

Review of concept and laboratory test methods of asphalt mixture rutting performance

Nadheer Albayati¹✉ and Mohammed Qadir Ismael²

¹ Expressway Directorate, Roads and Bridges department, Ministry of construction and housing, Baghdad, Iraq

² University of Baghdad, Faculty of Engineering, Civil Engineering Department, Baghdad, Iraq

Corresponding author:
Nadheer Albayati

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Faculty of Civil Engineering and
Architecture Osijek
Josip Juraj Strossmayer University
of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA



Abstract:

Asphalt pavement is subjected to considerable recurring stresses that reduce its lifespan and impair its condition, mostly owing to repeated traffic loads and environmental factors, as well as construction quality. As the application of asphalt mixtures in paving roads has increased, asphalt mixture components have attracted interest as they are closely linked to its durability and performance. This paper provides a comprehensive review of the theory of permanent deformation (rutting formation) in asphalt pavements. Types and factors that influence rutting are also discussed. More importantly, laboratory tests are categorized into four fundamental concepts related to the permanent deformation, which aids in selecting the proper test for evaluation, each containing many assessment methods according to American and European practices to analyse the structural behaviour of pavements and changes in their properties over time, which results in significant rutting. Solutions to enhance resistance to rutting are discussed. The paper concludes that rutting is unavoidable when both high temperatures and frequent heavy loads are present. Geosynthetics are an effective approach to reducing permanent structural and non-structural deformation; they have demonstrated effectiveness in field applications, in contrast to methods primarily validated through laboratory testing.

Keywords:

asphalt mixtures; rutting; permanent deformation; geosynthetics; asphalt cement

1 Introduction

Roads are infrastructure projects that are often expensive to construct and require significant funding [1]. They indicate the extent to which a nation has been urbanised. During the early 20th century, asphalt mixtures were frequently employed, predominantly in parking lots, highways, harbour facilities, and airports [2]. Roads are primarily classified into three categories: flexible, rigid, and composite (a combination of flexible and rigid) [3]. The choice of category is contingent upon the availability of raw materials and construction costs [4].

Asphalt pavements are prevalent globally because of the availability of raw materials, straightforward manufacturing and production, and low building costs compared with concrete pavements [5]. They can endure the loads applied by vehicle tires and transmit them to the underlying layers [6]. However, many defects and damages occur during their service life, which diminish their efficiency and durability, leading to discomfort and poor safety for road users [7]. These defects are caused by loads and extreme weather conditions, particularly temperature fluctuations, which reach 70 °C in some regions [8]. The asphalt mixture comprises two substances with different properties: elastic mineral aggregates and complex viscoelastic asphalt cement, whose performance behaviour is altered by temperature [9]. Aggregate is inherently durable and can sustain large weights and adverse weather conditions [10], whereas asphalt is influenced by heat; it becomes more fluid and less viscous at high temperatures and reacts with oxygen, causing aging that results in more hardening over time [11]. The three most popular terms that accurately characterise asphalt mixtures are durability, performance, and temperature susceptibility.

The degree to which a binder preserves its initial properties under typical weathering and aging conditions is known as durability. The mechanical performance of the asphalt mixture is determined by the mix design, aggregate characteristics, and effectiveness of the adhesion between the aggregate particles and asphalt cement. Cohesion, defined as the ability of asphalt cement to hold aggregate particles, is related to the chemical and physical properties of asphalt. The temperature susceptibility of asphalt ensures that it remains sufficiently fluid at high temperatures to enable the coating of aggregate particles during mixing and for the particles to navigate one another during compression [12]. A crucial characteristic of an asphalt mixture that affects the ability of a road pavement to support loads is its stiffness, which is related to the asphalt cement properties. A phenomenon known as permanent deformation (rutting) is caused by non-recoverable pavement deformation, which is also related to stiffness [13]. Throughout its lifespan, asphalt pavements are subjected to compression and tension stresses caused by frequent vehicle loads, where tension causes fatigue cracks, and compression causes permanent deformation [14]. Thus, the engineering properties of asphalt mixtures should be tested and evaluated in both damaged and undamaged states under tension and compression.

The mechanical performance of asphalt mixtures is indicated by their ability to withstand repeated loads at specific temperatures [15]. The two main types of distress that appear in asphalt pavements and are related to mechanical performance are rutting (permanent deformation) and fatigue cracks [16]. The appearance of these distresses reduces the serviceability of asphalt pavements. The serviceability level serves as an indicator of the level of service that a road offers to its users [17] and the maintenance costs it incurs [18]. Therefore, the selection of a proper combination of materials is essential to achieve enduring performance [19].

The primary objective of this paper is to present the concept of permanent deformation in asphalt mixtures, commonly referred to as rutting distress, along with the factors that contribute to its occurrence and progression. Additionally, it aims to fill a research gap by describing and aiding the selection of laboratory tests to investigate this phenomenon under various conditions and variables, as well as summarising the primary methods for mitigating or reducing its manifestation.

2 Concept, types, and factors that influence permanent deformation (rutting)

Rutting is a trench in an asphaltic pavement surface formed along the wheel path; it is load-induced permanent deformation attributable to shear failure (lateral displacement of the mixture materials). It is described as the accumulation of unrecoverable small deformations resulting from the repetitive application of vertical loads on the pavement surface. The peril lies in the development of a severe groove that alters the horizontal cross-section of the roadway, resulting in challenges for vehicle manoeuvrability. Furthermore, water accumulation within this groove diminishes safety by increasing the risk of vehicle slippage and accidents while also impairing driver visibility owing to water splashing caused by tire passage over the gathered water [20].

Asphalt pavements contain air voids ranging from 2-6 %, resulting in rutting occurring in two stages: The initial stage involves densification, where air voids are reduced owing to vehicle tire loads (depression along the tire is occurring). The second stage occurs when the density reaches its maximum, at which point the vertical load produces horizontal forces that cause the particles to move laterally. Upheaving occurs parallel to the rutting groove. Repetitive vertical loads increase the lateral displacement of the particles that upheave, which leads to their separation from one another and shear failure [21].

Rutting can occur in the subgrade, base, and surface layers [22]. It may exhibit a groove depth of less than 5 mm owing to the consolidation of pavement materials beneath the wheel path caused by vertical traffic loads [23]. Two main types of rutting exist in asphalt paving: structural and non-structural failure. The structural type is formed by layers beneath the pavement structure that exhibit brittleness and yield ability. These strata are affected by vehicular loads. Asphalt pavements deform to conform to the underlying layers (unbound materials or subgrades) if they possess adequate flexibility. Ruts resulting from subsidence are often between 750 and 1000 mm in width. They remain intact and have a shallow saucer configuration. If the asphalt pavement lacks flexibility, fatigue cracks develop along the entire wheel path. Occasionally, ruts exhibit a high gradient with fractured edges surrounding the wheel path, and occasionally, certain sections may resemble a punch-out failure characterised by fragmented debris displaced downward [24]. Figure 1a) shows the structural form of rutting. The non-structural type occurs in two forms, the first of which is called wearing rutting. This occurs when abrasive factors are present, such as studded tires, wear, or softening of aggregate particles in the wheel path. This may also be the result of ravelling, which is a lack of adhesion between particles due to inadequate compaction, low bitumen content, or severe bitumen age. These particles are dislodged by rolling tires to create ruts. Non-structural rutting can also be induced by the shear deformation of asphalt mixtures when the ingredients shift laterally owing to the periodic vertical traffic pressure. Grooves and side upheaves are present along both sides of the wheel path. The major cause of rutting involves the consolidation of the top-layer materials owing to tire stresses. The lack of stability within the mixture leads to the separation of bitumen under traffic loads [25]. Figures 1b) and c) show the non-structural rutting.

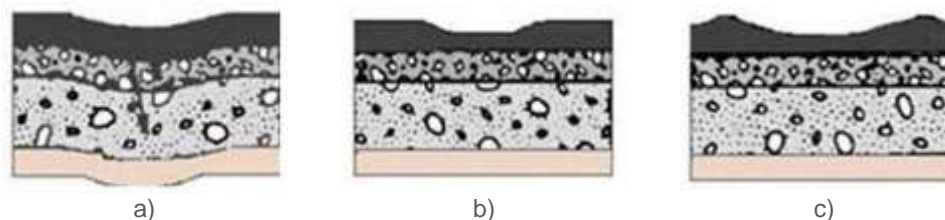


Figure 1. Structural and non-structural rutting: a) Structural rutting (deformation in underlying layers); b) wearing rutting (abrasive loss of surface material); and c) shear deformation rutting (lateral movement within the asphalt layer) [25]

Any phenomenon must have contributing factors to exacerbate. The three primary factors that influence the occurrence of rutting (permanent deformation) are internal factors, external factors, and construction quality [26].

Internal factors are represented by the asphalt mixture and pavement structure (layer thickness). Because the asphalt mixture is composed of two separate components with different characteristics (aggregates and asphalt cement), altering one of their characteristics will either resist or increase the occurrence of permanent deformation [27].

Asphalt cement characteristics have a significant influence on the rutting resistance of asphalt mixtures. The main function of asphalt cement is to hold the non-cohesive aggregates in contact with one another and prevent them from being dislodged by rolling tires; it must be sufficiently strong to prevent particle separation and withstand shear forces produced at particle contact points by traffic loads [28]. High-consistency asphalt with a higher rutting resistance is indicated by lower asphalt grades that have lower penetration values [29]. The asphalt content also plays a crucial role in rutting performance, in which mixtures with a high binder dosage exhibit lower rut resistance than those with a lower dosage [30].

Aggregate characteristics such as angularity, gradation, absorption, affinity for asphalt, shape, texture, and strength have a major influence on the stability of asphalt mixtures [31]. Pavement performance is influenced by the material and thickness of the pavement layers. Thus, to achieve proper pavement performance and long life, the thickness is considered in the structural design of asphalt pavements [32; 33].

External factors include environmental factors (temperature and moisture) and load conditions. The asphalt binder provides the viscous characteristics of the asphalt mixture. Asphalt mixtures exhibit viscous, linear, and non-linear elastic properties, depending on the loading rate and ambient temperature. Temperature plays a significant role in the rutting process under various environmental conditions. During winter (low temperature), rutting does not occur because the mixture behaves elastically, and all strains developed on the pavement by traffic are returned by elastic recovery. During the spring (moderate temperature), the asphalt mixture exhibits elastic properties. Viscous behaviour is present; however, the stiffness is sufficiently strong to restrict rutting. During summer (high temperatures for a long duration), the rutting problem is exacerbated. Asphalt mixtures behave as viscous materials; when their stiffness decreases, the strain imposed by traffic increases. Permanent deformation results from a portion of the strain in the viscous component that is not recovered [34].

Moisture with the friction force of tires may result in early wear of the rutting type along the wheel path, where aggregates dislodge from the asphalt surface pavement. Proper drainage facilities and road geometric design play crucial roles in mitigation [35].

Loading is the most important factor that correlates with temperature. It is represented by the axle weight (contact pressure), traffic volume (repetition or frequency of loading), and speed (time of loading) [36]. Cheung [37] investigated the influence of the frequency and loading waveform on the permanent deformation in two repeated loading experiments. The study found that compared with sinusoidal waves, a square waveform produced 10 % higher permanent strains. Additionally, larger permanent deformations occurred at lower frequencies, and thus at lower loading speeds than at higher frequencies. Lourens [38] gathered test results from various speed-load tests on the time effect. The study found that the deformation responses were approximately 27% higher at a loading speed of 12 km/h than at 80 km/h. Korkiala [39] concluded that bituminous materials are significantly more important for the loading speed and temperature effects of permanent deformation. Rutting increased by approximately 20-25 % under warm conditions (25 °C) and by 10-15 % under colder conditions (10 °C) when the loading speed was reduced from 80 to 12 km/h.

Construction quality is related to worker efficiency and the equipment used for construction. Aggregate segregation, temperature of asphalt mixtures during construction, and degree of compaction significantly affect rutting. Efficient paving is achieved by using appropriate equipment for the asphalt-laying process and compaction equipment with suitable weights. The compaction process is important for reducing air voids in asphalt pavements to increase their stiffness. A combination with an asphalt mixture that contains 4% air voids is

recommended [40]. The rutting potential results from the lowest percentages of air voids created by high asphalt binder concentrations. The asphalt binder fills the gaps in asphalt mixtures with fewer than 2 % air voids, rendering the mixtures weaker and unable to withstand rutting from an applied traffic load at high temperatures [41].

3 Laboratory approaches to assess permanent deformation (rutting)

Evaluating the performance of asphalt mixtures is essential to understanding their responses to loading over time at elevated temperatures [42]. The viscoelastic behaviour of bitumen and its high sensitivity to temperature changes directly affect pavement performance. The mechanical properties of asphalt mixtures are tested using bitumen and compacted asphalt mixture testing. Bitumen testing focuses on the rheological properties of the binder, whereas mixture tests reflect the actual behaviour of asphalt under various loads and environmental conditions. Laboratory tests are conducted and divided into four sections according to their relationship with the rutting performance indicators.

3.1 Performance-based tests

In this category, the tests are based on the properties of materials. The model response of the materials under a load can be directly predicted using the measured engineering attributes. Regarding bitumen tests, American standards adopt several tests for the assessment of rutting resistance. The Strategic Highway Research Program (SHRP) began establishing new tests in 1987 to measure the mechanical characteristics of asphalt, leading to the design of the Superpave binder. It is referred to as a "binder" because it serves both modified and unmodified asphalt cement. The Superpave test assesses mechanical properties that correlate directly with the field performance through basic engineering concepts. Superpave binder tests are also performed at temperatures relevant to the service pavement conditions [43]. Four properties are related to Superpave performance: handling and pumping, permanent deformation, fatigue cracking, and thermal cracking. The test equipment related to the permanent deformation (rutting) and fatigue cracking (structural cracking) performance is a dynamic shear rheometer (DSR). The binder condition utilised in a DSR is the origin, short-term aging in the thin-film oven test (RTFO), and long-term aging by the pressure aging vessel (PAV). The DSR measures two parameters: phase angle (δ), which is the time lag between the applied stress and the resulting strain, and complex shear modulus $|G^*|$, which is a measure of a material's overall resistance to deformation when subjected to repetitive pulse shear stress. The rheometer operates at moderate-to-high temperatures [44]. Permanent deformation (rutting) is controlled by restricting $|G^*|/\sin\delta$ at the test temperature to values higher than 1,0 kPa for the original binder and 2,2 kPa for the aged binder by the thin film oven test according to AASHTO M320 [45], ASTM D-7175 [46], and EN 14770-12 [47]. The viscoelastic behaviour of bitumen under oscillating loads can be effectively evaluated using DSR testing.

Rutting develops as a result of non-recoverable pavement deformation. Because of the development of performance requirements for rutting resistance, a test that simulates the reality of the field more accurately should be adopted. Therefore, the DSR test was developed and complemented by a multiple stress creep and recovery (MSCR) test, which provides important indicators of bitumen performance against rutting [48]. This test procedure determines the asphalt binder recovery and non-recoverable creep compliance percentage. The purpose of this test method is to ascertain whether an asphalt binder exhibits an elastic response during shear creep and recovery at two stress levels at a particular temperature. The specimen is subjected to a constant stress for 0,1 s and then allowed to recover for 0,9 s. Twenty creep and recovery cycles are conducted at a creep stress of 0,1 kPa, followed by ten creep and recovery cycles at a creep stress of 3,2 kPa [49; 50]. Creep compliance (J_{nr}) is limited by AASHTO M332 [51], with a maximum value of 0,45 kPa for standard designation (equivalent single axle load less than 10 million and standard speed > 70 km/h), 0,2 kPa for heavy designation (equivalent single axle load 10 to 30 million and standard speed 20 to 70

km/h), 0,1 kPa for very heavy designation (equivalent single axle load > 30 million and standard speed < 20 km/h), and 0,05 kPa for extremely heavy designation (equivalent single axle load > 30 million and standing traffic < 20 km/h such as port facilities or toll plazas).

This method has important advantages, including its sensitivity to the nature of the rheology, as it distinguishes between the elastic and viscous behaviours of the asphalt binder and its behaviour under different loads at various temperatures. This method is considered to be technically advanced. However, it has limitations, including the sensitivity of the results to the specimens in terms of thickness and the presence of bubbles, and most importantly, it does not capture the bitumen behaviour that is modified by some types of additives whose recovery responses are delayed [52; 53]. Table 1 summarises the general concepts of the DSR and MSCR tests.

Table 1. General concept of a DSR and MSCR tests [52; 53]

Item	MSCR	DSR
Type of test	Creep-recovery	Oscillatory shear
Binder type	Aged (RTFO)	Unaged, Aged (RTFO, PAV)
Cycle number	10 cycles each stress level (0,1 s load, 0.9 s recovery)	Sweep (frequency/heat)
Behaviour	Non-linear	Linear
Rutting factor	Jnr, % recovery	$G^*/\sin\delta$
Rutting interpretation	<ul style="list-style-type: none"> - Lower Jnr indicates a high rutting resistance - High % recovery indicates a high rutting resistance 	<ul style="list-style-type: none"> - High $G^*/\sin\delta$ indicates high rutting resistance
Output sensitivity	Accurate and effective with modified bitumen	Inaccurate with modified bitumen (may give misleading results)
Correlation with rutting	Strong	Middle
Purposes	To identify traffic categories (heavy, standard, and extreme)	To determine the performance grade of the bitumen
Factors affecting results	<ul style="list-style-type: none"> - Binder properties (grade, chemical composition) - Temperature (high temperature led to an increase in Jnr, decrease in % recovery) - Stress level (high stress leads to a high rutting, nonlinear behaviour) <ul style="list-style-type: none"> - Load application accuracy - Air bubbles - Test equipment, such as plate slippage or uneven thickness 	<ul style="list-style-type: none"> - Binder properties (grade, chemical composition) - Temperature (high temperature led to high G^* and lower δ) - Loading frequency (high frequency (high speed) leads to the binder behaving as stiff, and lower frequency (low speed) leads to the binder behaving as soft) <ul style="list-style-type: none"> - Binder aging - Binder modification - Air bubbles - Test equipment, such as plate slippage or uneven thickness

Although bitumen tests are considered a fundamental step in understanding the rheological behaviour and resistance to permanent deformation at high temperatures, these tests alone do not reflect the actual performance of pavements under repeated traffic loads. This is because rutting is the result of complex interactions between the asphalt binder and the aggregate characteristics. Hence, compacted asphalt mixture tests are important. As bitumen behaves viscoelastically under normal loading conditions, asphalt mixtures exhibit viscoelastic characteristics. Consequently, asphalt mixtures cannot be described using linear elastic theories, which are determined by the Young's modulus. Asphalt mixtures can be characterised based on their stiffness modulus, which is influenced by the temperature, loading

rate, and applied load. The stiffness of asphalt mixtures (stress–strain relationship) is generally directly related to rutting and can be assessed using numerous tests. Static and dynamic moduli are terms used to describe the stiffness. The elastic or dynamic stiffness is defined when the applied test force is dynamic (short loading rate). Static stiffness is defined when the applied test load is static (long loading time) [54].

A static compressive creep test measures the total strain–time relationship of a mixture in a laboratory, either confined or unconfined. Either a load–unload cycle or an incremental load–unload cycle (repeated) can be used in the static creep test, which results in adequate information to identify the instantaneous elastic (recoverable) and plastic (irrecoverable) deformation according to the response of the material. A standard sample size is 100 mm in diameter and various heights (40, 50, 65, and 100 mm), which is often prepared by either coring or compacting to the required dimensions [55]. During the unconfined static creep test, a cylindrical specimen is subjected to an axial load of 100 kPa for one hour at 40 °C. Because the sample may fail too soon, the applied pressure and test temperature should typically not be higher than 206,9 kPa and 40 °C, respectively [56]. Similar to the unconfined static compressive creep test, the confined static compressive creep test (also called the triaxial creep test) uses a confining pressure of approximately 138 kPa, which enables the test conditions to resemble field conditions more closely [57]. In repeated compressive creep tests, the haversine pulse load consists of 0,1 s loading and 0,9 s resting during a 3-hour total test time (approximately 10000 cycles) [58].

A typical relationship between the loading time or cycle and the obtained total strain can be predicted from the static and repeated compressive creep tests using the power models in Equations 1 and 2, as shown in Figures 2a) and b).

$$D(t) = at^m \tag{1}$$

Where $D(t)$ denotes strain at any time (viscoelastic compliance); t denotes time; a and m denote model coefficients.

$$\varepsilon_p = aN^b \tag{2}$$

Where ε_p denotes strain at any cycle; N cycles (1 to 10.000); a and b denote model coefficients.

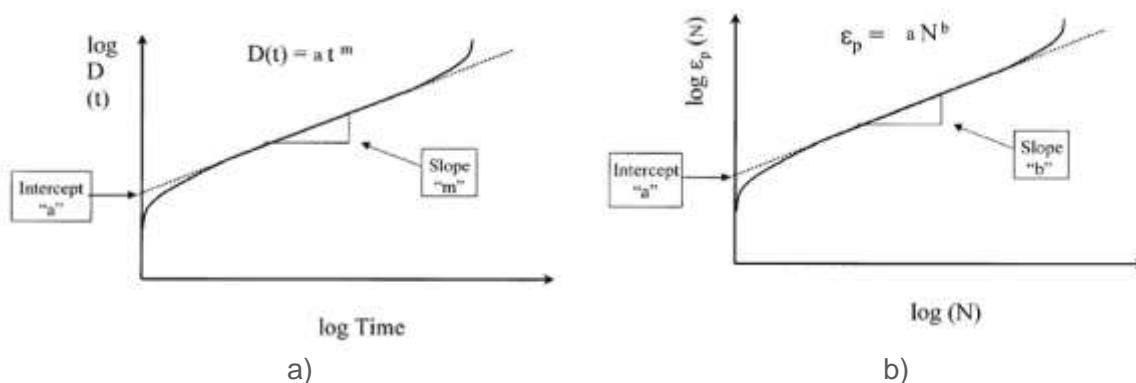


Figure 2. Typical relationship of static and repeated creep tests: a) static creep test results; and b) repeated creep test results [55]

The coefficients of the power model indicate permanent deformation. A larger coefficient a denotes higher strain and a lower modulus (high rutting sensitivity). In addition, a higher slope angle (m and b) suggests an increased rutting sensitivity.

In dynamic modulus tests, a specimen is subjected to a repeated axial cyclic load with a defined frequency and cycle duration. The loading cycles and frequencies of the dynamic modulus tests differ from those of the repeated static load tests. Dynamic modulus tests are employed with loads over a range of frequencies (often 1, 4, and 16 Hz) for a time of 30-45 s

at different temperatures [57]. Table 2 lists the general concepts of the static and dynamic creep tests.

Table 2. General concept of static and dynamic creep tests [55]

Item	Static	Dynamic
Load type	Continuous constant load at a constant temperature	Repeated (pulsing) load
Load simulation	Simulates the effect of a constant load on the road	Simulates vehicle traffic (more realistic)
Strain relationship	With the time of loading	With the number of cycles
Advantages	<ul style="list-style-type: none"> - Simple and easy to implement - Gives a clear idea about the creep characteristics 	<ul style="list-style-type: none"> - Much closer to real service conditions - Its accuracy is higher in assessing rutting resistance
Drawbacks	<ul style="list-style-type: none"> - Does not simulate the actual load of vehicle movement - Less accurate in predicting real rutting 	<ul style="list-style-type: none"> - More complex - Requires advanced equipment - It is more time-consuming
Rutting assessment	Primary assessment	Final accurate assessment
Factors affecting results	<ul style="list-style-type: none"> - Temperature - Binder properties (grading and chemical composition) - Aggregate type, binder content, and air voids - Load level (high load leads to faster creep) - Specimens compaction type and level - Load duration (high load duration leads to high permanent deformation) 	<ul style="list-style-type: none"> - Temperature - Binder properties (grading and chemical composition) - Aggregate type, binder content, and air voids - Specimens compaction type and level <ul style="list-style-type: none"> - Loading frequency - Loading type (magnitude and number of repetitions)

Another measure is the dynamic modulus in terms of the complex modulus $|E^*|$ and phase angle (lag between the highest recoverable strain and highest stress) by applying axial compressive stress, as well as a performance-based test for rutting. Dynamic modulus tests can be classified into three categories: unconfined, confined, and shear dynamic tests. A cylindrical test specimen is subjected to an axial haversine load to perform the unconfined dynamic modulus test, and lower specimen heights may be successfully employed. The confined dynamic modulus test enables the calculation of the phase angle and is similar to the unconfined test (same load and specimen dimensions) with an applied lateral confining pressure [57]. A hydraulic testing machine called an asphalt mixture performance tester (AMPT) can apply axial loads to test asphalt specimens over a wide range of frequencies and temperatures to determine the dynamic modulus, phase angle, and flow number. Four standards explain the preparation of asphalt mixture specimens and their testing using this device. The dynamic modulus test is one of the oldest methods and was first established in 1979 by ASTM D3497 [58]. The purpose of this standard is to prepare specimens and determine the dynamic modulus $|E^*|$ used in the mechanistic-empirical design. Currently, it has been withdrawn because of the emergence of more efficient, accurate, and suitable testing methods for current applications. Similar to the ASTM D3497 method, AASHTO T 378 [59] is used to determine the dynamic modulus $|E^*|$ and flow number for rutting evaluation and provides the basic input for the mechanistic-empirical design guide. The procedure is intended for mixtures that are dense and gap-graded, with nominal-maximum aggregate sizes of up to 37,5 mm. AASHTO T 342 [60] involves the preparation and testing of hot mix asphalt (HMA) to determine the dynamic modulus and phase angle and their alteration according to temperature and loading speed variation in the viscoelastic response, and predicts pavement

behaviour. The dynamic modulus is a material property, rather than a specimen property. Therefore, the specimen size does not influence the dynamic modulus. Consequently, the standard AASHTO TP132 [61] describes the test method by utilising a small-scale specimen with a diameter of 38 mm and height of 110 mm, which was adopted in 2019. Small specimens can be obtained from the field for the direct assessment of as-built pavement properties, or numerous small specimens can be cored from a single gyratory compactor sample. The use of small specimens tends to improve test reliability.

AASHTO TP79 [62] is another test that uses the AMPT device to determine $|E^*|$, phase angle, and flow number. A specimen with a diameter of 100 mm and a height of 150 mm is compacted using a Superpave gyratory compactor. Dense and gap-graded asphalt mixtures with a maximum aggregate size of 37,5 mm are used in the test. This test is suitable for mixes used on expressways and urban roads, as well as for polymer-modified mixes. Axial loads are applied at frequencies ranging from 0,01-25,00 Hz, with or without lateral pressure. The stress–sweep rutting (SSR) test, according to AASHTO TP134 [63], is an available rutting test. This test, which began with the flow number test configuration and was initially developed to be compatible with the AMPT, exposes the test specimen to two temperatures (high and low) depending on the pavement location. Several vertical load pulse blocks (200 loading cycle repeats) with deviatoric increased stress of 689, 482, and 896 kPa for the high-temperature test and 482, 689, and 896 kPa for the low-temperature test. The test is conducted with frequencies load for a time of 0,4 s, followed by 3,6 s resting for the high-temperature test, and 0,4 s load followed by 1,6 s resting for the low-temperature test. A constant confining pressure of 69 kPa is applied. A shift model can be developed using the results of the two SSR experiments at high and low temperatures. To predict the permanent deformation of asphalt layers under different deviatoric stress levels, loading durations, and temperatures as functions of pavement depth and time, the shift model is integrated into the pavement performance prediction program FlexPAVETM as a rutting strain index (RSI) factor. Additionally, a performance-engineered mix design for asphalt mixtures can be used for the SSR test results. The results can be used to create a 'rutting master curve', which defines the rutting potential of the mix under various traffic and temperature combinations [64]. Table 3 summarises the advantages and drawbacks of these standards [58-63].

Lateral movement (shear failure) occurs as a result of permanent deformation under axial loads. Therefore, additional tests are occasionally conducted alongside routine tests to gain a deeper understanding and assessment of the shear resistance properties of asphalt mixtures. The shear dynamic modulus test is referred to as the frequency sweep at constant height test. The shear dynamic modulus equations are the same as those mentioned above; however, the term $|E^*|$ is typically substituted by $|G^*|$ to signify the shear dynamic modulus. Two different testing devices can be used to determine the shear dynamic modulus: the Superpave shear tester (SST) and the field shear tester (FST). According to AASHTO TP 7 [65], the simple shear test (SST) device to assess the fatigue cracking and permanent deformation properties of HMA was established using the SHRP to determine the characteristics of mixtures that can be utilised to predict their performance. Two aluminium plates were used to glue the cylindrical test specimen, which has dimensions of 150 mm in diameter and 50 mm in height. From the bottom plate, the specimen is loaded with shear using a sinusoidal loading pattern. The standard for this test was withdrawn in 1994, and the reason was not specified. However, organisations withdraw any standard specification for reasons such as developing the test to be more modern and effective or perhaps due to insufficient performance requirements. A quasi-direct shear dynamic modulus field shear tester (FST) was launched as part of NCHRP Project 9-7 to control the hot asphalt mixtures produced by Superpave. Only three differences exist between FST and SST devices: specimen position (horizontal in SST, vertical in FST), technique of maintaining specimen height (axial force in SST, rigid spacer in FST), and method of shear loading (applied stress to maintain a constant strain of approximately 100 microstrains in SST, while applying stress and measuring the shear strain in FST) [55]. ASTM D 7312 [66] and AASHTO T 320 [67] specified a method test to determine the stiffness complex shear

modulus $|G^*|$, phase angle δ , and permanent shear strain of asphalt mixtures using a device test developed through the Superpave program.

Table 3. Advantages and limitations of the tests that utilize the AMPT device [58-63]

Test	Advantages	Limitations
ASTM D3497	<ul style="list-style-type: none"> - Provides data on mechanical performance. - It covers a wide range of load frequencies and temperatures, helping to understand the viscous and elastic properties of the asphalt mixture. 	<ul style="list-style-type: none"> - Complicated and time-consuming. - It is old and requires specialized and precise equipment that may not be available in all laboratories.
AASHTO T 378	<ul style="list-style-type: none"> - Provides data to create a master curve that is important for the mechanical properties, important for evaluating performance across a wide range of frequencies and temperatures. - Its methodology helps improve the design of mixes and increase the lifespan of paving, which leads to reduced maintenance. 	<ul style="list-style-type: none"> - Preparing the specimen requires following precise procedures and may be prone to human error. - The test requires a long time (4-8 hrs).
AASHTO TP342	<ul style="list-style-type: none"> - Its accuracy is good - Predicting the performance of mechanistic-empirical pavement design is more accurate. - Assessment of the model's stiffness under repeated loads, which is directly related to the formation of rutting. - Generate a master curve with various temperatures and loading frequencies. - Provides comprehensive stiffness measurements. 	<ul style="list-style-type: none"> - Less efficient than other tests - It takes longer than other tests because the examination is conducted in detail. - Master curve models require expertise, so a lack of experience may reduce design accuracy. - It is essential to prepare all specimens consistently to obtain reliable results.
AASHTO TP132	<ul style="list-style-type: none"> - It is possible to better predict the behaviour of asphalt pavements under real traffic loads and temperatures (designed for permanent deformation measure). - Provides important data for pavement design. - It is possible to test over a wide range of temperatures and various load frequencies. - Since utilizing small specimens, it is considered a material saving. 	<ul style="list-style-type: none"> - The equipment is complex and requires trained technicians with specialized expertise, which increases labour costs. - It is difficult to compact small samples to achieve laboratory compaction, so extracting from larger samples may be challenging, increase costs, and require the use of specialized equipment. - The test requires strict quality to obtain accurate results.
AASHTO TP79	<ul style="list-style-type: none"> - Provides data that are directly related to the mechanical performance of the mixture, and the findings are used in a mechanistic-empirical design - Allows testing at different temperatures and load frequencies 	<ul style="list-style-type: none"> - Specimen preparation requires precision, time, and effort - The testing time is long (4-8 hrs).
AASHTO TP134	<ul style="list-style-type: none"> - Designed for permanent deformation measurement under various stresses and temperatures - The output is reliable and provides the possibility of using its outputs in design software, where rutting during the service life of the road can be predicted. 	<ul style="list-style-type: none"> - It takes time to prepare the specimens. - The proportion of air voids greatly affects the examination, so care is needed in preparing the specimens.

The examination comprises two procedures: procedure A is a frequency sweep test, and procedure B is a repeated shear test at a constant specimen height. Cylindrical specimens (150 mm in diameter and 50 mm in height) made in a laboratory using a gyratory are used in both procedures. These tests are recommended for combinations with a nominal maximum

grain size of 12,5 mm. The difference between procedures A and B is the loading type. In procedure A, repeated sinusoidal shear loading is administered at ten frequencies at a specified temperature, whereas a variable axial load is delivered to inhibit specimen dilation. In procedure B, a cyclic haversine shear stress with a magnitude of 69 ± 5 kPa is applied for 0,1 s, followed by a 0,6-s rest interval. Throughout the examination, the specimen height remains constant within a range of $\pm 0,0013$ mm via adequate axial load application.

Another method is to determine the complex shear modulus using a DSR according to the ASTM D 7552 standard [68]. Rectangular test specimens 49 ± 2 mm in length, 12 ± 2 mm wide, and $9 \pm 1,5$ mm thick can be extracted from field cores or gyratory or Marshall laboratory compacted specimens. The test is implemented over a range of 10 to 70 °C temperature at frequencies of 0,01 to 25 Hz and strains of 0,001-0,100%. A complex shear modulus at 0,01 % strain at 10 separate frequency values ranging from 0,01-10,00 Hz has been calculated from the resulting master curve. The test is not suitable for open-graded or stone mastic asphalts because of the geometry of the specimens tested, whereas it is advisable for densely graded asphalt mixtures containing 19 mm or smaller nominal maximum size aggregates.

Other measurements besides the dynamic modulus are directly related to the rutting performance. One of the earliest performance tests was the resilient modulus (MR) (stress/strain ratio). It is an important parameter for pavement structural thickness design using the AASHTO 1993 design method [69], and it can also be used as an input for pavement assessment, as well as for assessing the quality of materials. The relatively easy testing process outlined in ASTM D7369 [70] can be performed on field cores and laboratory-compacted cylindrical specimens. A Marshall specimen or gyratory-compacted 63,5 mm in height and diameter in 101,6 or 152,4 mm, can be tested at a temperature of 25 °C with a specified repeated load between 22,2 and 89,0 N, loading frequency (haversine waveform), and load duration (0,1 s and a rest period of 0,9 s). The test series can alternatively be performed at several temperatures, such as 5, 15, 20, and 25 °C, with a single loading frequency for each temperature.

The American Association of State Highway and Transportation Officials (AASHTO) developed new guidelines to enhance information about the rutting potential of asphalt mixtures using AASHTO TP 116 [71]. According to this standard, the incremental repeated load permanent deformation (iRLPD) test is performed at a critical temperature based on degree-days and depth from the surface in four 500-cycle varying repeated haversine axial compressive load pulses of 0,1 s every 1,0 s applied on either 150 mm diameter and 115 mm height specimens in one increment 500 cycles without confining pressure or maintaining a constant confining pressure of 69 kPa in four increments of 500 cycles. The cumulative axial strain is measured as a permanent deformation property of the asphalt mixture, and the result is provided by the minimum strain rate (m^*), which is defined as the lowest permanent axial strain in the last cycle of each increment. Dense and gap-graded mixes with a nominal maximum aggregate size of 37,5 mm are the targets of this procedure.

The ASTM D 8360 [72] committee published another approach to assess the rutting resistance of asphalt mixtures that have a nominal maximum size aggregate of 19 mm or less at higher temperatures of 50 ± 15 °C, based on the local climate. The specimens can be gathered from a cored asphalt pavement in the field or compacted cylinders with a diameter of 150 ± 2 mm that have been compacted by Superpave gyratory compactors. The loading device maintains a constant average deformation rate of 50 ± 2 mm/min when the compressive load is applied. The rutting resistance is assessed using the rutting tolerance index (RT index), which is determined from the peak load. Overall, a higher rutting resistance and, hence, a smaller rut depth in the field, is associated with higher RT index values.

The European standard adopted numerous tests for determining the stiffness modulus of asphalt mixtures following EN 12697-26 [73]. Any one of the following tests suffices to determine the stiffness modulus, which is divided into three main categories of tests: indirect tensile, bending, and direct uniaxial tests.

The indirect tensile test measures the elastic stiffness of the bituminous mixes using cylindrical specimens of different thicknesses (30–75 mm) and diameters (80, 100, 120, 150, and 200

mm) according to an aggregate size that is either cored from a road pavement or produced in a lab. A load is applied to the specimen, resulting in a lateral displacement of 0,005 % of its diameter (maximum stress recorded). The load is given as a pulsed frequency with a cycle duration of $3,0 \pm 0,1$ s. The test temperature of 40-60 °C may be employed, provided it is consistently maintained over the examination duration. Upon completion of the inspection, the specimen is rotated by an angle of 90°, after which the test is repeated in the new orientation, and the average is recorded. This test is simple and cost-effective [73], Annex C.

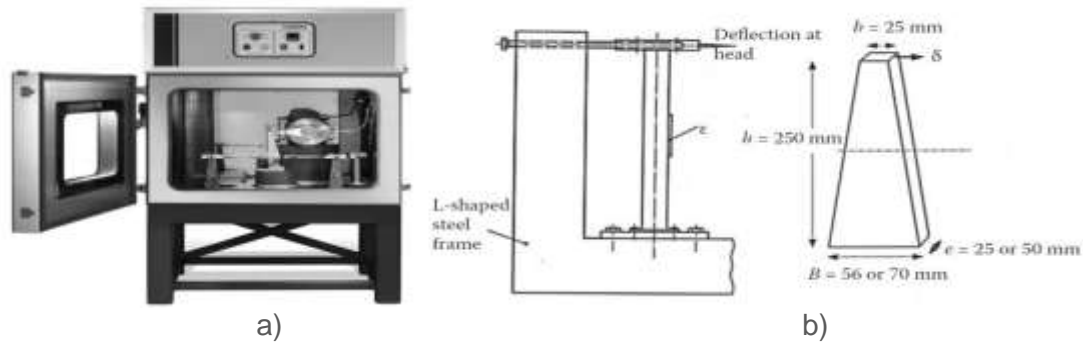


Figure 3. Two-point bending device: a) device; and b) schematic of the specimen [54]

Bending tests are another method used to determine the stiffness, which involves three- or four-point bending tests on prismatic specimens. The prismatic specimens were exposed to three- or four-point periodic bending with free rotation and (horizontal) translation. To achieve the desired strain amplitude of 50 ± 3 microstrains, a sinusoidal periodic loading (force) is applied. For the three-point bending test, the usual loading frequency and temperature settings are 15 °C and 10 Hz, and for the four-point bending test, 20 °C and 8 Hz, respectively. Figure 4 shows a schematic of the three- and four-point bending tests [73], Annex B. Both tests permit a wider range of temperature to 40 °C based on viscoelastic behaviour and environmental conditions.

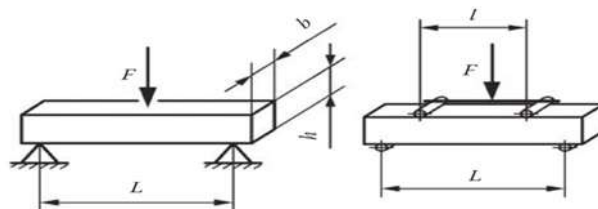


Figure 4. Scheme of three- and four-point bending tests [54]

Direct uniaxial tests are applied to a cylindrical or prismatic specimen sawed from laboratory-made slabs or taken from a road pavement to determine the stiffness modulus. At a specified temperature, usually 15 °C, but permits use of 40-50 °C based on requirements. The tensile load (0,02 s loading time) and the resulting strain is recorded. To derive the stiffness and master curve in terms of the loading times, at least four loading times are required for at least one temperature, and at least two loading times for the other test temperatures. The specimens are maintained at the test temperature for at least 4 h during temperature stabilisation if their diameter or width was less than 100 mm and for at least 8 h under other circumstances [73] Annex D.

Two test procedures are outlined in EN 12697-25 [74] to ascertain the resistance of the bituminous mixture to permanent deformation during cyclic compression with confinement. Method A uses a uniaxial cyclic compression test with some confinement to ascertain the creep properties of bituminous mixes. This type of approach performs well in estimating the achievable rutting behaviour of gap-graded mixes, particularly when there is a significant stone

proportion. Method B uses a triaxial cyclic compression test to ascertain the creep properties of the bituminous mixes. High temperatures are typically used: 40 °C for the base course and 60 °C for the wearing course. Other temperatures may be used based on local requirements, and modified or unmodified asphalt reaching 60-70 °C.

3.2 Performance related-tests

A test is associated with engineering characteristics that are indirectly related to the performance. Physical tests on asphalt cement can be used to deduce or predict its performance during permanent deformation. The stiffness of an asphalt mixture is a crucial attribute pertaining to the load-bearing capacity of road pavements. The binder contributes to the stiffness of the mixture, as demonstrated by the fact that a stiffer binder results in a stiffer asphalt mixture. Consequently, the asphalt cement stiffness must be defined within a specification as it pertains to the properties of the binder related to the stiffness [54]. The asphalt industry has undertaken substantial efforts to delineate the performance-related specifications for paving binders. Testing the mechanical characteristics at high, medium, and low service temperatures is the main emphasis of many paving bitumen requirements. Among the properties of the binder relevant to permanent deformation at elevated temperatures, which are covered in most standards, is the softening point of bitumen tested using the ring-and-ball test according to EN 1427 [75], ASTM D36 [76], and AASHTO T53 [77]. The softening point provides an understanding of the effect of elevated temperature on the binder performance. Dynamic viscosity measurement using a capillary tube, according to EN 12596 [78] and ASTM D 2171 [79], is a common test used in most national standards as an elevated service-temperature parameter. Needle penetration, according to EN 1426 [80], ASTM D5 [81], and AASHTO T49 [82], has been employed for decades to test binder stiffness at intermediate temperatures.

3.3 Empirical tests

Empirical tests revealed the presence of potential rutting. Conventional Marshall and Hveem mix design tests may be considered empirical tests. Although these tests do not measure any fundamental material characteristics based on or related to rutting, they can be correlated with in-service pavement rutting indicators such as Marshall stiffness, which arises from Marshall stability divided by flow [42].

3.4 Simulative tests

The test involves a miniature road simulation. In the laboratory, the test parameters are configured to simulate a road. The test results are merely responses to the applied loading. One of the simulated tests is the wheel-tracking test. A rut formed by repeatedly passing a loaded wheel at a steady temperature is used to measure the susceptibility of the asphalt mixtures to deformation. Wheel-tracking test methodologies are employed in Europe and the United States to assess resistance to permanent deformation or sensitivity to rutting. Laboratoire Central des Ponts et Chaussées (LCPC) rut testers are widely used in France. A 400-mm diameter pneumatic tire pressurised to 600 kPa was used to apply a 5000-N load to the two specimens in an air chamber. The specimens were 500 mm in length, 180 mm in width, and either 100 or 50 mm in thickness, based on the laid pavement thickness (50 mm for pavement thicknesses less than 50 mm and 100 mm for pavement thicknesses greater than 50 mm). The temperature test is 50, or 60 °C with a limit rut depth of 10 mm at 30000 and 10000 passes, respectively. Throughout the test, the rut depth in the LCPC rut tester has been observed, and a correlation with the cycle number was found [42].

The Georgia loaded wheel tester was developed in the mid-1980s by the Georgia Institute of Technology and the Georgia Department of Transportation. The load was applied using a saddle-shaped aluminium wheel. On the surface of the specimen, an inflated rubber hose is straddled between the saddle and the specimen surface. The loaded wheel rotates back and forth. During the testing process, a wheel load of 500 N is applied to produce a hose pressure

of 690 kPa at a constant temperature of 40,5 °C. A statistical correlation between the rut depth and cycle number was found [42].

Full-scale testing facilities that apply full-scale loading in a short period are known as accelerated pavement testers (APTs). The results of the laboratory tests are confirmed using APTs. This is particularly useful when studying pavement structures. Generally, these tests fall into three categories: test tracks, circular tests, and linear tests. The full-scale outdoor pavements built specifically for testing are known as test tracks. Full-scale trucks are driven onto pavement sections to apply loads. In the circular test, the loads are applied along a circular path. Circles less than 20 m in diameter are typically maintained in structures with climate control. Tests with larger diameters, frequently between 20 and 40 m, are conducted outside without artificial climate control. Linear testers provide linear loads to short pavement section lengths (often 10-20 m) at low speeds of 10-20 km/h. Some linear testers are inside a climate-controlled facility or outdoors at speeds of 10-40 km/h [42].

One of the earliest wheel-tracking tests, the Hamburg wheel-tracking test (HWT), was initially developed in Germany in the 1970s and has been utilised by numerous organisations in the US. AASHTO T 324 [83] specifies the test approach. The test evaluates the susceptibility of the bituminous mixture to moisture, as well as its resistance to permanent deformation. Four cylindrical specimens, each with a 150 mm diameter and 62 mm thickness, may have been evaluated with the apparatus simultaneously. Alternatively, 320 mm long by 240 mm wide prismatic specimens can be employed. The thickness can range from 40 to 120 mm based on the maximum nominal size of the aggregates. The air voids required for these specimens are $7 \pm 1\%$. The specimen's surface is directly subjected to the solid metal wheel load of 705 ± 2 N and frequency of 26,5 cycles/min, which is 204 mm in diameter and 47 mm wide, without the rubber pneumatic hose. The test temperature is 25-70 °C, but frequently 50 °C, and the specimens are submerged in water. The test endures roughly six hours and twenty minutes, with 10,000 load cycles (20,000 wheel passes). After a set number of wheel passes, the rut depth is measured, and the representative rut depth of the bituminous mixture under test is the average of at least four measurements. The minimum number of passes required to achieve a 0,5-inch rut depth is recommended to be 15,000 for an equivalent standard axle load under 10 million, and 20,000 passes for an equivalent standard axle load ranging from 10-30 million passes.

Pavement agencies in the United States are increasingly using relatively new asphalt pavement analyser (APA) tests. AASHTO T 340 [84] specifies the test methodology. This test is one of the essential performance tests of the Superpave mix design. The APA has been employed to assess the endurance of the HMA mixtures to rutting, fatigue, and moisture. The apparatus of APA enables the simultaneous testing of three prismatic specimens (beams) that are 125 mm wide and 300 mm long, vibratory compacted, or two to six cylindrical specimens with a diameter of 150 mm and gyratory compaction. The thickness of each specimen is typically 75 mm. The air voids required for each type of specimen are $4 \pm 1\%$. A solid steel wheel positioned on top of a rubber pneumatic hose pressured at 690 kPa and placed at the centre of the specimen surface applies a load of 445 N to the specimens. The test temperature is typically 64 °C, and it endures for 8000 load cycles, or approximately two hours and fifteen minutes. Typically, tests are conducted in air. The representative rut depth of the bituminous mixture under test was determined by averaging the values of the six specimens measured during loading. The recommended minimum maximum rut depth is 5 mm for an equivalent standard axle load of less than 10 million, 4 mm for an equivalent standard axle load ranging 10-30 million, and 3 mm for an equivalent standard axle load greater than 30 million.

Table 4 shows the fundamental differences between the APA and HWT tests.

Table 4. Difference between APA and HWT tests

Item	APA	HWT
Purpose	Permanent deformation	Permanent deformation and moisture damage
Test condition	Air at 64 °C	Hot water at 50 °C
Load	Rubber pneumatic hose	Steel wheel
Findings	Rut depth	Rut depth and failure behaviour with the stripping point
Field simulation and use in modern specifications	The middle field simulation is used for assessment only	High field simulation is used to accept or reject the asphalt mixtures
Number of cycles	8000	10000

4 Approaches for improving resistance to permanent deformation (rutting)

Permanent deformation has been a concern for asphalt pavement engineers since the initial use of asphalt in the late 1970s and 1980s. Since then, researchers and engineers have endeavoured to find methods to enhance the resistance to this phenomenon or mitigate its intensification. The factors related to the asphalt mixture itself (the materials that make up the asphalt mixture) and the external factors, which are represented by the surrounding environmental conditions and applied loads, can be considered the primary factors influencing this phenomenon, as clarified in Section 2. Undoubtedly, environmental and climatic conditions cannot be monitored in places where roads are constructed. In addition to preventing heavy vehicles from passing on the road, this will not satisfy the purpose for which the route is constructed. However, a particular vehicle weight can be controlled through heavy-vehicle-weighting stations. Because asphalt mixtures consist of two materials with various properties that significantly affect rutting, they can be altered to enhance certain properties related to rutting resistance. Therefore, it is vital to discuss common methods employed to overcome rutting.

4.1 Asphalt mixture design method

During the period from the 1950s to the 1970s, Marshall and Hveem's mixed design methods became popular. The Marshall stability requirements were enhanced, and voids in the mineral aggregate (VMA) were introduced. In most cases, both methods remain unmodified. In the late 1980s, the National Cooperative Highway Research Program (NCHRP) produced an innovative mix design approach called asphalt aggregate mixture analysis system (AAMAS). Consequently, AAMAS became the starting point for the Strategic Highway Research Program (SHRP), which devised another mixed design method called Superpave. Superpave has recently undergone an investigation, and numerous agencies are currently employing the new approach. In 1984, in the wake of severe rutting concerns, the AASHTO began releasing studies recommending ways to improve rutting [42].

Superpave is an efficient method for selecting materials for the design of asphalt mixtures formulated using SHRP. Superpave describes the contribution to permanent deformation resistance by applying performance-based criteria. The selection of materials and mix design directly reduces or regulates permanent deformation and other primary problems, such as fatigue and low-temperature cracking. It considers the influence of age and moisture sensitivity on the development of key distress factors [85; 86].

Stone mastic asphalt (SMA) was developed in Germany in the late 1960s to withstand the wear of studded tires. It has a long service life and is resistant to permanent deformation. It is a hot asphalt mixture with gap-graded particles that utilises the maximum aggregate fraction held by mastication (asphalt cement and filler). Reinforcement with carbon fibres, cellulose, other mineral fibres (slag wool and rock wool), and polymers (styrene-butadiene-styrene (SBS) and polyolefin) prevent the binder from draining down (stabilising additive) [87; 88]. Studies showed a significant alteration in polymeric SMA properties when heated at a temperature of

180–190 °C, and they recommended not to heat above 176 °C [89]. A SMA design method was adopted according to the BS EN 13108-5 standard [90].

By using asphalt cement with exceptional rigidity, the French Administration Roads developed asphalt mixtures known as Enrobé à Module Élevé (high modulus asphalt) "EME" in the 1980s. It exhibits a high level of resistance to rutting and permanent deformation [91; 92]. The European standard BS EN 13108-1 [93] is the standard of high-modulus mixtures.

Open-graded porous asphalt mixtures are differentiated by their free-draining characteristics, which enable water to flow easily through the mixture. Typically, they operate as a surface layer to drain water from the pavement surface. Under most circumstances, a thin surface layer of less than 50 mm is used. Because the fine aggregate or asphalt binder to separate the coarse aggregates is insufficient (pushing the coarse aggregates away from each other), the mixture exhibits a strong aggregate skeleton characterised by stone-to-stone contact, which provides good rutting resistance. In high-volume roadways, thick layers are unstable. Another benefit is that it minimises rutting in wet weather, resulting from the dislodging of aggregates from the pavement surface by the tires, and prevents hydroplaning accumulation, providing safety by maintaining driver visibility [34].

The LCPC mix design method was developed in France in the 1970s. Specialised testing has been employed on major highways and highways with high traffic volumes to prevent fatigue, low-temperature cracking, and rutting. A specific piece of equipment was developed for each test. The LCPC developed a laboratory compaction effort that imitates the compaction occurring during construction using a designated standard rolling compactor (similar to the Texas gyratory) [94].

4.2 Modification of asphalt binder

The asphalt binder significantly affects the properties of asphalt mixtures. It contributes to the stiffness of the asphalt mixture. Temperature affects the consistency; therefore, the stiffness varies, thereby altering the mechanical properties of the asphalt mixture. Overall, the mixture is stiffer and more resistant to long-term deformation when asphalt binder is used. Modifiers are mixed to stiffen asphalt binders at high temperatures by altering their specific properties. The demand for modified asphalt initially appeared during the 1970s when, owing to the high number of asphalt sources, heterogeneity in asphalt characteristics was observed. Modified bitumen serves four primary purposes in paving: it improves the asphalt adhesion to aggregate particles, increases the asphalt fatigue life, increases the asphalt stiffness modulus, and increases the asphalt resistance to permanent deformation. The aforementioned duties must be completed without impairing the workability of the mixture, if possible [95].

Polymers are the most commonly used asphalt-binder modifiers. It forms in three categories: Thermoplastic elastomers such as SBS, styrene-butadiene rubber (SBR), styrene–isoprene–styrene (SIS), styrene–ethyl–butadiene–styrene (SEBS), ethylene-propylene heteropolymer (EPDM), isobutene–isoprene copolymer (IIR), polybutadiene (PBD), natural rubber, and crumb rubber.

Thermoplastic polymers (plastics) include ethylene vinyl acetate (EVA), ethylene methyl acrylate (EMA), ethylene butyl acrylate (EBA), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS).

Thermosetting polymers (resins) include epoxy, acrylic, polyurethane, and phenolic resins. All these polymers were mixed with the asphalt binder at an optimum percentage to provide the highest resistance to permanent deformation, increase stiffness, improve cohesion, and improve thermal susceptibility.

Hamid et al. [96] investigated 2 % of SBS mixed with neat asphalt binder. The study showed an increase in viscosity at temperatures 135–165 °C. An increase in rutting factor $|G^*|/\sin\delta$, which increased by 1,51; 1,64; and 1,78 times at temperatures of 52; 58; and 64 °C. The asphalt mixtures were assessed using the Hamburg wheel rut test at 44 °C, and the rutting depth decreased by 80 % compared with the control mixture.

Mahmood and Kattan [97] investigated the effects of altering the asphalt binder (80/100) on its susceptibility to rutting by using SBS at concentrations of 1, 2, 4, and 5 % and crumb rubber

at levels of 3, 6, 9, and 15 % by asphalt binder weight, utilizing a vertical stirring mixer. A Hamburg wheel tracker machine was used to evaluate the rutting susceptibility. The study showed the optimum percentage of SBS was 3 %, which led to an enhanced rutting resistance of 3,5 times, whereas 9 % of crumb rubber led to an enhancement of 2,46 times compared to the control mixture.

Hemmati et al. [98] investigated two types of asphalt binders (PG 64-22 and PG 76-22) modified by several contents of SBR of 4, 6, and 8 % by asphalt binder weight. Rutting factor $|G^*|/\sin\delta$ and Multiple stress creep recovery (MSCR) tests at 64 and 76 °C have been used for rutting resistance. The study showed notable enhancement in the rutting resistance of asphalt binders resulting from the incorporation of SBR content.

Asphalt binder (PG 64-22) modified by 5, 10, 15, and 20 % by weight of styrene–isoprene–styrene (SIS) was investigated for rutting resistance by Mazumder et al. [99]. Rutting resistance has been assessed using $|G^*|/\sin\delta$ (rutting factor) from the DSR. The use of 5, 10, 15, and 20 % SIS content enhanced rutting resistance by 6, 30, 56, and 64 times, respectively.

To improve the 85-100 penetration grade resistance of asphalt binder to permanent deformation, Rahi et al. [100] examined the efficiency of modifying it with 2, 4, and 6 % by weight of styrene-ethylene/propylene-styrene (SEPS) using the Superpave specification factor, $|G^*|/\sin\delta$, from a DSR frequency sweep test conducted on both the neat and modified specimens at 40, 50, and 60 °C. The study's findings indicated that the neat asphalt binder's resistance to rutting can be enhanced by SEPS modification. The best percentage was 6%, which enhanced the rutting resistance for 40, 50, and 60 °C.

Xing et al. [101] investigated the rutting resistance of the modified asphalt binder PG 64-22 using PE from domestic waste. The percentages were 4,0; 6,0; and 7,5 % by asphalt binder weight; in addition, 3 % by weight of SBR was added to the PE-modified asphalt. They concluded that PE modification enhanced bitumen performance at high temperatures. The combined PE and SBR alteration improved the high-temperature performance of modified bitumen.

Vamegh et al. [102] investigated the performance of a mix of two types of polymers added to an asphalt binder of 60-70 penetration grade. Several ratios of 70:30, 50:50, and 30:70 of SBR/PP were mixed at several percentages of 3, 4, and 5 % of the weight of the binder. A dynamic creep test was used to evaluate the rutting, and the outcome value was the number of flows. The results showed that when compared with the control mixture, polymer-modified mixtures, particularly the 5 % 70:30 SBR/PP mixture, exhibited the lowest deformation owing to increased flexibility of mixtures containing a high ratio of SBR.

Chemical modifiers, such as polyphosphoric acid (PPA), are commonly utilised in asphalt binders; they can be utilised in combination with polymers to boost the high-temperature stiffness [103]. Experts in the field have discovered that adding small amounts of PPA (approximately 0,5 %) to polymer-modified binders enhances their performance and handling [104].

Jafari et al. [105] investigated the rutting resistance of a PPA-modified asphalt cement (PG 58-22). Three PPA concentrations (0,5; 1,0; and 1,5 %) by weight of asphalt cement were utilised. The unconfined complex modulus test at two testing temperatures of 40 and 55 °C was utilised to assess the rutting characteristics of asphalt mixtures. The study showed an enhancement in rutting resistance for both testing temperatures of 40 and 55 °C; the maximum improvement ratio was 2,21 times for the mixture modified by 1,5 % of PPA tested at 40 °C.

Liu et al. [106] investigated the effectiveness of the application of asphalt binder modified using waste engine oil (WEO) and PPA in asphalt mixtures. Initially, 2, 4, and 6 % of WEO were incorporated into neat asphalt to create the WEO-modified asphalt. The proportions of PPA (1 and 2 %) were subsequently integrated to formulate WEO-PPA-modified asphalts using a high-speed stirrer. The rutting performance was assessed using the rutting factor from the DSR test. The study demonstrated that the rutting factor of asphalt treated with 2 % WEO and 2 % PPA exhibited the most significant increase of 31,2 % relative to the original asphalt, indicating a remarkable enhancement in high-temperature performance.

4.3 Use of additives

One common method for reinforcing HMA is to add fillers and fibres [107]. Generally, the filler constitutes approximately 5 % of the mixture volume. Certain types of fillers interact with asphalt cement and alter its properties, in addition to filling the voids between the aggregate particles [108], and can affect the asphalt mixture characteristics [109]. When asphalt cement and filler are mixed, the asphalt–filler mastic that is created is considered to affect the performance of asphalt pavements [110]. Hamidi et al. [111] investigated the effects of three types of fillers: silica sandstone powder, Portland cement, and recycled lime powder from eggshells with three contents: 1, 3, and 5 % on asphalt mixture properties and performance. Static creep testing at 40 °C was used to determine the susceptibility of asphaltic materials to rutting. Their study showed that the rutting resistance of asphalt materials is significantly influenced by 5 % recycled eggshell lime powder. Several filler types significantly enhance rutting resistance, such as blast furnace slag and lime, fly ash, and hydrated lime [112-114]. A recent approach to reinforcing asphalt involves the addition of various types of fibres to the asphalt mixture. In practical applications, fibres have attracted much interest owing to their benefits as asphalt mixture additives because of their easy compliance with manufacturing techniques and superior reinforcing effects [115]. The addition of fibres to an asphalt mixture has been shown in numerous experiments to increase resistance to fatigue and permanent deformation, such as cellulose fibres at a dosage of 0,3 % by total asphalt mixture weight [116]. Several lengths (10, 20, and 30 mm) and percentages (0,25; 0,50; 0,75; 1,00; 1,25; and 1,50 % of total aggregate weight) were studied by Khaled et al. [117]. The study showed that a mixture containing 0,5 % with a length of 20 mm exhibited the greatest rutting resistance. Albayati and Ismael [118] improved rutting performance by adding various percentages of carbon fibres (0,20; 0,25; and 0,30 %) to the asphalt mixture's overall weight. Al-Saad and Ismael [119] investigated ceramic fibre, a cheap, easily obtained fibre, with contents of 0,75; 1,50; and 2,25 % by total weight of the combination. The study found that 1,5 % was the optimal ceramic fibre concentration for the best rutting resistance. Zhang et al. [120] assessed lignin, basalt, polyester, and polyacrylonitrile fibres with varying contents (0,15; 0,30; and 0,45 %) by total mix weight. For lignin fibre and polyester fibre, the ideal fibre percentage was 0,30 %, whereas for polyacrylonitrile fibre and basalt fibre, it was 0,15 %.

4.4 Optimizing aggregate interlock

Approximately 95 % of the asphalt mixture weight is composed of aggregate, which is its primary component. The internal friction angle accounts for 80 % of the shear resistance of the aggregate [121]. A higher aggregate interlock, which is beneficial for improving the rutting resistance, is achieved using high-friction aggregates that result from the angularity of the surface [122]. One of the physical characteristics of aggregates that contribute to their resistance to rutting is their particle shape and surface texture (smooth or rough). The roughness of an aggregate is represented by the presence of sharp edges on its surface, which enhance the internal friction between the aggregates and provide a good surface texture [123]. The crushed aggregate has a rougher surface than the round aggregate. The angularity of fine aggregates plays a crucial role in determining the skeletal strength. In densely graded asphalt mixtures, it plays an effective role in transferring loads and is embedded between the coarse particles. When fine aggregates are smooth and rounded, it permits the gravel to move easily, but rough and irregular aggregates lodge within the coarse aggregates and maintain a strong skeleton [124].

The aggregate gradation (particle size distribution) is crucial for relating the asphalt pavement response to loads, particularly with resistance to rutting [125]. Many gradation types of asphalt mixtures exist, such as densely graded, open graded, gap graded, stone matrix graded, and Superpave gradation [126]. Lira et al. [127] observed that a mixture's resistance to permanent deformation is influenced by the overall amount of coarse material. The mixture that matched a type of SMA mixture exhibited the least amount of rutting, whereas the combination that represented a gap-graded mixture exhibited the highest rutting. Thushara et al. [128] examined

the mechanical behaviour of bituminous mixtures made with aggregate gradations. Continuous and gap gradations are the two designed gradations discussed in the evaluation. The gap-graded aggregate mix exhibited superior rut resistance. Li et al. [129] concluded that when the aggregate skeleton structure is at its densest, which is obtained using the lowest VMA values, mixtures exhibit the best rutting resistance. To improve the high-temperature rutting performance, the aggregate gradation must be optimised. Lv et al. [130] found that the rutting resistance of asphalt mixtures is significantly affected by particles that pass through a 4,75 mm sieve. Uniform gradation of every size exhibits the lowest rutting resistance because smaller particles force the coarse aggregates to drift away from one another, destroying the integrity of the gradation.

The design aggregate structure is the distribution of aggregate particle sizes for a particular type of aggregate mixture. Common gradation systems are the Fuller formula and the Federal Highway Administration 0,45 power chart. The Bailey approach was initially developed by Robert Bailey at the Illinois Department of Transportation. This refers to the packing of aggregates to create good interlocking. Superior aggregate packing leads to a good rutting performance, which is typically achieved using a Bailey-type aggregate gradation. In addition, Bailey ratios are useful classification strategies for creating appropriate aggregate interlocks [131]. Almbaidheen et al. [132] assessed the influence of aggregate gradation types, such as gap-graded, FHWA-graded, UAE-graded, and Bailey-graded, on the rutting performance of HMA in the hot climate of the United Arab Emirates. The study and test findings provided an overview of the behaviour and performance of asphalt mixtures with various aggregate gradations. The findings indicated that in both the dynamic modulus and flow number tests, the gap and Bailey gradations had the highest rutting resistance.

In contrast, nominal maximum aggregate size plays a crucial role in the rutting, as mixtures containing a 12,5 mm maximum aggregate size have more rutting resistance than mixtures containing 9,5 mm [133]. Rutting resistance increased when the aggregate size of stone matrix asphalt increased from 9,5 to 25,4 mm with different temperature tests [134].

4.5 Enhance the asphalt pavement structure

Flexible pavements typically comprise a roadbed (subgrade) prepared under subbase, base, and surface course layers. Each layer is composed of a mixture of crushed rock or gravel, sand or crushed stone, filler, or bitumen in certain proportions. Throughout their lifespan, asphalt pavement structures are susceptible to several forms of strain, mostly rutting, fatigue, or thermal cracking. Geosynthetics are artificial polymer substances employed to enhance pavement performance against rutting. For asphalt pavement strengthening, geogrids, geotextiles, and geocomposites are commonly utilised between the soil and granular layers [135]. Base layer reinforcement is performed by limiting lateral shifts through material confinement, which increases the horizontal stress while decreasing the vertical stress, minimising the vertical strain on the top layer, and minimising the shear stress under the layer [136], as shown in Figure 5.

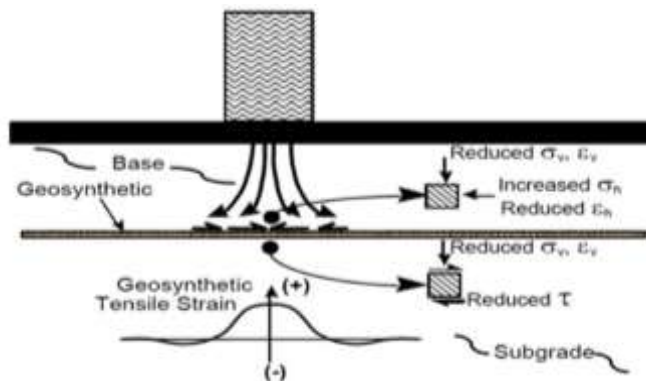


Figure 5. Base layer reinforcement scheme [136]

A study by Sun et al. [137] investigated the effect of geogrid-stabilized flexible pavements. The system consisted of three layers: an asphalt layer, granular base, and subgrade. A geogrid layer was utilised between the layers (asphalt base and base subgrade). The study showed that the geogrid acted as a lateral restraint and tensioned membrane, was positioned at the bottom of the asphalt layer, and exhibited greater benefits in terms of rutting reduction and tensile strain relief. Bertuliene et al. [138] evaluated the rut depth on an experimental road segment from the day of construction and compared the control and geosynthetic-reinforced portions. Their research revealed that geosynthetics limited pavement ruts related to shear deformation.

5 Conclusions

The following conclusions can be drawn:

- Under both high temperatures and frequent heavy loads, rutting is inevitable, irrespective of the material performance efficiency of the asphalt mixture.
- Wearing rutting develops when the asphalt pavement is poorly executed or when the surface is subjected to studded tires.
- Despite the importance of the attributes of the substances that constitute the asphalt mixture and their influence on the appearance of the rutting phenomenon, they can be easily handled using materials that have desirable properties.
- When evaluating asphalt mixtures, an objective must be established to select the appropriate test. If the objective is to assess the resistance of a mixture to rutting, the wheel-tracking test is the best and most efficient selection because it simulates real traffic conditions in the field. However, if the objective is pavement design and a description of the asphalt mixture behaviour, tests that provide the dynamic modulus, flow number, and phase angle values are certainly the best.
- The recommended rut depth values in the Asphalt Pavement Analyzer (APA) test are utilised to determine the appropriate mix during design or to assess the conformity (quality control) of the asphalt mixes in field manufacturing.
- No method is preferable over another for evaluating rutting resistance, but some factors must be considered when selecting an appropriate test. For example, the dynamic modulus provides indicators of the stiffness of an asphalt mixture under different temperatures and loads, which are closely related to the rutting performance and are suitable for pavement design. The APA applies wheel loads that simulate field conditions and is suitable for directly assessing rutting. The Hamburg wheel tracking (HWT) test is preferable when pavements are exposed to hot and humid climates. Dynamic creep simulates and plots the accumulation curve of rutting with the number of cycles or time, through which the flow number is determined, quality is assessed, and the service life of the pavement is predicted. Static creep provides a general concept of creep resistance under constant and continuous loads; however, it is less accurate for simulating traffic. The Marshall stiffness is the least accurate in terms of predicting and correlating with rutting and is considered a measure of the strength of the sample under load at a constant temperature. Thus, this is a useful preliminary indicator. However, an important factor influencing the selection of a test is the availability of laboratory equipment.
- In terms of evaluating the asphalt binder, the dynamic shear rheometer (DSR) and multiple stress and creep recovery (MSCR) testing methods, together with other conventional tests, are used because they are physical rheological tests that simulate the real performance of the binder at different temperatures and are crucial for modern applications and for obtaining a comprehensive evaluation. Conversely, conventional tests can be considered as experimental tests to determine which binder is the best in a group.
- Asphalt mixture and bitumen tests are essential to obtain a realistic and accurate assessment of pavement performance during service. This is because the rutting

phenomenon results from the integrated behaviour of the asphalt mixture. In addition to the bitumen properties, the characteristics of the aggregate, mix proportions, air voids, and compaction level directly affect the rutting resistance.

- Superpave is considered one of the most significant approaches to designing asphalt mixtures because it is directly related to rutting resistance.
- Fine aggregates are more important than coarse aggregates in asphalt mixtures because they act as fillers for asphalt cement between the coarse particles. Thus, there is no point in using coarse crushed aggregates that have acute angles that generate effective texture interlocking when mixed with fine rounded aggregates, where the latter become the balls on which the coarse aggregates roll.
- Because the utilisation of polymers to modify asphalt cement characteristics is vital for minimising rutting, it may be ideal and economically viable to mix two or more types of inexpensive materials to generate asphalt cement with optimum attributes.
- Geosynthetics are considered to be a very effective and widely adopted approach for reducing permanent structural and non-structural deformations; their value is evident in the field compared to other methods that are limited to laboratory tests. However, their use depends on the cost and application.

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