Dr. B. C. Roy Polytechnic

BCRP Journal of Innovative Research in Science and Technology (BJIRST)

A peer-reviewed open-access journal
ISSN: 2583-4290
Journal homepage: https://bcrpjournal.org/

BJIRST

Numerical Prediction of Rutting in Flexible Pavements under Moving Overloaded Traffic Considering Nonlinear Material Effects

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ABSTRACT

Axle overloading significantly impacts pavement structural behavior due to its progressive damage. In India, pavement structures experience high temperatures and heavy traffic. Their adverse impact on the pavement structure takes into account rutting that causes the serviceability problem on the pavement and requires pavement rehabilitation. This research investigates the effect of non-linear material behavior on the rutting resistance of pavement. The loading response due to moving vehicle loads on the pavement's surface is compared to evaluate the overloading damage potential. A three-dimensional (3D) finite element analysis was performed using the commercial FE software ANSYS to model and develop the flexible pavement structure. Non-linear subgrade soil, granular base-subbase properties, and viscoelastic properties of the bituminous layer are used to simulate the 3-D FE pavement model. The vertical deflection and rutting strain are determined considering the overloading factors of 1.0, 1.25, and 1.5. The analysis result shows that overloading conditions increase pavement deflection and rutting strain. Furthermore, load repetitions to cause rutting are reduced at a higher overloading factor.

Keywords— Axle Overloading, Flexible Pavement, Rutting Resistance, Nonlinear Material Behavior, Finite Element Analysis, Viscoelastic Bituminous Layer.

1. INTRODUCTION

The road surface is exposed to a variety of vehicular loading conditions throughout its service life. The term "vehicular loading" refers to the movement of various axle categories, as static, dynamic, and impact loads. In addition to the forces caused by vehicular movement, the vehicle's weight acts as an axle load when it passes over a paved surface. Under such loading conditions that exceed the capacity of the pavement, pavement structures deteriorate even before they reach their design life. The behavior of flexible pavement to such loads varies with subgrade stiffness, material properties, pavement depth, and traffic category [1]. Most roads are continuously overloaded due to increased speeds and heavier axle loads, resulting in unexpected forces damaging the pavement structure. Compared to standard axle load repetitions, overloaded vehicles have an immense potential to cause damage, which can severely affect the structural responses [2]. Furthermore, according to the literature, increasing axle loads by 30% degrades pavement life by half [3-4]. When vehicles with exceeding loads are present, pavement maintenance costs increase by more than 100% compared to vehicles with permitted loads [5]. According to past studies, the percentage of overloaded traffic, estimated load equivalency factor, vehicle speed, life cycle cost analysis, and enforcement strategies were the most critical factors in determining the potential damage caused by traffic overloading. According to a study by Rys et al. [6], an overloaded vehicle with a 20 percent overload decreases in its mechanical performance by about half. Additionally, the recent research by Assogba et al. [7] demonstrated that the overloaded traffic with low speeds has a substantial impact on the service life of pavements. With variations in loading type, if the vertical compressive strain is too high due to subgrade overloading, the pavement structure deforms permanently, resulting in pavement ruts [8]. The negative impacts of overloaded vehicles on a road surface include rutting, which induces the pavement's serviceability challenge.

Rutting represents the most prevalent form of distress in pavement structures, and the repetitive movement of vehicles causes it. Rutting occurs more frequently at higher temperatures, like in a hot tropical climate or during the summer season [9]. The bituminous mixes cannot resist deformation resulting from the loading effect at high temperatures. Due to that, shearing or uplifting of the pavement surface at the edge of the ruts occurs with large uncertainty. As a result, the temperature is one of the crucial aspects affecting pavement design and performance [10].

According to the literature [8-12], a rutting resilient pavement requires proper material selection and suitable quality and design measures. In terms of pavement design, pavement thickness is dependent on the strength of the subgrade, and the overall pavement performance is heavily affected by the resilient modulus and deformation properties of the subgrade. Pavement failures usually take place when the traffic is overloaded [13]. Therefore, pavement layers should be sufficiently thick and stiff to resist the expedited impacts of overloaded traffic [14]. Practically, the primary method of rutting is the cumulative accumulation of deformation as the frequency of the loading cycle increases. However, the complexities of the dynamic loading characteristics and the nonlinear constitutive response of pavement materials make predicting rutting a complex process. Improving the performance and management involves analyzing a simplified simulation analysis with realistic load cases.

Several numerical studies have been conducted to investigate rutting in flexible pavements using advanced finite element modeling approaches implemented in software packages such as ANSYS [15, 16]. A detailed and effective prediction of pavement behavior under diverse loading and environmental conditions helps highway agencies with the necessary results for improving pavement system design. However, it is always difficult to accurately represent the parameters of paving structures and materials while ensuring less computation time and memory. This necessitates a careful selection of the FE model. The stress and strain in the pavement are predicted by FE pavement modeling techniques, which are then used to estimate the results of the critical responses. Several studies have been done to assess the impact of various pavement design factors on pavement performance. Unfortunately, layered elastic material properties cannot be an effective consideration for pavement performance prediction, due to bituminous layers' viscoelastic characteristics [9]. To simulate the actual pavement behavior, FE simulation tools must consider vehicular moving load, field boundary conditions, and realistic material behavior.

Overloaded vehicles are a severe problem in India, which leads to early pavement deterioration. The existing design approach is primarily based on axle loading without allowing for the realistic overload problem and the dynamic behavior of moving vehicles. Therefore, there is a significant gap concerning this design standard and the actual loading circumstances of a moving load. The proposed study aims to improve the understanding of the rutting resistance of flexible pavement structures in relation to the design parameters of the pavement. Flexible pavement responses under moving loads were analysed using three-dimensional nonlinear material parameters. Using the FE program ANSYS, a computational analysis has been conducted. Evaluation at the critical locations was done by taking into account the pavement surface deflection, the top of the subgrade deflection, the vertical compressive strain at the surface of the subgrade, and the pavement rutting life at standard loading, as well as at overload of 1.25 and 1.5 times the design load.

2. FINITE ELEMENT MODELLING OF PAVEMENT STRUCTURE

2.1. Material Parameters

The properties of pavement layers in finite element (FE) analysis are defined through the elastic modulus, Poisson's ratio, and mass density of each constituent material. The viscoelastic behavior of bitumen-based mixtures can be accurately represented in ANSYS through a Prony series for shear relaxation [17].

The mechanical behavior of the granular base and sub-base layers is represented using a nonlinear K–θ elastic model [18], which effectively captures stress-dependent stiffness characteristics of unbound granular materials. Temperature effects are incorporated by considering 40°C for the wearing course and 35°C for the binder course, based on the spatial temperature variation formulation recommended by the Strategic Highway Research Program (SHRP) [19].

The subgrade layer is also modeled as a nonlinear material, and its behavior is simulated using the Mohr–Coulomb plasticity model. For this purpose, cohesion (c), angle of internal friction (φ), and dilation angle (ψ) are specified as input parameters. The combined use of viscoelastic modeling for bituminous layers, the K–θ model for granular layers, and the Mohr–Coulomb plasticity model for the subgrade has been widely adopted by researchers due to its computational simplicity and ability to realistically represent pavement response under traffic loading.

The subgrade plasticity model parameters are considered from the study of Banerji et al. [20], incorporating waste beverage bottles as polyethylene terephthalate (PET) and Terrasil chemical stabilizer in clayey soil. Table 1 lists the material properties and pavement layer thickness considering 7% CBR values. The damping material parameter for subgrade has been taken as 5% [11].

TABLE 1 PAVEMENT MATERIAL PROPERTIES AND DIMENSIONS

Layer and Thickness	Table Column Head	
	Material Property	*Values*
Wearing Course (BC): 40mm	Viscoelastic properties Shear Modulus (G) MPa: 286, 43.18, 136, 13.19, 335.91 Relaxation Time (s): 0, 20, 2.0, 1.0, 0.2 Poisson's ratio: 0.35	
Binder Course (DBM): 125 mm		
Granular layer (Base): 250 mm	Elastic modulus (MPa) Density (kg/m^3) Poisson's ratio n (material constant)	352 MPa 1800 0.4 0.11
Granular layer (subbase): 200 mm		
Subgrade (Infinite)	Elastic modulus (MPa) Density (kg/m^3) Cohesion (kPa) Internal friction angle (°)	62 MPa 1900 45 39

2.2. Finite Element Model geometry

Pavement systems are made up of surface course, aggregate base, granular subbase, and soil subgrade. The surface course is composed of two separate layers: the upper wearing course & lower binder course. A Three-Dimensional Finite Element (FE) Model of the pavement structure was created with ANSYS 2020 R1 software. As illustrated in Figures 1(a) and (b), the FE Mesh of the Pavement Geometry and Interfaces between Layers of the Pavement System is assumed to be fully continuous and completely bonded.

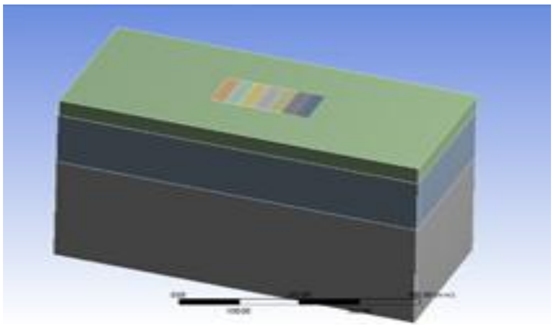

FIG. 1 (A). PAVEMENT MODEL CONSIDERED IN THE FE ANALYSIS.

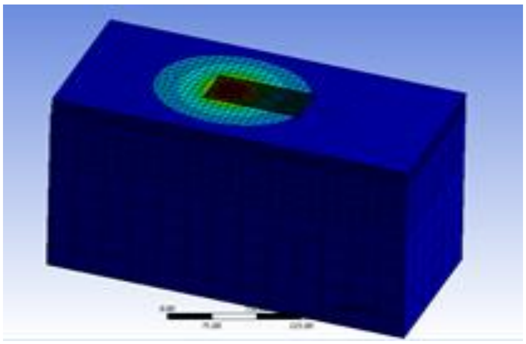

FIG. 1 (B). PAVEMENT MODEL MESHING VIEW.

A 3-dimensional ANSYS Finite Element model was developed using SOLID45. SOLID45 is a Linear Brick Solid 8-Noded Element that allows for Translational Movement along the X, Y, and Z directions of the X-Y-Z axes, allowing for 3 Degrees of Freedom per Node. The overall dimensions of the model were 2.5 meters in the traffic direction, 1 meter in the transverse direction, and 3.16 meters in depth. To reduce the computation time of the model, a Quarter Section of the Pavement Structure was simulated by applying half of the Axle Load during the Finite Element Analysis [21]. Thicknesses of individual pavement layers shown in Table 1 were chosen from the Design Catalogue for 50 million standard axles corresponding to a subgrade CBR Value of 7% [20].

2.3. Modelling of the moving wheel load

The contact area of a tyre with a pavement surface depends upon several variables, including tyre inflation pressure, wheel load, and the type of tyre used. In almost all prior studies, the tyre/pavement contact area has been modelled as either circular or rectangular in shape. For finite element modelling of flexible pavements, it is common to simplify the tyre contact imprint and represent this imprint as an equivalent rectangular contact area to be applied over the pavement surface [15-17, 21]. In this study, symmetrical longitudinal and transverse loads have been applied to a pair of tyres carrying a total gross weight of 80 kN, with 40 kN on each wheel. During the simulation, a tyre contact pressure of 560 kPa was applied uniformly over the designated loading area. To represent overloaded traffic conditions on the pavement surface, hypothetical scenarios were considered by applying overloading factors of 1.25 and 1.5 to the standard single-axle truck load. The dimension of the small rectangle is obtained by a computation using one-half of the wheel load's corresponding length on the pavement [22]. Since the propagation of time with respect to the change in area selected over the region of load applied, with three different cases, can be achieved. In the present study, at the initial step, the load is applied over 1, 2, 3 regions area of 220 X 160 mm. Whereas, in further step propagation, the load is moved to the region of 2, 3, 4, and so on. After the completion of each step in the load analysis process, the total load is transferred to a relatively small rectangular region. In the meantime, numerous load analysis sub-steps are established within each load analysis process to increase the accuracy of the computation. The region can be identified in Fig. 2. The rate of change of load with respect to time in static conditions acts as a moving load.

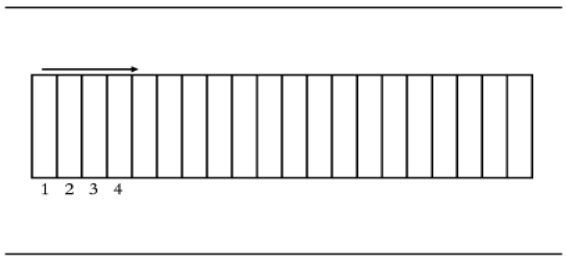

FIG. 2. MOVING LOAD SECTION.

2.4. FE mesh and boundary conditions

The pavement response obtained from finite element (FE) analysis can vary considerably depending on the type and size of elements adopted in the model. Therefore, in accordance with prior F.E. research on flexible pavements, discrete models described in previous studies [23-25] were followed. Thus, a fine mesh was developed directly below the point where the tire contacted the pavement in order to accurately calculate stresses and deformations; whereas, the mesh in areas remote from the load path was made coarse to minimize computational time, as shown in Figure 1b.

To establish the optimal size of finite elements necessary to produce reliable results using F.E., a mesh convergence study was undertaken. Variations in the total deformation of an unstabilized and stabilized pavement subjected to a standard axle load having a tire contact area of 220 mm x 160 mm were studied for different element sizes. The material properties utilized in the convergence analysis are listed in Table 1. At the location of the tire imprint, the element size was gradually decreased until it reached 0.05 mm x 0.05 mm x 0.05 mm. Results showed that after an element size of 1 mm x 1 mm x 1 mm, the difference in deformation at the tire contact area was less than 1.0 percent.

To simulate the conditions found in the field, the displacement of each face of the model perpendicular to the plane of symmetry between the tires was restricted along the corresponding side faces of the model. Additionally, a fixed support was placed at the bottom surface of the model to simulate the subgrade layer; roller supports were placed on all vertical surfaces remote from the wheel loads. These boundary conditions have been utilized by other researchers in previous studies [15, 16, 20, 21].

2.5. Model assumptions

Assumptions are made in this research to streamline the investigation of the underlying factors and the realistic pavement structure. It is assumed that the bituminous layer behaves like a viscoelastic material with prony constants, base and sub-base behave non-linearly elastic, and the subgrade is modelled as nonlinear using the Mohr–Coulomb plasticity model to the imposed moving loads. The FE mesh employed and the modelled pavement geometry had completely continuous (perfectly bonded) interface layers. It is also considered that there is no vertical or horizontal movement at the bottom of the soil layer; hence, the bottom of the finite element model is restrained to zero in the x, y, and z directions.

3. RESULTS AND DISCUSSIONS

The primary focus of this research was to identify the responses of pavements subjected to both standard axle loads and axle loads increased by 1.25 and 1.50 times their original values. Based upon the parameters listed in Table 1, FE models were developed for use in conducting the numerical analysis portion of this research. The data contained within Table 2 is a comparative summary of the pavement response characteristics, such as surface deflections, deflection of the bottom of the bitumen layer, and sub-grade deflection based upon the various loading conditions. The data provided in Table 2 indicates that the impact of increased levels of axle loading has an obvious effect on the vertical deflection behavior of pavements. In addition, the data illustrated in Table 2 illustrates that the maximum deflection of 0.32 mm occurs when the pavement is subjected to a 1.50 times overload. The data also indicated that there is a noticeable increase in the resistance of the pavement to deformation when comparing the 1.25 and 1.50 overload cases to normal axle load conditions; this resistance to deformation ranged from 11% to 20%. This information suggests that as the percentage of axle load increases, so does the resulting pavement surface deflection. Although the permissible overload limit in India is 25% [26], the results of this FE analysis show how overloading affects the deflection profile. The deflection at the bottom of the bituminous layer and subgrade, when compared to the deflection at the surface, varies. In the case of deflection on top of subgrade, a considerable variation is observed, as it shows a transition of 9.7 %, 12 % and 12.24 % under the three different loading cases.

The changes in the vertical strain throughout the pavement due to overloading are shown in Figure 3. This figure shows that maximum vertical compressive strain occurs at the surface of the subgrade and increases with greater overload values. The vertical compressive strain at the surface of the subgrade is approximately 10% and 16% greater than the standard value when the overloading factors are 1.25 and 1.5, respectively.

For this study, the rutting performance of pavements was evaluated with axle loads of 40, 50, and 60 kN under both standard loading and overloaded conditions. Rutting life is described as the cumulative number of standard axle load repetitions that a pavement can endure before experiencing a critical rut depth of 20 mm. Rut depth is assumed to be developed from repeated traffic loads, and relationships between surface rut depths and numbers of load cycles were determined. A rut depth profile as a function of the number of load cycles to failure is illustrated in Figure 4. The rutting life was significantly reduced with an increase in axle load, especially under the highest overloading factor of 1.5. Rutting life was found to decrease by approximately 4.84% and 7.23%, compared to standard loading conditions, due to increased overloading levels. Therefore, these results demonstrate that standard axle loads are associated with less rutting damage; however, rutting damage to pavements is greatly increased with the introduction of axle overloading.

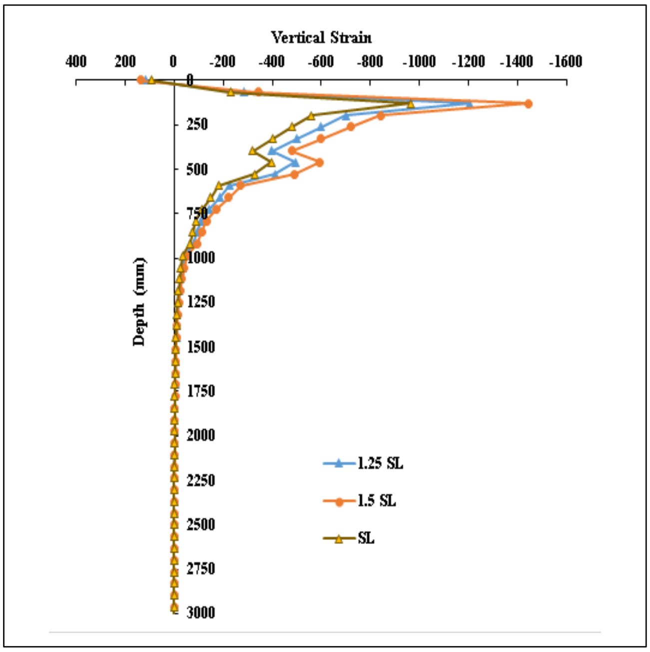

FIG. 3. COMPARISON OF VERTICAL STRAIN DISTRIBUTION.

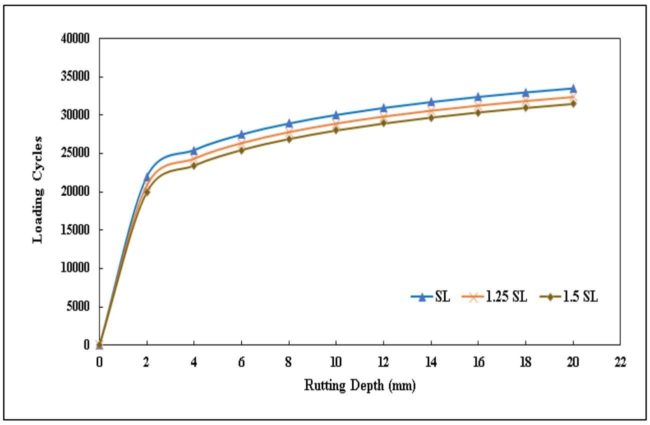

FIG. 4. VARIATION IN THE RUTTING PERFORMANCE.

4. CONCLUSION

The effects of axle overloads on the rutting behavior of flexible pavements are evaluated using a finite element (FE) framework. A FE model of the pavement structure was created using the bituminous layers as visco-elastic materials and the granular layers and the soil subgrade as nonlinear materials. The FE model was verified with available analytical solutions, which assumed the same material models. The developed FE model was used to simulate the responses of the pavement under overloaded traffic conditions equal to 1.25 and 1.5 times the standard axle load. The results of the FE analysis lead to the following conclusions:

- Compared to standard loading, the resistance to deformation under overloading conditions is increased between 11% and 20% for the overloading factors of 1.25 and

1.5, respectively. These results indicate that surface deflections increase with increasing axle load magnitudes.

- The deflection at the top of the subgrade exhibited a significantly different trend than the surface deflection. Variations of 9.7%, 12.0%, and 12.24% were noted in the deflection at the top of the subgrade under the three loading conditions.
- When the axle load was increased to 1.25 and 1.5 times the standard load, vertical compressive strains at the top of the subgrade were increased by approximately 10% and 16%, respectively.
- Rutting life decreased significantly with increasing axle load; in particular, rutting life under the 1.5 overloading condition was reduced by approximately 4.84% and 7.23% compared to standard loading.

Overall, this study contributes to the development of a reliable FE modeling framework for predicting the structural response of flexible pavements under traffic overload conditions. In addition, the results of the study suggest that pavement design should be based on actual traffic loading conditions instead of standard loads. Further, with the increasing levels of axle overloading, it becomes increasingly important to establish more stringent regulations to prevent damage to pavements. While the current study is limited to a few specific material properties, future studies may include a broader scope of rutting predictions, including varying layer thicknesses and material properties.

5. ACKNOWLEDGMENT

The authors would like to express their sincere appreciation to the institution for providing the necessary resources to conduct the research; they also appreciate the assistance and support provided by ANSYS to utilize their commercially available finite element software to complete the required numerical modeling portion of this study. The authors wish to extend special gratitude to the previous researchers who were able to contribute valuable information, data and knowledge that assisted in developing and validating the current numerical model.

REFERENCES

[1] Raheel, M., Khan, R., Khan, A., Khan, M. T., Ali, I., Alam, B., & Wali, B. (2018). Impact of axle overload, asphalt pavement thickness, and subgrade modulus on load equivalency factor using modified ESALs equation. Cogent Engineering, 5, 1528044.

[2] Pais, J., Amorim, S., & Minhoto, M. (2013). Impact of traffic overload on road pavement performance. Journal of Transportation Engineering, 139(9), 873–879.

[3] Salem, H. M. (2008). Effect of excess axle weights on pavement life. Emirates Journal for Engineering Research, 13(1), 21–28.

[4] Jihanny, J., Subagio, B. S., Yang, S. H., Karsaman, R. H., & Hariyadi, E. S. (2021). The overload impact on design life of flexible pavement. International Journal of Geomate, 20(78), 65–72.

[5] Ojha, K. N. (2019). A comparative study between standard and overloading condition. American Scientific Research Journal for Engineering, Technology, and Sciences, 58(1), 159–181.

[6] Rys, D., Judycki, J., & Jaskula, P. (2016). Analysis of effect of overloaded vehicles on fatigue life of flexible pavements based on weigh-in-motion (WIM) data. International Journal of Pavement Engineering, 17(8), 716–726.

[7] Assogba, O. C., Tan, Y., Sun, Z., Lushinga, N., & Bin, Z. (2021). Effect of vehicle speed and overload on dynamic response of semi-rigid base asphalt pavement. Road Materials and Pavement Design, 22(3), 572–602.

[8] Behiry, A. E. A. E. M. (2012). Fatigue and rutting lives in flexible pavement. Ain Shams Engineering Journal, 3(4), 367–374.

[9] Norouzi, A., Kim, D., & Richard, K. Y. (2016). Numerical evaluation of pavement design parameters for fatigue cracking and rutting performance of asphalt pavements. Materials and Structures, 49, 3619–3634.

[10] Banerji, A. K., Topdar, P., & Datta, A. K. (2023). Study on the effect of wheel load and temperature on rutting damage of composite flexible pavement using finite element method. In Proceedings of the International Conference on Advances in Structural Mechanics and Applications (pp. 202–212).

[11] Deng, Y., Shi, X., Zhang, Y., & Chen, J. (2021). Numerical modelling of rutting performance of asphalt concrete pavement containing phase change material. Engineering with Computers, 1–16.

[12] Erlingsson, S. (2012). Rutting development in a flexible pavement structure. Road Materials and Pavement Design, 13(2), 218–234.

[13] Mishra, S., Sachdeva, S. N., & Manocha, R. (2019). Subgrade soil stabilization using stone dust and coarse aggregate: A cost-effective approach. International Journal of Geosynthetics and Ground Engineering, 5(1), 1–11.

[14] Almeida, A., Moreira, J. J., Silva, J. P., & Viteri, C. G. (2019). Impact of traffic loads on flexible pavements considering Ecuador's traffic and pavement condition. International Journal of Pavement Engineering, 22(6), 700–707.

[15] Gupta, A., & Kumar, A. (2014). Comparative structural analysis of flexible pavements using finite element method. International Journal of Pavement Engineering and Asphalt Technology, 15(1), 11–19.

[16] Sahoo, U. C., & Reddy, K. S. (2010). Effect of nonlinearity in granular layer on critical pavement responses of low volume roads. International Journal of Pavement Research and Technology, 3(6), 320–326.

[17] Berthelot, C. F., Allen, D. H., & Searcy, C. R. (2003). Method for performing accelerated characterization of viscoelastic constitutive behavior of asphaltic concrete. Journal of Materials in Civil Engineering, 15(5), 496–505.

[18] Ghadimi, B., & Nikraz, H. (2017). A comparison of implementation of linear and nonlinear constitutive models in numerical analysis of layered flexible pavement. Road Materials and Pavement Design, 18(3), 550–572.

[19] Kennedy, T. W., Huber, G. A., Harrigan, E. T., Cominsky, R. J., Hughes, C. S., Quintus, H. V., & Moulthrop, J. S. (1994). Superior performing asphalt pavements: The product of the SHRP asphalt research program (SHRP-A-410). National Research Council.

[20] Banerji, A. K., Topdar, P., & Datta, A. K. (2022). Effect of axle overloading on pavement structural behaviour with improved clayey subgrade using PET fibres. Civil Engineering and Architecture, 10(6), 2410–2425.

[21] Hadi, M. N., & Bodhinayake, B. C. (2003). Non-linear finite element analysis of flexible pavements. Advances in Engineering Software, 34(11–12), 657–662.

[22] Banerji, A., Kumar Datta, A., & Topdar, P. (2017). Finite element analysis of vehicle pavement interaction based on static and transient dynamic loading. In Indian conference on applied mechanics (INCAM). MNIT Allahabad.

[23] Patra, S., & Bera, A. K. (2021). Development of design chart for jute geotextiles reinforced low volume road section by finite element analysis. Transportation Infrastructure Geotechnology, 8(1), 88–113.

[24] Kim, M., Tutumluer, E., & Kwon, J. (2009). Nonlinear pavement foundation modeling for three-dimensional finite element analysis of flexible pavements. International Journal of Geomechanics, 9(5), 195–208.

[25] Saad, B., Mitri, H., & Poorooshasb, H. (2006). Three-dimensional finite element analysis of flexible pavement with geosynthetic reinforcement. Journal of Transportation Engineering, 132(5), 402–415.

[26] Savio, D., Nivitha, M. R., Bindhu, B. K., & Krishnan, J. M. (2016). Overloading analysis of bituminous pavements in India using ME PDG. Transportation Research Procedia, 17, 607–616.G.