PERMANENT DEFORMATION EVALUATION OF MODIFIED ASPHALTIC PAVEMENT BASED ON NUMERICAL SIMULATION MODELS

Akram ALHELYANI¹,*, Shuwen ZHANG¹

¹ Yellow River Laboratory, Zhengzhou University, Zhengzhou, China.
* corresponding author: akramhazaa1994@gmail.com

Abstract
Since the use of additives supplies the different properties required to develop better-performing roadways, modification with additives has been used as one of the attractive alternatives when the base asphalt does not satisfy the requirements for traffic load, climate variations, and paving structure. This study evaluates the effect of additive materials of improving the ability of the surface layer to withstand permanent deformation. In addition, it discusses to what extent using waste materials as additive materials affects permanent deformation resistance and the extent of using waste materials as alternative modifiers to commercial polymers to enhance permanent deformation resistance. In this study, the simulation using the ABAQUS program under the conditions of using different percentages of the additives, changes in the thickness of the surface layer, and increasing the temperature on permanent deformation of the asphalt layer was investigated. The simulation results showed that using modified mixtures improved the Hot Mix Asphalt HMA’s properties and decreased the mixtures’ temperature susceptibility, which manifested as a decrease in permanent deformation (lower rutting depth) when compared to an unmodified mixture. Furthermore, using waste materials led to the greatest decrease in permanent deformation among all models.

Keywords:
Permanent deformation; Additive; Crumb rubber (CR); Styrene-butadiene-styrene (SBS); Finite element.

1 Introduction
Changes in time and temperature influence the characteristics and behavior of flexible pavement. Because the occurrence of permanent deformation is related to time and temperature, and due to the rapid advancement of transportation, the growth in their loads and tire pressure, as well as climatic changes bringing on high temperatures, permanent deformation is now the predominant mode of failure in flexible pavements. This resulted in the emergence of serious issues that jeopardized the safety of road users while also lowering the performance quality of flexible pavement and shortening the road’s useful life. This kind of distress results from the buildup of permanent deformation in one or more pavement layer layers. Most of the permanent deformation occurs in the surface layers rather than in the subgrade [1]. Along with having a negative effect on asphalt pavement performance and serious risks for highway users, rutting can also cause other types of pavement distress, like cracking or stripping [2]. The pavement's properties are represented by the characteristics of its surface, which also, to a large extent, reflect the pavement's serviceability. The standard of their surface qualities is thus the target parameter for pavement serviceability and safety [3].

To satisfy the high-performance requirements of modern highways, this necessitates the construction of asphalt pavements that meet certain standards criteria and high specifications, which in turn necessitates asphalt mixtures with strong resilience to loading and environmental conditions. To get the highest performance out of road paving, bitumen's characteristics must be upgraded and improved. When the manufactured asphalt does not match the requirements for the traffic load, climate variations, and paving structure, modification with additives has been employed as one of the
appealing options. Additives supply the numerous attributes needed to build roads that have better performance [4].

For over 150 years, modification of asphalt has been done in many forms, where using additive materials supplies the diversified properties required to build roads that have better performance when conventional asphalt does not meet the requirements of pavement [5], and leads to produce an optimum modified asphalt with great permanent deformation resistance and has a particular impact on change temperature performance [6]. The chosen additives for modification must be compatible with asphalt and keep their characteristics through the mixing process. Also, the used modifiers ought to be cost-effective [7]. Since the 1960s, Crumb rubber (CR) has become increasingly used as a binding agent for HMA applications [8]. The good results that were achieved in improving paving performance, including the effect on permanent deformation as well as environmental advantages, led to CR becoming one of the most effective methods of improving paved road performance and have attracted researchers’ attention to evaluate the performance of crumb rubber HMA mixtures [9, 10]. On the other hand, Styrene-butadiene-styrene (SBS) is a type of elastomer polymer and is common all around the globe and is considered one such technique to reduce rutting, so SBS is often used to enhance rutting resistance and durability in surface courses [11, 12].

This research study is to investigate the potential of using crumb rubber (CR) and styrene butadiene styrene (SBS) as modifiers in hot mixed asphalt pavement mixtures, and so then evaluate the extent of using waste materials CR as alternative modifiers to commercial polymers SBS which are considered as expensive modifiers. The demand for numerical approaches has increased to provide analytical solutions to the majority of practical engineering problems [13] because this technique is regarded as one of the most effective methods for simulating the behavior response of various structural engineering issues and is considered the best method to model a pavement as well [14]. This method seeks to provide an approximate numerical solution to difficult engineering issues by breaking the complex structure down into infinitesimal, tiny components, analyzing the tiny parts, and then obtaining a general estimation for the complicated structure by summing the answers of the small parts [15]. So to achieve this study objective and to clearly understand the distribution and evolution of permanent deformation that occurs in the surface pavement layer when various types of additional materials are utilized, a three-dimensional finite element models were created using the ABAQUS 6.14-5 software program.

This study initially discusses the impact of various types and percentages of additive materials on the ability of the surface layer to withstand permanent deformation compared to the conventional mixture AC. Crumb rubber CR with 7, 10 % and Styrene-butadiene-styrene with 3, 5 % were utilized as additives. The loads applied for a constant axle load of 80 KN were tire pressure of 0.69 MPa. Secondly, we searched for the effects of various additives on the ability of the surface layer to withstand permanent deformation when the thickness of the asphalt layer changes while maintaining the same other conditions. Finally, the effects of various additive materials have been studied on the performance of permanent deformation when the temperature is raised to 40 °C, at various thicknesses, and under the same other conditions. The results showed that the use of modified mixtures enhanced the HMA's characteristics and reduced the mixtures' temperature susceptibility compared with the conventional mixture. It also improved the mixtures' flexibility qualities, which showed up as a decrease in permanent deformation (lower rutting depth) compared to that of an unmodified mixture. The study demonstrated to what extent the use of tire waste materials as modifiers for asphalt mixtures improves the resistance to permanent deformation; using 10 % CR resulted in the greatest reduction in permanent deformation among all models, and thus CR provides a successful economic alternative to the commercial polymer modifiers, which are considered expensive, including SBS, especially in developing countries. Furthermore, the use of waste materials provides one of the solutions to environmental problems represented by the disposal of unused tires.

2 Research methodology

It is impractical to undertake too many lab tests with different material combinations because it is both costly and time-consuming. As a result, using numerical modelling can provide the ability to handle a large range of tests with varied material mixtures, loads, and environmental conditions in a short period with acceptable results [16]. This study demonstrates how to acquire the data needed for the analysis using the ABAQUS 6.14-5 program, as well as how to assess and estimate permanent deformation in asphalt pavements using the finite element method. The primary goal of an ABAQUS program is to represent a specific situation or problem and then come up with a solution. Because an
ABAQUS model is made up of a number of distinct components that collectively describe the physical issue that needs to be studied and the outcomes that should be obtained, it becomes necessary to work with the program in steps. The following information serves as a summary of the analysis model steps used in the current study:

2.1 Model geometry and element type

The simulation of any finite element starts with defining the fundamental geometry of the physical structure. The fundamental geometry of the physical structure that is modeled in ABAQUS is defined by elements and nodes. The physical structure is represented by many separate elements, each of which itself is made up of many parts that are connected to each other by nodes. The set of all these nodes and elements in the model is called the mesh.

The three-dimensional, deformable solid model from ABAQUS was employed in this investigation to simulate pavement geometry. The model contains surface, base, and subbase layers of various materials that make up the multiple-layered pavement structure. The surface layer is directly exposed to changes in traffic volume and weather. The impact of traffic loads is distributed and transferred to the subbase layer via the base layer beneath the surface layer. The vertical dimensions for the pavement model were 100 & 50 mm, 200 mm, and 300 mm for the surface asphalt layer, base layer, and subbase layer, respectively, as shown in Fig. 1. To reduce the amount of inaccuracy caused by the edges, the dimensions 3600 mm * 4000 mm have been applied in longitudinal and transverse directions to complete the 3-D section of flexible pavement [17, 18].

![3-D section of flexible pavement model.](image)

Furthermore, all model's parts were represented by using an element that is capable of displaying significant deformation, which is the 8-node continuum three-dimensional brick element C3D8R with three degrees of freedom at each node with reduced order numerical integration, and the figure below showed the shape of the continuum element.

2.2 Element properties and sections assignment

The ABAQUS program enables the modelling of any number of various materials in a simulation model, after which the section properties referring to the material name will be assigned to the various model components. Many materials depend on the linear elastic theory, which is widely applied to pavement structural analysis. The main principle of the linear elastic theory is that stress and strain have a linear relationship, which further implies that the material has linear elastic behaviour at low strain rates and that the stiffness of the material, known as the elastic modulus or Young’s modulus, is constant. The stress and strain are measured as:

\[
\sigma = \frac{F}{A},
\]

where: \( \sigma \) - the stress [MPa], \( F \) - the force in the material [N], \( A \) - the current area [mm²].

\[
\varepsilon = \int_{l_0}^{l} \frac{dl}{l} = \ln \left( \frac{l}{l_0} \right),
\]

where: \( \varepsilon \) – the strain, \( l \) - the current length [mm], \( l_0 \) - the original length [mm].

Each layer of the multi-layer pavement system is homogeneous and isotropic. The pavement system study was predicated on the premise that all the materials used to build the layers in the model
would show a linear elastic response. The strain-stress formula is applied in the currently used model and for the purpose of modelling linear elastic behavior in ABAQUS; pavement layers were given material properties with specified elastic modulus and Poisson's ratio, as shown in Table 1. In this model, solid homogeneous sections were created and defined the materials for these sections. After that, sections were assigned to the different layers.

Table 1: Material properties of multi-layer pavement model [6, 19].

<table>
<thead>
<tr>
<th>Layers</th>
<th>Mixture</th>
<th>Additives</th>
<th>Elastic modulus [MPa]</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control temperature 20 C⁰</td>
<td>40 C⁰</td>
</tr>
<tr>
<td>surface</td>
<td>AC</td>
<td>-</td>
<td>1030</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>CRMA</td>
<td>7 % CR</td>
<td>2690</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>10 % CR</td>
<td>3060</td>
<td>612</td>
</tr>
<tr>
<td></td>
<td>SBSMA</td>
<td>3 % SBS</td>
<td>1540</td>
<td>273</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>5 % SBS</td>
<td>2915</td>
<td>451</td>
</tr>
<tr>
<td>Base</td>
<td>-</td>
<td></td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Sub Base</td>
<td>-</td>
<td></td>
<td>72.45</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Surface contact and interaction model

Many engineering problem models have two or more components. The goal of contact simulation is to locate the point of contact and compute the pressures that result from that contact, allowing forces to be transferred from one component to another within the same model. The interaction between contacting surfaces in ABAQUS is defined by the assignment of a master-slave contact algorithm. ABAQUS provides interaction modelling to represent the interaction between the pavement layers (surface, base, and subbase). Surface-to-surface contact between the layers of both (surface and base) and (base and subbase) was taken into account in this model.

2.4 Boundary conditions and load assignment

2.4.1 Boundary condition

The boundary conditions were defined in the first step and have a considerable impact on predicting the model's response. For this model, the subbase layer boundary conditions are assumed to be fixed at the bottom surface of this layer, restricting horizontal and vertical motion for any subbase layer nodes, whereas the asphalt and base layers of the pavement model are free to move in only the vertical direction and are fixed in the horizontal direction.

2.4.2 Loads applying

In general, when a vehicle moves over a road, the wheel effect area on the road surface is irregular and consists of a rectangle between two semi-circular parts and is dependent on tire pressure. In order to simplify simulation of the shape of tire pressure in ABAQUS, which is made up of a rectangular and two half circles, Huang [1] recommended utilizing an equivalent rectangle shape with an area of $0.5227 L^2$ and a width of $0.6 L$ as illustrated in Fig. 3.
To simulate the moving load on the pavement surface, the moving load path was used in the longitudinal direction and divided into a series of steps as the equivalent rectangle shape represented one step (needed 10 steps to complete one wheel cycle). In the current study, it is assumed that the axial load of 80 KN is transferred to the pavement surface through a single tire's contact pressure, which is equivalent to tire pressure. The uniform tire pressure is defined as a static distribution in-step module with an assumed value of 690 kPa for the amplitude. According to the principle of equivalent rectangle area, based on the load of one tire and the tire pressure, the stress equation can be used to calculate the equivalent rectangle of contact area that represents one step, which after calculating is equal to 200 * 290 mm. 10,000 wheel cycles were used over the top layer of the pavement at intervals of 100 seconds for the pavement model's investigation of permanent deformation. This provides 0.01 seconds for each wheel load pass on the asphalt layer.

2.5 Mesh model

In general, the mesh is just an approximation of the actual geometry of the structure. The mesh consists of a large set of nodes and finite elements, and the mesh density is majorly affects the accuracy of the obtained results as well as the effect on the analysis time of the model. The purpose of meshing is to make the problem solvable and increase the accuracy of the results. The lower the meshing dimensions, the longer the analysis time and the more accurate the results will be. As a result, the mesh size is chosen so that the model can be workable and produce results with an acceptable level of accuracy. To accomplish this goal, this model used a fine mesh around the loading
region along the wheel path, where stress and strain gradients were larger. Far from the loading
region, a reasonably coarse mesh is used in both vertical and horizontal directions. The fine finite
element mesh employed in this study provides more accurate stress and strain values at each point.
Meshing is done for each section by parts, which are shown in Fig. 5.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Number of nodes</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 [mm]</td>
<td>2310 3465</td>
<td>1116 2232</td>
</tr>
<tr>
<td>600 [mm]</td>
<td>798 798</td>
<td>360 360</td>
</tr>
<tr>
<td>Total</td>
<td>4305 5460</td>
<td>2196 3312</td>
</tr>
</tbody>
</table>

### Table 2: Number of nodes and element at different thickness.

#### 2.6 The calculation

Nowadays, analysis of pavement based on the multi-layer elastic theory is replaced with
analysis based on the finite element method, which involves breaking the problem down into simple
finite elements within a complicated domain. The nodal displacements are used to interpolate the
deformations within each finite element. In order to make the model balanced (the net force acting on
each node must be zero), the equilibrium equation between the external load and the internal load at
each node is often applied. The nodal displacements are then determined as follows:

If any element $i$ with three nodes $a$, $b$, and $c$ in the model is randomly chosen, the equation (3)
gives the strain in this model.

$$\epsilon_i = \frac{u_b - u_a}{L},$$

where: $u_b$ and $u_a$ - the displacements at nodes $b$ and $a$ on the element $i$, and $L$ = the length of the
element [mm].

And for elastic materials, the stress can be determined by multiplying the strain by the elastic
modulus $E$, as shown:

$$\sigma_i = E \times \epsilon_i.$$

Because elements’ characteristics are related to one another, the relationship between material
properties, internal force, and displacements of the element $i$ with sectional area $A$ can be determined
as:

$$I_i = \sigma_i \times A = E \times \epsilon_i \times A = \frac{E \times A}{L} (u_b - u_a).$$

In light of this, the equilibrium equation at node $a$ can be expressed as follows:

$$P_a + \frac{E \times A}{L} (u_b - u_a) = 0.$$

Similarly, the equilibrium equation at node $b$ can be constructed by taking into consideration the
internal forces acting on both elements connected at that node.

$$P_b - \frac{E \times A}{L} (u_b - u_a) + \frac{E \times A}{L} (u_c - u_b) = 0.$$

And for node $c$ the equilibrium equation can be obtained as follows:

$$P_c - \frac{E \times A}{L} (u_c - u_b) = 0.$$

To determine the displacements of all the nodes, the equilibrium equations must be solved
concurrently, which is best accomplished using matrix methods. So, the exterior and internal force
contributions are represented as matrices. If two elements have the same attributes and dimensions,
then the equilibrium equations can be simplified as:
\[
\begin{bmatrix}
P_a \\
P_b \\
P_c 
\end{bmatrix} - \left( \frac{E}{L} \right) \begin{bmatrix}
1 & -1 & 0 \\
-1 & 2 & -1 \\
0 & -1 & 1 
\end{bmatrix} \begin{bmatrix}
u_a \\
u_b \\
u_c 
\end{bmatrix} = 0.
\]

\[
\begin{bmatrix}
P_a \\
P_b \\
P_c 
\end{bmatrix} - \begin{bmatrix}
K_1 & -K_1 & 0 \\
-K_1 & (K_1 + K_2) & -K_2 \\
0 & -K_2 & K_2 
\end{bmatrix} \begin{bmatrix}
u_a \\
u_b \\
u_c 
\end{bmatrix} = 0.
\]

### 3 Results analysis

To achieve this study objective, in this model, different jobs were created to evaluate the effects of a change in additive material and change in additive quantity (change in material properties), the effect of different thicknesses, and the effect of different temperatures on permanent deformation performance in flexible pavements. After finishing all the modelling steps and applying all the loads and changes to the model, the pavement structure models using the finite element method were submitted for analysis and the results were as shown below.

#### 3.1 Results when change additives materials

The ABAQUS program was used to create a linear elastic model under repeated applied wheel loads to simulate the case study for flexible pavement systems, and all models go through the same modelling process. The elastic modulus \(E\) and the Poisson's ratio (as indicated in Table 1) are the two most important parameters to apply to these models. Permanent deformation values are the basis of comparison between these models in this study. The vertical displacement (vertical deformation) in this analysis is regarded as a response to the application of traffic loads. The vertical surface deformation results that were obtained from the ABAQUS program for the pavement system layers for conventional and modified mixtures models are shown in Fig. 6.

![Fig. 6: Permanent deformation for conventional and modified mixture.](image-url)
From the surface deformation results, it can be seen that the conventional surface layer has a peak surface deformation. Furthermore, it is clear that the modified asphalt mixes perform much better than the base asphalt mixture, and the performance is good. This shows that the permanent deformation performance of the mixtures has been significantly improved after the asphalt has been modified. This stipulates that the strength of the surface layer changes with the type and ratio of additives, which is represented by the clear increase in elastic modulus $E$ in the modified mixtures. The surface layer modified with 10 % CR decreases the peak surface deflection of the pavement structure to the lowest value of 1.120 mm (shows a reduction in surface deformation of about 22 % than the conventional surface layer model).

### 3.2 Results when change asphalt layer thickness

The cost of construction of a road is greatly influenced by the thickness of the flexible pavement. In this study, the impact of various types of additives on the resistance of the road to permanent deformation when the pavement's thickness changes is examined using an asphalt layer at various thicknesses of 50 mm and 100 mm.

According to the results shown in Fig. 7, reducing the thickness of the surface asphalt layer from 100 mm to 50 mm causes the rutting depth to increase by about 20 % for the conventional mixture because the ability of pavement structure to carry traffic loads decrease which show the effect of asphalt surface layer in increase capacity of pavement structure to carry traffic loads. Using additives causes the value to decrease by 18 %, 19 %, 12 %, and 18 % for 7 % CRMA, 10 % CRMA, 3 % SBSMA, and 5 % SBSMA, respectively. This decrease in surface deformation for pavement that uses modified mixtures is due to the fact that additive materials strengthen the asphalt mixture and increase its stiffness, which leads to an increase in the capability of the pavement to resist repeated traffic loads on the surface layer even when the thickness decreases.

![Fig. 7: Permanent deformation for different mixture at 50 mm thickness.](image)

### 3.3 Results when change the temperature

Permanent deformation becomes the most typical type of failure in asphalt pavement in hot weather and high temperature conditions. In addition, high temperatures can exacerbate the detrimental effects of stress, strain, and surface deflection. For the aforementioned reasons, the ABAQUS program was used to study the impact of different additive types on the road's ability to withstand permanent deformation under heat loading circumstances. In addition, to examine the induced behaviour of the modified mixture under rising temperature on permanent deformation of
flexible pavement. The permanent deformation results for the pavement system layers for all models with increasing the temperature of the surface layer to 40 °C at 100 mm thicknesses of the surface layer are shown in Fig. 8.

From results, increasing the temperature to 40 °C causes a 30 % rise in rutting depth for conventional mixture AC with 100 mm thickness of surface layer, this high percentage of increasing show the high significance effect of temperature on deformation since it affects both the stiffness of the asphalt mix and the unbound layers. Using additives at this temperature with 100 mm thickness will lead to reduce this rutting depth by 28 %, 31 %, 23 % and 28 % for 7 % CRMA, 10 % CRMA, 3 % SBSMA, and 5 % SBSMA mixture respectively compared to conventional mixture. This improvement in the deformability performance of modified mixtures is due to the fact that additive materials increase the viscosity of asphalt and thus require high temperatures to convert the asphalt to a liquid state, which leads to a decrease in the sensitivity to high temperatures and an improvement in the permanent deformation performance of pavement in high temperature conditions.

Fig. 8: Permanent deformation for different mixture at 40 °C.

3.4 Results when change the thickness and the temperature

The effect of decreasing the thickness of the surface layer along with increasing temperature on permanent deformation has been investigated for additional details and a deeper knowledge of the behaviour of modified mixes and their permanent deformation performance as shown in Fig. 9.
According to the findings in Fig. 10 for all conventional and modified mixtures when thickness was reduced to 50 mm and temperature was raised to 40 °C, the effect of changing thickness and temperature together had a greater impact on the permanent deformation than either change in thickness or temperature alone. Furthermore, compared with conventional mixtures, the modified mixtures still keep their efficacy in decreasing the deformation even under such conditions and will lead to reduced rutting depths of 16 %, 20 %, 11 %, and 17 % for 7 % CRMA, 10 % CRMA, 3 % SBSMA, and 5 % SBSMA mixtures, respectively.

Fig. 10: The effect of changing thickness and temperature on permanent deformation.

4 Conclusions

This study focuses on the finite element methodology of simulation of the flexible pavement system using the ABAQUS program to study the impact of CR and SBS as additive materials on the improvement of permanent deformation performance of flexible pavement under moving wheel load.
Based on the results obtained from the ABAQUS program can summarize the following concluding remarks:

1) Using modified asphalt to produce mixtures that are used in surface layers leads to improving the strength of pavement and reducing the sensitivity of the asphalt mixture to high temperatures, which in turn leads to reducing the depth of rutting and improving the permanent deformation resistance of the asphalt mixture compared with the base asphalt mixture. The strength of the surface layer changes with the type and ratio of additives.

2) The use of tire waste materials as asphalt mixture modifiers enhances the permanent deformation resistance; using 10 \% CR achieved the best surface deformation performance (showed the highest decrease in rutting depth), and thus CR provides a successful economic alternative to commercial polymer modifiers, which are considered expensive, particularly in developing countries. Furthermore, the use of waste materials provides one of the solutions to the environmental problems represented by the disposal of unused tires.

3) The small difference in the reduction value in surface deformation between increasing the asphalt layer's thickness and using additives leads us to consider the importance of these additives not only in the improvement of permanent deformation performance but also in the possibility of reducing the total cost of road projects.

References


