DOI: 10.2478/sspjce-2025-0015

Fatigue Behavior of Bitumen-bound Materials in Nonstandard Temperature Conditions

Tomáš Olexa[1*], Ján Mandula[1], Brigita Salaiová[1]

[1]Civil Engineering Faculty, Institute of Structural Engineering, Technical University of Košice, Slovakia
*e-mail: tomas.olexa@tuke.sk

Abstract

The thermal sensitivity of bitumen-bound materials is a well-documented phenomenon. Variations in temperature significantly alter the mechanical response of asphalt mixtures, transitioning their behavior from predominantly elastic to viscous, and affecting parameters such as complex modulus, phase angle, and other rheological characteristics. This investigation evaluates the influence of elevated and reduced temperatures on the fatigue performance of an asphalt mixture intended for road surface layers. Experimental assessments were conducted using the four-point bending test on an asphalt concrete with a nominal maximum aggregate size of 11 mm, incorporating polymer-modified bitumen. The high-temperature condition was set at 27 °C, in accordance with the Slovak pavement design methodology, while the low-temperature condition was defined at 5 °C, constrained by the operational limits of the testing apparatus. Standard fatigue testing temperatures, as stipulated by European specifications, include 10 °C, 15 °C, and 20 °C. Material structural evolution under cyclic loading was analyzed via energy dissipation calculations per loading cycle. The primary objective of this study was to characterize the mechanical response of the asphalt mixture under non-standard thermal conditions.

Keywords: bitumen-bound materials, fatigue, nonstandard temperature, thermal sensitivity

1 Introduction

Asphalt mixtures, serving as fundamental materials in pavement construction, are characterized by specific deformation properties that are adversely affected by temperature fluctuations. This thermal susceptibility is a critical factor contributing to the reduced service life of road surfaces. Elevated temperatures induce a transition in the behavior of bitumen-bound composites from elastic to viscous, thereby classifying asphalt mixtures as viscoelastic materials. Under sinusoidal cyclic loading, a viscoelastic asphalt mixture eventually reaches a steady-state response, wherein the induced strain mirrors the applied stress in frequency but exhibits a phase lag (φ), indicative of energy dissipation and internal structural rearrangement. Consequently, the linear viscoelastic behavior of such materials is confined to defined temperature and loading regimes.

The impact of extreme thermal conditions on the mechanical integrity of bituminous materials remains a pertinent subject in contemporary research. Numerous studies have addressed the role of temperature in permanent deformation mechanisms within asphalt layers [1,2], while a limited number have explored the fatigue resistance of these materials under elevated thermal exposure [3]. The present study aims to elucidate the fatigue characteristics and structural transformations of a specific asphalt mixture subjected to temperatures of 5 °C and 27 °C, which deviate from the conventional testing range of 10 °C to 20 °C as prescribed by European standards. The selected temperatures were determined based on representative annual conditions in Slovakia for summer and winter periods. The winter condition was set at 0 °C; however, the long-term testing apparatus cannot sustain continuous operation at this temperature. Therefore, a temperature of 5 °C was adopted to ensure operational reliability and safety. Considering the material requirements for the number of samples needed to determine fatigue parameters at a specific temperature, this study employed only two temperature conditions. In this case, no comparison was made with analytical models, nor was any consideration given to frequency effects.

2 Materials, methods and experimental conditions

The test material was an asphalt concrete (AC 11), commonly used in Slovak road construction for surface and binder layers. The mixture featured a continuously graded aggregate structure with a maximum particle size of 11 mm and was bound using a polymer-modified bitumen (PMB 25/55-65) enhanced with an adhesion-promoting additive. Prior to fatigue testing, the mixture underwent standard empirical characterization in accordance with type testing procedures for asphalt materials. The corresponding results are presented below (Table 1).

Table 1: Empirical material parameters

Material parameter	Unit	Limit value	Measured value	Standard
Binder content (B)	%	5.4 >	5.8	STN EN 12697-8
Air void content (V_m)	%	2.5 ~ 4	3.4	STN EN 12697-8
Void content filled with bitumen (VFB)	%	70 >	80.1	STN EN 12697-8
Indirect tensile strength ratio (ITSR)	%	80 >	98	STN EN 12697-12
Wheel tracking slope (WTS_{AIR})	mm/10^3cycles	< 0.07	0.04	STN EN 12697-22
Proportional rut depth (PRD_{AIR})	%	< 5.0	3.7	STN EN 12697-22

The testing shows that this material is suitable for pavement construction for use on heavily loaded road sections as well. Differences between the measured values and the limit values were minimal. These values support the assumption that the fatigue performance of the mixture is expected to perform adequately under unconventional temperature conditions.

Fatigue performance was evaluated using the four-point bending test on prismatic beam specimens, in accordance with European testing standards. Specimens measured 400 × 50 × 50 mm, were mounted in a four-point configuration, with outer supports allowing

rotational freedom and inner supports applying sinusoidal loading in the vertical direction. To regulate the temperature during the test, a temperature chamber is used, capable of maintaining the ambient temperature within a range from −15 °C to +60 °C, with a temperature fluctuation of ±1 °C. Air circulates inside the chamber to ensure a constant temperature throughout its interior. However, the four-point bending apparatus itself can operate continuously only at a minimum temperature of 5 °C. At each load level under a specific temperature condition, a homogeneous set of five specimens was tested. For every sample set, the standard deviation, the correlation coefficient, and the remaining service life were computed.
The material fatigue lifespan was observed at a constant frequency of 10 Hz. In this study the fatigue parameters of the asphalt mixture were observed at high and low temperatures as a simulation of summer and winter temperature conditions. The used temperatures 5 °C and 27 °C should impact the visco-elastic behavior of asphalt mixture from mostly elastic to almost viscous state.
Fatigue parameters were evaluated by two different fatigue failure criteria, which are described below. The primary reason for applying both criteria was to monitor of structural changes (micro-cracks) in tested samples.

3 Applied fatigue failure criteria

Fatigue failure criteria are essential for delineating the damage evolution within asphalt mixtures and for accurately predicting their service life. An effective criterion should reliably identify the onset of macro-cracking in the material structure [4].
The conventional fatigue failure criterion is based on the relationship between tensile strain and the number of load repetitions until failure. Typically, failure is defined as a 50% reduction in the initial stiffness modulus (So), a threshold widely accepted in constant strain mode testing. This approach, originally proposed by Van Dijk and Visser (1977), has been adopted by researchers such as Tayebali and Abojaradeh, and later formalized by AASHTO as a provisional standard. It is also incorporated into current European testing protocols. Despite its widespread use, this criterion is inherently arbitrary and may not accurately reflect the true fatigue failure point. For instance, Rowe demonstrated that stiffness values below 50% of the initial modulus can occur without visible macro-cracking, indicating potential discrepancies in failure identification. Nevertheless, this criterion (1) remains prevalent due to its simplicity and practical reliability.

$$Failure \quad po\,int : \frac{S_i}{S_0} \leq 0.5 \tag{1}$$

To gain deeper insight into fatigue behavior, an alternative criterion based on dissipated energy analysis was employed. Dissipated energy represents the energy lost per loading cycle due to internal friction, heat generation, and microstructural damage. This method is typically applied in flexural fatigue tests under either controlled stress or strain conditions. For each cycle, strain (ε_i), stiffness (S_i), and phase angle (φ) are recorded, allowing calculation of dissipated energy (DE_i) using Equation 2.

$$DE_i = \pi . \varepsilon_i^2 . S_i . sin\varphi \tag{2}$$

Among various energy-based criteria, the Ghuzlan & Carpenter method was selected for this study. Ghuzlan and Carpenter proposed a method that shows the similarity between the two types of loading, constant strain and constant stress (Figure 1). A new failure criterion was defined as the change in dissipated energy between cycles i and i_{+1} (or ΔDE_i) divided by the dissipated energy of a load cycle i (or DE_i). This change was calculated approximately every 100 load cycles. A defined energy ratio ($\Delta DE/DE$) plotted versus load cycles gives a curve that decreases rapidly during the first number of cycles, then stays constant for a large number of cycles and then increases rapidly at the end. This trend was the same for both constant stress and constant strain tests. The failure point (N_f) is defined as the number of load cycles at which the change in the energy ratio begins to increase rapidly. It was found that under the same load control, the location of the 50 percent reduction in initial stiffness varied considerably from test to test. Also, for the same initial conditions, but different load controls, it was found that the location of the 50 percent reduction in initial stiffness is not the same. It was also concluded that the change in dissipated energy ratio represents typical material behaviors and shows the point at which damage accumulation in the mixture has produced an inability of the mix to resist further damage independent of the mode of loading. It was concluded that the change in dissipated energy between two load cycles provides a more fundamentally correct indication of damage being done by one load cycle to the next one than does cumulative dissipated energy. This approach, however, has some limitations in such a way that the failure point cannot be accurately located and may differ from one operator to another. It is also not practical to have the values of energy damage accumulation ratio every 100 cycles, especially for long-life specimens. The energy ratio method provides a more fundamental representation of damage progression, although its practical application is constrained by the need for frequent data sampling and potential operator variability [5].

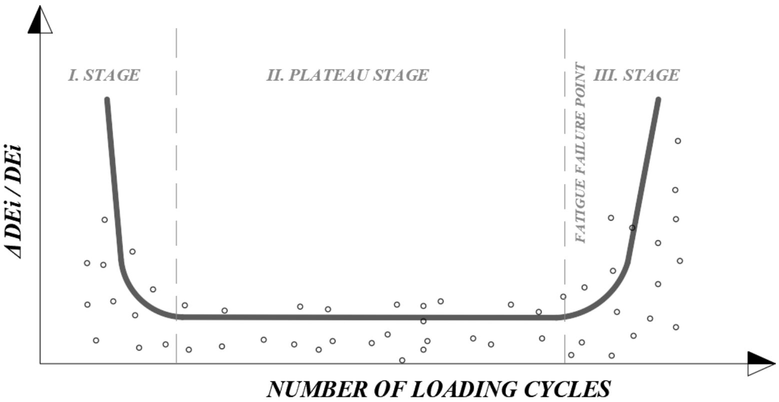

Figure 1: Evaluation of fatigue lifespan using Ghuzlan & Carpenter dissipated energy method

4 Results and evaluation of results

Fatigue resistance of the asphalt mixture was assessed through cyclic loading tests, during which phase angle, stiffness, and dissipated energy were continuously monitored. Tests were conducted at constant temperatures of 27 °C and 5 °C, each under three distinct strain levels. The viscoelastic nature of the material was evident through energy dissipation during loading and unloading cycles. In purely elastic materials, applied energy is stored and fully recovered upon unloading, resulting in coinciding loading and unloading curves. In contrast, viscoelastic materials exhibit a hysteresis loop due to phase lag between stress and strain, indicating energy loss through mechanical work, heat, or damage. The area enclosed by the hysteresis loop quantifies the dissipated energy per cycle. Figure 2 illustrates the difference in hysteresis behavior between initial and final loading cycles at both test temperatures.

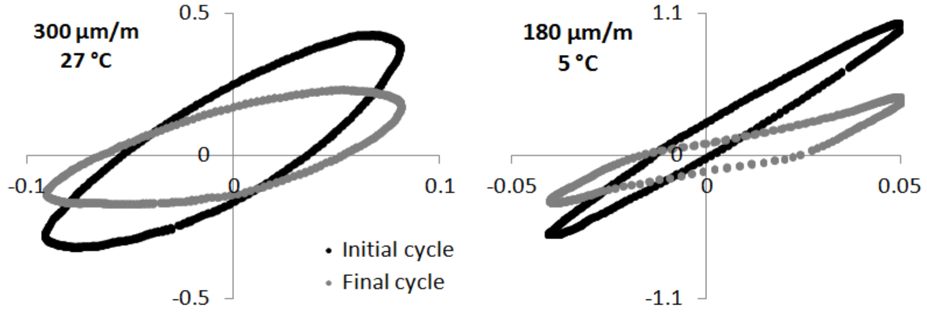

Figure 2: Hysteresis loop of initial and final cycle for both observed temperatures

Fatigue data were first evaluated using the dissipated energy criterion. Figures 3 and 4 present the progression of the energy ratio over load cycles. At 27 °C, the energy ratio curve remained stable in the final phase, suggesting no significant structural degradation per the Ghuzlan & Carpenter method. Conversely, at 5 °C, a distinct failure point was observed in all specimens, with a continuous increase in the energy ratio, indicating fatigue damage accumulation.

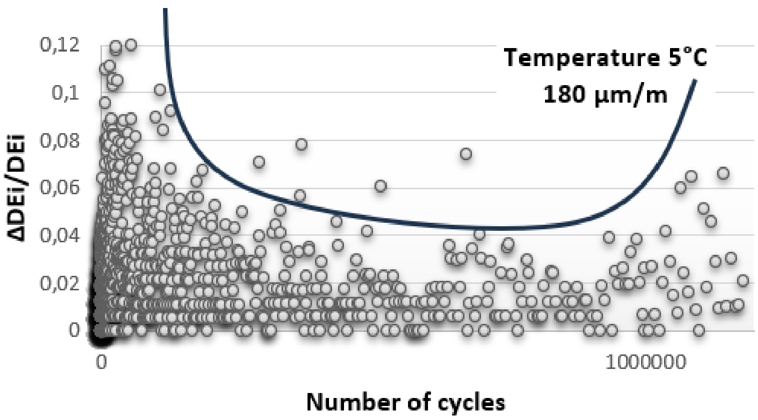

Figure 3: Plot of the energy ratio and number of cycles for temperature 5 °C

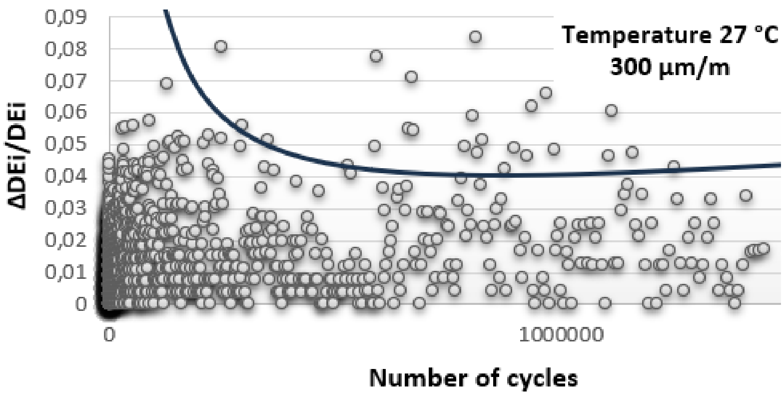

Figure 4: Plot of the energy ratio and number of cycles for temperature 27 °C

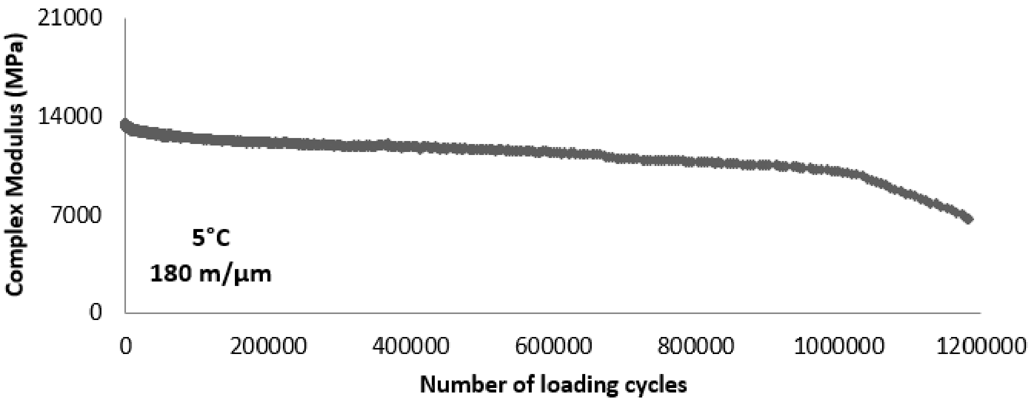

Figure 5: Plot of the complex modulus reduction and number of loading cycles (5 °C)

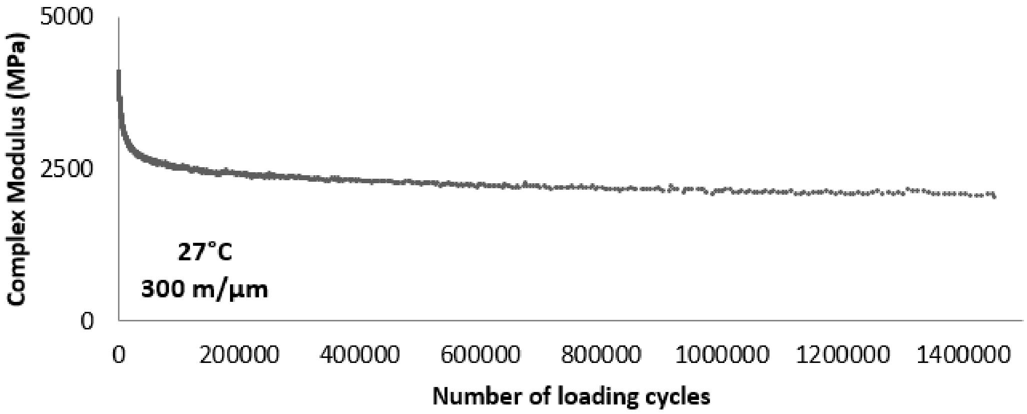

Figure 6: Plot of the complex modulus reduction and number of loading cycles (27 °C)

The same dataset was also analyzed using the conventional AASHTO criterion. Figures 5 and 6 show the reduction in complex modulus over time for both temperature conditions. The results confirm that the mixture maintains adequate fatigue resistance even under non-standard thermal conditions, supporting its suitability for use in heavily trafficked pavement sections. The table of fatigue test results is presented below (Table 2).

Table 2: Results of fatigue test

Temperature (°C)	Initial stiffness 10 Hz (MPa)	Strain level (µm/m)	Lifespan (AASHTO)	Lifespan (Ghuzlan Carpenter)
5 °C	12 600	180	313610	224446
		170	737395	612508
		160	1237909	929442
27 °C	5000	340	171341	-
		300	211230	-
		260	1613190	-

The test temperature of 27 °C notably influenced the progression of complex modulus degradation during fatigue testing. Unlike the classical fatigue curve, the third phase—typically associated with rapid stiffness loss prior to failure—was absent. The initial phase constituted approximately 10% of the specimen's total fatigue life, during which the complex modulus decreased to roughly 65% of its original value. The second phase accounted for the remaining 90% of the fatigue life, characterized by a gradual decline in stiffness. The overall trend of modulus reduction at 27 °C resembled a semi-logarithmic function.

In contrast, fatigue behavior at 5 °C adhered to the conventional three-phase model of asphalt mixture fatigue. The first phase exhibited a steep reduction in stiffness, followed by a second phase with nearly constant modulus or minimal decline. The third phase involved a renewed steep reduction leading to failure. AASHTO criterion was applicable for both of observed temperatures despite the different curves of complex modulus reduction.

5 Conclusion

This study investigated the influence of non-standard temperature conditions on the fatigue performance of an asphalt mixture used in surface layers of Slovak road infrastructure.

The temperature conditions in Slovakia exhibit significant seasonal variations. At higher temperatures, as demonstrated by the measurement results, fatigue cracks tend to occur only after a greater number of loading cycles. However, under these conditions, where partial healing of fatigue cracks may even occur large permanent deformations develop. Conversely, lower temperatures throughout the year limit the formation of permanent deformations, but the asphalt pavement material becomes brittle, leading to the initiation of fatigue cracks after a smaller number of loading cycles.

The fatigue failure point, as determined by the Ghuzlan & Carpenter energy-based criterion, was not consistently identifiable across all strain levels at 27 °C, whereas it was clearly observed at 5 °C. The energy ratio progression served as a key indicator of internal structural changes, enabling comparative analysis between the two temperature regimes.

The conventional AASHTO criterion, based on a 50% reduction in complex modulus, was successfully applied at both temperatures. However, the fatigue life curve at 27 °C lacked the final degradation phase, with failure occurring at the end of the second phase. Notably, the modulus had already decreased to 65% of its initial value during the first phase, indicating significant early damage. At 5 °C, the modulus degradation followed the classical three-phase pattern, with each phase occupying a comparable portion of the fatigue life.

From a fatigue resistance perspective, elevated temperature (27 °C) appeared to extend the overall fatigue life of the asphalt mixture. Nevertheless, it is important to consider that only a small fraction (approximately 10%) of the fatigue life was spent with the modulus above 65% of its initial value, suggesting early onset of structural softening.
Based on results pavement design should not rely solely on standard testing temperatures (10–20 °C) because real-world conditions often deviate significantly. Material selection and layer thickness must consider seasonal extremes to balance resistance to rutting at high temperatures and cracking at low temperatures. Incorporating temperature-dependent fatigue models or performance-based specifications can improve prediction accuracy and extend pavement service life.

References

[1] Al-Mosawe, H. (2016). *Prediction of permanent deformation in asphalt mixtures*. University of Nottingham: Department of Civil Engineering.

[2] Remišová, E. & Zatkalíková, V. (2016). Evaluation of bituminous binder in relation to resistance to permanent deformation. *Procedia Engineering 153 on XXV Polish-Russian-Slovak Seminar "Theoretical Foundation of Civil Engineering"*(pp. 584-589). Žilina: Elsevier.

[3] Chen, J., Wang, H., Li, M. & Li L. (2016). Evaluation of pavement responses and performance with thermal modified asphalt mixture. *Materials and Design. Volume* (111), (pp. 88-97). https://doi.org/10.1016/j.matdes.2016.08.085.

[4] Zhang, J., Saburi, M., Guddati, M. N. & Kim, R. (2013). Development of a failure criterion for asphalt mixtures under fatigue loading. *Road Materials and Pavement Design Volume (14),* (pp. 1-15). http://dx.doi.org/10.1080/14680629.2013.812843.

[5] Abojaradeh, M. (2013). Development of fatigue failure criterion for hot-mix asphalt based on dissipated energy and stiffness ratio. *Jordan Journal of Civil Engineering, Volume 7, No. 1*, (pp. 54-69).

[6] Zheng et al. (2024). Measurement and characterization of asphalt fatigue behavior under multi-factor effects. *Materials and Structures. Volume (57),* (article number 193). https://link.springer.com/article/10.1617/s11527-024-02473-0

[7] Liu et al. (2025). Mechanical Response and Fatigue Life Analysis of Asphalt Pavements Under Temperature-Load Coupling Conditions. *Applied Sciences, Volume 15, Issue 13*, https://www.mdpi.com/2076-3417/15/13/7441