Visco-elastic analysis of asphalt concrete

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Abstract: One of the load-bearing elements of the pavement is the asphalt binder, a viscoelastic, thermoplastic substance that has the stiffness of an elastic solid body but also flows and loses energy as a viscous fluid due to frictional losses. Asphalt materials have been studied using creep testing at multiple service temperatures. One of the most significant pavement distresses is persistent strain or rutting. It is thought that the primary cause of rutting in asphalt pavements is the accumulation of tension in the asphalt binder driven due to traffic. The commercial software ABAQUS CAE is utilized to simulate the creep behavior of asphalt concrete samples modeled as 2D bar elements. The viscoelastic properties of the material are characterized using the Prony series, enabling the numerical results to closely align with experimental observations. The outcomes of the analysis are presented as strain-time and displacement-time graphs.
Keywords: Asphalt-concrete, ABAQUS, Creep test, Visco-elastic analysis

1. Introduction

Granular composites including mineral aggregates, asphalt binder, and air spaces compose asphalt pavements. The binder and the mineral aggregates are the two load-bearing ingredients in asphalt mixtures. The refinement of crude oil yields asphalt binders. They are made from the thick residue left behind after fuels and lubricants are refined. Under the majority of pavement operating circumstances, asphalt, a thermoplastic substance, exhibits viscoelastic qualities. [1] Permanent deformation or rutting, which happens at high operating temperatures and is considered to be primarily caused by the accumulated strain in the asphalt binder, is one of the distress modes of asphalt pavements. Rutting is characterized by longitudinal surface depressions along the wheel paths of a pavement. The gradual buildup of longitudinal depressions in a wheel path under repeated loading is identified as rutting in asphalt pavements.[2] Air voids, asphalt binder, and mineral aggregates make up the viscoelastic asphalt mixture. One of the load-bearing ingredients in asphalt mixtures, asphalt binder is a viscoelastic, thermoplastic substance that has the stiffness of an elastic solid body but also flows and loses energy as a viscous fluid due to frictional losses.[3] Its characteristics are dependent on time and temperature[4] The asphalt material softens and takes on characteristics of a viscous fluid at higher temperatures and longer loading periods. The asphalt material stiffens and behaves more like an elastic material at lower temperatures and faster loading. Because of this, rutting is particularly important in slower-moving traffic and throughout the year's hotter months.

[5]. In 1987, the Federal Highway Administration launched a national research initiative known as the Strategic Highway Research initiative, or SHRP, after realizing the shortcomings of the conventional asphalt binder characterisation process [6]. Superpave® (Superior Performance Asphalt Pavements) was the end result of the SHRP research project. The Superpave® was created to offer performance-related characteristics that logically connect to pavement performance [5]. In 1993, Superpave® introduced the Dynamic Shear Rheometer (DSR), a device for measuring the mechanical characteristics of binder. This tool offered a practical way to assess the ability of the binder for withstanding rutting. The DSR works on the basis of applying sinusoidal, oscillatory stresses or strains to a thin bitumen disc that is positioned between two parallel plates throughout a range of temperatures and loading frequencies. [6] According to Anderson et al. [6], the strain-stress curve's calculation of the total dissipated energy is what causes rutting.

$$W_i = \pi \times \tau_0^2 \times \frac{1}{\frac{G^*}{sin\delta}} \quad (1)$$

Wi = total energy dissipated at the ith cycle, τ_0 - maximum stress applied, G* -complex modulus, δ = phase angle. |G*|/sin δ was introduced as the rutting parameter. Equation 1 shows that increasing the rutting parameter |G*|/sin δ causes dissipated energy to decrease and, as a consequence, more rutting occurs.

Materials can exhibit various mechanical characteristics, including linear elastic (Figure 1), viscous, and viscoelastic behaviors. Viscoelasticity combines the properties of elasticity and viscosity and is often modeled using mechanical analogs such as the Maxwell (Figure 3) and Kelvin models.[7]

In a linear elastic material(Figure 1), deformation occurs upon the application of a load, but when the load is removed, the material returns to its original shape, exhibiting no permanent deformation.

$$\varepsilon=\frac{\sigma}{E} \ (2)$$

where: ε-strain, σ-stress, E-elastic modulus.

Conversely, viscous materials (Figure 2) experience permanent deformation when a load is applied, as they cannot recover their original form after the load is removed.

$$\dot{\varepsilon}=\frac{\eta}{\sigma} \ (3)$$

Where $\dot{\varepsilon}$=strain rate, η= viscosity, and σ=applied stress. The relationship between stress and strain can be expressed in terms of compliance, (t)

The Maxwell model (Figure 3) represents a viscoelastic material as a combination of an elastic spring and a viscous dashpot in series. This configuration captures the time-

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dependent strain behavior under stress, resulting in a nonlinear strain-time relationship. [8,9,10]

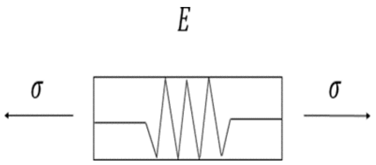

Figure 1. Elastic linear material.

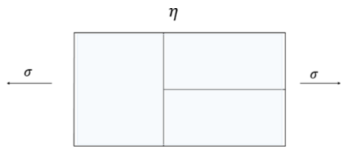

Figure 2. Linear Viscous Dash-pot

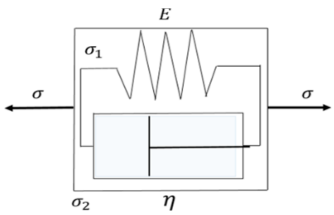

Figure 3. Maxwell model

2. Methods and materials

2.1. Creep test modeling in ABAQUS

Creep is a highly significant phenomenon in the world of mechanics and materials. The importance of creep analysis is due to its occurrence in various industries and the huge and irreversible damage it can cause. Consequently, extensive studies have been conducted on this phenomenon and its reasons. Creep is typically a time-dependent phenomenon that occurs slowly and inconspicuously, sometimes catching us off guard. This highlights the importance of creep analysis and simulation.[11] Creep is a time-dependent deformation of materials occurring at elevated temperatures and within the range of stresses below the elastic limit of the material. [12] One of the methods for creep analysis is simulation and creep analysis in Abaqus. Abaqus is a powerful finite element simulation software that is highly efficient in analyzing and studying phenomena such as creep. Creep is a time-consuming phenomenon therefore, its analysis and investigation in experimental tests are challenging and costly. However, Abaqus software provides users with the capability to perform creep analysis with less time and cost. So far, numerous models have been developed for creep analysis, and Abaqus creep incorporates some of the best creep analysis models. In the following sections, we will introduce some of these models. [13,14] The creep behavior of asphalt concrete was simulated using the commercial finite element software ABAQUS CAE. A two-dimensional bar (Figure 4) model with dimensions of 100 cm in length and 10 cm in height was constructed for the analysis. The boundary conditions were defined such that one end of the bar was fully constrained in both the x- and y-directions, while the opposite end was subjected to a uniform pressure load. The simulation was conducted over a duration of 3600 seconds to evaluate the time-dependent deformation characteristics under sustained loading conditions, providing insight into the creep response of the material.

Figure 4. Material geometry, load and boundry conditions

2.2. Material definition and loading

To conduct viscosity analysis in ABAQUS, Prony series constants are essential. These constants are derived through the Prony series procedure to determine the coefficients of the generalized Maxwell Model. The Prony series model is commonly employed to represent relaxation moduli, a critical parameter characterizing the viscoelastic properties of bitumen. This model consists of one linear spring element and 'n' Maxwell elements, each characterized by an elasticity modulus for the springs and a viscosity coefficient for the dashpots. In asphalt pavement finite element analyses, Prony series[15,16] are extensively utilized for numerical modeling. Equations 4 in the provided model describe the primary equations for the time domains.

$$G(t) = G_{\infty} + \sum_{j=1}^{n} (G_j \cdot e^{\frac{-t}{\tau_j}}) \quad (4)$$

where G (t) is the complex modulus, G_{∞} , G_j and τ_j are the Prony series coefficients.

By employing time-temperature superposition, the relaxation modulus can be determined across various temperatures, as expressed in Equation 3

$$\tau_j(T) = \alpha_T \cdot \tau_j \quad (5)$$

Here, $\tau_j(T)$ represents the relaxation times at any given temperature, while α_T denotes the shift factors applied to fit the William-Landel-Ferry (WLF) function.Subsequently, the Prony series constants were calculated based on the obtained data. Table 1 shows elasticity modulus of bitumen and Poisson's ratio.

Table 1

Instantenous elastic modulus and Poisson's ratio

Young's modulus (kPa)	Poisson's ratio
3060	0.37

Table 2

The Prony series constants

g_i(shear modulus)	k_j(bulk modulus)	tau_i
0.074	0	436
0.1460	0	0.06
0.314	0	0.000143
0.376	0	7E-07

2.3. Meshing

This was achieved using the CAX4R element type, which is a 4-node bilinear axisymmetric quadrilateral element with reduced integration and hourglass control**.** The finite element meshing of the model was performed using quadrilateral elements of uniform size across the entire domain to ensure consistent accuracy in the analysis. A total of 650 elements were generated, employing reduced integration to mitigate hourglass effects and enhance computational stability. The simulation spanned a total duration of 3600 seconds, with the maximum number of increments set at 10,000. The time increment parameters were defined as an initial increment size of 0.01 seconds, a minimum increment size of 1E-12 and an adaptive strategy to ensure convergence. The solution technique utilized a full Newton-Raphson method to accurately capture the nonlinear viscoelastic behavior. The analysis was conducted using a dynamic implicit approach, which is well-suited for capturing time-dependent deformation phenomena such as creep in viscoelastic materials**.**

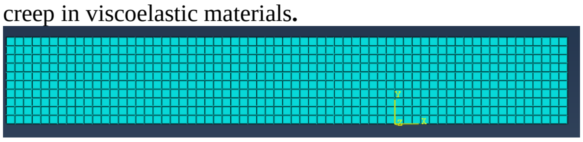

Figure 5. Meshing

3. Results and discussions

The creep test simulation performed in ABAQUS yielded critical insights into the mechanical behavior of the modeled asphalt concrete bar under sustained loading conditions. The results included the displacement in the x-axis (Figure 6), which provides a detailed representation of the time-dependent lateral deformation (Figure 7) of the material. This displacement data is crucial for assessing the viscoelastic response of the asphalt concrete and understanding its dimensional stability under prolonged stress.

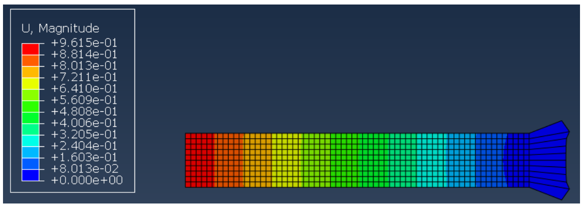

Figure 6. Displacment x-axis in the simulation

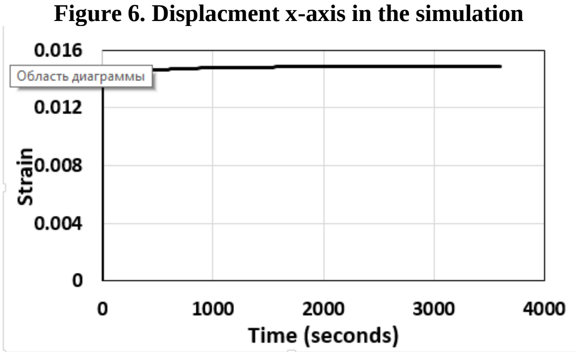

Figure 7. Strain-time relationship

In addition to displacement, the simulation produced von Mises stress (Figure 8) distributions throughout the bar. This stress metric is particularly valuable as it captures the equivalent stress, accounting for multi-axial loading conditions within the material. The von Mises stress distribution highlights regions of stress concentration, which can be indicative of potential failure zones or areas prone to accelerated creep deformation.

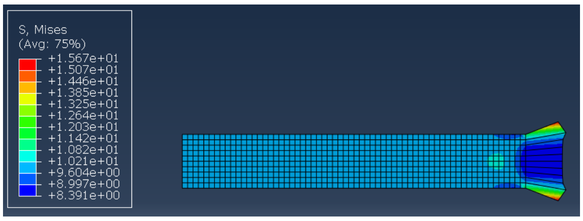

Figure 8. Von Mises Bau stresses in the simulation

These outcomes not only validate the material model employed in the simulation but also offer a foundation for comparing the numerical predictions against experimental results. Furthermore, they provide practical insights into the material's long-term performance, particularly in applications where durability and reliability under sustained loads are critical.

4. Conclusion

This numerical model serves as a valuable tool for enhancing our comprehension of the visco-elastic properties inherent in asphalt-concrete. Furthermore, it lays the groundwork for prospective endeavors involving experimental validation and further numerical simulations. By elucidating key characteristics, such as the discplacement-time, strain-time this model not only deepens our understanding but also provides a platform for future research aimed at refining our grasp of bitumen behavior under varying conditions.

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