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Influence of Asphalt Viscoelastic Properties on Pavement Deformation under High-Temperature Conditions

Meng Jiayi

China Merchants Chongqing Transportation Research and Design Institute Co., Ltd., Chongqing, 400000, China
3427105902@qq.com

Abstract: *To elucidate the mechanism by which asphalt viscoelastic properties affect pavement deformation under high-temperature conditions, this study investigated AH-70 asphalt pavements with AC-13 and AC-20 structures. Viscoelastic parameters were obtained through dynamic modulus tests at multiple temperatures, as well as creep and relaxation experiments. These parameters were combined with laboratory rutting tests and fiber Bragg grating (FBG)–based layered monitoring to analyze the accumulation of deformation and the evolution of rutting in different structural layers under elevated temperatures. The results indicate that high temperatures lead to a pronounced reduction in dynamic modulus and an increase in phase angle, reflecting a decline in elastic stiffness and an enhancement of viscous flow behavior. Under extreme high-temperature conditions, the deformation contribution of the middle and lower layers increases significantly. The degradation of viscoelastic properties at high temperatures is identified as the primary factor driving the downward extension and accelerated development of rutting from the surface layer into deeper layers. The findings provide a theoretical basis for pavement design and maintenance in high-temperature regions.*

Keywords: *high-temperature environment; asphalt viscoelastic properties; pavement deformation; rutting*

1. Introduction

Asphalt pavements are prone to permanent deformation, particularly rutting, during high-temperature seasons. The fundamental cause lies in the strong temperature sensitivity of the viscoelastic properties of asphalt mixtures. Elevated temperatures lead to a reduction in dynamic modulus and an increase in phase angle, indicating a transition from predominantly elastic behavior to viscous and viscoplastic dominance [1]. This transition substantially weakens the ability of pavement layers to resist compressive and shear deformation. Existing studies have largely focused on the macroscopic evolution of surface rutting, while the quantitative relationship between temperature-induced variations in viscoelastic parameters and the accumulated internal deformation of individual structural layers remains insufficiently understood. In particular, the deformation contribution of deep layers under extreme high-temperature conditions has yet to be systematically verified. In response to this gap, it is necessary to conduct integrated experimental investigations and mechanistic analyses from three perspectives: material viscoelastic properties, layered mechanical responses, and the rutting development process. Such efforts can provide a scientific basis for asphalt pavement structural design and distress mitigation in high-temperature regions.

2. Temperature-Dependent Mechanisms of Viscoelastic Properties of Asphalt Mixtures

2.1 Fundamental Theory of Viscoelasticity of Asphalt Mixtures

Asphalt mixtures are classified as linear viscoelastic materials, exhibiting mechanical characteristics of both elastic solids and viscous fluids. Under dynamic loading, the stress response of an asphalt mixture lags behind the applied strain. The complex modulus, E^*, is commonly used to characterize the overall resistance of the material to deformation [2].

$$E^*=E'+iE'' \quad (1)$$

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Here, E′ represents the recoverable elastic contribution, while E″ corresponds to viscous energy dissipation.

The magnitude of the dynamic modulus, |E*|, represents the overall stiffness of the material at a given loading frequency. The phase angle δ describes the lag of stress relative to strain and reflects the proportion of the viscous component; as δ increases, viscous effects become more pronounced.

2.2 Mechanisms of Temperature Effects on Viscoelastic Properties

The viscosity of the asphalt binder is highly sensitive to temperature. As temperature increases, intermolecular forces weaken and the resistance to flow of the binder decreases rapidly, resulting in a reduction in the elastic response and a corresponding increase in viscous behavior of the mixture. Under high-temperature conditions, the asphalt mastic can no longer maintain its original cohesive structure, and the load transfer mechanism within the aggregate skeleton shifts from binder-controlled behavior to one dominated by aggregate interlock[3]. During loading, the recoverable portion of strain diminishes and stress lag becomes more evident, causing the material response to be increasingly governed by viscous effects.

3. Experimental Materials and Research Methods

3.1 Asphalt Mixtures and Pavement Structural Configurations

AH-70 road petroleum asphalt was used as the binder. Its penetration, ductility, and softening point satisfy the high- and low-temperature performance requirements of asphalt mixtures, as summarized in Table 1. The optimum asphalt–aggregate ratio was determined using the Marshall test, yielding values of 4.8% for AC-13 and 4.2% for AC-20.

Crushed basalt was selected as the coarse aggregate, manufactured sand as the fine aggregate, and mineral powder as the filler. The proportions of each aggregate size fraction were determined strictly in accordance with relevant specifications to ensure the formation of a stable interlocking aggregate skeleton.

Tab.1 Technical properties of AH-70 road petroleum asphalt

Item		Technical requirement	Test method
Penetration (25℃, 100 g, 5 s)/0.1mm		60~80	GB/T 4509
Softening point (Ring-and-Ball) /℃		46~54	GB/T 4507
Ductility (15℃)/cm		≥100	GB/T 4508
Ductility (25℃)/cm		≥150	GB/T 4508
Density (25℃)/($g·cm^{-3}$)		≥1.01	GB/T 8928
Flash point (open cup)/℃		≥260	GB/T 267
Solubility (carbon tetrachloride or trichloroethylene)/%		≥99.5	GB/T 8929
After rolling thin film oven test (RTFOT)	Mass change/%	within ±0.8	JTG E20 T0610
	Penetration retention/%	≥61	
	Ductility (25℃)/cm	≥40	

3.2 Test Methods for Viscoelastic Properties

Viscoelastic properties were evaluated using dynamic modulus tests at multiple temperatures, together with high-temperature creep and relaxation tests. The dynamic modulus test characterizes the frequency-domain behavior of materials under different temperatures and loading frequencies, whereas the creep and relaxation tests supplement the time-dependent viscous and relaxation characteristics.

(1) Dynamic modulus tests were conducted in a temperature-controlled chamber at 20℃, 30℃, 40℃, 50℃, 60℃, and 70℃. Loading frequencies were set to 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, and 10 Hz. Axial sinusoidal loading was applied, with the stress level controlled within the linear viscoelastic range of the material. During testing, complete stress–strain time histories were recorded, from which the dynamic modulus E*, phase angle δ, storage modulus E′, and loss modulus E″ were calculated to describe the

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stiffness, viscous energy dissipation, and elastic energy storage of asphalt mixtures at different temperatures.

(2) Creep tests were performed under uniaxial static loading at temperatures of 40℃, 50 ℃, and 60 ℃. A constant stress was applied during the loading stage for 100~300 s, followed by unloading and recording of residual strain during the recovery stage. The resulting creep curves reflect the tendency for viscous flow and the potential for deformation accumulation. Relaxation tests were conducted under constant strain conditions, and the decay of stress over time was recorded to obtain the relaxation response, from which the maximum relaxation stress and relaxation time parameters were determined.

3.3 Experimental Method for Monitoring High-Temperature Pavement Deformation

A laboratory rutting test system was employed to simulate the deformation behavior of asphalt pavements under repeated traffic loading in high-temperature environments. The loading device used a solid rubber wheel, with the contact pressure controlled at 0.7 MPa by an air pressure system. The wheel moved reciprocally at a frequency of 42 passes per minute. Tests were conducted in an enclosed temperature-controlled chamber at 40 ℃, 50 ℃, and 60 ℃. Loading commenced after the internal temperature of the specimens had become uniform and remained stable for 2 h. The number of load applications was set to 5040, following the principle of simulating cumulative traffic loading, to capture the full deformation development process.

To obtain the internal deformation distribution within the pavement structure, fiber Bragg grating (FBG) sensors were embedded in each structural layer during specimen fabrication. The sensors were placed at depths of 30 mm, 55 mm, 80 mm, and 105 mm below the pavement surface. Each sensor was encapsulated in a polypropylene sleeve and fixed using epoxy adhesive to ensure coordinated deformation with the surrounding asphalt mixture while minimizing disturbance to the structural continuity. Prior to embedding, all sensors underwent rigorous bending and temperature calibration, with linear correlation coefficients between wavelength shift and strain exceeding 0.99.

4. Evolution of Asphalt Viscoelastic Properties under High-Temperature Conditions

4.1 Temperature Dependence of Dynamic Modulus and Phase Angle

The dynamic complex modulus $|E^*|$ and phase angle δ of asphalt mixtures exhibit pronounced temperature dependence in the high-temperature range. Test results show that the $|E^*|$ of LSAM-50 decreases from approximately 15 000 MPa to about 1 200 MPa as temperature increases from 20 ℃ to 60 ℃. The modulus remains relatively high at low temperatures, enters a rapid decay stage in the intermediate temperature range, and gradually stabilizes at a low level dominated by the aggregate skeleton at high temperatures. The reduction trend of the storage modulus E' is generally consistent with that of $|E^*|$, indicating a rapid loss of elastic energy storage capacity at elevated temperatures [4].

The loss modulus E'' and phase angle δ reach their peak values in the intermediate temperature range. The phase angle increases from approximately 10 ° to about 35 °, indicating an enhanced dominance of viscous energy dissipation. When the temperature further rises above 45 ℃, the increase in δ slows and E'' begins to decrease.

4.2 Analysis of High-Temperature Creep and Relaxation Characteristics

Under conditions of 0.7 MPa and 60 ℃, the creep curve of the asphalt mixture consists of three components: instantaneous elastic deformation, delayed deformation, and viscous flow. Compared with that at 20 ℃, the instantaneous deformation increases by more than three times, indicating a substantial reduction in initial stiffness. The slope of the delayed deformation stage increases markedly with temperature, and at 60 ℃ the viscous flow component accounts for more than 80% of the total deformation. After unloading, only a limited proportion of delayed strain is recoverable, and the overall deformation is dominated by permanent deformation.

Stress relaxation curves further demonstrate the difficulty of maintaining internal stress at high temperatures. Under constant strain, the stress decay rate at 60 ℃ is significantly higher than that at low and intermediate temperatures, with a pronounced reduction in residual stress level. Within the same relaxation time, the residual stress at high temperature is only about 20% of that at 30 ℃, indicating a substantial decrease in stress retention capacity and a greater tendency for the structure to enter a stage

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of plastic deformation accumulation.

4.3 Viscoelastic Master Curves and High-Temperature Equivalent Regimes

Based on the time–temperature superposition principle, viscoelastic parameters measured at different temperatures were shifted to a reference temperature of 20 ℃ to construct a dynamic modulus master curve covering a wide frequency range [5]. High-temperature conditions correspond to the low-frequency end of the master curve, where the slope becomes relatively gentle, indicating that the mechanical response of the material is markedly less sensitive to changes in loading rate at elevated temperatures.

Two key indicators can be extracted from the master curve to quantify high-temperature performance. The first is the low-frequency plateau modulus, defined as the asymptotic value of the dynamic modulus as the reduced frequency approaches zero. This parameter characterizes the ultimate deformation resistance of the material under near-static loading conditions, and its attenuation is directly associated with the development of pavement rut depth. The second indicator is the characteristic relaxation time, obtained by fitting the master curve using a generalized Maxwell model.

5. Effects of High-Temperature Viscoelastic Properties on Internal Pavement Deformation

5.1 Accumulated Deformation Characteristics of Structural Layers under High-Temperature Conditions

From the pavement surface downward, the magnitude of accumulated deformation decreases progressively across layers. However, the influence of temperature on deformation development differs markedly among the structural layers, as summarized in Table 2.

Tab. 2 Accumulated deformation and temperature sensitivity of different structural layers under high-temperature conditions

Structural layer	Deformation (mm)				Deformation increase (%)
	50℃	55℃	60℃	65℃	
Surface layer	0.70	0.72	0.75	0.85	21.4
Intermediate layer	0.55	0.57	0.60	0.71	29.1
Bottom layer	0.28	0.34	0.38	0.48	71.4

As shown in Table 2, for the same number of load applications, the accumulated deformation in all layers increases with temperature, while the magnitude of increase exhibits pronounced layer-dependent differences. The surface layer shows a relatively moderate increase in deformation, which can be attributed to its strong three-dimensional confinement and a deformation mechanism dominated by compaction. The intermediate layer exhibits a more evident increase in deformation, consistent with its mechanical state under high temperatures, where the dynamic modulus decreases most markedly and the layer is subjected to relatively high shear stresses.

5.2 Relationship between Viscoelastic Parameters and Internal Deformation

By correlating viscoelastic parameters, such as the dynamic modulus $|E^*|$ and phase angle δ, with the accumulated deformation of each layer, the direct influence of viscoelastic degradation on structural deformation becomes evident. Taking the AC-16 mixture in the intermediate layer as an example, its viscoelastic parameters and corresponding accumulated deformation at different temperatures are summarized in Table 3.

Tab.3 High-temperature viscoelastic parameters and accumulated deformation of the AC-16 mixture in the intermediate layer

Temperature/℃	Dynamic modulus|E*|(MPa)	Phase angle δ (°)	Accumulated deformation S (mm)
50	1520	28.5	0.55
55	780	32.8	0.57
60	450	35.2	0.60
65	260	33.1	0.71

Under 60 ℃, the dynamic modulus of the AC-16 mixture in the intermediate layer decreases by approximately 70% compared with that at 50 ℃. Correspondingly, the accumulated deformation of the

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intermediate layer increases from 0.55 mm to 0.60 mm, representing an increase of about 9%. This indicates that, under the same loading conditions, the proportion of recoverable strain is reduced and internal stresses can no longer be maintained in a stable distribution, causing a larger fraction of deformation to manifest as irrecoverable components.

5.3 Rutting Formation Mechanism Governed by High-Temperature Viscoelastic Properties

Surface rut depth represents the sum of vertical accumulated deformation across all structural layers. Rut depths measured in the test section at 50 ℃, 55 ℃, 60 ℃, and 65 ℃ are 0.85 cm, 0.88 cm, 0.93 cm, and 1.05 cm, respectively. By analyzing the proportional relationship between interlayer deformation differences and total rut depth, the contribution rates of individual structural layers can be quantified.

This variation highlights the strong temperature dependence of the rutting formation mechanism. Within the temperature range of 50~60 ℃, the intermediate layer becomes the critical zone governing shear deformation development, as it experiences the most pronounced reduction in modulus while simultaneously sustaining the highest shear stresses. Consequently, rutting formation is primarily controlled by the intermediate layer in this temperature interval. When the temperature further increases to 65 ℃, the viscosity of the asphalt binder in the intermediate layer decreases sharply, resulting in insufficient shear resistance and a deformation response that approaches that of a viscous fluid.

6. Conclusions

This study investigated the influence of asphalt viscoelastic properties on pavement deformation under high-temperature conditions through a combination of dynamic modulus tests at multiple temperatures, as well as creep and relaxation experiments. A dynamic modulus master curve was constructed, revealing that in the high-temperature range, the dynamic modulus of asphalt mixtures decreases substantially, while the phase angle and loss modulus reach peak values in the intermediate temperature range and subsequently transition to aggregate skeleton–controlled behavior at extremely high temperatures.

By integrating laboratory rutting tests with fiber Bragg grating–based layered monitoring, the accumulated deformation characteristics and rutting contribution rates of the surface, intermediate, and bottom layers at different temperatures were clarified. Elevated temperatures, particularly extreme high-temperature conditions, significantly increase the participation of the intermediate and bottom layers in deformation, driving rutting evolution from surface-dominated behavior toward coordinated deformation involving deeper structural layers. The results demonstrate that temperature-induced viscoelastic degradation amplifies permanent pavement deformation through two coupled pathways: a reduction in elastic stiffness and an enhancement of viscous flow.

References

[1] Jiang, Y., Yi, Y., Tian, T., et al. Viscoelastic properties of large-stone asphalt mixtures and their temperature dependence. Journal of Building Materials, 2024, 27(4): 327–331, 342.
[2] Wang, L. Evaluation of Asphalt Fatigue Failure and Viscoelastic–Plastic Damage Modeling. PhD Dissertation, Dalian Maritime University, Dalian, 2024.
[3] Wang, J., Zeng, Q., Gui, K., et al. Preparation of high-viscosity asphalt for porous pavement and its high-temperature rheological properties. Shanxi Architecture, 2024, 50(11): 116–119.
[4] Xu, X. Analysis of high-temperature creep characteristics of PVA fiber asphalt pavement. Heilongjiang Transportation Science & Technology, 2024, 47(8): 64–68, 73.
[5] Li, L. Damage Characteristics of Crumb Rubber–SBS Composite Modified Asphalt and Mixtures Based on Viscoelastic Mechanics. PhD Dissertation, Jilin University, Changchun, 2023.