A Viscoplastic Modeling for Permanent Deformation Prediction of Rubberized and Conventional Mix Asphalt

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Abstract. Using the three-dimensional (3D) finite element method (FEM), a viscoplastic model was developed and applied for conventional and rubberized asphalt mixtures to simulate wheel track tests and predict rutting depth. The viscoplastic creep model can predict the response of asphalt materials where permanent deformation is a concern. The time-hardening formula was used for the law of creep strength and is one of the common methods for describing the viscoplastic behavior of asphalt mixtures in the ABAQUS program. The results showed that through a comparison between the two conventional models and the rubberized model, the rubber pavement rutting is 37\% less compared to the conventional model.

Keywords: Finite element; rutting; rubberized asphalt; crumb rubber; viscoplastic.

1. Introduction

Rutting or permanent deformation is one of the most common types of failure in hot mix asphalt (HMA) pavement [1]. It's described as longitudinal depressions in the wheel paths followed by side upheavals [2]. Rutting on the pavement has several negative impacts, including reducing pavement service life and reducing driving safety in the highway transportation network. Increased road roughness and trapping water, accelerating water damage and requiring expensive repair or reconstruction [3]. Hot mix asphalt is a thermoplastic liquid material at low temperatures or during fast-loading. It acts like an elastic solid, and it behaves like a viscous liquid at high temperatures or when loaded slowly. Therefore it is necessary to improve the performance of the asphalt binder to reduce the cracking (fatigue) at low temperature and plastic deformation (rutting) at high temperature [4]. Conventional or unmodified asphalt binders are often unable to high variations temperature changes, high axle loads, and tire pressures, resulting in surface distress or damage [5]. Therefore, it is imperative to enhance the properties of the conventional asphalt content as well as the advancement of successful asphalt mix design technology [6,7].

To ensure the pavements survive as long as possible without deterioration and develop national and global economies, it is vital to develop expense steps continuously. Natural ingredients, factory byproducts and waste materials, and carefully designed products, are among the commercially available modifiers. Recycled rubber, fillers, plastics, catalysts, extenders, and polymers are only a few more general types (natural and synthetic). Crumb rubber (CR) is one of the most successful ways to dispose of scrap tires by improving the properties of asphalt pavements [8]. The materials' characteristics significantly affect how flexible pavement reacts to traffic loads [9]. Some (3D) finite element simulations have been designed to investigate flexible pavements' responses [10, 11]. The asphalt mixture can act as elastic, viscoelastic material (recoverable), as well as plastic, viscoplastic material (irrecoverable). This behavior is due to the amount of stress applied under the wheel loads and temperatures [12].
At low traffic volumes and temperatures, elastic and viscoelastic reactions are observed while at high traffic volumes and temperatures, plastic and viscoplastic reactions are observed. To simulate permanent deformation of flexible pavements using finite element modeling, it is necessary to choose an adequate constitutive law that takes into account the creep behavior of asphalt mixes and calibrates the parameters through creep tests [13]. Several parameters have been used to create local prediction models for creep activity. In the ABAQUS library, the creep power law is available. Creep tests or accelerated pavement tests (APT) are also used to evaluate the ABAQUS time-hardening variant [14, 15]. The following is the outline for this paper; the coupled nonlinear viscoplastic model is briefly defined in “Nonlinear Viscoplastic Material Constitutive Model” the developed FE models, pavement structure, and material parameter recognition are described in finite element Simulations.

In this paper, to predict pavements' viscoplastic reaction, a three-dimensional finite element (FEM) model was constructed using flexible pavements made from rubberized and conventional asphalt mixtures. The asphalt layer was modeled as a viscoplastic substance using ABAQUS software's time-hardening version of the creep power-law model. Then a comparison 3D finite element (FEM) model was made between the rubberized and conventional asphalt mixture.

2. Viscoplastic behavior of flexible pavements

The reaction to traffic and environmental pressures is assumed to be elastic in flexible pavement designs. However, this assumption's feasibility is limited to the lower temperatures and rapidly applied vehicle loads, and when a load is removed from an asphalt surface, the deformation was not permanent, and the surface returns to its original state. The kind of plastic deformation associated with viscous activity occurs on flexible pavements at high temperatures and in the presence of slow-moving loads. The creation of a new model was motivated by the need to replicate the mechanical reaction of rubberized and conventional asphalt mixes. The elasticity needed to simulate the pavement's immediate response, viscosity to simulate the pavement's mechanical behavior in terms of loading time as a function of the strain rate, as well as plasticity to simulate plastic flow in terms of permanent deformation are all characteristics of this model by including their time-hardening creep parameters. Creep is the time-dependent action of a solid material to continue to bend under a steady stress less than the material's yield stress. There are three zones of creep; Primary, secondary, and tertiary zone. Creep strain begins quickly, is delayed by strain hardening in the second process, and then accelerates again in the third step. Figure 1 illustrates these steps.

![Figure 1. Creep stages](attachment:image.png)

Asphalt mixture is a type of rheological material, and creep models have shown that it reflects the asphalt mixes deformation. In ABAQUS, there are two types of creep models that are widely used. Which are the hyperbolic-sine model and the power-law model. The power-law model has both a time-hardening and a strain-hardening version. While it is a simplistic model, it is thought to be adequate for explaining the creep action of asphalt mixture materials. Current and overlay asphalt materials should be modeled to capture their viscoplastic behavior, including time-hardening creep parameters. During
the creep process, as the variation of stress varies in a small range, Eq. 1 gives the differential expression of the time-hardening variant [14].

\[ \varepsilon_{vp} = A \sigma^n t^m \]  

(1)

Where

- \( \varepsilon_{vp} \): creep strain rate,
- \( \sigma \): uniaxial deviator stress,
- \( t \): total loading time.

\( A, n, m \): creep parameters. \( A, n, \) and \( m \) are determined by laboratory testing, where \( A > 0, n > 0, -1 < m \leq 0 \).

### Table 1. Parameters of creep power law [17].

| Mix type          | \( A \times 10^{-5} \) | n   | m      |
|-------------------|-------------------------|-----|--------|
| Rubberized asphalt| 4.2                     | 1.5 | -0.609 |
| Conventional asphalt | 7.3                 | 1.5 | -0.570 |

Asphalt viscosity, aggregate size, and aggregate angularity are all factors that influence these parameters [18]. The creep power-law model's built-in constituent equations relatively simple but effective approach to modeling the non-recoverable tension of the problem presented [19].

### 3. Finite-element model formulation

There are different methods for predicting flexible pavement deformation. Examples of these methods are; multilayer elastic theory, boundary element methods, analytical methods, hybrid methods, finite difference methods, and finite element methods (FEM) [20]. Compared to other analytical techniques, the finite element method, FEM ability to simulate and model the behaviors of materials, temperature, and type of loading makes it very precise in pavement analysis and permanent deformation prediction [21]. Using three-dimensional FE models can solve the problems that two-dimensional FE models cannot solve under static and repeated loading. As a result, a 3D FE model was used to simulate the rubberized and conventional asphalt mixes in this study. Therefore, in this study, a 3D finite element model has been adopted to analyze the rubberized and traditional asphalt mixes. This model includes viscoplastic properties of pavement as well as the moving load. Where the ABAQUS has been used, it is one of the finite element programs. It is a suite of powerful engineering simulation codes according to the FEM. It can solve both simple problems (linear analyses) and complicated problems (nonlinear analyses). ABAQUS has a large library of finite element models and many material models, when it comes to nonlinear analysis, and it automatically selects acceptable increments and tolerances for convergence [22].

### 4. Model geometry, boundary conditions, and meshing

For the model to be analyzed, it is essential to find appropriate dimensions, boundary conditions, and mesh size. The simulation's primary purpose is to model asphalt mixtures' effectiveness of rubberized and conventional asphalt mixes in wheel tracking tests (WTT) to measure rut depth at various loads, and the wheel's cumulative number passes. The established model's dimensions conform to the actual specimen measurements used in WTT, which are \( (300 \times 300 \times 50) \) mm. These dimensions were selected to match the wheel tracking test slabs studied by Bakhsh et al. [17]. The model's boundary conditions are modeled following specimen circumstances in the wheel tracking test. Boundary conditions have a significant influence on expected responses. Since it has a substantial impact on the reaction of the form. The bottom surface of the bituminous wheel tracking test slab is assumed to be fixed. The bottom surface was restrained in both directions to have a completely fixed end, which means the nodes at the bottom could not travel horizontally or vertically, simulating the experimental conditions. While the upper surface is free, and displacements of the layer edges are still restricted in horizontal directions but unrestricted in vertical directions as shown in Figure 2.

In the finite element method, the body is divided into a large number of small, discrete, finite elements that are all resolved simultaneously. Simple (3D) eight node, linear brick reduced integration
elements (C3D8R) were used for all simulations. For every simulation, these finite elements are connected by shared nodes, and the mesh is formed by the combination of nodes and elements, as shown in Figure 3. The scale of the element mesh has a significant impact on the numerical accuracy. The fine mesh scale, on the other hand, takes longer to compute. As a result, both computational efficiency and accuracy should be considered when determining the fine element mesh dimension. The number of elements used in a mesh determines the density of it.

![Figure 2](image2.png)

**Figure 2.** Boundary conditions and loading of the wheel tracking slab.

![Figure 3](image3.png)

**Figure 3.** The finite element model mesh.

5. Material characterization
In this study, viscoplastic models for the rubberized and conventional asphalt mixes were developed. The viscoplastic permanent deformation properties of the flexible pavement materials parameter are usually determined using a dynamic creep test. The elastic modulus and creep power-law parameters were the primary variables in the mixtures. All material model parameters were collected from the laboratory results conducted by Bakhsh et al. [17]. The elastic modulus at 40°C was 3800 MPa, and the Poisson’s ratio was 0.35. The creep parameters used in the simulation are shown in Table 1.
6. Loading configuration and results

A uniform longitudinal loading pressure of 150 kPa is applied to the pavement surface as a moving load using ten small rectangular areas to reflect a tire footprint to apply the wheel's movement over an asphalt layer slab, with widths of 50 mm and lengths of 30 mm, as shown in Figure 2. The wheel load applied transitions to the pavement surface layer through the tire's contact pressure with the pavement surface. The contact pressure would equal tire pressure when the tire wall's stiffness effect is neglecting [23]. In finite element modeling, simulating the real loading sequence in wheel tracking is a challenging task. Hua invented and adopted an alternative and quick loading process [23], Uzarowski followed suit [24]. The static load was applied to the whole wheel's length route. The total accumulative loading time was calculated using the total number of wheel passes and the time required to cross wheel in one pass, as shown in Figure 4.

![Figure 4. One pass load duration conversion.](image)

The wheel's average speed was roughly 1.1 km/h and the time in one pass is about 0.14 sec for loading and 0.07 sec for unloading. It is a real load, and the loading time for one pass in three-dimension modeling was 0.21 s. it is a converted load, according to Hua [23]. As a result, the average static loading time for the 10000 passes was 2100 s, as shown in Figure 5, and for repeated load lasts up to 2800 seconds as shown in Figure 6.

![Figure 5. Static load.](image)
Figures 7 and 8 represent the deformed structure of rubberized and conventional samples after 10,000 passes in ABAQUS software in three-dimensional modeling at static load 150 kPa.

**Figure 6.** Repeated load diagram.

**Figure 7.** Predicted deformed shape of conventional asphalt.

**Figure 8.** Predicted deformed shape of rubberized asphalt.
7. Conclusions
The 3D finite element technique was used to forecast the rutting phenomena of rubberized and conventional hot mix asphalt in Wheel Track Testing. By using the finite-element program ABAQUS. As a result, led to the following conclusions:

- The results showed the numerical models' ability to predict rutting
- In the rubber model, the rutting was 37% less compared to the conventional model.
- CR positively influenced rut depth reduction, as rut depth reduction improved as tension levels increased.

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