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Finite Element Modeling by ABAQUS for Rutting in Flexible Pavement

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Abstract Flexible pavement is complex in nature, as it consists of multiple layers made up of different materials. A common type of distress, "Rutting" is formed on the surface of pavement due to heavy and repeated loading. In addition, the pavements undergo rutting due to poor quality control during construction. However, laboratory investigations have very limited effectiveness in predicting rut depth. The present research employs a finite element analysis using ABAQUS software to study the performance of the pavement against rutting. The pavement system is assumed to have a multilayer component, with each layer being homogeneous and isotropic. Two different thicknesses of pavement structures, as per Indian Road Congress (IRC) 37-2018, are modeled and analyzed by considering 10 million standard axles (msa) and 50 msa of design life, corresponding to 5% California Bearing Ratio (CBR) value. The findings of the research show that the maximum rut depth occurred nearly at the center of the model, i.e., at 137.594 mm, and the rut depth for the 50 msa design life was marginally lesser, to the extent of 8.64% compared to 10 msa. The maximum stresses occurred at the surface layer and decreased towards the base and sub base layers by 5.86%, 11.10%, and 12.60%, respectively, at the surface, base, and sub base layers for 50 msa compared to a 10 msa design life. The finite element modeling by ABAQUS proved highly effective in simulating the responses of flexible pavement under the influence of external loads and facilitated a comprehensive assessment of deformation and stress throughout the pavement layers.

Keywords Flexible Pavement, Rutting, Finite Element, ABAQUS, IRC 37-2018, Deformation, Stress

1. Introduction

A typical flexible pavement consists of several layers, which typically include surface, base, sub base, and subgrade layers [1]. These layers are supposed to carry heavy traffic and repeated loads during their service life. However, the very nature of flexible pavement makes it susceptible to deformation under heavy vehicular traffic loads and variations in temperature and climatic conditions. The surface layers, mainly made of bituminous material, are the crucial layer of pavement, as they are in direct contact with the vehicles. Hence, it is designed to be stronger and more durable to bear the stresses. On the other hand, the base and sub base layers play a very important role in transferring stresses to the subgrade layers. The pavement thickness is mainly determined by the subgrade strength of the soil, namely, CBR (California Bearing Raito) [2]. While flexible pavement has numerous advantages, it also comes with inherent disadvantages such as vulnerability to temperature variations, heavy traffic loads, periodic maintenance, etc. These factors, along with poor quality control and construction practices, cause the pavement surface to undergo early failure or distress [3]. The most commonly found types of distress or failures are cracking, shoveling, rutting, edge breaks, potholes, etc. [4,5]. Rutting is considered one of the crucial factors in the performance of flexible pavement; if left unattended, it may lead to skidding and accidents. In hot climatic conditions, rutting poses significant challenges to the service life of pavement and the safety of vehicles. Rutting is characterized by longitudinal depression along the wheel path on the pavement surface, mainly driven by heavy and repeated traffic loads. Hence, during the design of pavement, the designers consider rutting as a crucial factor [6]. The adoption of optimized mix design and advanced pavement assessment methods provides a promising avenue for extending the lifespan of pavement and reducing the repair and maintenance costs of pavement [7,8].

In this context, many research studies were carried out around the world, focusing on parameters that affect the performance of pavement, namely, pavement structures, traffic conditions, climatic conditions, construction materials, etc. [9]. However, the experimental investigations on the performance of pavement against rutting are not very effective in predicting the rut depths. Hence, this necessitates the adoption of advanced methods such as modeling, which predicts the onset and prediction of rutting and helps the designers formulate the bituminous mixture blend with greater resilience [10]. Since the performance of the bituminous mixes depends on factors like time, stress, and temperature, it is crucial to predict their rutting performance and utilize suitable models that consider different parameters such as plasticity, elasticity, viscoelasticity, and creep to characterize the behavior of the bituminous mixes [11,12].

Finite Element (FE) modeling has become a powerful tool to solve complex mathematical models in various engineering applications [13,14]. The methodology mainly involves building a complicated object with simple blocks or dividing the complicated object into simple, manageable pieces. This approach proved to be highly efficient in addressing engineering problems, and its implementation has become widespread across different fields. ABAQUS is one such software, known for its versatility and high level of accuracy, and can tackle a wide range of engineering problems, particularly vital for pavement analysis [15,16]. It facilitates modeling and analysis, and enables the simulation of complex material behavior, encompassing linear, non-linear, and viscoelastic attributes [17,18]. In addition, it can accommodate multiple factors such as crack, damping, static, and dynamic loading, making it the most preferred choice for the researchers. The previous research studies suggest that input parameters such as modulus of elasticity, poisons ratio, pressure, load, etc. are important factors that affect the performance of pavement [19,20]. ABAQUS proved highly effective in simulating the responses of pavement against external loads [21,22] and predicting the rut depth in the pavement surfaces [23,24].

The present research mainly aims to study the performance of the pavement layers against rutting by adopting finite element analysis using ABAQUS software. The pavement crust thickness is modeled in accordance with IRC 37-2018 standards and specifications. The study is carried out on two different cases, namely, in the first case, the pavement crust is built by adopting 10 msa, and in the second case, adopting a 50 msa design life, both corresponding to 5% CBR value. By employing finite element analysis, the research aims to study the performance and resilience of the bituminous mixes against rutting. Overall, the study aims to use advanced analysis techniques, consider various design scenarios, focus on specific pavement material characteristics, and bridge the gap between sustainable pavement construction practices and reliable performance predictors, contributing to the design and maintenance of robust and eco-friendly road networks.

2. Materials and Methods

2.1. Methodology

The methodology adopted in the present research is presented below:

2.2. Finite Element Model Geometry

The pavement structure considered in the present studies consists of multiple layers of different materials, namely, surface, base, sub base, and subgrade layers. The pavement crust is modeled in ABAQUS as per IRC 37-2018 by considering 10 msa and 50 msa design life, respectively, corresponding to 5% CBR, as shown in Figure 1 [25]. The dimensions of the pavement are the length in the x-direction, the width in the y-direction, and the thickness in the z-direction. The size of each element in the model was fixed based on the convergent studies. The present study adopts a length of 640 mm, a width of 275 mm, and a thickness or height of 370 mm and 430 mm, for a 10 msa and 50 msa design life, respectively. The model geometry created in ABAQUS for both the cases are shown in Figures 2 and 3 respectively.

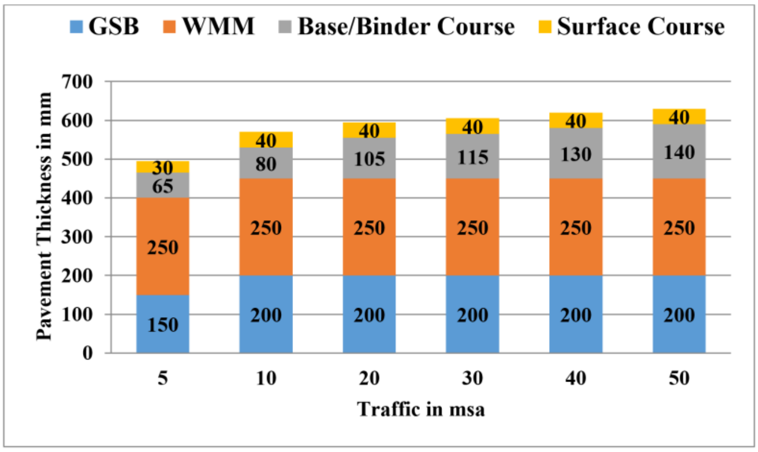

Figure 1. Pavement Catalogue for 5% CBR Value

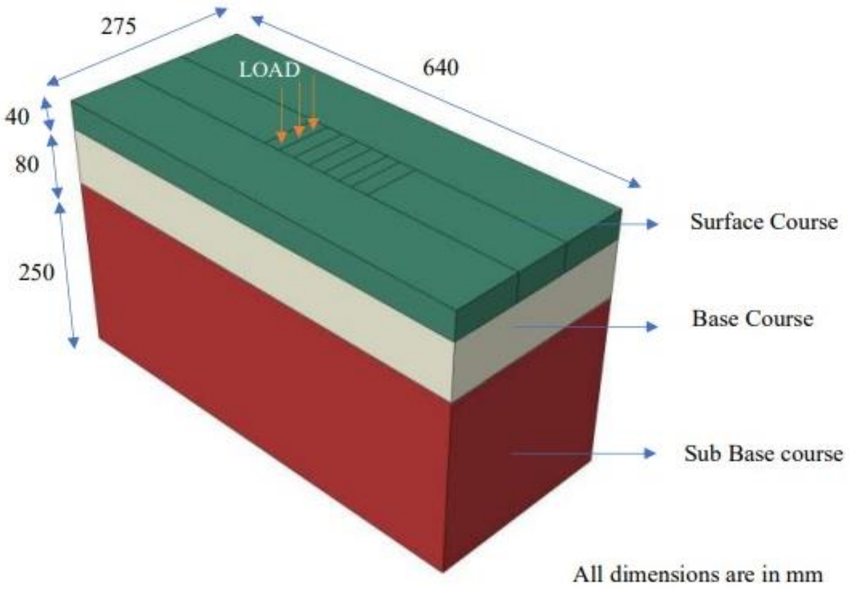

Figure 2. Model Geometry for 10 msa Design Life

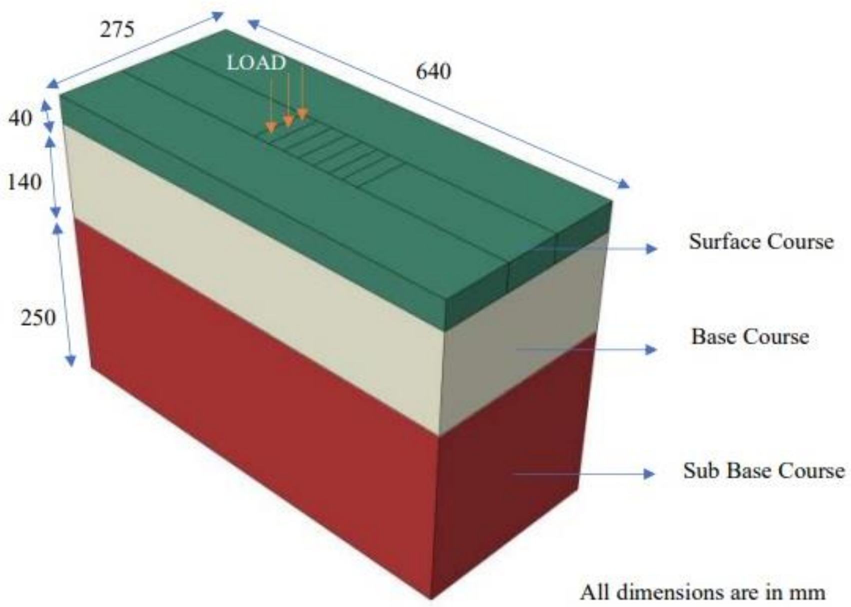

Figure 3. Model Geometry for 50 msa Design Life

2.3. Finite Element Meshing

It is assumed that the bottom of the subgrade layer is fixed both in horizontal and vertical directions (U1=0, U2=0), which means that nodes at the bottom of the subgrade or sub base and sides of the layer cannot move either in a horizontal or vertical direction [26]. The layers of the surface course, binder course, and base course layers are permitted to move vertically, which is represented by (U2) in ABAQUS [27]. The purpose of the element model is to simulate the dynamic interactions that occur among the various layers of the pavement layer, such as the bituminous surface course, binder course, and sub base courses. Accordingly, a model boundary is created in ABAQUS, and the boundary conditions have a significant effect on predicting the model responses. As specified by the boundary conditions, the finite element model utilizes the tie-contact to simulate the interactions between the flexible pavement layers [28]. The edges of each part of the model geometry are allowed to move only in the vertical direction and fixed in the horizontal direction to create a mesh [29], as shown in Figure 4.

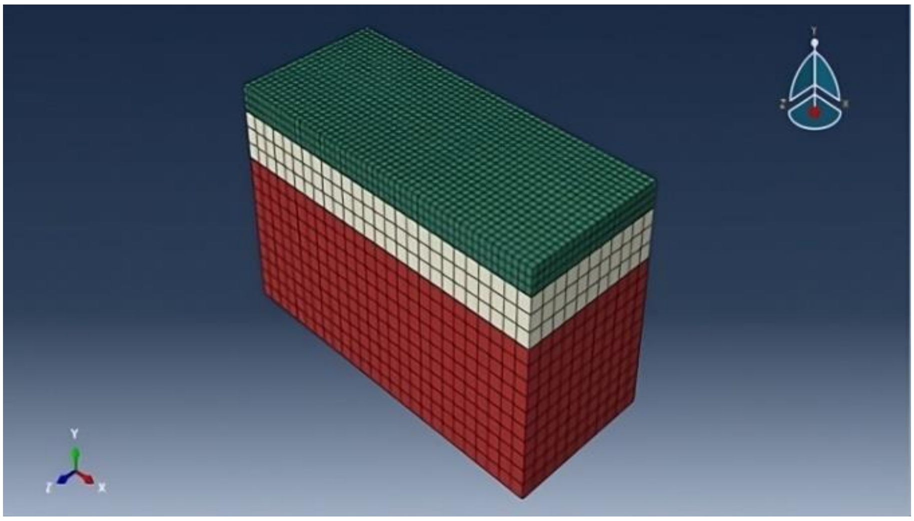

Figure 4. Meshing of Pavement Layers

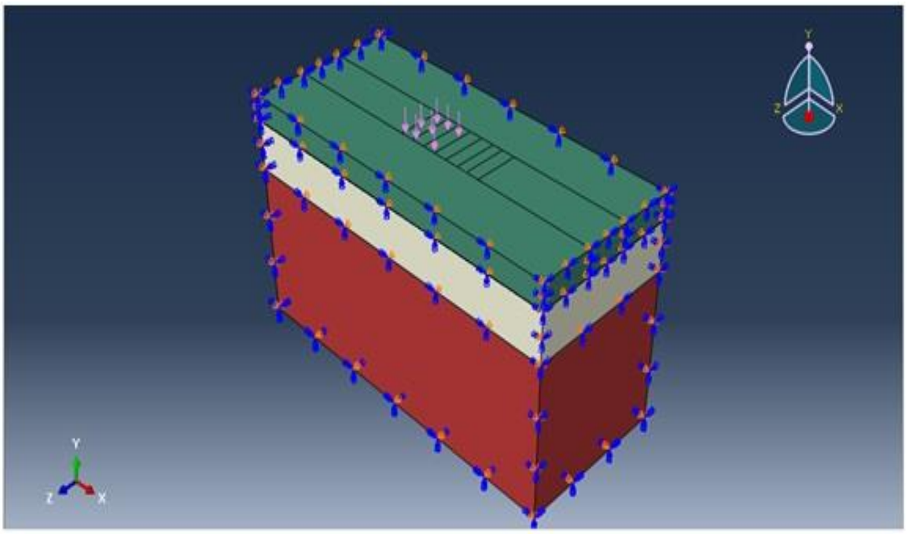

Figure 5. Creation of Boundary Conditions and Application of Load

The material properties of the bituminous are the crucial parameters in the analysis; namely, the elastic modulus and poison's ratio are identical in all directions [30], and they are adopted as per the standard values mentioned in IRC 37-2018. Material properties assigned to the different layers of pavement are shown in Table 1.

Table 1. Material Properties for Input in ABAQUS

Type of Material	Elastic/Resilient Modulus, MPa	Poison's Ratio
Surface layer	2000	0.35
Sub Base Layer	2000	0.35
Base Layer	450	0.35

2.4. Loading Conditions

The wheel load applied in the ABAQUS is distributed uniformly over the total contact area [31], and the resulting uniform contact pressure is 0.56 MPa, which is equal to the maximum tyre pressure as recommended by IRC 37-2018. A load is applied to simulate the wheel's horizontal motion at a predetermined speed. In this method, the load position is moved gradually to have a complete wheel roll. The path along the moving load is the longitudinal distance, which is divided into several steps (8 steps complete a one-wheel cycle), which is used to simulate the moving load on the surface of the pavement and is obtained by the application of the step module. The step module is used to generate this path, which is used to simulate the moving load on the pavement surface [32]. Finally, the interaction module using ABAQUS is used to simulate the interaction between different pavement layers [33] (bituminous, binder, and base course layers) with tie contact for both (bituminous and base) layers. The creation of boundary conditions and the application of load are shown in Figure 5. The input parameters entered in the ABAQUS software for the analysis are shown in Table 2.

Table 2. Input Parameters in ABAQUS

Parameters	CASE 1	CASE 2
CBR, %	5	
Design life, msa	**10**	**50**
Dimension for load parameters, mm	80x25	
Pressure applied (MPa)	0.56	
Number of cycles	8	
Number of steps	54	
Boundary condition	Bottom: Encasture Side: Pinned	
Surface layer thickness, mm	40	40
Base layer thickness, mm	80	140
Sub base layer thickness, mm	250	250

3. Results and Discussions

All the relevant data are entered and submitted for analysis. The results obtained by the software for displacement are analyzed. The results of the analysis for 10 msa and 50 msa design life corresponding to 5% CBR values and the pattern of deformation or rutting are shown in Figures 6 to 9. The values of deformation for both cases are shown in Tables 3 and 4.

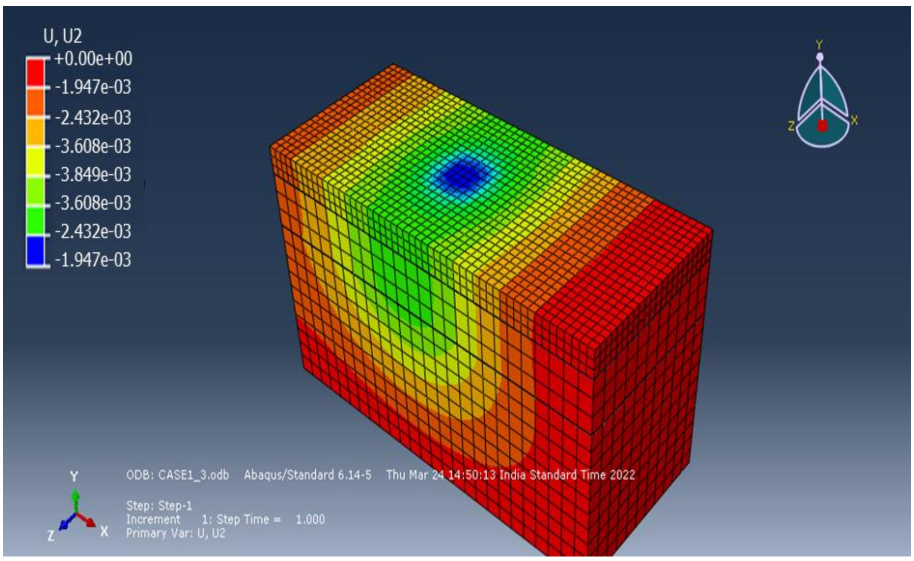

Figure 6. Results of Deformation for 10 msa Design Life

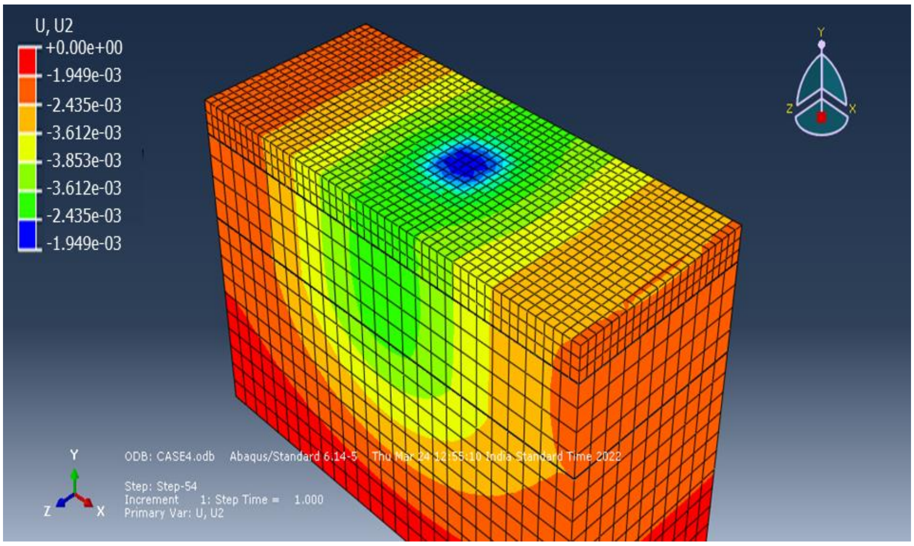

Figure 7. Results of Deformation for 50 msa Design Life

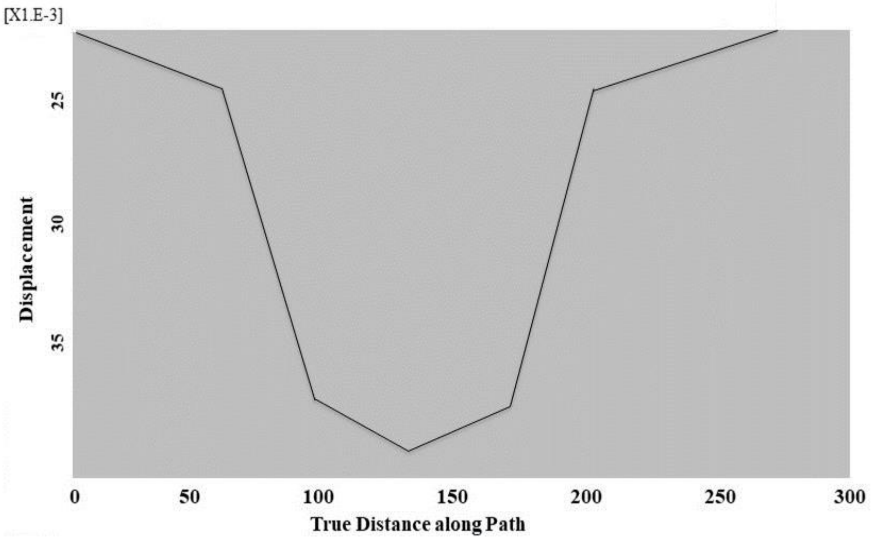

Figure 8. Trend of Displacement v/s Distance for 10 msa Design Life

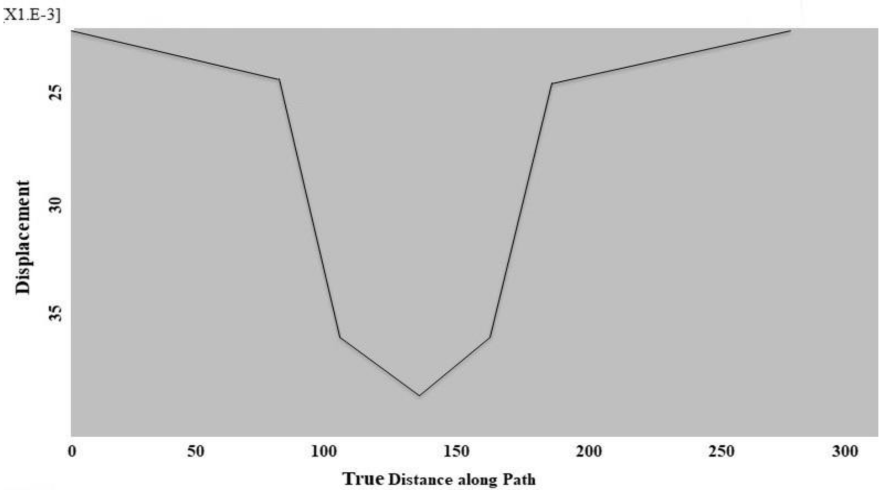

Figure 9. Trend of Displacement v/s Distance for 50 msa Design Life

Table 3. Deformation Values for 10 msa Design Life

Distance (mm)	Cycle	Step 1	Step 8	Step 16	Step 24	Step 32	Step 40	Step 48
		Deformation Values at the End of Different Cycles and Steps, m						
1	1	1.9475 E-03	1.9477 E-03	1.9481 E-03	1.9485 E-03	1.9489 E-03	1.9493 E-03	1.9497 E-03
85.4002	2	2.4324 E-03	2.4326 E-03	2.4331 E-03	2.4336 E-03	2.4341 E-03	2.4346 E-03	2.4351 E-03
110.927	3	3.6086 E-03	3.609 E-03	3.6097 E-03	3.6104 E-03	3.6111 E-03	3.6119 E-03	3.6126 E-03
137.594	4	3.84922 E-03	3.8496 E-03	3.85037 E-03	3.8511 E-03	3.8519 E-03	3.8527 E-03	3.8535 E-03
164.26	5	3.6086 E-03	3.609 E-03	3.6097 E-03	3.6104 E-03	3.6111 E-03	3.6119 E-03	3.6126 E-03
189.787	6	2.4324 E-03	2.4326 E-03	2.4331 E-03	2.4336 E-03	2.4341 E-03	2.4346 E-03	2.4351 E-03
275.187	7	1.9475 E-03	1.9477 E-03	1.9481 E-03	1.9485 E-03	1.9489 E-03	1.9493 E-03	1.9497 E-03

Table 4. Deformation Values for 50 msa Design Life

Distance (mm)	Cycle	Step 1	Step 8	Step 16	Step 24	Step 32	Step 40	Step 48
		Deformation Values at the End of Different Cycles and Steps, m						
0	1	1.7026 E-03	1.7028 E-03	1.7031 E-03	1.7035 E-03	1.7038 E-03	1.7042 E-03	1.7045 E-03
85.4002	2	2.1248 E-03	2.125 E-03	2.1255 E-03	2.1259 E-03	2.1263 E-03	2.1267 E-03	2.1272 E-03
110.927	3	3.283 E-03	3.2833 E-03	3.284 E-03	3.2846 E-03	3.2853 E-03	3.2859 E-03	3.2866 E-03
137.594	4	3.5164 E-03	3.5167 E-03	3.5174 E-03	3.5181 E-03	3.5188 E-03	3.5195 E-03	3.5202 E-03
164.26	5	3.283 E-03	3.2833 E-03	3.284 E-03	3.2846 E-03	3.2853 E-03	3.2859 E-03	3.2866 E-03
189.787	6	2.1248 E-03	2.125 E-03	2.1255 E-03	2.1259 E-03	2.1263 E-03	2.1267 E-03	2.1272 E-03
275.187	7	1.7026 E-03	1.7028 E-03	1.7031 E-03	1.7035 E-03	1.7038 E-03	1.7042 E-03	1.7045 E-03

The results of the finite element analysis show that in both cases, the maximum deformation occurred nearly at the center of the width, i.e., at 137.594 mm, and the deformation decreased as the radial distance increased from the point of loading. It is observed that deformation values are lower in case 2 compared to case 1 and decreased marginally by 8.64%, even though there was an increase in binder course layer thickness from 80 mm to 140 mm in case 2.

From Table 5, a very high value of stress was observed on the surface layer of pavement directly under the path of the wheel load and decreased laterally.

Table 5. Values of Stresses

Layer	Values of Stresses for 10 msa design life, MPa	Values of Stresses for 50 msa design life, MPa
Surface layer	0.5601	0.5423
Base layer	0.1004	0.0892
Sub base layer	0.0349	0.0305

In addition, it is observed that the stresses are maximum at the surface layer of the pavement and decrease at the base course layer. Most of the stresses get nullified at the base layer itself; only a marginal amount of stress gets transferred to the sub base layer of pavement. In addition, the stresses in case 2, compared to case 1, decreased by 5.86%, 11.10%, and 12.60% at the surface, base, and sub base respectively.

The study shows that the higher pavement thickness has little significance for the rutting resistance and the stress decrease in subbase and base layers compared to surface course layers. Furthermore, parameters such as the modulus of elasticity and the poison's ratio of the material are crucial in resisting rutting in flexible pavement compared to the thickness of the pavement. The above findings of the present research are much in line with the previous research findings.

4. Conclusions

The following are the conclusions drawn from the research:

- The finite element model analysis showed the instantaneous rutting depths on the different layers of pavement, i.e., at the surface, and base layers, and ABAQUS was very successful in simulating the pavement module. The maximum rut depth occurred nearly at the center of the width, i.e., at 137.594 mm.
- The finite element modeling by ABAQUS proved highly effective in simulating the responses of pavement under the influence of external loads. The modeling approach closely converges with the previous research work and real-world conditions, enhancing the credibility of the results.
- The research facilitated a comprehensive assessment of deformation and stress throughout the pavement layers. The stresses are concentrated near the point of loading and propagated throughout the pavement layer. The maximum value of stress for 10 msa design life was 3.853xE-03 and for 50 msa design life was 3.5202xE-03, respectively. This detailed analysis allowed for a thorough understanding of how these factors evolve and interact within the pavement structure, aiding in the prediction of performance.
- The research demonstrated that the different pavement layers have the ability to withstand without much distress, which helped in better understanding the relationship between pavement thickness and load-carrying capabilities.
- The study's analytical method for characterizing rutting behaviour and its correlation with laboratory tests empowers the industry to design and maintain pavements that are resistant to rutting.
- The finite element analysis facilitates optimizing the pavement design and provides insight into the material behaviour and pavement thickness, enhancing the pavement performance.
- Further studies may incorporate environmental factors such as temperature variations, moisture content, and freeze-thaw cycles, and their influence on pavement performance helps in the development of more resilient designs and mixes.

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