Moisture Damage in Asphalt Concrete Mixtures: State of the Art and Critical Review of the Test Methods

Pejoohan Tavassoti, *Ph.D., Senior Research Associate, Centre for Pavement and Transportation Technology (CPATT), University of Waterloo*
Hassan Baaj, Professor, *Ph.D., P.Eng., Department of Civil & Environmental Engineering, Director of the CPATT, University of Waterloo*

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ABSTRACT

Moisture-induced damage is among the four prevalent causes of premature failure of flexible pavements in Canada. Research on moisture damage evaluation of asphalt concrete mixtures dates back to approximately one century ago. However, relating the field performance of mixes to their associated properties captured through laboratory test methods is not fully developed yet. Several test methods have been utilized over the last few decades to assess the moisture-induced damage of mixes in the laboratory scale. Studying the Tensile Strength Ratio (TSR) or loss of indirect tensile strength (ITS) due to moisture conditioning of specimens with or without (a) freeze-thaw cycle(s) has been the most commonly used method in North America. Review of case studies indicates major shortcomings of this technique. For instance, in many cases a mix may pass the minimum TSR requirements in the laboratory, but would fail in the field and vice-versa. Therefore, many transportation agencies have been recently investing in finding alternative test methods such as Hamburg Wheel-Tracking Test (HWTT) and Moisture-induced stress tester (MiST) to better predict the moisture-related performance of flexible pavements. This study, provides a critical review of the existing methods for evaluation of moisture damage in asphalt mixtures along with their strengths and weaknesses for this purpose. The major parameters that contribute to this complex phenomenon are also discussed. A synthesis of the state of practice for design specifications and materials acceptance with respect to moisture damage by different agencies is also provided. Finally, the need to use domestically calibrated moisture conditioning, evaluation practices, and establishing customized acceptance thresholds that suit the climatic conditions in Canadian environment is highlighted. Recommendations are provided for an improved moisture damage assessment framework, based on the lessons learned from the past experiences as well as the identified promising techniques.

Keywords: Asphalt Concrete, Moisture Damage, Critical Review, Stripping, Laboratory Testing

1. INTRODUCTION

1.1. Action of Water in Flexible Pavements

For many decades, the presence and accumulation of water in pavement structures has been known to have major contributions to accelerated pavement deterioration. To fight against the adverse impacts of the water on flexible pavements performance, typically the surface layers are made to be impervious while granular courses with good drainage properties are utilized (e.g., base layer) to expedite the water removal from the pavement structure [1]. This is generally accompanied by the combined use of drainage facilities in both transverse and longitudinal directions and proper design of the geometric alignments. Nevertheless, the characteristics of pavement materials, bound and unbound, play an important role in the occurrence of moisture related damage in pavements [2]. In case of moisture sensitive and/or frost-susceptible soils, substantial loss of support or frost-heave related issues can pose serious challenges to the serviceability of affected pavements [3]. Overall, it is understood that moisture damage mitigation is a multidimensional problem which should be dealt with in a systematic manner. To this end, judiciously managing the surface drainage (e.g., through maintaining adequate grades and slopes, an impermeable surface layer, and sealing of cracks in a timely manner) and subsurface drainage (e.g. due to water table fluctuation, capillary rise, gravity flow) can significantly contribute to mitigating premature damage in pavements due to the detrimental effects of moisture [4], [5]. Overall, these factors can be summarized under two main approaches of: 1) providing an appropriate subsurface drainage and 2) minimizing water infiltration into pavement structures. Although all of these different aspects are important, the current paper is mainly focused on the crucial role of asphalt concrete materials in this process, and the available moisture-induced damage evaluation and screening techniques in the laboratory.

1.2. Problem Statement

There is a consensus among the pavement engineering and materials experts that fatigue cracking, rutting, thermal cracking, and moisture induced damages are the four most prevalent modes of deterioration in flexible pavements [6]. Research on better characterizing fatigue and rutting performance of asphalt concrete mixes has substantially evolved during the past few decades. Proper evaluation of the moisture-induced damage in asphalt concrete pavements, however, still remains a challenging task. This becomes especially challenging when establishing a correlation between the laboratory test results and the observed field performance. Moisture related damage was incorporated in the original Superpave^{TM} mix design method as one of the mandatory steps. The AASHTO T 283 test protocol, as a part of Superpave mix design, is currently the most commonly used method by several agencies for moisture damage evaluation and product acceptance. However, discrepancies have been reported in the literature, where a mix would pass the TSR criteria in the lab but fails in the field and vice versa [7]–[10]. Furthermore, the current protocols disregard the fact that specimen conditioning prior to the ITS test should reflect the climatic conditions of the region where the asphalt concrete layer would be built. Potential discrepancies in field performance prediction through the laboratory screening processes indicate the need for either adjusting the current protocols or developing new ones that suit the domestic materials, traffic, and climatic conditions.

1.3. Scopes and Objectives

The main objective of this paper is to provide a critical review of the state-of-the-art and the current practice of moisture-induced damage evaluation for asphalt concrete mixes. Over the past two decades, several techniques have been proposed by researchers, where some of them have been adopted by different agencies to replace the historically used methods. While moisture related damage in flexible pavements covers a very broad range of topics, this paper focuses on the materials aspect and tries to provide a practical synthesis of what has been done by other researchers and draw conclusions about the opportunities for improvement in Canadian environment. To this end, the main contributing mechanisms of moisture-induced damage are briefly discussed followed by the major available techniques to evaluate moisture susceptibility of asphalt concrete mixes. Afterwards, a summary of the current practice in evaluating moisture damage by some agencies in North America is provided. Finally, existing gaps in the knowledge and potential future research directions toward achieving a reliable moisture damage evaluation will be provided.

2. Definition of Moisture-Induced Damage and its Mechanisms

The loss of strength of compacted asphalt concrete layers due to the adverse impact of moisture in flexible pavements is defined as moisture-induced damage [11]. However, this phenomenon is typically not an isolated incident and is usually combined with other modes of failure, ultimately resulting in premature failure of flexible pavements. Several factors and mechanisms contribute to moisture damage in asphalt concrete layers. Therefore, in order to improve the reliability of the moisture susceptibility evaluation techniques, these contributing mechanisms should be considered and properly incorporated. Review of the existing knowledge reveals that six main mechanisms can be identified as the major contributors to moisture-induced damage in asphalt concrete materials, namely: 1- detachment, 2- displacement, 3- hydraulic scouring, 4- excess pore water pressure induced damage, 5- spontaneous emulsification, and 6- environmental impacts on the aggregate-asphalt system [12]–[17].

From a general perspective these factors can be classified under two main mechanisms of adhesion loss (aka stripping) and cohesion loss. Stripping results in an impaired bond between the aggregate and binder while through cohesion loss (softening) the bond within the asphalt itself would be weakened. Accordingly, the dominant failure mechanisms could be associated with either an adhesive or cohesive mode. Concurrent occurrence of stripping with other major distresses makes it a very complex phenomenon. Nevertheless, stripping can be attributed to either mechanical or physical or chemical or some combination of these three mechanisms. Table 1 provides a summary of 10 main contributing factors to stripping along with brief descriptions of their potential mechanisms.

Table 1. *Contributing mechanisms to moisture damage in asphalt concrete mixes (adopted from* [18]*)*

Contributing factor	Mechanism	Contributing factor	Mechanism
Cohesion	Loss of molecular cohesion in the binder	Film Rupture	Breakdown of the asphalt film to the edges of the aggregate
Adhesion	Loss of adhesion in aggregate-asphalt interface	Pore Pressure	Effect of saturated voids in the mix
Environmental Effects	Abrupt changes in climate	Spontaneous emulsification	Water penetration into the binder
PH Instability	PH fluctuation at the interfacial zone	Displacement	Water ingress through a crack in the asphalt and displacing the binder
Hydraulic Scouring	Action of tires on saturated surface, osmosis effect, salt	Detachment	Breaking asphalt film loss of adhesion

Potential parameters that can affect moisture damage in asphalt concrete pavements can be considered under three major categories: 1) materials related, 2) environmental, and 3) construction related. Environmental factors of the region where the flexible pavement of interest is situated would have a significant impact on its moisture-damage performance. To that end, factors such as the level of precipitations, temperature profile (and its daily and seasonal variation), number and the duration of freezing-thawing cycles, and the water table level (and its seasonal fluctuation) can be named as some of the important examples under this category.

Furthermore, it should be noted that although proper design and evaluation of asphalt concrete materials is a necessity, it would not be sufficient for achieving the desired pavement performance. In other words, even if the design and evaluation at the laboratory stage are impeccable, poor workmanship and poor construction practice can result in overall failure of the project. Mixing and production practices, plant mixing temperature, segregation of the materials during the hauling and/or placing stages, compaction quality and meeting the target air-voids level, permeability of underlying layers, maintaining surface slopes and grades for an effective drainage, and under-drain structures efficiency can be named as the most dominant parameters in this category [19], [20].

Finally, material-related issues, which are the focus of this paper, can cover a broad range of factors that could typically have multiple levels of interactions resulting in added complexity of moisture damage phenomenon in asphalt concrete mixes. To this end, some characteristics can be adjusted by, for example, controlling the mix design parameters such as the mixture gradation, air voids, VMA, and asphalt binder content [9]. Binder and aggregate chemistry and their compatibility plays a crucial role in moisture damage performance of asphalt concrete materials [21]. Generally, most of the inherent material properties are considered as fixed conditions depending on the existing raw materials sources such as specific quarries and AC suppliers. However, if not desirable, potential remedies can still be utilized to alleviate or mitigate any negative effects on the pavement performance. Examples include but not limited to the use of antistripping agents, changing the filler type, use of polymers, and fiber modification [22]. Other properties such as moisture content of aggregates can be, however, controlled through the use of proper production practices (e.g., drained stockpiling of the aggregates, proper storage in cold feed bins, and heating process details during the production). Looking into the history of asphalt concrete mix design and development of the volumetric parameters such as VMA and VFA, it can be recognized that one major role of meeting such requirements has been to assure the minimum required film thickness coating around the aggregate particles, which can be indirectly translated to durability of the asphalt concrete mixes [23], [24]. To this end, an asphalt film which is too thin can facilitate water diffusion and make the mix prone to moisture induced damage, while a too thick of an asphalt film may result in shear failures and permanent deformation at high service temperatures. Therefore, adequate film thickness and mastic characteristics can also contribute to an enhanced moisture resistance.

3. Moisture Sensitivity Evaluation Methods

Evaluating the durability of flexible pavements against the detrimental effects of moisture can be traced back to as early as 1920’s. Since late 1950’s numerous test methods and evaluation techniques have been developed by researchers to better understand the performance of different asphalt concrete mixes in terms of resisting moisture-induced damage in the laboratory. Generally, the existing test methods for this purpose can be classified under three categories including tests on: 1) asphalt concrete mix constituents (i.e., aggregates, asphalt cement, filler, and mastic), 2) loose mixture, and 3) compacted asphalt concrete specimens. Table 2 provides a summary of the major existing test methods for evaluating moisture damage sensitivity of asphalt concrete mixes. As discussed earlier, use of the indirect tensile strength (ITS) test is known to be the most commonly used technique to-date. However, more recently many transportation agencies have been investigating and adopting wheel tracking device-based tests such as Hamburg Wheel Tracking Test (HWTT) and Asphalt Pavement Analyzer (APA) as a better alternative to the traditional ITS testing [7], [25], [26]. Some of the major tests from this list are further discussed in this section.

Table 2. *Summary of test methods for moisture susceptibility evaluation of asphalt concrete mixtures*

Loose mixture and mix constituent tests	Tests on compacted specimens
USD Aggregate-Binder Compatibility Test	Modified Lottman Test (AASHTO T 283) or Tunnicliff and Root Conditioning
Surface Free Energy Measurements	Hamburg Wheel Tracking Device Testing
Binder Bond Strength (BBS) Test	Moisture-induced Stress Testing
Methylene Blue Test	Immersion Compression Test (AASHTO 165)
Quick Bottle Test	Uniaxial Dynamic Modulus Testing (AASHTO T-342)
Solutes Exposure Tests	Static Immersion Test (AASHTO T 182)
Rolling Bottle Method	Indirect Tensile Resilient Modulus Test
Boiling Water Test (ASTM D 3625)	Marshall Stability
Freeze/Thaw Pedestal Test	Ultrasonic Pulse Velocity Integrity Test

Figure 1 shows a summary of the current practice in the U.S. in terms of using different test methods for moisture-induced damage evaluation. As can be seen from this map Tensile Strength Ratio (TSR) is still the most commonly used approach, and Hamburg Wheel Tracking Test (HWTT) has been recently gaining more popularity. However, since publication of the results of this survey in 2017, some states have made changes in their specification (e.g. Illinois, Wisconsin, and Pennsylvania).

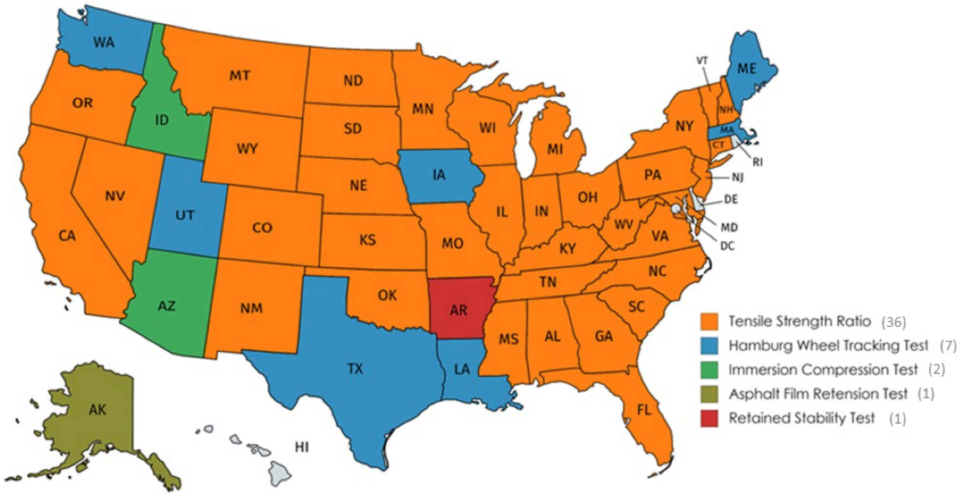

Figure 1. *Use of different moisture damage tests across the U.S.* [27]

3.1. Indirect Tensile Strength (ITS) Testing

Quantifying the extent of moisture-induced damage in asphalt concrete specimens in terms of their loss of indirect tensile strength due to moisture conditioning has been common practice for several decades. While some details about the sample preparation and loose- and compacted-mixture conditioning may vary from one agency to another, this method is generally based on two assessments, namely the Tensile Strength Ratio (TSR) and visual stripping quality ranking. In late 80's and early 90's, the Strategic Highway Research Program (SHRP) led several research projects with the goal of identifying the main roots of moisture damage in flexible pavements, aiming to develop better screening methods during the mix design stage. As a result of these studies from 1987 to 1993, AASHTO T-283 protocol was incorporated in the Superpave^{TM} volumetric mix design for moisture damage susceptibility evaluation [28], [29]. A summary of the different parameters considered in this study and during the NCHRP 9-13 project is presented in Table 3.

Table 3. *List of parameters investigated under NCHRP-9-13*

Investigated factor	Variable
Compaction method	Superpave, Gyratory, Marshall, Hveem kneading compactors
Specimen geometry	SGC 150x62 mm vs. Marshall and Hveem 100x62 mm
Aging of loos mix	16 hr at 60°C, 2 hr at 135°C, 4 hr at 135°C, and no aging
Freeze-thaw cycles	none versus one cycle
Type of anti-strip additive	none, liquid anti-strip, and dry hydrated lime on wet aggregate
HMA Mixing method	Laboratory vs field/plant mixed
Saturation level	55, 75, and 90%
Other factors	Aging of compacted HMA, aggregate types

Several advantages and disadvantages of using AASHTO T 283 have been reported in the literature. Availability of historical data for a wide range of materials tested using this method enables the researchers to develop an empirical criterion for screening the asphalt mixtures in the laboratory scale. The method also, to some extent, accounts for the level of saturation and effect of freezing and thawing on the mechanical integrity of the specimens. Nevertheless, review of the existing work indicates that mixed results have been reported by different agencies with respect to success and failure of this test protocol to distinguish between poor- and good-performing mixes. Such discrepancies can be expected as the method does not account for different traffic and climatic condition, and hence may not necessarily yield a good correlation with field performance [7]–[10]. Historical data from projects across North America reveals cases where a mix passes the minimum TSR criterion in the lab, but failed due to moisture damage in the field. In some cases, historically well-performing mixes could not pass the TSR requirements without addition of an antistripping agent [10], [26], [30]. Such mixed results from AASHTO T 283 have motivated several agencies to seek better alternatives for both screening and material acceptance purposes.

Discrepancies between the laboratory behavior and filed performance of asphalt mixes through AASHTO T 283 protocol point out that the protocol cannot be always treated as a reliable method of moisture sensitivity evaluation. For instance, the monotonic nature of the loading in the test prevents it from capturing the contribution of hydraulic scouring mechanism under traffic loading (see Figure 2), which is believed to play a crucial role in stripping of asphalt mixes. In other words, the way that moisture is introduced into the mix in the current Lottman's procedure is not a good representation of the real-world conditions. On the other hand, although the target saturation level (i.e., from 70% to 85% level) can considerably affect the mix performance, it is generally ignored that the pore size distribution within the mix and their interconnectedness (or accessibility) play a more important role. For example, in case the specimen could not be saturated through applying the recommended range of vacuum pressure and for the recommended duration, the standards require exceeding either or both the level of negative pressure or/and saturation duration to achieve the recommended saturation level. It is, therefore, neglected that forcing an impervious specimen to achieve the target saturation level would be unrealistic and may lead to potential material degradation which could be an artifact of the conditioning process, and hence misleading.

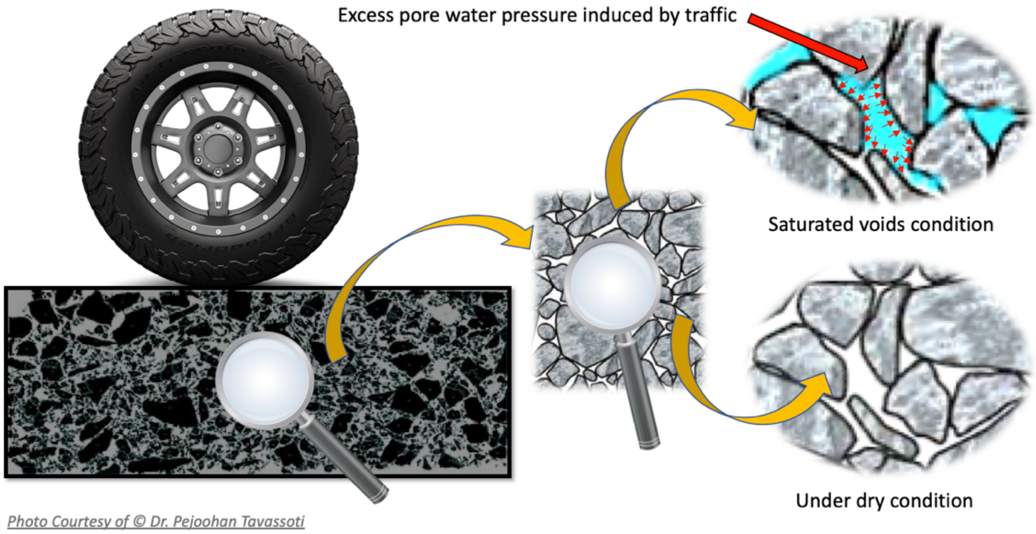

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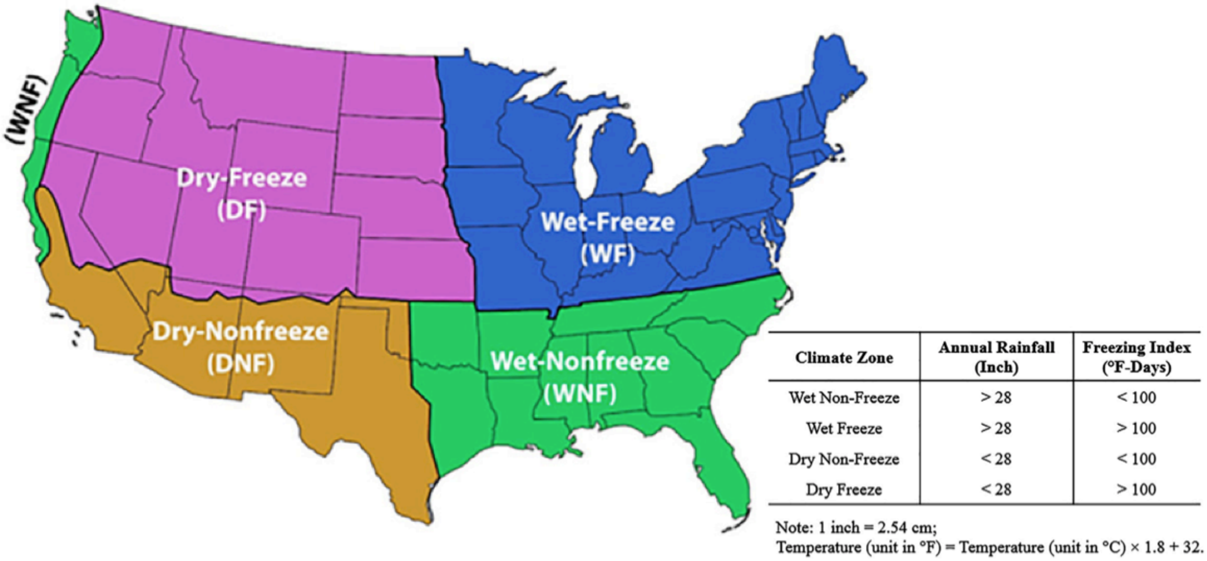
Figure 2. *Mechanical scouring under traffic loading*

Furthermore, the fact that different regions are typically associated with different climatic conditions (e.g., freeze-thaw cycles, temperature variation profiles, and moisture conditions) is barely reflected in the conditioning of specimens under AASHTO T-283 test. In other words, for a given asphalt concrete mixture, a criterion and testing protocol that works in a hot region with light traffic and low precipitation level may not yield reliable moisture sensitivity evaluation results if the mix is placed on a pavement within the wet-freezing region undergoing heavy traffic. Thus, it is intuitive that a proper moisture damage evaluation protocol should be able to account for the inherent differences among different zones and consider using different conditioning and pass/fail criteria. The four main climatic zones defined by the Federal Highway Administration [31] include wet-non-freeze, wet-freeze, dry non-freeze, and dry freeze, which is illustrated in Figure 3. According to Chen et al.[32] Ontario and Quebec can be categorized as wet-freeze climates as their predominant climate falls under this definition of Highway Performance Monitoring System (HPMS).



Climate Zone	Annual Rainfall (Inch)	Freezing Index (°F-Days)
Wet Non-Freeze	> 28	< 100
Wet Freeze	> 28	> 100
Dry Non-Freeze	< 28	< 100
Dry Freeze	< 28	> 100

Note: 1 inch = 2.54 cm;
Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

Figure 3. *Climatic zone illustration for pavement projects*

Finally, when the test is used to evaluate the effectiveness of antistripping treatment, the results can be misleading if the conditioned treated specimens are only compared with the dry set of the treated mix, and not the dry set of the untreated mixture. It should be noted that the results of NCHRP 444 report recommends the laboratories to carry out a structured laboratory program to determine the comparative behavior of their aggregates and binders prior to utilizing SGC 150 mm specimens. Although the study found that generally a no-freeze-thaw condition and one cycle of freeze-thaw condition provide similar evaluations, the report recommended using one cycle of freeze-thaw to be on the prudent side. Based on the results of the NCHRP study it was concluded that the TSR ratios from SGC 150 mm specimens agreed well with those from Marshall 100 mm specimens, while the results did not correlate well with SGC 100 mm and Hveem 100 mm [9]. This information should be considered, but verified as it can be especially pertinent to transitioning from the Marshall to Superpave method for some jurisdictions in Canada.

3.2. Hamburg Wheel Tracking Test (HWTT)

In search for better alternatives to replace AASHTO T-283 protocol, many agencies and researchers investigated the potentials of utilizing a wheel tracking device to run tests under wet condition through a series of comprehensive projects over the past two decades [33]–[35]. Wheel tracking devices were originally used to evaluate the resistance of asphalt concrete mixes to permanent deformation, performed under dry condition in an enclosed environmental chamber or wet condition to better maintain temperature equilibrium. Nowadays, HWTT is used to measure both rutting and moisture damage potential of asphalt concrete mixes under repeated loading exerted by a rolling steel wheel across the surface of a test specimen immersed in hot water.

Based on the results of HWTT, four key parameters can be calculated including: stripping inflection point (SIP), stripping slope, creep slope, and finally the ratio between stripping slope and creep slope. These parameters are then used to quantitatively describe the performance of different mixes with respect to moisture sensitivity and rutting potential. Figure 4 illustrates the different stages of HWTT and the corresponding parameters. Among the aforementioned parameters rutting rate and SIP are most commonly used to evaluate the mixture resistance to rutting and moisture damage, respectively. An advantage of the test is that the results can be obtained in a timely manner. In a recently completed NCHRP 09-49A project [36], which investigated 28 field HMA and WMA pavement projects within 2 to 10 years in-service life, HWTT successfully differentiated between the mixtures with and without anti-stripping agent, where the seven projects without antistripping additives corresponded to SIPs less than 16,000 cycles.

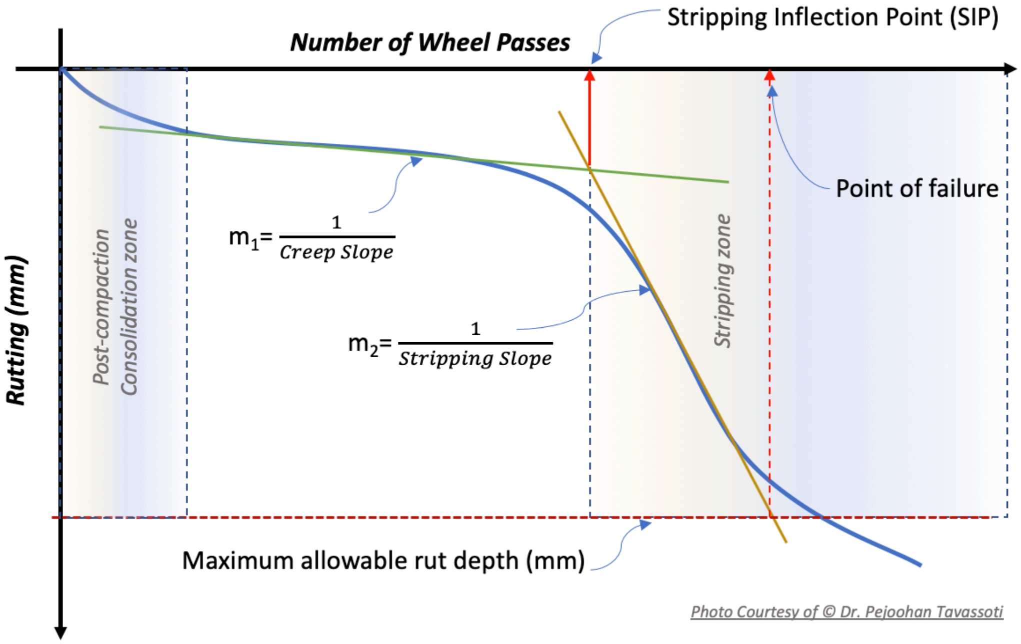


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Figure 4. *Conceptual demonstration of Hamburg Wheel Tracking Test (HWTT)stages*

Based on two recent surveys [37], [38] on the state of HWTT adoption by different agencies in the U.S. it can be recognized that the number of DOTs that have adopted or are evaluating HWTT as part of their moisture susceptibly evaluation specifications has been growing since 2007 (from only two DOTs) to date (i.e., seven and 12 in 2014 and 2016, respectively). The states that currently use HWTD tests towards acceptance of asphalt mixes are California, Colorado, Illinois, Iowa, Louisiana, Massachusetts, Montana, Oklahoma, Texas, Utah, Washington, and Wisconsin. Water temperature, number of passes, rut depth measurement locations, maximum rut depth, and stripping inflection point are the main information in agency specifications on HWTT [38]. There are currently four main vendors offering Hamburg test equipment and one vendor uses the Asphalt Pavement Analyzer (APA). According to Mohammad et al. 21 states use HWTT, and 17 states use APA, while the remaining 12 states do not use any. Based on our experience and review of the pertinent literature, the following list of questions covers some common concerns which have been raised by different stakeholders on the use of HWTT for moisture damage evaluation of asphalt mixtures:

a) What is the best temperature (or sets of temperatures) to perform the HWTT so that the test can discriminate between a good- and poor-performing mix?

b) How many cycles of loading should be applied if the rutting failure limit has not been reached yet?

c) What are the minimum and/or maximum specimen dimensions to avoid any boundary conditions effect during the test?

d) Is a single point measurement on the centerline sufficient or multiple measurement locations should be used to study the deformation basin as well as the maximum depression profile?

e) What are proper fail/pass thresholds and criteria for mixes of different type (e.g., WMA, SMA, PMA, HMA, RAP incorporated, etc.) and how would the results tie into the field performance?

This section tries to provide some guidance about the aforementioned questions, based on the existing knowledge about HWTT of asphalt concrete mixes. With respect to the determination of an ideal testing temperature, research is still being actively conducted by several researchers and different entities. The current version of AASHTO T 324 does not specify a testing temperature, rather leaves it to the states to modify the test method to reflect the local environmental conditions. For instance, the Departments of Transportation (DOTs) of some states such as Colorado, Montana, and Texas have set their own state specifications (i.e., CP-L 5112, MT-334, and Tex-242F, respectively), while other state DOTs use AASHTO T 324 or modified AASHTO T 324 as their specifications. At the moment, agencies have either set testing temperatures according to the asphalt binder's high temperature Performance Grade (H-PG) or a fixed temperature based on their existing climatic region. Reviewing the state specifications indicate that California, Colorado, Montana, and Utah use at least two temperatures, i.e., 44 and 56^{o}C, depending on PG grade of the binder. All other remaining states use a single temperature of 50^{o}C, except for Massachusetts which uses 45^{o}C. Figure 5 illustrates the different HWTT testing temperatures used by different states according to Mohammad et al.[38].

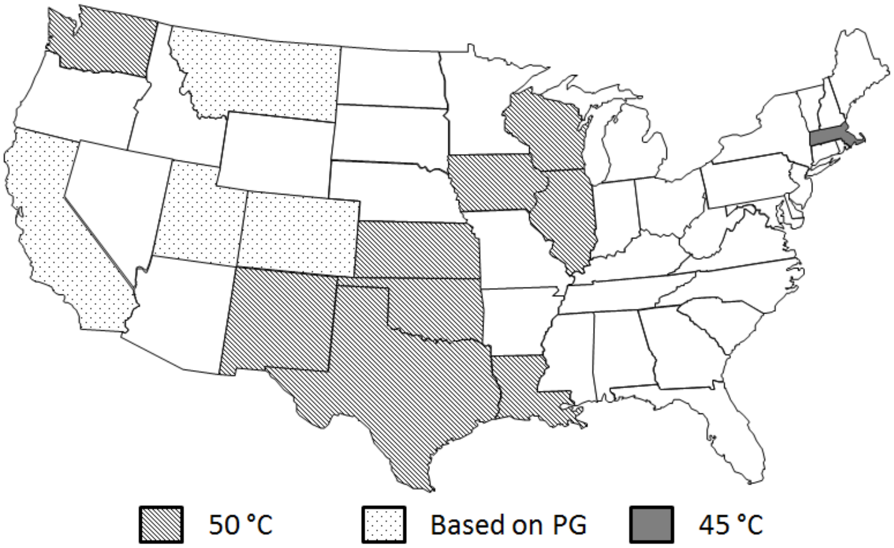

Figure 5. *Testing temperature across different states* [38]

Although there are minimum requirements set about the frequency of measurements in the specifications, the AASHTO T 324 protocol currently does not specify the number and locations of measurement points per each reading. Based on the result of a comprehensive study, Mohammad et al. recommended deformation readings at a minimum of 11 locations along the length of the track, (i.e., 0, ±23, ±46, ±69, ±91, ±114 mm) with zero being the midpoint of the track. Some more strict measurements are also being considered by other agencies, mainly for research purposes so far, with two additional measurement lines (i.e., one on each side of the centerline) resulting in 33 points per reading and yielding the complete basin shape. In Quebec, a total of 15 points (five on each line of measurement) can be used as illustrated in Figure 6 according to the LC21-410.

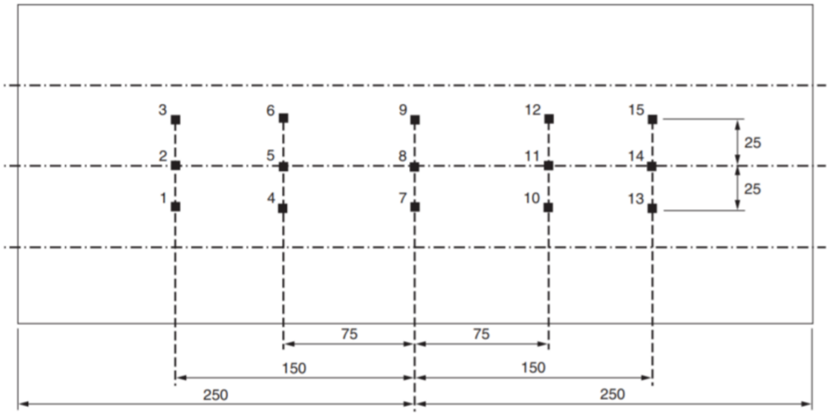

Figure 6. *Points of measurement as per LC 21-410*

A summary of the current practice with respect to defining proper thresholds and criteria for interpreting the test results is presented in this section. Among the states in the U.S. only Iowa, California, and Wisconsin use both the SIP and rut depth toward materials acceptance, while the remaining states only require meeting the rut depth criterion for acceptance purposes. Nonetheless, the maximum allowable rut depth is also variable among the state specifications. For example, some states such as California, Colorado, Illinois, Iowa, Louisiana, Montana, Texas, and Wisconsin explicitly require the minimum number of passes at a specific rut depth or the max rut depth at a specific number of passes. On the other hand, other state specifications do not include a specific rut depth and simply address the dependency of the criteria based upon the binder grade [27], [38]. In addition to the more commonly used parameters, results of a study by the IADOT showed that SIP parameter can be considered a reliable measure of stripping potential if the slope ratio (i.e., ratio of stripping- to creep-slope) is equal to or greater than 2.0. This study concluded that in cases where the slope ratios were less than 1.0, no significant stripping behavior was observed, meaning that SIP could not be used as a measure of stripping [7]. The study, however, did not explicitly take any positions about values between 1 and 2. Similarly, WisDOT also specifies that if SIP is to be used as an indicator of moisture damage, the slope ratio should be equal to or greater than 2.0.

In summary, it can be concluded that many agencies have been considering HWT for both rutting and moisture sensitivity testing. Based on a recent survey in the course of NCHRP 20-07 project on balanced mix design of asphalt mixtures, 29 states and 27 contractors indicated that they are considering this method for both moisture-induced damage and rutting tests [27]. The test was identified as a promising alternative by many DOTs and major contractors. However, further research and adjustment would be required to be able to fully exploit the capacities of this test.

3.3. Moisture-induced Stress Tester (MiST)

A more recently developed equipment toward studying the moisture related damage in asphalt concrete materials is the MiST or Moisture-induced Stress Tester [39]. Use of MiST, especially for the purpose of specimen conditioning, is very promising as the procedure simulates an important stripping mechanism (i.e., hydraulic scouring) which is typically ignored in most other protocols. As described earlier, saturated pores in compacted asphalt concrete materials can undergo variation in pore water pressure under the moving traffic. Therefore, MiST equipment consists of a pressurized enclosure where water ingresses in and out of the specimen in a cyclic manner, simulating the combined effect of saturation and exerted mechanical loading from moving vehicles. The specimens can be conditioned at different levels of water pressures and different temperatures. The moisture conditioning in MiST is believed to be typically more aggressive than the regular AASHTO T 283 conditioning without any freeze-thaw cycles. Figure 7 shows a general view of MiST equipment and schematic of its conceptual working mechanism.

So far, MiST has been used mainly as a conditioning method prior to conducting the ITS test on specimens. After applying the specified number of cycles in MiST, the density of the conditioned specimens would be measured in accordance with AASHTO T166 prior to testing them using an ITS setup. The results are typically reported as TSR, the percent changes in the air voids, and the swelling index. A recent study by IADOT concluded that swell from MiST can successfully rank the field performance of the mixtures. However, IADOT reported that the correlation between TSR values obtained using the MiST conditioned specimens and the conventional AASHTO T 283 was very poor, and in some cases the two tests provided conflicting pass/fail results with respect to 80% minimum threshold [7].

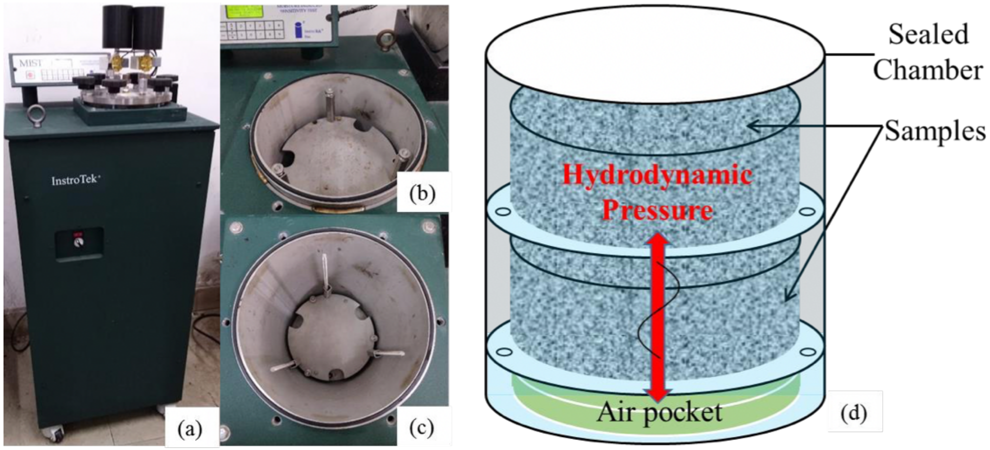

Figure 7. *General view and schematic of MiST setup*[40]

In addition to the fact that hydraulic scouring can be better simulated through MiST, the method is also advantageous because of its relatively short duration which makes the results available in about three hours. Such considerably shorter turnaround time compared to other tests such as AASHO T 283 can help agencies and contractors reduce the risk of a production problem when production continues before conventional lab results can be reported. This method is one of the promising tools for screening moisture sensitivity of HMA mixes at the laboratory scale. Some agencies are in the process of exploring the potential of this test method, and would possibly include it in their specifications in the future. Nevertheless, comprehensive studies are needed prior to proceeding with this method, since it has been explored to a lesser extent as compared to Hamburg Wheel Tracking device.

3.4. Wilhelmy Plate and USD Determination of Surface Free Energy

The three major techniques discussed up to this point are focused on the compacted asphalt concrete specimens. However, as explained under the stripping mechanisms, surface characteristics and chemistry of aggregates and asphalt binder are crucial in stripping phenomenon. Therefore, determination of surface free energy is among the methods that can be used to understand and evaluate compatibility of aggregates and asphalt binders, and provide insights of moisture damage potential for different mixes. This method is applicable to all mixture types and independent of both material and test method, which offers a great advantage over current empirical tests. By definition, the surface free energy of a material is defined as the amount of work required to create a unit area of new surface of that specific material [41]. Figure 8 shows a view of a Wilhelmy plate and the USD apparatus used to measure the surface free energy in the laboratory.

Figure 8. *View of Wilhelmy plate and USD apparatus for surface free energy determination*

Details of the method are outside of the scope of this paper, and readers are encouraged to refer to several published studies such as those briefly discussed here. Cheng [17] and Kim and Little [42] showed a correlation between the magnitude of reduction in free energy due to de-bonding and moisture sensitivity of different asphalt mixtures. Bhasin et al. indicated that surface free energy of asphalt binders and aggregates can be employed to predict the impact of additives on the moisture resistance of asphalt mixes, and established a correlation between the subjective field performance of certain asphalt mixtures and energy parameters. Recent attempts have focused on applying physical adsorption theories for this purpose [41]. According to Wake (1978) three basic concepts are fundamental to physical adsorption theory: 1) van der Waals forces operate between the adhesive and the substrate, 2) van der Waals forces consist of two components – polar and dispersion, and 3) thermodynamic work of adhesion, as an indication of the stability of the bond between the substrate and adhesive, can be calculated by using the two-component van der Waals forces. These components are also known as the Lifshitz–van der Waals (LW) or nonpolar component, the Lewis acid component, and the Lewis base component. By combining these three components the total surface free energy of a material can be obtained using Eq. 1:

$$\gamma = \gamma^{LW} + \gamma^{\pm} = \gamma^{LW} + 2\sqrt{\gamma^{+}\gamma^{-}} \qquad (1)$$

where γ is the total surface free energy of the material; γ^{LW} is the LW component, $\gamma^{\pm}$ is the acid-base component, γ^{+} is Lewis acid component, and γ^{-} is Lewis base component. By knowing the surface free components of the asphalt binder and aggregate, the work of adhesion between these components can be calculated as:

$$W_{AS} = 2\sqrt{\gamma_A^{LW}\gamma_S^{LW}} + 2\sqrt{\gamma_A^{+}\gamma_S^{-}} + 2\sqrt{\gamma_S^{+}\gamma_A^{-}} \qquad (2)$$

Subscripts A and S represent asphalt and aggregate (stone), respectively.

According to Apeagyei et al. [43] the physical adsorption theory-based moisture damage evaluation method is capable and applicable to both dry and wet conditions, but it is unable to account for the reversible moisture damage upon drying. Furthermore, However, the results of this method do not consider other contributing factors such as air void content and mechanical properties of the mixtures. Overall, this method is very useful as a screening tool to determine the moisture sensitivity of combination of different aggregates and binders based on their physico-chemical relationships, and can save substantial experimental costs, time, and efforts by providing compatibility evaluations.

4. State of the Art Test Methods and Other Approaches

Efficiency and practicality aspects should be kept within perspective when thinking of an alternative test method for moisture-induced damage evaluation purposes. However, the fast-paced advancement of technologies and instrumentation provides the possibility of conducting experimental studies which were not even possible a few decades ago. Such developments in the area of material characterization provide new opportunities for exploring innovative methods of evaluating asphalt concrete performance. Examples of such advanced methods include Attenuated Total Reflected Fourier Transform Infrared Spectrometer (ATRFT-IR), nano-indentation test, Computed Tomography, surface free energy measurements, nondestructive impact- and wave-based methods, and several others [41], [43]–[48].

4.1. Attenuated Total-Reflectance Fourier Transform Infrared spectrometer

Use of chemical analysis, such as Attenuated Total-Reflectance Fourier Transform Infrared Spectrometer (ATR FT-IR) has been recently further investigated in the area of asphaltic materials. In a study by Zofka et al., FTIR was used to evaluate the water collected from MiST conditioning of asphalt mixtures from Long Term Pavement Performance (LTPP) sections. The water samples obtained before and after MiST conditioning were analyzed using this technique. The results of their study indicated significant peaks in the spectrum associated with the presence of asphalt at various concentrations in the water after testing. Figure 9 shows an example of the typical post-MiST spectra for the water sample collected from the device chamber. The authors speculated that as stripping occurs, FT-IR would be able to quantify different levels of leached asphalt in the water sampled from the MiST device[47]. The method is still new and more comprehensive studies are required to draw solid conclusions about the moisture-induced damage level using the FT-IR analysis of the retained water from MiST.

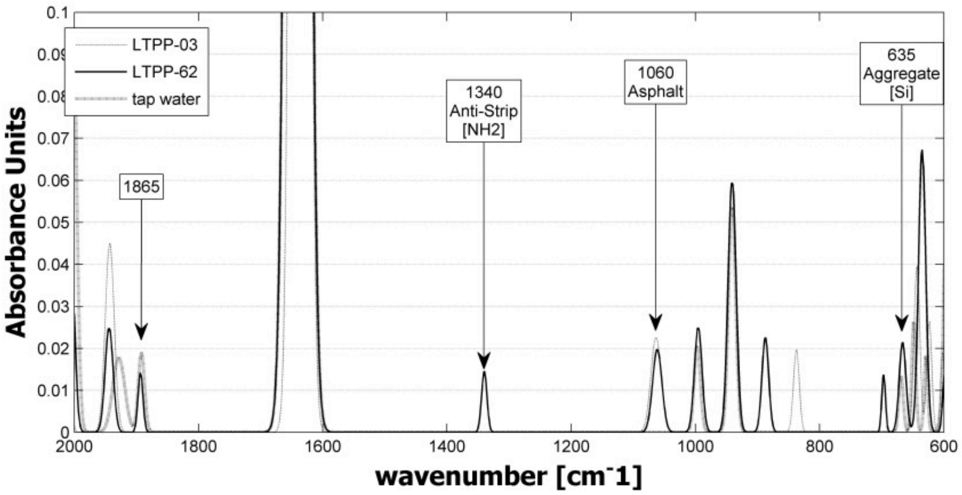

Figure 9. *Example of post-conditioning spectra for MiST water sample* [47]

4.2. Application of Non-destructive Tests

Nondestructive testing (NDT) methods have a considerable potential toward evaluation of asphalt concrete mixture integrity as a function of time and conditioning. Ultrasonic pulse velocity (UPV) method for evaluation of asphalt mixtures has been investigated by some researchers in the past [46], [49], [50]. The non-destructive nature of UPV enhances its use in asphalt mixture studies. Cheng et al. [49] used Ultrasonic Detection Method (UDM) to determine the ultrasonic wave transmission velocity through asphalt mixtures at different temperatures and water contents during the cycles of Water Temperature-Radiations (W-T-R). They reported that modulus measurements through this method can be used to quickly evaluate the damage state of asphalt mixture after the action of W-T-R cycles and it also effectively predicts the damage degree. Birgisson et al. [50] evaluated the changes in integrity of the compacted asphalt mixtures exposed to moisture-conditioning by measuring the velocity of compressional pulse wave passing through the thickness of HMA disks. They found that the method was sensitive to changes due to moisture damage, air void level, film thickness, and recovery after a period of drying. Repeatability of the UPV test is very high, both on the same specimen and among the replicates [51]. On the other hand, several other wave-based methods such as Impact Resonance (IR) and Resonant Column (RC) tests can also be used to evaluate the level of damage induced in a compacted asphalt concrete specimen and in a timely manner. Figure 10 shows a view of the Impact Resonance (IR) test setup for asphalt concrete materials evaluation. Due to their nondestructive nature these tests can be used prior to running any destructive mechanical tests to obtain valuable data about the materials properties.

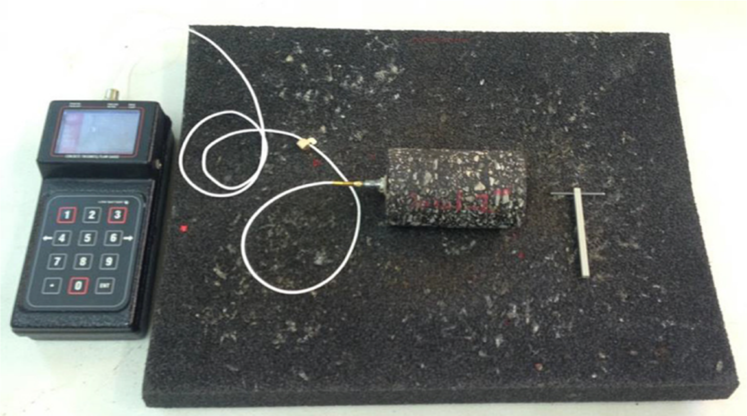

Figure 10. *View of IR test setup for asphalt concrete materials* [52]

4.3. Binder Bond Strength (BBS) Test

In order to evaluate the quality of bonding of asphalt binder to aggregates a limited number of tests have been developed so far. The Binder Bond Strength (BBS) test can be named as a good example of such methods developed at the University of Wisconsin Madison to evaluate moisture damage in hot applied binders and the rate of curing of fresh emulsions[53], [54]. BBS is a pneumatic adhesion test adapted from the paint and coatings industry (ASTM D4541). The test involves subjecting a pull stub adhered to an aggregate substrate to a normal force created by increasing pneumatic pressure. The bond strength is then defined as the maximum pull-off pressure exerted by the machine. The failure surface is visually examined after the test to determine whether the failure mode was adhesive or cohesive. The pull-out stub in the BBS test has a diameter of 20 mm and has a surrounding edge, used to control film thickness, where the stub edge has a thickness of 800 µm. In addition to the bond strength from BBS test, the contact angle between the binder and the rock can be measured to determine the tendency of two materials with dissimilar molecules to cling to one other, corresponding to the definition of adhesion. A view of the contact angel between asphalt binder and substrate made of aggregate and schematics of the BBS apparatus is shown in Figure 11.

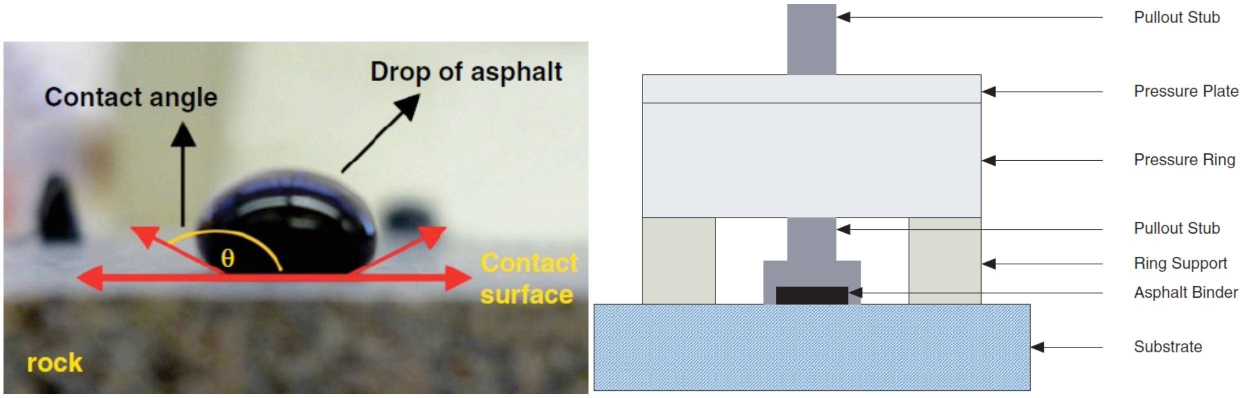

Figure 11. *Schematics of BBS test* [55]

Although BBS test offers an innovative approach, its use becomes somehow limited due to the challenges with preparing the substrate and the stub from the source rock as well as possible changes in surface texture of the substrate during cutting to obtain a smooth contact surface.

5. Long-term Moisture Conditioning and Bias Effects

Numerous tests have been explored by researchers in order to evaluate their suitability toward moisture-induced damage characterization of asphalt concrete mixes. Example include, but is not limited to, use of uniaxial dynamic modulus, uniaxial tension-compression fatigue, indirect tensile (IDT) resilient modulus, flow time and number, and uniaxial compressive strength testing on conditioned and dry specimens. Each of these tests offer some advantages and have certain limitations. Regardless of the testing method, studying the change in durability of asphalt concrete mixtures after long-term moisture conditioning can provide valuable insight into the moisture damage mechanism, which has been rarely investigated. To this end, in a novel approach Apeagyei et al. [43] studied the use of IDT resilient modulus testing on compacted specimens after varying duration of moisture conditioning in water bath at 60^{o}C for up to 70 days. The study covered a wide range of parameters including a limestone aggregate, two mineral fillers (granite and limestone), and a penetration grade binder, gyratory compacted to three different levels producing 4, 6, and 8% air void levels. The results showed that loss of strength after moisture conditioning is not necessarily due to the damaging action of water.

An important question with regard to the moisture conditioning practice in AASHTO T 283 is whether the loss of strength happens totally due to the detrimental effects of moisture in the compacted specimen or this partially is a temporarily reversible phenomenon. Apeagyei et al.'s study answered this question and reported reversibility of durability loss after letting the specimens dry. They found that moisture conditioned asphalt mixtures that had lost up to 80% of their initial stiffness when tested shortly after moisture conditioning, fully recovered both their stiffness and tensile strength at 20°C upon drying [43]. As a result, it was concluded that the reversible nature of moisture-induced degradation suggests a plasticization process through which the bulk mastic is softened and the critical stress concentration location is moved from the interfacial region of the aggregate-mastic bond into the bulk mastic. To test this hypothesis, they used micro-CT scans of the internal structure of the mixtures and found that the moisture diffusion was mainly restricted to the bulk mastic and not the aggregate-mastic interface.

Possibility of water diffusion through the mastic into the interface can be calculated by means of two key parameters, namely thickness of the mastic film and diffusion coefficient of the mastics. Ultimately, Apeagyei concluded that cohesive failure was the dominant mechanism rather than the adhesive failure regarding the durability of the mixtures under the long-term conditioning. Figure 12 shows a summary of IDT stiffness test results for the unconditioned, moisture-conditioned, and re-dried specimens, indicating the recovery of the moisture-induced loss of stiffness from the aforementioned study.

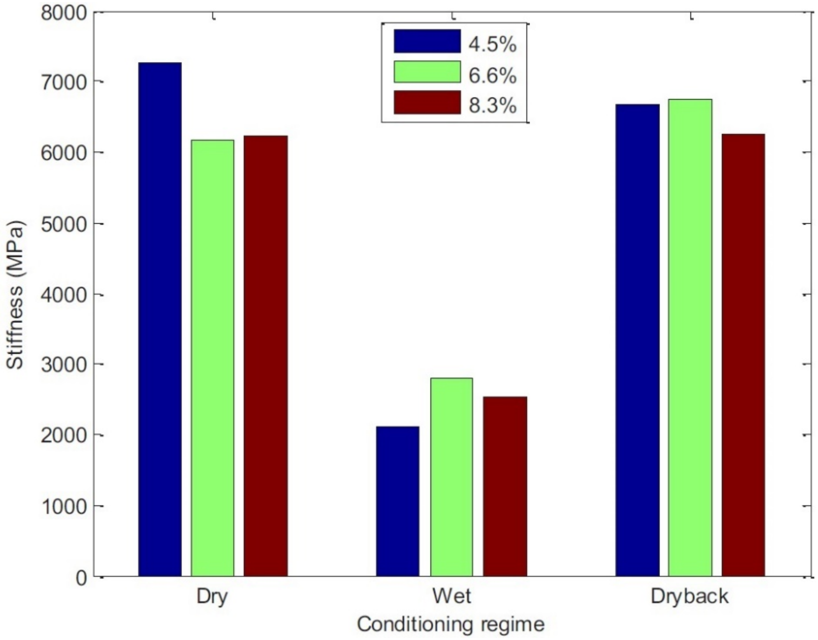

Figure 12. *Initial loss of stiffness and reversible loss for different conditioning practices [43]*

6. Summary Conclusions and Future Research Directions

The main goal of this study was to provide a critical review of the materials-related moisture damage in flexible pavements. To this end, a comprehensive literature review has been conducted to better understand this complex phenomenon and provide practical directions on the use of the existing techniques to yield reliable interpretation of the test results. Furthermore, some possible directions for future research in Canada is presented in this section to improve the current practice of materials selection, acceptance, and design of asphalt concrete mixes with respect to moisture damage resistance.

- Given the mostly empirical nature of the current AASHTO T 283 and its inability to consider major stripping mechanisms such as hydraulic scouring, the results of this test cannot provide reliable interpretation of mixed performance in terms of moisture-induced damage. Nevertheless, adjusting the details (e.g., number of freeze-thaw cycles, saturation level, and conditioning duration) may help with improving of the moisture damage evaluation quality.
- The visual inspection ranking is generally subjective and can be misleading, especially when cohesive failure is the dominant failure mechanism.
- Moisture-induced Stress Tester (MiST) simulates the dynamic effect of traffic on pore water pressure evolution in asphalt mixes. This method can also be used as an alternative conditioning tool when conducting ITS testing on conditioned and dry specimens in general accordance with the AASHTO T-283.
- Hamburg Wheel Tracking Test (HWTT) has been explored by several agencies in north America and can be a promising option to substitute the conventional moisture damage tests. Concurrent

simulation of rutting and moisture damage can be considered as a potential advantage for this method. However, details such as the ideal testing temperature, threshold criteria for SIP and slope ratio should be thoroughly investigated and established to reflect the field performance of different asphalt mix types.

- Regardless of the type of the test, review of the literature indicates the need for local calibration of test parameters and criteria to account for the effect of climatic zones and the expected service traffic level. Necessity of such considerations for domestic conditions is not limited to AASHTO T 283 test, but also applies to potential alternative methods in the future.
- At a higher level, and not for daily basis applications, use of surface free energy measurement as an advance technique to determine the compatibility of various combinations of aggregates, fillers, asphalt binders and additives can be very beneficial and save considerable amounts of time and cost for more extensive experimental studies. The method is independent of the climatic conditions and any empirical factors.
- When interpreting the HWTT results, literature indicated that a slope ratio of 2 or greater is needed in order to be able to use SIP as reliable measure of stripping.

Finally, moisture-induced damage in flexible pavements is a complex phenomenon, typically with root causes beyond only the materials aspect. In order to be able to establish a reliable correlation between the lab test results and field performance, it is essential that projects with material dominant issues be distinguished from those suffering from construction or other extrinsic factors. Reviewing the existing literature on moisture damage in asphalt concrete mixes and the state of practice and state of the art, the following directions for future research are recommended:

- Investigating the effect of temperature on the interpretation of HWTT results to achieve a reliable correlation with field performance and distinguishing poor- and good-performing mixes in Canadian jurisdictions.
- Local calibration through revising the existing specifications with respect to specimen conditioning (i.e., number of freeze-thaw cycles, saturation level, conditioning duration, etc.) and adjusting the pass/fail criteria to represent the climatic conditions and material properties in Canada.
- Development of a structured national database on flexible pavement performance to help identify moisture-induced damage failures and establish reliable criteria to evaluate and accept asphalt concrete mixes based on the laboratory scale testing and address the lack of well-documented field performance data.
- Conducting a national survey about the status of moisture damage evaluation practices, corresponding specifications, and anti-stripping treatment methods, used by different agencies, regions/municipalities, and asphalt producers in Canada in order to better understand the existing gaps and research needs in this area.

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