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FEM Modeling for Enhancing Fatigue Strength of Asphalt Pavements through an Optimum Tack Coat Layer Insertion †

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Abstract: A key factor in ensuring the stability and ductility of asphalt pavements is interlayer fatigue resistance. Interlayer bonding characteristics are one of the most significant elements influencing the lifespan of asphalt pavements. Poor bonding properties often lead to debonding, slippage cracking, and pavement deformation. The primary cause of interlayer slippage cracking is a lack of interface bonding between an asphalt overlay and underlayer, which is typically triggered by vehicle braking and turning. Emulsified asphalt, modified asphalt, and hot asphalt are just a few of the materials that are used as tack coats to address this issue. This paper examines five different bonding types between interlayers: a model with no tack coat, a model with SBS-modified hot asphalt, a model with SBS-modified asphalt emulsion, a model with an epoxy resin binder, and a model with SK-90 hot asphalt. This study evaluates the shear fatigue of asphalt pavement under a single wheel cycle load. A model is created using the Abaqus software to predict fatigue life while taking into account the various tack coat materials listed above. Considering the outcomes of this study, the best bonding type for asphalt pavement is SBS-modified hot asphalt. After selecting this material, various tack coat thicknesses were used until the optimum thickness of 6 mm was determined. The proposed model can withstand more load cycles and less rutting depth, which helps to prevent interlayer fatigue failure over the course of a pavement's design life.

Keywords: asphalt pavements; fatigue strength of asphalt pavements; tack coat; FEM modeling of asphalt pavements

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1. Introduction

Asphalt pavements are a critical component of transportation infrastructure. Their fatigue performance is essential to their long-term durability. A significant factor in asphalt pavement failure is fatigue cracking. It results from applying traffic loads repeatedly [1]. Placing a tack coat layer between the wearing course and base course can help asphalt pavements' fatigue strength. The purpose of tack coat layers, which are thin asphalt concrete coatings, is to strengthen the link between the wearing course and the base course. This can help to reduce the stress concentrations that can lead to fatigue cracking [2,3]. Finite element modeling (FEM) is a powerful tool that can be used to study the fatigue performance of asphalt pavements. FEM models can be used to explore the effects of various design factors on fatigue performance as well as to replicate the stress conditions that asphalt pavements encounter in the real world [4].

There have been several studies that have used FEM modelling to examine how well asphalt pavements resist fatigue with tack coat layers. One of the earliest studies was conducted by Al-Khateeb et al. (2005). Al-Khateeb et al. used FEM to study the effects of different tack coat thicknesses on the durability of asphalt pavements during fatigue. They discovered that as tack coat thickness was raised, asphalt pavement fatigue life also increases [5,6]. Another study was conducted by Li et al. (2010). Li et al. used FEM to study the effects of different tack coat materials on the fatigue performance of asphalt pavements. They discovered that when the tack coat material's stiffness grew, so did the asphalt pavements' fatigue life [7]. More recently, Wang et al. (2017) studied how varying tack coat thicknesses and materials affected the fatigue performance of asphalt pavements using FEM. Wang et al. found that the fatigue life of asphalt pavements increased with increasing tack coat thickness and stiffness. They also discovered that the kind of tack coat material had a big impact on fatigue performance [8]. Braunfelds et al. (2021) conducted an experimental study on the use of fiber Bragg grating (FBG) optical temperature and strain sensors to monitor asphalt concrete layers under the load of a moving wheel for road structural health monitoring (SHM) [9].

While previous work has shown that FEM modeling can be a useful tool for studying the fatigue performance of asphalt pavements with tack coat layers, but still there is a research gap and yet we have to study the effect of different bonding materials i.e., SBS-modified SBS-modified asphalt emulsion, hot asphalt, epoxy resin binder, and SK-90 hot asphalt on fatigue strength of asphalt layers. This study focuses on the elastic behavior of different bonding materials used as tack coats in asphalt pavements and identifies the most optimal material with the least fatigue damage and rutting depth [10].

2. Methodology

2.1. Geometric Details

Usually the asphalt pavements consist of:

1. Asphalt layer: They are hot mix asphalt (HMA) and cold mix asphalt (CMA). HMA is a mixture of asphalt binder and aggregate, while CMA is a mixture of asphalt binder and aggregate that can be mixed and placed at ambient temperature. Asphalt layers are durable, flexible, and resistant to wear and tear. They are also relatively inexpensive to produce and install.
2. Subbas: They are granular subbase and cementitious subbase in types. Granular subbases are made of crushed stone, gravel, or sand, while cementitious subbases are made of cement, sand, and water. Subbases provide a stable foundation for the asphalt layer. They also help to distribute traffic loads and prevent the asphalt layer from sinking.
3. Sand dunes: They are natural and composed of fine sand. Sand dunes are loose and unstable. They are also easily eroded by wind and rain.

In this study the modeling consisted of one simple model without a tack coat and four others with a tack coat layer. The model was generated in Abaqus, and its dimensions are outlined in Table 1 [10]. The comprehensive geometry of the model is visually represented in Figure 1.

Table 1. Dimensions of the Assembled Parts.

Layers	Length (mm)	Width (mm)	Depth (mm)
Asphalt	500	500	50
Tack Coat	500	500	5
Subbase	500	500	100
Sand Dunes	500	500	200

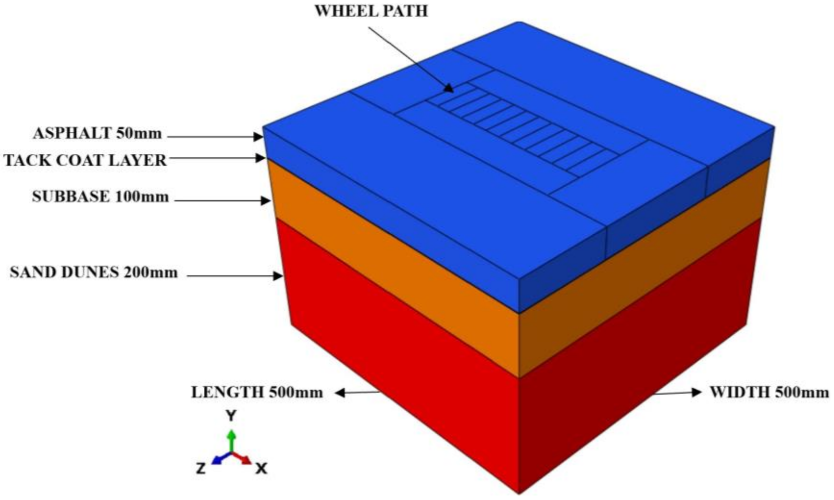


Figure 1. Geometry of the model.

2.2. Materials

The road pavement's asphalt layer exhibits viscoelastic properties [11,12]. To present this behavior in Abaqus, it is essential to incorporate relaxation modulus test data into the model, as outlined in Table 2. The material qualities of four different types of tack coat layers are described in Table 3. The subbase and sand dunes' attributes as well as other model components are described in Table 4 [10].

Table 2. Relaxation Modulus Test Data (Prony series) for Asphalt Layer.

g_i Prony	k_i Prony	tau_i Prony
0	0	$1.00 \times e^{-09}$
0	0	$1.00 \times e^{-08}$
0.5	0.5	$1.00 \times e^{-07}$
0.25	0.25	$1.00 \times e^{-06}$
0.125	0.125	$1.00 \times e^{-05}$
0.0625	0.0625	0.0001
0.0313	0.0313	0.001
0.0156	0.0156	0.01
0.0078	0.0078	0.1
0.0039	0.0039	1
0	0	10
0	0	100
0	0	1000
0	0	10000
0	0	100000

Table 3. Mechanical Properties of Tack Coat Layers.

Layers	Density (tonne/mm^3)	Elastic Modulus (Mpa)	Poisson's Ratio
Epoxy Resin Binder	$1.21 \times e^{-15}$	5000	0.35
SBS Modified Hot Asphalt	$1.13 \times e^{-15}$	6000	0.35
SK-90 Hot Asphalt	$1.14 \times e^{-15}$	5000	0.35
SBS Modified Hot Asphalt Emulsion	$1.32 \times e^{-15}$	2000	0.45

Table 4. Mechanical Properties of Subbase and Sand Dunes.

Layers	Elastic Modulus (Mpa)	Poisson's Ratio
Subbase	110	0.35
Sand Dunes	2	0.3

2.3. Loading, Boundary Conditions, and Interactions

In the ABAQUS simulation, a uniform load of 96 kg (equivalent to 0.96 kN) was added to the contact area. This resulted in a constant contact pressure of 550 kPa, resembling the pressure distribution beneath a tire that employs both longitudinal and transverse elements to evenly distribute vertical force across the loaded zone. This load was introduced to replicate the sideways motion of a wheel at a specific speed. Throughout this process, a gradual adjustment of the loading position was essential to ensure the smooth and complete rolling of the wheel. The behavior of the model also relies heavily on boundary conditions. In this scenario, the lower subgrade surface and the sides of the layers were assumed to be fixed, meaning that nodes at these locations could not shift vertically or horizontally. Additionally, tie constraints were employed to manage interactions between different surfaces within the model [10]. The load of one wheel cycle was applied to the orange surface of the pavement, as shown in Figure 3a. The specific loading point and boundary conditions are shown in Figure 3a. The movement of a tire on a road surface is illustrated in Figure 2.

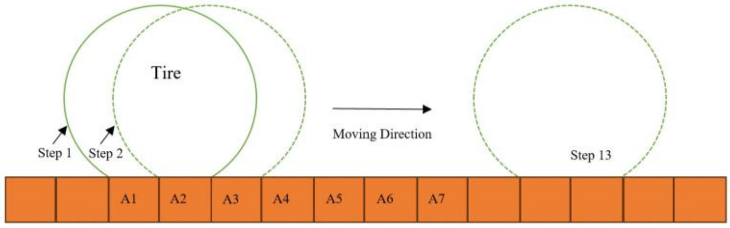
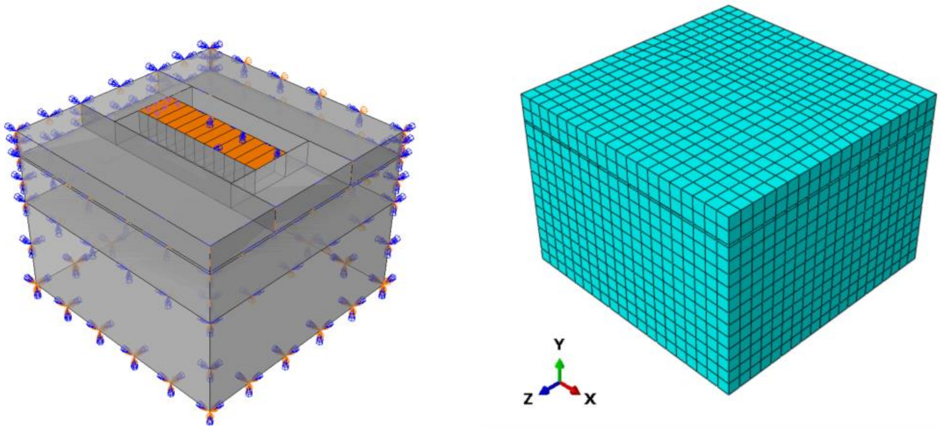


Figure 2. Schematic of a tire moving along a pavement surface.

2.4. Meshing

The model uses reduced order numerical integration and the three-dimensional brick element with eight nodes (C3D8R), a feature provided by ABAQUS (version 6.12-3). This element is capable of accurately representing significant deformations and allowing for both material and geometric nonlinearities. At each node, the solid element (C3D8R) has three degrees of freedom. To ensure the continuity of nodes between consecutive layers, a uniform shape is used for all layers (Massod, 2013). The mesh size of 25 mm was used for the modeling, the overall model configuration in Figure 3b.



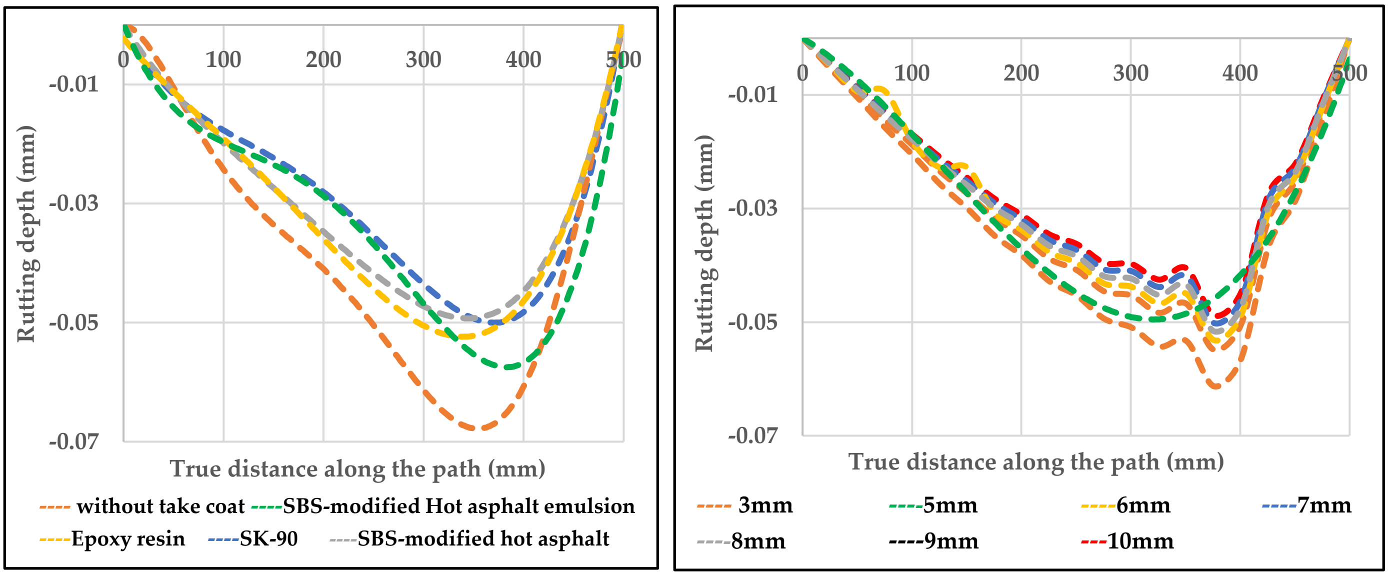
(**a**) (**b**)

Figure 3. (**a**) Load and Boundary Conditions; (**b**) Mesh geometry**.**

3. Results and Discussion

3.1. Results Comparison of Different Tack Coat Layers

Figure 4a compares different models with and without a tack coat. The model with a tack coat has a rutting depth of about 0.07 mm, while the model without a tack coat has a significantly higher rutting depth. Among all the tack coat layers, the SBS-modified hot asphalt has the least rutting depth of about 0.045 mm. This suggests that SBS-modified hot asphalt is the best tack coat layer for asphalt pavements, as it has more fatigue strength and life.



(**a**) (**b**)

Figure 4. (**a**) Comparison of rutting depth using FEM. (**b**) Thickness variation of SBS-modified hot asphalt.

3.2. Effect of Tack Coat Layer Thickness on Rutting Depth

Figure 4b compares the results of different thicknesses of SBS-modified hot asphalt take coat layer. The model with a 3 mm thickness of take coat layer has the highest rutting depth, followed by the 5 mm thickness. Take coats with thicknesses of 6, 7, 8, 9, and 10 have very little effect on rutting depth, as shown in Figure 4b. Considering economy, a take coat with a thickness of 6 mm is optimal for the design of asphalt pavements.

4. Conclusions

This study investigated the use of different tack coat layers in the asphalt pavement to improve the shear fatigue strength and life of asphalt pavement. According to this study, adding a tack coat layer to asphalt pavement increased its fatigue life and shear strength while reducing rutting depth. The findings showed that the tack coat layer with a thickness of 3 mm and made of SBS-modified asphalt had the least rutting depth of all the tack coat layers tested and could be used as an asphalt bonding layer in the design of pavements.

Based on the findings, the study identified several directions for future research and development:

Dynamic load behaviour: Examining how various tack coat thicknesses affect the fatigue shear strength and life under dynamic stresses (e.g., earthquakes, impact events).

Robustness against extreme loads: Examining the fatigue strength of asphalt using the different tack coat layers under extreme loading conditions (e.g., blast loads, progressive collapse).

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