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Minimizing Moisture Damage in Asphalt Pavements

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The University of California Pavement Research Center

Using innovative research and sound engineering principles to improve pavement structures, materials, and technologies.

The University of California Pavement Research Center (UCPRC) conducts research on pavements of all types, including concrete and asphalt. It has operated facilities at UC Berkeley since 1948 and at UC Davis since 2002, and also conducts research on California highways. Primary funding for the UCPRC is provided by Caltrans. Most of the UCPRC's work is done through the Partnered Pavement Research Center contract, whose mission is to apply innovative research and sound engineering principles to improve pavement structures, materials, and technologies through partnership between academia, Caltrans, and industry.

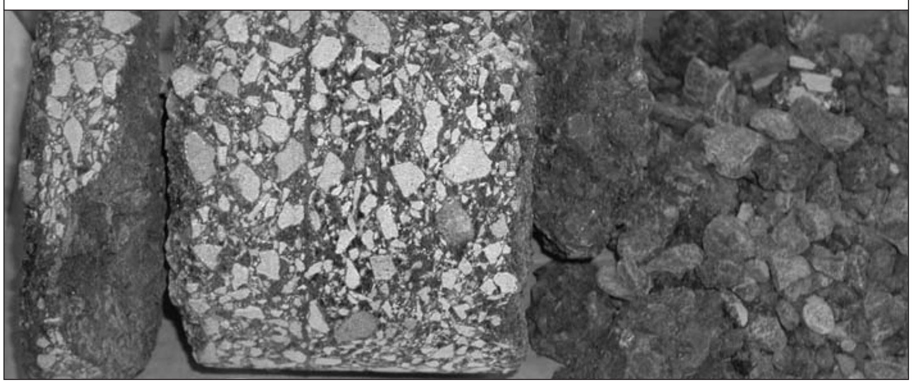
Introduction

The presence of moisture combined with repetitive traffic can adversely affect the performance of asphalt pavements. Moisture damage is caused by a **loss of adhesion**, commonly referred to as "stripping" of the asphalt film from the aggregate surface (Figure 1) or a **loss of cohesion** within the asphalt binder itself, resulting in a reduction in asphalt mix stiffness. Heavy traffic on a moisture-weakened asphalt pavement can result in premature rutting or fatigue cracking (Figure 2). The presence of moisture can also accelerate the formation of potholes or promote delamination between pavement layers (Figure 3). Moisture enters the pavement in both liquid and vapor form. Water can enter the surface of the asphalt mix from precipitation by gravity or hydraulic pressure from tire action, from the side by irrigation, and from the subgrade by capillary action. Moisture vapor can move upward from unbound aggregate layers or the subgrade and become entrapped in the asphalt mix. Moisture can also be present internally in the asphalt mix as a result of inadequately dried aggregate.

Factors Affecting Moisture Damage

Factors that contribute to moisture-related distress in asphalt pavements are summarized in Hicks, Santucci, and Aschenbrener [1]. The physical and chemical characteristics of aggregate play a major role in the resistance of asphalt pavements to water action.

FIGURE 1 Moisture-induced stripping in asphalt treated base layer



SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

Physical properties such as shape, surface texture, and gradation influence the asphalt content of the mix and hence the asphalt film thickness. Thick films of asphalt resist moisture damage better than thin films. Rough aggregate surfaces provide better mechanical adhesion with the asphalt than smooth surfaces.

Surface chemistry of the aggregate is also important. Aggregates range from basic (limestone) to acidic (quartzite) while asphalt has a neutral to acidic tendency depending on the asphalt source, which suggests that asphalt would adhere better to alkaline aggregates such as limestone than to acidic aggregates. Clay in the aggregate or present as a thin coating on the aggregate can contribute to moisture sensitivity problems. Clay expands in the presence of water and weakens the mix. As an aggregate coating, clay serves as a barrier to adhesion between the asphalt and aggregate surface.

The surface chemistry of asphalt can be altered with additives such as anti-strip agents to enhance adhesion between the asphalt and aggregate. Physical properties of asphalt such as viscosity and film thickness are also important in preventing moisture damage. Complete coating of the aggregate surface during mixing is critical in preventing moisture infiltration at the asphalt-aggregate interface. Lowering asphalt viscosity by raising mixing temperatures at the hot mix plant—or, in the case of warm mix asphalt, by using additives or foam technology—will help provide good coating of the aggregate. The lower asphalt viscosity allows deeper penetration into the interstices of the aggregate and thus results in a stronger physical bond between the asphalt and aggregate. The use of additives such as polymers or rubber in asphalt generally results in thicker films that help reduce the moisture sensitivity of the mix.

Moisture is a concern in the production of asphalt mixes at hot mix plants. Moisture from inadequately dried aggregate can escape as steam as the asphalt mix is heated or stored, potentially leading to stripping of the asphalt film from the aggregate. In some instances, water has been observed in mixes at the base of hot mix storage silos and at the edge of windrows of hot mix placed on the roadway prior to paving [2].

Good construction practices can produce moisture resistant asphalt pavements. The most important factor is good compaction. Compacting dense graded asphalt mixes to a high density (93 to 96 percent maximum theoretical density) lowers the air void content and permeability of the mix and reduces the ability of external water to enter the pavement. Well compacted mixes will be less susceptible to premature rutting, fatigue cracking, and binder oxidation and thus provide a longer pavement service life [3, 4].

Construction practices that should be avoided include the building of structures that trap moisture in pavement layers. For example, placing an open graded mix over a dense graded pavement with depressions or ruts can result in collecting water on the surface of the underlying pavement unless proper drainage is provided prior to the overlay. Placing a high air void content layer between two layers with low air void contents should be avoided. Moisture can also accumulate at the interface of impermeable interlayers placed between dense graded asphalt pavement lifts or under chip seals placed over moisture sensitive mixes.

FIGURE 2 Moisture-weakened asphalt mix promotes early pavement failure

Rutting

Fatigue Cracking

SOURCE (RUTTING): FEDERAL HIGHWAY ADMINISTRATION

Research on Moisture Damage

EARLY RESEARCH (1930-1999)

Numerous researchers have made significant contributions over the years to the literature on the subject of moisture damage in asphalt pavements. Many of these findings are still valid today. Most of the early research focused on adhesive failure or stripping rather than cohesive failure. Hubbard [5] discussed the importance of adhesion of asphalt to aggregate in the presence of water in 1938. Hveem [6] identified water resistance, consistency, durability, and setting rate as four engineering properties that need to be determined in the selection of quality asphalts for pavement construction in 1943.

In the 1950s, Goode [7] reported on the use of the immersion-compression test to evaluate the moisture sensitivity of compacted asphalt mixes. This test was later adopted as an ASTM standard. Thelan [8] found that the rate at which stripping occurs depends upon the surface energy of the materials involved. Andersland and

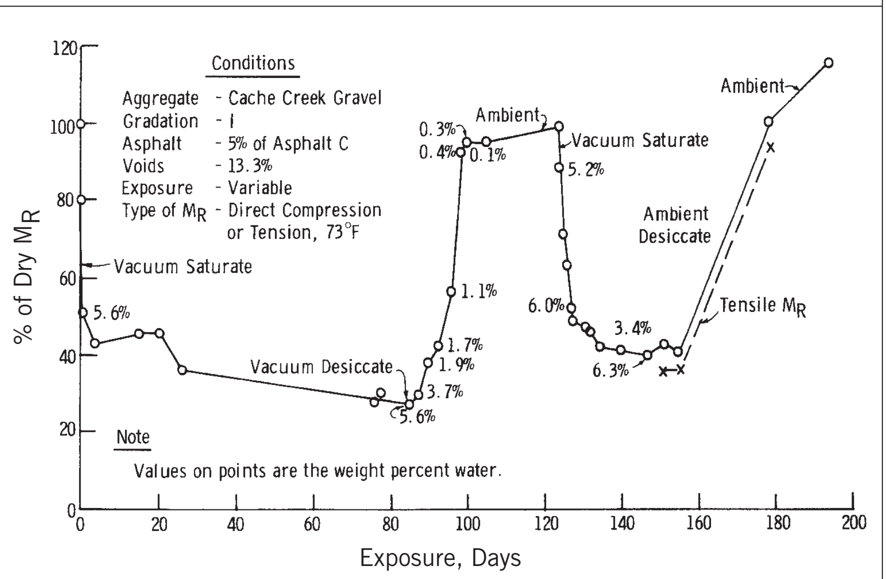
FIGURE 3 Moisture accelerates local pavement distress

Pothole **Delamination**

SOURCE (DELAMINATION): PICASAWEB.GOOGLE.COM/KALLOL87

Goetz [9] introduced a sonic test for evaluation of the stripping resistance of compacted asphalt mixes. Rice [10] examined the relationship between aggregate properties and moisture damage to asphalt mixes in an ASTM Symposium that included an extensive bibliography covering work on moisture sensitivity prior to 1959. He concluded that aggregate composition, surface texture, surface coatings, particle size and surface area, porosity and absorption, chemical reactivity, and surface energy are all important properties to evaluate. Skog and Zube [11], in 1963, stated "serious pavement failures may result from water action with little evidence of internal stripping," thus recognizing cohesive failure in the binder as a moisture damage issue. One of their proposed tests, the water susceptibility test, was offered as a way to predict cohesive failure in asphalt mixes used in California.

FIGURE 4 Effect of moisture on resilient modulus (stiffness) of asphalt mixes



SOURCE: SCHMIDT AND GRAF [12]

In 1972, Schmidt and Graf [12] used the resilient modulus test [13] to show the cycling effect moisture has on the stiffness of asphalt mixes (Figure 4). Combined with pavement structural analysis, this finding illustrates the damage cohesive failure can have on the performance of asphalt pavements. Lottman's extensive research [14, 15] in the 1970s on the detrimental effects of water and freeze-thaw cycling on asphalt mixes led to the development of the modified Lottman test, which measures the retained strength of asphalt compacted cores subjected to defined exposure conditions. The modified Lottman procedure was standardized and adopted as AASHTO Standard Method of Test T 283 and is widely used to measure the resistance of compacted asphalt mixes to moisture-induced damage.

Tunnicliff and Root [16, 17] presented their version of the Lottman procedure in the early 1980s in an extensive evaluation of anti-strip additives. Also in the 1980s, Kennedy et al. [18, 19] introduced the Texas freeze-thaw pedestal test and the Texas boiling water test as ways to evaluate moisture sensitivity of asphalt mixes. Measuring the bonding energy of asphalt-aggregate systems was the subject of research work by Ensley et al. [20] in 1984. Graf [21] extended work on moisture sensitivity with the pedestal test in 1986.

The next major contribution to research on moisture sensitivity of asphalt mixes came in the early 1990s as a result of the Strategic Highway Research Program (SHRP), which funded research for the development of performance based asphalt specifications to directly relate laboratory analysis with field performance. Curtis et al. [22] examined asphalt-aggregate interactions with emphasis on adhesion and absorption properties. They concluded that the interactions between asphalt and aggregate are dominated by aggregate chemistry with asphalt playing a lesser role. Aggregate modification with organosilanes was shown to improve the retention of asphalt in the presence of water for certain asphalt-aggregate combinations. Aggregate properties were also found to be more influential than asphalt properties in determining absorption of asphalt into the aggregate. Al-Swailmi and Terrel [23, 24] developed an environmental conditioning system (ECS) to evaluate moisture damage of asphalt mixes as part of the SHRP effort. The Hamburg wheel-tracking test (HWTT) was introduced in the United States at about the same time and was evaluated by several states (Colorado, Texas, and Utah) as a way to predict moisture damage [25, 26, and 27].

RECENT FINDINGS (2000-2010)

National Seminar on Moisture Sensitivity of Asphalt Pavements

In 2003, a national seminar on Moisture Sensitivity of Asphalt Pavements was held in San Diego, California. The California Department of Transportation (Caltrans) initiated the seminar to better understand how to deal with moisture sensitivity issues that had developed in northern parts of the state in the early 1990s. Selected experts from the United States, Canada, and Australia were invited to participate. The seminar was designed to examine moisture-related distress in asphalt pavements through a series of focused papers followed by breakout workshop sessions. Key topics addressed in the seminar were:

- Chemical and mechanical processes of moisture damage in hot mix asphalt (HMA) pavements
- Test methods to predict moisture sensitivity of HMA pavements
- Treatments
- Material production, mix design, and pavement design effects on moisture damage
- Production and construction issues for moisture sensitivity of HMA
- Field experiences
- Specifications to control moisture sensitivity problems in asphalt pavements

An important outcome of the seminar was the development of a road map to mitigate moisture sensitivity concerns in asphalt pavements. The road map included summaries of best practices for the various topics covered in the seminar and an identification of gaps in knowledge and research needs associated with moisture sensitivity of asphalt pavements. The compilation of papers and discussions presented at the seminar [28] is a valuable resource. Much of the information presented in this *Pavement Technology Update* is covered in greater detail in the referenced seminar document.

University of California Pavement Research Center Field Investigation

Caltrans also initiated and funded a study by the University of California Pavement Research Center (UCPRC) to conduct a statewide field investigation and laboratory testing to determine the severity and major factors associated with moisture damage [29]. The study was conducted from September 2002 to September 2005. The laboratory testing determined the effect of variables such as air void content and binder content on moisture damage and developed dynamic loading test procedures to evaluate moisture sensitivity. The effectiveness of the HWTT and the long term effectiveness of hydrated lime and liquid anti-strip additives were also evaluated.

The field investigation surveyed the condition of 194 pavement sections located in California. Although it was not a random sample, the general survey represents pavements encompassing a range of traffic and environmental conditions throughout California. The majority of the sections examined were dense graded asphalt concrete (DGAC), now referred to as HMA, and gap graded rubber modified asphalt concrete (RAC-G), now referred to as R-HMA. Based on the condition survey results, 63 sections were selected for a more intensive analysis that included permeability measurements in the field and the recovery of cores for testing in the laboratory. About 10 percent of the pavement sections showed moderate to severe moisture damage, suggesting moisture damage is an important factor to be considered in evaluating asphalt pavement performance in California.

Air void content was found to be a major factor affecting moisture sensitivity. Dense graded HMA sections with air void contents of 7 percent or less showed little or no moisture damage. Sections with air void contents greater than 7 percent showed medium or severe moisture damage. Based on limited data, R-HMA sections did not show an advantage in moisture resistance over dense graded HMA using conventional binders. Severe stripping was observed on a few R-HMA sections with high air void contents. Another observation from the field survey was the importance of adequate pavement drainage systems. Drainage systems need to be well designed and maintained to ensure removal of water from the surface and within the pavement during rain, since the amount of rainfall has a major effect on moisture damage.

The HWTT was found to be an effective predictor, correlating reasonably well with field performance, although in some cases the procedure may fail mixes that perform well in the field or give false positive results. Suggestions made to improve the prediction accuracy of the HWTT were: (1) use a test temperature consistent with the pavement location and (2) when the standard wet test yields poor results, run the test in a dry condition.

Based on both field and laboratory data, the researchers found hydrated lime and liquid anti-strip agents improved the moisture resistance of asphalt mixes. Hydrated lime and liquid anti-strip agents were also effective in improving moisture resistance during a conditioning period of up to one year. The effectiveness of the liquid anti-strip agents remained constant over the one year period while, in some instances, the hydrated lime showed increasing effectiveness over the same time period.

Mechanisms of Moisture Damage

Several mechanisms have been proposed to describe moisture damage in asphalt pavements. They include detachment, displacement, film rupture, spontaneous emulsification, pore pressure, hydraulic scour, pH instability, and environmental factors.

Detachment is the separation of an asphalt film from an aggregate surface by a thin film of water, without an obvious break in the asphalt film [30]. **Displacement** differs from detachment in that it involves displacement of the asphalt from the aggregate surface through a break in the asphalt film [31, 32]. **Film rupture** is sometimes described as a separate mechanism of moisture damage but, for purposes of this summary, it can be considered a subset of the displacement mechanism. **Spontaneous emulsification** results in an inverted emulsion of water in asphalt [31]. The formation of such emulsions is aggravated by the presence of emulsifiers such as clays or asphalt additives. The rate of emulsification depends on the nature of the asphalt and the presence of additives.

Pore pressure develops when stresses from repeated traffic load applications are imparted to entrapped water in the asphalt mix. Continued load applications worsen the damage as pore pressure buildup disrupts the asphalt film from the aggregate surface or generates micro-cracks in the asphalt mastic. **Hydraulic scour** occurs at the pavement surface. Stripping of the asphalt film from the aggregate results as water is sucked under the tire into the saturated pavement surface. It has been shown that the diffusion of water vapor through asphalt itself is considerable and that asphalt mastics can retain a significant amount of water [31].

Shifts in pH, or **pH instability,** of the contact water can affect chemical bonds and hence influence asphalt-aggregate adhesion [33]. The pH of contact water can also affect the value of the contact angle and the wetting characteristics of the asphalt-aggregate interface. **Environmental factors** such as temperature, air, and water can have a major effect on pavement durability [34]. In mild climates where good quality asphalts and aggregates are available, traffic loading may be the primary contributor to pavement distress. However, premature failure is likely to occur when poor materials are used in combination with severe weather such as excessive rainfall, wide temperature fluctuations, freeze-thaw conditions, and severe aging of the asphalt.

More detailed information about these mechanisms can be found in a paper by Little and Jones [35] that was presented at the 2003 National Seminar on Moisture Sensitivity of Asphalt Pavements. Table 1 lists the type of moisture damage, adhesive or cohesive, associated with each mechanism.

TABLE 1
Adhesive or cohesive failure associated with mechanisms of moisture damage

Mechanism	Adhesion	Cohesion
Detachment	●	
Displacement/ Film Rupture	●	
Spontaneous Emulsification		●
Pore Pressure	●	●
Hydraulic Scour	●	
pH Instability	●	
Environmental Factors	●	●

SOURCE: LITTLE AND JONES [35]

Tests to Predict Moisture Sensitivity

The numerous tests developed to predict the moisture sensitivity of asphalt mixes can be grouped into three general categories:

- Tests on asphalt mix components and component compatibility
- Tests on loose mix
- Tests on compacted mix

Table 2 provides a summary of the tests used for moisture sensitivity and references that contain detailed information about each test.

COMPONENT AND COMPATIBILITY TESTS

Some of the more common tests used on asphalt mix components to determine the potential for moisture damage include the sand equivalent test, the plasticity index, the cleanness value, and the methylene blue test.

The **sand equivalent test** determines the relative amount of clay material in the fine aggregate of a mix. The **plasticity index** gives an indication of the plastic nature of fine aggregate or soil while the **cleanness value** measures clay-like particles clinging to coarse aggregate. The **methylene blue test** was developed in France and is recommended by the International Slurry Seal Association as a way to quantify the amount of harmful clay in fine aggregates. The methylene blue test does not directly indicate stripping since no asphalt is used. However, the test results can be used to decide whether the potential for stripping exists since proper coating is unlikely to take place between the aggregate and asphalt if montmorillonite-type clay coats the aggregate.

The **net adsorption test** is used to determine the affinity and compatibility of an asphalt-aggregate pair and the sensitivity of the combination to water. The test was developed under SHRP in the early 1990s [22]. Net adsorption is the amount of asphalt remaining on the aggregate surface following an adsorption/desorption process involving an asphalt-toluene solution. Mixed conclusions were found in terms of correlation between net adsorption test results and moisture sensitivity results from indirect tension tests on compacted mixes. Little or no correlation was reported between net adsorption test results and wheel-tracking tests on compacted mixes [36].

TESTS ON LOOSE MIX

These tests are conducted on asphalt-coated aggregates in the presence of water. Examples include film stripping, immersion (static, dynamic, or chemical), surface reaction, Texas boiling water, and pneumatic pull-off tests. Advantages of tests on loose asphalt mix are that they are quick to run, cost little, and require simple equipment and procedures. Disadvantages are that the tests do not take into account traffic action, mix properties, and the environment. Results are mostly qualitative and require the subjective judgment and experience of the person performing the test. There is little evidence that results from these tests correlate well with field performance of asphalt mixes.

The **film stripping test** used in California involves placing an asphalt mix in an oven at 60°C for 15 to 18 hours, cooling the mix to room temperature, placing it in a jar with distilled water, and rotating the jar at 35 rpm for 15 minutes. The percentage of stripping is estimated by visual inspection under fluorescent light. In the **static immersion test**, an asphalt mix is cured two hours at 60°C and then cooled to room temperature. The mix is placed in a jar, covered with 600 mL of distilled water and placed in a 25°C water bath for 16 to 18 hours. The amount of stripping is visually estimated. The **dynamic immersion test** includes four hours of agitation to accelerate the stripping effect while the **chemical immersion test** uses varying concentrations of sodium carbonate in the distilled water as part of the test procedure.

The **surface reaction test** uses an acid reagent to generate gas pressure when exposed to stripped aggregate surfaces. A larger exposed surface area generates higher gas pressure. The **Texas boiling water test** requires adding an asphalt mix to boiling water and, after 10 minutes, allowing it to cool while skimming away stripped asphalt. The water is drained and the mix is allowed to dry on a paper towel prior to visual inspection to determine the percentage of stripped aggregate. The **pneumatic pull-off test** [37] measures the tensile and bonding strength of an asphalt binder applied to a glass plate as a function of time when exposed to water.

TABLE 2 Moisture sensitivity tests

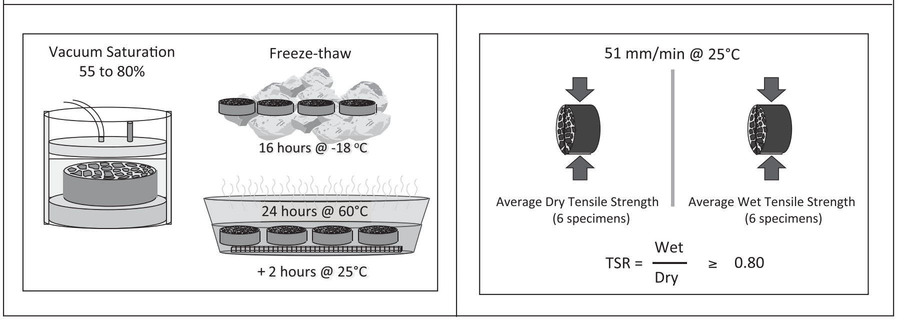
Test	Reference Information
Component and Compatibility Tests	
Sand equivalent	California Test 217 [46]
Plasticity index	California Test 204 [46]
Cleanness value	California Test 227 [46]
Methylene blue	Technical Bulletin 145, ISSA [47]
Net adsorption	SHRP-A-341 [22]
Tests on Loose Mix	
Film stripping	California Test 302 [46]
Static immersion	AASHTO T 182 [48]
Dynamic immersion	
Chemical immersion	Standard Method TMH1 (Road Research Laboratory, 1986) [49]
Surface reaction	Ford et al. [44]
Texas boiling water	Kennedy et al. [19]
Pneumatic pull-off	Youtcheff and Aurilio [37]
Tests on Compacted Mix Specimens	
Moisture vapor susceptibility	California Test 307 [46]
Immersion-compression	AASHTO T 165 [48]
Marshall immersion	Stuart [45]
Freeze-thaw pedestal	Kennedy et al. [18]
Original Lottman indirect tension	NCHRP Report 246, TRB [15]
Modified Lottman indirect tension	AASHTO T 283 [48]
Tunnicliff-Root	NCHRP Report 274, TRB [17]
ECS with resilient modulus	SHRP-A-403 [24]
Hamburg wheel-tracking	Tex-242-F, Texas DOT [50]
Asphalt pavement analyzer	

SOURCE: SOLAIMANIAN ET AL. [51]

TESTS ON COMPACTED MIX SPECIMENS

A multitude of tests on compacted asphalt mixes have been developed and modified. The tests are run on laboratory compacted specimens, field cores, or slabs. Examples include moisture vapor susceptibility, immersion-compression, Marshall immersion, freeze-thaw pedestal, Lottman indirect tension (original and modified), Tunnicliff-Root, ECS/resilient modulus, and wheel-tracking (Hamburg and Asphalt pavement

FIGURE 5
Conditioning and testing sequence for modified Lottman indirect tension test (AASHTO T 283)

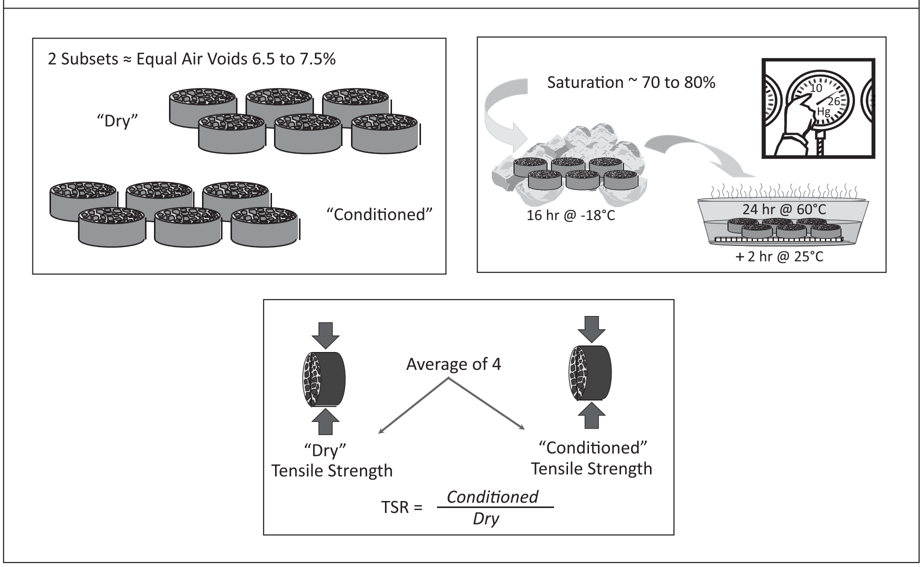


analyzer) tests. Many of these tests compare the strength of the compacted mix after being exposed to defined conditions such as temperature and freeze-thaw cycling to the dry strength of the specimen. Advantages of these tests are that they consider traffic, mix properties, and the environment and that they produce quantitative results rather than subjective evaluations. Disadvantages include long testing times, elaborate and expensive testing equipment, and test procedures that are laborious. Table 2 provides reference material for each test procedure on compacted asphalt mixes. For purposes of this discussion, we will focus on the more widely used tests, namely the modified Lottman indirect tension test and the HWTT.

The **modified Lottman indirect tension test,** which has been adopted as AASHTO T 283, is similar to the original Lottman indirect tension test with a few exceptions. One modification is that the vacuum saturation is continued until a saturation level of 55 to 80 percent is achieved compared to the original procedure that required a set saturation time of 30 minutes. Another change requires a loading rate and test temperature in the modified procedure of 2 inches/minute at 25°C, rather than the 0.065 inches/minute at 10°C used in the original procedure.

The test includes curing loose mixes for 16 hours at 60°C, followed by a 2 hour aging period at 135°C. At least six (often eight) specimens are prepared and compacted with final air void contents between 6.5 and 7.5 percent. Half of the compacted cores are vacuum saturated to between 55 and 80 percent and then subjected to an optional freeze period at -18°C for 16 hours and a 60°C water bath for 24 hours. The other half are unconditioned. The samples are then brought to a constant temperature and the indirect tension is measured on both the dry unconditioned and conditioned specimens (Figure 5). Caltrans introduced its version of the modified Lottman test in the early 2000s and designated it California Test 371 (CT 371). The main features of CT 371 are captured in Figure 6.

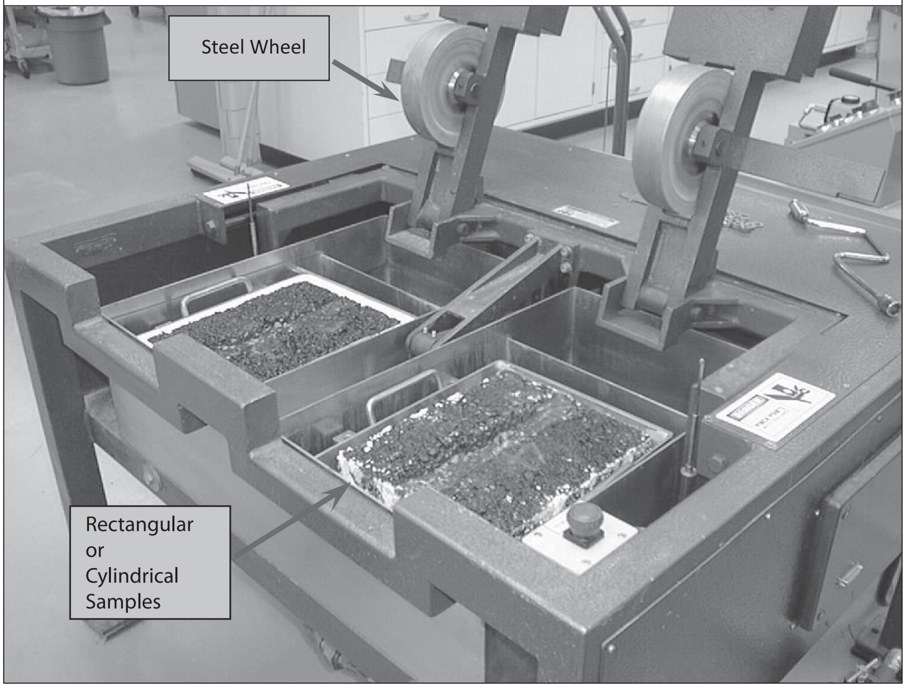
FIGURE 6 **Conditioning and testing sequence for California Test 371**



The **HWTT** measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of asphalt compacted specimens immersed in hot water. The wheel rolls back and forth on the submerged specimen. Test specimens can be made from laboratory compacted or field compacted cores or slabs (Figure 7).

The results from the HWTT define four phases of mix behavior: post compaction consolidation, creep slope, stripping slope, and stripping inflection point (Figure 8). The post compaction consolidation is the deformation measured at 1,000 passes, while the creep slope is the number of wheel passes needed to create a 1-mm rut depth due to viscous flow. The stripping slope is the number of passes needed to create a 1-mm impression from stripping. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. The Colorado Department of Transportation (CDOT) [25] found an excellent correlation between the stripping inflection point and pavements of known stripping performance. The stripping inflection point was more than 10,000 passes for good pavements and fewer than 3,000 passes for pavements that lasted only 1 year.

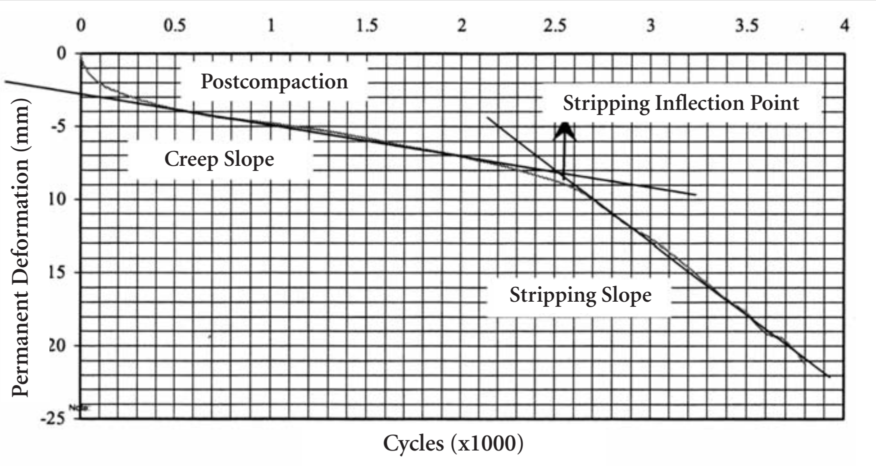
FIGURE 7 Hamburg wheel-tracking test (HWTT) device



SOURCE: SOLAIMANIAN ET AL. [51]

A survey conducted by CDOT in 2002 [38] showed that most agencies used some version of retained strength tests on compacted mixes (Lottman, modified Lottman, Tunnicliff-Root, or immersion-compression) to determine moisture sensitivity of asphalt pavements (Table 3). Despite the widespread use of AASHTO T 283, Kiggundu and Roberts [39] showed that the success rate of predicting moisture damage in the field has been limited (Table 4). In some instances, the procedure fails mixes that have a long history of good field performance. Some critics of the Lottman-type procedures question the severity of the accelerated vacuum saturation step and its effect on the asphalt-aggregate bond [40].

FIGURE 8 Typical Hamburg wheel-tracking test (HWTT) device results



SOURCE: SOLAIMANIAM ET AL. [51]

Treatment Methods

Once moisture sensitivity has been identified as an issue in a given pavement, the question becomes: what treatment methods are available to minimize damage to the pavement? The primary methods of treating moisture sensitive mixes involve the use of liquid anti-strip additives or lime. The use of organosilane compounds has also shown promise in reducing moisture damage in asphalt pavements.

Most liquid anti-strips are amine-based compounds that are usually added to the asphalt binder at a refinery or terminal, or through in-line blending at hot mix plants. The anti-strip is typically added at a rate of 0.25 to 1.00 percent by weight of asphalt. Liquid anti-strip additives are designed to act as coupling agents that promote better adhesion at the asphalt-aggregate interface. It is important to pre-test any liquid anti-strip agent with the job aggregate and asphalt to determine its effectiveness. Any change in asphalt source, aggregate source, or additive should generate additional tests to see how the changes may affect the moisture sensitivity of the mix.

Silane based additives used to pre-treat aggregates have been found effective at improving the moisture resistance of asphalt mixes [21, 22]. One recent example of an organosilane anti-strip agent used to reduce moisture damage of asphalt pavements is marketed under the trade name Zycosoil [41]. Zycosoil is added at a rate of 0.04 to 0.40 percent by weight directly to the hot asphalt binder. Unlike some amine-based liquid anti-strip agents, the addition of Zycosoil does not affect binder properties. Laboratory test results on a limited number of mixes showed a significant improvement in tensile strength ratio (TSR) values from the AASHTO T 283 test with the addition of Zycosoil.

TABLE 3
Agencies using different moisture sensitivity tests after SHRP

Test Method	Number of agencies using method
Boiling water (ASTM D 3625)	0
Static immersion (AASHTO T 182)	0
Lottman (NCHRP 246)	3
Tunnicliff and Root (ASTM D 4867)	6
Modified Lottman (AASHTO T 283)	30
Immersion-compression (AASHTO T 165)	5
Wheel-tracking	2

SOURCE: HICKS, SANTUCCI, AND ASCHENBRENER [1]

Lime treatment is widely used throughout the United States to improve the moisture resistance of asphalt pavements. Lime treatment helps mitigate adhesive and cohesive failure, tends to stiffen the mix, and appears to retard binder aging from oxidation, thus extending pavement life. The most common methods of lime treatment are dry lime on dry aggregate, dry lime on damp aggregate, dry lime on damp aggregate with marination, and lime slurry marination. Lime is generally added at about a rate of 1.0 to 2.0 percent by weight of dry aggregate or 20 to 40 percent by weight of asphalt. Most of these treatment methods seem to produce similar results, although some agencies feel lime slurry marination is slightly more effective. However, lime marination can be costly due to processing requirements and space limitations at the hot mix plant site. The literature contains several reports on the effectiveness of lime treatments, the most recent being a comprehensive study by Sebaaly et al. [42] at the University of Nevada, Reno.

Caltrans Strategy

Caltrans strategy for dealing with moisture sensitivity of asphalt pavements has evolved over the years. As a leader in asphalt pavement research in the 1940s, 1950s, and 1960s, Caltrans developed several laboratory tests such as sand equivalent, moisture vapor susceptibility, film stripping, and water susceptibility to identify materials in pavement construction that might be sensitive to moisture damage. This preemptive approach seemed to work well until the 1980s, when a rash of moisture sensitivity problems appeared in the northeastern part of California. Subsequently, moisture-related pavement issues also began to appear in the high mountain, high desert, and mid-coastal regions of the state. This led to the use of lime slurry marination and occasional use of liquid anti-strip additives as preventive measures to minimize moisture distress in asphalt pavements.

In the late 1990s, Caltrans and the asphalt industry partnered to identify the extent of the moisture sensitivity problem, develop reliable and repeatable laboratory test procedures that correlate with field performance, and determine when treatments were necessary and what treatments were effective. Based on a statewide assessment of environmental risks that contribute to moisture damage, such as precipitation level and freeze-thaw cycles, Caltrans introduced a testing and treatment matrix that considered environmental risk and laboratory test results on asphalt mix cores using CT 371. Treatment methods involving liquid anti-strips or various lime applications were suggested based on CT 371 test results and the level of environmental risk. The choice of treatments allowed depends on results from tests such as sand equivalent, cleanness value, or plasticity index to determine the presence or absence of clay in the job aggregate. Unfortunately, the relatively poor repeatability of CT 371 and sometimes unreliable correlation with field performance made the matrix approach controversial and impractical to implement. As a result, Caltrans implemented interim guidelines in 1999 and modified them in 2008.

Current Caltrans interim guidelines on moisture sensitivity treatment can be summarized with the following four strategies:

- For HMA sources that have no history of moisture sensitivity and have no documented history of being treated with an anti-strip agent, no treatment is required.
- For HMA sources that have no documented history of moisture sensitivity in past Region/District projects but have consistently been treated with lime or liquid anti-strip, specifications should call for the same treatment as used in the past.
- For HMA sources that have a documented history of moisture sensitivity in past Region/District projects, but may or may not have used anti-strip agents, specifications should call for liquid anti-strip or lime treatment.

TABLE 4 **Success rates of test methods used to predict moisture sensitivity**

Test Method	Minimum Test Criteria	% Success
Modified Lottman (AASHTO T 283)	TSR = 70%	67%
	TSR = 80%	76%
Tunnicliff-Root (ASTM D 4867)	TSR = 70%	60%
	TSR = 80%	67%
	TSR = 70%—80%	67%
10-minute boil test	Retained coating 85%—90%	58%
Immersion-compression (AASHTO T 165)	Retained strength 75%	47%

NOTE: TSR = tensile strength ratio.

SOURCE: KIGGUNDU AND ROBERTS [39]

- For new or unknown HMA sources with no documented history, each project should be handled on a case-by-case basis and specifications should call for liquid anti-strip or lime treatment unless the HMA source is in the immediate area of a known source with no documented history of moisture sensitivity, in which case the strategies listed above should be employed.

Caltrans recommends three methods of lime treatment: dry hydrated lime on damp aggregate (DHL), dry hydrated lime on damp aggregate with marination (DHLM), and lime slurry marination (LSM). Caltrans considers the treatments equivalent and allows the contractor to choose the treatment option unless clays are present in the aggregate source. According to CT 204, the plasticity index is used as an indicator of the presence of clay. If the plasticity index of the aggregate blend is less than 4, the contractor may choose DHL, DHLM, or LSM from the lime treatment options. For a plasticity index of 4 to 10, the contractor may choose DHLM or LSM.

Importance of Good Compaction

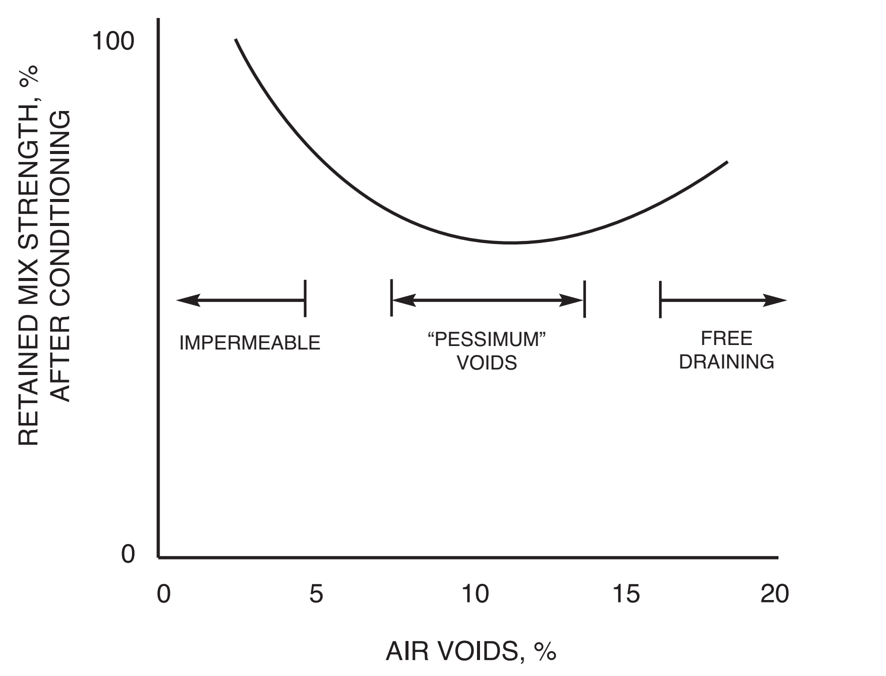
The **pessium voids concept** proposed by Terrel and Shute [34] is significant for those seeking ways to minimize moisture damage in asphalt pavements. The pessium voids theory suggests that moisture damage will be less for impermeable and for free-draining asphalt mixes as shown in Figure 9. The worst condition for dense graded asphalt pavements is in the range of 8 to 12 percent air void content, where moisture can readily enter the pavement but not easily escape. Improving compaction procedures to reduce the air void content of dense graded asphalt mixes to the 6 to 8 percent range will go a long way toward improving moisture resistance. In the field investigation portion of a recently completed study on moisture sensitivity [29], air void contents of dense graded mixes cored from 50 sites throughout California ranged from 2 to 14 percent with a mean value of about 7 percent. Reducing the mean and especially the variance of these air void contents would help reduce the risk of moisture damage.

Caltrans currently requires a compaction range of 91 to 97 percent maximum theoretical density (MTD) for dense graded asphalt mixes used on standard state construction projects (92 to 96 percent MTD for QC/QA projects) [43]. Penalties can be assessed when compaction levels fall below or above these limits. Raising the lower limit from 91 to 93 percent MTD can significantly improve the moisture resistance as well as the fatigue and rut resistance of asphalt pavements. Harvey et al. [3] identified the impact air void content has on the fatigue resistance and stiffness (rut resistance) of dense graded asphalt mixes used in California—first with laboratory tests and later verified with full scale Heavy Vehicle Simulator (HVS) tests on pavement sections. More recently, in laboratory tests on Kentucky dense graded mixes, Blankenship [4] showed that a 1.5 percent reduction in air void content (91.5 to 93 percent MTD) can increase mix fatigue life by 4 to 10 percent and increase rut resistance by 34 percent. Reduced air voids and lower mix permeability, which are associated with lower air voids, can also improve the long-term durability of the pavement by limiting oxidative hardening of the asphalt binder.

Conclusions

Moisture damage in asphalt pavements is caused by adhesive failure between the asphalt film and aggregate or cohesive failure within the asphalt binder itself. Factors contributing to moisture-related distress include material properties such as type,

FIGURE 9 Impact of air void content on retained mix strength after moisture conditioning



SOURCE: TERREL AND SHUTE [34]

shape, and porosity of the aggregate and viscosity, film thickness, and source of the asphalt binder. Hot mix plant production issues, including inadequately dried aggregate, can lead to moisture problems in the finished pavement. Construction practices that trap moisture in pavement layers, such as placing a high air void content mix between low air void content lifts or placing a chip seal over a moisture sensitive pavement, need to be avoided to minimize moisture damage.

Treatment methods to minimize moisture damage involve the use of liquid anti-strip additives or lime. Silane based additives have also shown promise in reducing moisture damage in asphalt pavements. Liquid anti-strips are usually added to the asphalt at the refinery or through in-line blending at hot mix plants. Lime treatment methods include dry lime on dry aggregate, dry lime on damp aggregate, dry lime on damp aggregate with marination, or lime slurry marination. Current Caltrans strategy involves the use of interim guidelines to determine the need for moisture sensitivity treatment. Based on whether a documented history shows no moisture problem or some level of moisture-related distress, Caltrans calls for no treatment or specifications for treatment with liquid anti-strip additives or lime. Caltrans recommends either dry hydrated lime on damp aggregate or some form of lime marination depending on past history or experience with moisture sensitivity.

Good compaction procedures to reduce the air void content of dense graded asphalt pavements have been shown repeatedly to improve moisture resistance. Slightly tightening existing requirements for maximum theoretical density will also improve the fatigue and rut resistance of asphalt pavements. Lower air void contents will tend to lower mix permeability and limit oxidative hardening of the asphalt binder, thus improving the long term durability of pavements.

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