TOPIC 7

Field Experiences

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Field performance is the ultimate test of laboratory performance prediction methods for identifying moisture sensitive asphalt concrete mixtures and the effects of antistripping agents. This paper presents the field experiences of four states (California, Nevada, Texas, and Virginia) in regard to their history of problems with moisture sensitive mixtures, solutions to these problems, performance prediction and forensic tools used to identify these mixtures, and specifications used to control moisture sensitivity. These four states are actively involved in research on this topic, and the solutions, tools, and specifications for each state are based on their research results, which are also described.

CALIFORNIA

The state of California has identified moisture-related pavement problems in some locations since the 1980s. The current treatment of choice has been lime slurry marination (LSM). This has largely eliminated the problem (interview with R. Neal based on work in District 2, North Region Redding Materials Laboratory, from 1983 to July 11, 2002). However, the practice of requiring LSM for all aggregate sources in specific geographic areas has, according to the quarry industry, resulted in good sources having to undergo LSM before use. This outcome, along with its attendant costs and logistical difficulties, has led Caltrans and industry to a reexamination of the problem and the solutions.

The following sections describe the steps Caltrans is making to address the issues of asphalt pavement performance with respect to moisture sensitivity and the practical aspects of using treatments to alleviate it.

History of Problem

In the early to mid-1990s, Caltrans personnel became increasingly concerned that moisture-susceptible mixtures were causing or contributing to premature distress on many miles of asphalt concrete (AC) pavement on the California highway system. This distress can develop as early as 2 years after the project is constructed and as late as 9 years after construction. The distress includes alligator cracking, raveling, potholing, and rutting with flushing, all of which can be associated with the effect of water on asphalt concrete (*1*, *2*). These concerns had developed in the 1980s in Northern California District 02, but were now no longer confined to only District 02 as other districts began using lime slurry marination treatment.

The approach that had been used in District 02 to avoid the construction of AC pavement having poor resistance to moisture damage was to require pretreatment of all the AC aggregate on all major projects. This pretreatment consisted of precoating all the AC aggregate with a lime slurry that was mixed at the plant. The pretreated aggregate was then stockpiled for a specified "marination" period of 24 h to 21 days to provide some time for a chemical reaction to take place on the aggregate surface. This pretreatment required several plant modifications such as the equipment to make the lime slurry, equipment to coat the aggregate with the lime slurry, and space for this equipment and for the stockpiles of treated aggregate. Initially, the AASHTO T283 test was used to qualify mixes requiring a tensile strength ratio (TSR) of 80 or above. The T283 test was discontinued owing to the industry's pressure on Caltrans, with the industry citing the test's high variability. It became District 02 policy to lime treat all of the aggregates for all asphalt concrete for all major projects after the test was discontinued. If lime treatment was required on all of the aggregate from all of the sources, there was no question about how the contractor prepared its bid.

Because the aggregate pretreatment approach appeared to have been successful in District 02, as Caltrans's concern in regard to AC moisture sensitivity became more widespread, the specifications requiring the LSM treatment of the AC aggregate began showing up in the special provisions for Caltrans projects statewide. At that time, alternative methods such as the addition of dry hydrated lime to wet aggregate were not allowed, owing to air quality issues. As a result, the asphalt pavement industry approached Caltrans with several concerns regarding the approach. Industry comments included concerns that many of the projects requiring the LSM pretreatment were in locations with no history of AC stripping and subsequent premature pavement distress. There was no apparent statewide uniformity on where these requirements were being included. The cost of the LSM equipment and space requirements for the equipment and the treated aggregate stockpiles were also of concern. Another concern was the reliance on T283 to predict the moisture sensitivity of AC. There was a general agreement that this test, which was based on extensive research by Lottman for NCHRP in the 1970s and 1980s, was the best test available to measure AC moisture sensitivity (*3*, *4*). However, the issues of test repeatability and reproducibility were very troublesome (*5*). Because the need for the LSM pretreatment was based on T283 results, situations were reported in which the prebid testing by the contractor indicated no need for LSM. Contractors prepared their bids accordingly. After the contract was awarded and there was presentation of the proposed AC materials and mix design to Caltrans, the Caltrans verification testing indicated the need for the LSM treatment. This situation was creating both cost and space problems for the contractors.

The additional costs resulted from several items:

1. Initial cost of the lime slurry plant,
2. Additional time and fuel to heat the mix to the proper temperature owing to the added water, and
3. Additional handling of the materials to form the stockpiles for the marination.

Some contractors had to enlarge their facilities to accommodate the additional stockpiles.

Another concern voiced by the industry was that the only acceptable treatment was LSM. Industry pointed out that the literature revealed many successes when dry lime was used to coat wet or damp aggregate or when a liquid antistrip was incorporated into the mix by combining it with the asphalt. The industry, therefore, argued that these alternative processes should be allowed where appropriate. Thus, the primary concerns were as follows:

1. There was no consensus concerning definition or identification of stripping.
2. AC aggregate treatment was being required where no history of stripping existed.
3. LSM was the only treatment allowed for major projects (when the T283 could no longer be used).
4. The precision and bias of the best laboratory test for moisture sensitivity (AASHTO T283) were poor.

These concerns resulted in the creation of several Caltrans–industry task groups to try to develop an approach that effectively addressed Caltrans' intent to require treatment for moisture sensitivity only in appropriate locations and with any treatment that had a good chance for success.

Subsequent work by the task groups was concentrated in two problem areas. The first was the absence of a repeatable, reproducible test that had good correlation with well-documented field performance. Although it was agreed that T283 was the best test method then available, such concerns needed to be addressed. *NCHRP Report 444* was used as the basis for evaluating several modifications of T283 to improve its repeatability and reproducibility (*5*). These efforts included round-robin testing by several Caltrans and industry laboratories. The results as shown in Table 1 were disappointing, because test reproducibility continued to be poor with a standard deviation for TSR of 8.3%. This seemed to be related to the range of void contents in the test specimens. The task group recommended further refinement of the compaction methods and a new round-robin.

The second area pursued was to try identifying appropriate treatments based on the climate at the job. This resulted in the creation of several matrices that included required California Test Method (CTM) 371 (modified T283) TSR values for various climatic combinations of wet–dry and freeze–no freeze. Also discussed at length was the effectiveness of treatment that is less time consuming, less expensive, and therefore less disruptive than LSM. Caltrans and industry agreement on these issues has not been reached.

Interim guidelines were developed, as shown in Table 2. They provide guidance to designers and specification writers about when a moisture sensitivity treatment is required. They are based on the pavement performance history where the work will be done. For example, if an antistrip treatment has been used in the past and stripping has not occurred, this treatment is required for the new work. If stripping has been a problem, LSM is required. A lack of uniformity in the statewide application of the interim guidelines was observed by the industry and reported to Caltrans during 2001. It was suggested that this situation might have been

TABLE 1 Caltrans's Round-Robin Test Results

Lab. No.	TSR (%)	Strength (kPa) Dry	Strength (kPa) Wet	Mean % Saturation	Air Voids Dry	Air Voids Wet	Max. Specific Gravity
1	42	1249.4	526.4	71.1	0.5	7.4	2.49
2	36	1432	516.9	68	0.4	7.5	2.484
3	39	850.8	332	68.4	0.6	6	2.458
4	43.6	700	304.9	67.6	1	7.1	2.499
5	29.5	1293.7	381.4	69.5	0.8	6.7	2.501
6	44	941.1	417.7	71.7	0.8	7.1	2.49
7	56.6	851.5	483.3	69.4	1.4	6.9	2.508
8	30	1188	360	70	1.1	7.2	2.493
9	36.7	1207.7	443.7	73.3	0.8	7.6	2.478
Standard Deviation	8.3	248.7	80.1	1.9	0.3	0.5	0.015
Average	39.7	1079.4	418.5	69.9	0.8	7.1	2.489

caused by too much reliance on judgment by the Caltrans materials engineers when using the interim guidelines. The industry also observed and reported the requirement of LSM in some questionable locations.

Solutions

Because of the importance of precluding moisture damage problems in Caltrans asphalt concrete pavements using an equitable, cost-effective approach, the department renewed its efforts to develop an approach that addresses both its needs and industry concerns beginning with a Caltrans/Industry Moisture Sensitivity Workshop on January 4, 2002. The result was the establishment of three joint Caltrans and industry subgroups to address concerns about the identification and documentation of stripping, the need for a reproducible test that provides results that coincide with pavement performance, and implementation issues such as retained strength acceptance criteria, specifications for dry lime on wet aggregate and liquid antistrip use, guidance on what treatments would be allowed, training needs, certification of testers, and laboratory accreditation.

After the three subgroups provided progress reports to the full Caltrans/Industry Moisture Sensitivity Committee at a meeting in May 2002, the attendees agreed to redirect their efforts for using the matrix approach to moisture sensitivity in 2003 (see Tables 3 and 4). As stated previously, this matrix involves evaluating the mix using TSR results and then using these data in conjunction with the climatic data (rain and freezing shown in Figure 1) to determine if the asphalt concrete mix needs treatment and which treatment will be allowable. Data furnished by the liquid antistrip industry and *NCHRP Report 373* influenced the development of the liquid antistrip specification that is currently a Caltrans standard special provision (*6*).

This decision to adopt the matrix approach for the 2003 construction season led to the creation of some short-term and long-term issues. The need for a reproducible, performance-related test continues. The need for moisture sensitivity test criteria that correlate with the severity of the climate still exists. The needs for mix design procedures and specifications for the various treatments were realized and developed. The need for laboratory accreditation and

TABLE 2 Caltrans Interim Guidelines on Moisture Sensitivity Treatment

<table>
<tr><td colspan="2">Caltrans, in conjunction with industry, is in the process of revising CTM-371 (AASHTO T283) to better identify aggregates susceptible to moisture damage (stripping). Our goal is to provide a CTM that is reliable and repeatable.
Until the new CTM is issued, these interim guidelines should be utilized. These guidelines supersede guidelines issued by the Materials and Engineering Testing Services Branch dated January 13, 1999, signed by Jim Stout.
During project plan and specification development, the District Materials Engineer should look at the project vicinity to determine if available aggregate sources have shown a past documented history of stripping. Documented history should include written reports, maintenance records, and in-service pavement performance. In addition the DME should also look at past treatments used, including lime, liquid antistrip, etc.</td></tr>
<tr><td colspan="2">Recommended strategies should include</td></tr>
<tr><td>1. Potential asphalt concrete sources that have no history of stripping and have no documented history of being treated with an antistripping agent.</td><td>Strategy: No treatment required.</td></tr>
<tr><td>2. Potential asphalt concrete sources that have no documented history of stripping in past Region/District projects. Asphalt concrete has consistently been treated with lime slurry with marination, or liquid antistrip.</td><td>Strategy: Specifications should call for past treatment.</td></tr>
<tr><td>3. Potential asphalt concrete sources that have a documented history of stripping in past Region/District projects. Asphalt concrete may or may not have utilized antistrip agents.</td><td>Strategy: Specifications should call for lime slurry with marination. AASHTO T283 should not be required</td></tr>
<tr><td>4. New or unknown potential asphalt concrete sources, with no obtainable documented history. Treat on a case-by-case basis. (If the asphalt concrete source is in the immediate area of a known source and has no documented history of stripping, refer to strategies number one or two above.)</td><td>Strategy: Specifications should call for lime slurry with marination. AASHTO T283 should not be required.</td></tr>
<tr><td colspan="2">When specifying lime slurry with marination the Standard Special Provision (SSP) for lime should be included, along with a statement in Section 10 (asphalt concrete) of the SSPÕs stating, ÒAttention is directed to ÔLime Treated AggregatesÕ elsewhere in these special provisions.Ó</td></tr>
<tr><td colspan="2">When specifying liquid antistrip additives the SSP for liquid antistrip should be included along with a statement in Section 10 (asphalt concrete) of the SSP stating, ÒAttention is directed to ÔLiquid Antistrip AdditivesÕ elsewhere in these special provisions.Ó</td></tr>
</table>

TABLE 3 Caltrans Low Environmental Risk Zone

TSR	***Mix Risk***	***Treatment***	***Required TSR After Treatment***
≥ 70	Low	None Required	
51–69	Moderate	LAS, DHL, LSM**	TSR ≥ 70
≤ 50	High	DHL, LSM**	TSR ≥ 70

**** Select one treatment.**
Liquid antistrip (LAS); dry hydrated lime with no marination (DHL).
Lime slurry with marination (LSM).

TABLE 4 Caltrans Moderate and High Environmental Risk Zone

TSR	*Mix Risk*	*Treatment*	*Required TSR After Treatment*
≥ 75	Low	None Required	
61–74	Moderate	LAS, DHL, LSM**	TSR ≥ 75
≤ 60	High	LSM	TSR ≥ 75

**** Select one treatment.**
Liquid antistrip (LAS), dry hydrated lime with no marination (DHL).
Lime slurry with marination (LSM).

FIGURE 1 Caltrans's proposed environmental risk region map 2002 (J. T. Harvey, draft recommendation concerning Caltrans pavement research contract, 2002).

personnel training and certification were realized, and Caltrans has developed a plan through its Independent Assurance Program for these needs to be met. All of those aspects have been assigned as short-term goals. Long-term goals assigned to the subgroups include a better understanding of AC performance problems due to moisture, an improved performance-related reproducible test, and a mechanism wherein all cost-effective moisture sensitivity treatments will be allowed.

Performance Predictions

Caltrans is not now able to predict performance if the mix is not lime treated, because it does not require a moisture sensitive test. However, with the adoption of CTM 371 (modified T283), it is planned to relate TSR to performance for the various environmental zones. The CTM 371 includes better control on compaction of specimens, additional specimens in which the high and low values from the sample group are not used, and better control of saturation levels. With these test changes, Caltrans is attempting to create a more repeatable test for predicting moisture sensitivity of asphalt concrete mix.

Specifications to Control Moisture Sensitivity

Caltrans has developed new and modified specifications to assist in controlling moisture damage. These include specifications for the following:

- Modified liquid antistrip additives,
- New dry lime on wet aggregate, and
- Modified LSM.

These specifications are to be used in conjunction with the matrix discussed earlier. The industry recently filed an ÒIndustry Dissenting Opinion.Ó Many items are cited in its documentÑincluding unproven aspects of the new test method, the new specifications, and the ability of Caltrans to properly identify stripping on a statewide basis. The proposed specifications and policies allow the contractors latitude on treating mixes for moisture sensitivity, joint training, and assistance on equipment calibration that was not previously allowed by Caltrans. Many changes were made at the contractorsÕ requests. The industry continues to express concern in regard to full implementation of proposed specifications and test methods without practical basis. Owing to the industryÕs concerns, Caltrans is not planning on a full implementation for the 2003 construction season. District 3 is planning on 10 pilot projects using the proposed specifications with CTM 371, and the projects are to be evaluated before the 2004 construction season. Both the industry and Caltrans hope that agreement can be reached.

Research on Moisture Sensitivity

Currently, Caltrans is engaged in a long-term contract with the Pavement Research Center at the University of California at Berkeley. One element of this project is to develop improved tests for moisture sensitivity. This will include the evaluation of the Hamburg device as well as other wheel-tracking devices.

The long-term research needs will be addressed at a National Moisture Sensitivity Seminar to be held in San Diego early in 2003. This meeting will provide an update on both fundamental and theoretical research and practical approaches currently under way to address AC moisture sensitivity. It should therefore help refine the initial use of the matrix approach in 2003 and provide direction for future work in this important subject area.

NEVADA

The Nevada Department of Transportation (NDOT) began requiring LSM exclusively in the 1980s to address moisture sensitivity in hot-mix asphalt (HMA). NDOTÕs specification to control moisture sensitivity includes a minimum wet–dry TSR and a minimum unconditioned indirect tensile strength. Also, NDOT adopted a number of other construction and material requirements to limit moisture damage.

The following sections describe the history of moisture damage in Nevada, solutions to this problem, performance prediction and forensic tools to evaluate mixtures, and corresponding specifications and research.

History of Problem

Moisture sensitivity of HMA mixtures in Nevada was first identified in 1983 when a pavement section I-80 near Deeth, Nevada, experienced severe moisture-related distresses shortly after opening to traffic (*7*). The project consisted of a 4-in. dense-graded mix and a ¾-in. open-graded mix over a layer of pulverized HMA and base mixed with 3% portland cement.

Shortly after opening the project to traffic, the open-graded layer began to ravel. Delaminations of the open-graded mix occurred at several locations. Raveling and delaminations continued throughout the winter and progressed into the dense-graded layer. By the end of winter, transverse cracking was present at numerous locations. At the time of construction of this project, NDOT's specifications did not require any antistripping additives for HMA mixtures.

An investigation was carried out to identify the causes of the distresses (*7*). The quality assurance and quality control data indicated that the great majority of materials properties and construction temperatures were within specification limits. A moisture sensitivity evaluation on cores obtained from the project indicated that the resilient modulus and tensile strength properties of the dense-graded HMA mixture were significantly reduced after one freeze–thaw conditioning cycle. Retained strength ratios were in the range of 15% to 30%, which indicates severe damage of the HMA mixture as a result of moisture conditioning. On the basis of this investigation, the following recommendations were made:

- Require a moisture sensitivity test with a freeze–thaw cycle as part of the mix design.
- Require a minimum dry tensile strength value as part of the mix design.
- Require in-place air voids limit as part of quality control during construction.
- Include aggregate gradation control requirements between sieves No. 16 and 200.

Solutions

The recommendations from the Deeth study were effectively implemented in the design and construction of HMA mixtures in Nevada. NDOT developed a modified version of the Lottman moisture conditioning procedure. The modified version includes one freeze–thaw cycle and measures the retained strength ratio based on the tensile strength of the unconditioned and conditioned mixture.

Initially, NDOT allowed various types of antistripping additives, but later experience showed that lime is the most effective additive. In 1986, NDOT began to require hydrated lime exclusively in all HMA mixtures north of US-6 and on selected projects south of US-6, and limits were placed on the air voids contents of compacted HMA pavements. In addition, NDOT increased the minimum Hveem stability under high traffic volumes from 35 to 37. In 1987, a cutoff date of November 1 was imposed on the placement of open-graded mixture in the northern portion of the state. Also in 1987, NDOT changed the plasticity index requirements on aggregates for HMA mixtures from 6 to nonplastic. In 1988, NDOT specified that a minimum of 5% moisture (by dry weight of aggregate) should be available for the complete hydration of lime in HMA mixtures. In 1990, NDOT developed the AC-20P specifications that allow the use of polymer-modified binders in HMA mixtures.

During the 1990s, NDOT completed several research efforts to control the moisture sensitivity problem. The work completed under these efforts is presented. In 1998, NDOT implemented the following:

- Maintain the unconditioned tensile strength requirement at 65 psi.
- Maintain the minimum retained strength ratio at 70%.
- Require mandatory marination for all HMA mixtures.

Performance Prediction and Forensic Tools

The modified Lottman procedure serves as NDOT's primary method for controlling the moisture sensitivity of HMA mixtures. Moisture sensitivity testing is conducted at the mix design stage and during construction activities. NDOT requires the conduct of a new mix design due to any changes in binder source or aggregate production. The new mix design ensures that moisture sensitivity is maintained under control.

During construction, NDOT requires sampling of the HMA mixture every 10,000 tons or twice a week from the completed mat (behind the paver). All behind-the-paver samples are evaluated for moisture sensitivity and subjected to the minimum specification on the unconditioned tensile strength of 65 psi and the minimum retained strength ratio of 70%. The evaluation of the behind-the-paver mixtures serves as an effective method for controlling the quality of the materials being placed on the road.

In some special cases, the modified Lottman procedure with multiple freeze–thaw cycles is used as a forensic tool. If a project is experiencing premature distresses, cores are obtained and subjected to 1 through 18 freeze–thaw cycles to evaluate their long-term resistance to moisture damage. The resilient modulus test is used to assess the properties of the HMA mixtures after various freeze–thaw cycles. The resilient modulus test is nondestructive, which allows testing of the same core after multiple freeze-thaw cycles. The multiple freeze–thaw conditioning has been very effective in assessing the true resistance of HMA mixture to moisture damage.

Specifications to Control Moisture Sensitivity

Nevada has had an extensive specification for moisture sensitivity since the mid-1980s (*8*). The specifications cover the mix design and construction activities. The following is a summary of the major points in NDOT's moisture sensitivity specifications:

- Mix design: Moisture sensitivity testing is required as part of the Hveem mix design. The modified Lottman procedure is used with one freeze–thaw cycle. The retained strength ratio is defined as the ratio of the unconditioned tensile strength over the conditioned tensile strength. Minimum values of the unconditioned tensile strength of 65 psi and a minimum retained strength ratio of 70% are required.
- Field mixtures: Field mixtures are sampled from behind the paver every 10,000 tons or twice a week and evaluated through the modified Lottman procedure with one freeze–thaw cycle. Minimum values of the unconditioned tensile strength of 65 psi and a minimum retained strength ratio of 70% are required.
- Construction practice: Currently, 48 h of marination is required for all aggregate sources throughout the state. Percent moisture for marination is 3% above the saturated surface dry condition. Marinated aggregates can be stockpiled for a maximum period of 60 days.

Research on Moisture Sensitivity

Nevada has conducted several extensive research studies on moisture sensitivity of HMA mixtures. Following is a brief description of Nevada's research efforts on moisture sensitivity.

Mix Design Versus Field Mixtures

The objective of this research was to monitor the variations in the moisture sensitivity of mix design and field produced materials for marinated and nonmarinated HMA mixtures (*9*). The goal was to assess the impact of marination on the percentage of mix design and field mixtures that pass NDOT's moisture sensitivity specification of minimum dry tensile strength of 65 psi and minimum retained strength ratio of 70%. This effort evaluated mixtures from 1997, 1998, and 1999 construction seasons. Table 5 summarizes the moisture sensitivity data for the 3-year period.

The 3 years of data presented in Table 5 lead to two major conclusions: the minimum unconditioned tensile strength of 65 psi is a very realistic limit, and the marination process significantly improved the moisture sensitivity properties of field-produced HMA mixtures. On the basis of these findings, NDOT maintained the minimum required unconditioned tensile strength at 65 psi and mandated the marination process.

Impact of Marination Time

The objective of this research effort was to assess the impact of marination period on the moisture sensitivity of HMA mixtures. A total of four aggregate sources were evaluated with three binders (*9*). Marination times included 48 h, 45 days, 60 days, and 120 days. The goal of this study was to identify the maximum benefit of marination without negatively affecting the resistance of HMA mixtures to moisture damage. Mixtures were marinated under outside conditions at the identified periods and then tested for their unconditioned tensile strength and retained strength ratios. Table 6 summarizes the moisture sensitivity properties of HMA mixtures at various marination periods.

The data from this study showed that longer marination times would not improve the resistance of HMA mixtures to moisture damage. In the majority of the cases, prolonging the marination time significantly reduced the retained strength ratio. On the basis of this finding, NDOT mandated a minimum of 48 h and a maximum of 60 days of marination time.

TABLE 5 NDOT Moisture Sensitivity Data of 1997–1999 HMA Mixtures

Property	Mix Design						Behind the Paver					
	Marinated			Nonmarinated			Marinated			Nonmarinated		
	97	98	99	97	98	99	97	98	99	97	98	99
No. of Samples	39	80	70	28	13	7	118	312	370	114	95	61
Uncond. Tensile Strength, psi[a]	101	87	99	122	121	140	94	88	97	118	143	131
Fail @ 65 psi, %	0	14	0	0	0	0	12	9	1	2	0	0
Strength Ratio, %[b]	84	90	94	81	84	86	89	90	94	76	82	81
Fail @ 70%	13	1.3	1.4	25	15	0	3.4	2.2	3.8	30	16	8

[a] Average unconditioned tensile strength.

[b] Average retained strength ratio.

TABLE 6 NDOT Moisture Sensitivity Properties at Various Marination Periods

Agg. Source	Binder Grade	48 h		45 days		60 days		120 days	
		Strength	Ratio	Strength	Ratio	Strength	Ratio	Strength	Ratio
Lockwood	AC-20	107	88	138	40	146	30	139	43
	AC-20P	75	85	101	38	72	46	96	50
	PG64-28	70	74	101	36	93	47	110	61
Dayton	AC-20	115	96	138	62	110	61	109	79
	AC-20P	82	95	85	70	75	63	91	75
	PG64-28	79	93	107	66	88	66	91	65
Lone Mtn	AC-20	164	91	142	96	138	100	143	97
	AC-20P	124	103	133	91	120	100	116	96
	PG64-28	100	90	127	63	104	68	92	69
Suzie Creek	AC-20	82	85	88	70	90	76	116	44
	AC-20P	52	133	60	89	67	74	62	66
	PG64-28	62	111	74	96	71	70	87	30

Impact of Lime and Lime Addition Method

The main objective of this effort was to identify the most effective method of adding lime to HMA mixtures (*10*). This research effort was conducted by the Pavement/Materials Program at the University of Nevada, Reno. The laboratory experiment evaluated the following five methods of adding lime to HMA mixtures:

1. No lime is added (no lime).
2. Dry lime is added to wet aggregate without marination (NDOT 0 h).
3. Dry lime added to wet aggregate with 48 hours marination (NDOT 48 h).
4. Lime slurry is added to aggregate without marination (L. S. 0 h).
5. Lime slurry is added to aggregate with 48 h marination (L. S. 48 h).

Two sources of aggregates were evaluated in this program: the Lockwood source in northwestern Nevada and the Lone Mountain source in southern Nevada. Two binders were used with the Lockwood source, AC-20P and PG 64-34, and one binder was used with the Lone Mountain source, AC-30. The AC-20P is a polymer-modified binder commonly used in northern Nevada, and the PG 64-34 binder is a performance-graded binder that meets the 98% reliability for northwestern Nevada. The AC-30 is a neat asphalt binder commonly used in southern Nevada.

Table 7 shows the tensile strength (i.e., TS) data generated from this research. This research effort indicated that the addition of lime improved the tensile strength properties of the HMA mixtures after single and multiple freeze–thaw cycling. The untreated mixtures showed drastic reductions in the tensile strength after one freeze–thaw cycle and, in some cases, complete disintegration after multiple freeze–thaw cycling. In summary, this laboratory experiment showed that adding lime to Nevada's aggregate is very effective in reducing the moisture sensitivity of HMA mixtures regardless of the method of lime application.

The portion of the laboratory study dealing with the evaluation of the method of lime application indicated that all four methods of application can produce similar results 80% of the time. In the remaining 20% of the time, the NDOT process for 48-h marination was shown to be the most effective. The data generated in this laboratory experiment showed that the addition of lime to wet aggregate without marination (NDOT 0 h) can be as effective as the addition of lime to wet aggregate with 48 h marination and the use of lime slurry with and without marination. However, it should be recognized that these observations were all made under ideal laboratory conditions where the lime is always added to perfectly wetted aggregates and thoroughly mixed to ensure uniform distribution and coating. Such ideal conditions are impossible to maintain under field applications, especially when dealing with the addition of lime to wet aggregate without marination. Therefore, based on the data generated in this experiment, the addition of lime to wet aggregates with 48 h marination (NDOT 48 h) would be the most desirable method of lime application, because it provides effective results and it is less susceptible to field problems than is the addition of lime to wet aggregates without marination.

Impact of Lime on Pavement Performance

The objective of this study was to assess the effectiveness of lime in reducing the moisture sensitivity of NDOT's HMA pavements (*10*). The research effort was conducted by the Pavement/Materials Program at the University of Nevada, Reno. The overall program evaluated samples from 8 field projects and analyzed pavement management system (PMS) data for 12 in-service projects. From the analysis of the laboratory data and field performance of untreated and lime-treated pavements, the following conclusions can be made:

- The properties of untreated and lime-treated mixtures from field projects in the southern and northwestern parts of Nevada indicated that lime treatment of Nevada's aggregates significantly improves the moisture sensitivity of HMA mixtures. The study showed that lime-treated HMA mixtures become significantly more resistant to multiple freeze–thaw cycling than do the untreated mixtures. Lime-treated HMA mixtures showed excellent properties in the wheelpath and in the between-wheelpath locations, which indicates that lime treatment helps HMA mixtures in resisting the combined action of environmental and traffic stresses. The untreated mixtures experienced very severe damage when subjected to multiple freeze–thaw cycling, which explains their poor performance in the northwestern part of the state (Reno area), because such conditioning simulates the environmental conditions of this part of the state. All of the lime-treated mixtures survived the damage induced by multiple freeze–thaw cycling, which would indicate good long-term pavement performance.
- The long-term pavement performance data of the 12 in-service pavements clearly showed the superior performance of the lime-treated HMA mixtures. The present serviceability index (PSI) was used as the performance indicator for the untreated and lime-treated HMA pavements. The effectiveness of lime treatment was evaluated by comparing the performance of projects constructed on the same route, which provided similar environmental and traffic conditions for both untreated and lime-treated mixtures. The long-term pavement performance data indicated that under similar environmental and traffic conditions, the lime-treated mixtures provided better-performing pavements with less need for maintenance and rehabilitation activities. In summary, NDOT was able to maintain a better average PSI on pavement sections built with lime-treated mixtures with less maintenance than for untreated HMA mixtures. Also, the pavements constructed with untreated HMA mixtures showed a more widespread reduction in PSI than did the lime-treated HMA mixtures (i.e., lower PSI over more locations within the project).

TABLE 7 NDOT Tensile Strength at 77°F Data for All Mixtures

Mix	Lime Treatment	Dry TS		TS After One F-T Cycle			TS After 18 F-T Cycles		
		Air Voids (%)	TS (psi)	Air Voids (%)	TS (psi)	Ratio (%)	Air Voids (%)	TS (psi)	Ratio (%)
Lockwood AC-20P	No Lime	7.1	123	7.2	49	40	7.3	0	0
	NDOT 0 h	7.3	104	7.3	113	100	7.3	81	78
	NDOT 48 h	7.2	143	7.2	139	97	7.2	112	78
	Lime Slurry 0 h	7.2	111	7.2	111	100	7.2	79	71
	Lime Slurry 48 h	7.2	125	7.2	135	100	7.0	113	90
Lockwood PG 64-34	No Lime	7.1	95	7.1	65	69	7.1	18	19
	NDOT 0 h	6.9	103	6.9	92	90	6.9	78	76
	NDOT 48 h	6.9	86	6.9	83	97	6.9	70	81
	Lime Slurry 0 h	7.4	102	7.4	86	84	7.4	75	74
	Lime Slurry 48 h	7.0	84	6.9	78	93	7.0	65	77
Lone Mountain AC-30	No Lime	6.7	150	6.7	53	35	6.5	10	7
	NDOT 0 h	6.7	123	6.7	129	100	6.5	62	50
	NDOT 48 h	6.4	113	6.3	124	100	6.3	55	49
	Lime Slurry 0 h	6.4	127	6.4	131	100	6.4	65	51
	Lime Slurry 48 h	6.7	115	6.6	121	100	6.6	48	42

- The analysis of the impact of lime on pavement life indicated that lime treatment extends the performance life of HMA pavements by an average of 3 years. This represents an average increase of 38% in the expected pavement life. The percent increase in pavement life of 38% compares very favorably with the percent increase in the cost of HMA mixtures of 6% ($2/ton) owing to lime treatment. Therefore, NDOT's policy requiring lime treatment of HMA mixtures has been very effective based on both the performance and life-cycle cost of flexible pavements in the state of Nevada.

TEXAS

The Texas Department of Transportation (TxDOT) uses approximately 12 million tons of HMA per year. These mixtures contain aggregates from more than 100 sources and asphalt binders, many of them modified, from more than 10 suppliers. This leads to numerous possible combinations of materials, some of which are susceptible to a range of distresses due to moisture damage caused by a loss of cohesion in the binder (stiffness reduction) or a loss of adhesion between the component materials (stripping). To address moisture sensitivity, TxDOT allows the use of hydrated lime or liquid antistripping agent. In 2003, TxDOT changed its specification for moisture sensitivity of HMA. The new specification requires the Hamburg wheel-tracking device (HWTD) instead of a wet–dry retained tensile strength ratio (TSR) criterion similar to AASHTO T283. This departure from conventional moisture sensitivity tests is based on extensive research and field studies in Texas that indicated that conventional tests are inadequate for performance prediction purposes while the HWTD is an effective tool to identify premature failures (see Figure 2).

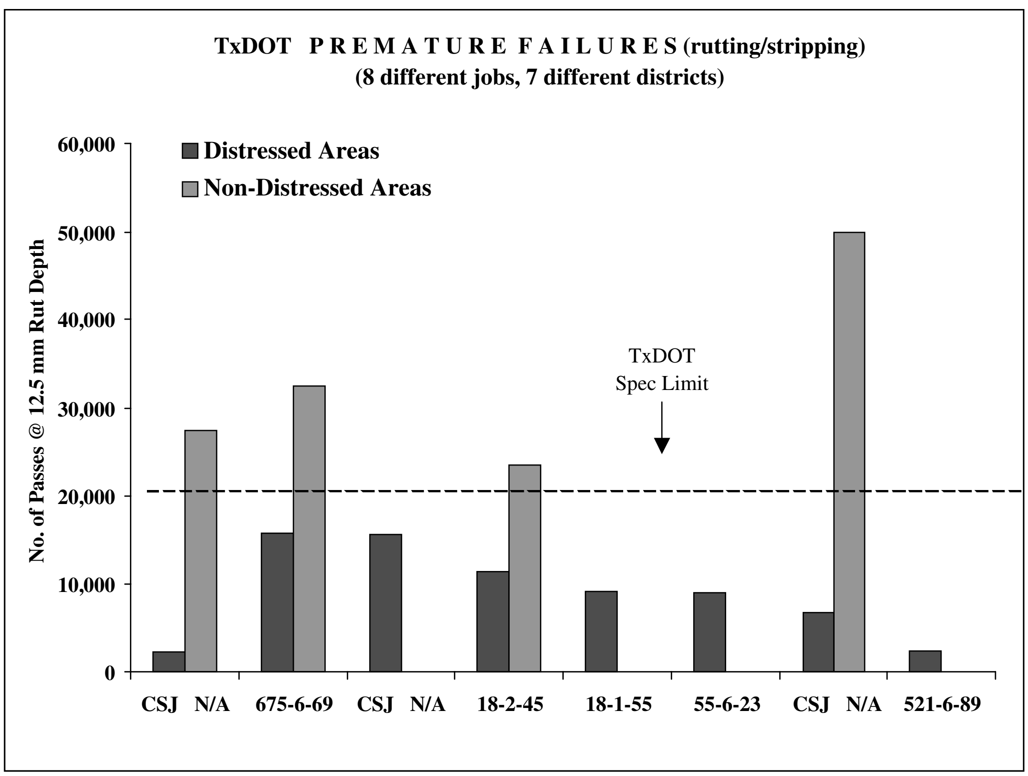

FIGURE 2 TxDOT premature failures predicted by the HWTD.

The following sections introduce the history of moisture damage in Texas and research undertaken to investigate this problem, highlight performance prediction and forensic tools to evaluate mixtures and proposed solutions, and describe the evolution of specifications to address moisture susceptibility.

History of Problem

The moisture sensitivity problem in Texas surfaced in the late 1970s and early 1980s (*11*, *12*) and prompted TxDOT in 1978 to initiate a 6-year research project conducted by the Center for Transportation Research (CTR) at the University of Texas at Austin (*11*, *12*). The objectives of this project were to define the extent and severity of the moisture sensitivity problem in Texas, to evaluate the effectiveness of antistripping treatments, and to define methods to minimize moisture damage and test procedures that identify moisture sensitive mixtures.

This 6-year project began with a survey of the 25 TxDOT districts and 14 other states. Results of the survey indicated that moisture sensitivity of HMA mixtures is prevalent throughout the southern United States. As shown in Figure 3, in Texas, this problem was concentrated in the east and southeastern parts of the state, where the environmental conditions (high annual rainfall and high water table) are most conducive (*11*). Isolated cases of moisture sensitivity were also cited in other dry parts of the state where the soil has a large potential to attract moisture. The presence of moisture is critical for this type of damage, and this project recognized the importance of in-place density by recommending a minimum of 93% of theoretical maximum. The survey also indicated that mixtures with siliceous river gravel were most prone to moisture damage, but testing of specific material combinations was strongly recommended, because susceptibility to this type of damage was recognized as a function of both the binder and the aggregate and their interaction. Both of these recommendations (adequate compaction, testing of specific material combinations) were repeated in every subsequent TxDOT research project on moisture sensitivity.

Two major premature pavement failures occurred in the early 1980s, and the first 6-year CTR research project recommended a validation study under field conditions (*11*, *12*). Thus in 1986, TxDOT initiated a second research project also conducted by CTR (*13*, *14*). The objectives of this project were to evaluate the effectiveness of antistripping treatments under field conditions, to verify tests used to predict field performance, to establish relationships between results of the different tests, and to improve the tests and establish specifications. Ninety-two test sections in eight districts that included 14 different antistripping treatments were evaluated in the laboratory and in the field. Very little evidence of moisture-related distress was found for these sections, which were 2 to 4 years old, probably because of adequate construction compaction (3% to 5% air voids under traffic), and continued monitoring was recommended.

Recognizing the need for long-term field performance data to validate laboratory tests evaluated in previous research projects, in 1992 TxDOT initiated a third project also conducted by CTR (*15*). The same field sections from the second project were monitored again, and laboratory testing of cores was also conducted. Again, there were no signs of moisture damage for the projects, which were now 6 to 7 years old with air void contents ranging from 2% to 5%.

TxDOT also conducted an informal research study on the long-term performance of most of these same test sections and found the same results (R. E. Lee and M. Tahmoressi, *Long-Term Effects of Stripping and Moisture Damage in Asphalt Pavements*, unpublished report, Texas Department of Transportation, Austin, 2000).

At this same time during the early to mid-1990s, districts in northeast Texas began having moisture sensitivity problems with HMA mixtures containing crushed gravel. Two districts decided to exclude this type of aggregate. As a result of these problems, TxDOT formed a task force in 1996 that included representatives from three districts and industry. This task force was charged with formulating recommendations for performance of HMA pavements in northeast Texas. A subsequent study in 1997 and 1998 by TxDOT evaluated the effects of these recommendations by examining 35 pavements in the field and the laboratory (*16*). Again, the young age of these pavements prevented an evaluation of long-term performance. On the basis of a recommendation to reevaluate these pavements in 3 years, in 2001, TxDOT initiated a research project conducted by the Texas Transportation Institute (TTI) at Texas A&M University (*17*). This project indicated that the recommendations were improving pavement performance in northeast Texas.

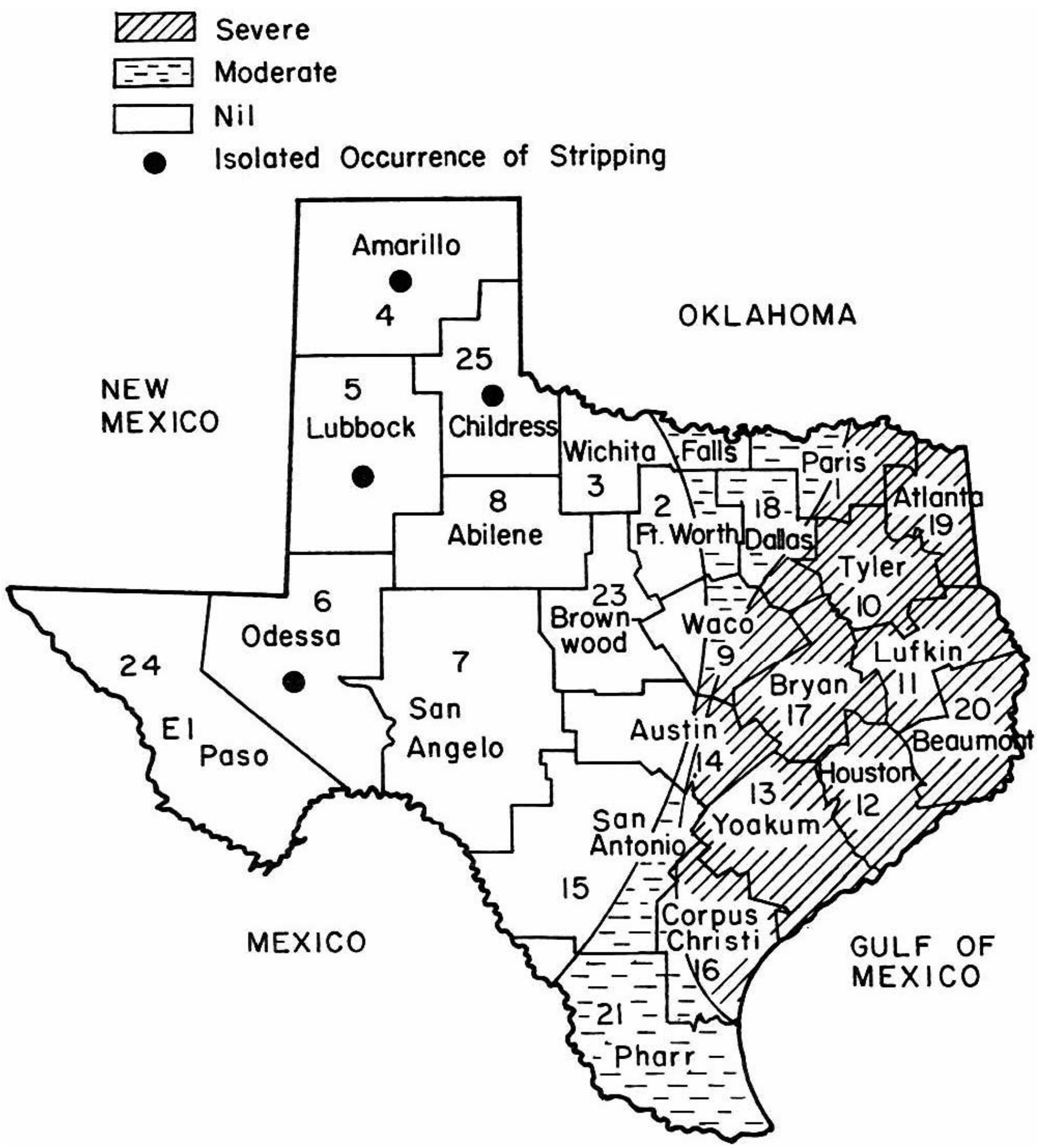

FIGURE 3 Extent of moisture damage in Texas (*11*).

Parallel efforts for and by TxDOT to address the inadequacy of conventional laboratory tests and to identify a test that provides the best indication of moisture sensitivity were also undertaken during the 1990s. TxDOT sponsored two projects conducted by the Center for Highway Materials Research (CHMR) at the University of Texas at El Paso (UTEP) to evaluate the Environmental Conditioning System (ECS) developed during the Strategic Highway Research Program (*18*, *19*). A database of HWTD results continues to be compiled by TxDOT, and a significant number of these results along with the results from the previous research projects and TxDOT studies contributed to the decision to significantly change the TxDOT specification for identifying moisture sensitive HMA mixtures. Other relevant findings from each of the research projects described are provided in the following sections.

Performance Prediction and Forensic Tools

Three laboratory tests were recommended by the first 6-year research effort to evaluate HMA moisture sensitivity, although researchers realized that these tests were tied only to general field performance, not to long-term performance in a formal validation study (*11*). Results from these tests include a visual assessment using a rating board after boiling (Tex-530-C) for short-term moisture evaluation, a wet–dry retained indirect TSR (Tex-531-C) with moisture conditioning at a constant degree of saturation (similar to but not exactly the same as AASHTO T283 or modified Lottman) for long-term moisture damage assessment, and the number of freeze–thaw cycles to fracture the specimen in a pedestal test (*11*, *20*, *21*). Although the freeze–thaw pedestal test was never adopted by TxDOT, all three tests were recommended because each test favors different antistripping treatments. For example, the boil test favors liquid antistripping agents, and the wet–dry TSR and freeze–thaw tests favor hydrated lime. Consideration of wet tensile strength was also suggested as a performance indicator for use in a specification.

During the second more extensive research project that involved laboratory and field evaluation, the wet–dry TSR (Tex-531-C) and the boil test (Tex-530-C) were used to test laboratory mixtures, plant mixtures, and field cores (*13*, *14*, *20*). Both tests were found to be effective in illustrating the positive effects of both lime and liquid antistripping agents. Lime was effective for gravel, limestone, and sandstone aggregates, but liquid antistripping agent was effective only for gravel. Good correlations were established between TSRs found using different moisture conditioning protocols and between TSRs and boil test results. The plant mixtures were similar to the field cores but showed higher test results (TSR and percent retained binder after boiling) when compared with results of laboratory mixtures. During the field evaluation of cores taken just after construction, at 6 months and yearly, the same laboratory tests correlated with visual condition surveys and were successful in illustrating the positive effects of lime treatment.

During the third research project, which continued the performance monitoring of the second project, the wet–dry TSR was used with conditioning according to the Texas procedure (Tex-531-C) and AASHTO T283 (*15*, *20*). The TSR results did not correlate with long-term performance according to visual condition surveys, and no consistent pattern in the laboratory results was found for the effect of antistripping treatments. In an informal research study on the long-term performance of most of these same test sections, TxDOT also found no correlation between TSR values and long-term performance (R. E. Lee and M. Tahmoressi, *Long-Term Effects of Stripping and Moisture Damage in Asphalt Pavements*, unpublished report, Texas Department of Transportation, Austin, 2000). The untreated mixtures performed better than the TSR predicted, and the lime-treated mixtures performed worse. This study recommended that criteria be established for antistripping treatment based on annual precipitation until an improved and satisfactory laboratory test tied to field performance is identified.

In a TxDOT study from 1995 to 1996, the wet–dry TSR (Tex-531-C) was evaluated in regard to degree of saturation, effectiveness of antistripping treatments, and water pH (*20*, *21*). The positive effects of antistripping treatments were illustrated, and TxDOT adopted a 30-min saturation time and a minimum TSR value of 80 based on the results of this study.

The first of two research projects conducted at the CHMR at UTEP evaluated the ECS that allows for traffic simulation and conditioning over a wide range of temperatures (*18*). The test protocol developed for TxDOT used a ratio of conditioned to unconditioned resilient modulus values, with a ratio greater than or equal to 0.8 indicating satisfactory resistance to moisture damage. Recommendations from this project included validation of the protocol and optimization to reduce testing time. A second recently completed project provided improved equipment, reduced but still lengthy testing time of 2 days, and validation of performance of three mixtures with unmodified binders (*19*). More validation is still needed before implementation by TxDOT, owing to the sensitivity of the results to the job mix formula and the lack of validation for mixtures with modified binders.

In the late 1990s, TxDOT was still not satisfied with the tools available to predict moisture sensitivity in HMA based on the cumulative results of research sponsored and conducted by TxDOT. As part of the continued search for a satisfactory laboratory test, a 1998 TxDOT study evaluated the HWTD for repeatability, sample shape, temperature, and effectiveness of antistripping treatments. The repeatability was considered good with six replicate samples, and cylindrical samples from the Superpave® Gyratory Compactor (SGC) were endorsed for comparing mixtures. Recommendations for testing temperature were based on the softening point of the binder, and the positive effects of antistripping treatments were shown.

Another TxDOT study in 1997 and 1998 evaluated the effects of recommendations by a 1996 task force to improve performance of pavements in northeast Texas (*16*). Thirty-five pavements were examined in the field and the laboratory. TSR values (with a different conditioning procedure than Tex-531-C) for mixtures treated with lime and liquid antistripping agents were similar, but visual examination of cores with mixtures treated with liquid antistripping agents indicated increased evidence of moisture damage.

Further field and laboratory evaluation of the same 35 pavements by TTI in 2001 also included a modified version of Tex-531-C in terms of the conditioning procedure and the HWTD at 50°C (*17*). Visual examinations of the field sections, of the cores in a wet and dry state, and after the HWTD were also conducted. The HWTD results correlated with the visual ratings. Eleven sections with good laboratory performance (less than 5-mm HWTD rut depth), and nine sections with fair laboratory performance (5- to 12.5-mm HWTD rut depth) were given average visual ratings of 87 and 80 (out of 100), respectively. The majority of sections (13 of 18) with poor laboratory performance (more than 12.5-mm HWTD rut depth) were given visual ratings less than or equal to 70 (out of 100).

The TxDOT HWTD database now contains approximately 1,000 test results. An analysis of approximately 750 mixtures with performance-graded (PG) binders conducted by TxDOT indicated that this test illustrates the positive effects of antistripping treatments. The HWTD tests mixture resistance to rutting and moisture sensitivity, in both binder stiffening and adhesion of the component materials.

Solutions

All of the TxDOT research projects, studies, and subsequent guidelines recommend hydrated lime added in the presence of water (either in slurry form or applied to wet aggregate) to address HMA moisture sensitivity problems (*11*, *12*, *14*, *16*, *17*, *22*, *23*). Crushed siliceous gravel is most susceptible to moisture damage and requires treatment (*16*, *17*). Lime is recommended for all TxDOT districts using this type of aggregate (*17*). Liquid antistripping agents also showed improved moisture sensitivity for specific material combinations (*17*).

Quality control testing of treated moisture susceptible mixtures during production is recommended, and TxDOT believes the HWTD is the relatively quick tool needed for this type of testing (*11*, *12*). TxDOT is also satisfied that the HWTD is also the best laboratory test for identifying moisture sensitive mixtures. The TxDOT HWTD database for mixtures with PG binders indicates that hydrated lime, hard aggregates, stiff binders, and stone-on-stone mixture types all have a positive effect on mixture resistance to both moisture sensitivity and rutting. TxDOT does recommend caution, however, in any attempt to improve mixture resistance to moisture sensitivity. It recommends that each specific material combination be tested in the HWTD.

Adequate compaction during construction was also highlighted as a solution to HMA moisture sensitivity problems in many of the research project recommendations and subsequent TxDOT guidelines (*11*, *12*). TxDOT has had an in-place density specification since the late 1970s to address this type of problem as well as other performance-related issues (*20*). Other recommendations include providing adequate drainage, reducing segregation using a material transfer vehicle, and possibly sealing the HMA layer, being careful not to trap moisture in this layer (*11*, *16*).

Another recommendation of the 1996 TxDOT task force to require a sand equivalent test on field sand used in HMA mixtures has improved performance (*16*, *24*). The use of modified binders was also recommended by this task force, and conflicting results have surfaced in regard to this point (*16*, *17*, *24*). Latex modification was shown to improve performance of limestone mixtures in the HWTD and visual inspection of cores, but earlier performance results indicated that latex modification was not effective in preventing moisture damage in limestone or gravel mixtures (*16*, *17*).

Specifications to Control Moisture Sensitivity

Recommendations from the first 6-year research effort to evaluate HMA moisture sensitivity led to the adoption of guidelines by TxDOT (*11*, *12*). Guidelines shown in Table 8 were issued to recognize the fact that each district may approach a moisture sensitivity problem in a different way (*12*). Antistripping treatment was required for mixtures with TSR values less than 0.60 or uncoated aggregate surface after boiling greater than 20%. Marginal mixtures were defined as those with TSR values between 0.60 and 0.80 or 10% to 20% uncoated aggregate surface after boiling. Treatment of these mixtures was also recommended.

In-place density specifications are also an important part of TxDOT's efforts to preclude moisture sensitive HMA mixtures (*20*). In the late 1990s, a directive from the executive director of TxDOT was issued on specifications for HMA moisture sensitivity. This directive indicated that districts can waive moisture sensitivity testing of HMA mixtures based on past performance trends. If moisture sensitivity is a concern, districts can require lime or liquid antistripping agents, wet–dry TSR testing with a minimum TSR of 0.80 and a minimum wet tensile strength

TABLE 8 Old TxDOT Guidelines for Moisture Sensitive HMA Mixtures Using Wet–Dry TSR and Boil Criteria (*12*)

Stripping Potential of Mix	Boiling Test Uncoated Aggregate Surface	Lottman Test Ratio of Condition to Dry Strength
Nonstripping	< 10%	> 0.80
Marginal Mix	10 to 20%	0.60 to 0.80
Stripping Susceptible	> 20%	< 0.60

of 70 psi (Tex-531-C) during mix design, or boil testing (Tex-530-C) during production (*24*; C. W. Heald, memo to district engineers: "Moisture Damage: Specifications and Testing," June 2, 1998). Districts can also lower the TSR requirement.

The new TxDOT specifications now use HWTD testing at 50°C during mix design and production. This test replaces previous moisture sensitivity testing and rutting testing. The requirements shown in Table 9 vary by binder grade (*25*).

VIRGINIA

Virginia's experience with moisture sensitive HMA mixtures began in the late 1960s before any of the other states surveyed in this paper, and the Virginia Department of Transportation (VDOT) began requiring antistripping treatment of all aggregates in the early 1970s to address this problem. VDOT's specification to control moisture sensitivity includes a minimum wet–dry TSR.

The following sections describe the history of moisture damage in Virginia, including the material and environment that contribute to the problem; laboratory and forensic testing to evaluate mixtures; and corresponding specifications and research.

History

Virginia has been concerned about moisture damage (stripping) since and possibly before the late 1960s. Antistripping additives began to be used in some surface mixtures in the early 1970s. Failures that were observed early on were often catastrophic and required complete removal of the layers that were responsible. Typical failures are shown in Figure 4. The first figure illustrates a pothole that developed after asphalt-rich spots were noticed on the pavement surface, and the second figure illustrates a pavement that had lost strength, which promoted a type of rutting deformation. Currently, these types of major failures are not commonly experienced, but cores removed from the pavements often exhibit excessive visual stripping.

In 1996, approximately 1,400 cores were taken statewide to determine whether any stripping still existed in Virginia's pavements (*26*). Approximately 40% to 50% of the sites that were cored displayed moderate to moderately severe visual stripping, although there was no indication of severe distress on the pavement surfaces from which the cores were taken. Most of the distress was limited to some type of cracking, which was usually not severe. The question arises concerning the effect the stripping has on serviceability. How much service life is lost because of stripping? If the loss is significant, how can the stripping be eliminated or minimized?

The Virginia Transportation Research Council is engaged in laboratory research to determine the effect of the degree of stripping observed in the pavements on fatigue durability. Fatigue tests are being performed on specimens that have been pretreated and preconditioned to produce various degrees of stripping. Results will determine the need or lack thereof to pursue additional methods of minimizing stripping.

TABLE 9 New TxDOT Specifications for Moisture Sensitive HMA Mixtures Using HWTD Criteria (*25*)

High Temperature PG Binder Grade	Minimum No. of HWTD Passes at 50^0C to 0.5-in. Rut Depth
PG 64	10,000
PG 70	15,000
$\geq$ PG 76	20,000

FIGURE 4 VDOT typical pavement stripping failures.

Virginia was one of the states that participated in the field evaluation phase of R. P. Lottman's NCHRP study (the 10-year evaluation phase was unpublished) designed to develop a moisture damage test that would predict the potential of an asphalt mixture to strip. Virginia installed one of the test sections located throughout the United States, ran Lottman's stripping test on the original mixture, and evaluated cores taken periodically from the section. This early work with the Lottman test helped develop interest and prompted further work in Virginia with a modified version of the test. Initially, Virginia used the boiling water test that was subjective and not believed to predict stripping susceptibility adequately. Such a doubt prompted the interest in the Lottman test, also known as the TSR test.

Materials and Environment

Virginia has good, sound aggregates, predominantly granites, that are used for surface and base mixtures, but there are some diabases/traprocks, quartzites/gravels, and other minor types. Limestones, which are prevalent in one part of the state, can be contained only in mixtures that are not used in pavement surfaces, because they are susceptible to polishing. Stripping occurs primarily in granites, because they are the predominate aggregates, but it also occurs with the other types of aggregate—even limestone. In fact, a quartzite was involved in major failures, and that source can no longer be used on major roadways. All asphalt mixtures must contain either chemical additive or hydrated lime, and most producers have chosen to use chemical additive because of its ease of handling.

Virginia's rainfall is approximately 100 cm per year, with some freeze–thaw cycling during the winter, and summer temperatures sometimes reach 35°C or slightly higher. Stripping failures usually become evident in the late winter rather than in the summer.

Laboratory Testing

The TSR test is used by contractors in their mix design process to ascertain whether the chosen antistripping additive is effective with the particular combination of aggregate and asphalt cement. It is also used as an occasional check by VDOT to make certain that the correct amount of additive has been used in the field production process. There have been instances in which the TSR test detected malfunctions in equipment when the proper amount of additive was not being added. Initially, the ASTM procedure without the freeze–thaw cycle was used with a 0.75 TSR minimum ratio acceptance value, which was later increased to 0.85. The method and criterion have been altered slightly through the years, and the Superpave TSR criterion of 0.8 was recently adopted to be used with AASHTO T283. Although there have been instances when the TSR predictions did not seem to coincide with field performance, it is the best practical test available today. Work needs to continue on developing a more reliable quick test that can be used by contractor and purchasing agency personnel to check mixtures for potential moisture damage.

Forensic Testing

Two methods have been used to evaluate stripping on field samples: visual inspection of cores and strength measurements of cores. In visual inspection, an attempt is made to estimate the percentage of coarse aggregate and the percentage of fine aggregate that are stripped. It is generally believed that the fine aggregate has a greater impact on stripping damage than does the coarse aggregate. Visual estimation is subjective; therefore, the results can be quite variable among evaluators. Visual assessment is easy to perform and quick; therefore, it is a popular method for field people to use.

Indirect tensile strength measurements on field cores have been used to evaluate stripping. It has been postulated that a strength deterioration curve can be developed similar to that shown in Figure 5*a* (*27*). Ideally, a strength development curve of a pavement that is aging normally with no stripping would appear as the top curve identified by "unstripped." As shown on the lower curve, the "stripped" strength will initially increase and then decrease as stripping starts to overshadow the aging-stiffening effect.

Three points obtained from tests on the cores are used to develop a pseudo "deterioration curve" (see Figure 5*b*). To determine how much damage has been done, the strength of the material in its present condition and the strength of the material if stripping had not occurred must be known. The ratio of the present strength to the unstripped strength gives an indication of the damage that has occurred as a result of stripping. The unstripped strength can be measured using dried cores or cores that have been remolded. The true unstripped strength is probably somewhere between these two values. Remolding stiffens the mix owing to heating, and the drying process is never able to remove all of the moisture and produce complete healing. A prediction of future damage can be obtained by preconditioning and testing a third set of cores. A freeze–thaw preconditioning procedure similar to that used in the AASHTO T283 is used.

Status Summary

Testing and attention to the introduction of antistripping additives have resulted in a decrease in the severity of stripping failures. Although stripping has improved, there is visual evidence from cores that it still exists. An attempt is being made through a laboratory study to determine its effect on service life.

COMPARISON OF FIELD EXPERIENCES

Moisture sensitivity surfaced as a problem in HMA pavements in the late 1960s in Virginia, in the late 1970s in Texas, and in the early 1980s in California and Nevada. In Nevada and Virginia, moisture sensitivity problems are widespread, and these states require the addition of antistripping treatments for all aggregate sources. In Nevada, only hydrated lime is allowed, and a 48-h to 60-day marination period is required. In Virginia, liquid antistripping agents or hydrated lime is allowed. In California and Texas, moisture sensitivity problems surfaced primarily in a particular region of these large states, in the northern part of California and the eastern and southeastern part of Texas. This led to guidelines based on past performance and treatment for different climates in different districts or regions. Lime slurry marination and application of lime in the presence of water showed the best field performance in California and Texas, respectively, but other treatments are also allowed in these states.

The experience of California, Nevada, Texas, and Virginia described in this paper indicates that an improved laboratory test or criterion to identify moisture sensitive HMA mixtures is urgently needed. These states have used or currently use the best test available, usually a modified version of AASHTO T283, during mix design or production. All cite exceptions to or lack of a correlation between the wet–dry TSR requirement and long-term field performance. Also, the larger states in terms of HMA tonnage (California and Texas) are not satisfied with the repeatability and reproducibility of their selected version of AASHTO T283. The use of different equipment may also be contributing to increased variability. Nevada and Virginia produce relatively fewer tons of HMA per year and therefore use fewer laboratories for mixture testing. These smaller states are currently satisfied with the variability of their selected

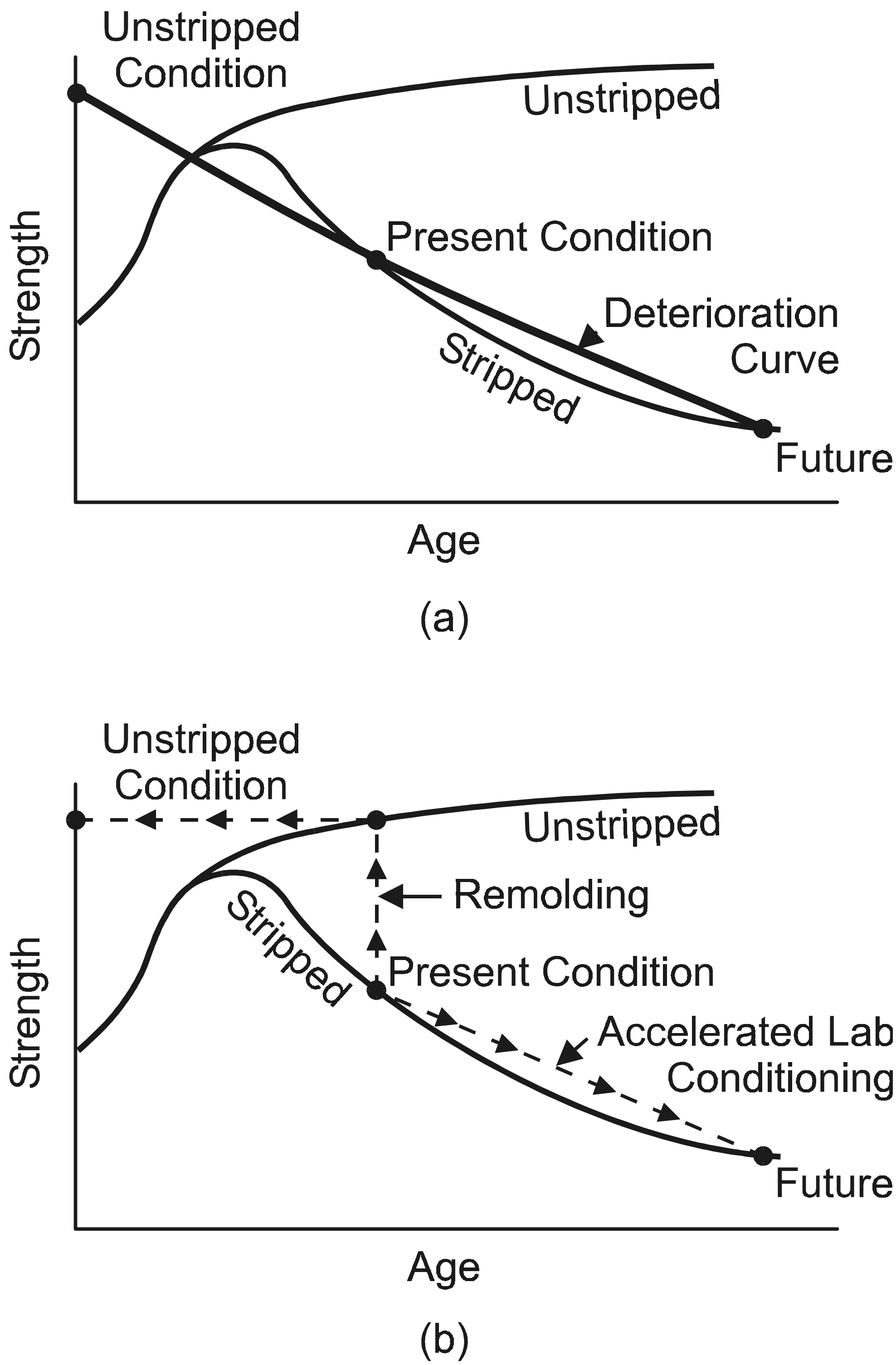

FIGURE 5 Development of the VDOT deterioration curve.

laboratory test. This experience suggests the need for round-robin testing programs when multiple laboratories are used to assess and reduce variability.

These four states have also incorporated other laboratory tests in specifications or forensic studies. Virginia and Texas have used a visual evaluation after a boil test in the past. A minimum dry indirect tensile strength is required in Nevada, and a minimum wet indirect tensile strength has been used in Texas. This year, Texas abandoned wet–dry TSR as criteria for identifying moisture sensitive HMA mixtures and adopted the HWTD. This test is also being evaluated in a research project in California. In Virginia, current research is examining the loss of service life resulting from moisture sensitivity. Nevada uses resilient modulus testing after multiple freeze–thaw cycles for forensic testing. Virginia constructs a deterioration curve to predict remaining life of field cores.

RECOMMENDATIONS

Recommendations based on the field experience of California, Nevada, Texas, and Virginia include the following:

- Develop an improved laboratory test or criterion tied to long-term field performance to identify moisture sensitive HMA mixtures.
- Establish and reduce variability through round-robin testing programs when multiple laboratories are used for mixture testing.
- Test each combination of materials for moisture sensitivity during mix design and production.
- Adopt other measures, such as in-place density specifications, to help control moisture sensitivity problems in HMA pavements.
- Gain better understanding of the mechanism of moisture damage in HMA.
- Continue sharing field experiences with other states and agencies.

This national seminar on moisture sensitivity will provide a start toward implementation of these recommendations.

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TOPIC 7

Questions and Answers

AMY EPPS MARTIN
Texas A&M University, Speaker

DALE RAND
Texas Department of Transportation, Speaker

DEAN WEITZEL
DARREN TEDFORD
Nevada Department of Transportation, Speaker

PETER SEBAALY
University of Nevada, Reno, Speaker

LEROSE LANE
California Department of Transportation, Speaker

G. W. MAUPIN, JR.
Virginia Transportation Research Council, Speaker

Q1—Tim Aschenbrener, Colorado Department of Transportation
Question, I guess for Dale from Texas. I see that you've indicated that AASHTO T283 is highly variable and has poor reproducibility. I was wondering, how did you quantify that?

A—Dale Rand
I might have to refer this one to Mansour. Actually, I think he did the study on this one. I don't know if you want to try and address this. We've done some studies both in-house doing proficiency testing and preparing samples, sending them out to folks and getting results that were all over the board. We did a formal study that Mansour headed up that came to that same conclusion, that the test was highly variable. The multiple lab variability was high and our experiences have shown us that on projects. The contractor results passed with 95 TSR and then the district tests it and it's a 70 TSR. We referee test it and get an 80 TSR, and we all do it again and we do it a few more times.

Q2—Tim Aschenbrener, Colorado Department of Transportation
And I had a follow-up comment for Caltrans as they are going through an implementation process. I appreciate seeing the matrix there and I would offer just one word of caution regarding doing your round-robin. If the results of the round-robin are not reasonable, it appears you might go back to status quo. I would offer an experience from Colorado. We have a quality assurance program, and in that program, we test all of our materials, whether asphalt, concrete, or soils, on a regular basis. Every round-robin is accompanied by a series of findings and recommendations. And probably very much like Texas found one year, the finding was that our version of the T283

was not reproducible. I think that we had 33 labs participating—16 of those were DOT labs. The average TSR result was about 85, if I remember correctly, and the standard deviation was 15. As you look at the scatter through those 33 labs, the finding was how do we know if the material passes or fails? So the recommendation was that we needed to make improvements. So actually, it was over a 3-year time period that it took multiple round-robins to identify what boiled down to about three key elements of the test procedure that you have to pay really close attention to. And at our last round-robin, and I think we still have 33 labs participating, the standard deviation is now 5. I think that in terms of reproducibility, the concerns can be addressed. I also think it would be optimistic to believe that you could get good reproducibility the first time out of the chute, so to speak. So I would encourage at least a couple of iterations of round-robins and identifying the key items of the test procedure before going back to the status quo.

Q3—Bob Humer, Asphalt Institute
Dean, in your notes it says marinated, and I want clarity. Because I'm familiar with lime slurry marination, I want to make sure how it differs from that.

A—Dean Weitzel
When I use the term "marination," I'm talking about the fact that we're putting dry lime on wet aggregates and we stockpile it for 48 hours. To me, the marination is giving the lime time to affect the PI of the aggregate. The other procedure is you add water to the lime and you make a slurry and then you add that to the aggregate, and we're not doing that. So when I use the term marination, it's just giving it time in the stockpile to affect the PI.

Q4—Dick Root, Root Pavement Technology
Dean, I'm not trying to be an obstructionist, but I'm looking at your time marination study, particularly for your north aggregates. I think you told us that those are your high PI materials and therefore marination benefits them the most. And I am looking at 45 days, and I see one that meets your minimum criteria and all the others fail on the TSRs. I'm wondering, is 45 days too long and you're out at 60?

A—Dean Weitzel
You know, what we've found was probably at 45 to 60. It really is an individual composition. We wanted to give the contractors enough time to get out there to crush and advance. I will tell you we handed that out to the contractors and we told them, our recommendation is you use it as fast after the 48 hours as you can. If you choose to go to 45 days or 60 and it fails, we're going to get it behind the paver and you're shut down. That's not our problem. I'll give them 120 days but when they fail, they're going to get shut down.

Q5—Dick Root, Root Pavement Technology
I guess that would be the point. No requirement necessary. We're going to test it as we use it.

A—Dean Weitzel
And we do. Like I say, we wanted to put a maximum because we didn't want them to get out there in November, crush it, stockpile it, and then have it sit there till June. We're just asking for a fight at that point in time. I will tell you, in the last 3 years, I can think of one instance where it went over the 60 days, even the 45 days. We don't refuse to let them use it even if it goes over

the 60 days. What we do then is add an additional % lime and retest it according to the AASHTO T283. We do the modified Lottman. If it passes, we let them use it. And so it's not a total loss if it goes past that drop-dead date and you don't get to use it.

Q6—Mansour Solaimanian, Pennsylvania State University
I just had a comment regarding what Tim mentioned on the repeatability and reproducibility of the AASHTO T283 and what he did for improvements. We looked at variability in Texas method 531-C, which in some ways is different from AASHTO T283 in regard to the vacuum saturation. In T283, you have 55% to 80% saturation, and in Tex 531-C, you conduct the saturation phase for 30 minutes. This creates some differences between the two methods.