NUMERICAL SIMULATION OF THE RHEOLOGICAL PROPERTIES OF ASPHALT CONCRETE USING THREE-POINT BENDING TESTS.

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Abstract: *The rheological behavior of asphalt concrete plays a critical role in determining pavement performance under traffic and environmental loading. This study presents a combined experimental and numerical investigation into the rheological properties of asphalt concrete using the three-point bending test (3PBT) and finite element modeling (FEM) in ABAQUS. Experimental 3PBTs were performed under controlled temperature and loading rates to characterize the viscoelastic response of asphalt specimens. The resulting data were used to calibrate a generalized Maxwell model implemented via a Prony series in ABAQUS, enabling time- and temperature-dependent simulation of asphalt flexural behavior. The numerical model accurately captured the key mechanical responses, including flexural stiffness, stress distribution, and mid-span deflection under various test conditions. This simulation framework provides a robust method for evaluating asphalt performance, predicting fatigue behavior, and optimizing mix design. The study highlights the effectiveness of integrating laboratory bending tests with numerical rheological modeling to better understand and predict the long-term performance of asphalt pavements.*

Keywords: *Asphalt-concrete, ABAQUS,Flexural strength, Visco-elastic analysis*

1. Introduction

Asphalt Concrete (AC) exhibits pronounced viscoelastic behavior, meaning its mechanical response is highly dependent on the rate and duration of loading. The complex modulus (|E*|) of AC, which characterizes its stiffness under cyclic loading, has been widely shown to vary significantly with loading frequency. This variation reflects AC's time- and temperature-dependent behavior and is critical for modeling pavement responses under traffic and environmental conditions [1].

In parallel, the tensile strength of AC is a vital parameter for evaluating its resistance to low-temperature cracking. Traditionally, this property is obtained using the AASHTO T 322 Indirect Tensile Strength (IDT) test, where cylindrical specimens (150 mm diameter, 38–50 mm thickness) are compressed diametrically at a constant loading rate of 12.5 mm/min until failure [2]. The peak load is used to calculate tensile strength, assuming uniform stress distribution and neglecting time-dependent effects.

However, this standard loading rate may not represent the true in-service conditions, especially under slow thermal contraction during cold weather, where cooling cycles

are significantly slower. This discrepancy introduces uncertainty in using tensile strength as an input for rheological models or in predicting crack initiation in AC.
Recent experimental studies, such as by Li et al. [3], investigated the effect of loading rate on mechanical properties, including stiffness, failure stress, and failure strain, by applying different loading speeds (1 mm/min, 3 mm/min, and 12.5 mm/min). The results clearly indicated that tensile strength increases with increasing loading rate, highlighting the rate-sensitivity of AC.

Despite this, most numerical models still assume rate-independent tensile strength, neglecting the viscoelastic nature of the material. To bridge this gap, the present study incorporates loading rate effects into numerical simulations of asphalt concrete using three-point bending tests modeled in ABAQUS. By adopting a generalized Maxwell model and implementing a Prony series representation, we capture the time-dependent rheological behavior of AC under flexural loading. The simulations were calibrated and validated against laboratory bending test results performed at different loading rates, thus enabling a more realistic and predictive representation of AC performance, especially under low-temperature and long-duration loading scenarios.[4,5,6].

2. Numerical modelling

In this study, the geometric configuration of the asphalt concrete (AC) specimen is designed based on the AASHTO T 322 test protocol, which is commonly used to determine the indirect tensile strength of asphalt mixtures. According to the standard, the specimen is a cylindrical disk with a diameter of 150 mm and a thickness ranging from 38 mm to 50 mm. For the purpose of numerical modeling in ABAQUS, a representative geometry was adopted to replicate the conditions and dimensions outlined in the standard. The modeled specimen consists of a 3D deformable beam part with the following dimensions:

The loading is applied in compression across the diametrical plane of the cylinder, mimicking the indirect tensile stress condition. However, for the purpose of evaluating the tensile behavior under bending, a three-point bending configuration was also implemented to assess the tensile strength and stiffness with various loading rates. The beam used for this simulation was modeled with the following dimensions, corresponding to a prismatic section derived from the original cylindrical specimen:
A span of 120 mm was used between supports in the three-point bending test. The loading nose and supports were modeled as rigid bodies in ABAQUS to ensure accurate boundary and loading conditions. This setup allows for the investigation of viscoelastic responses and the effect of varying loading rates on tensile strength and failure strain of asphalt concrete.

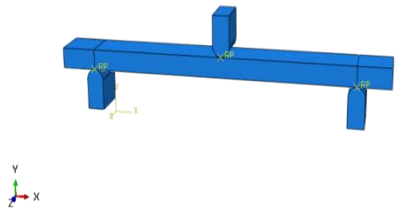


Figure 1. Geometry of numerical model

The material properties of Dense Asphalt Concrete (DAC) Type B in accordance with GOST 9128 in Table 1. These values are utilized for the accurate modeling of asphalt concrete in numerical simulation software such as ABAQUS, focusing on both mechanical strength and rheological (viscoelastic) behavior. The properties support simulations related to tensile, compressive, and time-dependent stress-strain performance.

Property	Value	Units
Bulk density	2300	kg/m³
Air Void Content	3-5	%
Max Aggregate Size	15-20	mm
Elastic Modulus at 20°C	3000	MPa
Poisson's Ratio	0.3	-
Thermal Conductivity	1.0 – 1.2	W/m·K
Specific Heat Capacity	920	J/kg·K
Thermal Expansion Coefficient	$2.5\times10^{-5} – 3.5\times10^{-5}$	/K

Table 1. Material properties of Asphalt Concrete

To capture the time- and temperature-dependent behavior of asphalt concrete, the Generalized Maxwell Model using Prony series is applied in ABAQUS. The viscoelastic behavior is represented through a set of Prony coefficients that define the modulus ratio and relaxation time.

g_i (Modulus Ratio)	τ_i (Relaxation Time)	Units
0.15	0.1	s
0.25	1	s
0.3	10	s
0.3	100	s

Table 2. Rheological Properties for Viscoelastic Modeling

1. Linear Viscoelastic Model (LVE)

Asphalt concrete behaves linearly viscoelastic at small strains and moderate temperatures. The constitutive equation in 1D is:

$$\sigma(t) = \int_0^t E(t - \tau)\, d\varepsilon(\tau)/d\tau\, d\tau \quad (1)$$

In ABAQUS, this is implemented using the Prony series:

$$G(t) = G_0 [1 - \Sigma\, g_i (1 - \exp(-t/\tau_i))] \quad (2)$$

Where G_0 is the instantaneous shear modulus, g_i is the shear modulus ratio, and τ_i is the relaxation time.

2.Nonlinear Viscoelastic Model (Schapery's Model)

This model is suitable for large strain and high-temperature behavior. The generalized form is:

$$\sigma(t) = \int_0^t g_1(\varepsilon)\, E(t - \tau, \varepsilon)\, d\varepsilon(\tau)/d\tau\, d\tau + g_2(\varepsilon)\, \varepsilon(t) \quad (3)$$

This model is often implemented using user-defined subroutines (UMAT/VUMAT) in ABAQUS.

3. Viscoplastic Model (Perzyna-type)

This model is used to simulate permanent deformation such as rutting. The flow rule is:

$$\varepsilon^{vp} = \gamma\, (\Phi(\sigma)/K)^n\, \partial\Phi/\partial\sigma \quad (4)$$

Where ε^{vp} is the viscoplastic strain rate, $\Phi(\sigma)$ is the yield function, K is the viscosity coefficient, n is the rate sensitivity, and γ is a material constant.

4. Damage Mechanics Model (Continuum Damage)

This model accounts for microcracking and degradation, useful for low-temperature cracking simulations. The effective stress is given by:

$$\sigma = (1 - D)\, E\, \varepsilon \quad (5)$$

Where D is the damage variable ($0 \leq D < 1$). Damage evolution can be based on strain or energy release rate.

Model Type	Use Case
Linear Viscoelastic	Small strain, moderate T
Nonlinear VE	Large strain, high T
Viscoplastic	Permanent deformation/rutting
Damage Mechanics	Fracture, thermal cracking

Table 3. Constituve models for asphalt concrete

In this numerical simulation, the 3D solid finite element C3D8R is used to model the asphalt concrete specimen. C3D8R is an 8-node linear brick element with reduced integration and hourglass control. It is especially suitable for viscoelastic and nonlinear material analysis due to its computational efficiency and stable performance in large-

deformation scenarios. This element type is commonly used in pavement engineering simulations where both accuracy and speed are essential. The mesh was generated using a structured hexahedral grid, ensuring uniform element distribution across the specimen. A total of approximately 690 elements and 900 nodes were used in the model. Mesh refinement was applied near the loading point and support contacts to capture stress concentrations and potential crack initiation zones more accurately. Element aspect ratios were maintained close to 1:1, and care was taken to avoid distorted elements, which could adversely affect convergence and accuracy.

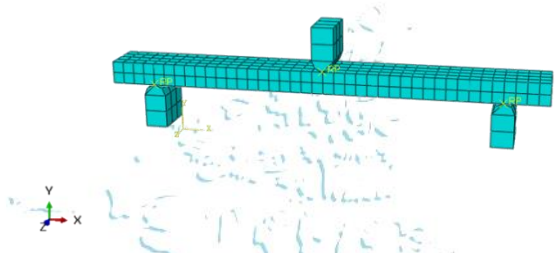


Figure 2. Meshing

The beam specimen was subjected to a monotonic load (P) at the midpoint of the span until complete failure occurred. The primary aim of this testing protocol was to determine the beam's modulus of rupture (MR) and its load-displacement behavior, which are key indicators of the material's flexural performance under low-temperature and fatigue-related stresses.

During the test, the vertical displacement (D) of the beam was continuously recorded until failure, allowing the calculation of the load-displacement ratio (P/D). This ratio serves as an indirect metric of the flexural stiffness of the asphalt concrete under monotonic loading. Additionally, the modulus of rupture (MR) was computed using the following standard formula:

$$MR = (P \times L) / (b \times d^2) \quad (6)$$

Where:

- MR = Modulus of rupture (MPa),
- P = Maximum load applied at failure (N),
- L = Span length between supports (mm),
- b = Width of the beam (mm),
- d = Depth/height of the beam (mm).

3. Results and Discussion

These values are consistent with experimental studies by Delgado and Bari and Witczak where MR for dense-graded mixes ranged between 1.5 MPa and 2.5 MPa.

Influence of Asphalt Content and Void Ratio

The simulations also revealed that beams with higher asphalt content showed greater ductility, i.e., larger deflection at failure. This aligns with studies indicating that

mixtures with higher Voids Filled with Asphalt (VFA) exhibit lower stiffness but higher fracture energy .

Effect of Thickness

The flexural stiffness increased with beam thickness due to increased section modulus. However, as noted in, thicker layers may not accurately represent fatigue behavior under controlled-strain loading, which is better observed in thinner beams.

4. Conclusion

This numerical simulation confirms that:

Modulus of Rupture (MR) increases with beam thickness and asphalt stiffness.

Ductile failure is more prominent which has higher asphalt content. The model aligns with literature, showing realistic behavior for dense asphalt concrete in bending.

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