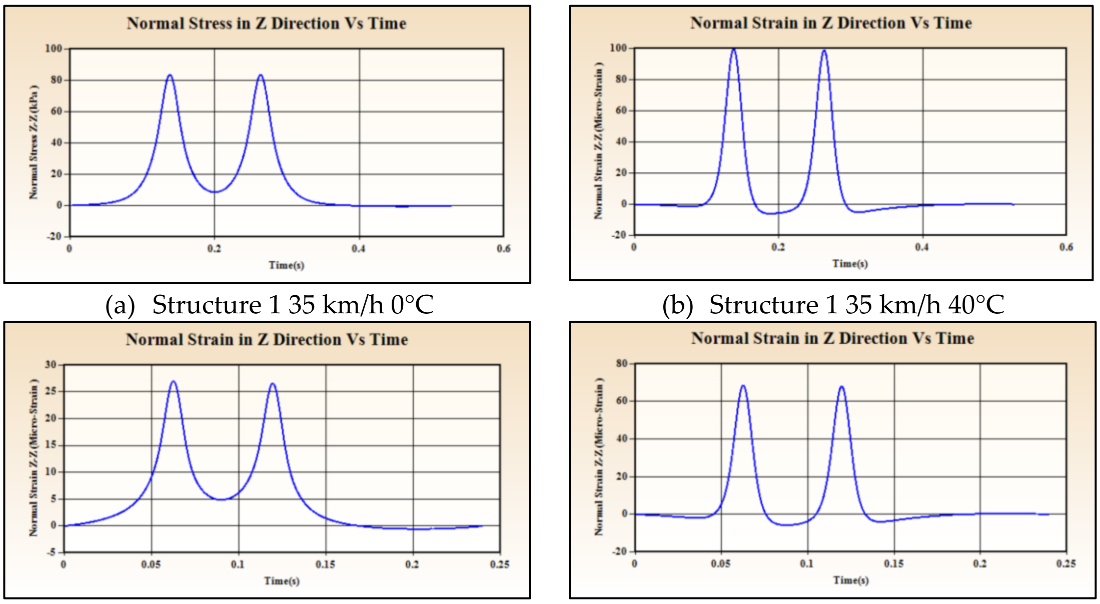
Figure 8. Comparison of displacement values under different conditions

The analysis reveals that temperature variations exert a substantial influence on deflection outcomes, with higher temperatures significantly increasing pavement deflection due to the reduced stiffness of asphalt mixtures under elevated thermal conditions. Conversely, increasing vehicle speed results in a marginal reduction in deflection values; however, this effect is comparatively negligible when contrasted with the pronounced temperature-induced variations. These findings underscore the dominant role of thermal effects over loading frequency characteristics in governing the mechanical response of viscoelastic pavement materials.

On the other hand, modifying the surface layer material composition reveals that reduced material modulus leads to greater vertical deformation under loading. This phenomenon arises from decreased stiffness and load-bearing capacity, resulting in diminished resistance to compressive stress and accelerated permanent deformation. Lower modulus values alter stress distribution patterns, intensifying surface rutting and compromising long-term serviceability.

4.2 Analysis of Strain Response at Asphalt Layer Bottom

To evaluate the long-term performance of pavement materials, the tensile strain at the bottom of the asphalt layer was selected as the critical analysis indicator. Using the results from Structure I as the analytical basis, this section discusses the influence of various input parameters on the mechanical response of the pavement system. This analysis aims to identify key factors governing fatigue resistance and durability, thereby providing quantitative guidance for material optimization and structural design.



(a) Structure 1 35 km/h 0°C (b) Structure 1 35 km/h 40°C

(c) Structure 1 77 km/h 0°C (d) Structure 1 77 km/h 40°C

Figure 9. Comparison of displacement values under different conditions

The results indicate that temperature exerts a pronounced influence on compressive strain at the bottom of the asphalt layer. Under low-temperature conditions, the mitigating effect of increased vehicle speed on strain values remains relatively marginal. However, as temperature rises, higher vehicle speeds contribute to more noticeable reductions in strain magnitudes. This phenomenon can be attributed to the viscoelastic nature of asphalt mixtures: at elevated temperatures, the material exhibits greater time-dependent deformation characteristics, rendering the loading duration effect, governed by vehicle speed, more influential on the overall mechanical response. These findings demonstrate the coupled thermo-mechanical behavior of asphalt pavements, where the relative significance of loading frequency effects intensifies with increasing temperature.

5. Conclusions

This study employed 3D-Move Analysis software to investigate the mechanical response and long-term performance of asphalt pavements under coupled thermal-mechanical loading conditions. Through systematic parametric analysis, the following conclusions are drawn:

(1) Dominant temperature effects. Temperature exerts the most significant influence on pavement mechanical response, substantially increasing surface deflection and asphalt layer strain at elevated temperatures due to reduced material stiffness. This effect outweighs vehicle speed variations, underscoring the necessity of thermal considerations in pavement performance evaluation.

(2) Temperature-dependent speed effects. While higher vehicle speeds generally reduce mechanical responses, this mitigating effect is marginal at low temperatures but becomes more pronounced as temperature increases. This reflects the viscoelastic nature of asphalt mixtures, where loading frequency effects intensify with temperature, demonstrating coupled thermo-mechanical behavior.

(3) Material modulus influence. Comparative analysis reveals that surface layer composition significantly affects structural performance. Reduced material modules lead to greater vertical deformation and accelerated permanent deformation. SMA-structured pavements exhibit superior deformation resistance compared to conventional SBS-modified asphalt, highlighting the importance of high-modulus materials for enhanced durability.

The 3D-Move Analysis effectively captures multi-factor coupling effects, providing reliable simulation of pavement behavior under complex environmental and loading conditions. These findings offer quantitative guidance for material selection and structural optimization in pavement engineering practice.

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