

A Review of Fatigue Cracking in Asphalt Mixtures: Mechanism, Influencing Factors, Testing, and Mitigation Methods

Una revisión del agrietamiento por fatiga en mezclas asfálticas: Mecanismo, factores que influyen, pruebas y métodos de mitigación

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Abstract

Effectively preventing early failure and assessing the impact of new materials and technologies on cracking performance depend on a thorough understanding of the mechanics behind pavement cracking. One of the most common distresses on asphalt pavements is fatigue cracking. Tensile stress owing to repetitive traffic loads produces increasing damage every day. Two types of fatigue fractures happen in asphalt pavement. Top-down cracks lead to penetrating water and dust; therefore, potholes will occur, leading to an uneven pavement surface and rider discomfort. Bottom-up fatigue cracks lead to pavement structure degradation. This paper presents a review of fatigue crack propagation mechanisms, the elements that affect and hasten their development, and evaluation by small-scale laboratory and large-scale on-site experiments. A literary review of prior experiments that involved the use of asphalt modifiers, fibers, and geosynthetics for the objective of strengthening asphalt mixes to minimize or restrict the formation of fatigue fractures and lengthen the lifespan of the asphalt pavement. It found that fatigue cracks are unavoidable owing to the exposure of asphalt pavement to repetitive loads and harsh ambient environmental conditions. Laboratory tests done on asphalt mixes are used solely to compare asphalt mixtures with one another because there are no specific or critical values for test results approved by American and European norms. However, considering the astounding pace at which technology is evolving, this may have a promising future.

Keywords: Asphalt mixtures; Fatigue endurance; Fatigue life; Bottom-Top crack; Pavement performance; Asphalt stiffness.

Resumen

Prevenir eficazmente el fallo prematuro y evaluar el impacto de nuevos materiales y tecnologías en el rendimiento frente a grietas depende de una comprensión profunda de la mecánica detrás del agrietamiento del pavimento. Uno de los deterioros más comunes en los pavimentos de asfalto es la fisuración por fatiga. El esfuerzo de tracción debido a las cargas repetitivas del tráfico produce un daño creciente cada día. Dos tipos de fracturas por fatiga ocurren en el pavimento de asfalto. Por un lado, las grietas de arriba hacia abajo, estas permiten la penetración de agua y polvo, y por lo tanto, la formación de baches; lo que genera una superficie de pavimento irregular e incomodidad para los conductores. Por otro lado, las grietas por fatiga que se originan desde abajo conducen a la degradación de la estructura del pavimento. Este artículo presenta una revisión de los mecanismos de propagación de grietas por fatiga, los elementos que afectan y aceleran su desarrollo, y la evaluación mediante experimentos de laboratorio a pequeña escala y pruebas in situ a gran escala. Una revisión bibliográfica de experimentos previos que involucraron el uso de modificadores de asfalto, fibras y geosintéticos con el objetivo de fortalecer las mezclas de asfalto para minimizar o limitar la formación de fracturas por fatiga y alargar la vida útil del pavimento de asfalto. Se encontró que las grietas por fatiga son inevitables debido a la exposición del pavimento de asfalto a cargas repetitivas y a condiciones ambientales adversas. Las pruebas de laboratorio realizadas en mezclas de asfalto se utilizan únicamente para comparar unas mezclas de asfalto con otras, ya que no existen valores específicos o críticos para los resultados de las pruebas aprobados por las normas estadounidenses y europeas. Sin embargo, considerando el asombroso ritmo al que evoluciona la tecnología, esto puede tener un futuro prometedor.

Keywords: Mezclas de asfalto; Resistencia a la fatiga; Vida útil a la fatiga; Grieta de abajo hacia arriba; Rendimiento del pavimento; Rigidez del asfalto.

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1. Introduction

Asphalt mixtures are the predominant substance used in pavement construction; they consist of an aggregate skeleton and asphalt binder, known as flexible pavements (Albayati & Ismael, 2024a; Song et al., 2024; H. Yang et al., 2024). Asphalt mixes are produced as hot, warm, and cold mixtures that are applied to construct the pavement layers (Liu et al., 2024). Considering the escalating population development and the pressing necessity to construct new roads, the demand for the industry has surged due to the accessibility of raw materials and the relative simplicity of manufacture and implementation in the field compared to rigid pavement (Albayati & Ismael, 2024b; Shen & Wang, 2024; Songqiang et al., 2024). In general, asphalt pavement comprises several layers of different thicknesses and properties; it is referred to as bound materials or bound layers (wearing or surface, binder, and base) supported by unbound layers referred to as subbase and subgrade (Jamieson et al., 2024; Kumar et al., 2025; Marik et al., 2024). Asphalt pavement offers beneficial features that make it attractive for use on roadways, including load resistance, free dust, riding comfort, abrasion resistance, and smooth surface (low noise) (Albayati & Ismael, 2025; Neupert et al., 2024; Vila et al., 2021).

Due to exposure to heavy traffic and severe weather, asphalt pavement develops numerous flaws that shorten its lifespan and compromise the safety of drivers (Amani et al., 2024; Omranian et al., 2024). As a result, the road loses its intended function and requires significant financial resources to be repaired. Asphalt pavement is frequently exposed over the service life to temperatures varying from high, moderate, and low (de Melo et al., 2019; Sadeghi & Goli, 2024; Swarna & Hossain, 2022; Vila et al., 2021).

The stiffness of asphalt pavement (a measure of resistance) varies with temperature. As a result, the permanent deformation growing at high temperatures is referred to as rutting and shoving, while at moderate temperatures, fatigue cracking develops, and at low temperatures, thermal cracks exceeding (Huang et al., 2025; A.-U.-R. Khan et al., 2024). Over time, following the opening of the newly constructed road to traffic, it gradually deteriorates due to several factors, including traffic load, weather conditions, solar radiation, and others (Adnan & Wang, 2024; Q. Yang et al., 2024). These aspects make asphalt pavements lose their functional and structural quality. This is commonly attributable to the deterioration of the worn-out pavement constituent materials (Gul & Alwi, 2024).

The deterioration or distress in asphalt pavements can be categorized into four basic distresses: cracking, distortion, disintegration, and loss of skid resistance. Cracks develop on the asphalt pavement surface in either hairline or branching line patterns (Meng et al., 2024; Ren et al., 2024; Zokaei & Hesami, 2024). Fatigue cracking typically happens at intermediate temperatures because asphalt mixtures are more brittle than at high temperatures, while low thermal cracking tends to develop at low temperatures (Haimei et al., 2024; H. Li et al., 2024; Xiao et al., 2024). Cracks are one of the structural and functional performance criteria that are used to ensure asphalt pavement satisfies good performance during service life, such as the international roughness index and serviceability index (Azarhoosh et al., 2024; Mohammed & Abed, 2024; Zhuang et al., 2024). Premature pavement failure from cracking reduces ride quality and increases the risk of traffic accidents (C. Li et al., 2024; Shafabakhsh et al., 2024). Additionally, cracks allow water and harmful substances to enter, hastening the formation of other pavement distresses such as potholes and base/subbase material deterioration (A. R. Khan et al., 2024).

The characteristics of asphalt mixture design that influence cracking performance are typically not specified. Recent advancements in laboratory testing to describe fracture characteristics of asphalt concrete mixtures, however, offer promising paths toward the creation of performance-based requirements to deal with pavement cracking. Therefore, this paper provides a general concept of cracking, the factors that affect the occurrence, the laboratory test methods for evaluation, and methods of mitigation.

The main objective of this paper review is to provide a comprehensive understanding of fatigue cracking in asphalt mixtures. The specific objectives of this study are as follows:

- To present the fundamental mechanisms of fatigue crack initiation and propagation in asphalt pavements.
- To identify and discuss the key internal and external factors influencing fatigue cracking behavior.
- To review and compare laboratory testing methods and field evaluation techniques used to assess fatigue performance.
- To examine the effectiveness of different mitigation strategies, including asphalt binder modification, fiber reinforcement, and geosynthetics.
- To highlight current limitations in fatigue evaluation and suggest potential directions for future research and development.

The remainder of this paper is organized as follows. Section 2 presents the mechanisms of fatigue cracking and the main factors influencing its development. Section 3 reviews the laboratory and field testing methods used to evaluate fatigue performance. Section 4 discusses the main

mitigation and preventive approaches, including mixture design, binder modification, fiber reinforcement, and geosynthetics. Finally, Section 5 summarizes the main findings and conclusions of the study.

2. Mechanisms and Factors Influencing Fatigue Cracking

Fatigue, known as alligator or bottom-up cracking, is signified by branched and interwoven cracks that create polygonal blocks, like the texture of an alligator's skin. It occurs due to asphalt pavement subjected to cycling or repeated loads (Nikolaides, 2014). During each cycle of traffic loading, tensile strain occurs at the bottom of the asphalt concrete pavement. The quantity of tensile strain that is generated in pavements is based on applied load (Islam & Tarefder, 2020). According to a site investigation conducted by Pell & AASHO (1965), the tensile strain ranged from 30 to 200 microstrains and was induced by applied standard 8-tonne wheel loads. These cracks manifest as fatigue cracking, which is considered a main failure mode. Furthermore, the load-induced cracking theory claims that a few critical loads produce permanent damage, including cracks, but not in the early life of asphalt pavement (Xu, 2024).

However, one of the main factors influencing cracking performance may be changes in the mixture's characteristics over the pavement's life, which make the mixture stiffer, more brittle, and less able to heal. Therefore, fatigue damage is characterized by the reduction in flexibility of asphalt concrete pavement under cyclical loads. In terms of fatigue failure upon exposure to tension, bituminous mixtures undergo an evolution from the undamaged linear viscoelastic phase to the undamaged nonlinear viscoelastic phase, ultimately arriving at the damaged phase. The critical nonlinear viscoelastic point, referred to as the endurance limit for fatigue, delineates the boundary between the nonlinear viscoelastic phase and the damaged phase. In the linear viscoelastic phase, the stress-strain relationship remains constant; all of the energy generated by the mixture is recovered. In contrast, energy is lost or dissipated during the nonlinear phase. When the endurance limit is reached, the mixture's material characteristics begin to alter, the flexibility gradually decreases, and cracks start to appear (Huang & Di Benedetto, 2015).

The cracks originate as micro-compositional flaws in the binder called "bee structures" when air voids have been compressed during the compaction process. As the density increases due to applied stress, the "bee structures" combine with the remaining air voids to initiate cracks. This phase is known as the formative phase and ends when there is a maximum number of cracks present. Following, the larger cracks begin to merge with the smaller ones, which minimizes the overall number of cracks that are established in the prior phase. This phase is known as coalescent. The crack growth eventually moves into the unitary phase when the number of cracks has finally come together to form a single crack. The cracks may develop as cohesive or adhesive fractures. The thin binder films that cover the aggregates in a mixture are susceptible to adhesive fracture. Cracks develop along the interface between the aggregate and the binder in adhesive fracture. In the thicker films, cohesive fracture only happens inside the binder (Huang & Di Benedetto, 2015).

Several factors can be divided into two categories: internal factors related to the asphalt mixtures, including the chemistry of asphalt binder, its quantity, aggregate gradation, aggregate type, volumetric characteristics of the mixtures, and external factors such as traffic load, moisture, temperature, and aging, are known to affect the fatigue cracking resistance of asphalt mixtures.

The chemical constitution of the asphalt binder influences its mechanical performance. The breakdown of the adhesion bond between the aggregate and the asphalt binder is the cause of premature failure or poor performance of asphalt pavements. Polar components originating from the asphaltenes' heteroatoms have a crucial role in the adhesion bond between the asphalt binder and particles. Furthermore, at a lower temperature, the non-polar components (maltenes) will crystallize and become more brittle, making asphalt pavement prone to cracking (Speight, 2015). To ensure an adequate level of fatigue resistance in the asphalt mixture, a minimum quantity of bitumen plays a crucial role in this aspect. This minimum amount of bitumen enables greater binding of the aggregates, which promotes the overall resilience and lifetime of the pavement. Consequently, great consideration must be paid to the bitumen quantity throughout the mixture design process to obtain optimal performance under varied traffic circumstances. A study by Oliver (2011) demonstrated that where an increase in film thickness was induced by an increase in asphalt binder content, the increase in fatigue cracks occurred. The fatigue resistance of asphalt mixtures is greatly influenced by asphalt mastic, which is formed of mineral fillers and asphalt binders. If fillers are present, they might change how the asphalt binder is distributed at the mastic scale. This will then change the fatigue properties of the binder/filler composite. A study by Jiang et al. (2020) demonstrated that a thinner and more uniform binder film distribution is presented by asphalt mastic with higher filler contents and a finer filler size distribution. The bituminous mixture's fatigue resistance means its capacity to endure repeated bending without fracturing. The properties of the materials that make up the asphalt mixture have an important effect on their mechanical performance. Therefore, the aggregate gradation plays a major role in fatigue

resistance. A 20 mm gap gradation of stone matrix asphalt showed more fatigue resistance than a 20 mm wearing coarse dense grading asphalt tested at temperatures of 20 °C by indirect tensile fatigue test (Suo & Wong, 2009). Several thicknesses (50, 80, 100, 120, 140, 160, 180, and 210 mm) of dense and gap-graded stone matrix asphalt and Texas gap gradation were studied by Bharath et al (2021). Gap-graded mixes exhibited extended fatigue lifetimes relative to dense-graded mixes, attributable to their increased binder content. Larger asphalt binder proportions need to be added to mixtures that pass through or above the restricted zone of Superpave gradation; it seems to perform better in terms of fatigue than gradations that pass below the restricted zone (Sousa et al., 1998). An essential factor in guaranteeing longer pavement endurance is the impact of aggregate type on the fatigue behavior of asphalt mixtures. When assessing the fatigue behavior of aggregates of the same origin, the aggregate's texture and shape are crucial characteristics; also, it's crucial to consider the chemical makeup of aggregates of various origins in addition to their shape and structure (Valdes-Vidal et al., 2019). Because asphalt concrete is subjected to a range of temperatures throughout its service life, fatigue cracking happens over a temperature range rather than at one particular temperature (Moreno Navarro et al., 2018). Asphalt mixtures are often tested for fatigue resistance at temperatures of 10, 20, and 30 °C. At a temperature of 30 °C, some asphalt binders have low stiffness values; nevertheless, failure may be from plastic flow instead of fatigue cracking. At a temperature of 10 °C, some asphalt binder exhibits very high stiffness, which leads to loss of adhesion between the asphalt binder and aggregate. A temperature of 20 °C is more common for fatigue tests, which represents an adequate temperature for materials testing because it represents reality, as the average of temperatures most of the time during fatigue. Bitumen has average properties at 20 °C: it is neither brittle to break, nor soft to deform (Kuchiishi et al., 2019). The aging of the asphalt binder is largely responsible for the degradation of asphalt pavement during its in-service period. Asphalt aging was influenced by several factors: the asphalt's properties and composition; the distribution of aggregate and particle sizes; the mix's void content; and production-related variables like temperature and time. Asphalt binder aging is oxidative hardening, the formation of ketones and sulfoxides during the oxidation process (Speight, 2015). The aging mechanism is irreversible and is demonstrated by the binder's chemical changes, which affect the rheological characteristics, making the asphalt binder more brittle, which is subject to cracking under tensile stress. (Ziari et al., 2020) studied the aging effect on the fatigue behavior of asphalt mixtures. Two types of neat and styrene-butadiene-styrene (SBS) copolymer-modified asphalt binders, PG64-22 and PG58-22, were subjected to short-term aging by rolling thin film oven and long-term aging by pressure aging vessel. The study showed the negative impact of aging on fatigue resistance for both types of neat and modified asphalt. (Moreno Navarro et al., 2018) inferred from their research that the impact of asphalt mixture aging on fatigue resistance, noting a detrimental effect of aging. Because traffic loading causes stress and strain on the HMA pavement, it is evident that this causes fatigue cracking in asphalt pavements. Early fatigue cracking in the pavement is caused by heavier tire loads and higher traffic volumes. The thickness of the base and other layers of the pavement, as well as their modulus, have a major impact on the possible site of fatigue crack and the number of tensile strains. When moisture is present, asphalt mixtures weaken their durability, stiffness, and strength. Reduction of adhesion between aggregate and asphalt binder causes cracks to occur in asphalt pavement (Zhou et al., 2016).

There is another form of fatigue cracking called top-down fatigue cracks. It has garnered significant interest from pavement engineers and researchers. This cracking occurs at the asphalt pavement's surface and spreads downward through the asphalt layer. It typically develops both within and outside of the wheel path in a longitudinal and transverse orientation (Islam & Tarefder, 2020). This crack is generated due to the tensile strain generated on the asphalt surface by tire loads. Top-down cracking has no discernible impact on the pavement's structural strength. Over time, surface distresses like potholing are accelerated by moisture degradation and raveling, which also negatively affect the pavement's functional serviceability.

The growth of top-down cracking can be separated into three-phase periods. The early phase involves the formation of one or more short longitudinal cracks positioned beside the wheel path. During the second phase, with the continuance of repeated load, the current short longitudinal crack lengthens and expands, while additional cracks emerge parallel to the original crack. In the third phase, the transverse cracking appears and interconnects with the longitudinal cracking (Harmelink et al., 2008).

A variety of parameters related to top-down fatigue cracking, such as the material composition, binder type, binder content, aggregate gradation, binder-aggregate adhesion, and pavement structure, are related to layer thickness, so that an asphalt layer of less than 100 mm or more than 200 mm may experience top-down cracking, traffic (Lytton et al., 2013). The environment has a substantial impact, such as rainfall, solar radiation, and wind speed. Furthermore, the load of the wheel and its frequency (Zhou et al., 2016).

3. Testing and Evaluation Methods

3.1 Laboratory Testing

Fatigue is predicated on the concept that increasing cumulative damage from repeated wheel load applications results in pavement distress manifested as cracking in the wheel paths. When loading the asphalt specimen, one cannot observe the onset of cracking with the human eye (Nikolaides, 2014). Graphing the number of load applications and the consequent strain is the only way to identify it, as shown in Figure 5. Some researchers believe that the point of fatigue failure is where the curve's slope alters suddenly and significantly. The general Equation 1, which describes the fatigue life in terms of tensile strain. Any model that relies on a mathematical relationship derived from experiments is called an empirical model. These models do not explain the physical behavior of the material under repeated loads; rather, their outcome is an estimate of how long the pavement will last (calculate the number of cycles at failure). The mechanistic models link the mechanical properties of materials with their behavior under repeated loads. These models depend on the concepts of damage evolution, stress and strain, and dissipated energy.

$$Nf = k \times (1/\varepsilon)^n \quad (1)$$

Where:

Nf = No. of cycles

k, n = Parameters of the predictive equation

ε = Tensile strain at the centre of the specimen

A Hamburg wheel tracking test (HWTT) described by (AASHTO-T324, 2014) is a laboratory procedure available to assess the top-bottom fatigue empirical model in addition to rutting and moisture damage. Because surface cracks are sometimes seen alongside rutting in the field, wheel tracking investigations are used to assess top-down cracking. Usually, two adjacent gyratory compacted specimens or extracted from field cores are used. A 47 mm thickness of steel or rubber wheel that can be applied with a load of 705 N, moving across a dry or wet (inside water bath) sample for 20,000 cycles, or until 20 mm of vertical deformation occurs. According to Wang et al (2003), surface cracks may begin to form at high temperatures, such as 60 °C. Utilizing the same wheel tracking test procedure, no noticeable cracks or long-term strains were seen at 25 °C. Figure 1 shows the Hamburg wheel tracking test machine.

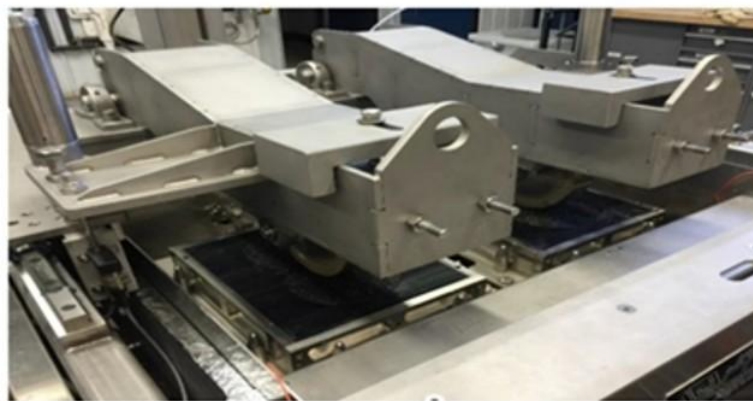


Figure 1. Hamburg wheel tracking test machine (Zhang et al., 2020).

To assess and analyze the fatigue behavior of asphalt mixtures by mechanistic-empirical models, numerous laboratories for bottom-up fatigue tests have been developed. Applying this testing assumes a direct correlation between field pavement cracking distress and laboratory fatigue test findings. The empirical-mechanical approach uses physical equations to predict the behavior of asphalt mixtures, while employing the empirical method to translate the physical behavior into a realistic service life.

The (AASHTO-T321, 2017) and (ASTM-D7460, 2010) are improved versions of the flexural beam fatigue test, which has been in use for many years. 380 × 50 × 63 mm is the size of the beam specimen sawed from a large slab compacted by a roller compactor or field compacted with air

voids of 7 ± 0.5 %. Although a haversine wave load rate of 5 to 10 Hz can be permitted, the load rate is typically fixed at 10 Hz. Although there are two modes for conducting the test—stress-controlled and strain-controlled—the strain-controlled mode is utilized significantly more frequently since it seems to yield results that are more comparable to field observations. The testing is often conducted at intermediate temperatures, typically 20 ± 0.5 °C. Four properties can be measured in this test: the fatigue life (number of cycles), stiffness decay, dissipated energy, and the predicting fatigue equation. The flexural beam fatigue test often requires a universal test apparatus. Field fatigue cracking and the results of flexural beam fatigue tests are highly correlated. The flexural beam fatigue test is used in many pavement design techniques, including AASHTOWare Pavement Mechanistic-Empirical design, to generate fatigue equations for asphalt mixtures. The time required to finish the test ranged from a few hours to more than a month, depending on strain level. A high strain of 400-800 microstrains may take a few hours, while a lower strain of 50-100 microstrains may take more than a month. Figure 2. Show the flexural beam fatigue apparatus



Figure 2. Flexural beam fatigue apparatus (Wang et al., 2025).

To make sure the fatigue lives fall between 10,000 and 2 million cycles, the test is conducted at 20°C or 10°C using three levels of the chosen loading method. Failure occurs when the asphalt stiffness modulus drops to half of its initial value after a certain number of cycles. The Apparatus of this test is similar to that utilized in the (AASHTO-T321, 2017) and (ASTM-D7460, 2010), which are mentioned above.

As an empirical- mechanistic fatigue failure, the European norms according to (CEN-EN-12697-24) consider the number of load applications at which the asphalt's complex stiffness modulus is dropped to half of its initial value under the repeated load effect. This specification includes indirect tensile tests and bending tests in its three types: the two-point bending test, the three-point bending test, and the four-point bending test.

The indirect tensile test according to (CEN-EN-12697-24 Annex E), a cored cylindrical specimen from a laboratory compacted slab or cored from the pavement in the field with a diameter of 100 mm and a thickness of 40 mm if the maximum aggregate size is not greater than 25 mm. The specimen size should be 150 mm in diameter and 60 mm in thickness for aggregate sizes greater than 25 mm and up to 38 mm. The temperature of testing may be 10, 15, or 20 °C. Three stress levels are applied on three specimens for each stress level for 0.1-second loading and 0.9-second rest. The load and the resulting horizontal deformation are recorded at predetermined intervals (number of loadings) throughout the test to calculate the tensile strain. The least-squares regression relationship between tensile strain and the number of loadings utilized to predict fatigue life is shown in Equation 2. Figure 3 shows the indirect tensile test configuration.

$$\log(Nf) = k + n \log(\varepsilon) \quad (2)$$

Where:

Nf = No. of loading (fatigue life)

K, n = Parameters of the predicted equation

ε = Tensile strain at the center of the specimen

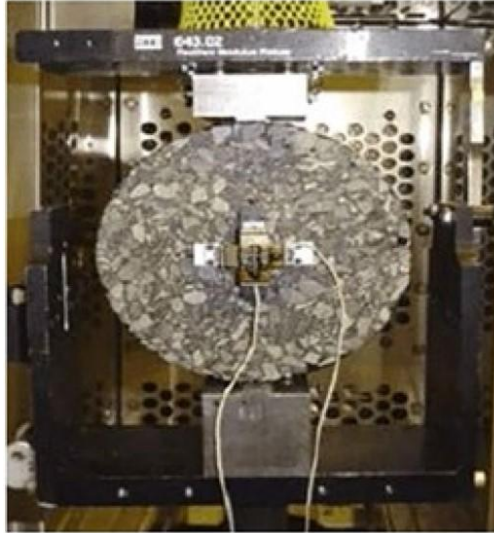


Figure 3. Indirect tensile test configuration (Wang et al., 2025).

Bending tests are more commonly used to simulate asphalt pavement layers under traffic loads. A trapezoidal shape specimen sawn from a laboratory compacted slab or cored from a field with a minimum thickness ≥ 40 mm is utilized to test with controlled displacement by a two-point bending test according to (CEN-EN-12697-24 Annex A). The test is suitable for asphalt mixtures with a maximum aggregate size of 20 to 40 mm. The test must be performed using a minimum of six specimens per applied deformation level. For the fatigue test to be completed, a minimum of 18 specimens is needed. A horizontal sinusoidal loading at a frequency of 25 Hz is delivered to the specimen's head once the test temperature has been reached in a thermostatic chamber, usually 10°C . This results in a constant displacement of $\pm 5\ \mu\text{m}$. To establish the fatigue line, the strain and the number of load cycles at the failure point are recorded. Figure 4 shows the two-point bending test machine.

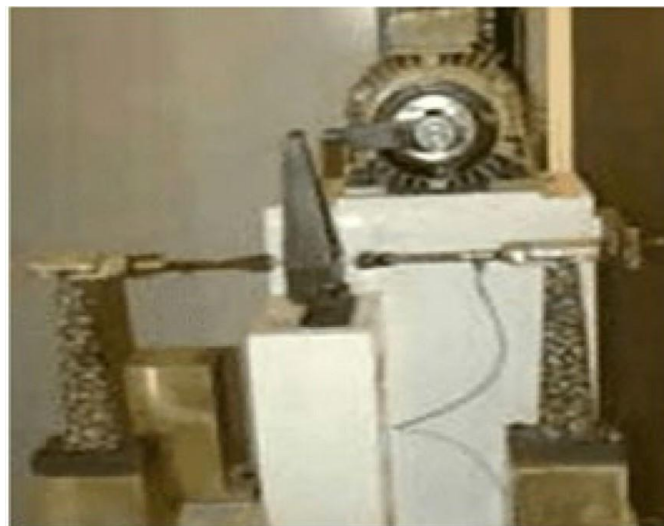


Figure 4. Two-point bending test machine (Wang et al., 2025).

A prismatic beam-shaped specimen with a size $50 \times 50 \times 300$ mm sawing from a laboratory compacted slab or cored from a field with a minimum thickness ≥ 50 mm is utilized to test with controlled displacement by a Three-point bending test according to (CEN-EN-12697-24 Annex C). The test is suitable for asphalt mixtures with a maximum aggregate size of 22 mm. A piston rod with a wave frequency of 10 Hz applies a constant amplitude sinusoidal displacement to the mid-span point of the specimen, which is clamped at both edges. The test must be performed using a minimum of ten specimens. The relationship between strain, the number of load cycles at failure, and the related energy law is used to evaluate the fatigue law. Figure 5 shows the three-point bending beam test.

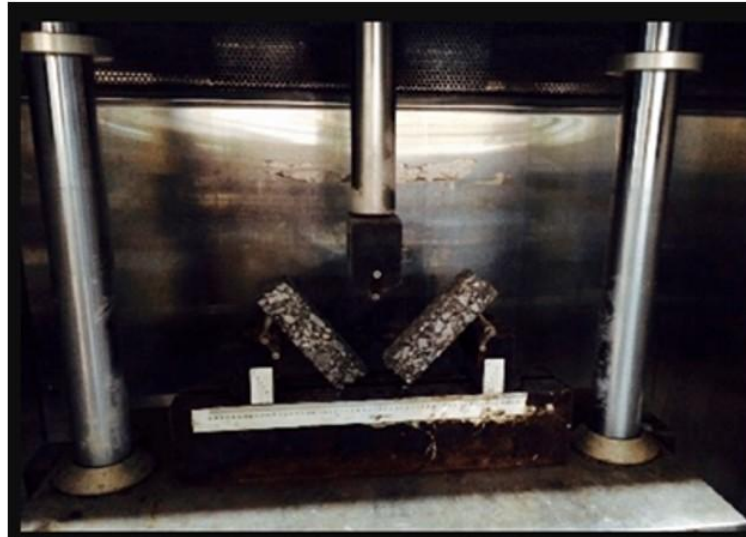


Figure 5. Three-point bending beam test (Zhou et al., 2021).

A prismatic beam-shaped specimen with a size 60×60×380 mm sawing from a laboratory compacted slab or cored from a field is utilized to test with controlled displacement or force by a Four-point bending test with inner and outer clamps according to (CEN-EN-12697-24 Annex D). This method is considered the most accurate for simulating the stress condition at the midpoint of the specimen.

There are two tests considered fundamental to the development of the mechanical model for inspection, as they take into account the amount of energy consumed to initiate and propagate cracks.

Louisiana Transportation Research Center (LTRC) proposed a Semi-circular bend (SCB) as a test method to measure critical strain energy release rate for fatigue cracking assessment at the intermediate temperature, which was adopted by (AASHTO-TP105, 2013). The LTRC-SCB test is a relatively simple test to execute, and it can be done with a lot of universal hydraulic testing machines, giving a fair correlation with field cracking (Kim et al., 2012). A semi-circular of 150 mm in diameter and 57 or 50 mm in thickness, compacted in the laboratory with air voids of $7 \pm 0.5\%$, is utilized in the test. Three specimens, each with a different notch length of either 25.4, 31.8, or 38.1 mm, are required for one sample, as shown in Figure 6. It is typical to evaluate a specimen at room temperature, which is $25\text{ }^{\circ}\text{C}$, with a loading rate of 0.5 mm/min. Critical strain energy release rate is the slope of the relation between fracture energy and notch depth. Better fracture-resistant mixes should have higher critical strain energy release rate values, of which 0.65 kJ/m² has been recommended as a minimum criterion for failure (Wu et al., 2006).

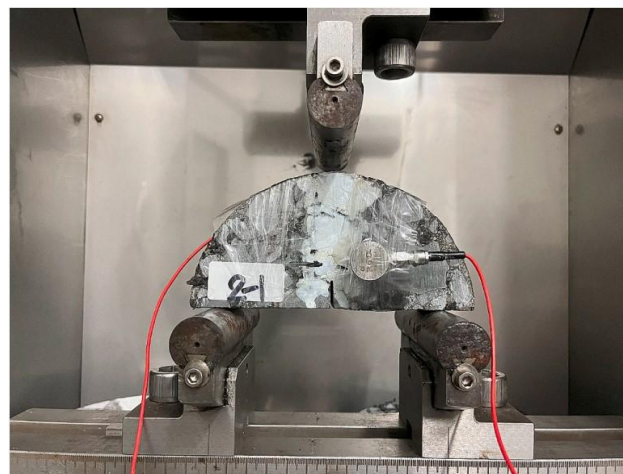
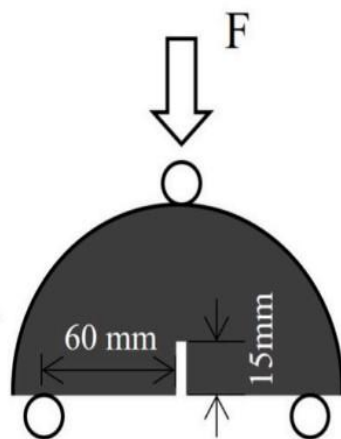


Figure 6. Semi-circular specimen (Shi et al., 2025).

The (AASHTO-TP107, 2014) indicates that the Simplified Viscoelastic Continuum Damage (S-VECD) fatigue test is used to determine the damage characteristic using direct tension cyclic fatigue tests. A controlled and repeated cyclic tension-compression loading with a frequency of 10 Hz at a target strain ranging between 50 and 75 microstrain is applied until failure to a cylindrical asphalt concrete specimen that has a diameter of 100 to 104 mm and height 127.5 to 132.5 mm cored from a tall Superpave gyratory specimen inside the chamber with a controlling temperature. It is recommended to wrap each specimen in polyethylene and preserve it for longer than 2 days and less than 2 weeks. A total of three tests need to be done at three different strain levels. The test temperature relies on the PG temperature of the asphalt binder; it should be the average high and low PG temperature minus 3, and not larger than 21°C. The cracking parameter for fatigue estimation is the Fatigue equation (the curve that results from graphing the pseudo secant modulus on the y-axis and the damage on the x-axis), and damage parameters, or predicted number of cycles (failure cycle, which is the cycle during which the measured phase angle steadily increases during cyclic loading and then abruptly decreases). Figure 7 shows the test specimen.



Figure 7. S-VECD test specimen (Jia et al., 2025).

There are several technical and environmental reasons and factors for evaluating fatigue in asphalt mixtures. (i) The test should simulate operating and environmental conditions in terms of expected temperature and traffic. (ii) The nature of the load and the loading method (load pattern), and the distribution of stress and strain. (iii) The properties of the asphalt mixture materials (bitumen and aggregate). (iv) Engineering requirements and achieving the approved standards, and defining the purpose of the test, whether it is for design or for predicting long-term mechanical performance. Table 1 shows the major differences between tests.

As shown in Table 1, it is not possible to rely on the results or evaluation of a single test alone, given the differences in the simulation of failure mechanisms. The tests conducted according to the standards of AASHTO, ASTM, and EN 12697-24 assess fatigue resistance through repeated bending tests and a reduction in stiffness to 50% of its initial value. Conversely, the SCB test evaluates cracking resistance based on fracture energy. Meanwhile, the S-VECD test provides an advanced mechanical description of damage development and predicts fatigue life based on dissipated energy. This variety of tests, through different specimen forms, loading patterns, and failure criteria, underscores the need to use a comprehensive set of tests to achieve reliable and thorough prediction and assessment of the performance of asphalt mixtures against this type of damage.

3.2 In-Field Evaluation Techniques

Relying on observations of actual pavement behavior is essential to enhance modeling and comprehension of fatigue mechanisms as well as crack localization and propagation phenomena in bituminous pavements (Hornych et al., 2008). Accelerated loading tests are useful because they enable the production and observation of full-scale pavement deterioration mechanisms in a significantly shorter amount of time than on the actual road network. Two accelerated pavement testing equipment are available: the FABAC machine, a small-scale linear accelerated testing facility, and the LCPC fatigue test track, a large-scale accelerated testing facility.

In 1995, the construction of tiny, frequent traffic simulators called Fatigue-Altération-Bond-Asphalt-Concrete (FABAC) fatigue devices was witnessed. The four dual tires on the machines are positioned in a close loop along a chain. With a single or dual tire load ranging between 30 and 75 kN, it can be applied by a section length of 2 m. Without lateral wandering, the loads travel at a maximum speed of 7 km/h with a frequency of 50 loads per minute (Chupin et al., 2020). The parameters often measured include longitudinal and transverse dimensions within the pavement layers, as well as temperatures. Alternative sensors may be employed for specific purposes, such as cracking, or LVDT gauges and sensors to instrument a particular device, provided the test is not associated with a pavement structure. Additionally, surface monitoring tests and visual surveys are used to keep an eye on the roads. Regular measurements include crack surveys, profile transverses (rut depth measurements), and deflection measurements at the Benkelman beam. It is also possible to do adhesion tests, radar, or wave propagation experiments (Chabot et al., 2008).

Table 1. The differences between the test characteristics.

Test	Specimen properties	Environmental and load pattern	Failure scale	Purpose of the test
Hamburg Wheel Tracking (HWTT)/ AASHTO T324	2 or 4 cylinder specimens (150×62mm) or slabs (320×260mm) compacted at 7±1% air voids	Wheel load (705N) at a frequency of 52 ± 2 passes/minute at a temperature of 50 °C, or according to the area	The cracks are monitored visually	Rutting and moisture. However, it is possible to derive the failure index of the top-bottom fatigue.
AASHTO-T321, 2017	6 prism specimens, 380×63×50 mm compacted at 7±0.5% air voids	Sinusoidal load at 5-10 Hz with constant strain at 20 °C	Reduction of stiffness to 50% of the initial value	Fatigue crack resistance under four-point bending
ASTM-D7460 (2010)	6 to 9 prism specimens, 380×63.5×50 mm compacted at 7±0.5% air voids	Sinusoidal load at 10 Hz with constant strain at room temperature	- Reduction of stiffness to 50% of the initial value - Peak of dissipated energy	Determining the failure point through the stiffness coefficient
EN-12697-24 Annex E (indirect tensile strength)	6 cylinder specimens dia. 100 or 150 mm, and thick 30 or 80 mm compacted at 4 to 7% voids	Pulse or sinusoidal constant stress to produce indirect tensile at 10 to 30 °C	Occurrence of a complete fracture in the sample or a specific diagonal deformation	Measuring Fatigue Resistance to Traffic Loads
EN-12697-24 Annex A (2-point bending test)	6 to 18 trapezoidal specimens, base 56, top 25, height 250 mm, compacted at 4-5% air voids	Sinusoidal load at constant stress or strain at a temperature of 20 °C	Reduction of stiffness to 50% of the initial value	Characterization of fatigue behavior for trapezoidal samples
EN-12697-24 Annex C (3-point bending test)	6 prismatic beam (length 250, width 40, height 40mm) compacted according to the requirements	Sinusoidal load at mid of the specimens at the required temperatures	Reduction of stiffness to 50% of the initial value	Study of Fatigue Resistance for Prismatic Samples
E N-12697-24 Annex D (4-point bending test)	6 prismatic beam (length 400, width 50, height 50 mm) compacted at 4 – 7% air voids or according to requirements	Sinusoidal at constant strain with 30 Hz at 20 °C temperature	Reduction of stiffness to 50% of the initial value	Study of Fatigue Resistance for Prismatic Samples at a constant moment
AASHTO-TP105/ SCB test	4 to 6 cylinder specimens (150×50 mm) and a groove depth of 15 mm compacted at 7±0.5% air voids	Constant monotonic load applied to a half-grooved cylinder at 10 to 24 °C temperature	Fracture energy	Assessment of crack resistance at low temperatures
AASHTO TP107 / S-VECD	Minimum 3 cylinder specimens (100×150 mm) compacted at 7±0.5% air voids	Cyclic sinusoidal tension without rest time by the AMPT device at 18 to 24 °C temperature	Relationship between dissipated energy and number of cycles	Comprehensive prediction of the fatigue age

Nantes's accelerated pavement testing facility, called Laboratoire Central des Ponts et Chaussées (LCPC), is a 40-meter-diameter outdoor circular carousel with four arms reaching a speed of 100 km/hr. Different load configurations, such as single or dual wheels, and single, tandem, or triple axles, can be placed on the arms. A single half axle can support loads ranging from 45 to 80 kN, and numerous axles can support loads up to 135 kN (Hornych et al., 2008). Top-bottom crack can be observed with a specified cycle length. Several pavement sections can be built with various

asphalt mixture materials and evaluated in the test. In actuality, the conditions of the examination are the same as the environmental surroundings in the field (temperature, sunlight, and rainfall).

4. Preventive and Mitigation Approach

4.1 Asphalt Mixtures Design Approach

When designing asphalt mixtures that have been formulated by the SHRP, Superpave is an effective way to choose the materials. Superpave uses performance-based indicators to describe the contribution to fatigue endurance. Fatigue, low-temperature cracking, and permanent deformation are all directly reduced or controlled by material selection and mix design. It considers how age and moisture sensitivity affect the emergence of these major distresses. Selecting the appropriate components for the asphalt mixture—*asphalt cement and aggregate*—is the focus of this approach. The dynamic shear rheometer test (DSR) yields significant indications for asphalt cement's ability to withstand fatigue, notably, $|G^*| \times \sin \delta$. Superpave specified a maximum value of 5000 kPa, where is a low value of $|G^*|$ and δ indicates desirable attributes to fatigue resistance (Asphalt-Institute, 2003).

Stone matrix asphalt (SMA) is a proper mix design and is widely used for permanent deformation and fatigue resistance. Stone matrix asphalt (SMA) has a different structure than ordinary asphalt because it incorporates *gap-graded aggregates and a high concentration of optimal asphalt binder*, which improves durability and fatigue resistance. Notwithstanding its advantages, SMA's disadvantages include the possibility of various fat spots developing on the surface, the high cost of SMA (because of the high amounts of optimal asphalt binder content), and the drain down of mastic (asphalt binder + filler). According to the aforementioned drawbacks, and enhancing its benefits, particularly fatigue resistance. Regarding this, fiber is typically used in the production of SMA pavements as an additive or stabilizer to reduce drain down (Hamedi et al., 2025).

4.2 Modification of asphalt binder

To create high-performance asphalt mixtures, researchers have been utilizing bitumen-modified materials ever since asphalt mixtures were first produced. One such material is synthetic polymers, which are frequently utilized to enhance the performance characteristics of asphalt cement.

A polymer is a complex macromolecule composed of many components. The name polymer derives from Greek, signifying 'many parts'. Polymers can be categorized according to molecular forces: Elastomers, Fibres, Thermoplastics, and Thermosetting polymers. The copolymer is formed from multiple types of polymers. Common copolymers that are used to enhance the fatigue life of asphalt mixtures are thermoplastic elastomers and thermoplastic plastomers (Behnood & Gharehveran, 2019).

One of the most effective and often used modifiers for polymer-modified asphalts to satisfy the rising demand for superior paving materials is styrene-butadiene-styrene (SBS) triblock copolymer. Thermoplastic elastomer SBS is produced via anionic polymerization. The structure of SBS, whose parameters include molecular weight, styrene content, and SB diblock content, may have an impact on the characteristics of modified asphalts (Xu et al., 2021). A study by Yao et al. (2023) concluded an 8% of SBS contains 30% styrene-modified asphalt cement showed the best resistance to fatigue life. (Alani et al., 2021) investigated four percentages of SBS 2.5, 4.2, 4.8, and 6.1% of asphalt cement weight, where the fatigue parameter ($G^* \times \sin \delta$) was shown to decrease with decreasing temperature. The results demonstrated that adding SBS to the asphalt binder enhanced fatigue resistance. 6.1% SBS produced the best results against fatigue cracking. Some investigators have endeavored to achieve an optimal formulation of bitumen modification by combining SBS with additional substances. Two forms of carbon nanomaterials, graphene oxide and carbon nanotubes, were combined with styrene-butadiene-styrene (SBS) by Wang et al. (2021). A 3% of SBS with varying percentages of 0.5, 1, and 1.5% of graphene oxide, or carbon nanotubes combined by weight of 60/70 asphalt cement, was studied for fatigue life. By using the linear amplitude sweep (LAS) tests, graphene oxide and carbon nanotube nanoparticles can both increase the asphalt binder's fatigue life. Increased 1.5% graphene oxide or carbon nanotube content can increase SBS's tolerance to fatigue. (Men et al., 2024) studied the effect of a composite of epoxy resin and SBS polymer on the fatigue life of asphalt mixtures. The modifier composition has been used in proportions of 4%, 6%, 8%, 10%, and 12% of the weight of asphalt cement penetration grade 60/80. The study showed that when the modifier content is higher than 8%, the fatigue performance significantly improves. It is recommended to modify asphalt by over 10% for actual engineering applications. The polyphosphoric acid has been mixed with SBS polymer to modify asphalt cement and investigated for fatigue resistance by Wang et al (2023). The study showed an improvement in the fatigue life of asphalt mixtures with this composition.

Styrene-butadiene rubber (SBR) is another thermoplastic elastomer copolymer that is used to modify asphalt cement. (Hemmati et al., 2021) modified the asphalt cement by SBR with percentages of 4, 6, and 8% of asphalt cement weight. This study demonstrated a significant enhancement in fatigue resistance. (Xie et al., 2024) concluded that 30% of SBR polymer-modified asphalt cement provides excellent bond properties between asphalt cement and aggregate, thus improving fatigue resistance.

Styrene Isoprene Styrene (SIS) copolymers are a kind of thermoplastic elastomer made up of segments of isoprene and styrene monomers and have resilience and elasticity similar to rubber. The desirable properties of this substance led researchers to employ it in the modification of asphalt cement, and they found an improvement in the performance of asphalt mixtures (Kok et al., 2022; Yun et al., 2024).

Styrene-ethylene-butadiene-styrene (SEBS) block copolymer is a kind of thermoplastic elastomer that can be utilized to modify asphalt cement and make it thermoplastic rubber (Gurjar et al., 2025).

Researchers have focused on using modifiers with low-cost additives, such as crumb rubber (CR) obtained from waste vehicle tires, to enhance the efficiency of polymer modification. With over 50 years of existence, crumb rubber-modified asphalt has drawn the attention of several researchers from a variety of disciplines. Tire disposal waste was recycled economically; in addition, the asphalt's performance is much enhanced. The addition of crumb rubber to asphalt cement is called the wet method (Liang et al., 2020), modified by weight, the asphalt cement PG 64-16, and PG 70-10 with 5 and 10% of crumb rubber. The study showed that the rubberized mix's fatigue life was increased, and this benefit was particularly noticeable at low strain levels. Due to the mix's increased stiffness, increasing the rubber percentage from 5% to 10% negatively impacted the strain-controlled test's improvement in fatigue resistance. A study by Saeed et al. (2017) examined the effects of crumb rubber content on the fatigue life of warm mix asphalt mixes. A range of crumb rubber percentages was used, including 5, 10, and 15% by weight of 80/90 penetration grade asphalt cement. An indirect tensile fatigue test was used to assess the fatigue life, and the results showed that the mixtures containing the crumb rubber modifier had more cycles before failure than the unmodified control mixture. The asphalt mixtures with 20% crumb rubber added had the longest fatigue life.

Crumb rubber is a low-cost waste material that can be mixed with other expensive materials to generate an acceptable-cost material that has a favorable influence on improving the properties of asphalt cement. Results from a study by Chen et al. (2024) show that the styrene-butadiene-styrene/crumb rubber composite modifier significantly increases the fatigue resistance of asphalt binders at both low and high strain levels. A study by Nasr et al. (2022) attempted to discover whether waste crumb rubber-polypropylene composites with styrene-butadiene-styrene might be employed as modifiers to improve the performance characteristics of asphalt binders and mixtures. According to the findings of the mechanical tests, the modified combinations of styrene-butadiene-styrene and crumb rubber-polypropylene increased their indirect tensile strength, improving their resistance to fatigue damage.

A family of copolymers is represented by the term plastomer, which was created by combining the terms plastic and elastomer. Several types of thermoplastic plastomers, copolymers such as Ethylene-vinyl acetate (EVA), ethylene-methyl acrylate (EMA), ethylene-butyl acrylate (EBA), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS). Thermoplastic elastomers, also referred to as thermoplastic rubbers, are a category of copolymers or physical mixes of polymers (typically a plastic and a rubber) that exhibit both thermoplastic and elastomeric characteristics (Nikolaides, 2014).

In the study by Ameri et al (2013), the relative performance of bitumens modified with ethylene vinyl acetate (EVA) by bitumen weight modifications of 2, 4, and 6% was assessed in terms of the three primary distress mechanisms of flexible pavement: low-temperature cracking, fatigue damage, and rutting. The Superpave performance criteria were used to test and characterize four modified and original base bitumens. According to the results of the DSR fatigue test, the inclusion of EVA lowers the modified bitumens' fatigue parameter $G \times \sin \delta$, which indicates extending the fatigue life. An indirect tensile fatigue test on the asphalt mixes modified with EVA revealed that the inclusion of EVA increases the asphalt mixtures' fatigue resistance in comparison to the asphalt mixture that included the original base bitumen.

Overall, EVA-modified asphalt performed exceptionally well at high temperatures, but because of its stiffness, it performed poorly at low temperatures. Additionally, it was discovered that the EVA-modified asphalt's fatigue performance was comparatively poor when exposed to high-strain circumstances (He et al., 2023). (Chegenizadeh et al., 2021) Examine how ethylene vinyl Acetate (EVA) affects the fatigue of stone matrix asphalt (SMA). The modified bitumen was made by blending EVA with the C320 bitumen. Doses of EVA ranged from 2% to 6%. To evaluate

the fatigue damage, a four-point flexural beam test was utilized. The study showed that as the percentage of EVA increased, the cycle to failure in the four-point bending test improved. (Liang et al., 2017) investigated the behavior of fatigue resistance of ethylene vinyl acetate with different contents of vinyl acetate of 12, 18, 25, 32, and 40% of copolymer weight to the modification of two types of asphalt cement. The study showed that the percentage of 18% vinyl acetate is essential for achieving the best performance at both high and low temperatures, as well as for balancing stability and viscoelastic characteristics.

The most widely used plastic worldwide is polyethylene (PE). This material is semi-crystalline and has a variety of characteristics, including good fatigue and wear resistance and exceptional chemical resistance. Its structure is really basic. The influence of high-density polyethylene on the fatigue resistance of hot mix asphalt was studied by (Moghadas Nejad et al., 2014). A 5% of high-density polyethylene (HDPE) by weight of 60/70 penetration grade bitumen. Fatigue resistance was evaluated by the indirect tensile fatigue test; the results showed an increase in the asphalt mixtures' stiffness and modulus of rupture at intermediate temperatures of 15 °C and 20 °C. HDPE lowers the risk of fatigue cracking at intermediate temperatures.

(Hamedi et al., 2020) investigated the addition of 2 and 4% of ultra-high-molecular-weight-polyethylene (UHMWPE) by weight of the PG 64-16 asphalt binder. To forecast the fatigue life of asphalt mixes, the DSR test and the indirect tensile fatigue test (ITFT) were performed. The study demonstrated that at middle temperatures, as UHMWPE increased following long-term aging, G^* decreased and phase angle (δ) increased, indicating a decrease in the fatigue parameter $G^* \times \sin \delta$. Additionally, to increase resistance to fatigue cracking, the fatigue parameter was reduced by lowering the energy wasted in each loading cycle. According to the results of an indirect tensile fatigue test, samples with 4% UHMWPE had a longer fatigue life than samples with 2% UHMWPE.

4.3 Use fibers

Recently, several researchers have discovered that in fiber composite materials, the interface between the fiber and the asphalt matrix has a transitional effect and reinforcement of asphalt mixtures. The contact acts as a bridge for the transfer of stress, leading to crack propagation resistance (Wu, Pei, et al., 2022). Fibers can be classified into three classes: natural plant-based, such as bamboo, hemp, and coconut, or called coir, jute, lignin, sisal, and natural minerals, such as asbestos, and basalt fibers, and synthetic fibers such as polypropylene, polyester, carbon, ceramic, glass, aramid, and steel fiber (Guo et al., 2023). Sustainable structures can make use of natural fibers. Usually added to asphalt mixtures, these fibers increase the pavement's strength and stability while lowering the likelihood of cracks and other damage (Masri & Baqadeem, 2023). A massive woody plant, bamboo is a member of the Poaceae family of grasses. This wood plant grows remarkably quickly and can keep growing even after being chopped. The majority of bamboo is found in temperate, tropical, and subtropical areas, such as South America and Southeast Asia. Research on how to enhance the mechanical performance of asphalt mixtures, as studied by Jia et al (2021), benefits greatly from the addition of bamboo fibers due to their strength and durability properties. Asphalt mixture specimens containing 0.3% bamboo fiber were created using a Superpave gyratory compactor and evaluated by a cyclic fatigue test. The asphalt mix's fatigue life was enhanced by the addition of bamboo fiber, resulting in a 13.83% increase in the number of cycles at failure.

One type of natural fiber that is a member of the Tiliaceae family is jute. Jute fiber's fine texture, low heat conductivity, and low price have made it popular in the textile, building, and automotive industries. It has several benefits, including great strength, biodegradability, environmental compatibility, and annual renewability (Mansourian et al., 2016). (Gallo et al., 2021) performed a semi-circular test to assess the fatigue resistance of asphalt mixtures with a constant length of 20 mm and varying contents of jute fibers (0.1, 0.2, and 0.3% by weight). The asphalt cement had a 50/70 penetration grade. According to the study, fibers reduce test specimens' brittle failure and aid in preventing crack growth. With a length of 20 mm, the ideal jute fiber percentage was determined to be 0.2% by total weight.

One of the most popular natural fibers is sisal, which is also quite easy to grow. Sisal fiber is extracted from the sisal plant's leaves. Between 200 and 250 leaves are produced by a sisal plant, and each leaf has 1000–1200 fiber bundles (Abiola et al., 2014). In order to strengthen the pavements' resistance to fatigue, Makendran (2024) added sisal fiber to the bituminous mixture. The fibers were utilized in 7.5, 10, 12.5, 15, and 17.5 mm lengths and were added in varied percentages of 0.06, 0.12, 0.18, 0.24, and 0.30% of the total weight. Lastly, a comparison of the outcomes showed a considerable improvement in fatigue resistance that was tested by the four-point beam test at 25 °C. The mixtures containing fiber length of 17.5 mm and 0.30% content exhibited the maximum fatigue life, where it reached 1000 cycles with an increase of 25% compared to the control mixtures.

Lignin is one of the most common natural polymers on Earth. It is mostly extracted from wood and contains 30% non-fossil organic carbon. (Zahedi et al., 2020) added lignin to asphalt mixtures in several amounts: 3, 6, 9, and 12%, and assessed the fatigue cracking. The fatigue test was conducted with a haversine load, loading time of 250 ms, and rest time of 1250 ms at three different tensile stress levels (250, 350, and 450 kPa) at 20 °C. The results indicated that 6% was the ideal lignin usage amount. Because lignin and bitumen make a strong bond and lignin absorbs some bitumen, the bitumen that is retained provides the coated aggregate greater adhesion strength, extending the fatigue life of asphalt mixtures enhanced with lignin. (Wang et al., 2024) added lignin fiber and a modified corn stalk fiber asphalt mixture at concentrations of 0.1%, 0.2%, 0.3%, and 0.4%. At 15 °C, the fatigue test was assessed using a three-point bending test with a 200 ms haversine wave. The results showed that the optimal fiber contents for lignin and modified corn in asphalt mixtures were 0.3% and 0.2%, respectively, increasing fatigue life by 61% and 76% compared with the control mixture.

One kind of mineral fiber is basalt fiber, which is produced by melting natural volcanic rock at a high temperature (Wu et al., 2020). (Wu, Meng, et al., 2022) concluded that in 0.4% of basalt fibers, when added by weight to asphalt mixtures, the fatigue life and accumulated dissipation energy increased by up to three to four times. Fatigue resistance was evaluated by a four-point bending fatigue test at 15 °C in several strain levels of 450, 650, and 850 ms. (Zhu et al., 2022) concluded that the addition of 0.25% to the total weight of the asphalt mixture that was tested by a four-point bending fatigue test at a temperature of 20 °C and 800 ms strain level enhanced the asphalt mixtures significantly fatigue resistance.

Synthetic fibers are materials created by humans using processes including spinning, polymerization, and filament processing. Ceramic fibers are continuous fibers composed of ceramic materials that exhibit resistance to elevated temperatures up to 1600 °C. Dehnad et al. (2025) examine how ceramic fiber affects the glassphalt's mechanical characteristics. Three percentages, 1, 3, and 5% of total weight, were added to glassphalt to improve fatigue resistance. An indirect tensile fatigue test was adopted to evaluate the modified mixtures for fatigue at 15 °C. According to the study results, samples with 1, 3, and 5% ceramic fibers had fatigue resistance of approximately 79%, 114%, and 65%, respectively, longer than the control sample. Wang et al. (2018) reinforced the asphalt mixtures with 6 mm lengths and several percentages of 0.15, 0.3%, and 0.45% polyacrylonitrile fibers by total weight of mixtures to enhance the fatigue performance. The study showed an increase in the fatigue life of fiber-reinforced mixtures, where the mixtures containing 0.3% polyacrylonitrile fibers exhibit the maximum fatigue resistance. The effect of polypropylene and polyester fibers reinforcing asphalt mixtures on fatigue resistance was evaluated by Vadood et al. (2015). Two different lengths, 10 and 20 mm, with several contents of 1, 1.5, and 2.5% by total weight, were utilized. The study demonstrated that all reinforced mixtures exhibited resistance to fatigue failure, where the mixture reinforced by 20 mm length and 2.5% content of polypropylene fibers reached the maximum resistance to fatigue compared to the control mixture, while the mixtures containing 20 mm length with 4% content of polyester fibers exhibited the maximum fatigue resistance compared to the control mixture.

The mixing of two types of fibers was also evaluated for fatigue resistance. The mixing of lignin and ceramic fibers added to the stone matrix asphalt was evaluated by Pang et al (2023). The ratio of lignin to ceramic fiber content utilized was 0.3%/0, 0.2%/0.1%, 0.15%/0.15%, 0.1%/0.2%, and 0/0.3% by total weight. Fatigue performance was evaluated by an indirect tensile fatigue test at a temperature of 15 °C. The study showed that all reinforcing asphalt mixtures demonstrated resistance to fatigue failure compared to the control mixture, and the mixtures containing a ratio of lignin to ceramic fiber content of 0.1%/0.2% exhibited the maximum resistance to fatigue failure.

4.4 Geosynthetic-reinforcement utilization

In order to enhance the performance of asphalt pavements during both initial construction and maintenance, geosynthetics are a class of stabilization and reinforcing techniques (Gkyrtis & Kokkalis, 2024). Various kinds of interlayers have been employed since the 1970s to impede the propagation of cracks through the asphalt pavement overlay (Golestani et al., 2018). The researchers used a variety of raw materials from which geosynthetics are produced in order to assess the performance of asphalt mixtures reinforced with geosynthetics for fatigue in the lab. (Sudarsanan et al., 2020) evaluated three types of jute-woven geotextile, coir geogrid, and fiberglass grid composite for fatigue life when utilized as reinforcement of asphalt pavement. Four-point bending test was employed for the assessment, the specimen was sawed from a small asphalt pavement (4 length and 3 wide) constructed in the field. The work included leveling and compacting the subgrade. A polymeric geosynthetic layer was applied as a separator over the subgrade to make it simple to identify the asphalt pavement layers from the subgrade. After laying and compacting a lower layer of 50 mm thick asphalt pavement, three different types of geosynthetic interlayers are applied and fixed with a tack coat. Lastly, a 90 mm thick top layer was applied and compacted. Slabs 140 mm thick and 260 × 465 mm in plan were extracted based on the location of where they were reinforced and where they weren't. The final dimension specimens were sawn from slabs. Three different

temperatures, 10, 20, and 30 °C were employed for assessment. The study showed that depending on the type of reinforcement and temperature, the reinforcement increased the asphalt concrete beams' fatigue life by 1.2–12 times. (Kumar et al., 2021) studied three separate kinds of geosynthetics, termed biaxial polypropylene geogrid, polyester geogrid, and glass geogrid composite for fatigue life. The study's approach consisted of producing 200 mm square slabs compacted using a square plate weighing 50 N, dropped from a height of 500 mm; the number of blows used was determined when the mixtures achieved 6% air voids. The slabs were created with a thickness of 90 mm compacted in two layers, the bottom 30 mm and the upper 60 mm, with the geosynthetics that were fixed with the tack coat. After that, the standard specimens were sawn with sizes of 400 mm in length, 50mm in width, and 90 mm in thickness. The fatigue life was assessed by a four-point bending test. Based on the test results, a design example has highlighted the reduction in the thickness of asphalt layers when involving geosynthetic reinforcements. The reductions recommended were in the amount of 5.9%, 17.6%, and 23.5% for polypropylene, polyester, and glass geogrid, respectively. (Silva & Correia, 2024) examined three geosynthetics with different physical properties: bitumen-pre-coated self-adhesive paving grid, bitumen-coated fiberglass grid with a high percentage of oxidized bitumen coating (light thermally bonded), and bitumen-coated fiberglass grid (heavyweight heat-bonded) using cyclic Leutner shear tests. The findings of dynamic shear tests on geosynthetic-reinforced interfaces indicate that permanent shear displacement rates under cyclic shear loading are influenced by the various physical characteristics of the geosynthetics. The bitumen coating content had a good impact on the bitumen-pre-coated self-adhesive paving grid's shear fatigue life.

5. Conclusions

The review work leads to the following findings.

The aging of the asphalt binder leads to changes in the characteristics of asphalt concrete, rendering it brittle over time, especially in terms of stiffness; hence, fatigue cracks in asphalt concrete are inevitable, even under minimal applied loads. Fatigue cracks originate either at the interface between aggregates and asphalt binder, influenced by adhesive strength, or within the asphalt binder film, determined by the cohesive strength of the asphalt binder that is based on asphaltenes and maltenes components and temperature. The thickness of asphalt pavement significantly influences the development of fatigue cracks, which manifest in thinner asphalt layers at early ages due to repeated loads from heavy traffic volumes. Consequently, forecasting the traffic volumes traveling on asphalt pavement throughout its service life and the suitable structural design of the asphalt pavement layers are crucial for optimal performance.

Top-down cracks don't necessarily mean that asphalt pavement is structurally deteriorating, but they do play a big role in the formation of other problems like potholes, which lead to an uneven pavement surface, decreased road user safety, decreased vehicle speed, increased fuel consumption, tire wear, discomfort, and a greater need for emergency repairs. Top-down cracks can form simultaneously with rutting at moderate temperatures and high applied loads.

Although laboratory tests are widely used to evaluate and compare the performance of asphalt mixtures, there are still no standardized threshold values for fatigue failure adopted in international specifications, whether European or American, as the definition of failure varies depending on the test method and the evaluation criterion used. However, the developments in experimental techniques and mechanical models indicate the possibility of adopting more accurate standards in the future.

The diversity in specimen types, loading patterns, and failure criteria enhances the accuracy of describing structural behavior and predicting the service life of pavement. Therefore, using a variety of laboratory tests is important to evaluate the performance of mixtures against fatigue failure.

Although field tests are costly and time-consuming, theories that forecast the occurrence of deformations can be developed, and multiple asphalt structures can be evaluated simultaneously in the same weather conditions due to advancements in computers, surveillance, technological equipment, and strain gauges.

Since the Superpave method considers fatigue, rutting, and moisture damage while selecting the components for the asphalt mixture, it is among the best methods for designing the mixture.

An effective, financially feasible, and practically applicable method of increasing the fatigue resistance of asphalt mixtures is the modification of asphalt binders with polymers. Waste can also be mixed with other polymers to achieve a sustainable approach and dispose of environmentally hazardous waste.

Adding fibers requires mixing technology because these fibers are lightweight and can produce substantial amounts of waste. In addition, asphalt mixtures are produced in substantial amounts; thus, there is a need for massive quantities of these fibers. Natural ones are limited in production, and industrial ones may not be economically feasible.

Geosynthetic reinforcement is also an effective and field-applied approach that results in prolonging the life of pavement, not only in fatigue fractures (Bottom-up cracks) but also in limiting the appearance of permanent deformation, thermal cracks, and reflection cracks to avoid costly maintenance work.

Future research should focus on developing standardized fatigue failure criteria, improving the correlation between laboratory and field performance, and integrating advanced materials and technologies for enhancing fatigue resistance.

6. Declaration of generative AI and AI-assisted technologies

In preparing this manuscript, AI-assisted technologies (Grammarly) were used to support the structuring of the text and improvement of clarity, readability, and presentation. All outputs generated with the assistance of these technologies were carefully reviewed and edited by the authors, who take full responsibility for the content of the manuscript.

7. Notes on Contributors

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