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Original Article

Modeling the Progression of Deformation in a Flexible Pavement using the Boussinesq Model with Monte Carlo Simulation

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Abstract - *Road safety is a fundamental issue for developing countries, given its impact on the economic and social development of the country, thus ensuring the safety of users and goods. The goal of this approach is to create resilient pavement design and maintenance strategies that effectively tackle the challenges posed by fluctuating load conditions and temperature variations. This analysis is based on a case study of a road section subjected to mechanical loads that are modeled and studied in order to analyse the effectiveness of the current design of road pavements in relation to deformation resistance. On this, it is possible to create an effective design strategy in relation to the possible challenges. In this study, the Boussinesq model is selected to be studied as an example of an elastic model. It is carried out with the aim of initiating the establishment of a Moroccan Pavement Management System based on models predicting roadway performance. This System aims to ensure road safety and prevent issues such as rutting, cracking, and a shortened pavement lifespan. By modeling the stresses and deformations for each type of traffic using the Boussinesq model, the impact of cumulative loading and time variation turns out to be significant. A flexible pavement under TPL4 or TPL5 type traffic appears, according to the results of the present study, to have good homogeneity and performance characteristics in relation to loading, whereas a flexible pavement subjected to TPL6 type traffic, requires special attention, especially in relation to high temperatures. Indeed, a cumulative loading over ten years will lead to a deterioration of the road structure. Special attention should be paid to the hottest areas when designing for the temperature variation.*

Keywords *- Boussinesq model, Monte carlo simulation, Flexible pavement deformation, Traffic load, Pavement management system, Roads.*

1. Introduction

In order to maintain the safety and efficiency of transport systems, the durability of road structures is an essential subject to be addressed. The advancement of long-lasting road infrastructure has emerged as a crucial global priority, driven by increasing demands due to rapid urbanisation, rising environmental issues, and the urgent need for sustainable and eco-friendly transportation options [1].

As rapid urbanisation continues globally, existing road networks face mounting challenges in accommodating growing traffic volumes and evolving mobility demands. At the same time, addressing climate change and minimising the environmental impact of transportation infrastructure has highlighted the critical importance of developing eco-friendly and resilient road networks [2].

In the same sense, to ensure the durability of the road surface, several pathologies must be remedied after analysis of the main causes of the latter. Alligator cracking and long/trans cracking are the most widespread failures in road networks; they result from asphalt fatigue under traffic loads combined with environmental effects [3]. Also, block cracking is generated by mechanical loading [4].

Therefore, understanding the behaviour of road structures is necessary to develop a sustainable and long-lasting road network. Generally, following an increasing loading of the roadway, its durability is called into question. So, it will first be necessary to understand the development of the roadway reaction to traffic loads. Let's start by studying the deformation generated by a mechanical load. The deformation of roadways under traffic loads is a major issue in geotechnical engineering. Several models can be used to estimate these deformations, including the Boussinesq elastic model, a fundamental tool. This model provides a rigorous analytical framework to study the distribution of stresses and strains in elastic materials. In particular, it allows the evaluation of vertical stresses and strains at different depths of the roadway structure under the influence of vehicle loads [5].

However, the complexity of the associated calculations, as well as the high time and costs they generate, require the use of numerical methods such as Monte Carlo simulations. These allow for a better understanding of the effects of load variations and temperature fluctuations on roadway deformation. By randomly sampling key parameters (such as applied stresses or Young's modulus), this method facilitates in-depth analysis of the factors influencing deformation over time [6].

The objective of this study is, therefore, to simulate different load scenarios (daily, monthly and annual) to identify deformation trends and propose appropriate design and maintenance strategies. A highlight is then made to accentuate the critical damage zone following fatigue cycles. Particular attention will be paid to the impact of thermal variations on material properties, highlighting the importance of designing resilient pavement structures.

Problematic: In a context where traffic loads and climatic fluctuations affect the durability of pavements, how can the application of the Boussinesq model, combined with Monte Carlo simulations, improve the prediction and management of pavement deformations in order to optimise their longevity and performance?

2. Methodology

Through this study, a definition of Monte Carlo simulation is made, and some examples of its application in scientific fields, including civil engineering and project management, are given.

Firstly, for modeling the behavior of a road structure, several models can be used, including the Boussinesq model that will be defined.

Secondly, a flexible pavement structure is chosen to be studied, given the frequency of its use in Morocco. By changing the basic data, including the load applied to the pavement and its thickness, a study of its co-damping and its response via the deformation obtained is made.

Third, a fatigue study of the material through its elastic and plastic state is made to identify the critical fatigue zone.

Afterwards, a projection in time is necessary, 10 years as a lifespan to project the behavior of the pavement as the load accumulates.

Finally, a comparative study of two areas with different average temperatures is made to implement the impact of meteorological parameters.

3. Results

3.1. State of the Art

3.1.1. Monte Carlo Simulation

Overview

The Monte Carlo simulation is a commonly employed technique for probabilistic analysis in engineering systems. It uses numerical experiments to derive the statistical characteristics of the output variables [7].

This method involves repeated random sampling and statistical analysis to obtain results. It identifies a statistical distribution for each input parameter from which random samples are generated. These samples are used to produce output parameters representing possible simulation outcomes. Statistical analysis of the results guides decision-making [8].

Application

Monte Carlo simulation can be used in several fields.

Table 1. Examples of applications of Monte Carlo Simulation [8]

Field	Application
Finance	Analysts use it to model differentiated scenarios.
Reliability Analysis and Six Sigma	It is used to assess, from the conditions determined in a defined time, the capacity of a system to perform its required functions.
Mathematics and Statistical Physics	It is used in the numerical resolution of complex multidimensional partial differentiation and integration problems.
Engineering	It is used to estimate component reliability.

In civil engineering, for example, Cardoso et al. [6] explored a methodology for calculating the probability of structural failure by combining neural networks and Monte Carlo simulation.

They claim that this is a suitable tool for solving reliability problems. However, for assessing very low failure probabilities, using this method requires a significant number of structural analyses.

In the field of project management, Kwak and Ingall [9] assert that Monte Carlo simulation can measure the impacts of risk and uncertainty on project timelines and budgets.

This approach provides project managers with statistical indicators of project performance, including estimated completion dates and budgets. Therefore, Monte Carlo simulation is then a powerful technique for modeling and analysing real-world systems and scenarios.

In the same field, Sharma [10] used Monte Carlo simulation to evaluate risks in construction project management. He found that this method allows for better risk management by identifying, assessing, and controlling potential risks.

Stewart et al. [11] studied the applied Monte Carlo simulation to assess the reliability and structural performance of reinforced concrete bridges over time, focusing on the effects of corrosion on bridge components. The study found that bridges subject to high levels of chloride-induced corrosion showed significant reductions in reliability, especially after 40 years of service. Monte Carlo simulations helped quantify the failure probability and provided insights for maintenance and retrofit strategies to extend the bridge lifespan [11].

3.1.2. Boussinesq Model

Overview

The deformation of roadways under traffic loads is a major issue in geotechnical engineering. Several models can be used to estimate these deformations, including the Boussinesq elastic model, a fundamental tool. This model provides a rigorous analytical framework to study the distribution of stresses and strains in elastic materials.

In particular, it allows the evaluation of vertical stresses and strains at different depths of the roadway structure under the influence of vehicle loads [12]. It constitutes an essential basis in geotechnics and road engineering for estimating the stresses transmitted in soil layers by loads applied to the surface.

When applying the Boussinesq model, certain assumptions are made. First, the soil is assumed to be linearly elastic, homogeneous, and isotropic. Second, the load is static and applied pointwise to the surface. And finally, the domain is an infinite half-space with no lateral edges or interfaces. Through its simple and quick-to-use analytical formulation, this Tool is practical for preliminary estimations of vertical constraints.

Application

For Dutykh et al. [13], a numerical model is developed to resolve the sliding and wave motion. It is also functional in shallow water mode. Comparing the two approaches, the example studied shows that the Boussinesq model predicts a stronger wave rise than the shallow water model.

According to Gomi et al. [14], an approach based on the mathematical decomposition of the vertical components of the velocity into a series of functions according to the water depth is made to construct a Boussinesq model.

It was concluded the improvement of the linear dispersion, the reproduction of the vertical profile of the velocity, and the management of the slope of the bottoms and the steep slopes. Shahrour et al. [5] used finite element modeling to compare the Boussinesq solution to an elastoplastic analysis in civil engineering.

Table 1. Comparative study of models for calculating deformation and fatigue of pavements

Model's type	Advantages	Inconvenience
Boussinesq's Model	Assuming a linear elastic material, the model tends to provide conservative estimates of stresses, which can be useful for preliminary analyses.	The model assumes a homogeneous, isotropic and linearly elastic material, which does not faithfully reflect the real behavior of bituminous mixes, which are heterogeneous and viscoelastic.
Fatigue damage model [15].	The model captures the three characteristic phases of the evolution of the stiffness of bituminous mixes under cyclic loading: initial heating, stabilisation, and then macrocracking.	Identifying model parameters requires specific experimental tests and careful calibration, which can be cumbersome in practice.
Fatigue resistance assessment [16].	By focusing on damage evolution, the model more faithfully captures material degradation mechanisms, thus providing a more accurate assessment of fatigue resistance.	The method requires precise monitoring of the evolution of E (the complex modulus of the material) during testing, as well as corrections for various side effects, which can complicate its implementation in the laboratory.

Comparative Study

In this research, the Boussinesq method is used due to its rapid estimation of stresses in a roadway subjected to surface loading; thus, it has a simple analytical formulation and is computationally inexpensive.

Due to the preliminary nature of this research, this method is useful for analysing and validating numerical models. This will provide a reliable basis for comparison to evaluate the effects of loads on road structures.

3.2. Case Study

3.2.1. Explanation of the Context

To model the behavior of pavements, we will calculate the stresses applied to the road pavement. To do this, several models and approaches are used in civil engineering, depending on the desired accuracy, the materials of the roadway, and the nature of the applied loads. Elastic models include Boussinesq Theory, Burmister Model, Three-dimensional Elastic Analysis Models, Viscoelastic Models, Numerical Models (Finite Element Methods), Empirical and Mechanical-Empirical Models, or Simplified Models and Approximations. However, the choice of application of the Boussinesq model is made given the simplicity of calculating the stresses under a load.

This study involves defining the problem, utilising the Boussinesq model equations, performing Monte Carlo simulations to account for parameter variability, and conducting a comprehensive statistical analysis of the simulation results. In order to study the different possible scenarios for a flexible road pavement, we will dissect, case by case, the behavior of a road section in relation to the variation of the traffic load and the thickness of the layer.

Before setting the search parameters, it is essential to clarify the traffic classes. This is chosen following the calculation of the cumulative traffic in equivalent axles of 13 T or 8T expected per direction over the chosen period and to compare it with Table 3 to determine the class.

Starting with a roadway belonging to the traffic class TPL4 (Heavy load traffic n°4) to the class TPL5 (Heavy load traffic n°5) and the class TPL6 (Heavy load traffic n°6). The thickness of the layer, however, varies for each class according to the soil's bearing capacity. By comparing the results of the deformations obtained and comparing them to the admissible deformation, a particular study proves important. The temperature of the site studied is a parameter not to be neglected during the study of the dimensioning of road pavements; we will study the impact of the temperature variation on the behavior of the roadway with respect to the stresses.

3.2.2. Application of the Method

The design of pavements in Morocco is based on mechanical and empirical models to predict the deformations and durability of pavements, and some catalogues are developed in this direction, such as the catalogue established by the Moroccan Industrial Standardization Service (SNIMA) or the catalogue of new structures established by the Ministry of Equipment and Water. The main parameters taken into consideration are:

- Traffic characteristics: Volume, heavy vehicle load, and axle distribution.
- Material properties: Modulus of elasticity, compressive and tensile strength of pavement layers (subbase, base, overlay).
- Climatic conditions: Temperature, precipitation, and their impact on materials.
- Soil bearing capacity: Measured by tests such as the CBR (California Bearing Ratio).
- Expected service life: Number of years the pavement is expected to remain functional.

Based on the catalogue of new structures established by the Ministry of Equipment and Water, the sizing of road pavements is based on initial parameters concerning the section of road to be built or reinforced. The first parameter to be determined is the average daily traffic or the cumulative traffic on an axle equivalent to a specific tonnage (8T or 13T, for example), which reflects the operating load applied to the roadway. In the figure below, we present a modeling of road pavement components.

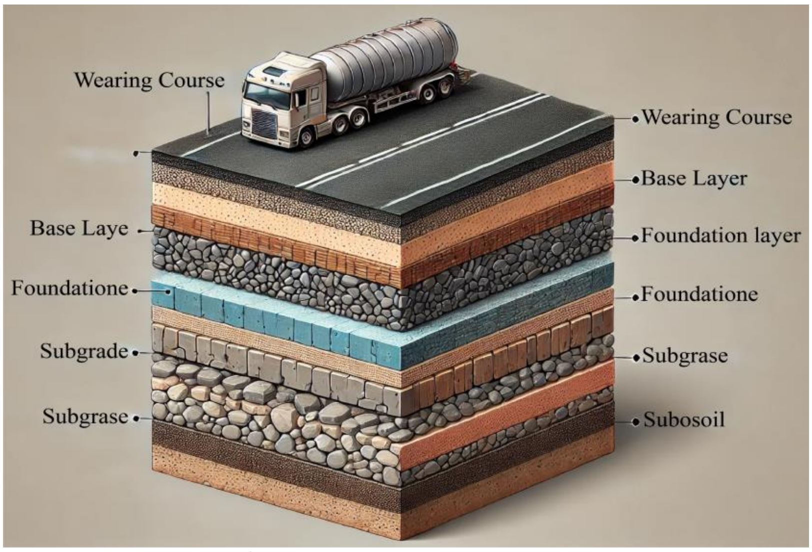


Fig. 1 Modeling of road pavement components generated by ChatGPT

To gain insight into the progression of the impact of traffic on the response of the studied road section, we will conduct a detailed study over time, covering a day, a month, and a year. This progression will naturally take into account the recent census results organised in 2024 by the Kingdom of Morocco.

This census yielded an initial population growth rate of 8.8%, according to the Minister of Interior [17]. This demographic growth rate serves as the variable r_{pop} in the following traffic projection equation:

$$T_{futur} = T_{initial} * (1 + r_{pop})^t$$

t: the concerned period.

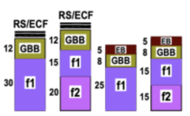
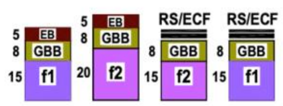
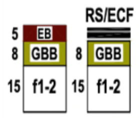
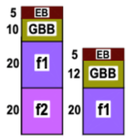
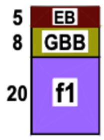
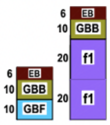
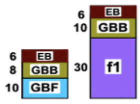
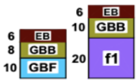
In this regard, according to the equation mentioned and the catalogue of typical structures of new pavements produced by the roads and highways department of the Ministry of Equipment and Water, the margin of values of the traffic in equivalent axles of 8T expected per direction is presented in the following table (the upper and lower value for each traffic class) (TPL: Heavy goods vehicle traffic):

Table 3. The number of heavy vehicles equivalent to 8 tons for each traffic class

Structure	Lifetime		TPL1	TPL2	TPL3	TPL4	TPL5	TPL6
Flexible or semi-rigid	One day	min	0	5	50	125	250	325
		max	5	50	125	250	325	450
	One month	min	0	5	50	126	252	327
		max	5	50	126	252	327	453
	One year	min	0	14	138	344	688	894
		max	14	138	344	688	894	1238

In line with Figure 1, the roadway thickness is another factor that affects the road section's response to applied loads. This is determined by analysing the subgrade and assessing the soil's bearing capacity. Based on the expected lifespan, the bearing capacity of the soil, and the traffic, a structure adapted to the case study is recommended. In our case, and to follow up on the research done on bituminous coatings, we chose to deal with the case of flexible pavements made of bituminous coatings in the wearing course with the bituminous gravel material in the base course. According to the catalogue of typical structures of new pavements produced by the Roads and Highways Department of the Ministry of Equipment and Water, the following illustrative table presents the different possible pavement structure proposals.

Table 4. Structuring roadways with a base layer of GBB (gravel bituminous) bitumen.

	P2	P3	P4	Lifetime	Legend
TPL4				Short	
TPL5					
TPL6					

In this application, we have decided to simulate the behavior of a road section with a traffic level of TPL4, TPL5, or TPL6. Based on the catalogue of typical new pavement structures provided by the Roads and Highways Department of the Ministry of Equipment and Water, and considering a short lifespan as well as the bearing capacity of the supporting soil, the TPL4 traffic level includes four different thicknesses as well as the TPL5 traffic level. The TPL6 traffic level presents five different thicknesses.

3.2.3. Application of Boussinesq Model Context

The Boussinesq solution for stress distribution in a half-space due to surface loads is widely applied in geotechnics and road engineering. It is based on the assumption of a homogeneous, isotropic, and linearly elastic half-space for the soil medium [5].

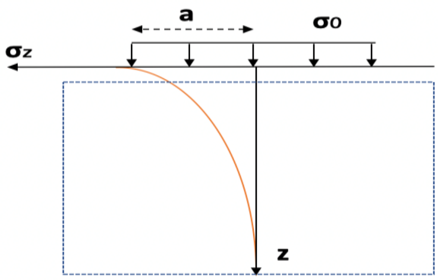


Fig. 2 Modeling of the surface load applied by the passage of a heavy truck wheel

Proposed in 1885, the Boussinesq model provides a method for calculating the distribution of stresses and deformations in a uniform mass under a point load or distributed load beneath a flexible plate. This model allows for the calculation of axial stress σz and axial strain εz as functions of the applied surface load σ0, Young's modulus E, Poisson's ratio μ, the radius of the loading plate a, and the depth z. The axial stress σ_z is calculated using the following equation:

$$\sigma_z = \sigma_0 * \left(1 - \frac{z^3}{(a^2+z^2)^{1,5}}\right) \quad (1)$$

The axial strain ε_z is calculated using the following equation:

$$\varepsilon_z = \frac{(1+\mu)*\sigma_0}{E} * \left((1-2*\mu) + \frac{2*\mu*z}{(a^2+z^2)^{0,5}} - \frac{z^3}{(a^2+z^2)^{1,5}}\right) \quad (2)$$

Results

Firstly, we need to calculate the stress applied at the center of the contact area of a heavy vehicle tyre equivalent to an 8-ton axle using the basic equation:

$$\sigma_0 = \frac{P}{A} \quad (3)$$

With:

P: the load applied by a heavy truck;
A: the contact surface of a heavy truck tyre with the pavement.

Case by case, for each traffic class and each period studied, specifically one day, one month, and one year, we generate the applied surface load presented in the following table:

Table 5. Calculated stress σ0

Lifetime	Stress σ0 (MPa)	TPL4	TPL5	TPL6
One day	Min	250	500	650
	Max	500	650	900
One month	Min	252	504	655
	Max	504	655	906
One year	Min	688	1376	1788
	Max	1376	1788	2476

Secondly, due to the complexity of the calculations, we performed them using MATLAB 2024 with a customised script to translate the proposed equations. The steps followed are:

- Define the parameters;
- Initialise result matrices;
- Monte Carlo simulation:
  - Generate random values for the parameters;
  - Calculate vertical stress with the given equation;
  - Calculate deformation with the given equation;
  - Store the results;
- Generate the plots;
- Display the result statistics.

On this, the distributions generated on a case-by-case basis are as follows:

Traffic Class TPL4

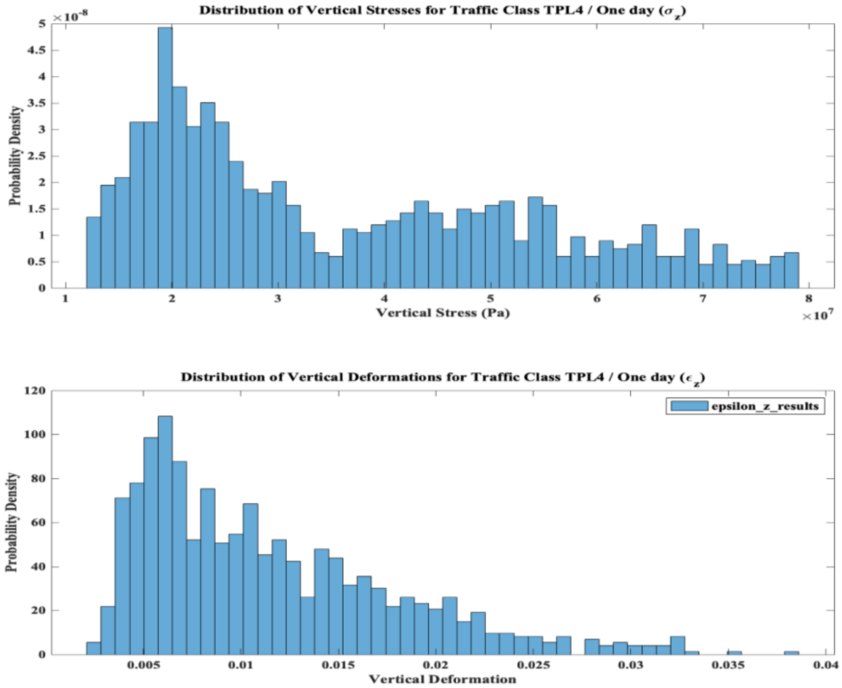


Fig. 3 Distributions of Vertical Stresses and Deformations for Traffic Class TPL4/One-day

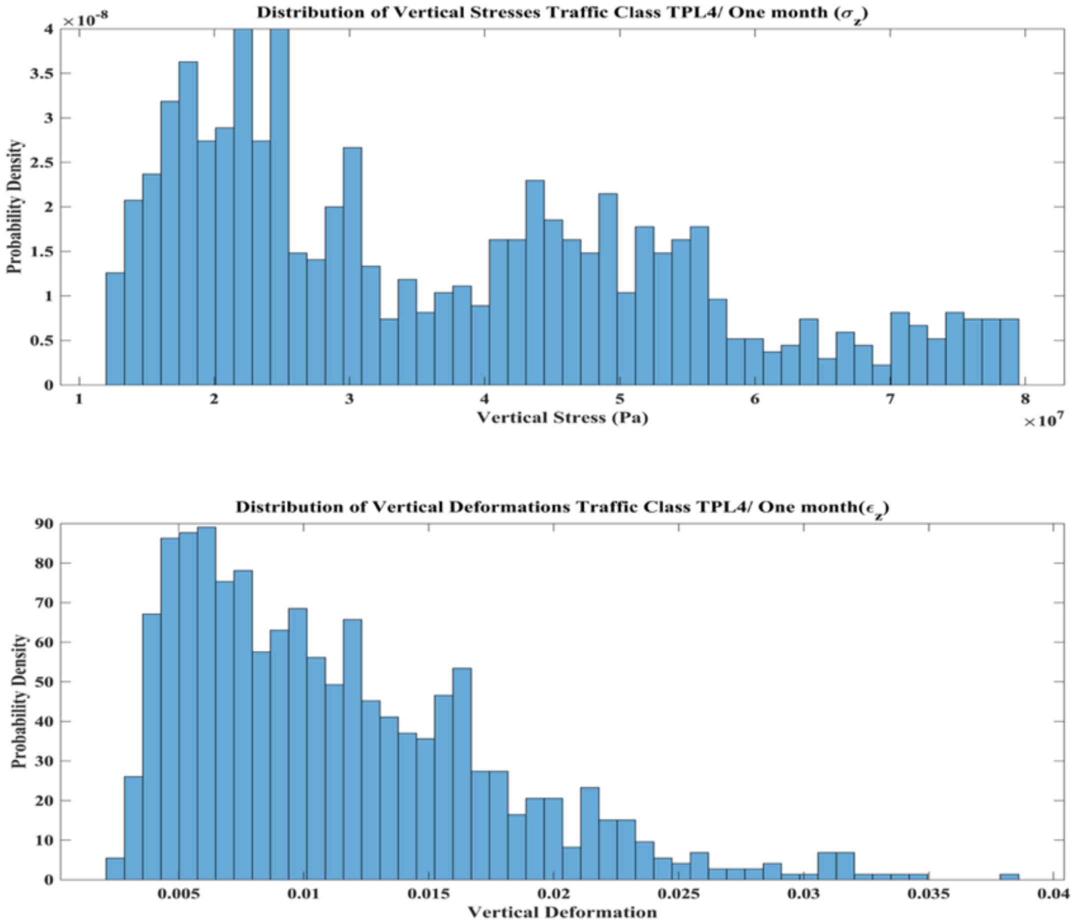


Fig.4 Distributions of Vertical Stresses and Deformations for Traffic Class TPL4/ One month

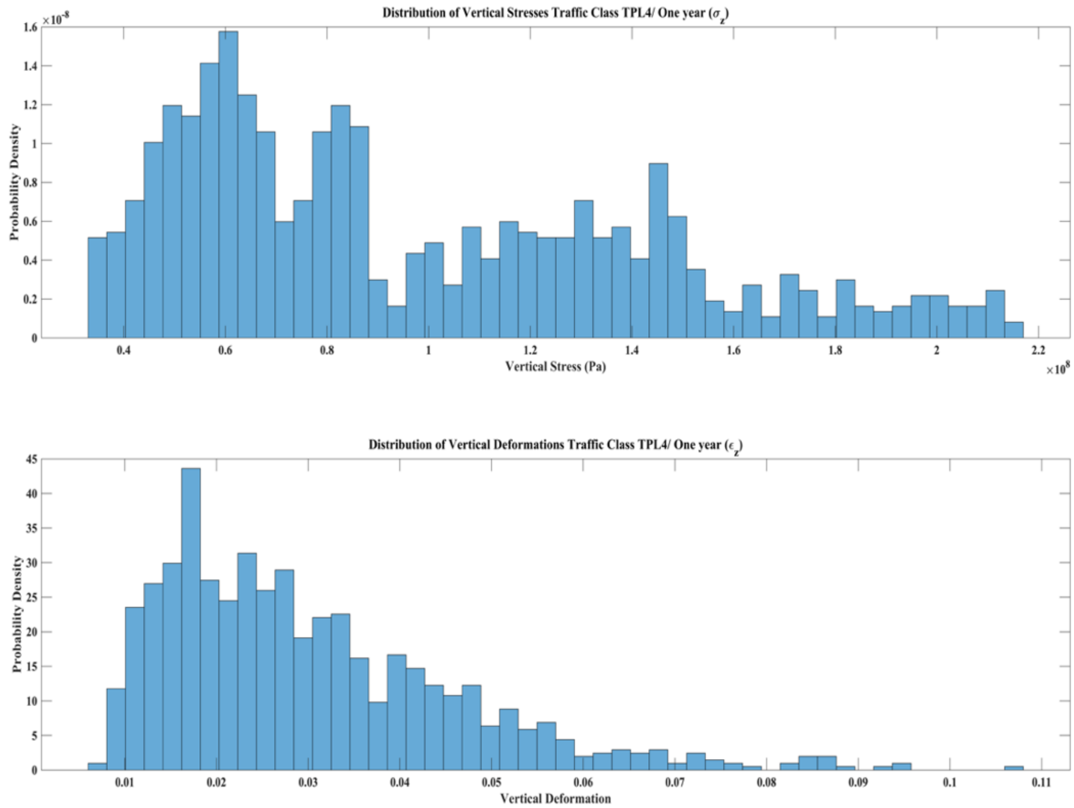


Fig. 5 Distributions of Vertical Stresses and Deformations for Traffic Class TPL4/One-year

Traffic Class TPL5

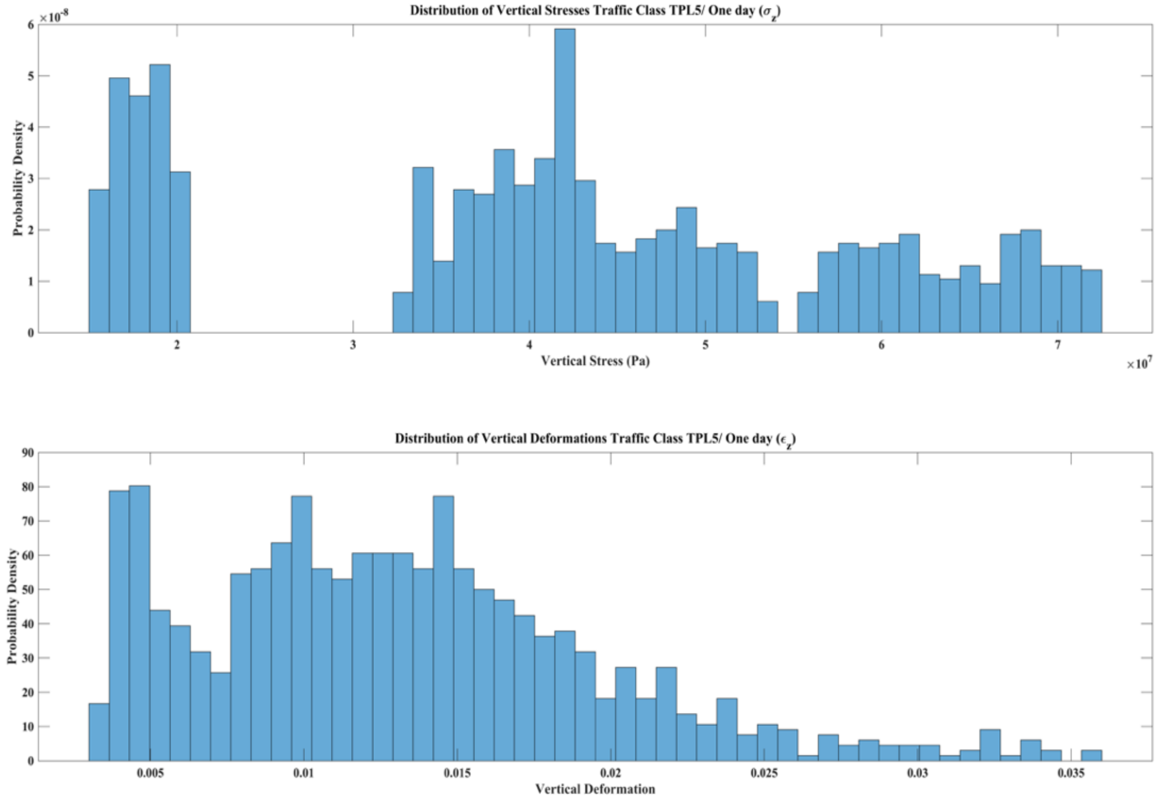


Fig. 6 Distributions of Vertical Stresses and Deformations for Traffic Class TPL5/One-day

Fig. 7 Distributions of Vertical Stresses and Deformations for Traffic Class TPL5/ One month

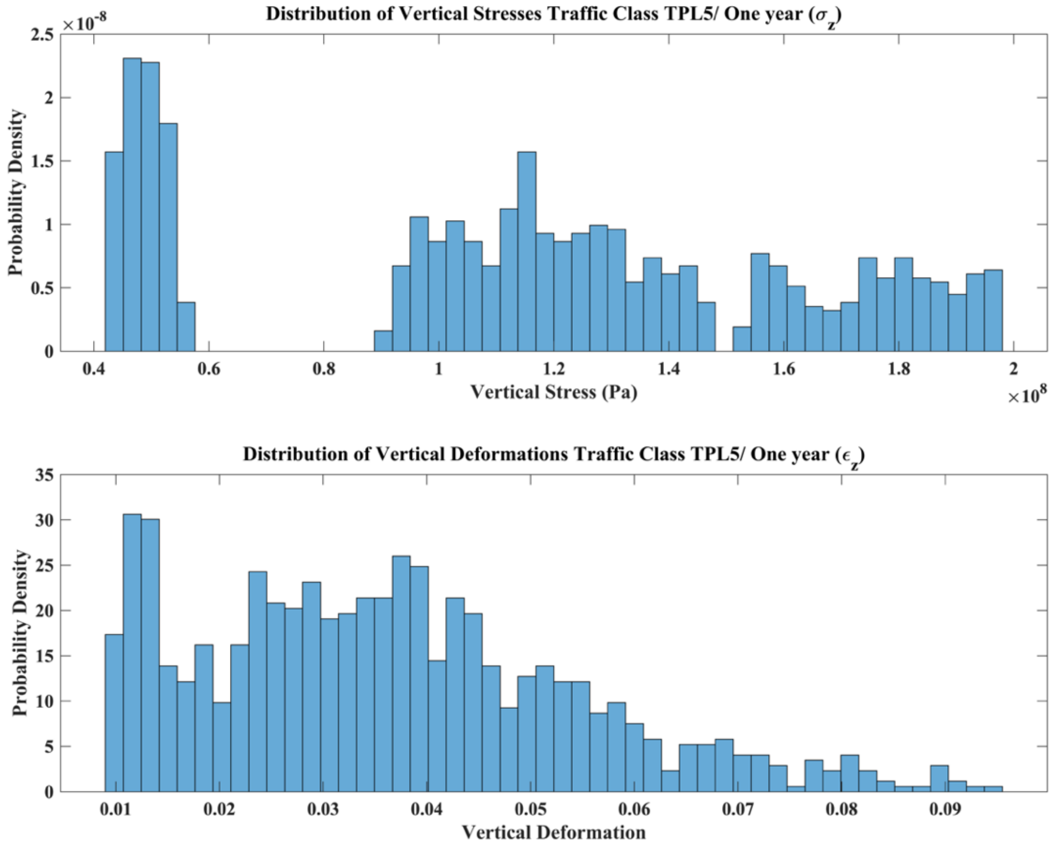


Fig. 8 Distributions of Vertical Stresses and Deformations for Traffic Class TPL5/ One year

Traffic Class TPL6

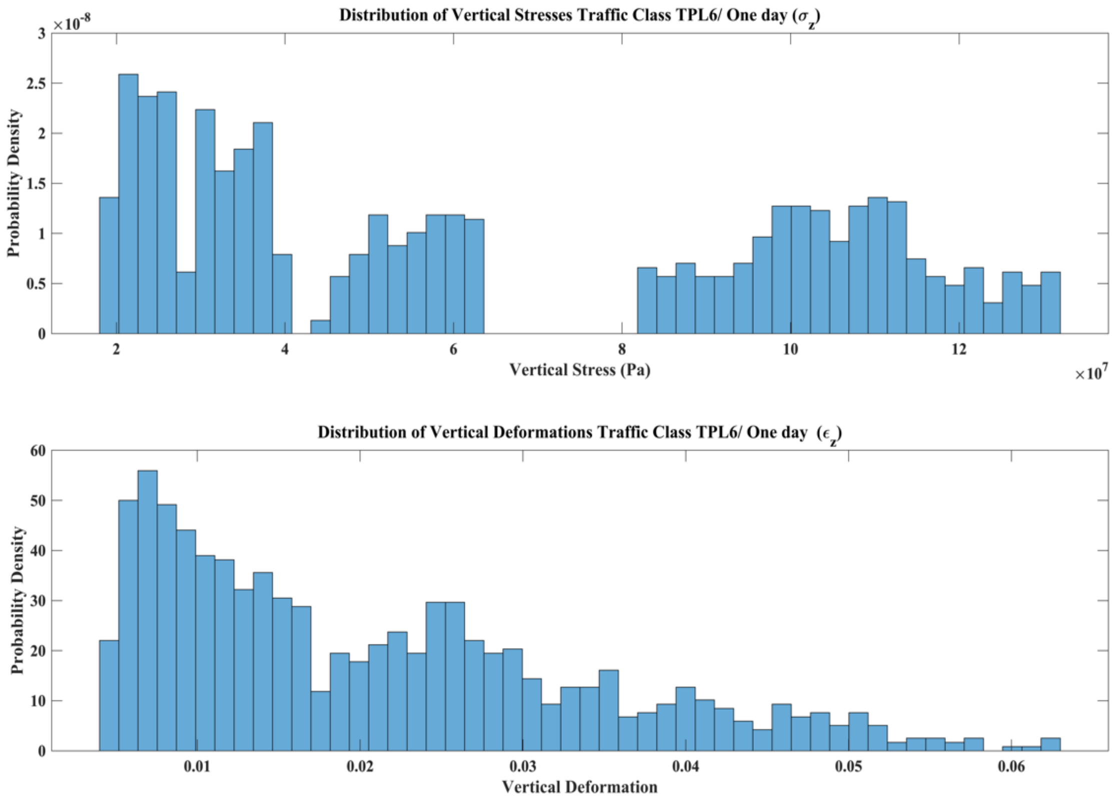


Fig. 9 Distributions of Vertical Stresses and Deformations for Traffic Class TPL6/One-day

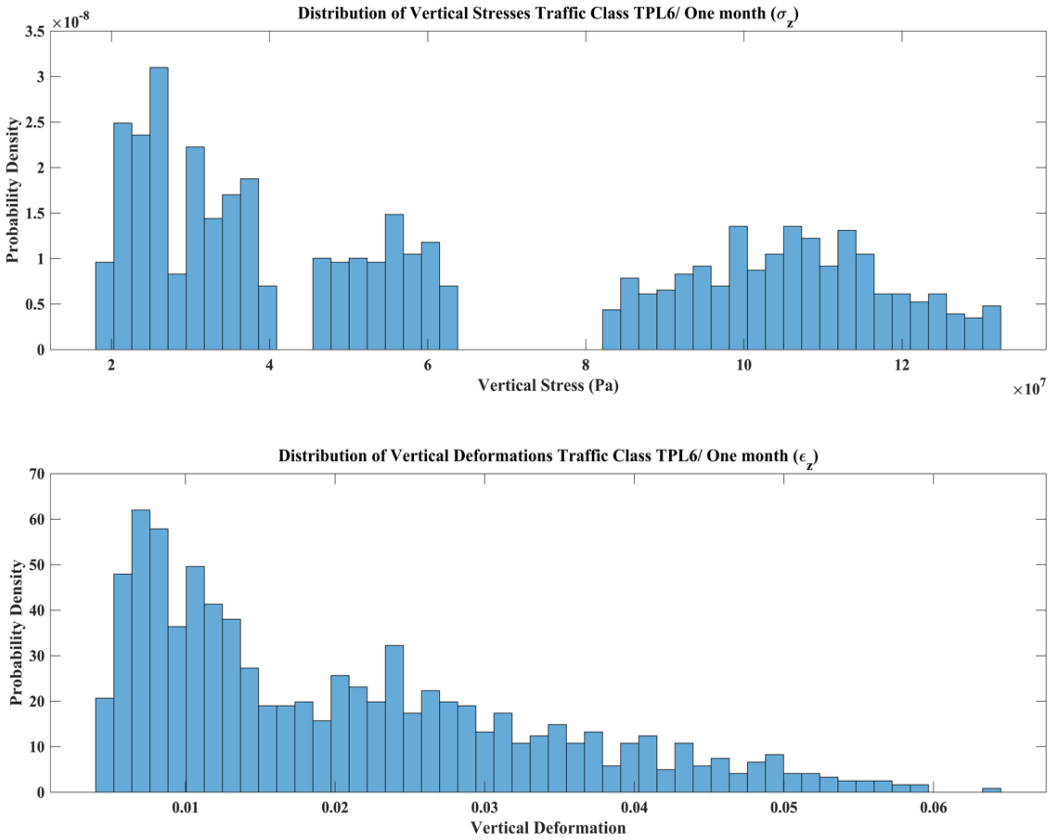


Fig. 10 Distributions of Vertical Stresses and Deformations for Traffic Class TPL6/ One month

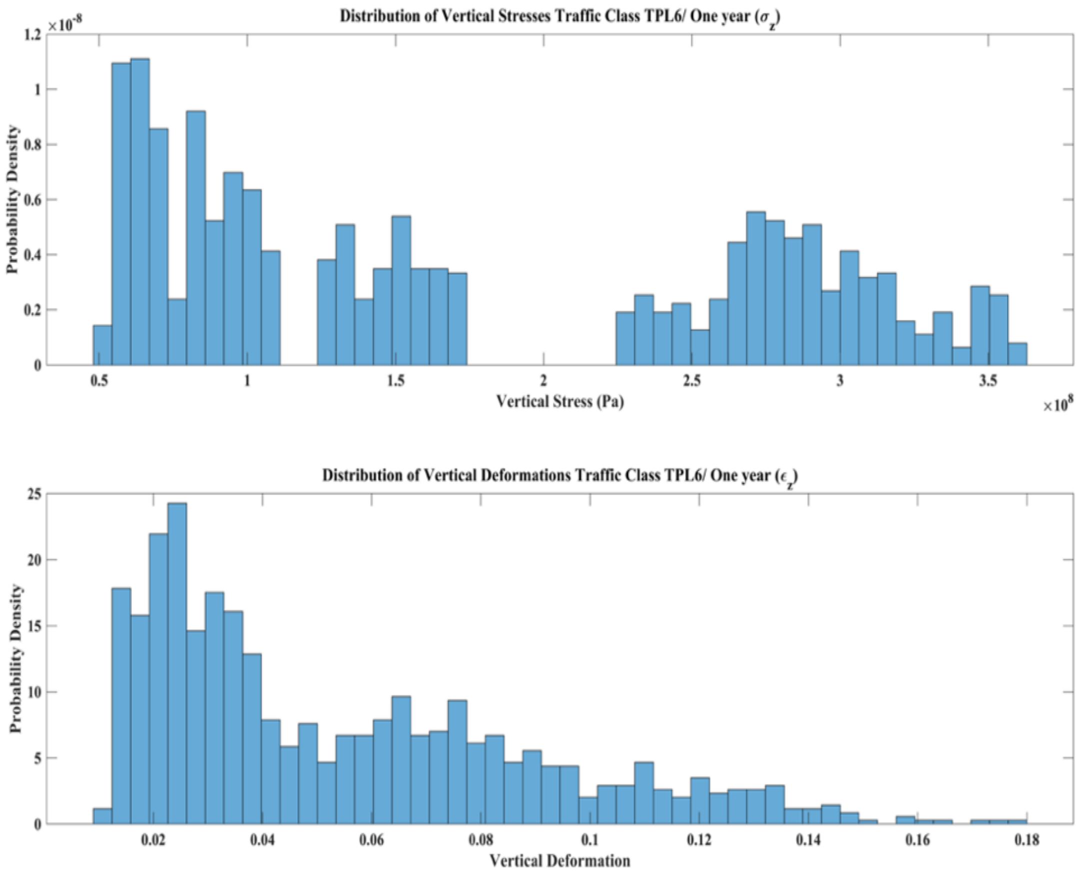


Fig. 11 Distributions of Vertical Stresses and Deformations for Traffic Class TPL6/ One yea

For a day: The strain is relatively low due to lower stresses. Average strains may indicate good material behavior for short-term loads.

For a month: The strains increase due to slightly higher stresses. Variations in strains may indicate potentially weak areas in the material.

For a year: The strains are highest due to significantly higher stresses. This may indicate fatigue accumulation and an increased risk of material failure under prolonged loads.

In summary, analysing the strain distributions and statistics for the different periods allows us to assess how the applied stresses affect the performance and durability of the road section over time. This information is essential for planning and maintaining road infrastructure.

In order to visualise the impact of cumulative traffic load on a road section, we propose combining the deformation graphs for each traffic class to observe the change and development of the resulting deformation due to the applied load.

Traffic Class TPL4

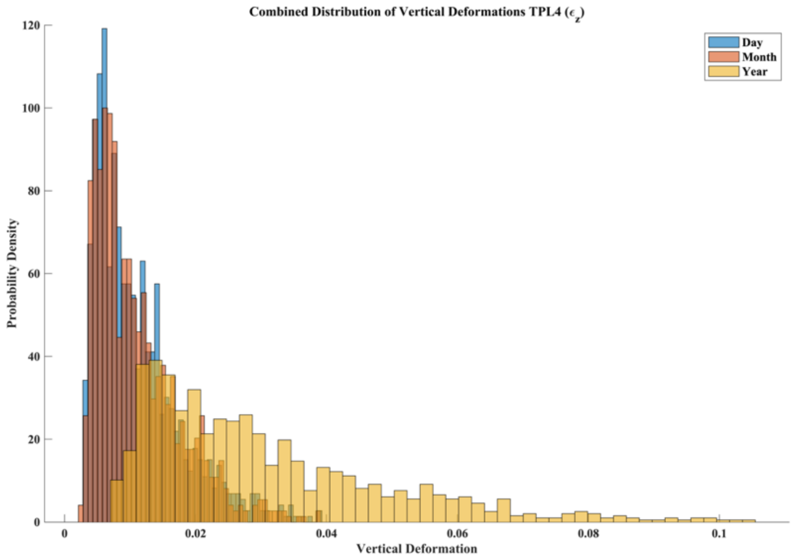


Fig. 12 Combined Distribution of Vertical Deformations TPL4

Traffic Class TPL5

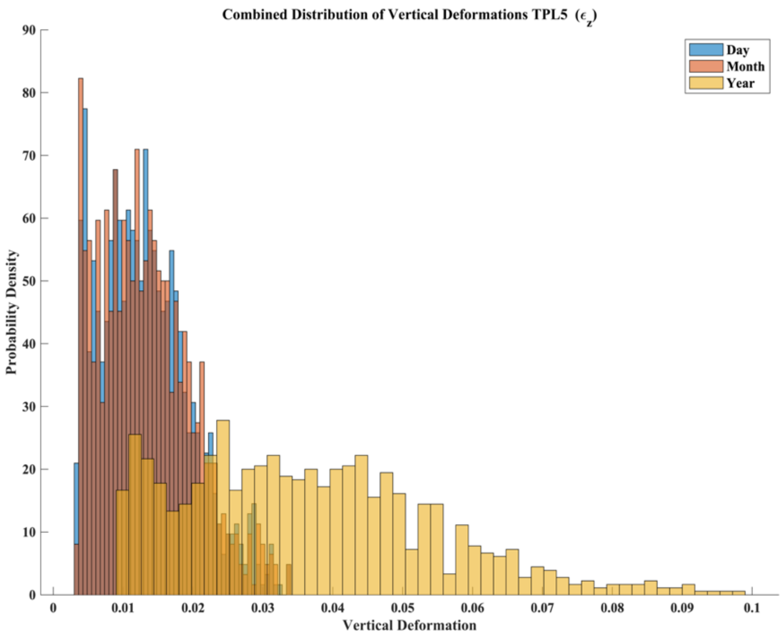


Fig. 13 Combined Distribution of Vertical Deformations TPL5

Traffic Class TPL6

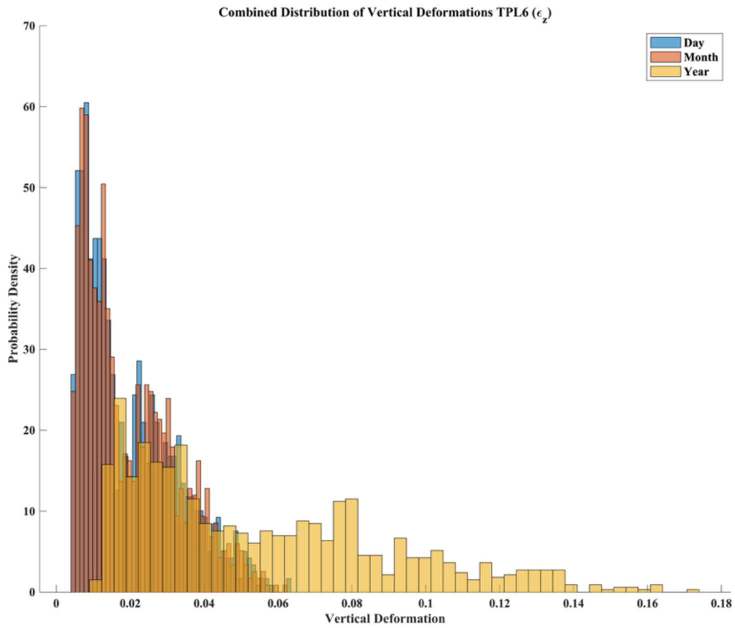


Fig. 14 Combined Distribution of Vertical Deformations TPL6

The comparison of vertical strain ϵz histograms over a day, a month, and a year illustrates how strains evolve over time under increasing stress levels. Generally, strains increase with time due to higher stresses applied over extended periods. This indicates fatigue behavior or deformation accumulation under repeated loading. For the one-year period, the distributions of the three traffic classes are found to be broader and more spread out, which may indicate higher variability in the deformation responses due to variations in parameters such as thickness, Young's modulus, etc. According to the results of the means and standard deviations of the vertical deformation they are summarised in the following table:

Table 6. Standard Deviation and Mean Values of the Vertical Deformation

Traffic Class	Lifetime	Mean Vertical deformation	Standard Deviation of the vertical deformation
TPL4	One day	0,011	0,006
	One month	0,011	0,006
	One year	0,030	0,017
TPL5	One day	0,013	0,006
	One month	0,013	0,006
	One year	0,036	0,017
TPL6	One day	0,019	0,012
	One month	0,020	0,012
	One year	0,054	0,012

3.2.4. Fatigue Simulation and Modeling

Bituminous coating fatigue is a damaging phenomenon that occurs under the action of a number of low-amplitude stress cycles. Damage is defined as a progressive degradation of the mechanical characteristics of the material until failure [16].

In order to study the fatigue of bituminous material subjected to regular traffic, we will visualise its behavior following several load cycles from the modeling on MATLAB. A material under a load goes through two stages and reacts in two different ways: one stage, whose behavior is elastic and the second stage, whose behavior is plastic. In our case, we choose to model the elastic behavior by the Boussinesq model and the plastic behavior by the Miner-type fatigue model on MATLAB.

Following the modeling of one million cycles of a road section subjected to TPL6-type traffic for one year, we will have the cumulative damages presented in Figures 15 and 16.

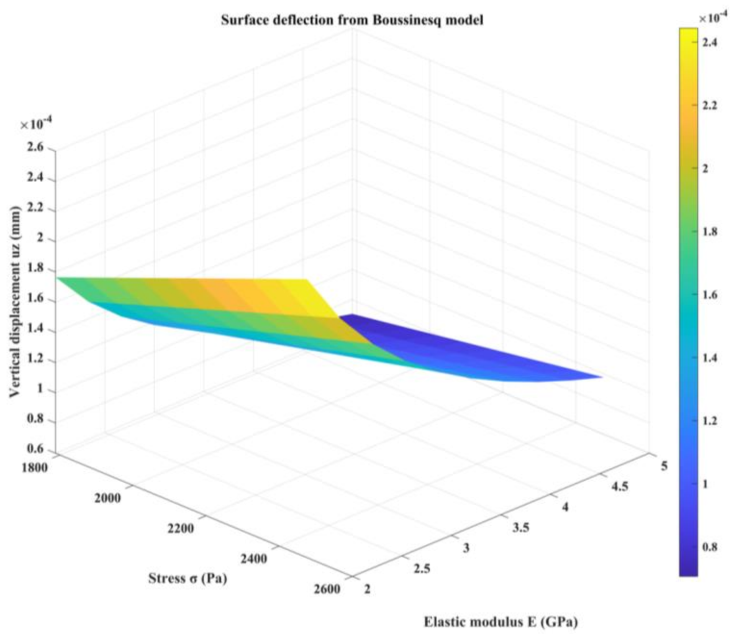


Fig. 15 Surface deflection from the Boussinesq model

As can be seen in Figure 15, in the abscissa axis, stress σ (Pa) ranges from about 1800 Pa to 2600 Pa. In the ordinate axis, Elastic modulus E (GPa) ranges from 2 GPa to 5 GPa, while in the vertical axis, Vertical displacement uz (mm) is multiplied by 10^{-4}. The displacement values range from about 0.6×10^{-4} mm to 2.7×10^{-4} mm. From the figure, the following interpretations can be made:

- Effect of stress (σ): for a fixed modulus E, the higher the applied stress σ (displacement to the right on the σ axis), the greater the vertical deflection (the surface rises).
- Effect of elastic modulus (E): for the same stress σ, a higher E (toward the E axis) leads to decreased displacement. In other words, a stiffer material deforms less under load.
- Interaction σ × E: the surface is inclined in these two directions, illustrating that both parameters act simultaneously on deflection. The slopes are more pronounced when moving from low to high stresses, especially from low modules (bottom left area where the surface is steepest).

For physical interpretation, and before moving on to plastic analysis (Miner's rule), this analysis has proven to be useful for estimating the elastic response. It allows for predicting the surface deformation of a pavement modeled as an elastic half-space (Boussinesq) as a function of the applied load (σ) and the stiffness of the material (E).

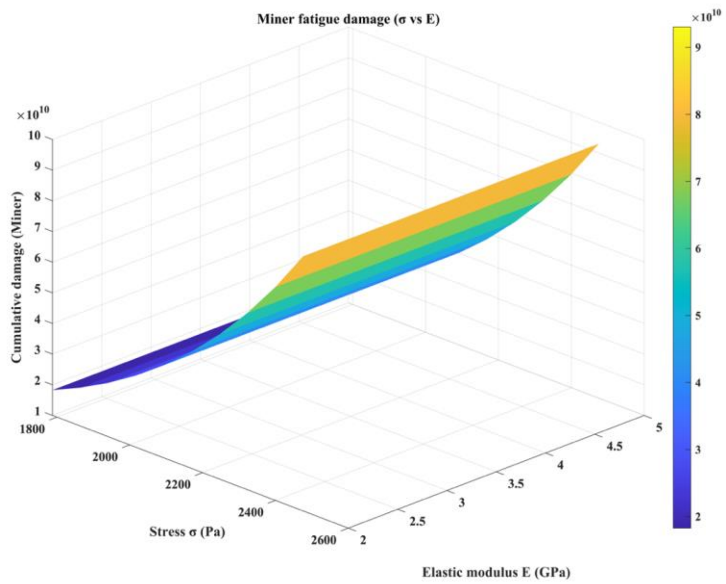


Fig. 16 Miner fatigue damage

In Figure 16, we can observe in the abscissa axis the stress σ (Pa), varying from about 1800 Pa to 2600 Pa, in the ordinate axis (depth): the elastic modulus E (GPa), from 2 GPa to 5 GPa and in the vertical axis: the cumulative damage according to Miner's rule, expressed in units of 10^{10} (for example, "2" on the axis means 2×10^{10} equivalent cycles). From the figure, the following interpretations can be made:

- Effect of stress σ: for the same E, the Miner damage increases rapidly as the stress increases; the surface area rises sharply to the right.
- Effect of modulus E: at constant stress, a higher modulus (stiffer material) leads to slightly more cumulative damage, according to this model. The increase in damage along the E axis is less pronounced than along σ, but still present.
- Interaction σ × E: the inclined plane shows that fatigue is maximised both for high loads and for a stiff material.

For physical interpretation, this surface provides an estimate of the "accumulated damage" in fatigue cycles, according to Miner's rule, for a half-space modeled elastically and then evaluated plastically. It allows one to determine how close the structure is to fatigue failure for a given combination of stiffness and load.

The critical damage zone's visualisation is possible by adjusting the parameters of the S-N law, the number of cycles and the stress. Figure 17 allows us to visualise a damage coefficient of less than 1, meaning the material is still resistant.

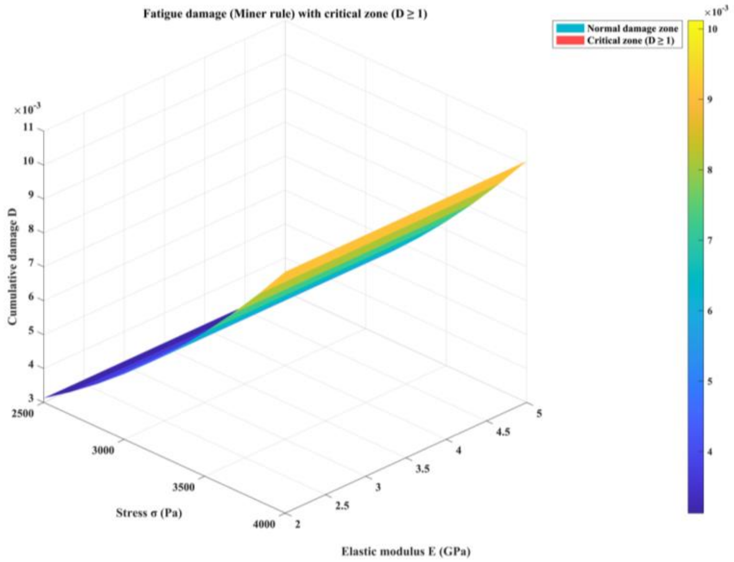


Fig. 17 Fatigue damage with critical zone

From Figure 17, the normal zone surface represents the "normal" zone where D < 1 (no fatigue failure yet), while the red surface indicates the critical zone where D ≥ 1 (failure threshold reached or exceeded). This visual delineation allows for immediate identification of dangerous (σ, E) combinations.

As before, D increases as σ increases and, to a lesser extent, E increases. Therefore, the critical zone appears for the highest stresses (> ~3,500 Pa) and high moduli (> ~4 GPa), a sign that beyond these values, the structure reaches its fatigue threshold.

Some key points can be extracted, including:

- Critical threshold: As soon as the surface turns red, the number of equivalent cycles ("damage") reaches the failure threshold (D = 1).
- Safe zone: For σ below ~3,000 Pa and moderate E (< 4 GPa), the color remains cyan, with D well below the threshold.
- Abrupt transition: The surface's color and shape show that the transition to the critical zone can be quite sudden when σ or E exceed certain levels.

This representation allows us to define operational limits: for example, not to exceed σ = 3,500 Pa for a material with a modulus of 4–5 GPa.

To go further, we can extract the transition curve D=1 in the (σ, E) plane and deduce a "safety boundary". On an operational level, load and traffic control exercised on a road section with Young's modulus data can give us a visualisation of the possible damage to the pavement.

4. Discussion

For traffic class TPL4 and TPL5 (as shown in Table 6), the standard deviation indicates that the observed deformations do not deviate much from the mean. It also indicates that the behavior of the road section under the applied stresses is relatively predictable. The deformation values are consistently concentrated around the mean with few extreme variations, which means less variability and dispersion in the results. For the material quality, it is suggested that it is homogeneous and has uniform mechanical properties. This is a positive sign of the quality and performance of the material under the applied loads.

For traffic class TPL6, the standard deviation value means that the observed deformations have a greater spread around the mean compared to the standard deviation for traffic classes TPL4 and TPL5, suggesting greater variation in the deformation responses. This standard deviation value means that the behavior of the road section under the applied stresses is somewhat less predictable, which may indicate less uniform mechanical properties of the material used for the road section. This traffic class requires increased attention when planning maintenance and repairs, as there may be areas where deformations are more significant.

Given the complexity of the TPL6 traffic class, special attention must be paid to designing a road section of this class. To visualise the progression of the behavior of a roadway of this type, we propose a 10-year projection of the applied loads, taking into account the population growth rate already mentioned.

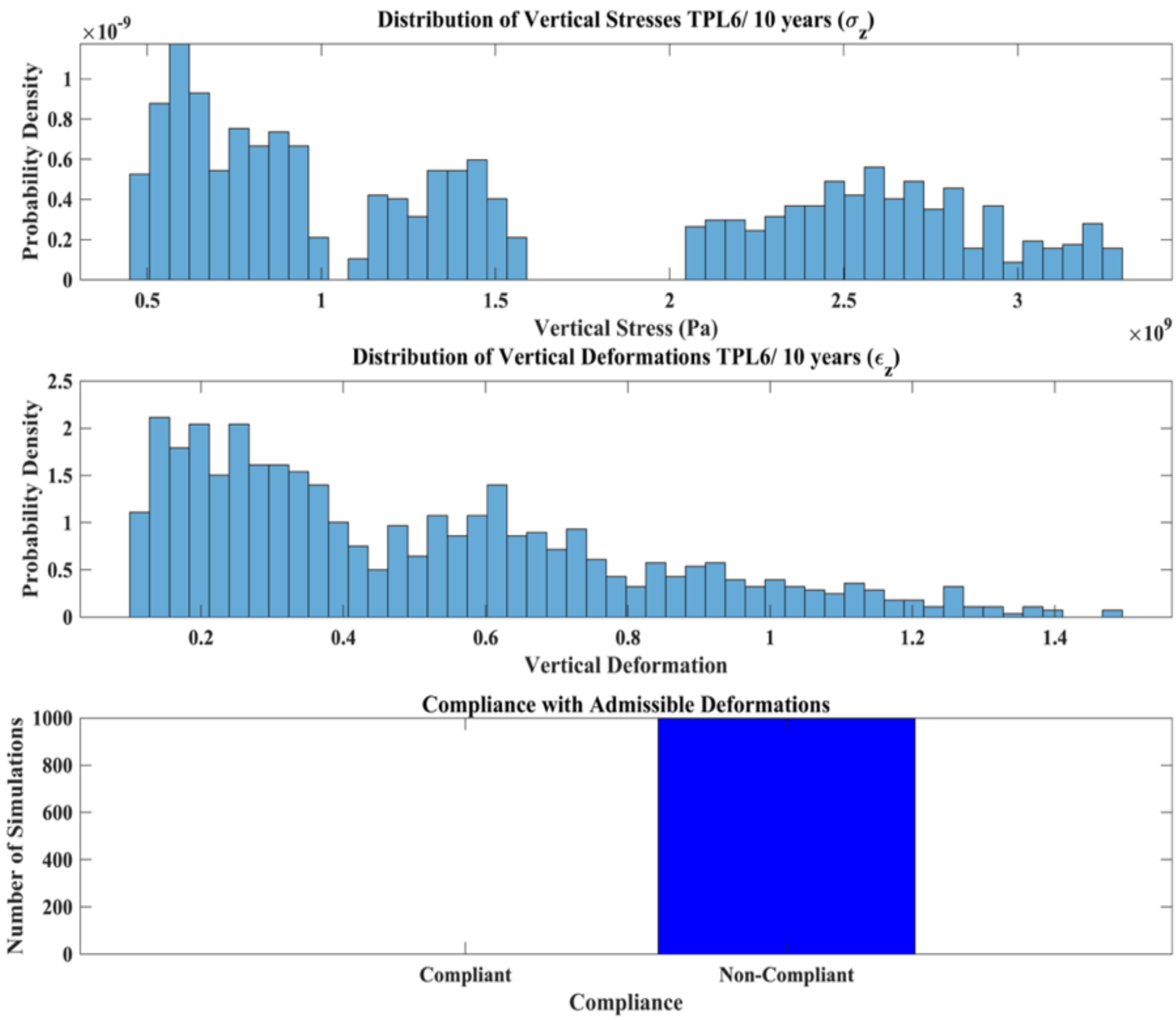


Fig. 18 Distributions of Vertical Stresses and Deformations TPL6/ 10 years and the compliance with admissible deformations

Considering an allowable deformation of 0.01, the calculated deformations appear inconsistent with the allowable deformation. These excessive deformations suggest that the pavement will deteriorate more rapidly under the current loads.

Therefore, the maintenance frequency must be increased to repair the damage before it becomes severe. Therefore, regular inspections and preventive repairs will be necessary to extend the life of the pavement.

Still, with the aim of data variation to explore the different parameters that can impact the calculation, we propose to briefly study the variation of Young's modulus according to the temperature of the site by comparing two structures with the same traffic class and the same pavement components but at two different temperatures, one at 20°C and the other at 40°C.

We choose to study a 56cm thick road section (z) whose components are indicated in the figure below.

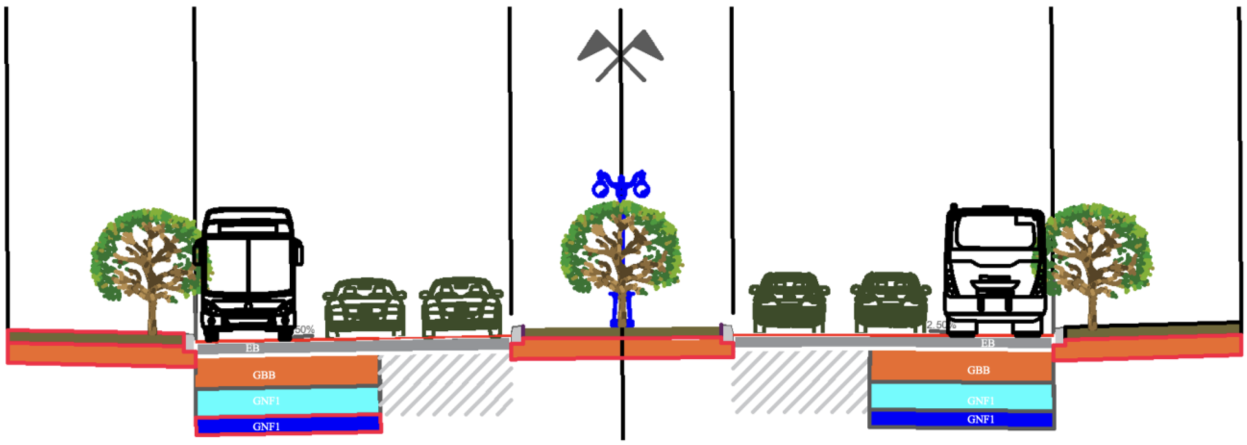


Fig. 19 Cross-sectional profile of a roadway under Traffic Class TPL6 (Made in AutoCAD)

The stress duration of the section is one month; hence, the stress applied to the surface varies from 655 MPa to 906 MPa. According to Sylvain [18], who studied the variation of the Young's modulus, it varies from 2000 MPa to 5000 MPa at 20°C and from 1000 MPa to 2000 MPa at 40°C. By doing the simulation on MATLAB 2024, we arrive at the following results:

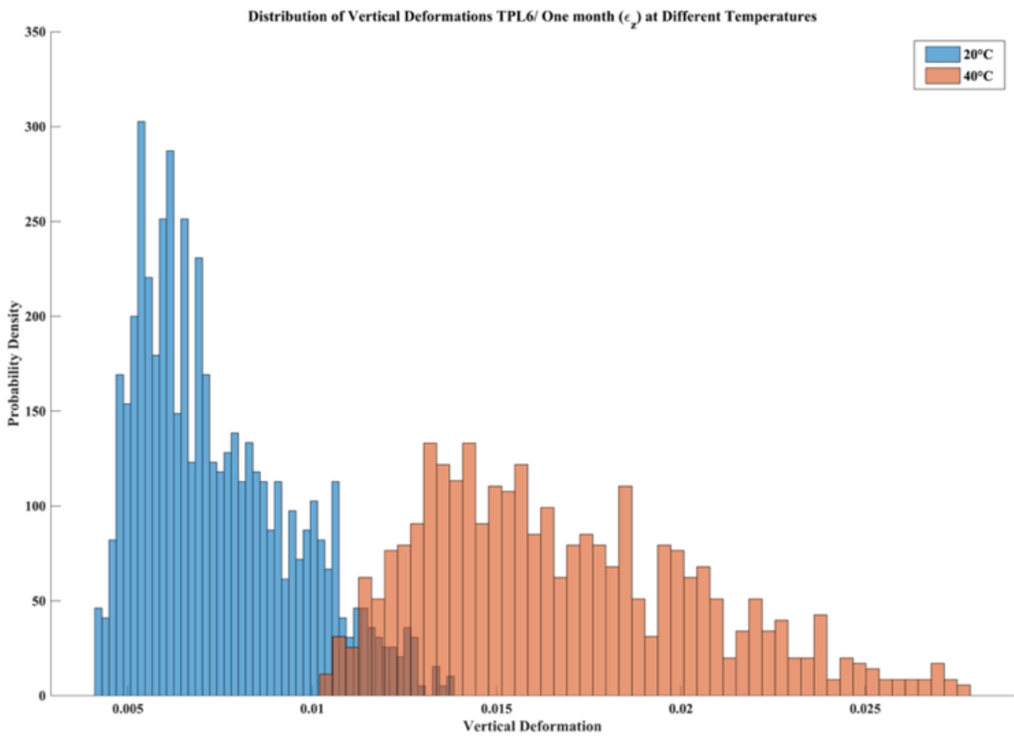


Fig. 20 Distribution of Vertical Deformations Traffic Class TPL6/ One month at different temperatures

The results show that the mean vertical deformation is higher at 40°C compared to 20°C, indicating that the material deforms more at higher temperatures (as shown in Figure 17), which is expected since materials tend to become softer and less stiff as the temperature increases. Comparing the Standard Deviation of Vertical Deformation, that is 0.0020967 at 20°C and 0.0037487 at 40°C, and this indicates that there is more variability in the deformation at 40°C than at 20°C. This suggests that the material's behavior is less consistent at higher temperatures, possibly due to increased sensitivity to other factors such as stress and microstructural changes.

Talking about pavement design and maintenance, in order to interpret the results of the simulation, here are some insights that will help in making informed decisions to enhance the durability and performance of the pavement over time:

Pavement Design:

- Material Selection: Materials that are more resistant to temperature-induced deformation should be considered, especially in regions with high temperatures, including fiber-reinforced concrete, prestressed concrete (rarely used for roads), modified asphalt, and bituminous concrete;
- Thickness Adjustment: Increasing the thickness of the pavement could help mitigate the effects of higher deformations at elevated temperatures, but this increase must take into account Table 2, summarising the regulations as well as the cost that this increase may generate;
- Reinforcement: Incorporating reinforcement materials that can withstand higher temperatures might improve the performance of the pavement.

Maintenance Planning:

- Increased Monitoring: More frequent inspections might be needed during hotter months to monitor and address any excessive deformations such as fiberglass mesh, metal fibers and polymers;
  - Surface Treatments: Applying surface treatments that can protect the pavement from high temperatures and reduce deformation;
  - Repairs and Resurfacing: Planning for periodic repairs and resurfacing to address any deformation-related damage that occurs more rapidly at higher temperatures.

Despite the strong results provided by the analysis of mechanical stresses on road behavior, this study remains much less extensive in covering all the stresses that a road section may undergo. In order to overcome the limits of this study and model the approximate reality, we propose an analysis that takes into account thermal, chemical and mechanical stresses.

5. Contribution

According to the method of programming road structure repair or reinforcement projects in Morocco, a site visit is generally scheduled to report the visual condition of the road structure with the help of the presence of an expert. Thus, they can use measurement methods such as mechanical auscultation through a profilometer or deflectometer to measure the deformation of the road section under loads. Among these types of investigations, it is possible to cite the National Center for Road Studies, where enormous efforts are made to report the state of the national road network. After a national investigation, laboratory studies are carried out, and a maintenance program is subsequently established.

This research constitutes an essential step in digitising the procedure through modeling by neural networks by applying equations such as the Boussinesq model. It will not only minimise test and displacement loads and avoid errors related to expert feedback but also be a basis and starting point for other researchers to set up a pavement management system at the national level.

Using the Boussinesq model to calculate the stresses applied to roads and modeling them using neural networks, a highly effective artificial intelligence method, this study will contribute to modeling and predicting road section deformation using only traffic data.

To the best of our knowledge, this represents one of the first research efforts in Morocco to predict pavement performance solely from traffic input. Such modeling significantly reduces the need for on-site investigations, minimises time and resource consumption, and enables real-time visualisation of deformation. Ultimately, this work lays the groundwork for an intelligent road management system capable of analysing the condition of the road network and optimising maintenance scheduling or traffic redistribution.

Table 7. Comparison with existing research findings

	Modeling the Progression of Deformation in a Flexible Pavement using the Boussinesq Model with Monte Carlo Simulation.	Predicting the fatigue life of asphalt concrete using neural networks.
Context	There is a need to improve road safety in Morocco by developing more resilient road design and maintenance strategies. This research considers Modeling the Progression of Deformation in a Flexible Pavement using the Boussinesq Model with Monte Carlo Simulation.	The fatigue of asphalt mixes is expensive to evaluate experimentally. This study explores using Artificial Neural Networks (ANN) to predict fatigue life.
Application	The Boussinesq model is used to model the deformation of pavements under different mechanical loads (daily, monthly, and annual). Monte Carlo simulation allows the analysis of the combined effects of load and temperature variations on pavement durability.	The model is trained on a dataset from several studies, with variables such as binder content, void ratio, imposed strain and temperature.

Results	The results show that cumulative deformation becomes significant under heavy loads and high thermal conditions, which affects pavement durability. High-temperature areas require more resistant designs.	A high binder content significantly improves service life. The effect of voids depends on the binder level.
Contribution	The study demonstrates the interest in coupling the Boussinesq model with the Monte Carlo method to improve the prediction of deformations and optimise the management and design of pavements, with the aim of sustainability. Once trained, neural networks allow instant prediction of deformations without going through the complex calculations of the Boussinesq model.	The study demonstrates the effectiveness of ANNs in capturing complex relationships between formulation parameters and fatigue and provides an open-source database.

6. Perspectives

In this study, using only the traffic data applied to a road section, Young's modulus and the region's temperature, it is possible to visualise and predict the performance of the roadway.

Based on this, several perspectives can be considered for advancing this research. New parameters influencing pavement conditions can be incorporated, such as the chemical influence of the external field. Thus, several studies will follow to ensure the continued resolution of this problem, including:

- By inspecting pathologies spread in Morocco and studying the parameters causing each type of pathology, it will be possible to identify the factors influencing performance.
- Application of the Monte Carlo dropout method to identify the optimal structure and study the influence of each parameter on the performance of the roadway
- Resulting in an equation grouping together all the parameters that can influence the performance of the roadway based on the data of materials available in Morocco.

7. Conclusion

By modeling the deformation of the pavement under mechanical loads in several scenarios, its behavior can be understood to produce effective tools for sizing, predicting and modeling performance. This model will not only help in predicting performance but also in maintaining the durability and efficiency of the road network. Through this study, the deformation is modeled of the pavement under three types of traffic in the case of flexible pavement; thus, a comparison of the behavior of the same type of pavement under two different temperatures is made.

The comprehensive analysis of road pavement deformation using the Boussinesq model provides valuable insights into the behavior of pavement structures under varying load conditions and temperatures. The simulation approach employed in this study, which includes Monte Carlo simulations, allows us to account for the variability in key parameters such as applied stress, thickness, and Young's modulus. By changing the stress applied to the roadway for TPL4 and TPL5 traffic, it was found that the flexible material guarantees homogeneity and performance after loading. A roadway under TPL6 traffic requires special attention, especially when loading under high temperatures.

In conclusion, using the Boussinesq model and Monte Carlo simulation provides a robust framework for predicting pavement deformation and informing effective design and maintenance strategies. Understanding the impact of temperature and load variations on pavement performance makes it possible to develop more durable and reliable road structures, ultimately enhancing the safety and efficiency of transportation systems.

During the course of this study and other similar ones dealing with mechanical, thermal, and chemical stresses and their combination, the development of a pavement management system is feasible. It is recommended to perform similar simulations with other varying parameters, such as the chemical interaction of the roadway with the outside world, the loading under very high or very low temperatures and finally, the combination of these variants with a mechanical loading ultimate and of service.

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