Moisture damage in asphalt mixtures: A review of the causes, testing, and mitigating methods

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Abstract:
The early 1900s saw the commencement of the production and utilization of asphalt mixtures for road paving. Asphalt pavements carry heavy repetitive traffic loads under extreme environmental conditions over their service life. Several issues and defects have emerged, resulting in highway deterioration and failure. One of the main reasons for asphalt pavement failure is moisture damage, and poor rainwater drainage, with the associated accumulation of water on the pavement surface, can exacerbate the consequences. Moisture damage in asphalt pavements refers to the reduction in stiffness and shortened lifespan owing to a lack of adhesion between the bitumen and aggregate or rupturing of the bitumen. This study consists of several sections: a comprehensive review of the concepts, theories, and causes of moisture damage in asphalt mixtures; a discussion of the factors contributing to damage; and a survey of the laboratory testing procedures used to assess the durability of asphalt mixtures against moisture effects. Several methods that focus on developing and strengthening asphalt mixtures to withstand the adverse impact of water are discussed. The study's main conclusion is that poor bitumen–aggregate adhesion is the primary cause of moisture damage in asphalt mixtures. Several laboratory techniques aid in assessing this damage, but each has limitations. To increase moisture resistance, several methods are suggested, including mix design optimization and fibre, polymer treatment, and additive utilization. The most important finding of the study is that mixing various modifiers may be economically beneficial in moisture damage resistance.

Keywords:
asphalt mixtures; asphalt cement; durability; moisture damage; moisture susceptibility

1 Introduction

Transportation is essential for maintaining interconnected communities and plays a role in national economies [1]. Transportation is also a significant factor in advancing and developing a nation [2]. Therefore, well-designed roads that ensure smooth and problem-free traffic are required, contributing to comfortable and efficient transportation [3-5]. Therefore, a significant portion of funding is dedicated to large development plans for constructing highway, indicating that the maintenance of their viability and extension of their service life are critical for avoiding massive future maintenance costs [6]. Major highways employ asphalt concrete because it is more flexible and less expensive to construct than Portland cement concrete [7-9]. Asphalt concrete construction requires aggregates and asphalt [10-11]. The strength of an asphalt mixture is generally related to the strength of adhesion between the asphalt and aggregate, which is the main component, making up 90-95 % of the total weight of the asphalt mixture and capable of withstanding the stresses caused by traffic loads and surrounding environmental conditions [12-14]. Heavy loads and climatic conditions can cause rutting, moisture damage, cracks, potholes, shoving, and other defects in asphalt pavements. Moisture damage is a widespread problem and fundamental cause of asphalt road failure [15-17]. Moisture damage is related to stripping, in which water ingress between the aggregate and asphalt reduces the adhesion forces, resulting in an unstable pavement under repetitive loads [18-20]. Moisture damage is one of the factors often affecting durability and generates a set of flaws in the structure of asphalt roads [21-23]. Water infiltrating asphalt pavements may originate from rainfall, vapour in the air, or the capillary characteristics of groundwater [24; 25]. The durability of asphalt mixtures refers to their ability to withstand extreme weather conditions and traffic loads and is dependent on the degree of adhesion between the asphalt cement and aggregate [26; 27]. Moisture damage causes pavement layer particles to dislodge, producing tiny potholes that could grow into deep pits which hinder manoeuvrability, thus affecting safety and road user comfort and increasing the likelihood of accidents [28-30].

Several research and review studies have investigated moisture damage in asphalt mixtures. However, a research gap remains in the selection of methods for strengthening asphalt mixtures to resist moisture damage and testing methods. This study aims to provide a comprehensive definition, concept, and cause of moisture damage and an understanding of the procedures for assessing asphalt mixtures for moisture effects. Finally, an overview of prior studies that have used various methods for strengthening asphalt mixtures to mitigate moisture damage is presented.

2 Concept, causes, and factors influencing moisture damage

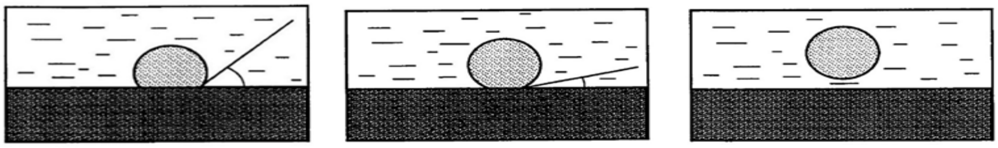
First and foremost, to identify the basic concept, moisture damage is defined as "stripping", meaning the separation or detaching of aggregate grains from asphalt. Because asphalt mixtures consist of aggregates and asphalt, stripping occurs through two common mechanisms: adhesion and cohesion. Adhesion is a bonding phenomenon between two materials and is typically described as the connection between two substances via chemical interaction. Cohesion is the chemical bonding of the material molecule itself [31; 32].

In terms of the adhesion failure mechanism, aggregates typically have a higher affinity for water than asphalt. Water ingress between the asphalt and aggregate occurs via osmosis, resulting in stripping. In this case, the rate of water osmosis between the asphalt film and aggregate surface is contingent on the film thickness and pressure differences across it. Moreover, the viscosity of asphalt has a significant influence in this instance because low-viscosity asphalt is permeable to water [33-35].

Cohesion failure occurs within aggregates or asphalt. Cohesion failure within the aggregate refers to the rupture of the aggregate structure caused by water action, which is directly related to aggregate porosity. When water inside aggregate voids freezes, the volume increases, resulting in significant internal tension that in turn causes the aggregate surface to rupture [36]. Asphalt cement failure occurs when water and asphalt cement combine, resulting in an absence of cohesiveness in the asphalt cement. Two failure stages can be distinguished in the cohesive failure of the asphalt cement. The first stage involves the softening of the asphalt cement when water is present: failure occurs in the asphalt film that coats the aggregate. The second involves the softening of the asphalt cement: the bond between the asphalt cement and aggregate weakens, causing a split between them. Therefore, cohesion failure is a combination of cohesion loss followed by adhesion loss [37; 38].

Water can also be trapped inside the air voids in asphalt pavements. As the temperature increases, water evaporation produces sufficient pressure to rupture the asphalt film. In addition, when the temperature decreases, the water freezes and expands inside the asphalt voids and generates tensile stresses inside the asphalt paving, which may result in the rupture of asphalt films [39; 40].

Based on thermodynamic theory, adhesion occurs as a result of the interfacial forces that form between an adhesive and a substrate, as well as the molecular interaction between them. The level of connection between the two materials is determined by their wetting properties, which, in turn, depend on the relative surface energy, represented by the contact angle (which ranges from 0–90°). High wettability is necessary for good adhesive bonding which results in a high contact angle [41], as shown in Figure 1 a). Because of the interaction between the asphalt cement and water, the water enters between the aggregate surface and asphalt droplet, causing the aggregate to attract water and thereby reducing the contact area and contact angle, as shown in Figure 1 b). The contact angle becomes zero when the asphalt droplet is fully removed from the aggregate surface, indicating that stripping has occurred, as shown in Figure 1 c).



a) b) c)

Figure 1. Illustration of the stripping process: a) large contact angle; b) small contact angle; c) zero contact angle [41]

The presence of mineral clays or other asphalt additives can produce spontaneous emulsification, which leads to stripping. Although rare, this can occur in hot mix asphalt (HMA) mixtures, weakening the asphalt-to-asphalt binding as a result of water in the asphalt [42].

Moisture damage occurs primarily via water, originating from fog, rain, or groundwater. This leads to a type of failure known as stripping. Cracks, potholes, and ravelling are other types of failure that can occur in asphalt pavements when subjected to traffic stresses. These types of failure are referred to as structural stripping [43].

The durability and stiffness theory of asphalt pavement revolves around the behaviour of the "Body Sticky" which determines the level of adhesion between different materials, namely the adhesion between aggregates and asphalt cement, whose natural characteristics differ.

Four primary concepts are presented to explain the adhesion between asphalt cement and aggregates. The mechanical theory relates to aggregate properties, such as porosity, surface texture, particle size, and surface area. The chemical reaction theory relates to the interaction between aggregates and asphalt cement. The surface energy theory relates to asphalt cement viscosity, and the wettability of asphalt cement is dependent on its viscosity, with low-viscosity asphalt having a more potent wettability than high-viscosity asphalt. Finally, the molecular orientation theory states that when asphalt cement and aggregate surfaces come into contact, the asphalt molecules orient themselves to meet the energy needs of the aggregate. That is, molecules attract one another because of their opposing charges. Despite the polar compounds of asphalt cement, asphalt molecules are considered non-polar, unlike water, which is classified as dipolar (having both positive and negative charges). Water molecules, with their higher polarity, can effortlessly meet the energy demands of an aggregate surface.

This is perhaps the reason why aggregates have a higher affinity for water than asphalt cement. However, certain types of asphalt (mostly non-predominant) contain low amounts of dipolar compounds, which have a higher effective energy demand than water, allowing the compounds to displace water molecules and provide high resistance to moisture damage [41]. Figure 2 illustrates the molecular orientation response to surface charges.

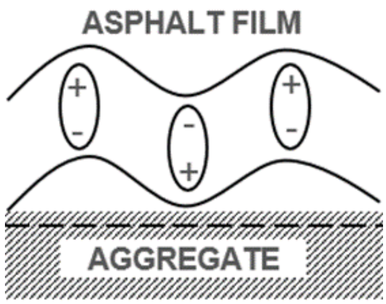


Figure 2. Molecular orientation [41]

Once the concept and causes of moisture damage are clarified, the factors affecting their occurrence can be defined. Knowledge of these aspects can help prevent or minimise the impact of moisture damage. The first aspect relates to the quality of the asphalt mixture or the features of the raw materials used to form it. The second aspect comprises external factors, characterised by environmental influences during and after construction.

The characteristics of asphalt concrete, including those of the aggregate and asphalt cement, and type of asphalt mixture are critical to the mechanisms of moisture damage. Aggregates consist of various minerals with different origins. Each aggregate has a characteristic chemical composition and crystalline structure. The physical properties of aggregates, such as porosity, surface texture, surface area, pore size or diameter, and mineralogy, play a significant role in stripping. Classification of an aggregate based on its water affinity is dependent on the physical phase in the stripping process. Hydrophilic aggregate has a stronger attraction for water than for asphalt cement, whereas hydrophobic aggregate has a stronger attraction for asphalt cement than for water and provides greater stripping resistance than hydrophilic aggregate [41].

Aggregate particles smaller than 75 µm are considered to be dust. An aggregate coated with clay or dust may hinder the ability of the asphalt binder to adhere to the aggregate surface and causes a bond-breaking effect which separates the asphalt binder film from the aggregate surface. The asphalt binder thus only coats and adheres to dust particles and does not coat large aggregate particles. Extensively removing dust or clay from the aggregate improves the ability of the asphalt binder to adhere to the aggregate. Some specifications for densely graded asphalt mixtures specify a dust portion in the asphalt mixture of 0,6-1,2 % relative to the asphalt cement weight [42].

The characteristics of asphalt cement play a primary role in stripping. Researchers have concluded that high-viscosity asphalt cement is more resistant to water displacement than low-viscosity asphalt cement [43].

Because each type of mixture has different characteristics and purposes, the stripping resistance of densely graded HMA and openly graded cold mix asphalt differ. Appropriate stripping resistance is achieved by using a suitably designed, densely graded HMA with adequate binder quantity and sufficient air voids. In addition, open-graded cold asphalt mixtures with anti-stripping properties provide excellent stripping resistance [44].

Weather during the construction of asphalt roads plays a significant role in moisture damage. The combination of cold and wet weather and the rapid heat loss in the mixture causes weak compaction, and the resultant broad air voids can significantly increase the likelihood of moisture damage [44]. After pavement construction, environmental conditions, such as

temperature fluctuations, wet–dry cycles, freeze–thaw cycles, and traffic load, play a primary role in the appearance of moisture damage. Finally, improper water drainage systems can significantly increase the risk of moisture damage [44].
The increasing moisture damage can be attributed to reasons other than those described above and other variables significantly contribute to the occurrence of moisture damage. These include insufficient construction processes related to stockpile segregation which could result in the appearance of pores and improper volumetric characteristics in asphalt pavements. This pore development allows water to infiltrate the pavement structure, thereby causing harm. Further, improper blenders in asphalt plants may encourage mixture segregation, which can result in the poor performance of asphalt mixtures when exposed to moisture. Finally, inefficient drying of aggregates results in moisture retention which hampers the adhesion of the asphalt to the aggregate, leading to the manufacture of asphalt concrete with a poor ability to withstand moisture damage. Furthermore, insufficient paving and compaction can result in a water-permeable mat [43].

3 Laboratory test methods for assessing moisture damage

The development of tests for identifying the tendency of asphalt mixtures to suffer moisture degradation dates back to the 1930s. Since then, several tests have been conducted to determine the sensitivity of mixtures to moisture. The testing methods used to examine the moisture damage vary. In general, assessment testing is categorized as follows:
Loose or uncompacted asphalt mixtures used for testing, with a close examination of the aggregate grains from which the asphalt has been stripped. Most researchers view this as a qualitative indicator of how well the aggregates and asphalt binder adhere to one another [45]. This category includes the boiling water test, performed according to ASTM D3625 [46] and CEN EN 12697-11-part C [47]. This approach outlines an easy procedure for visually detecting the separation of uncompacted bituminous-coated aggregate mixtures. For the stripping process, the mixture is boiled in distilled water for 10 min. After cooling, the aggregate is visually inspected to observe the presence of the bitumen coating. A bitumen-coated aggregate of less than 90 % indicates a moisture problem. This test is commonly used on new aggregate for rapid testing [48].
Each test has several advantages and disadvantages. Table 1 lists the advantages and disadvantages of the boiling water test.

Table 1. Advantages and disadvantages of the boiling water test [41]

Damage assessment	Advantages	Disadvantages
Visual inspection	- Could be employed for the initial assessment. - Minimum equipment needed. - It is suitable for assessing additive material efficiency. - Could be employed for quality control. - Can use different mixes, lab, batch, and from field.	- Personal evaluation. - use a loose mix. - Coating retention may be impacted by the purity of the water. - Difficult assessment of stripping with fine aggregates. - greatly depends on the viscosity of the asphalt.

The rolling bottle test is performed according to CEN EN 12697-11-part A [49]. The rolling bottle test method visually determines the affinity by measuring the percentage of bitumen coating the aggregate particles after hand mixing and rotating the loose bituminous mixture in the presence of water. Although this test is straightforward and subjective, it is inadequate for highly abrasive aggregates. The test methodology includes washing and drying the aggregate either passing through an 11,2 mm sieve and retained on an 8 mm sieve or passing through an 8 mm sieve and retained on a 5.6 mm sieve. The aggregate is then mixed with 3 % asphalt by mixture weight. The loose mixture is placed on a metal plate at a temperature of 20 ± 5 °C for 12-64 h. The loose mixture is then divided into three equal parts and placed in glass bottles filled with distilled water. The bottles are placed inside a rotating device for 6 h ± 15 min at an ambient temperature ranging from 15-25 °C. One or two skilled operators will visually measure the asphalt coating the aggregate. Subsequently, the process is repeated, after which the mixture is returned to the glass bottles and placed inside a rotary device resting for 5-7 h. The repetition of the process (inside the rotatory device) is stopped when a 10 % lump of the mixture is formed.

The static test method is performed according to CEN EN 12697-11-part B [50]. The static test method visually determines the affinity by measuring the percentage of bitumen coating the aggregate particles after immersing the coated aggregates in water for a specified time. The test methodology includes washing and drying the aggregate passing through a 10 mm sieve and retained on a 6 mm sieve. The aggregate is then mixed with 4 % asphalt by weight for 5 min. If the particles remain uncoated after 5 min of mixing, the new aggregate percentage is mixed with an increasing proportion of bitumen in increments of +0.5%. After coating the aggregate, the mixture is sprayed with a 50/50 glycerol/dextrine compound. The loose mixture is left in one or two trays for 1 h ± 5 min. Thereafter, the loose bituminous mixture is submerged in distilled water at a constant temperature of 19 ± 1 °C for 48 ± 1 h. After drying the loose mixture at 19 ± 9 °C, the binder of each particle is checked for incomplete coating. The test is repeated for three more samples if the sample contains more than three aggregate particles with an incomplete binder coating. Each time a test is performed with imperfect binder coatings on several particles, they are counted. The average of these counts is then calculated and presented as an outcome. In addition, the amount of bitumen used is tracked and reported.

Compacted asphalt specimens or cores extracted from constructed asphalt concrete have been utilized for testing. This assessment calculates the conditional tensile strength or conditional modulus of elasticity as a percentage of the unconditional values. This is primarily regarded as a quantitative examination of the cohesion and adhesion of the asphalt binder and particles. Several laboratory test methods used to accurately measure the moisture damage resistance of asphalt mixtures can closely simulate field conditions [45].

The Lottman indirect tension test [51] is one of the approaches used to assess moisture damage. The examination consists of nine cylindrical specimens measuring 101 mm in diameter and 63.5 mm in height, compacted to 4-8 % air voids and divided into three groups of three specimens each. Each group is subject to a diametral resilient modulus or diametral tensile strength test. Group I evaluates unconditionally, Group II is tested after vacuum saturation, and Group III is tested after one freeze–thaw cycle. By dividing the conditional strength or modulus by the unconditional strength, the index of retained strength (ISR) or index of retained modulus (IRM) is a ratio for evaluation. According to Lottman [51], the moisture resistance indicator should be 70 % or greater. Table 2 lists the advantages and disadvantages of the Lottman indirect tension test.

Table 2. Advantages and disadvantages of the Lottman indirect tension test [41]

Damage assessment	Advantages	Disadvantages
Index of retained strength (ISR) or index of retained modulus (IRM)	- Conducted on lab, field mixes, or core. - Severe test. - Ability to distinguish various levels of additives.	- Time-consuming (about 3 days for one freeze-thaw cycle). - Amount and type of equipment required is not always readily available.

The Lottman test, modified according to AASHTO T283 [52], determines the ability of compacted HMA to withstand damage caused by moisture. The conditioning procedure is the primary distinction between this test and the previous tests described. The indirect tensile test involves compacting specimens to achieve a 7 ± 1% air void, saturating them under vacuum to a moisture content of 55-80 % and then subjecting them to a freeze cycle followed by a warm-water soaking cycle. A ratio of 70 % or higher (conditioned strength to unconditioned) is advisable. The tensile strength ratio (TSR) in Eq. (2) is obtained by dividing the tensile strength of the conditioned sample by that of the unconditioned sample in Eq. (1). Table 3 presents a comprehensive overview of the advantages and disadvantages of the AASHTO T283 test.

$$St = \frac{2P}{\pi t D} \quad (1)$$

Where *St* denotes tensile strength (kPa), *P* maximum load (kN), *t* height of specimen (mm), *D* diameter of specimen (mm).

$$TSR = \frac{Stm}{Std} \cdot 100\ (\%) \quad (2)$$

Where *TSR* denotes tensile strength ratio (%), *Stm* average tensile strength of the moisture-conditioned subset, *Std* average tensile strength of the dry subset.

Table 3. Advantages and disadvantages of the AASHTO T283 test [41]

Damage assessment	Advantages	Disadvantages
Tensile strength ratio (TSR)	- Conducted on lab, field mixes, or core. - Severe test. - Ability to distinguish various levels of additives.	- Time-consuming (about 3 days for one freeze-thaw cycle). - Amount and type of equipment required is not always readily available.

The ASTM D-4867 [53] standard test method is used to evaluate the effect of moisture on asphalt mixtures. Specimens for this test are 101 mm in diameter and 63.5 mm in height, compacted with a void content of 7 ± 1 %. Different samples of varying sizes, depending on preference, can be used. When utilising aggregates of 25 mm or more, specimens must have a minimum diameter of 150 mm. The primary objective of the test is to regulate the saturation level of the specimen. If the test specimen does not achieve 55 % saturation during initial soaking, it is subsequently immersed under vacuum until a saturation level ranging from 55–80% is achieved. If the test specimen has a saturation level over 80 % after initial soaking, the specimen is excluded. The saturation level is necessary to ensure sufficient moisture for stripping. The TSR in Eq. (2) is obtained by dividing the tensile strength of the conditioned sample by that of the unconditioned sample in Eq. (1). The conditioning process involves either soaking the specimen in distilled water at 60 °C for 24 h (for moisture damage) or tightly sealing it in a plastic bag with 3 ml of distilled water and then placing it inside a freezer at -18 °C for 15 h (for freeze–thaw damage). Table 4 lists the advantages and disadvantages of the ASTM D-4867 test.

Table 4. Advantages and disadvantages of the ASTM D-4867 test [41]

Damage assessment	Advantages	Disadvantages
Tensile strength ratio (TSR)	- Conducted on lab, field mixes, or core. - Mixtures with or without additives. - The time required for the test is moderate.	- To determine the air void level or degree of saturation, the trial specimen can be needed. - It may not be severe enough.

The water sensitivity of bituminous specimens is determined by indirect tensile testing according to CEN EN 12697-12 (2008) [54]. The specimen diameter should be 100 ± 3 mm when the bituminous mixture's nominal maximum particle size is 22 mm and 150 ± 3 mm or 160 ± 3 mm for nominal maximum particle sizes exceeding 22 mm. For two subgroups of three or more specimens each, the average bulk density and length of the specimens are approximately equal. The difference in average bulk density cannot exceed 30 kg/m^3, and the difference in height between the two subgroups cannot exceed 5 mm. One subgroups should

be tested under dry conditions at 20 ± 5 °C temperature, and the other group should be tested under wet conditions through immersion in distilled water under vacuum for 30 ± 5 min at a constant temperature of 20 ± 5 °C. The subsequent cycle under wet conditions involves submerging the specimens in distilled water under atmospheric pressure for 30 ± 5 min at 20 ± 5 °C. In the final cycle under wet conditions, the specimen is maintained under water at 40 ± 1 °C for 68–72 h. The TSR in Eq. (2) is obtained by dividing the tensile strength of the conditioned sample by that of the unconditioned sample in Eq. (1).
Several agencies use immersion compression testing according to ASTM D 1075 [55] and AASHTO T 165 [56]. During these investigations, six cylindrical specimens measuring 101 mm in diameter and 101 mm in height and divided into two groups (conditional and unconditional) are compacted using a double plunger approach under a final pressure of 20.68 MPa for 2 min to achieve 6% air voids. The conditional specimens are subject to water immersion at 60 °C for 24 h or 50 °C for 4 days, followed by immersion in a water bath at 25 °C for 2 h before applying a compressive force. Generally, acceptance requires an average ratio of the retained strength index (conditional/unconditional) equal to or above 70 %. The ISR is calculated based on Eq. (3). Table 5 lists the advantages and disadvantages of the immersion compression test.

$$ISR = \frac{S2}{S1} \cdot 100\ (\%) \tag{3}$$

Where $S1$ denotes compressive strength of dry specimens (unconditional), and $S2$ compressive strength of immersed specimens (conditional).

Table 5. Advantages and disadvantages of the immersion compression test [41]

Damage assessment	Advantages	Disadvantages
Unconfined compression at 25°C and 5 mm/min	- Utilize actual mix.	- The time needed is 4 days plus. - Air void amount plays a crucial role. - It's possible that the equipment isn't readily available.

Wheel tracking tests, in which the sample is compacted in water, have recently gained prominence as a method for predicting moisture levels. The Hamburg loaded wheel test, performed according to AASHTO T 324 [57], uses a steel wheel to continuously track a specimen underwater at a particular temperature, usually between 40-60 °C, to assess rutting and moisture sensitivity in asphalt mixtures. Specimen deformation is measured during the test and plotted against the total number of loading cycles. According to numerous asphalt technologists, the test condition is severe in its determination of the possibility of moisture damage. Typically, user agencies employ maximum deformation after several loading runs as their criterion. Other researchers believe that the stripping slope and stripping inflection point indicate the sensitivity of the mixture to moisture degradation, as shown in Figure 3.

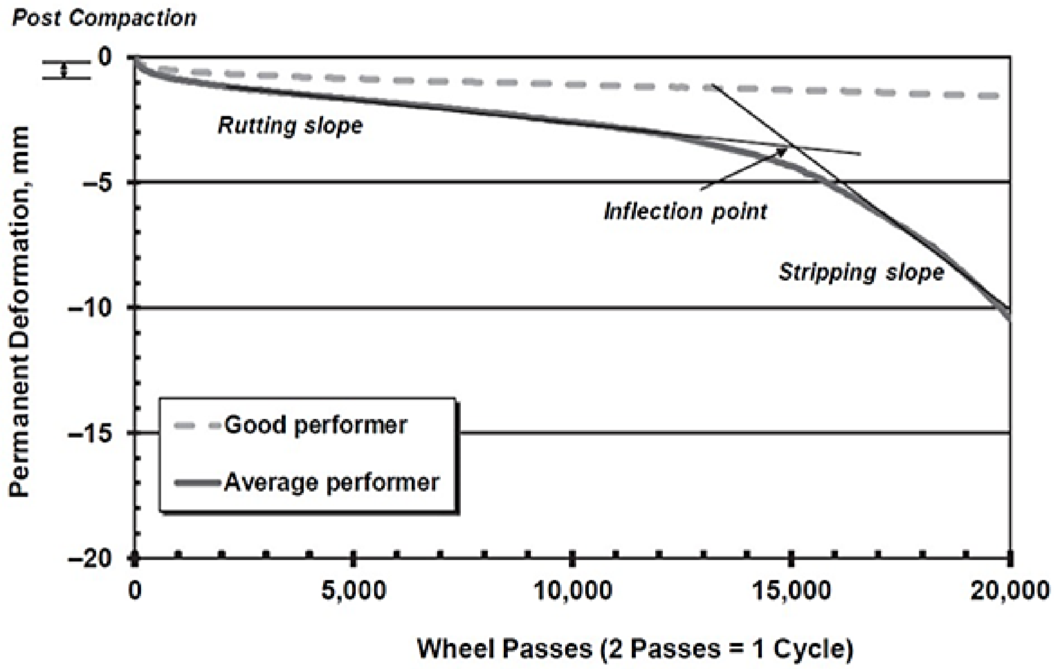
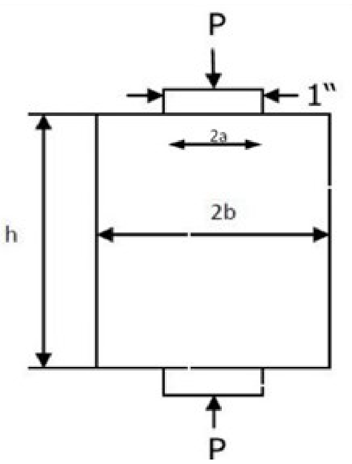


Figure 3. Typical Hamburg wheel tracking test results (wet test at 50 °C) [43]

The University of Arizona has developed a double punch shear method to assess the extent to which the binder is stripped from aggregates. The condition group specimens are immersed in a water bath at 60 °C for 30 min. Two cylindrical steel punches (25,4 mm in diameter) are positioned on the top and bottom surfaces of the cylindrical specimen to ensure central loading. The applied load rate is 25,4 cm/min, and the maximum load is recorded on failure [58]. Punching stress is calculated using Eq. (4) [59]. Figure 4 shows a double shear punch.

$$Punching\ stress = \frac{P}{\pi(1{,}2bh - a^2)}\ (Pa) \tag{4}$$

Where *P* denotes maximum load (N), *b* specimen radius (mm), *h* specimen height (mm), and *a* radius of punch (mm).



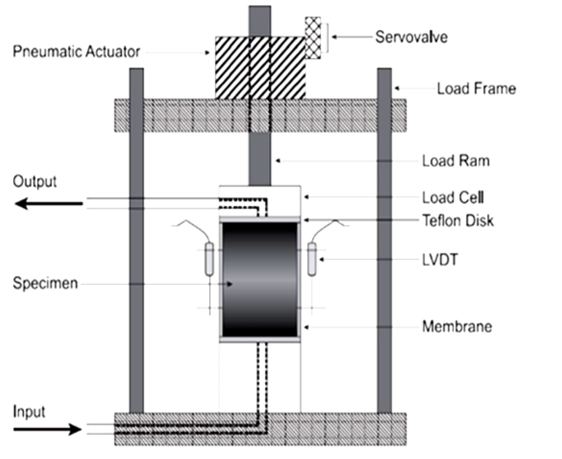
a) b)

Figure 4. Double shear punch: a) sample geometry; b) double shear punch apparatus [59]

Following AASHTO TP 140 [60] and ASTM D7870 [61], the moisture-induced stress tester (MIST) is effective for simulating the mechanisms of asphalt stripping in HMA pavements because it exposes the conditioned samples to three factors which increase the likelihood of moisture damage, namely water, stress, and temperature. Stress is induced by cyclic hydraulic pressure ranging from 200-420 kPa for 3500 cycles), and temperatures are high, ranging from 30-60 °C. Three specimens measuring 100 mm in diameter and 63 mm in height are compacted to achieve air voids between 6,5-7,5 %. The tensile strength test findings are used to assess the sensitivity of the mixture to moisture damage (within 6 h of conditioning). Figure 5 shows the MIST apparatus from MATEST [62].

Figure 5. MIST apparatus from MATEST [62]

The belief held by several asphalt technicians that they have been overly lenient has led to the approval of moisture-sensitive mixes [42]. The Strategic Highway Research Program (SHRP) developed a new conditioning and testing methodology for assessing moisture susceptibility. The test procedure comprises four cycles. Specimens must be conditioned inside an environmental chamber equipped with a loading frame wherein the specimen can be saturated under vacuum. Figure 6 a) shows a schematic of the conditioning chamber. The specimens are exposed to a hot conditioning cycle at 60 °C for 6 h while simultaneously subjected to repetitive axial loads. Following conditioning, the specimen is heated to 25 °C for 4 h to calculate its resilient modulus (first cycle for initial water sensitivity). The resilient modulus test is conducted at 25 °C after two cycles under the hot condition (second and third cycles for long-term damage). The fourth cycle concludes with an optional freeze conditioning step at -18 °C for 6 h. The resilient modulus test is then conducted after 4 h at 25 °C [42]. Figure 6 b) shows typical test output results.



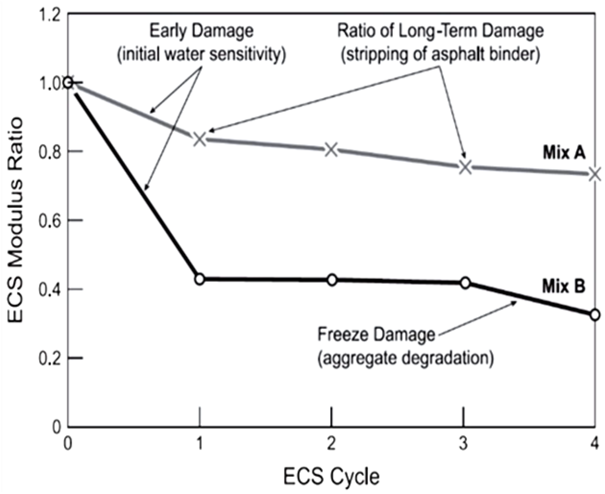


Figure 6. Environmental conditioning system test: a) schematic of the conditioning chamber, b) typical output results [42]

Although stripping can occur on every particle in an aggregate, the finer the aggregate, the more significant the stripping. If stripping is limited to large aggregates, the damage is minimal; however, if finer aggregates form a foundational matrix, severe damage occurs.
The freeze-and-thaw pedestal test created by the Laramie Energy Technology Center (LETC), has been updated and evaluated for Texas aggregate asphalt mixtures that use a uniform aggregate (passing through a No. 20 sieve and retained on a No. 35 sieve) obtained via crushing. The cylindrical briquet specimen, which has a diameter of 41.33 mm and height of 19,05 mm, is compacted under a constant force of 27,6 kN for 20 min. The resultant briquet is cured for 3 days before being placed on a stress pedestal, immersed in distilled water in a temperature control room, and freeze–thawed at -12 °C for 24 h and then at 60 °C for 24 h. The specimen is examined at the end of each cycle to determine whether the briquet surface has fractured. Freeze–thaw cycles are necessary to induce breakage in the briquet as a water susceptibility indicator. If a crack appears after fewer than ten cycles, moisture is a risk. If a crack forms after more than 20-25 cycles, the material is moisture damage resistant [63]. Table 6 lists the advantages and disadvantages of the pedestrian test.

Table 6. Advantages and disadvantages of the pedestal test [41]

Damage assessment	Advantages	Disadvantages
Visual observation	- This tool is solely for research purposes and does not provide any other functionality.	- Utilizes just a tiny portion of the mixture; the void content is not understood. - Necessitates specialized apparatus. - Takes time, 1 day for each cycle. - Only the fine aggregates are considered.

The retained Marshall stability test is another method used by organisations, primarily in the United States, for assessing the effects of moisture on bituminous mixtures. The test consists of preparing Marshall specimens and testing them under both wet and dry conditions after a specified saturation period. Currently, no standardisation of saturation conditions exists. The maintained Marshall stability is calculated by dividing the average Marshall stability of the wet specimens by that of the dry specimens and expressing the result as a percentage.

4 Methods for enhancing moisture damage resistance

Owing to increased production and construction costs, road and transportation researchers and engineers place a high value on asphalt pavement longevity. Several distresses have occurred over the history of asphalt construction, threatening the longevity of pavements, necessitating costly maintenance and harming the environment. Currently, there is a global movement toward using eco-friendly technologies to safeguard and preserve the environment. Several strategies have been developed for improving the durability of asphalt concrete against moisture-induced degradation.

4.1 Sufficient mix design method

The careful design of asphalt mixtures to improve moisture damage resistance is essential. Mixture design entails the selection of specific types and proportions of raw materials, such as aggregates and asphalt binders. This involves calculating the appropriate temperatures for mixing and compaction and evaluating volumetric characteristics and field densities. The proper selection of these factors is essential to ensure the desired qualities of the mixtures are achieved. Apeagyei et al. [64] evaluated the ability of four aggregate types (limestone, basalt, greywacke, and granite) to resist moisture damage. The study findings showed that moisture damage in the asphalt mixture and the amount of asphalt absorbed by the aggregates is dependent on the type of aggregate used. The study concluded that granite aggregates, being the most absorbent, exhibit inferior moisture damage performance than the other three varieties.

4.2 Polymeric aggregates treatment method

Researchers believe that even the best asphalt mixture design cannot sufficiently resist moisture damage and that improving the raw material qualities that comprise the asphalt mixture by adding additives to the asphalt binder materials or improving the aggregate properties (polymeric aggregate treatment) is critical for resisting harsh climates.

Polymeric aggregate treatment involves changing the surface charge characteristics of the aggregate before mixing it with asphalt to reduce the surface energy required to coat the aggregate. A key motivation for changing the aggregate surface is to improve the strength of the asphalt–aggregate bond, and consequently, improve the resistance of the asphalt aggregate mixture to moisture damage. This treatment includes wetting the aggregate with a polymeric material formulation, which dries to form a water-resistant covering around the aggregate and bonding well with both the aggregate and asphalt. Nejad et al. [65] assessed the effects of asphalt mixtures on moisture damage using two different types of polyethylene (high and low density) to coat two types of aggregates (granite and limestone). The test findings were then adopted for the indirect tensile strength and stiffness modulus to evaluate moisture damage. The results of the laboratory tests showed that combinations containing limestone exhibited higher levels of damage resistance than those containing granite. In addition, the presence of polyethylene enhanced the ability of the asphalt binder to coat the aggregate by improving the bond between the asphalt binder and aggregate, particularly in mixtures that include granite aggregate. Mixtures containing aggregates (both types) treated with high-density polyethylene exhibited superior resistance to moisture damage. Raza et al. [66] tested the polymeric aggregate treatment method for moisture damage in HMA utilising high-density Polyethylene and styrene-butadiene-rubber (SBR) latex. The study found that their strategy for treating aggregates significantly improved the resistance of HMA to moisture degradation. Wasiuddin et al. [67] investigated the moisture damage resistance of HMA containing aggregates treated with an SBR polymer. According to the study, the SBR polymer significantly affected the mixing of the aggregate and asphalt binder and changed the aggregate from hydrophilic to hydrophobic. These improvements rendered the HMA more resistant to moisture damage. Nejad et al. [68] tested the effects of Zycosoil, a nanomaterial coating, on the moisture damage of asphalt mixtures using two types of aggregate (limestone and granite). The investigation demonstrated that coating both types of aggregate with an appropriate chemical increased the indirect tensile strength of the asphalt mixtures compared with the control mix. That is, the moisture damage resistance results indicated that the mixtures manufactured with the treated granite aggregate were stronger.

4.3 Anti-stripping utilisation method

Researchers in the field of road materials have made considerable advances in the mixing of anti-stripping materials with asphalt cement to improve the moisture resistance of asphalt mixtures. Since the 1930s, liquid anti-stripping additives (LAS) were mixed with asphalt cement to enhance the moisture damage resistance of asphalt pavements. The primary objective of the additives is to reduce the asphalt surface tension, promote the coating of aggregates with asphalt, and provide the asphalt with an electrical charge opposite to that on the aggregate surface. To ensure homogeneity between the additive and the asphalt, anti-stripping agents can be mixed with the asphalt in the liquid state. These anti-stripping agents can be classified into two types: acids and amines.

Ghabchi et al. [69] assessed the susceptibility of HMA to moisture-induced damage. Different amounts of polyphosphoric acid—0,5 %, 1,0 %, 1,5 %, and 2,0 % by binder weight—were added to the asphalt binder. In addition, an anti-stripping agent, specifically an amine-based liquid, was added to the binder at a concentration of 0,5 % by binder weight. The additives and asphalt binder were combined before mixing with the aggregates. Using the Hamburg wheel tracking test, the study demonstrated that combinations containing additives were insensitive to the influence of moisture. Ameri et al. [70] assessed the moisture susceptibility of asphalt mixtures using indirect tensile strength tests. An anti-stripping agent (Zycotherm nanomaterial and Evonik, a liquid polyamine fatty material) was added to the asphalt cement (60-70) at concentrations of 0,1 % and 0,3 % by bitumen weight. The study concluded that adding specific Evonik and Zycotherm anti-stripping chemicals strengthened the bond between the aggregates and asphalt binder. The study also found that among the various additives examined, the binder additives (0,1 % Zycotherm and 0,3 % Evonik) exhibited superior moisture resistance.

4.4 Modified asphalt cement method

Several standard requirements for asphalt durability performance are extremely stringent. Therefore, the characteristics of conventional asphalt mixtures do not meet these requirements, necessitating asphalt cement modification to improve the binding ability by adding synthetic polymers, natural rubber, sulphur, lignin, and certain organometallic compounds to repair or develop their properties. Polymers are the most common type of bitumen modifier and consist of thermoplastic elastomers, thermoplastic polymers (plastics), and thermosetting polymers (resins).

Gong et al. [71] explored the moisture damage mechanisms in SBS-modified asphalt under water and heat coupling conditions using atomic force microscopy (AFM) and Fourier transform infrared spectroscopy (FTIR). The study demonstrated how changes in the surface morphology, mechanical properties, and chemical functional groups affect the moisture heat sensitivity of both virgin and SBS-modified asphalt. The interactions of water, asphalt surface chemicals, and SBS modifiers are complex. Choosing an appropriate modifier or stabiliser that considers both hydrophilic activity and water stability can help improve the adhesive behaviour of SBS-modified asphalt under high-temperature and wet conditions. Wang et al. [72] investigated the impact of three types of organic nano-clays on moisture damage in SBS-modified asphalt mixtures. The study utilized SBS polymer at 5 % by asphalt weight and nano-clays at 1 %, 2 %, and 3 % by modified asphalt weight. The results showed that nano-clays improved the moisture damage resistance of the combination. The efficiency of nano-clays is dependent on their type and quantity. The study concluded that the increase in moisture damage resistance may be owing to the presence of both the acidic and basic components found in all modified binders, resulting in a reduction in non-polar components. These non-polar components have a significant impact on the overall surface free energy of binders. Vamegh et al. [73] examined the manner in which SBR/polypropylene (PP) polymer mixtures affect the moisture resistance of asphalt mixtures. The study recommended a combination of two polymers as the binder ingredient to improve the efficiency of asphalt mixtures with respect to moisture damage. To this end, SBR and PP were blended in various ratios (70:30, 50:50, and 30:70) before mixing with a virgin binder at 3 %, 4 %, and 5 % by binder weight. The study found that asphalt mixtures containing a polymer blend exhibited a clear improvement in moisture resistance compared with the control mixture, and no significant difference in moisture resistance was found between the asphalt mixtures containing the polymer blend, which could lead to cost savings. Nguyen et al. [74] investigated the effect of moisture damage on stone matrix asphalt (SMA). The properties of SMA were enhanced by combining polyvinyl chloride (PVC) and nano-silica (NS) as asphalt modifiers. The results showed that the addition of PVC and NS to SMA materials independently improved their physical and mechanical qualities. When NS and PVC were combined in SMA, the material properties improved considerably. Hamedi et al. [75] investigated the effect of SBR polymer-modified asphalt binders on the moisture susceptibility of asphalt mixtures. The asphalt mixtures were made from two different types of aggregates: acidic granite and basic limestone. Two percentages of SBR were utilised, namely 2 % and 4 % by asphalt binder weight. The study found that employing SBR polymer improved the durability of the asphalt mixtures against moisture degradation, particularly in specimens containing granite aggregate.

4.5 Synthetic fibre addition method

Although fibres are not classified as polymers and their addition to asphalt mixtures does not induce the components of the mixture to interact, several studies have found that adding fibres to asphalt mixtures significantly increases their stiffness, which improves rutting resistance and reduces fatigue cracks. In addition, some studies have found that adding fibres to asphalt mixtures increases their hardness, which allows them to resist moisture damage.

Hussein et al. [76] investigated the moisture damage resistance of asphalt mixtures containing coarse recycled concrete aggregate and Rockwool fibres at 0,5 %, 1,0 %, 1,5 %, and 2,0 % by weight. According to the study, the best asphalt mixtures for resistance to moisture damage were those with 30 % recycled concrete aggregate and 1,5 % rock wool fibres. The aim of environmental sustainability was partially met by this study. Mawat and Ismael [77] reported that the resistance of asphalt combinations to moisture damage was enhanced by the addition of carbon fibres. Indirect tensile and immersion compression tests were conducted using various lengths (10, 20, and 30 mm) and quantities (0,1 %, 0,2 %, and 0,3 % by total weight) of carbon fibre. Mixtures with 20 mm carbon fibre at 0,3 % of the mixture weight performed better than those with 10 and 30 mm carbon fibre at 0,2 % and 0,1 % of the mixture weight, respectively.

4.6 Lime addition method

Lime is a fine, highly alkaline inorganic powder and was first used in the 1950s and 1960s to remedy moisture damage. Lime can be employed as either a hydroxide ($Ca(OH)_2$) or oxide (CaO) in asphalt mixtures. Generally, a lime-to-aggregate weight ratio of 1,0-1,5 % is adequate. For finer aggregates, their larger surface areas might necessitate a higher percentage of hydrated lime to sufficiently protect the aggregate from stripping [41]. The optimum asphalt amount in HMA is typically somewhat greater when hydrated lime is included and ranges from 0,1-0,3 % by dry aggregate weight [42]. Four methods may be applied to asphalt mixtures: dry lime to dry aggregate, dry lime to moist aggregate, lime as a slurry, and hot (quicklime) slurry [41].

Al-Marafi [78] added hydrated lime and nano-hydrated lime at 5 %, 10 %, 20 %, and 30 % by asphalt binder weight to evaluate the effect on the moisture damage in asphalt mixtures. This study showed that mixtures containing 30 % hydrated lime and 20 % nano-hydrated lime exhibited a significant increase in moisture damage. Albayati et al. [79] investigated the moisture damage of asphalt mixtures containing various hydrated lime sizes, that is, regular-, nano-, and sub-nano-hydrated lime, which were replaced with limestone dust as a filler at 1,0 %, 1,5 %, 2,0 %, 2,5 %, and 3,0 % by total aggregate weight. The results showed that asphalt mixtures containing hydrated lime showed an increase in moisture damage resistance, with mixtures containing 2,0 % and 2,5 % nano-hydrated lime exhibiting the greatest increase.

4.7 Chemical powder addition method

The surface chemistry of aggregates influences the ability of an asphalt mixture to withstand moisture damage. Consequently, researchers have suggested that the inclusion of iron, magnesium, calcium, and perhaps even aluminium is beneficial. In contrast, sodium and potassium may have negative effects.

Ugla and Ismael [40] examined asphalt mixtures containing alumina waste, representative of secondary aluminium dross replaced at 10 %, 20 %, and 30 % by filler weight. The study found that resistance to moisture damage improved, and 20 % secondary aluminium dust was the ideal amount for improvement. Cao et al. [80] evaluated the performance of asphalt mixtures containing nano-alumina. In this investigation, the wet mixing method using kerosene as the auxiliary solvent was used to more evenly propagate nano-alumina into the asphalt mixture. Nano-alumina was added at 3 %, 6 %, 9 %, and 12 % by bitumen weight. The study concluded that the optimal performance of the asphalt mixtures was achieved when the nano-alumina content was 9%. Sarsam and Tuwayyij [81] examined the moisture damage of asphalt mixtures containing iron filler rather than sand for the fraction passing the No. 8 sieve (2,36 mm) and retained on the No. 50 sieve (0,3 mm) at various percentages of 2 %, 4 %, 6 %, and 8 %. By comparing the asphalt concrete combination with the control mixture, the investigation reported that the addition of iron infill reduced the stripping resistance.

5 Conclusions

This study presents a review of moisture-induced distress in asphalt mixtures. The concepts and theories underlying stripping-induced exacerbation were clarified. Subsequently, the common laboratory methods for determining moisture damage were discussed. Previous studies have investigated methods to alleviate or eliminate this deterioration. Given the subjects covered in these sections, the following conclusions were drawn:

Applied temperature and heavy loads significantly aggravate the stripping of asphalt mixtures because they are uncontrollable in the field. Adhesion failure is the primary and most common cause of moisture damage in the presence of water because of its interaction with asphalt cement; therefore, a good drainage system, including sufficient cross-slope, longitudinal slope, or subsurface culvert, may mitigate this distress.

Cohesion failure occurs when dust originates from either aggregate or asphalt cement, which is relatively rare. This is because the dust in the coarse aggregate is disposed of either by washing or rotating the dryer in HMA plants. The use of good-quality fine aggregates without dust restricts this failure. The quality of fine aggregates is typically assessed using the sand equivalent test, with the sand equivalent preferably not be less than 45 %. In the hydrometer experiment, the highest permissible value for fine materials is 5 %. The amount of plastic particles or clay is determined by the plasticity index obtained from the Atterberg Limit tests for materials passing through the No. 40 sieve. Most standard specifications propose that the plasticity index to be below 4. In addition, the use of asphalt cement free of impurities mitigates this failure because the percentage of impurities allowed in asphalt cement is adhered to. The percentage of impurities can be assessed by examining solubility in a solution of trichloroethylene, with a value of not less than 99%. Cohesive failure is also likely to occur with the aging of asphalt cement.

Because aggregate characteristics play an important role in moisture damage, using appropriate materials for asphalt pavement construction may assist in avoiding moisture damage. Soundness tests simulate the resistance of aggregates to disintegration resulting from the expansion caused by water freezing. The suggested range for aggregate soundness is 6-20 %. In addition, certain requirements specify 0,5 % aggregate porosity as the maximum allowable value.

Neither of the approaches are deemed more preferable than the others for assessing moisture damage in the laboratory; rather, the method is selected based on the availability of the testing equipment and number of samples required.
Improving asphalt mixtures to resist moisture damage using one of the improvement methods is dependent on the type of aggregate used in the asphalt mixture, cost and local availability of additives, and compatibility of the additive and asphalt cement. Combining two or more additive materials, both expensive and inexpensive, can result in cost savings and ideal resistance to moisture damage.

References

[1] Albayati, N.; Ismael, M. Q. Influence of Carbon Fibers on the Rutting Susceptibility of Sustainable HMA Mixtures with Untreated Recycled Concrete Aggregates. *Journal of Studies in Science and Engineering*, 2024, 4 (1), pp. 123-141. https://doi.org/10.53898/josse2024419
[2] Albayati, N.; Qader-Ismael, M. Rutting performance of asphalt mixtures containing treated RCA and reinforced by carbon fibers. *AiBi Revista de Investigación, Administración e Ingeniería*, 2024, 12 (1), pp. 18-28. http://doi.org/10.15649/2346030X.3436
[3] Liu, N.; Liu, L.; Li, M.; Sun, L. A comprehensive review of warm-mix asphalt mixtures: mix design, construction temperatures determination, performance and life-cycle assessment. *Road Materials and Pavement Design*, 2024, 25 (7), pp. 1381-1425. https://doi.org/10.1080/14680629.2023.2268194
[4] Yaro, N. S. A. et al. Mixture Design-Based Performance Optimization via Response Surface Methodology and Moisture Durability Study for Palm Oil Clinker Fine Modified Bitumen Asphalt Mixtures. *International Journal of Pavement Research and Technology*, 2024, 17, pp. 123-150. https://doi.org/10.1007/s42947-022-00224-4
[5] Sahile, A.; Agon, E. C.; Geremew, A.; Gudina, O. Recycled concrete aggregate and cinder gravel as base course construction materials. *Advances in Civil and Architectural Engineering*, 2024, 15 (28), pp. 102-118. https://doi.org/10.13167/2024.28.8
[6] Mocelin, D. M.; Isied, M. M.; da Costa, R. F.; Castorena, C. Availability adjusted mix design method as a tool to mitigate the adverse effects of RAP on the performance of asphalt mixtures. *Construction and Building Materials*, 2024, 422, 135813. https://doi.org/10.1016/j.conbuildmat.2024.135813
[7] Amani, S.; Jahangiri, B.; Karimi, M. M. Performance characterization of asphalt mixtures under different aging levels: A fracture-based method. *Construction and Building Materials*, 2023, 383, 131126. https://doi.org/10.1016/j.conbuildmat.2023.131126
[8] Jia, H. et al. Effect of long-term aging on the fatigue properties of aramid fibres reinforced asphalt mixture. *International Journal of Pavement Engineering*, 2023, 24 (1), 2231606. https://doi.org/10.1080/10298436.2023.2231606
[9] Albayati, A.; Sukhija, M. Univariate and Multivariate Exploration of Resilient Modulus for Warm Mix Asphalt Mixtures. *Journal of Testing and Evaluation*, 2024, 52 (4), pp. 2538-2558. https://doi.org/10.1520/JTE20230426
[10] Albayati, A. H. Factors affecting asphalt concrete permanent deformation: Experimental dataset for uniaxial repeated load test. *Data in Brief*, 2024, 53, 110224. https://doi.org/10.1016/j.dib.2024.110224
[11] Nandal, M.; Sood, H.; Gupta, P. K. A review study on sustainable utilisation of waste in bituminous layers of flexible pavement. *Case Studies in Construction Materials*, 2023, e02525. https://doi.org/10.1016/j.cscm.2023.e02525
[12] Albayati, A. H.; Oukaili, N. K.; Obaidi, H.; Alatta, B. M. Mitigating Reflection Cracking in Asphalt Concrete Overlays with ECC and Geotextile. *Engineering, Technology Applied Science Research*, 2024, 14 (1), pp. 12850-12860. https://doi.org/10.48084/etasr.6650

[13] Yu, H. et al. Characterization and evaluation of coarse aggregate wearing morphology on mechanical properties of asphalt mixture. *Construction and Building Materials*, 2023, 388, 131299. https://doi.org/10.1016/j.conbuildmat.2023.131299
[14] Cruz, G. K. A.; Arruda, S. M.; de Medeiros Melo Neto, O.; de Figueiredo Lopes Lucena, L. C. Comparative analysis of lateritic and granitic aggregates in asphalt mixtures: morphological properties and performance implications. *Innovative Infrastructure Solutions*, 2024, 9, 150. https://doi.org/10.1007/s41062-024-01472-y
[15] Kusumawardani, D. M.; Wong, Y. D. Effect of Aggregate Shape Properties on Performance of Porous Asphalt Mixture. *Journal of Materials in Civil Engineering*, 2021, 33 (8). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003801
[16] Wu, C.; Li, L.; Wang, W.; Gu, Z. Experimental characterization of viscoelastic behaviors of nano-tio2/caco3 modified asphalt and asphalt mixture. *Nanomaterials*, 2021, 11 (1), 106. https://doi.org/10.3390/nano11010106
[17] Mirzababaei, P.; Nejad, F. M.; Hajikarimi, P. Multi-scale measurement of constitutive viscoelastic properties of bituminous composites considering moisture and deicing conditions. *Case Studies in Construction Materials*, 2024, e03175. https://doi.org/10.1016/j.cscm.2024.e03175
[18] Joumblat, R. et al. State-of-the-Art Review on Permanent Deformation Characterization of Asphalt Concrete Pavements. *Sustainability*, 2023, 15 (2), 1166. https://doi.org/10.3390/su15021166
[19] Baba, S. N.; Singh, E. B. Identification of Problems Faced in Road Maintenance. *International Journal of Innovative Research in Engineering Management (IJIREM)*, 2023, 10 (3), pp. 29-37.
[20] AL-Janabi, A. J.; Obaid, H. A. Assessment of highway pavement distresses subjected to overloading in Hilla city: A Road No. 80 Case study. *Kufa Journal of Engineering*, 2024, 15 (3), pp. 47-67. https://doi.org/10.30572/2018/KJE/150304
[21] Skaf, M.; Ortega-López, V.; Revilla-Cuesta, V.; Manso, J. M. Bituminous pavement overlay of a porous asphalt mixture with ladle furnace slag: a pilot project. *Road Materials and Pavement Design*, 2023, 24 (11), pp. 2780-2793. https://doi.org/10.1080/14680629.2022.2154251
[22] de Negreiros Duarte, É. V. et al. Rheological properties of asphalt binder modified with reactive/non-reactive polymer and polyphosphoric acid. *Transportation Research Record: Journal of the Transportation Research Board*, 2023, 2677 (3), pp. 1567-1578. https://doi.org/10.1177/03611981221125716
[23] Aljbouri, R. Q.; Albayati, A. H. Investigating the effect of nanomaterials on the Marshall properties and durability of warm mix asphalt. *Cogent Engineering*, 2023, 10 (2). https://doi.org/10.1080/23311916.2023.2269640
[24] Albayati, A. H.; Latief, R. H.; Al-Mosawe, H.; Wang, Y. Nano-Additives in Asphalt Binder: Bridging the Gap between Traditional Materials and Modern Requirements. *Applied Sciences*, 2024, 14 (10), 3998. https://doi.org/10.3390/app14103998
[25] Chakravarty, H.; Sinha, S.; Kumar, A. Influence of Air Voids and Aggregates Composition on Moisture Damage Sensitivity of Bituminous Mixes. *International Journal of Pavement Research and Technology*, 2023, 16 (4), pp. 862-872. https://doi.org/10.1007/s42947-022-00167-w
[26] Omar, H. A.; Yusoff, N. I. M.; Mubaraki, M.; Ceylan, H. Effects of moisture damage on asphalt mixtures. *Journal of Traffic and Transportation Engineering*, 2020, 7 (5), pp. 600-628. https://doi.org/10.1016/j.jtte.2020.07.001
[27] Tavassoti, P.; Baaj, H. Moisture damage in asphalt concrete mixtures: state of the art and critical review of the test methods. In*: 2020 Transportation Association of Canada (TAC) Conference*. September 27-23, 2020, Online, Transportation Association of Canada, 2020.
[28] Cui, P. et al. 3D reconstruction of moisture damage resulted volumetric changes in porous asphalt mixture. *Construction and Building Materials*, 2019, 228, 116658. https://doi.org/10.1016/j.conbuildmat.2019.08.039

[29] Afkhamy Meybodi, P.; Khani Sanij, H.; Hosseini, S. H.; Olazar, M. Effect of crushed glass on skid resistance, moisture sensitivity and resilient modulus of hot mix asphalt. *Arabian Journal for Science and Engineering*, 2019, 44, pp. 4575-4585. https://doi.org/10.1007/s13369-018-3475-9

[30] Najafi Moghaddam Gilani, V.; Hosseinian, S. M.; Safari, D.; Bagheri Movahhed, M. Investigation of the Impact of Deicer Materials on Thermodynamic Parameters and Its Relationship with Moisture Susceptibility in Modified Asphalt Mixtures by Carbon Nanotube. *Arabian Journal for Science and Engineering*, 2021, 46, pp. 4489-4502. https://doi.org/10.1007/s13369-020-05000-9

[31] Alkofahi, N.; Khedaywi, T. Stripping Potential of Asphalt Mixtures: State of the Art. *International Journal of Pavement Research and Technology*, 2022, 15, pp. 29-43. https://doi.org/10.1007/s42947-021-00003-7

[32] Wang, F.; Li, Y.; Yu, L.; Pang, W. Study on Influencing Factors of Asphalt-Aggregate Stripping Mechanism. *Advances in Materials Science and Engineering*, 2021, 2021 (1), 6619118. https://doi.org/10.1155/2021/6619118

[33] Little, D. N.; Allen, D. H.; Bhasin, A. Chemical and Mechanical Processes Influencing Adhesion and Moisture Damage in Hot Mix Asphalt Pavements. In: *Modeling and Design of Flexible Pavements and Materials*. USA: Springer; 2018, pp. 123-186 https://doi.org/10.1007/978-3-319-58443-0_4

[34] Ameri, A.; Haghshenas, H. F.; Fini, E. H. Future Directions for Applications of Bio-Oils in the Asphalt Industry: A Step to Sequester Carbon in Roadway Infrastructure. *Energy & Fuels*, 2023, 37 (7), pp. 4791-4815. https://doi.org/10.1021/acs.energyfuels.2c03824

[35] Kakar, M. R. Effects of adhesion failure on moisture damage of warm mix asphalt containing Cecabase additive. [doctoral thesis], Universiti Sains Malaysia, Malaysia, 2015. Accessed: April 13, 2025. Available at: https://eprints.usm.my/55429/

[36] Dong, M.; Hao, Y.; Zhang, C.; Li, L. Failure mechanism analysis of asphalt–aggregate systems subjected to direct shear loading. *Materials and Structures*, 2017, 50, 218. https://doi.org/10.1617/s11527-017-1080-0

[37] Canestrari, F. et al. Adhesive and Cohesive Properties of Asphalt-Aggregate Systems Subjected to Moisture Damage. *Road Materials and Pavement Design*, 2010, 11 (Issue sup1), pp. 11-32. https://doi.org/10.1080/14680629.2010.9690325

[38] Abouelsaad, A.; White, G. Review of Asphalt Mixture Ravelling Mechanisms, Causes and Testing. *International Journal of Pavement Research and Technology*, 2022, 15, pp. 1448-1462. https://doi.org/10.1007/s42947-021-00100-7

[39] Chaturabong, P.; Bahia, H. U. Effect of moisture on the cohesion of asphalt mastics and bonding with surface of aggregates. *Road Materials and Pavement Design*, 2018, 19 (3), pp. 741-753. https://doi.org/10.1080/14680629.2016.1267659

[40] Ugla, S. K.; Ismael, M. Q. Evaluating the moisture susceptibility of asphalt mixtures containing RCA and modified by waste alumina. *Civil Engineering Journal*, 2023, 9, pp. 250-262. http://dx.doi.org/10.28991/CEJ-SP2023-09-019

[41] Hicks, R. G. Moisture damage in asphalt concrete. No. 175. Transportation Research Board, 1991.

[42] Asphalt Institute. MS-24Moisture sensitivity - Best Practices to Minimize Moisture Sensitivity in Asphalt Mixtures. 1st Edition, Asphalt Institute, 2007.

[43] Asphalt Institute. *MS-2 Asphalt Mix Design Methods*. 7th Edition, Asphalt Institute, 2015.

[44] Varveri, A.; Zhu, J.; Kringos, N. Moisture damage in asphaltic mixtures. *Advances in asphalt materials - Road and Pavement Construction*, 2015, pp. 303-344. https://doi.org/10.1016/B978-0-08-100269-8.00010-6

[45] Jakarni, F. M. et al. An overview of moisture damage performance tests on asphalt mixtures. *Jurnal Teknologi*, 2016, 78 (7-2). https://doi.org/10.11113/jt.v78.9497

[46] American Society for Testing and Materials. ASTM D3625. *Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water*. USA: ASTM; 2012.

[47] European Committee for Standardization. CEN EN 12697-11 part C. *Bituminous mixtures – Test methods for hot mix asphalts – Part 11: Determination of the affinity between aggregate and bitumen*. Brussels: CEN; 2012.

[48] Xiao, R. et al. Measuring moisture damage of hot-mix asphalt (HMA) by digital imaging-assisted modified boiling test (ASTM D3625): Recent advancements and further investigation. *Construction and Building Materials*, 2022, 350, 128855. https://doi.org/10.1016/j.conbuildmat.2022.128855

[49] European Committee for Standardization. CEN EN 12697-11 part A. *Bituminous mixtures – Test methods for hot mix asphalts – Part 11: Determination of the affinity between aggregate and bitumen*. Brussels: CEN; 2012.

[50] European Committee for Standardization. CEN EN 12697-11 part B. *Bituminous mixtures – Test methods for hot mix asphalts – Part 11: Determination of the affinity between aggregate and bitumen*. Brussels: CEN; 2012.

[51] Lottman, R. P. Predicting moisture-induced damage to asphaltic concrete: ten year field evaluation. Final Report, NCHRP Project 4-8(4), Transportation Research Board, National Research Council, Washington, D.C, 1986.

[52] American Association of State Highway and Transportation Officials. AASHTO T283. *Resistance of compacted hot mix asphalt (HMA) to moisture-induced damage*. USA: AASHTO; 2011.

[53] American Association of State Highway and Transportation Officials. ASTM D-4867. *Standard test method for effect of moisture on asphalt concrete paving mixtures*. USA: AASHTO; 2014.

[54] European Committee for Standardization. CEN EN 12697-12. *Bituminous mixtures – Test methods for hot mix asphalts – Part 12: Determination of the water sensitivity of bituminous specimens*. Brussels: CEN; 2008.

[55] American Society for Testing and Materials. ASTM D-1075. *Standard test method for effect of water on compressive strength of compacted bituminous mixtures*. USA: ASTM; 2011.

[56] American Association of State Highway and Transportation Officials. AASHTO T 165. *Standard method of test for effect of water on compressive strength of compacted bituminous mixtures*. USA: AASHTIO; 2013.

[57] American Association of State Highway and Transportation Officials. AASHTO T 324. *Standard method of test for Hamburg wheel-track testing of compacted hot mix asphalt (HMA)*. USA: AASHTO; 2011.

[58] Sarsam, S. I.; Alwan, A. H. Impact of moisture damage on rutting resistance, shear and tensile properties of asphalt pavement. *International Journal of Scientific Research in Knowledge*, 2014, 2 (10), pp. 453-462.

[59] Khalil, S. M. Assessment of the durability of stone matrix asphalt concrete. [master thesis], University of Baghdad, Civil Engineering Department, 2015.

[60] American Association of State Highway and Transportation Officials. AASHTO TP 140. *Standard method of test for moisture sensitivity using hydrostatic pore pressure to determine cohesion and adhesion strength of compacted asphalt mixture specimens*. USA: AASHTO; 2020.

[61] American Society for Testing and Materials. ASTM D7870. *Standard practice for moisture conditioning compacted asphalt mixture specimens by using hydrostatic pore pressure*. USA: ASTM; 2013.

[62] Matest. Manufacturer of material testing equipment for the construction industry. Accessed: June 15, 2024. Available at: https://www.matest.com/en/company/

[63] Kennedy, T. W.; Anagnos, J. N. Modified test procedure for Texas freeze-thaw pedestal test (No. FHWA-TX-85-46+ 253-7). Texas State Department of Highway and Public Transportation, 1984.

[64] Apeagyei, A. K.; Grenfell, J. R. A.; Airey, G. D. Influence of aggregate absorption and diffusion properties on moisture damage in asphalt mixtures. *Road Materials and*

Pavement Design, 2015, pp. 404-422. https://doi.org/10.1080/14680629.2015.1030827

[65] Moghadas Nejad, F.; Arabani, M.; Hamedi, G. H.; Azarhoosh, A. R. Influence of using polymeric aggregate treatment on moisture damage in hot mix asphalt. *Construction and Building Materials*, 2013, 47, pp. 1523-1527. http://dx.doi.org/10.1016/j.conbuildmat.2013.06.060

[66] Raza, A. et al. Evaluation of moisture damage potential in hot mix asphalt using polymeric aggregate treatment. *Materials*, 2022, 15 (15), 5437. https://doi.org/10.3390/ma15155437

[67] Wasiuddin, N. M.; Zaman, M. M.; O'Rear, E. A. Polymeric Aggregate Treatment Using Styrene-Butadiene Rubber (SBR) for Moisture-Induced Damage Potential. *International Journal of Pavement Research and Technology*, 2010, 3 (1).

[68] Moghadas Nejad, F. M.; Azarhoosh, A. R.; Hamedi, G. H.; Azarhoosh, M. J. Influence of using nonmaterial to reduce the moisture susceptibility of hot mix asphalt. *Construction and Building Materials*, 2012, 31, pp. 384-388. https://doi.org/10.1016/j.conbuildmat.2012.01.004

[69] Ghabchi, R.; Rani, S.; Zaman, M.; Ali, S. A. Effect of WMA additive on properties of PPA-modified asphalt binders containing anti-stripping agent. *International Journal of Pavement Engineering*, 2021, 22 (4), pp. 418-431. https://doi.org/10.1080/10298436.2019.1614584

[70] Ameri, M.; Vamegh, M.; Naeni, S. F. C.; Molayem, M. Moisture susceptibility evaluation of asphalt mixtures containing Evonik, Zycotherm and hydrated lime. *Construction and Building Materials*, 2018, 165, pp. 958-965. https://doi.org/10.1016/j.conbuildmat.2017.12.113

[71] Gong, Y.; Xu, J.; Chang, R.; Yan, E.-H. Effect of water diffusion and thermal coupling condition on SBS modified asphalts' surface micro properties. *Construction and Building Materials*, 2021, 273, 121758. https://doi.org/10.1016/j.conbuildmat.2020.121758

[72] Wang, H. et al. Effect of Nanoclays on Moisture Susceptibility of SBS-Modified Asphalt Binder. *Advances in Materials Science and Engineering*, 2020, 2020 (1), 2074232. https://doi.org/10.1155/2020/2074232

[73] Vamegh, M.; Ameri, M.; Naeni, S. F. C. Experimental investigation of effect of PP/SBR polymer blends on the moisture resistance and rutting performance of asphalt mixtures. *Construction and Building Materials*, 2020, 253, 119197. https://doi.org/10.1016/j.conbuildmat.2020.119197

[74] Nguyen, H. P.; Cheng, P.; Nguyen, T. T. Properties of stone matrix asphalt modified with polyvinyl chloride and nano silica. *Polymers*, 2021, 13 (14), 2358. https://doi.org/10.3390/polym13142358

[75] Hamedi, G. H.; Sahraei, A.; Pirbasti, M. H. An Experimental Investigation into the Effect of Asphalt Binder Modified with SBR Polymer on the Moisture Susceptibility of Asphalt Mixtures. *Periodica Polytechnica Civil Engineering*, 2021, 65 (2), pp. 546-555. https://doi.org/10.3311/PPci.16691

[76] Hussein, F. K.; Ismael, M. Q.; Huseien, G. F. Rock Wool Fiber-Reinforced and Recycled Concrete Aggregate-Imbued Hot Asphalt Mixtures: Design and Moisture Susceptibility Evaluation. *Journal of Composites Science*, 2023, 7 (10), 428. https://doi.org/10.3390/jcs7100428

[77] Mawat, H. Q.; Ismael, M. Q. Assessment of Moisture Susceptibility for Asphalt Mixtures Modified by Carbon Fibers. *Civil Engineering Journal*, 2020, 6 (2), pp. 304-317. http://dx.doi.org/10.28991/cej-2020-03091472

[78] Al-Marafi, M. N. I. Effects of hydrated lime on moisture susceptibility of asphalt concrete. *Advances in Science and Technology*, 2021, 15 (2), pp. 13-17. https://doi.org/10.12913/22998624/135585

[79] Albayati, A.; Wang, Y.; Haynes, J. Size effect of hydrated lime on the mechanical performance of asphalt concrete. *Materials*, 2022, 15 (10), 3715. https://doi.org/10.3390/ma15103715

[80] Cao, Y.; Liu, Z.; Song, W. Performance and overall evaluation of nano-alumina-modified asphalt mixture. *Nanotechnology Reviews*, 2022, 11 (1), pp. 2891-2902. https://doi.org/10.1515/ntrev-2022-0485

[81] Sarsam, S. I.; Al Tuwayyij, H. M. Impact of iron filling on the durability of asphalt concrete. *Journal of Recent Activities in Infrastructure Science*, 2021, 5 (1), pp. 36-45.