Investigation into the Effects of Traffic-Induced Moving Loads on Flexible Pavement: A 3D Finite Element Approach

Md. Nazmul Hossain*[1], Zafir Raian[2], Nirmal Chandra Roy[3] and Mahajabin Islam[4]

[1] *Student, Hajee Mohammad Danesh Science and Technology University, Bangladesh, e-mail: nazmulabid.936@gmail.com*
[2] *Student, Hajee Mohammad Danesh Science and Technology University, Bangladesh, e-mail: raianzafir@gmail.com*
[3] *Assistant Professor, Hajee Mohammad Danesh Science and Technology University, Bangladesh, e-mail: nir120072@gmail.com*
[4] *Student, Hajee Mohammad Danesh Science and Technology University, Bangladesh, e-mail: mahajabinislam05@gmail.com*

***Corresponding Author**

ABSTRACT

In the context of increasing vehicular traffic and road usage in Bangladesh, the structural performance of flexible pavements under dynamic loading has become a critical area of study. This research investigates the effects of traffic-induced moving loads on flexible pavement using the Beladanga-Dinajpur road as a case study. A detailed three-dimensional finite element model was developed using MIDAS GTS NX to simulate the pavement structure, incorporating real geometric and material properties. An HL-93 standard truck load was applied at varying speeds ranging from 40 kmph to 120 kmph. The numerical simulations revealed that vertical displacement decreased with the increase in speed and stress increased up to around 90 kmph. Beyond this threshold, a decline in stress was observed, suggesting that stress waves could not fully develop at higher speeds due to reduced load-pavement interaction time. This nonlinear behavior highlights the importance of incorporating speed-sensitive dynamic analysis into flexible pavement design, particularly in regions with rapidly increasing traffic loads. This study provides insight into the influence of vehicle speed on pavement behavior, which is essential for designing durable and safe road infrastructures in developing regions.

Keywords: *Flexible Pavement, Finite Element Modeling (FEM), MIDAS GTS NX, Pavement Response, Moving Wheel Load*

1. INTRODUCTION

Flexible pavement is an important component of the road transportation system in Bangladesh. Flexible pavements are one of the most widely used pavement systems for highways and other transportation infrastructure. Given the growing number of heavy vehicle loads and in particular, trucks with HL-93 axle load application on pavements, it is important to develop an understanding of stress distribution and displacement patterns within pavement layers. The traditional foundation design methods usually rely on empirical approaches developed from limited field data and simplified assumptions. However, these methods do not properly describe the complex interaction between pavement materials and moving vehicle loads. Advances in the tools of computation such as Finite Element Method (FEM) have enabled gaining a better understanding and more realistic model for behavior of pavement materials by considering various material properties, boundary conditions, and dynamic loading effects. The Finite Element Method with MIDAS GTS NX software was used to look at how the flexible pavement held up under the moving HL-93 truck load at different speeds of traffic. This work aims to evaluate the effect of vehicle speed on pavement material movement and stress distribution.

The early road development procedures were entirely based on empphirical formulas. The first of these were the California Bearing Ratio (CBR) Test done by the (California Division of Highways, 1929). The design charts developed during this test became the foundation for many emphirical methods and is still in use today. The elasticity theory by (Boussinesq, 1885) was the first place where analytical methods were used. His study formulated a solution for the stress and displacement in a homogeneous, isotropic, semi-infinite elastic half-space under a surface point load which explains how stress is spread with depth. (Burmister, 1943) formulating the theory of a multilayer elastic system for stresses and displacements was a major advancement. His method allowed the stress, strain, and deflection in a multi-layer pavement to be calculated on the basis of having two models and the modulus and thickness of each layer. This procedure has become the first model to represent robustly flexible pavement material, consisting of asphalt surface, base, subbase and subgrade layers in an exact way.

The Mechanistic–Empirical (M–E) design procedure originated in the 1990s by (AASHTO, 2008) was the first to recognized the limitations of purely empirical designs. As science & technology advances many new procedures & methods are invented to better design flexible pavement. Finite Element Method (FEM) is among the new tools to help design pavements. This method uses computer programs to predict pavement responces under various condtions which provides a better understanding of the interaction between vehicles and the pavement.

Researchers conducted numerous studies employing FEM to analyse pavement response. During earlier studies researchers compared field data with data obtained from numerical analysis. One such study preformed by (Siddharthan et al., 1996) found that the difference was less than 14% between the predicted response from numerical analysis and those measured in field. (Hadi & Bodhinayake, 2003) did a study considering realistic material properties & changing traffic loads. They concluded that non-linear materials are impotent during designing pavement to avoid early collapse. (Yin et al., 2007) considered factors such as loading time and temperature of pavement in their study. Their study revealed that loading time has a more pronounced impact on pavement response in the summer season. (Al-Qadi et al., 2010) compared isotropic and anisotropic models in their study. Their study proved that incorporating anisotropy and stress-dependency provides more accurate deflection predictions against field measurements. (Saha et al., 2024) found in their study that increasing base layer thickness is the primary factor in lowering displacement and stress in pavement construction. FEM has come a long way in terms of assisting engineers to design flexible pavement but more research is needed to understand all the factors that govern pavement response. One of these factors is the effect of vehicle speed on the pavement surface. Vehicle speed is concerning factor that should be taken into consideration while designing flexible pavements. In this study, the pavement response due to the variation of speed are analyzed.

2. METHODOLOGY

The analysis was carried out using the finite element software MIDAS GTS NX Version 2022. A detailed recreation of the pavement geometric model is possible using this software. In MIDAS GTS NX material properties of each layer can be assign depending on their various characteristics. In this software the pavement response can be analyzed under various factors. For this study the effect of vehicle speed was taken under consideration.

2.1 Study Area

A road from Dinajpur district was selected as the study subject of the research. The name of the road is (N-508) Beldanga-Dinajpur Road, which is locally known as Doshmile-Dinajpur Road. This is a highway which connects Rangpur & Thakurgaon to Dinajpur. This road is located northern part of Dinajpur. It is a two-lane road carrying different types heavy vehicles.

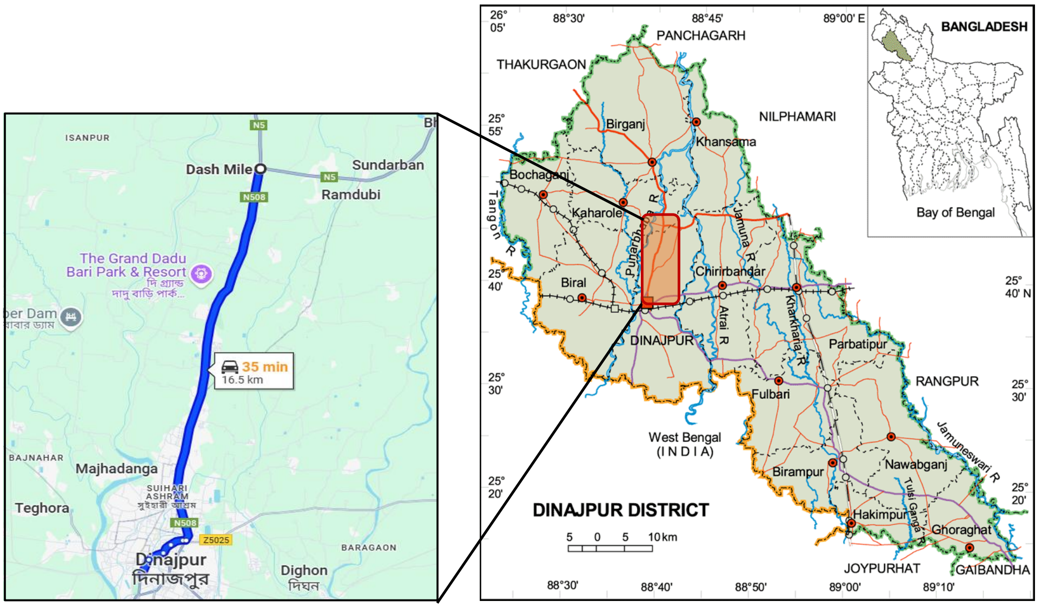

Figure 1: Map of (N-508) Beldanga-Dinajpur Road

2.2 Data Collection

The details of pavement of (N-508) Beldanga-Dinajpur road was collected from Roads & Highways Department (RHD), Dinajpur. RHD provided all the necessary data required for this research. The following data was provided by RHD:

Table 1: Thickness & CBR Chart for (N-508) Beldanga-Dinajpur Road

Layer Name	Thickness (mm)	CBR (%)
Wearing Course	50	110
Bitumen Binder Course	150	100
Aggregate Base Type-1	200	80
Aggregate Base Type-2	250	50
Sub-Base	250	25
Improved Subgrade	300	8

2.3 Loading Configuration

HL-93 truck was selected as vehicle load for the study. It is one of the heaviest trucks available. It was chosen to obtain the maximum possible deflection that can occur due to vehicle load. This truck consists of three axles (front axle, middle axle & rear axle). According to AASHTO standards, for HL-93 truck the center-to-center distance between front and middle axle is 4.3m and distance between middle and rear axle is 9m. The center-to-center distance between on each axel is 1.8m. The total load acting on the front axle is 36kN and the total load on the middle & rear axle is 145kN (AASHTO, 2020). To define the truck load in software each tire side was modeled separately. Thus, the axle loads were equally divided onto each side. For each side of the truck the loading configuration was inputted into the software according to table 2.

Table 2: HL-93 Truck load configuration for each side.

Distance(m)	Load(kN)
0.00	18
4.30	72.5
9.00	72.5

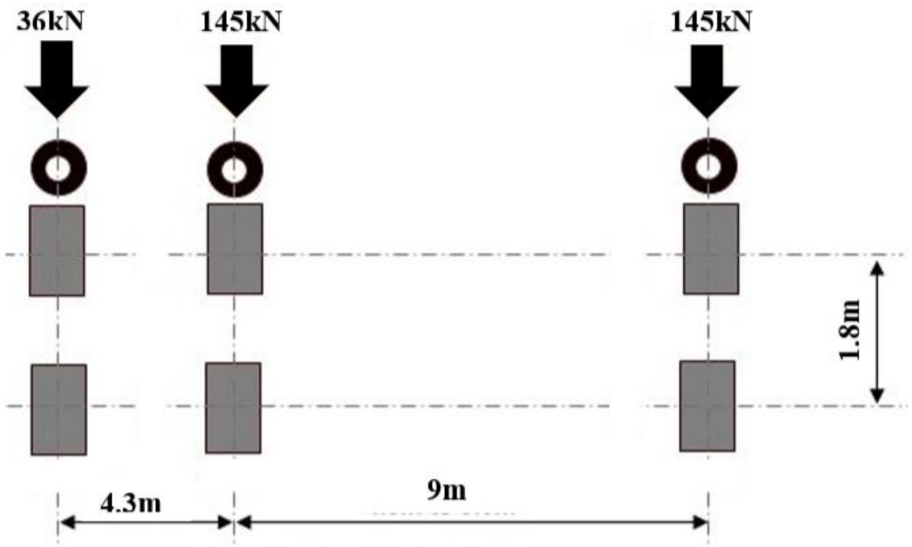

Figure 2: Tire plan of HL-93 truck

2.4 FEM Analysis

The first part of analysis is used to generate the geometric model and for that MIDAS GTS NX provides wide range of tools. The geometric model was prepared using the pavement dimensions provided by RHD, Dinajpur. After preparing the model the material properties for each layer were assigned. But the data obtained from RHD was not sufficient to input into the software to properly define material properties. Additional data of each layer of materials will be required. The additional data required for the analysis are-

1. Modulus of elasticity (MOE)
2. Poisson's ratio
3. Unit weight

To determine modulus of elasticity (MOE), the CBR values have to be converted into resilient modulus (MR). The following empirical equations is used-

Resilient modulus from CBR value (Adama Dione et al., 2014),

$$MR = 91.226 + 0.017x(CBR)^2 \quad (1)$$

Equations of Modulus of Elasticity from Resilient modulus are-

For Subgrade (Vincent P Drnevich et al., 1990),

$$MOE = 0.83\ x\ MR \quad (2)$$

For Sub-base (AASHTO, 1993b),

$$MOE = 1.1\ x\ MR \quad (3)$$

For Base (AASHTO, 1993b),

$$MOE = 1.3\ x\ MR \quad (4)$$

Bituminous concrete (BC) (R D Barksdale et al., 1997),

$$MOE = 26.8\ x\ (MR)^{0.84} \quad (5)$$

The Poisson's ratios for the materials were obtained from the previous findings (S. F. Brown, 1973).

The unit weights for wearing course and bitumen binder course (AASHTO, 2021), Aggregate Base Type-1 & Aggregate Base Type-2 (AASHTO, 2018), Sub-Base, Improved Subgrade and Natural Subgrade were taken according to AASTHO (AASHTO, 1993a). All the material property data compiled in table 3.

Table 3: Materials properties of each layer

Layer Name	Thickness (mm)	CBR (%)	Resilient Modulus (MPA)	Modulus of Elasticity (MPA)	Poisson's Ratio	Unit Weight (kN/m^3)
Wearing Course	50	110	296.9	3200	0.4	24
Bitumen Binder Course	150	100	261.2	2873.37	0.4	23
Aggregate Base Type-1	200	80	200	260	0.3	22
Aggregate Base Type-2	250	50	133.7	173.81	0.3	21
Sub-Base	250	25	101.85	112	0.3	19
Improved Subgrade	300	8	92.3	76.61	0.4	17
Natural Subgrade	7200	6	91.84	76.23	0.4	16

Using all the material property data a 3D meshed model was generated with dimensions of 10m in X direction, 60m in Y direction & 8.4m in Z direction. Appropriate boundary conditions such as ground surface spring for Eigenvalue determination and ground surface spring with damping constant for vehicle speed variation analysis were employed. Analysis cases for each vehicle speed using the loading configuration were generated and the analysis was conducted.

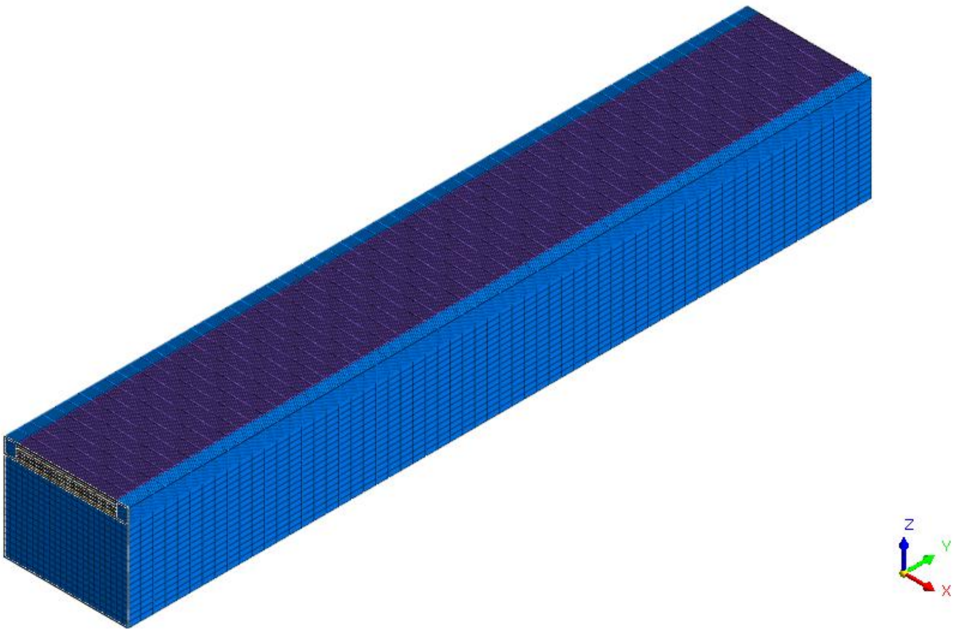

Figure 3: 3D mesh model of pavement structure

3. NUMERICAL ANALYSIS RESULTS

The analysis was performed for five cases with the following vehicle speeds, 40 kmph, 60 kmph, 80 kmph, 100 kmph & 120 kmph. For all these cases the displacement and stress of the wearing course was observed. Displacement for all the cases was found to be highest at node 177012 which is at the middle of axle on the wearing course. But the stress was found to be the highest under the wheel base at different nodes along the length of the pavement.

Figure 4 & 5 shows a graphical representation of the variation of displacement and stress for 40 kmph, 80 kmph & 120 kmph speed case with respect to vehicle travel time respectively. These show the peak point of displacement and stress that occurs with the vehicle travel time.

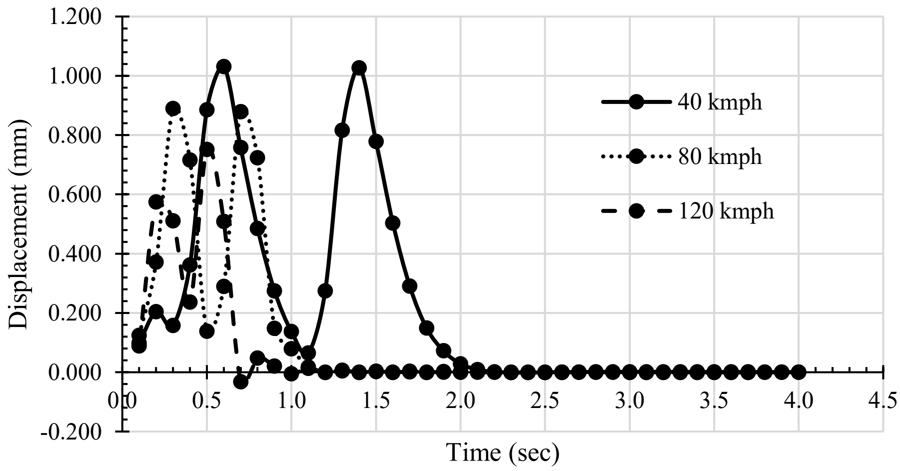

Figure 4: Variation of displacement at different vehicle speeds with respect to time

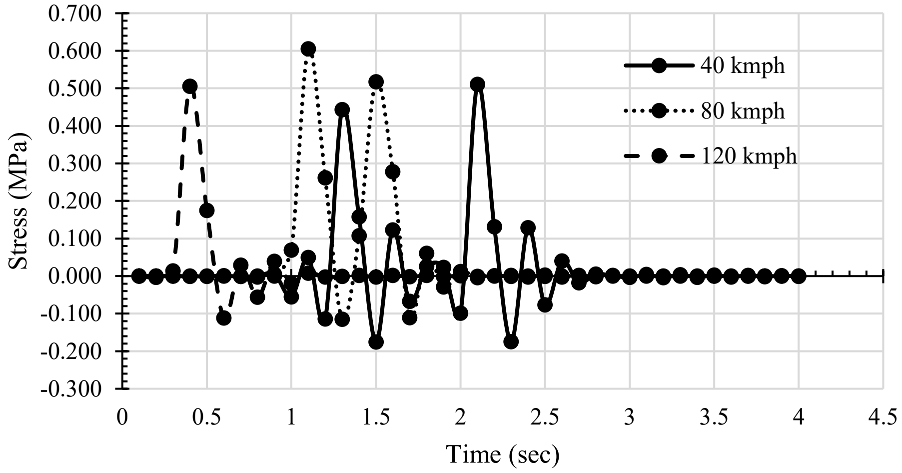

Figure 5: Variation of stress at different vehicle speeds with respect to time

Table 4 shows the data from the numerical analysis of the highest displacement and stress values from Figure 4 & 5 and also the data of 60 kmph and 100 kmph vehicle speed analysis case. Figure 6 & 7 shows a visual representation of variation of displacement and stress with respect to vehicle speed respectively.

Table 4: Highest displacement and stress values with respect to speed.

Speed (kmph)	Displacement (mm)	Stress (MPa)
40	1.031	0.511
60	0.919	0.576
80	0.904	0.605
100	0.826	0.600
120	0.751	0.505

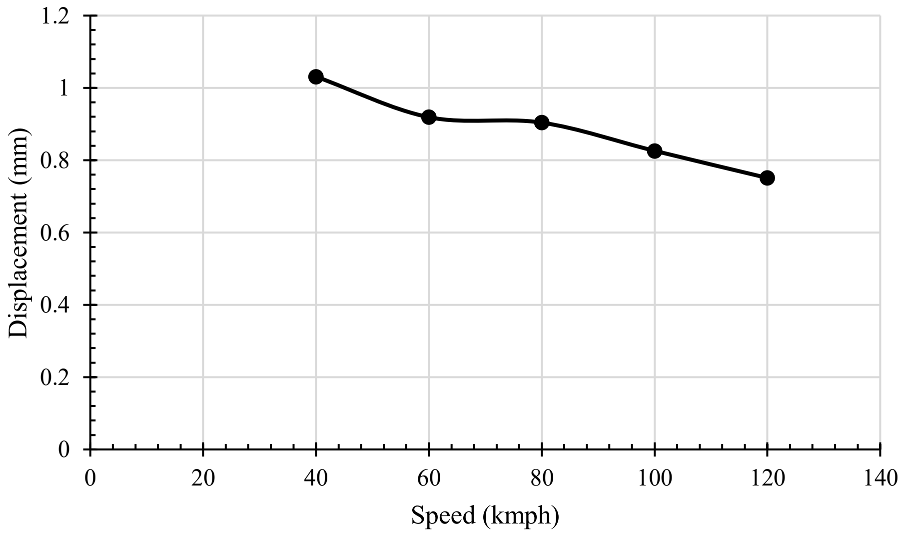

Figure 6: Variation of displacement with respect to vehicle speed

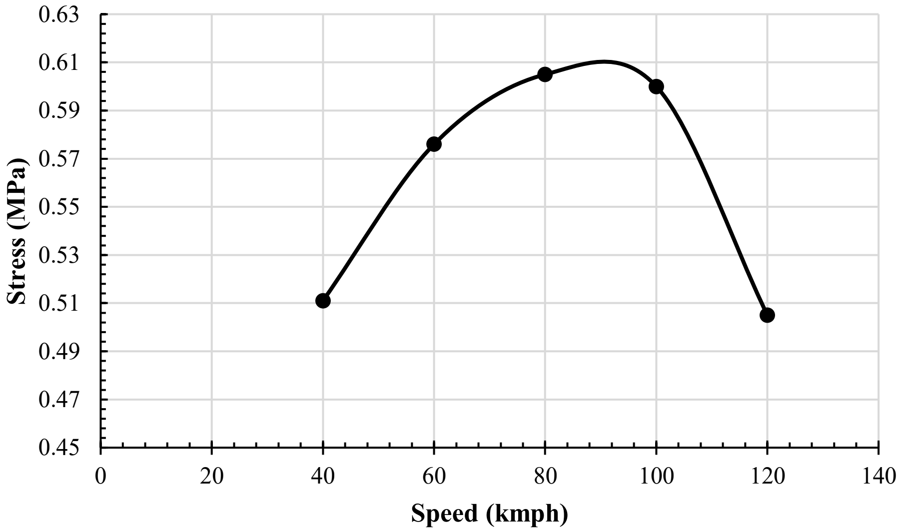

Figure 7: Variation of stress withrespect to vehicle speed

4. CONCLUSIONS

All the speed cases were carefully analyzed under the same parameters. MIDAS GTS NX provided detailed results for every analysis case taken into account for this study. Analyzing the results provided promising conclusions that could be put to good use in the design procedure of flexible pavement.

The conclusions are summarized below:

1. After the increase of vehicle speed beyond 40 kmph the displacement gradually decreased. The pavement experienced a 27% decrease in displacement when vehicle speed was increased from 40 kmph to 120 kmph. This was due to the pavement not getting enough time to respond to the higher vehicle speeds.
2. With the gradual increase of vehicle speed the pavement experienced a peak point of stress. The stress gradually increased up to the peak point of around 90 kmph, the stress again started to decreased afterwards. This is because at higher speeds, the shorter loading times make the pavement unable to transfer the stress to the layers below, increasing stress up to about 90 kmph; beyond this, the pavement cannot respond properly, so stress decreases.

At higher vehicle speeds the displacement decreases but stress increases, the higher stress causes micro damage to the pavement and if the micro damage accumulates over time the pavement may experience failure. This information can be helpful in designing flexible pavements and for future researchers in their study.

DECLARATION OF USE OF AI

The authors declare that no artificial intellegence tools were used in this manuscript. All the contents of this manuscript are the authors own.

REFERENCES

AASHTO. (1993a). *AASHTO Guide for Design of Pavement Structures*.

AASHTO. (1993b). *Interim Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials.*

AASHTO. (2008). *Mechanistic–Empirical Pavement Design Guide: A Manual of Practice. American Association of State Highway and Transportation Officials.*

AASHTO. (2018). *Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base, and Surface Courses, AASHTO M 147-65 (2018)*.

AASHTO. (2020). *AASHTO LRFD Bridge design specification.* (9th ed.).

AASHTO. (2021). *Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Asphalt Mixtures, AASHTO T 209-21*.

Adama Dione, Meissa Fall, Yves Berthaud, Farid Benboudjama, & Alexandre Michou. (2014). *Implementation of Resilient Modulus – CBR relationship in Mechanistic Pavement Design.*

Al-Qadi, I., Wang, H., & Tutumluer, E. (2010). Dynamic analysis of thin asphalt pavements by using cross-anisotropic stress-dependent properties for granular layer. *Transportation Research Record*, *2154*, 156–166. https://doi.org/10.3141/2154-16

Boussinesq, J. (1885). *Applications des potentiels aux problèmes de l'équilibre et du mouvement* (Vol. 2). Gauthier-Villars.

Burmister, D. M. (1943). *Theory of stresses and displacements in layered systems and application to the design of airport runways. Highway Research Board, Record No. 23*.

California Division of Highways. (1929). *The California Bearing Ratio (CBR) Method of Soil Testing for Pavement Design: Laboratory Test Procedures and Field Applications*.

Hadi, M. N. S., & Bodhinayake, B. C. (2003). Non-linear finite element analysis of flexible pavements. *Advances in Engineering Software*, *34*(11–12), 657–662. https://doi.org/10.1016/S0965-9978(03)00109-1

R D Barksdale, J A Lago Alba, N P Khosla, R Kim, P C Lambe, & M S Rahman. (1997). *Laboratory Determination of Resilient Modulus for Flexible Pavement Design* (Issue 14). Transportation Research Board. https://doi.org/10.17226/21960

S. F. Brown. (1973). *"Determination of Young's Modulus for Bitu minous Materials in Pavement Design.," Highw Res Rec, no. 431,*. 38–49.

Saha, S., Hossain, Md., & Nibir, S. (2024). A Finite Element Analysis for Investigating the Effects of Moving Loads on Flexible Pavements. *American Journal of Traffic and Transportation Engineering*, *9*(5), 79–88. https://doi.org/10.11648/j.ajtte.20240905.12

Siddharthan, R., Yao, J., & Sebaaly, P. E. (1996). Field Verification of Moving Load Model for Pavement Response. *Transportation Research Record: Journal of the Transportation Research Board*, *1540*(1), 125–131. https://doi.org/10.1177/0361198196154000117

Vincent P Drnevich, M Makbul Hossain, Jianren Wang, & Ronnie C Graves. (1990). *Determination of Later Moduli in Pavement Systems by Nondestructive Testing* (Issue 1278, pp. 18–26). Transportation Research Board.

Yin, H., Solaimanian, M., Kumar, T., & Stoffels, S. (2007). The effect of loading time on flexible pavement dynamic response: A finite element analysis. *Mechanics of Time-Dependent Materials*, *11*(3–4), 265–288. https://doi.org/10.1007/s11043-008-9047-8