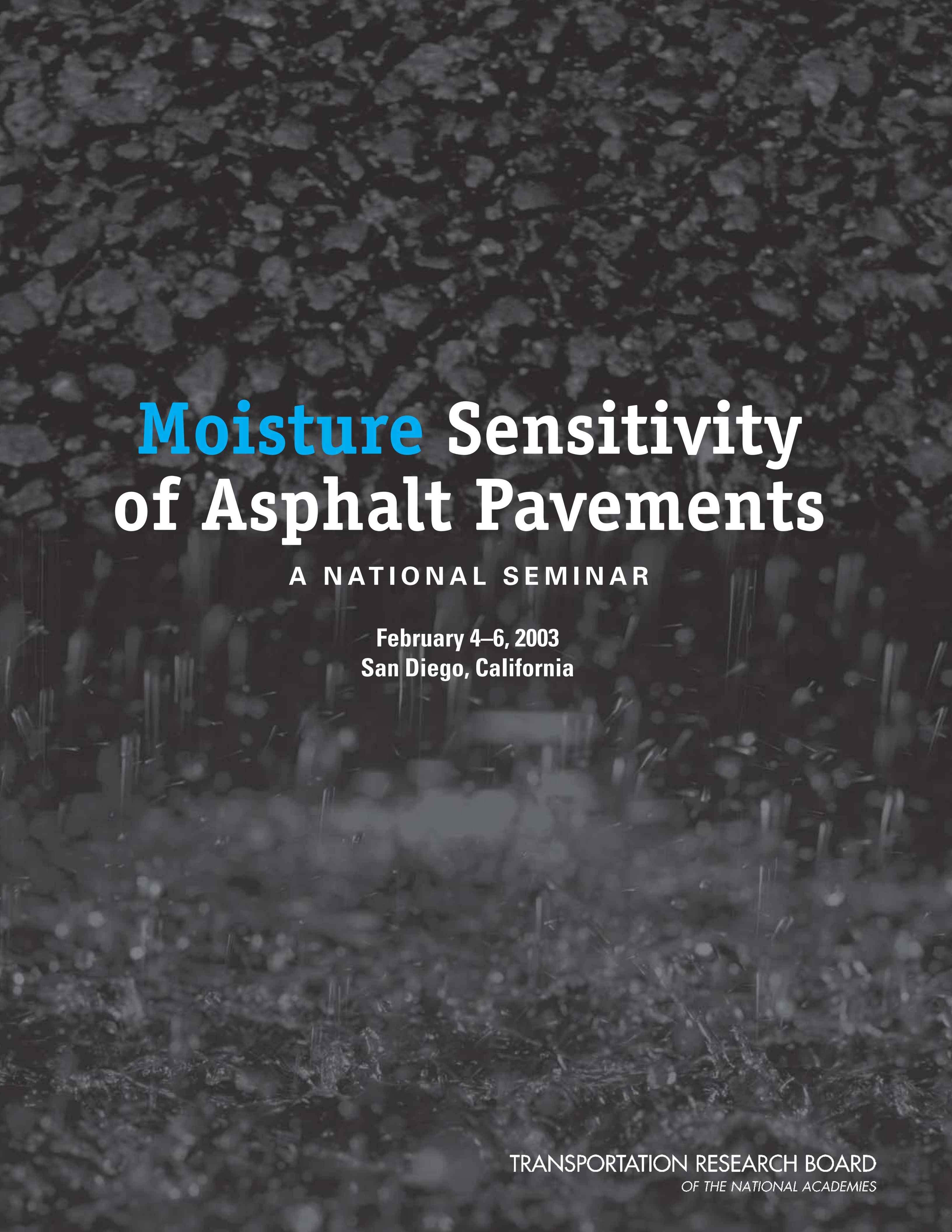

Moisture Sensitivity of Asphalt Pavements

A NATIONAL SEMINAR

February 4–6, 2003
San Diego, California

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Moisture Sensitivity of Asphalt Pavements

A NATIONAL SEMINAR

February 4–6, 2003
San Diego, California

TRB Committee on
Bituminous–Aggregate Combinations to Meet
Surface Requirements

Sponsored by
California Department of Transportation
Federal Highway Administration
National Asphalt Pavement Association
California Asphalt Pavement Alliance
Transportation Research Board

TRANSPORTATION RESEARCH BOARD
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Preface

Moisture damage in asphalt pavements is a national concern. Correctly identifying the problem and isolating the contributing factors—materials and construction—are equally challenging. The goals of this national seminar are twofold: technology transfer on the topic from leading experts and the start of a road map to solve this problem. The topics addressed include the following:

- Identification of the problem—distinguishing between materials-induced and construction-related factors,
- Fundamental concepts—binder and aggregate considerations and failure mechanisms,
- Test methods—laboratory and field,
- Remediation—additives and construction practices,
- Field performance and case studies,
- Specifications—shortcomings and need for improvements, and
- Environmental and health issues.

The papers included in this volume document the work accomplished during the national seminar held in La Jolla, California, on February 4–6, 2003. The objectives of the papers, and the breakout sessions that followed, were to identify

- Best practices,
- Gaps in knowledge, and
- Research needs.

More than 100 people participated in the national seminar, and this document contains the proceedings of the meeting. In addition to the papers, summaries of the questions raised and answers given are included. Questioners and respondents were informed and gave permission for their inclusion. Special thanks are extended to the sponsors of the seminar, especially the California Department of Transportation, which provided the major portion of the funding. Thanks are also extended to the members of the steering committee, who planned the event:

- Mike Anderson, Director of Research, The Asphalt Institute;
- Tim Aschenbrener, Materials Engineer, Colorado Department of Transportation;
- Elissa Brainard, Director, Meeting Planning Division, Woodward Communications;
- Mike Cook, Office of Flexible Pavements Materials, California Department of Transportation;
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- Sundaram Logaraj, Akzo Nobel Surface Chemistry LLC;
- Dale Rand, Flexible Pavements Branch, Texas Department of Transportation;
- Larry Santucci, Pavement Research Center, University of California, Berkeley; and
- Jim St. Martin, Executive Director, Asphalt Pavement Association.

The proceedings are being published by the Transportation Research Board under the sponsorship of Committee A2D03, Characteristics of Bituminous-Aggregate Combinations to Meet Surface Requirements, a cosponsor of the seminar.

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Introduction and Seminar Objectives

TOPIC 1

Introduction and Seminar Objectives

R. GARY HICKS
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TIM ASCHENBRENER
Colorado Department of Transportation

Moisture sensitivity in asphalt pavements is a national issue. This was demonstrated through a recent survey of state highway agencies throughout the United States. This national seminar is designed to address moisture-related distress in asphalt pavements through a series of focused papers followed by working breakout sessions. An introduction to the issues and the national seminar is given in this paper. The following items are covered:

- The extent of the problem,
- The purpose and scope of the national seminar,
- Definition of moisture sensitivity in asphalt pavements,
- Identification of moisture sensitivity problems,
- Causes of moisture sensitivity problems,
- Potential solutions to the problems, and
- Expected deliverables for the seminar.

In this paper, the stage is set for what is to occur over the ensuing 2½ days.

BACKGROUND

National Problem

Moisture sensitivity in hot-mix asphalt (HMA) is a national issue. In a recent survey (dated August 4, 2002) of 55 agencies conducted by the Colorado Department of Transportation that included 50 state departments of transportation, 3 FHWA Federal Land offices, the District of Columbia, and 1 Canadian province, it was determined that 82% of the agencies require some sort of antistrip treatment. Of those that treat, 56% treat with liquids, 15% with liquid or lime, and 29% with lime (see Figure 1). Eighty-seven percent of the agencies test for moisture sensitivity (Figure 2). Of those that test,

- 82% use a tensile test (AASHTO T283, ASTM D4867, or similar),
- 10% use a compressive test (AASHTO T115 or similar),
- 4% use a retained stability test, and
- 4% use wheel-tracking tests and tensile tests.

When testing is specified, 62% test for mix design only, and 38% test for mix design and field acceptance (Figure 3). Details of the results of the survey are given in Appendix A of this paper.

The impact of moisture sensitivity problems on pavement performance or pavement costs is not clearly defined, but 20% of the agencies continue to fund research to

- Understand the fundamental chemical nature of the problem,
- Refine an existing test procedure or develop an improved procedure, and
- Identify the ability of the test procedure to correlate to field performance.

Though moisture sensitivity is a national issue, the various states have used different strategies to mitigate the detrimental effects of moisture in pavements. These strategies as well as others will be discussed in this 2½-day seminar.

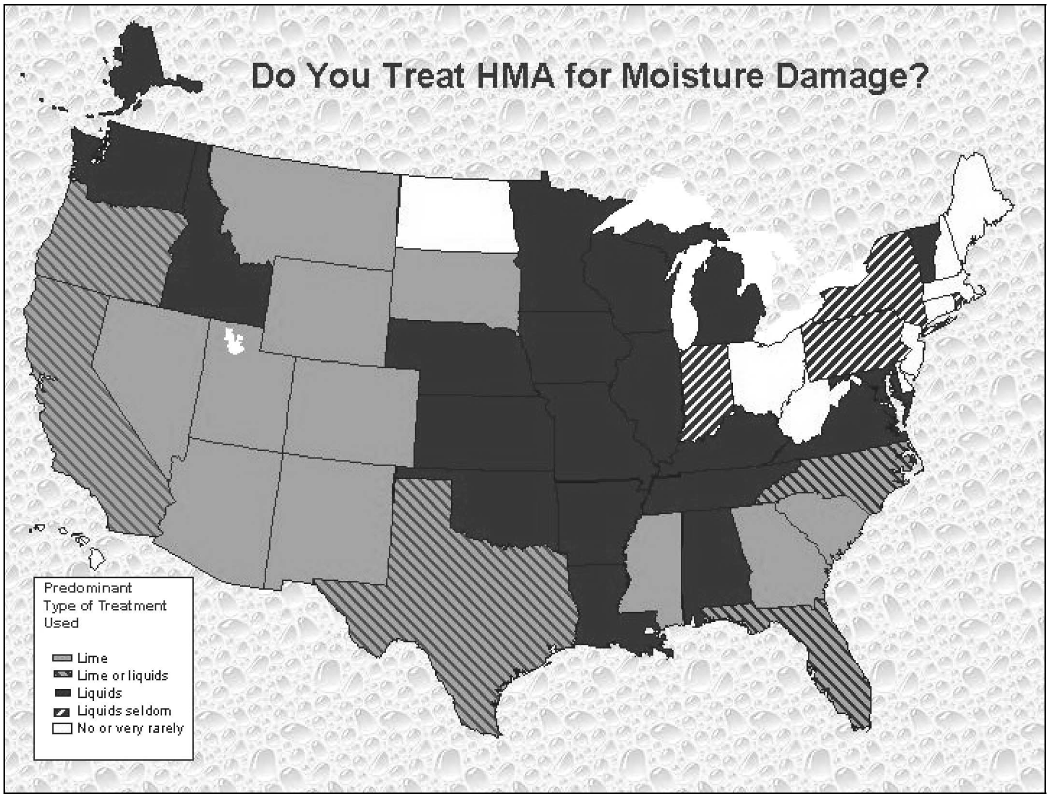


FIGURE 1 States that treat HMA for moisture damage.

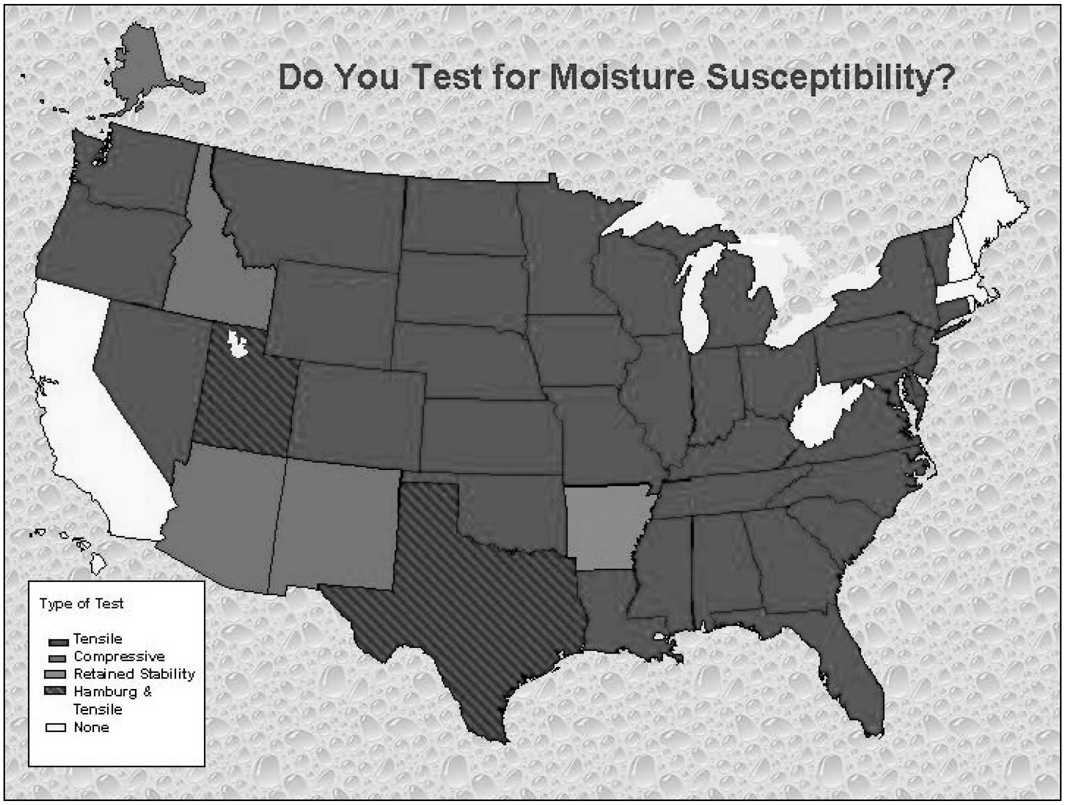


FIGURE 2 Tests used for moisture susceptibility.

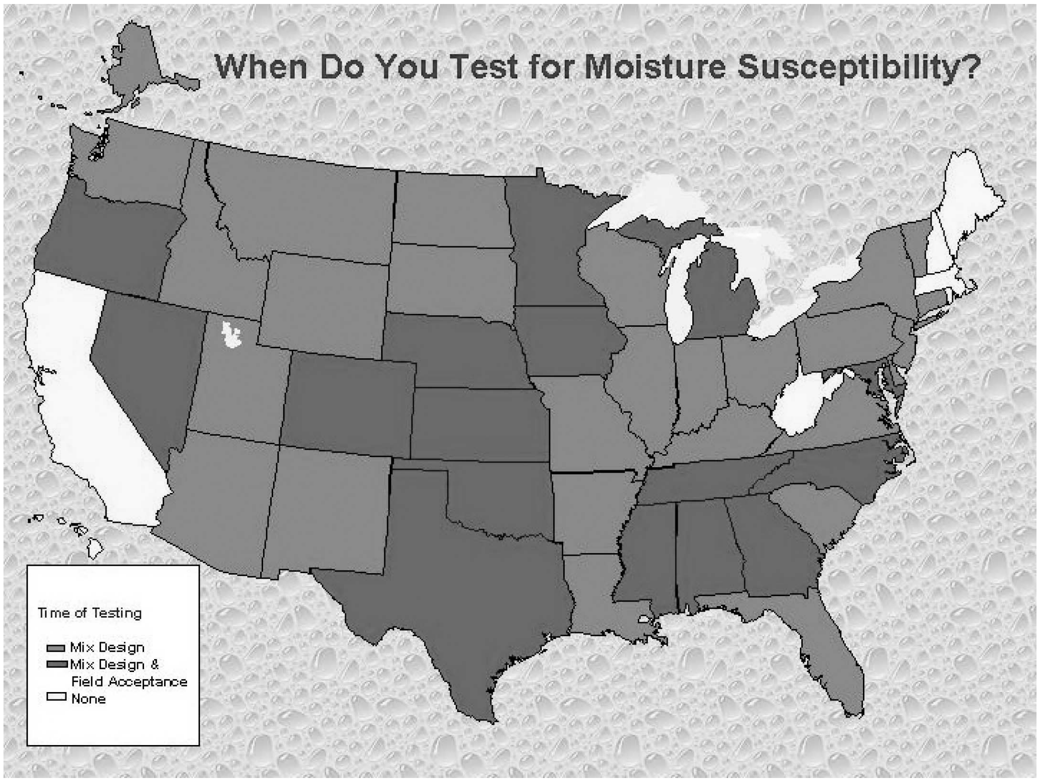


FIGURE 3 Time of testing for moisture sensitivity.

Purpose and Scope of Seminar

The goals of the national seminar are twofold: first, to provide a forum for technology transfer of the latest information relative to moisture sensitivity by leading experts in the field; and second, to develop a road map to help solve this problem. Specific topics to be covered include

- *Identification of the problem*, which includes distinguishing between materials- and construction-related factors;
- *Fundamental concepts* for understanding the interaction between the binder and aggregate;
- *Test methods* along with the advantages and disadvantages of existing laboratory and field test procedures;
- *Remediation strategies*, including the use of additives and improved design and construction practices;
- *Field performance with case studies* showing what works and what does not;
- *Specifications* and shortcomings of existing practices and how they might be improved; and
- *A road map for the future* that includes an implementation package for eliminating the problem.

The seminar will consist of a series of focused lectures followed by breakout sessions to identify

- Best practices,
- Gaps in knowledge, and
- Research needs.

The breakout sessions will focus on tasks to solve the problem and generate a road map to success for agencies to follow in minimizing the adverse effects of moisture on asphalt pavements.

MOISTURE SENSITIVITY: DEFINITIONS AND DISTRESS MANIFESTATIONS

Definition of Moisture Sensitivity

Moisture-related problems are due to or are accelerated by

- Adhesive failure—stripping of the asphalt film from the aggregate surface, or
- Cohesion failure—loss of mixture stiffness.

These mechanisms can be associated with the aggregate, the binder, or the interaction between the two ingredients. Moisture-related distresses are also accelerated by mix design or construction issues, including those given in Table 1. These factors will be the topics of the papers that follow and focused discussions in the breakout sessions later in the seminar.

Moisture-Related Distress Manifestations

Moisture-related distress is similar in many ways to distress caused by other factors (materials, design, construction). Moisture tends to accelerate the presence of the distress types. The types of distress that can be related to moisture, or the other factors, are described below:

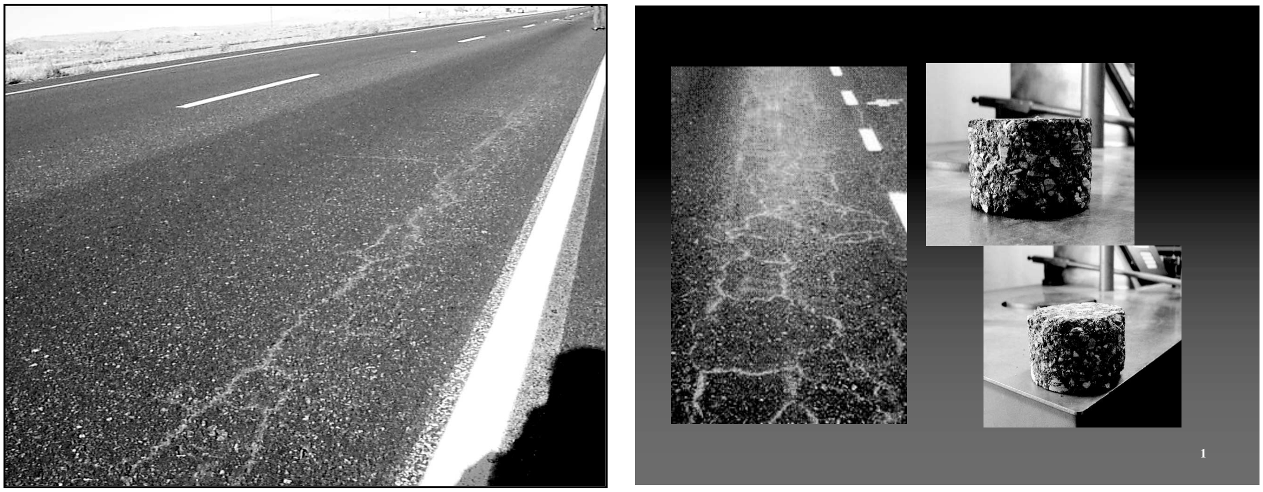
- *Bleeding, cracking, and rutting*: These distresses are caused by a partial or complete loss of the adhesion bond between the aggregate surface and the asphalt cement. This may be caused by the presence of water in the mix due to poor compaction, inadequately dried or dirty aggregate, poor drainage, and poor aggregate–asphalt chemistry. It is aggravated by the presence of traffic and freeze–thaw cycles and can lead to early bleeding, rutting, or fatigue cracking. Figures 4 and 5 show some of the various manifestations of this type of moisture-related distress.
- *Raveling*: Progressive loss of surface material by weathering or traffic abrasion, or both, is another manifestation of moisture-related distress. It may be caused by poor compaction, inferior aggregates, low asphalt content, high fines content, or moisture-related damage, and it is aggravated by traffic. Figure 6 shows different stages of this type of moisture-related distress.

TABLE 1 Factors That Can Contribute to Moisture-Related Distress

MIX DESIGN	• Binder and aggregate chemistry • Binder content • Air voids • Additives
PRODUCTION	• Percent aggregate coating and quality of passing the No. 200 sieve • Temperature at plant • Excess aggregate moisture content • Presence of clay
CONSTRUCTION	• Compaction—high in-place air voids • Permeability—high values • Mix segregation • Changes from mix design to field production (field variability)
CLIMATE	• High-rainfall areas • Freeze–thaw cycles • Desert issues (steam stripping)
OTHER FACTORS	• Surface drainage • Subsurface drainage • Rehab strategies—chip seals over marginal HMA materials • High truck ADTs.

(a) **(b)**

FIGURE 4 Pavement damage: (*a*) bleeding; (*b*) rutting.



(a) **(b)**

FIGURE 5 Pavement distress—cracking: (*a*) early stages; (*b*) advanced stages.

(a) **(b)**

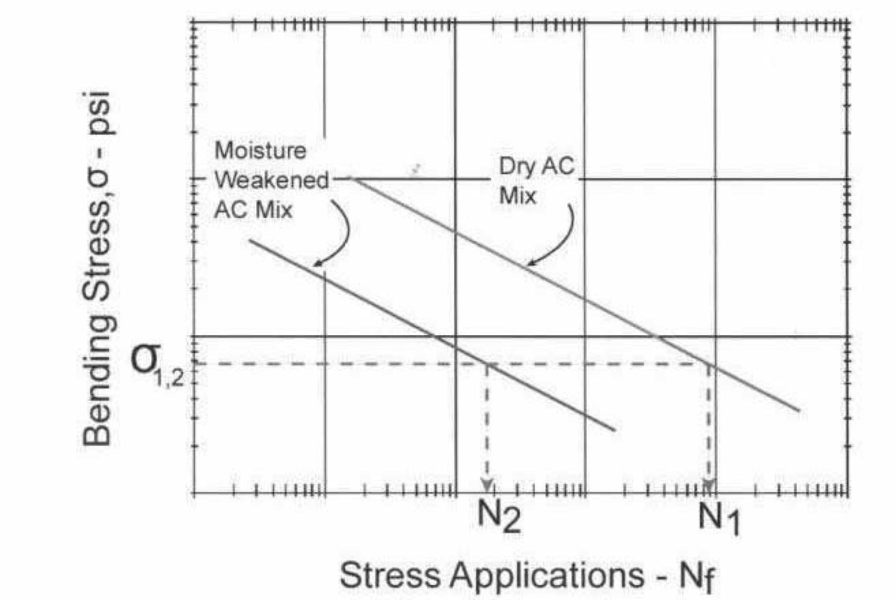
FIGURE 6 Pavement distress—raveling: (*a*) early stages; (*b*) advanced stages.

FIGURE 7 Pavement distress—localized failures.

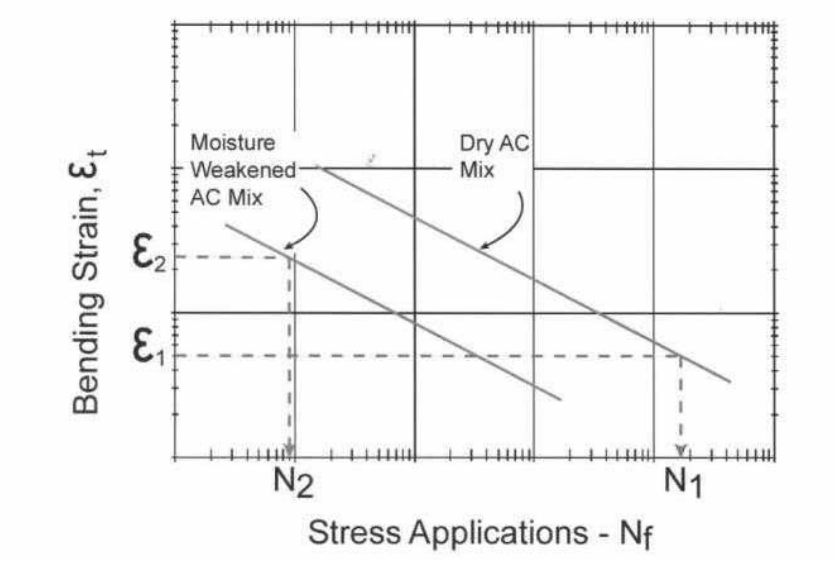
- *Localized failures*: This type of distress can be the end result of either of the types discussed above. It is progressive and can be due to the loss of adhesion between the binder and the aggregate or the cohesive strength in the mix itself. Figure 7 shows this type of distress.
- *Structural strength reduction*: This is a result of a cohesive failure causing a loss in stiffness in the mixture. Figure 8 illustrates this type of moisture damage, and Figure 9 shows the effects of moisture on stiffness.

Summary

A major product of this seminar needs to include methods for identifying what pavement distress is moisture related. In the next section, a first attempt is made to provide a framework for addressing this problem.



(a)



(b)

FIGURE 8 Moisture-related distress—effect on fatigue: (*a*) σ versus N_f; (*b*) ε versus N_f.

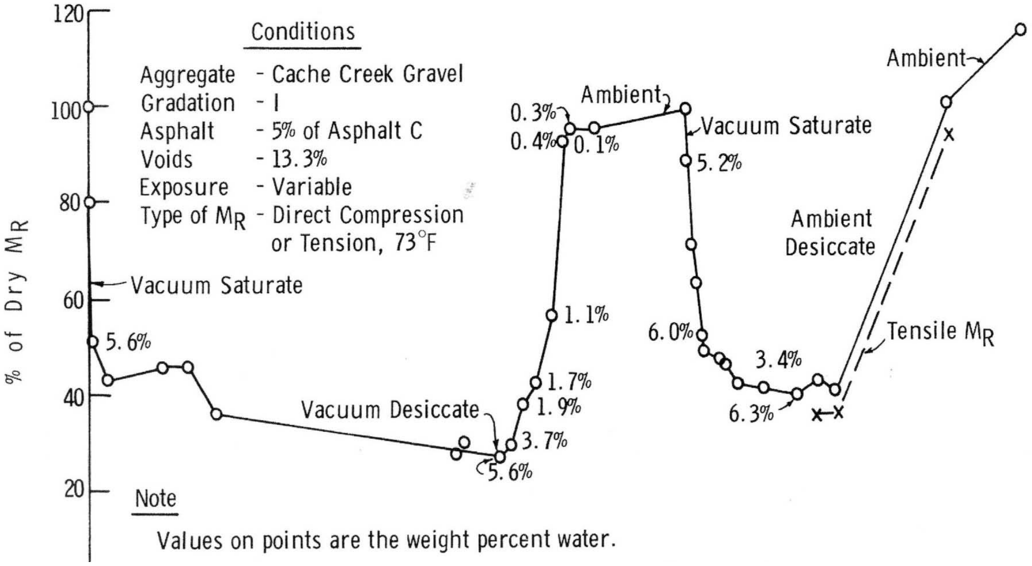


FIGURE 9 Moisture-related distress—effect on asphalt mix stiffness.

IDENTIFICATION OF MOISTURE SENSITIVITY PROBLEMS

How can engineers distinguish between moisture-related problems and problems associated with poor construction practices? This is a difficult question, since the distress types associated with stripping (rutting, bleeding, early fatigue cracking, localized potholes) and raveling (rock loss) can also be caused by inadequate design or construction factors such as the following:

- Mix design—too much or too little asphalt,
- Low compaction—high voids and permeability, and
- Poor mix gradation.

The larger question is whether the distress is associated with poor materials, design, or construction, or an adhesion or cohesion problem associated with moisture in the asphalt mix. Sampling and testing the in-place hot mix are often required to isolate the cause of the observed distress.

Figures 10 and 11 are examples of simple flowcharts that could be used to assist engineers in determining whether the distress is caused by moisture. Certain pavement distresses are often attributed to moisture and as a result require the use of additives. In some cases, the distress can be directly related to poor construction practices. This will be addressed in more detail during the course of the seminar.

Moisture-sensitive mixes need to be identified during the course of the mix design process. Numerous laboratory tests have been used to identify moisture-related problems. These include tests on (*a*) loose mix to determine coating during water immersion or in boiling water and (*b*) compacted mix to evaluate the retained strength or stiffness and the amount of rutting or disintegration during wheel-tracking tests. Both types of tests measure the effects of moisture on adhesion, cohesion, or some combination of the two (see Figure 12). However, many of the tests have shortcomings, including the following:

- They are not performance related.
- They exhibit poor reproducibility between laboratories.
- They do not provide a good indication of the effects of traffic or climate.

New tests continue to be developed and evaluated. A considerable amount of field evaluation will be required to determine whether they will do a better job of predicting moisture-related distress.

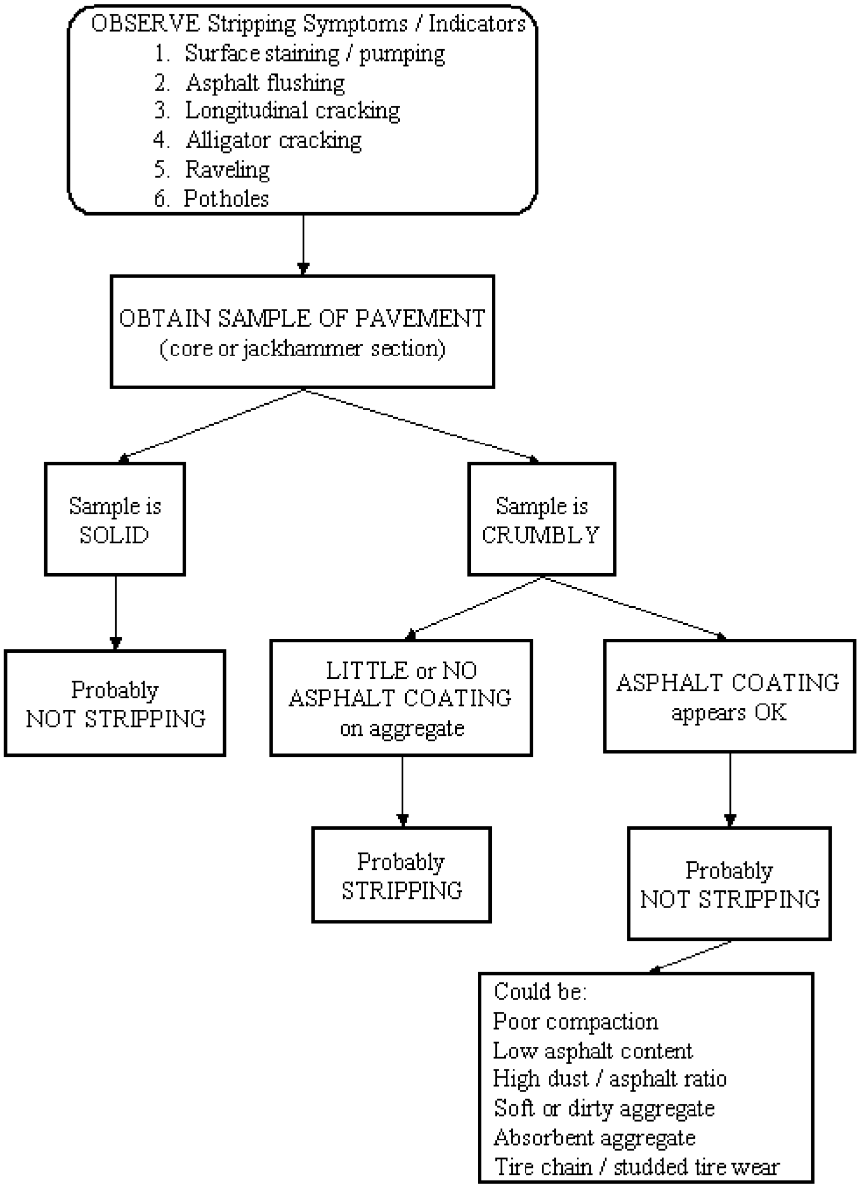
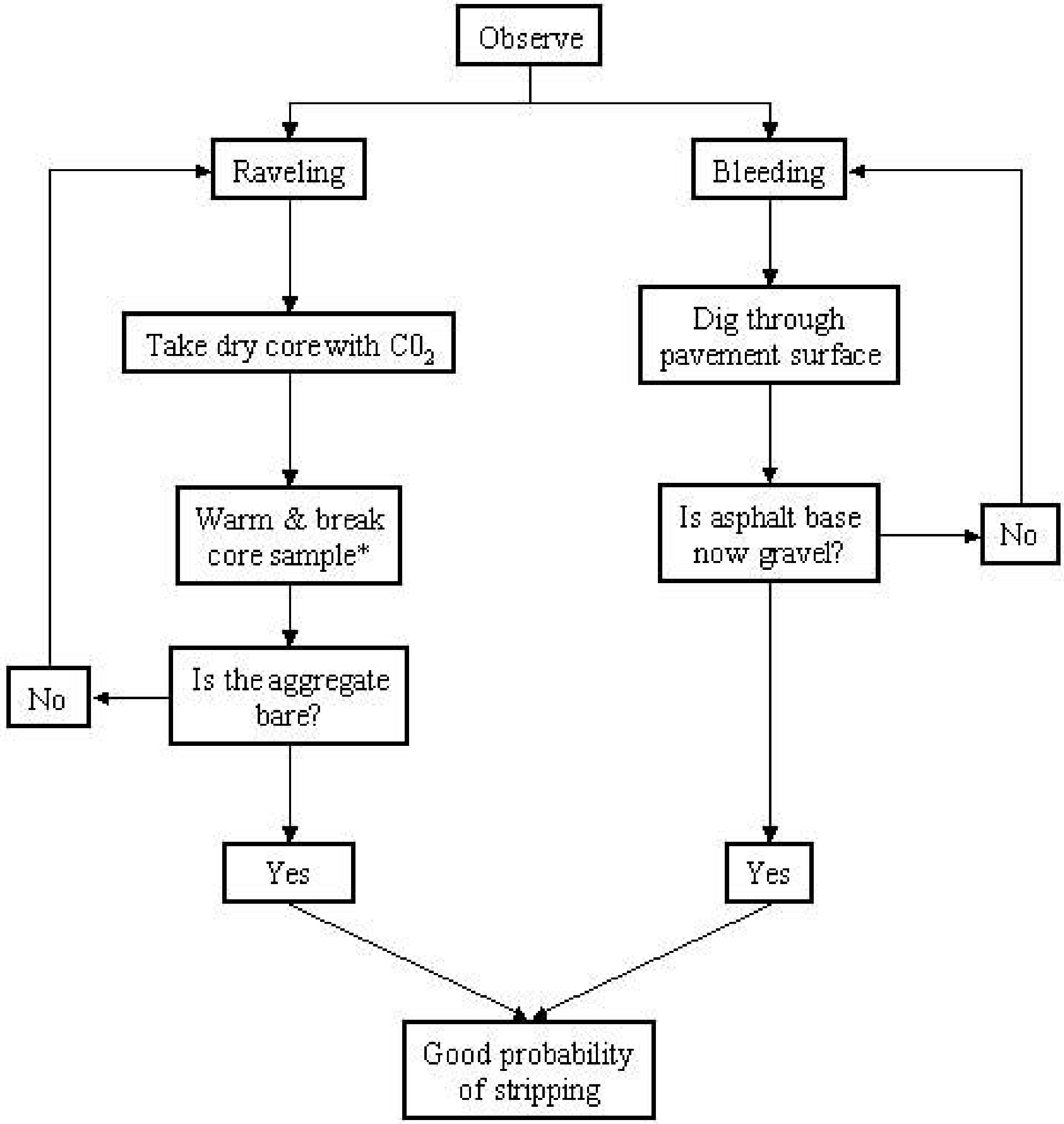
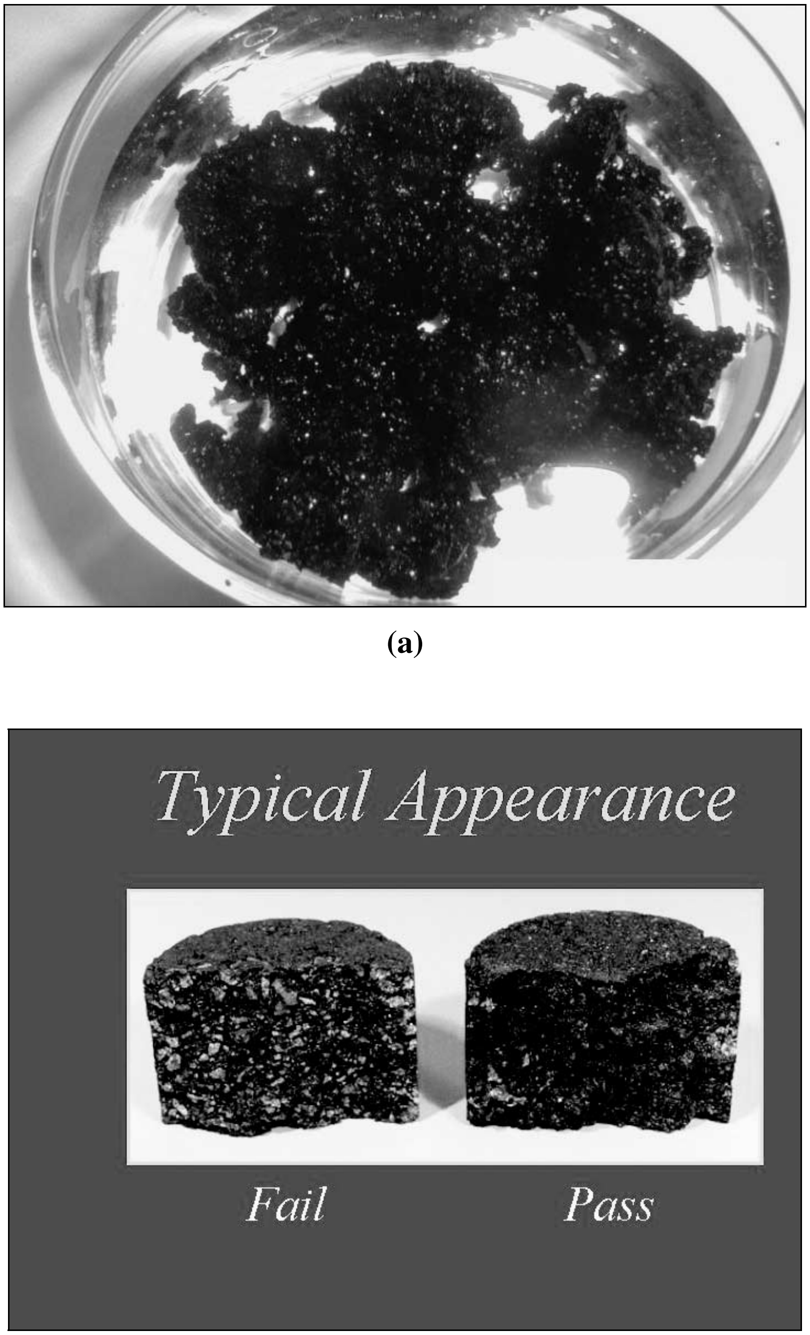


FIGURE 10 Generalized flowchart for identifying moisture-related distress.



* May be able to observe stripping with or without warming and breaking.

FIGURE 11 Example flowchart for determining moisture-related distress for bleeding and rutting.



(a)

(b)

FIGURE 12 Typical appearance of stripped mixes: (*a*) loose mix; (*b*) compacted mix.

CAUSES OF MOISTURE-RELATED DISTRESS

Numerous factors can contribute to moisture sensitivity problems in asphalt pavements (see Table 1). Some of these factors are discussed briefly in this section. They are addressed further in the technical papers that follow and in the subsequent breakout sessions.

Moisture-Sensitive Aggregates

Aggregates can greatly influence whether a mixture will be moisture sensitive or not. The aggregate surface chemistry and the presence of clay fines are important factors affecting the adhesion between the aggregate and the asphalt binder. Common methods of combating these factors are through the use of antistrip agents such as liquids or lime and by the elimination of detrimental clay fines through proper processing or specification. These issues are discussed in more detail in the paper dealing with chemical and mechanical processes.

Asphalt Binder Sensitivity

The asphalt binder can influence both the adhesion between it and the aggregate and the cohesion of the mastic. Adhesion is influenced by the chemistry of the asphalt as well as by the stiffness of the binder. The cohesive strength of the asphalt matrix in the presence of moisture is also influenced by the chemical nature of the binder and processing techniques. The fundamentals of binder sensitivity to water are also treated in the paper on chemical and mechanical processes.

Presence of Water and Traffic

Moisture-related problems do not occur without the presence of water and traffic, which provides energy to break the adhesive bonds and cause cohesive failures. Repeated freeze–thaw cycles can also accelerate the distress in the pavement. Moisture comes from rain infiltration or from beneath the surface. Once the moisture is in the pavement, it can affect either the adhesive bond or cohesive strength.

Test methods, which have historically been used to evaluate mixes for moisture sensitivity, have generally examined the effect of moisture on the mix strength or the coating on the aggregate. They have not included the effect of traffic on accelerating the moisture-related distress. In the paper on test methods the strengths and weaknesses of present tests and their relationship to pavement performance are addressed, and new methods and future directions are discussed.

Pavement Design Considerations

Pavements may have fundamental design flaws that trap water or moisture within the structural layers. There must be good drainage design, both surface and subsurface, since water causes moisture-related distress. The application of surface seals to a moisture-sensitive mix can also be a factor in accelerating moisture damage. The paper on design and production issues addresses these factors and others in more detail.

Material Production Issues

The paper on design and production issues also addresses material production issues that can affect the moisture sensitivity of asphalt mix. Some of the issues to be discussed are as follows:

- The influence on moisture damage of the method used to refine the binder, particularly the effects of acids and bases;
- Aggregate production issues including cleanliness, moisture content, and hardness; and
- Mix handling, including the use of storage silos.

Construction Issues

A number of construction issues can affect the moisture sensitivity of the mix. Weather conditions are important in that they can affect mix compaction or trap mix moisture. Mix handling techniques (e.g., windrows truck loading) can influence segregation and affect the permeability of the mix. Joint construction techniques can also affect compaction and permeability. The amount of compaction achieved (relative density) has a major effect on the air void content, the permeability of the finished pavement, and the mix sensitivity to moisture damage. Control (or lack thereof) of required additives can influence the long-term performance of the mix. These factors are discussed in the paper on construction issues.

POTENTIAL SOLUTIONS

The factors discussed in the prior sections contribute to moisture-related distress. How can industry prevent these problems? Potential solutions are discussed in the remaining papers.

Treatments

In the paper on treatments, the various types of treatments used and their effectiveness are discussed. The various methods to add lime to asphalt concrete are discussed, and documented evidence on the effectiveness of the various methods is provided. Similarly, the merits of adding different types of liquids and the effectiveness of each method are discussed. Finally, the cost-effectiveness of the various treatments is presented. All of the treatments work under some conditions. Guidelines need to be developed to ensure that the treatment selected is the best and most cost-effective for the application.

Field Experiences

Documentation concerning what has worked and what has not is given in the paper on field experiences. The paper includes a discussion of selected case histories from throughout the United States. For each agency, the following items are discussed:

- History of problems with moisture sensitivity,
- Solutions to moisture sensitivity problems,
- Performance relations or forensic tools,
- Specifications to control moisture sensitivity, and
- Ongoing research on moisture sensitivity.

Specifications

The factors that need to be specified to minimize moisture-related problems, including the material properties that must be monitored, were discussed in a presentation, which is not included in this proceedings. According to the presentation, the material properties could include the compatibility between the binder and the aggregate, the quality and condition of the aggregate, the need for additives as determined by the mix design tests, and other items. The importance of field quality control/quality assurance testing on loose mix, field cores, and the actual in-place pavement was also discussed. Defining appropriate acceptance criteria to mitigate moisture-related distress and validating the quality of field-produced mixes are essential.

Implementation

In the last paper on implementation, the group is challenged to document best practices, identify barriers or gaps in knowledge, and outline future research needs. It is expected that at the end of the breakout sessions, the following will have been identified:

- Best practices,
- Gaps in knowledge and barriers to progress, and
- Research needs and options to find funding to complete the research.

EXPECTED DELIVERABLES FROM THE SEMINAR

Deliverables

The expected deliverables from this seminar are focused in the following areas:

- *Identify best practices*: A number of agencies have studied and evaluated moisture problems in pavements and have developed procedures to deal with them. This seminar will result in the identification of these procedures to mitigate the problem so others can take advantage of their experiences.
- *Identify gaps in knowledge and barriers to progress*: An important part of the seminar will be to identify which procedures and processes have been successful and which have not. In addition, it will be important to identify the knowledge gaps that result in a lack of understanding of the causes of the problem and the barriers that need to be addressed.
- *Identify research needs*: Once the gaps in knowledge and other barriers are identified, it will be possible to develop a set of research needs and prepare preliminary research problem statements for each issue.
- *Road map for the future*: A road map presents options for FHWA and the state highway administrations to deal with short- and long-term solutions to the problem.

The products from this seminar will be the papers, a summary of the breakout sessions, and a road map with options for solving this national problem.

Specific Questions to Be Addressed

Specific questions that should be addressed during the breakout sessions include but are not limited to the following:

- Session 1: Fundamentals
  - What is moisture-related distress?
  - How can moisture-related distress be distinguished from distress resulting from construction-related problems?
  - What are the mechanisms causing moisture-related distress?
  - Are processes available for identifying moisture-sensitive aggregates and asphalts?

  - What are the major gaps in knowledge?
  - What fundamental issues still need to be addressed?
- Session 2: Testing and Treatments
  - What test methods are best for identifying moisture-related problems? Which relate to field performance?
  - Are improvements to existing test methods still needed?
  - How effective are the various additives in minimizing the effects of moisture?
  - Is there documented evidence on how they affect pavement life? If not, why not?
  - What issues still need to be addressed?
- Session 3: Design and Specifications
  - What mix design procedures are most effective in controlling moisture-related problems?
  - What items in the specifications should be controlled to minimize problems?
  - Are all the major factors in design and specifications being considered? If not, what additional factors need to be considered to minimize the effects of water on the asphalt pavement?
- Session 4: Construction and Field Performance
  - What construction issues need to be controlled to reduce moisture problems?
  - What has worked and what has not worked?
  - What information is needed to make better decisions when it comes to preventing moisture-related distress?

Summary

Pavement problems related to moisture are being addressed through use of additives, improved mix design, construction practices, and better specifications. This seminar will result in the documentation of best practices to control the problem and produce a road map with options for improving the ability to deal with the problem.

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AASHTO Survey

RESULTS OF SURVEY ON MOISTURE DAMAGE OF HOT-MIX ASPHALT PAVEMENTS

Compiled by Tim Aschenbrener, Colorado Department of Transportation

August 4, 2002

State	Treat for Moisture Damage Problems in HMA Pavements	Treatment Method / Approach	Test for Moisture Susceptibility	Test Method(s) Used	Stage When Testing Is Done	Currently Funds Moisture Damage Research	Research Topics
AL	YES	Alabama requires any mixes with less than 80% TSR or that show any signs of visual stripping to use antistrip. Both liquid and lime antistrips are allowed. Liquid antistrips are more economical for the contractor. **Liquid**	YES	Modified AASHTO T283 (without the freeze cycle and with less "curing " time). **Tensile**	During mix design, field QC, and field QA. **Mix / Acceptance**	YES	Two research projects under way related to moisture in HMA. NCAT is doing the research. Contact NCAT for details. 1. Measurement of Rate of Water Intrusion into Pavement Layers Constructed with Superpave-Designed Asphalt Concrete. 2. Development of HMA Moisture Susceptibility Test for Alabama.
AK	YES	Liquid antistrip agent. **Liquid**	YES	A variation of static immersion test. **Compressive**	During the mix design to determine the amount of liquid antistrip to add to the asphalt cement. **Mix**	NO	N/A
AR	YES, if it is indicated as necessary during the HMA design phase. In such case, an antistrip additive must be used.	If an antistrip additive is needed, a heat-stable liquid antistrip additive from the Qualified Products List shall be added at the rate of 0.5% or 0.75% by weight of the asphalt binder as determined by laboratory analysis. **Liquid**	YES All mix designs are required to be tested for water sensitivity.	The agency uses a test modified from an Asphalt Institute test several years ago. Water sensitivity is based on Marshall stabilities before and after conditioning for stripping potential. AHTD Test Method 455A is used; 6-in. gyratory samples are used as test specimens. **Stability**	At the design phase. The contractor is required to design the HMA and provide samples for the design to be verified by the department. The department does not normally verify the water sensitivity test results. In the recent past, the department has used a high percentage of modified asphalt binders, PG 70-22 and PG 76-22, and few designs have required antistrip. **Mix**	YES: One just concluded: TRC-9804 "ERSA" (Evaluator of Rutting and Stripping in Asphalt) Wheel Track Testing for Rutting and Stripping; Principal Investigator: Dr. Kevin Hall, Univ. of Arkansas.	Primary objective was to develop test specs for determining the rutting and/or stripping potential of an asphalt concrete mix using ERSA, to supplement the Superpave mix design procedure for asphalt concrete. A follow-up research project has just begun: TRC-0201, "ACHM Lab Test for Rutting and Stripping"; Principal Investigator: Dr. Kevin Hall, Univ. of Arkansas. Two main global objectives of the research: to finalize criteria for judging mix acceptability relative to the stripping potential of an asphalt mix and to develop mixture design specs for relatively high-performance ACHM targeted for use in intersections.
AZ	YES Treatments are used if the I/C fails. This is about 98% of the time.	Lime or portland cement is added to moist aggregates (4% moisture). **Lime**	YES	Immersion / compression test similar to AASHTO T165. **Compressive**	Mix design only - no field acceptance. **Mix**	NO	N/A

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CA	YES	Liquid antistripping additive added at the hot plant. Hydrated lime slurry and marination. **Liquid / Lime**	NO, not at this time	Caltrans is in the process of implementing a test similar to AASHTO T283 for next construction season.		NO	None
Canada (Ontario)	YES	Canada allows both liquid and hydrated lime. However, it only permits the use of lime for dolomitic limestone in dense friction courses. Aggregates are allowed to be prelimed at the supply/quarries provided contractor's QC plan clearly states how the quality in the aggregates is assured before use prior to mixing. Drum premixing with wet aggregates and lime slurry in stockpile are permitted in the specs. **Liquid / Lime**	YES	Stripping potential is assessed by Ontario Laboratory Standard Immersion Marshall (vacuum saturation ratio of wet to dry retained stability >70%), Superpave AASHTO T283. (Studies showed Ontario method equates well with AASHTO T283.) **Stability**	At mix design and verified by QA. **Mix / Acceptance**	NO, not currently. But had jointly funded a project a few years back with Transport Association of Canada.	The study was to compile a background document on causes, identification, testing, and mitigation of moisture damage of asphalt pavements and antistripping additives (where methods by Ontario and AASHTO were compared).
CO	YES	Colorado requires hydrated lime. Dry lime on wet aggregates is most commonly used. Lime slurry and marinating are also allowed. **Lime**	YES	Modified AASHTO T283. Similar to the original Lottman test. **Tensile**	For mix design, field QC, and field QA. **Mix / Acceptance**	NOT at this time	None
CT	NO	**None**	Conditional YES: Only for Superpave mixes.	AASHTO T283 **Tensile**	As part of the mix design performed by the contractor. **Mix**	NO	N/A
DC	YES	Antistrip agents are required in all mixes. Liquid or hydrated lime in slurry form is used. **Liquid / Lime**	YES	ASTM D4867. **Tensile**	Mix design. **Mix**	NO	N/A
DE	NO	Aggregates are very good for HMA. No treatments have been needed.	YES	AASHTO T283. **Tensile**	Mix design only. **Mix**	NO	N/A

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FL	YES	Florida will allow either liquid antistrip (most common approach) or lime (either added in the mixing operation before the addition of the asphalt cement or as a slurry in the aggregate). **Liquid / Lime**	YES	Modified AASHTO T283 with a retained strength of 80%, a minimum unconditioned tensile strength of 120 psi, and a higher saturation level. **Tensile**	For the mix design. **Mix**	YES	Florida has a contract looking at the basics of moisture damage and focusing on the standardization of the conditioning procedure.
GA	YES	Georgia requires hydrated lime. The addition of hydrated lime to the aggregate may be accomplished by Method A or B as follows: Method A: dry form; Method B: lime/water slurry. **Lime**	YES	Modified Lottman test, GDT-66. **Tensile**	Every mix design, and field QC/QA samples. **Mix / Acceptance**	NO, not at this time.	N/A
HI	NO	**None**	NO			NO	None
IA	YES	Iowa does treat for moisture damage when aggregate blend contains a high percentage of siliceous aggregates. Most of Iowa's mixtures use limestone or dolomite. Until this year, hydrated lime was required for treating moisture damage. The agency was forced by the industry to allow liquid antistrips this year. **Liquid**	Conditional YES: Only test for moisture susceptibility when liquid antistrips are used or when the contractor attempts to prove that an antistrip is not needed even though the aggregates used would require it by specs.	AASHTO T283. **Tensile**	Testing is performed on the mix design by the contractor and on QA samples by the agency. **Mix / Acceptance**	YES: Funding research with Iowa State University to develop a more reliable test.	The research in progress is intended to find a dynamic test for moisture damage that will simulate the high hydraulic pressure encountered in pavements under traffic.
ID	YES	Essentially all plant mix contains antistrip. Typically 1/2%. The respondent is pushing for a comeback to hydrated lime. **Liquid**	YES	Immersion Compression AASHTO T165. **Compressive**	As part of the mix design confirmation. Consultants include test in mix design. **Mix**	NO	N/A
IL	YES	Illinois uses liquid antistrip when an additive is required. Hydrated lime is also allowed and has been required on a couple of contracts awarded this year. Primarily liquids are used. **Liquid**	YES	Modified AASHTO T283. **Tensile**	During mix design with a TSR criterion of 0.75 or greater. **Mix**	NO	None

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IN	Yes; only a small percentage (about 10%) need it.	Almost exclusively liquid antistrip. **Liquid / None**	YES	AASHTO T283 with no modifications. The freeze-thaw cycle is required. **Tensile**	Mix design only. **Mix**	Not at this time.	
KS	YES	Kansas allows liquid antistrip agents or lime. Liquids are by far the most commonly used. Approximately 30% to 50% of the mix designs require treatment. **Liquid**	YES	Modified AASHTO T283. **Tensile**	Kansas test on design and samples from behind the paver are tested for QC and QA. **Mix / Acceptance**	NO; watching the national effort.	None
KY	YES	Kentucky uses liquid antistripping additives exclusively. Hydrated lime is an option, but no contractors use it. **Liquid**	YES	Slightly modified version of ASTM D4867. **Tensile**	Kentucky tests for moisture damage in the mix design phase by specification and occasionally in the field for information. **Mix**	NO	Not applicable.
LA	YES	Louisiana requires liquid antistrip and Lottman with one freeze-thaw cycle for mix design approval. Louisiana also requires modified asphalts, which have improved resistance to moisture. **Liquid**	YES	Modified AASHTO T283. Similar to the original Lottman test with one freeze-thaw cycle. **Tensile**	At design submittal, at plant for JMF verification, and again every 40,000 tons. **Mix**	NO: Louisiana is not but has in the past.	None
MA	NO	Not much treatment is done. If any treatment is used, it is typically a liquid antistripping additive. **None**	NO	N/A	NO	NO	Some may be done in the future on Superpave requirements.
MD	YES	Chemical **Liquid**	YES	ASTM D4867. **Tensile**	Mix design, field QC and QA. **Mix / Acceptance**	NO	N/A
ME	NO	N/A **None**	NO	N/A	N/A	NO	No, but discussions on this are in progress.
MI	YES	Allow antistrip agents. Contractors choose the manufacturer and recommended dosage. **Liquid**	YES	AASHTO T283 or ASTM D4867; whichever the contractor chooses. **Tensile**	The test is required for mix design, and field samples are requested if the results from the TSR test are deemed marginal or if the materials used in the mixture are from a questionable source. **Mix / Acceptance**	NO	N/A

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MN	YES	Allow liquid antistripping additives. They are needed in approximately 30% of the mixes. **Liquid**	YES	A version of ASTM D4867 is used. **Tensile**	Mix design and field acceptance. **Mix / Acceptance**	NO	N/A
MO	YES	The contractor is given the option of hydrated lime or a commercial antistrip additive. Although lime was primarily used in the past, liquids are the primary treatment used at this time. **Liquid**	YES	AASHTO T283 with one freeze-thaw cycle is used. **Tensile**	Currently the mix design is tested; testing of field cores is being investigated. **Mix**	YES	The testing of plant-produced mix and field cores is being investigated.
MS	YES	With hydrated lime - dry lime on wet aggregate. Note: failing test. **Lime**	YES	Modified AASHTO T283. Similar to the original Lottman test. **Tensile**	For mix design, field QC, and field QA. **Mix / Acceptance**	NO	N/A
MT	YES	Montana requires hydrated lime. Dry lime added on the cold feed is most common. **Lime**	YES	Modified AASHTO T283. Similar to the original Lottman test. **Tensile**	For the mix design. **Mix**	NO	None
NC	YES	The use of an antistrip additive is required: either hydrated lime, chemical additive, or a combination of the two as needed to obtain the TSR requirements. **Liquid / Lime**	YES	Modified AASHTO T283 with no freeze-thaw cycle. **Tensile**	Testing is required both during mix design and during production. **Mix / Acceptance**	NO	N/A
ND	NO	North Dakota has in past years, but recently including additions into the mix has been suspended. Testing is currently being increased, and treatments may be included in future projects. Lime was the predominant addition. **None**	YES	Modified Lottman. **Tensile**	Mix design. **Mix**	NO	N/A

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NE	YES	Nebraska allows the contractor to select which antistrip additive is used; liquid additives are being used. Whatever liquid additive is used, it must be added to the binder by the supplier and the binder must meet MP-1 after antistrip is added. **Liquid**	YES	AASHTO T283. **Tensile**	For mix design approval. If an antistrip is required, the agency samples at project start-up to verify the design and then make adjustments whenever the TSR is less than 80%. If above or once above 80%, no more samples are taken during production. **Mix / Acceptance**	Not at this time.	None
NH	NO	**None**	NO	New Hampshire has tested for moisture susceptibility in the past, but because no problems have been revealed in the test results or historically in the field, this testing has been discontinued.	N/A	NO	N/A
NJ	Not routinely.	On the few occasions that the agency has treated, it has used liquid antistrip, but the respondent is not convinced of the efficacy of these treatments. **None**	YES	AASHTO T283. **Tensile**	New Jersey requires T283 at time of design only. **Mix**	NO	None
NM	YES	New Mexico requires 1.5% lime in all asphalt concrete mixes. **Lime**	YES	AASHTO T165. **compressive**	For mixture design acceptance (laboratory). **Mix**	NO	N/A
NV	YES	NDOT uses hydrated lime added to damp aggregate and stockpiled for a minimum of 48 hours. **Lime**	YES	Modified AASHTO T283 Lottman with freeze-thaw cycle. **Tensile**	During the mix design and on samples taken from behind the paver. **Mix / Acceptance**	NO: not at this time.	N/A
NY	YES: only when aggregates from specific area of the state are used. This is about 10%.	The agency leaves it up to the producers to use any additives as long as the TSR minimum value is achieved. On the basis of the test results, liquid antistripping additives are most commonly used. Polymer-modified asphalts also seem to help. **Liquid / None**	Conditional YES: NYSDOT does not test routinely unless necessary. The testing is generally left up to the producer.	If necessary to test, New York uses AASHTO T283. **Tensile**	During the mixture design phase. **Mix**	NO	None. However, the agency has placed small test sites in one area of the state where gravel is the predominant aggregate. These sites were placed to investigate effects of different additives in the HMA in relation to moisture damage.

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OH	Not routinely. Rarely treat.	Lime or liquid is allowed but must raise to passing level. **None**	YES	AASHTO T283 with some modifications in air voids and saturation. **Tensile**	Mix design only routinely, but can test by spec at any time. **Mix**	YES	Ohio has a study to look at 6 inch versus 4 inch and overall AASHTO T283 procedure.
OK	YES	Chemical antistrip additives are used almost exclusively. Lime has been used for some gravel mixtures, but this is rare. **Liquid**	YES	OHD L-36 for Hveem mix designs. It is similar to AASHTO T283, which is used for Superpave mixtures. **Tensile**	For mix design and field control tests. Mix design T283's TSR is required to be 0.80 minimum. 0.75 is required as a field criterion. OHD L-36 requires 75% retained strength after the freeze-thaw cycle for both field and mix design. In the field it is a go-no go type of spec. Resident engineers decide whether the project may continue if failing results are found. No mix design is transferred if three consecutive failures occur on that mix design. **Mix / Acceptance**	YES, surface energy research on some aggregates and binders is being funded at the University of Oklahoma.	Surface energies for a few aggregates in mixtures that failed moisture sensitivity tests and control aggregates and some asphalt binders will be examined. The actual surface energy testing will be performed at Texas A&M. Both universities will collaborate. Texas A&M, through the Texas Transportation Institute, presented a paper at Association of Asphalt Paving Technologies this year.
OR	YES	Oregon uses different treatments depending on location and risk of stripping. The use of lime is mandated in the most severe climates. In less severe areas lime, ultra-pave, or other liquid antistrip agents are allowed on the basis of results of TSR testing. When lime is used, dry lime on wet aggregates is used almost exclusively. **Liquid / Lime**	YES	AASHTO T283. **Tensile**	During the mix design phase and again early on during production. **Mix / Acceptance**	Not at this time.	N/A
PA	YES; not often.	Predominately, Pennsylvania's HMA plants have elected to use chemical additives added directly to the asphalt cement. A very low percentage of mixes require treatment. **Liquid / None**	YES	Modification of AASHTO T283. **Tensile**	Required as part of mix design approval. **Mix**	NO	N/A
RI	YES	Liquid antistrip is required in friction courses. **Liquid**	NO	N/A	N/A	NO	N/A

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SC	YES	South Carolina requires hydrated lime. The agency requires to damp mix hydrated lime in a pug mill with at least 3% moisture in the aggregate. This system has worked for South Carolina for some time now. **Lime**	YES	Modified AASHTO T283. **Tensile**	For mix design and has an option for field QC. **Mix**	NO	None: In the past, both South Carolina and Georgia had done extensive research in the area of hydrated lime use for moisture susceptibility purposes and should have several good research reports on this topic.
SD	YES	South Dakota requires hydrated lime. **Lime**	YES	ASTM D486 for Marshall mix designs and AASHTO T283 for Superpave mix designs. **Tensile**	At the mix design stage by the contractor with DOT verification. **Mix**	YES	South Dakota is in third year of a 3-year study on moisture damage. Peter Sebaaly from the University of Nevada is the researcher evaluating the use of hydrated lime and liquid antistripping agents. South Dakota would like to find a moisture damage test that could be conducted in the field in less time than the current AASHTO T283 procedure.
TN	YES	A majority of the mixes require treatment. Liquid antistripping additives are used. **Liquid**	YES	A version of AASHTO T283 is used. **Tensile**	Mix design and field acceptance. **Mix / Acceptance**	NO	N/A
TX	YES	Texas allows hydrated lime or liquid antistrip agents that prove effective. Lime works best on siliceous aggregates but is not always effective on limestone (yes, limestone can strip). **Liquid / Lime**	YES	Modified AASHTO T283. Similar to the original Lottman test. Texas is looking at eliminating this test in favor of the Hamburg wheel track test results. The Hamburg is the more severe test. **Tensile/Hamburg**	Test for mix design. A companion Louisiana boil test is performed on mix that passes the modified Lottman. The Louisiana boil test is performed during production (QC) and is used to screen for running the modified Lottman. If the boil test fails, the agency runs the modified Lottman as a QA. The agency also runs Hamburg on the mix design (either lab or trial batch). The agency runs at least one additional Hamburg during production; however, the agency can run as many as needed to verify mix compliance. **Mix / Acceptance**	YES; Texas is currently supporting a pooled-fund study, and the agency continues to support Hamburg testing research.	Stripping and Hamburg testing.

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UT	YES	Utah uses a hydrated lime slurry with three parts water and one part lime by weight. The lime content is 1.0% by weight of the aggregate. Marinating is also allowed, but with 1.5% lime. **Lime**	YES	AASHTO T283 and the Hamburg rut test. **Tensile/Hamburg**	Mix design approval. Utah reserves the right to spot test if it perceives a problem. **Mix**	NO	N/A
VA	YES	Virginia allows either hydrated lime or chemical antistripping additive. If hydrated lime is used, it must be applied to moist aggregate (at least 3% moisture). Liquid antistripping additives are used almost exclusively. **Liquid**	YES	AASHTO T283. **Tensile**	During mix design; depending on the district, production is occasionally checked. **Mix**	YES	Virginia has a current project to try to determine whether the magnitude of visual stripping observed in a statewide coring survey several years ago is detrimental from a reduced service-life standpoint. Note: cores revealed quite a bit of visual stripping but mostly only cracking as a distress. The agency is simulating various degrees of stripping on laboratory specimens and running fatigue tests on the specimens.
VT	YES	Vermont requires the use of an antistrip additive in any mix that contains granite or quartzite materials unless testing shows otherwise. The agency requires a minimum of 0.50% additive. When required, all producers currently use a liquid additive. The additive is generally "Wet-Fix 312" produced by Akzo Nobel. Hydrated lime is acceptable but not required. Additive can be blended in asphalt storage tank or added by an in-line injection system. Most use injection system. **Liquid**	Conditional YES: only on new aggregate sources and all Superpave designs.	AASHTO T283 is used with 4-inch specimens. **Tensile**	Testing is done prior to acceptance of any new aggregate source and is required on all Superpave designs. Designing of all mixes is the responsibility of mix producer. **Mix**	NO; not to the respondent's knowledge.	N/A
WA	YES	Washington uses liquid antistrip, on the basis of results from a modified Lottman test. **Liquid**	YES	Modified Lottman. **Tensile**	At the time the design mix is developed in the agency's laboratory. This is true for all mixes. **Mix**	NO, not directly, although several groups with which the agency is affiliated are reviewing moisture susceptibility tests.	None

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August 4, 2002

State	Treat for Moisture Damage Problems in HMA Pavements	Treatment Method / Approach	Test for Moisture Susceptibility	Test Method(s) Used	Stage When Testing Is Done	Currently Funds Moisture Damage Research	Research Topics
WI	YES	Contractors are allowed to use either hydrated lime or liquid antistripping agents (any liquid agents used are further restricted by specification limits that tie to changes in the viscosity and penetration of the original asphalt binder). Liquid antistripping agents have been the additive of choice for the agency's contractors since about 1994-1995 (otherwise a lot of hydrated lime was seen here as well). **Liquid**	YES	ASTM D4867 with a minimum threshold limit of 70% without the aid of additives, and a minimum 75% if additives are being used. **Tensile**	It is required as part of meeting original mix design parameters, but only requires field QC testing if a mixture had indicated the need for use of an antistripping agent. At the present time, the department does not do any sampling or testing as part of its QA verification process (dependent on contractor data during production). **Mix**	YES	Research was funded 3 years ago and is currently ending an additional funded project from 2001-2002 budgets. The title is "Evaluation of the Extent of HMA Moisture Damage in Wisconsin as it Relates to Pavement Performance."
WV	NO	West Virginia has not had moisture damage issues. **None**	NO	N/A	N/A	NO	N/A
WY	YES	Wyoming requires hydrated lime. Dry lime on wet aggregate is most commonly used. Slurry is allowed, and marinating would be allowed if precautions are taken to prevent leaching. **Lime**	YES	Modified AASHTO T283 with freeze cycle. Will most likely use the new T283 without modification when it is published. **Tensile**	Wyoming requires for mix design testing and does some mixture checks; no QA testing at this time. **Mix**	NO	None
FHWA (CFLHD)	YES: it is required on all mixes with the exception of CA or limestone aggregates.	Dry lime on wet aggregates through a pug mill with at least 15 seconds of retention time. **Lime**	YES	AASHTO T283 for Superpave and compaction is allowed by either Kneading (T247) or gyratory compactor. ICs are used for Hveem mixes. **Tensile**	Mix design and on test strip samples. **Mix / Acceptance**	NO	None
FHWA (EFLHD)	YES, when needed.	99% of the time, liquid antistrip is used. **Liquid**	YES	AASHTO T283. **Tensile**	Mix design only. **Mix**	NO	None
FHWA (WFLHD)	YES	Hydrated lime added to wet aggregates and mixed prior to entering the heating and mixing drum. **Lime**	YES	AASHTO T165 and T167 Immersion-Compression. **Compressive**	Mix design. **Mix**	NO	None

RESULTS OF SURVEY ON MOISTURE DAMAGE OF HOT-MIX ASPHALT PAVEMENTS

Compiled by Tim Aschenbrener, Colorado Department of Transportation

August 4, 2002

State	Treat for Moisture Damage Problems in HMA Pavements	Treatment Method / Approach	Test for Moisture Susceptibility	Test Method(s) Used	Stage When Testing Is Done	Currently Funds Moisture Damage Research	Research Topics
SUMMARY: ***A total of 55 responses have been received and tabulated in this survey. A brief summary of the results is given below:***							
	YES/NO Tally	**Type of Treatment**	**YES/NO Tally**	**Type of Test**	**Time of Test**	**YES/NO Tally**	**See above topics.**
	42 YES's	**25** Liquid antistripping additive	**44** YES's	**39** Tensile (AASHTO T283, ASTM D4867, etc.)	**30** Mix design only	**11** YES's	
	3 YES(not often)	**7** Liquid or lime	**4 YES's** with condition	**5** Compressive test (AASHTO T165)	**18** Mix design and field acceptance	**44** NO's	
	10 NO's	**13** Hydrated lime total	**7** NO's	**2** Retained stability			
		Breakdown of Hydrated Lime Total **15** Dry lime on wet aggregates **6** Lime slurry **4** Lime slurry and marination		**2** Wheel-tracking and tensile test			
TOTAL	**55**	**45**	**55**	**48**	**48**	**55**	

TOPIC 2

Chemical and Mechanical Processes of Moisture Damage in Hot-Mix Asphalt Pavements

TOPIC 2

Chemical and Mechanical Processes of Moisture Damage in Hot-Mix Asphalt Pavements

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Historically, six contributing mechanisms to moisture damage have been identified: detachment, displacement, spontaneous emulsification, pore pressure–induced damage, hydraulic scour, and the effects of the environment on the aggregate–asphalt system. However, it is apparent that moisture damage is usually not limited to one mechanism but is the result of a combination of processes. It has become necessary to seek a more fundamental understanding of the moisture damage process by carefully considering the micromechanisms that influence the adhesive interface between aggregate and asphalt and the cohesive strength and durability of the mastic. Factors that influence the adhesive bonds in asphalt mixtures and the cohesive strength of the mastic in the presence of water are presented and discussed as a fundamental approach to calculating adhesive bond strength in asphalt mixtures in the presence of water on the basis of surface free energy measurements. The adhesive bond that determines the durability of asphalt mixtures in the presence of water is described in this paper to be based on a nonuniform distribution of charges in the asphalt and on the aggregate surface. The polar compounds in the asphalt that react with the aggregate polar sites determine the strength and durability of the adhesive bond. Several processes are presented that affect this bond. The effect of aggregate mineralogy, surface properties, and the pH at the water–aggregate interface is discussed.

BACKGROUND

Description of Moisture Damage

Moisture damage can be defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture. Moisture damage can occur because of a loss of bond between the asphalt cement or the mastic (asphalt cement plus the mineral filler—74 µm and smaller aggregate) and the fine and coarse aggregate. Moisture damage also occurs because moisture permeates and weakens the mastic, making it more susceptible to moisture during cyclic loading.

The literature (Taylor and Khosla 1983; Kiggundu and Roberts 1988; Terrel and Al-Swailmi 1994) refers to at least five different mechanics of stripping: detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour. Kiggundu and Roberts (1988) suggest additional mechanisms that may well play a part in moisture damage. These include pH instability and the effects of the environment or climate on asphalt–aggregate material systems.

Detachment

Detachment is the separation of an asphalt film from an aggregate surface by a thin film of water without an obvious break in the film (Majidzadeh and Brovold 1968). Theories that explain adhesive bond energy provide the rationale to understand detachment. Several factors are involved in detachment. First of all, it is necessary to develop a good bond between the asphalt and the aggregate. Such a bond is initially dependent on the ability of the asphalt to wet the aggregate. Wettability of aggregate increases as surface tension or free surface energy of adhesion decreases (Majidzadeh and Brovold 1968). According to Majidzadeh and Brovold (1968), if a three-phase interface consisting of aggregate, asphalt, and water exists, water reduces the free energy of the system more than asphalt to form a thermodynamically stable condition of minimum surface energy. Surface energy measurements at Texas A&M University have established that when the free energy at the asphalt–aggregate interface is calculated in the presence of water, energy is released, meaning that the aggregate surface has a strong preference for water over asphalt. The negative values of free energy in Column 5 of Table 1 establish that this is true for each of four asphalt–aggregate combinations listed in Table 1. The more negative the value, the stronger is the preference for detachment of asphalt from aggregate in the presence of water. The thermodynamic basis for these calculations is presented by Cheng et al. (2002).

Work at the Road Research Laboratory in 1962 suggests that most asphalts have relatively low polar activity and that the bond that develops between the aggregate and asphalt is chiefly due to relatively weak dispersion forces. Water molecules are, on the other hand, highly polar and can replace the asphalt at the asphalt–aggregate interface. Recent work at Texas A&M University by Cheng et al. (2002) has established this to be the case and will be discussed later. Texas A&M researchers have developed a methodology to measure component surface energies and to calculate adhesive bond strengths from these measurements (Cheng et al. 2002).

Displacement

Displacement differs from detachment because it involves displacement of asphalt at the aggregate surface through a break in the asphalt film (Tarrer and Wagh 1991; Fromm 1974). The source of the break or disruption may be incomplete coating of the aggregate surface, film rupture at sharp aggregate corners or edges, pinholes originating in the asphalt film because of aggregate coatings, and so forth. Scott (1978) states that chemical reaction theory can be used to

TABLE 1 Comparison of Free Energy of Adhesion (ergs/gm) and Rate of Damage Under Repeated Load Triaxial Testing (After Cheng et al. 2002)

Mix	Cycles to Accelerated Damage	Loss of Contact Area (Debonding), %	Free Energy of Adhesion (Dry)	Free Energy of Adhesion (Wet)
AAD + Texas Limestone	275	34	141	-67
AAM + Texas Limestone	550	27	205	-31
AAD + Georgia Granite	250	35	150	-48
AAM + Georgia Granite	455	26	199	-30

explain stripping as a detachment mechanism. Some authors describe film rupture as a separate mechanism of moisture damage, but it can be incorporated as part of the displacement mechanism. The process of displacement can proceed through changes in the pH of the water at the aggregate surface that enters through the point of disruption. These changes alter the type of polar groups adsorbed, leading to the buildup of opposing, negatively charged, electrical double layers on the aggregate and asphalt surfaces. The drive to reach equilibrium attracts more water and leads to physical separation of the asphalt from the aggregate (Scott 1978; Tarrer and Wagh 1991).

Spontaneous Emulsification

Spontaneous emulsification is an inverted emulsion of water droplets in asphalt cement. Fromm (1974) demonstrated how an emulsion forms and that once the emulsion formation penetrates the substrata, the adhesive bond is broken. Some research indicates that the formation of such emulsions is further aggravated by the presence of emulsifiers such as clays and asphalt additives (Asphalt Institute 1981; Fromm 1974; Scott 1978). Fromm (1974) observed that spontaneous emulsification occurs when asphalt films are immersed in water and that the rate of emulsification depends on the nature of the asphalt and the presence of additives. However, commercial amine-based asphalt additives, which are organic amine compounds, are chemically different from cationic asphalt emulsifiers, and they cannot function as an emulsifier in their amine form to make normal oil in water–asphalt emulsions. The cationic emulsifier solutions are obtained by reacting amines such as fatty amines with dilute hydrochloric or acetic acid to produce an amine salt (Morgan and Mulder 1995). Furthermore, organic amines, which are basic nitrogen compounds, bond strongly to aggregates in the presence of water (Robertson 2000). Kiggundu (1986) demonstrated how the rate of emulsification is dependent on the nature and viscosity of asphalt, with an AC-5 emulsifying in distilled water much faster than an AC-10. He also demonstrated that the process is reversible upon drying.

Pore Pressure

Pore pressure development in water that is entrapped can lead to distress. Stresses imparted to the entrapped water from repeated traffic load applications will worsen the damage as the continued buildup in pore pressure disrupts the asphalt film from the aggregate surface or can cause the growth of microcracks in the asphalt mastic. Bhairampally et al. (2000) used a tertiary damage model developed by Tseng and Lytton (1987) to demonstrate that well-designed asphalt mixtures tend to “strain harden” on repeated loading. This “strain hardening” is of course not classical strain hardening that occurs when metals are cold-worked to develop interactive dislocations to prevent slip but is the “locking” of the aggregate matrix caused by densification during repeated loading. On the other hand, some mixtures exhibit microcracking in the mastic under heavy repeated loading. This results in progressive cohesive or adhesive failure, or both, and is evident in a plot of accumulated permanent strain versus number of load cycles as the rate of damage dramatically increases as the microcracking progresses. The rate of this accelerated or tertiary damage is exacerbated in the presence of water as the pore pressure developed in the microcrack voids increases the rate of crack growth and damage through the development of higher pressures at the crack tip and through a weakening of the mastic and of the adhesive bond between the mastic and the aggregate.

Terrel and Al-Swailmi (1994) described the concept of pessimum air voids, which is the range of air void contents within which most asphalt mixtures are typically compacted (between about 8% and 10%). Above this level the air voids become interconnected and moisture can flow out under a stress gradient developed by traffic loading. Below this value the air voids are disconnected and are relatively impermeable and thus do not become saturated with water. In the pessimum range, water can enter the voids but cannot escape freely and is, thus, subjected to pore pressure buildup upon repeated loading.

Hydraulic Scour

Hydraulic scour occurs at the pavement surface. Here stripping results from the action of tires on a saturated surface. Water is sucked under the tire into the pavement by the tire action. Osmosis and pullback have been suggested as possible mechanisms of scour (Fromm 1974). Osmosis occurs in the presence of salts or salt solutions in aggregate pores and creates an osmotic pressure gradient that actually sucks water through the asphalt film. Researchers are mixed on support of this process. Mack (1964) supports it, while Thelen (1958) feels it is too slow to be valid. However, several factors support the potential occurrence of this mechanism, including the fact that some asphalts are treated with caustics during manufacture, some aggregates possess salts (compositionally), and asphalt films are permeable. In fact, Cheng et al. (2002) have demonstrated that the diffusion of water vapor through asphalt cement itself is considerable and that asphalt mastics can hold a rather surprisingly large amount of water. Table 2 compares the water vapor diffusion rates and the amount of water that can be accommodated by two compositionally very different asphalts (AAD-1 and AAM-1). They also showed that the amount of water held by these asphalts is related to the level of moisture damage that occurs in the mixtures using these asphalts.

pH Instability

Scott (1978) and Yoon (1987) demonstrated that asphalt–aggregate adhesion is strongly influenced by the pH of the contact water. Kennedy et al. (1984) investigated the effect of various sources of water on the level of damage that occurred in a boiling test. Fehsendfeld and Kriech (undated) observed that the pH of contact water affects the value of the contact angle and the wetting characteristics at the aggregate–asphalt interface region. Scott (1978) observed that the value of interfacial tension between asphalt and glass peaked at intermediate pH values, up to about 9, and then dropped as pH increased. Yoon (1987) found that the pH of contact water increased with duration of contact and was aggregate-specific and that the values stabilized after about 5 to 10 minutes of boiling. Yoon determined that the coating retention in boiling tests

TABLE 2 Effect of Moisture-Holding Potential of Asphalt on Moisture Damage in Triaxial Testing (After Cheng et al. 2002)

Parameter	Binder		Ratio, AAD-1/AAM-1
	AAD-1	AAM-1	
Diffusivity, m^2/s	0.0008	0.0029	
Water-holding potential, W_{100}, parts per 100,000	153	114	1.34
Percent debonding of binder from aggregate	34 (AAD/limestone) 35 (AAD/granite)	27 (AAM/limestone) 26 (AAM/granite)	1.26 1.35

decreased as pH increased. Kiggundu and Roberts (1988) point out that these results indicate that stabilization of the pH sensitivity at the asphalt–aggregate interface can minimize the potential for bond breakage; provide strong, durable bonds; and reduce stripping.

Tarrer (1996) concluded that (*a*) the bond between asphalt and aggregate depends on surface chemical activity, (*b*) water at the aggregate surface (in the field) is at a high pH, (*c*) some liquids used as antistrips require a long curing period (in excess of about 3 hours) to achieve resistance to loss of bond at higher pH levels, and (*d*) it is possible to achieve a strong chemical bond between aggregate and asphalt cement that is resistant to pH shifts and a high pH environment. This strong chemical bond can be achieved by the formation of insoluble organic salts (such as calcium-based salts), which form rapidly and are not affected by high pH levels or pH shifts.

Although pH shifts affect chemical bonds, it is important to keep the magnitude of the pH shifts in proper perspective. Normally pHs as high as 9 or 10 will not dislodge amines from the acidic surfaces of aggregates, nor will they affect hydrated lime. Values of pH greater than 10 are not normally developed in asphalt mixtures unless a caustic such as lime is added. However, pHs below about 4 can dislodge amines from an aggregate surface and can dissolve lime depending on the type of acid used; these low pHs are not found in hot-mix asphalt.

Environmental Effects on the Aggregate–Asphalt System

Terrel and Shute (1989) report that factors such as temperature, air, and water have a profound effect on the durability of asphalt concrete mixtures. In mild climates where good-quality aggregates and good-quality asphalt cements are available, the major contribution to deterioration is traffic loading and the resulting distress manifestations. Premature failure may result when poor materials and traffic are coupled with severe weather. Terrel and Al-Swailmi (1994) identify a number of environmental factors of concern: water from precipitation of groundwater sources, temperature fluctuations (including freeze–thaw conditions), and aging of the asphalt. They identify traffic and construction techniques, which are external to the environment, as important factors. Factors considered by Terrel and Shute to influence water sensitivity in asphalt mixtures are given in Table 3.

Adhesion Theories

Terrel and Shute (1989) describe four theories that are often used to explain the adhesion between asphalt and aggregate: (*a*) chemical reaction, (*b*) surface energy, (*c*) molecular orientation, and (*d*) mechanical adhesion. Most likely a combination of mechanisms occurs synergistically to produce adhesion, and no one theory describes adhesion. Terrel and Shute explain that the four theories are affected by the following factors: surface tension of the asphalt cement and aggregate, chemical composition of the asphalt and aggregate, asphalt viscosity, surface texture of the aggregate, aggregate porosity, aggregate cleanliness, and aggregate moisture content and temperature at the time of mixing with asphalt cement.

Chemical Reaction

Chemical reaction is based on the premise that acidic and basic components of both asphalt and aggregate react to form water-insoluble compounds that resist stripping. Rice (1958) suggests the possibility of selective chemical reactions between aggregate and asphalt species. Jeon et al. (1988) described chemisorption of asphalt functionalities on aggregate surfaces and quantified the amount of coverage using a Langmuir model. Thelen (1958) had previously proposed that a

TABLE 3 Factors Influencing Response of Mixtures to Water Sensitivity (After Terrel and Shute 1989)

Variable	Factor
Existing condition	Compaction method
	Voids
	Permeability
	Environment
	Time
	Water content
Materials	Asphalt
	Aggregate
	Modifiers or additives
Conditioning	Curing
	Dry versus wet
	Soaking
	Vacuum saturation
	Freeze–thaw
	Repeated loading
	Drying
Other	Traffic
	Environmental
	Age

bond formed by chemical sorption might be necessary in order to minimize stripping potential in asphalt–aggregate mixtures.

Robertson (2000) states that overall polarity or separation of charge within the organic molecules promotes attraction of polar asphalt components to the also polar aggregates. He explains that while neither asphalt nor aggregate has a net charge, components of both form nonuniform charge distributions and behave as if they have charges that attract the opposite charge of the other material. As established by Curtis et al. (1992), this is confounded by the fact that aggregates vary substantially in charge distribution and this charge distribution is affected by the environment. Robertson (2000) goes on to explain the types of reactions that might occur between the polar aggregate surface and asphalt cement. He states that, at a molecular level, basic nitrogen compounds (pyridines) adhere tenaciously to aggregate surfaces. He also describes carboxylic acids in asphalt cement. While they are quite polar and adhere strongly to dry aggregate, they tend to be removed easily from aggregate in the presence of water; but this varies with the type of acid. Plancher et al. (1977) explain that monovalent cation salts, such as sodium and potassium salts of carboxylic acids in asphalt, can be easily removed from the aggregate surface because they are essentially surfactants or soaps, which debond under the “scrubbing” action of traffic in the presence of water. On the other hand, Robertson (2000) indicates that divalent or doubly charged salts of acids (such as calcium salts from hydrated lime) are much more resistant to the action of water. This is also discussed by Scott (1978), Plancher et al. (1977), and Petersen et al. (1987). Robertson (2000) describes very recent observations at Western Research Institute (Williams et al. 1998) that indicate that aged asphalts may be much more prone to moisture damage than unaged asphalts. In some but not all asphalts, a very strongly acidic material appears with oxidation. Robertson (2000) indicates that if asphalt acids are converted to sodium salts (as can happen with some aggregates), a detergent will be formed.

However, calcium salts of detergents are far less moisture sensitive or are deactivated with lime. Robertson (2000) concludes by warning the user to ensure that the acids in asphalts are neither free nor in the form of monovalent salts.

Surface Energy and Molecular Orientation

From a simplistic viewpoint, surface energy may be described in terms of the relative wettability of aggregate surfaces by water or asphalt. Water is a better wetting agent than asphalt due to lower viscosity and a lower surface tension. However, the concept of using surface energy to calculate the cohesive strength of the asphalt mastic and the adhesive bond energy between aggregate and the asphalt cement or between aggregate and the mastic is a much more complex subject that is worthy of a more detailed discussion. This is presented in the section entitled "Nature of Asphalt–Aggregate Interaction."

Molecular orientation is coupled with surface energy because both are a part of a theory that considers structuring of asphalt molecules at the asphalt–aggregate interface and assumes that adhesion between asphalt and aggregate is facilitated by a surface energy reduction at the aggregate surface as asphalt is adsorbed to the surface (Hubbard 1938; Rice 1958; Sanderson 1952). Kiggundu and Roberts (1988) describe molecular orientation and surface energy as synergistic processes. They also mention the observations of researchers regarding surface phenomena. For example, Yoon (1987) and Tarrer (1996) described how aggregates that impart a relatively high pH to contact water or that have a relatively high zeta potential have a high stripping or debonding potential. Scott (1978) stated, "If water penetrates the asphalt film to the mineral aggregate surface under conditions where micro droplets form, the pH reached may be sufficient to ionize and dissociate adsorbed water molecules."

Mechanical Adhesion

This physical form of adhesion relies on physical aggregate properties, including surface texture, porosity or absorption, surface coatings, surface area, and particle size (Terrel and Al-Swailmi 1994). The philosophy is rather simple—to produce an aggregate surface capable of maximizing the surface area and texture to facilitate a strong physical bond that can synergistically improve the nature of the chemical bond between the asphalt and aggregate even in the presence of water. Aggregate properties that affect adhesion will be discussed in more detail later.

Cohesion Theories

Cohesion develops in the mastic and is influenced by the rheology of the filled binder. As will be discussed in more detail subsequently, Kim et al. (2002) describe how the resistance of a mastic to microcrack development is strongly influenced by the dispersion of mineral filler. Thus, the cohesive strength of the mastic is controlled not by the asphalt cement alone, but by the combination and interaction of the asphalt cement and the mineral filler. Terrel and Al-Swailmi indicate that water can affect cohesion in several ways, including weakening of the mastic due to moisture saturation and void swelling or expansion. Cohesion properties would logically influence the properties in the mastic beyond the region where interfacial properties dominate. A classic reminder of this is the work of Schmidt and Graf (1972), who show that an asphalt mixture will lose about 50 percent of its modulus upon saturation. The loss may continue with time, but upon drying, the modulus can be completely recovered. This is shown graphically in Figure 1.

Cheng et al. (2002) describe the severe weakening of asphalt mixtures when they are subjected to moisture conditioning. Figure 2 illustrates the strength loss in a repeated load triaxial test when subjected to 85% saturation. Cheng et al. (2002) indicate that this strength loss is predictable when one compares the wet adhesive bond strength between the asphalt and the aggregate with the much higher dry adhesive bond strength. But Cheng et al. (2002) go on to demonstrate that the rate of damage in various mixtures is also related to the diffusion of water into the asphalt mastic, and that the asphalts that hold the greatest amount of water accumulate damage at a faster rate.

Combining Theories

Kiggundu and Roberts (1988) attempted to combine some of the theories discussed above. They realized that no single theory properly explains moisture damage. They tabulated the primary and secondary contribution relationships in Table 4. This table attempts to relate theories that explain loss of adhesion to stripping mechanisms. For example, the mechanism of pH instability is, according to Kiggundu and Roberts, explained by both chemical reaction theory and physical and chemical components of interfacial energy theory. Detachment, as a second example, is believed by Kiggundu and Roberts to be explained by physical and chemical aspects of interfacial energy theory as well as physical aspects of mechanical interlock theory. The physical aspects are manifested, according to Kiggundu and Roberts, by surface energy, while the chemical aspects are contributed by the effect of polarity of the molecules present at the common boundary. Even with this attempt to simplify the interaction of different theories and mechanisms, the interactive complexity of the processes becomes clearly evident. For example, surface bond is not solely a physical process because surface bond is dictated by the chemical nature of bonding at the asphalt and aggregate surface as well as by the presence of broken bonds or incomplete coordination of atoms due to broken bonds resulting in an increase in free energy.

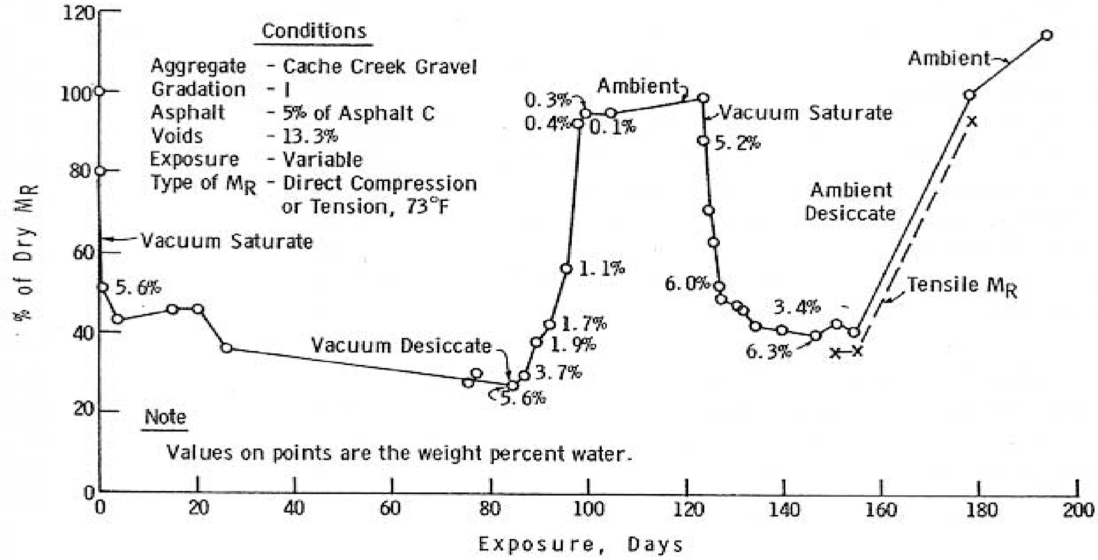


FIGURE 1 Effect of moisture on resilient modulus is reversible. (After Schmidt and Graf 1972.)

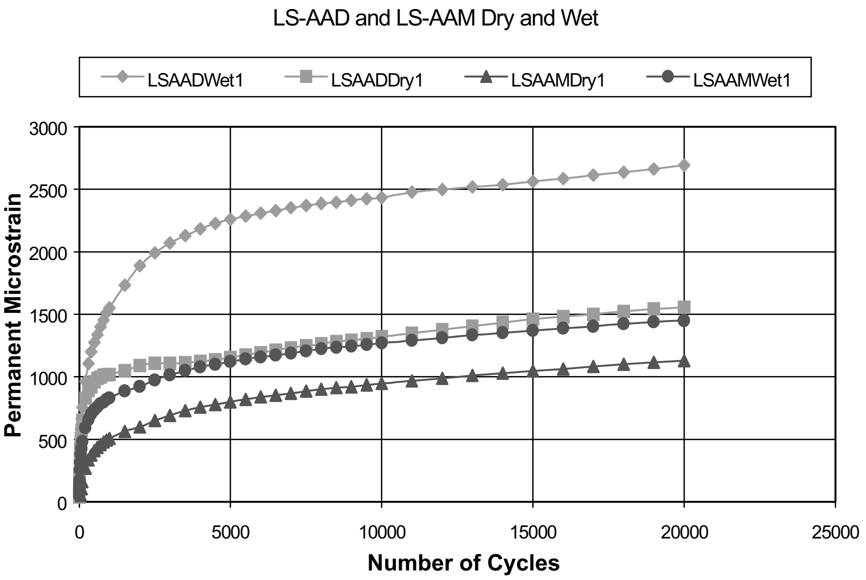


FIGURE 2 Repeated load permanent deformation experiments for AAD-limestone and AAM-limestone in the dry and wet conditions. (After Cheng et al. 2002.)

TABLE 4 Proposed Relationships Between Theories of Adhesive Bond Loss and Stripping Mechanisms (After Kiggundu and Roberts 1988)

		THEORY								
		Mechanical Interlock			Chemical Reaction			Interfacial Energy		
	Proposed Operating Mode	P	C	P-C	P	C	P-C	P	C	P-C
Stripping Mechanism	**Detachment**	S						S	W	
	Displacement					S		S		
	Spontaneous Emulsification				S	W				
	Film Rupture	S								
	Pore Pressure	S								
	Hydraulic Scouring	S								
	pH Instability					S				S

P = Physical
C = Chemical
P-C = Physical – Chemical
S = Primary Contributor
W = Secondary Contributor

NATURE OF ASPHALT–AGGREGATE INTERACTION

Adhesive Failure Versus Cohesive Failure

Damage in asphalt mixtures can occur within the mastic (cohesive fracture) or at the aggregate–mastic interface (adhesive fracture or failure). Whether or not a cohesive or adhesive failure occurs depends on the nature of the mastic and the relative thickness of the mastic around the coarse and fine aggregate. Lytton (personal communication, 2002) used micromechanics to assess the "thickness" of the asphalt film at which adhesive failure gives way to cohesive failure. Figure 3 is a plot of the cohesive and adhesive bond strength determined from cohesive and adhesive surface energies versus thickness of the asphalt binder or mastic. The theory essentially states that asphalt mixtures with thin asphalt films fail in tension by adhesive bond rupture, while those with thicker asphalt films (or mastic films) fail because of damage within the mastic (cohesive failure) as opposed to interfacial debonding. The thickness that differentiates these two types of failure is dependent on the rheology of the asphalt (or mastic), the amount of damage the asphalt or mastic can withstand prior to failure, the rate of loading, and the temperature at the time of testing.

Consider an example. According to Figure 3, when asphalt or mastic coatings are thin, adhesive strength controls performance. In this stage, the adhesive bond strength in the presence of water determines mixture strength and is the critical condition. On the other hand, when asphalt or mastic coatings are relatively thick, thicker than the transition point of Figure 3, cohesive properties limit or control damage resistance. Therefore, in this situation, the impact of moisture intrusion into the mixture may be the key to assessing moisture damage of the mixture. In this case it may be more important to consider the impact of how much moisture the mastic holds and the impact on rheology of this infused water (Table 1) than to consider adhesive bond strength in the presence of water.

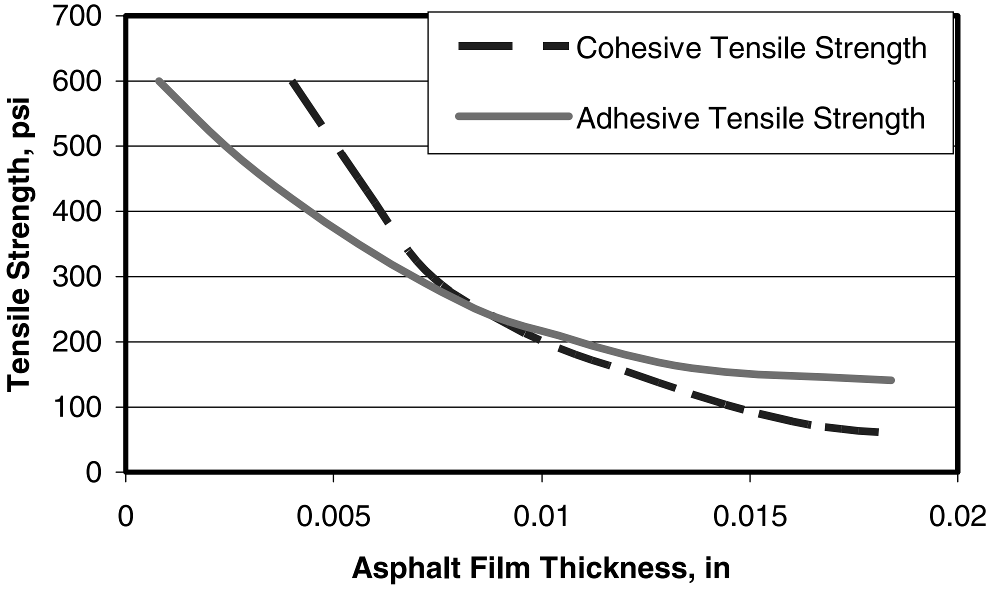


FIGURE 3 Adhesive versus cohesive bond failure based on asphalt film thickness.

Realistically, it is necessary to consider both adhesive bond and cohesive strength properties of the mixtures as mastic coatings range from relatively thin to relatively thick throughout the mixture. Mixture strength then becomes a question of the statistical distribution of conditions where adhesion or cohesion strengths control. Thus the effects of moisture on adhesive bond strength and cohesive mastic strength are perhaps equally important.

Kim et al. (2002) used dynamic mechanical analysis (DMA) testing to evaluate the rate of damage in asphalt binders and mastics. DMA subjects a cylindrical asphalt mastic to cyclic, torsional loading until failure occurs. Failure is due to the development and propagation of microcracks, which begin at the outer circumference of the cylindrical sample. Kim et al. (2002) demonstrated that the rate of damage and the amount of damage various mastics can accumulate before failure depend on the nature of the mastic. This is critically important because it essentially states that a mastic that is well designed will tolerate more damage prior to failure than one that is not. Kim et al. showed that mastics with the proper amount of and type of filler can accommodate more damage prior to failure than unfilled systems and that polymer-modified systems can accommodate more damage prior to failure than nonmodified systems. This indicates that the nature of the mastic (and the impact of the filler or modifier) strongly affects moisture damage because it helps control whether a cohesive or an adhesive bond failure occurs.

Figure 4 is a plot of accumulated dissipated pseudostrain energy (DPSE) versus number of torsional DMA load cycles to failure of representative mastics. The filled asphalts or mastics allow a higher accumulation of DPSE prior to failure than neat asphalt. The type of filler and its physicochemical interaction with the asphalt have a strong impact (Lesueur and Little 1999). The proposed mechanism of fatigue life extension is that properly designed mastics or modified asphalts affect the rate of microdamage accumulation and resist rapid, catastrophic failure via microcrack coalescence. The process may be a redistribution, redirection, or "pinning" of crack energy.

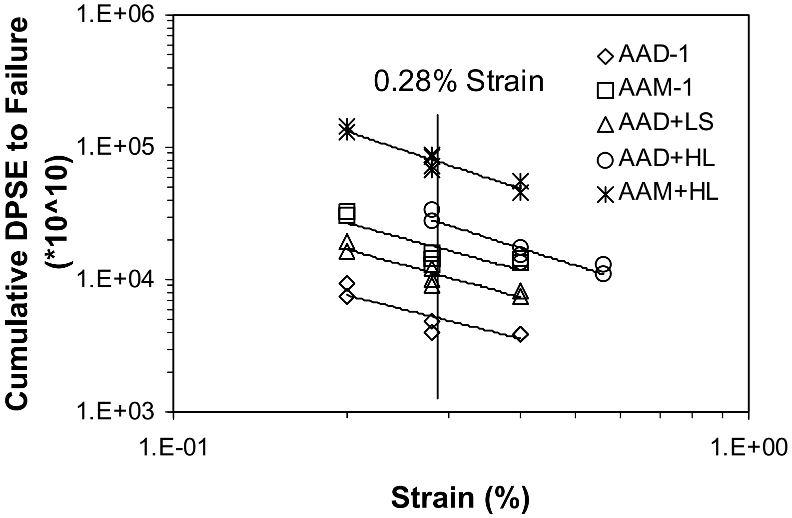


FIGURE 4 Relationship between cycles to failure (DMA) and DPSE for various mastics. (After Kim et al. 2002.)

Little et al. (1999) have shown that microcrack damage rates are related to cohesive mastic surface energies based on Schapery's viscoelastic fracture theory. Cohesive bond strength can be calculated on the basis of cohesive surface energy measurements of the dry or water-saturated mastic (Cheng et al. 2002). Moisture intrusion weakens the cohesive bond and makes the resulting mixture more susceptible to damage (Table 2).

Effect of Aggregate Characteristics

A general hypothesis has been that acidic aggregates are hydrophobic while basic aggregates are hydrophilic. However, there are notable exceptions (e.g., Majidzadeh and Brovold 1968; Maupin 1982). The general conclusion is that few if any aggregates can completely resist the stripping action of water (Tarrer and Wagh 1991).

Tarrer and Wagh (1991) list a number of factors that influence the asphalt–aggregate bond: surface texture, penetration of pores and cracks with asphalt, aggregate angularity, aging of the aggregate surface through environmental effects, adsorbed coatings on the surface of the aggregate, and the nature of dry aggregates versus wet aggregates.

Surface texture of the aggregate affects its ability to be properly coated, and a good initial coating is necessary to prevent stripping (Maupin 1982). Cheng et al. (2002) have demonstrated that the adhesive bond, calculated from basic surface energy measurements of the asphalt and aggregate, between certain granites and asphalt was higher than between limestone aggregate and asphalt when the bond was quantified as energy per unit of surface area. However, when the bond was quantified as energy per unit of aggregate mass, the bond energy was far greater for the calcareous aggregates than for the siliceous. These results agreed well with mechanical mixture testing. They point out clearly the importance of the interaction of the physical and the chemical bond. Besides the importance of a good mechanical bond promoted by an amenable surface texture, stripping has been determined to be more severe in more angular aggregates (Gzemski et al. 1968) because the angularity may promote bond rupture of the binder or mastic, leaving a point of intrusion for the water. Cheng et al. (2002) substantiate this as they have shown that, regardless of the strength of the bond between the asphalt and aggregate, the bond between water and aggregate is considerably stronger. Table 5 shows adhesive bond strengths calculated in ergs/cm^2 for five different liquids or semisolids (four binders and water) and three different aggregates. Note that the bond between water and either of the aggregates is at least 30% stronger than for any of the asphalts.

TABLE 5 Adhesive Bond Energy per Unit Area of Sample (ergs/cm^2) (After Cheng et al. 2002)

Binder	Aggregate		
	Georgia Granite	Texas Limestone	Colorado Limestone
AAD-1	153	141	124
AAM-1	198	205	179
Rubber asphalt	212	189	166
Aged rubber asphalt	171	164	145
Water	256	264	231

The effects of crushing of the aggregate are very interesting. One might expect that a freshly crushed aggregate surface would have a greater free energy than an uncrushed aggregate surface. This is because broken bonds due to fracture should substantially increase the internal energy even though having something of a countereffect on randomness (entropy increase). However, there is another side to consider. Tarrer and Wagh (1991) point out that sometimes newly crushed faces tend to strip faster than stockpiled aggregates. They state that it is characteristic of many aggregates that one or more layers of water molecules become strongly adsorbed on the aggregate surface as a result of electrochemical attractions. Thelen (1958) states that upon aging, the outermost adsorbed water molecules may become partially replaced or covered by organic contaminants present in air (e.g., fatty acids and oils) that reduce stripping potential. However, this seems unlikely because these fatty acids are relatively heavy and are not likely to volatilize. A general oxidation process reduces free radicals at the oxidation sites and may make weathered aggregates more resistant to stripping than freshly crushed aggregates. On the other hand, if the freshly crushed aggregate can be effectively coated with asphalt and the adsorption of the water layer can be prevented from the outset, the asphalt–aggregate bond developed may be the most effective. Certainly there is much room for advancement in the state of knowledge here.

Tarrer and Wagh (1991) and Hindermann (1968) discuss the effect of crushed aggregate surface on bond strength in light of the ways the aggregate surface may react to broken bonds created by crushing or cleavage. They discuss two potential reactions. In one, new coordination bonds may be formed by redirection inward to the atomic lattice. If this were the case, the aggregate would have no affinity for asphalt or water. This is a very unlikely process. In the second and more likely process, water, oil, or other contaminants in the air are attracted to the fresh surface to satisfy broken bonds. Since water is normally available, the driving force for the adsorption of water on the freshly crushed aggregate faces is that it reduces the free energy of the system. Although asphalts and other organics may also spread over the crushed faces of the aggregate, the rate at which they spread depends largely on their viscosity. Water is more prevalent and spreads much more quickly (Tarrer and Wagh 1991). Apparently, asphalt and organic materials spread over water films on an aggregate surface and tend to be stripped from water films by water (Tarrer and Wagh 1991), further complicating the process.

Clearly, Tarrer and Wagh (1991) make the case that heating aggregates that contain free water and adsorbed water films may remove free water and the outermost adsorbed water molecules, causing the interfacial tension between the aggregate and the asphalt to decrease (Thelen 1958; Majidzadeh and Brovold 1968), resulting in a reduction in stripping potential. The heating effect probably also reduces asphalt viscosity and allows better penetration into the aggregate surface, promoting a more effective physical bond.

According to Tarrer and Wagh (1991), the asphalt–aggregate bond is enhanced by three processes: (*a*) preheating the aggregate, (*b*) weathering the aggregate, and (*c*) removing aggregate coatings. When the aggregate surface is heated, the outermost adsorbed water layer is released, improving the state of interfacial tension between the asphalt and aggregate and, in turn, improving the bond between asphalt and aggregate. The weathering process results in a replacement of the adsorbed water layer with organic fatty acids from the air. This results in an improved asphalt–aggregate bond (Fromm 1974). A dust coating on the aggregate surface promotes stripping by preventing intimate contact between the asphalt and aggregate and by creating channels through which water can penetrate (Castan 1968).

Calculation of Asphalt–Aggregate Bond Strength

Fundamental Mechanisms

In 1984 Schapery proposed a basic viscoelastic fracture theory, which was derived from first principles of materials science and based on an energy balance. This theory states that the load-induced energy that causes fracture damage is balanced by the energy stored on newly formed crack faces. The energy imparted to the system can be quantified as the product of two properties of the materials in question: tensile creep compliance over the time of loading and the strain energy per unit of crack area produced from one tensile load to the next. The energy stored on fracture faces can be quantified by surface energy measurements of the material.

Fortunately, the material properties required to assess this energy balance can be effectively measured. Si et al. (2002) and Kim et al. (2002) demonstrate how to measure tensile creep compliance and the strain energy that causes damage (pseudostrain energy) during cyclic fatigue testing of asphalt mixtures. This concept of pseudostrain energy is not mysterious; it is merely a mathematical calculation that allows one to separate the dissipated energy that actually causes damage from the energy that is recovered over time and does not cause damage. Surface energies can also be measured. Cheng et al. (2001; 2002) have demonstrated how surface energy measurements on the aggregate and asphalt cement can be used to calculate surface energies of cohesion (related to fracture within the mastic—asphalt and filler) and adhesion (related to fracture at the asphalt–aggregate interface).

Using this fundamental look at fracture damage, it is easy to relate surface energy to pavement distress and to understand the wide-ranging importance of surface energy as an indicator of distress in asphalt pavements. Obviously, surface energy can be used to directly assess fracture potential: both cohesive and adhesive. But surface energy is also related to permanent deformation distress, the fatigue failure process, and cohesive strength reduction and adhesive failure (stripping) in the presence of moisture. It is important to briefly develop this connection.

As previously described, Bhairampally et al. (2000) used a tertiary damage model developed by Tseng and Lytton (1987) to demonstrate that well-designed asphalt mixtures tend to "strain harden" upon repeated loading. As previously discussed, this microcracking or tertiary damage leads to a departure from the typical "strain hardening" stress–strain curve representing an accelerated rate of damage due to the development of microcracking and the ultimate acceleration of microcrack growth. Cheng et al. (2002) have shown that the acceleration in damage, or tertiary damage, is related to cohesive and adhesive bond strengths of the mastic and asphalt mixtures in question. Table 1 presents the strong relationship between the number of cycles to failure in repeated load permanent deformation testing and cohesive and adhesive bond energies (which were calculated from bitumen and aggregate surface energy measurements). In Table 1 the free energy of adhesion in the presence of water is calculated. The negative sign indicates a preference of the aggregate for water over asphalt, and a less negative value represents a lower driving force to replace the asphalt in question with water. Thus it is consistent that asphalt AAM bonds more strongly with either the limestone or granite aggregate than asphalt AAD and that it is less likely to strip.

Two back-to-back studies for the Federal Highway Administration performed at Texas A&M University's Texas Transportation Institute have established the importance of the healing phenomenon in the fatigue damage process. Field validation of healing that occurs during rest periods was presented by Williams et al. (1998). Here the researchers measured a substantial recovery in modulus via surface wave measurement following rest periods. Little et al. (1999), Kim et al. (1997), Kim et al. (2002), and Si et al. (2002) measured the healing effect during repeated load tensile and torsional shear fatigue testing. They quantified the effect of healing in terms of recovery of dissipated energy during the rest period and in terms of extended fatigue life due to the cumulative effect of a number of rest periods. Little et al. (1999) further established that the healing process is composed of a short-term effect governed by the Lifshitz–Van der Waals component of surface energy and a long-term effect governed by the acid–base component of surface energy. All of these studies are consistent in their findings that a higher acid–base component of surface energy and a lower Lifschitz–Van der Waals component of surface energy produce a superior healing asphalt. Each of the studies referenced provide consistent and convincing experimental data substantiating this assertion.

The fact that surface energy of dewetting is fundamentally related to fracture and that surface energy of wetting is fundamentally related to healing is discussed by Little et al. (1998) and Little et al. (1999). In fact, Schapery presented a corollary to his viscoelastic fracture theory for healing in which he related long-term healing to surface energy and found that an increase in surface energy resulted in better healing. After studying the results of a large experimental matrix comparing surface energy with healing rate plots, Lytton discovered that healing has two components: short term and long term. He determined that the short-term healing rate (and magnitude) is inversely correlated with the Liftshitz–Van der Waals component of surface energy while the long-term healing rate (and magnitude) is directly related to the acid–base component of surface energy. When this is coupled with Schapery's theory of viscoelastic fracture, a much more complete understanding of the entire fracture fatigue process is achieved, because the fatigue process consists of fracture during loading and healing during rest periods between load applications. Lytton et al. (1993) showed that the healing process is responsible for the major component of the laboratory-to-field fatigue shift factor. Since this shift factor historically ranges between about 3 and more than 100, healing is indeed a significant part of the fatigue damage process.

A logical extension can be made from understanding adhesive fracture based on surface energy to understanding the debonding process between bitumen and aggregate in the presence of moisture (stripping). Cheng et al. (2002) present a detailed methodology by which to measure the surface energies (all components) of asphalt using the Wilhelmy plate method and the surface energies of aggregates (all components) using the universal sorption device (USD). They then show how to compute the adhesive bonding energy between the bitumen and the aggregate both in a dry state and in a wet state (in the presence of a third medium—water). Table 5 (Cheng et al. 2002) demonstrates that the adhesive bond calculated per unit area of aggregate is highly dependent on the aggregate and asphalt surface energies and that the values of the adhesive bond vary over a significant range. They further point out that the affinity of the aggregate for water is far greater than it is for asphalt, so that if water has access to the aggregate interface it is likely to replace the asphalt (strip), and the rate of replacement is a function of the aggregate–asphalt bond strength. In Table 6 the same results are presented in terms of energy per unit mass instead of energy per unit area. Energy per unit mass takes the surface area into account. This is shown to be very important as the rank order of adhesive bond energy changes when this conversion is made. The far greater surface area of the limestone ranks it ahead of the granite in terms of bonding energy per unit mass even though this particular granite actually has a higher bonding energy per unit area.

TABLE 6 Gibbs Free Energy per Unit Mass (ergs/gm × 10^3)
(After Cheng et al. 2002)

Binder	Aggregate		
	Georgia Granite	Texas Limestone	Colorado Limestone
AAD-1	158	614	375
AAM-1	206	889	536
Rubber asphalt	219	819	497
Aged rubber asphalt	178	714	435

Cheng et al. (2002) also measured the diffusivity and moisture-holding potential of various bitumens using the USD. Lytton developed a method by which to solve Fick's second law to differentiate adsorption from absorption in the sorption process so that diffusivity and moisture-holding potential could be determined. Using this approach, Cheng et al. (2002) found that diffusivity and water-holding potential vary significantly among bitumens and that the ultimate water-holding potential is related closely to damage. For example, asphalt AAD-1 has a lower diffusivity than asphalt AAM-1, but it has much greater water-holding potential (Table 2). This leads to a much higher level of damage in mixtures with AAD-1 than in mixtures with AAM-1. This damage may be due to two factors: the weakening of the mastic due to diffusion of water into the bitumen and the migration of water through the mastic to the mastic–aggregate interface causing stripping.

Fundamental Principles Shared by Material Processes

The preceding section points out that surface energy can be fundamentally related to material processes and failure mechanisms. From this background a set of principles can be established that can be used to measure material properties required to assess the basic distress processes. These principles are as follows:

1. All materials have surface energies, both asphalts and aggregates.
2. All surface energies have three components, all of which can be measured.
3. The theory of adhesive and cohesive bonding has been developed in industrial surface chemistry and chemical engineering and is used reliably and with confidence.
4. Fracture and healing involve two types of material properties: chemical and physical. Neither fracture nor healing can be properly described without the use of both properties: *chemical*—surface energies; *physical*—modulus and tensile strength and the way they change with age.
5. The presence of moisture at the asphalt–aggregate interface interrupts the bond and accelerates the rate of fracture damage. The presence of moisture in the mastic reduces cohesive strength and fracture resistance and, therefore, reduces the potential for microcracks in the mastic to heal.
6. On the basis of their surface energy characteristics, some combinations of aggregates and asphalts can be determined by calculations to bond well and heal well, whereas other combinations will not. In selecting materials for an asphalt pavement mixture from among

several available alternatives, it will always be possible to select the best combination of all of the available aggregates and asphalts to resist fracture, heal, bond well, and resist moisture damage. Predicting their performance will require the measurement of physical properties as well.

Effect of Asphalt Composition on Adhesion

Asphalt Composition

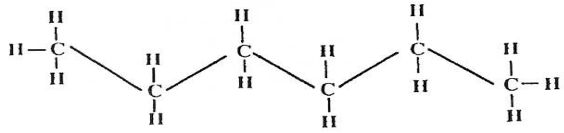
The chemistry of asphalt is complex. This brief overview is certainly a simplification of the complex nature of asphalt and is meant to provide (*a*) definitions of basic terms and (*b*) descriptions of basic asphalt components, which are used in discussion throughout this paper.

Elemental Composition

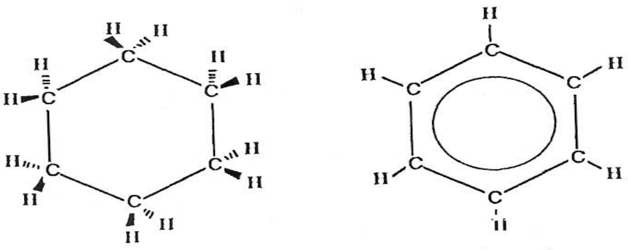
Asphalt molecules are comprised primarily of carbon and hydrogen (between 90% and 95%) by weight. However, the remaining atoms, called heteroatoms, are very important to the interaction of asphalt molecules and hence the performance of asphalt. They include oxygen, nitrogen, sulfur, nickel, vanadium, and iron.

Molecular Structure

Asphalt atoms are linked together to form molecules. Perhaps the simplest is the aliphatic carbon–carbon chain saturated with hydrogen bonds. The carbon–carbon bonds can also form rings saturated with hydrogen. These saturates are essentially nonpolar and interact primarily through relatively weak Van der Waals forces. A second class of asphalt molecules involves aromatics. This molecule has six carbon atoms in the form of a hexagonal ring. This ring possesses a unique bond with alternating single and double bonds between carbon atoms. Figure 5 shows representative examples of saturates (aliphaltic and cyclic) and aromatic structures.



Aliphatic
(Hexane, C_6H_{14})



Cyclic
(Cyclohexane, C_6H_{12})

Aromatic
(Benzene, C_6H_6)

FIGURE 5 Types of asphalt molecules. (From Jones 1992.)

Bonds Among Asphalt Molecules

Strong covalent bonds link atoms together to form asphalt molecules. These molecules interact with one another through much weaker bonds (Jones 1992): pi–pi bonds, hydrogen or polar bonds, and Van der Waals bonds. These are represented in Figure 6.

Pi–pi bonds are unique to aromatic molecules. They provide polarity and the ability of aromatic molecules to link together in unique configurations, including a stacked arrangement as shown in Figure 6. Heteroatoms among asphalt molecules develop polarity and link together by forming hydrogen bonds. Figure 6 shows a hydrogen bond between two very important asphalt functional groups: a sulfoxide and a carboxylic acid. Van der Waals bonding is the weakest of the secondary bonds. They form when molecules cool or stress is removed. Van der Waals bonding is responsible for the free-flowing nature of asphalt at high temperatures versus the semisolid nature at lower temperatures (Jones 1992). As a point of reference, it is important to understand that covalent primary bonds within the molecule are from 10 to 100 times stronger than secondary bonds.

Polar Versus Nonpolar Molecules

Polar molecules form “networks” through hydrogen and pi–pi bonds that give asphalt its elastic properties. Nonpolar materials form the body of the material in which the network is formed and contribute to the viscous properties of asphalt (Jones 1992). Degree of polarity is the most important property of polar molecules, while degree of aromaticity is the second most important. Highly polar and highly aromatic molecules form the most interactive and strongest molecular networks.

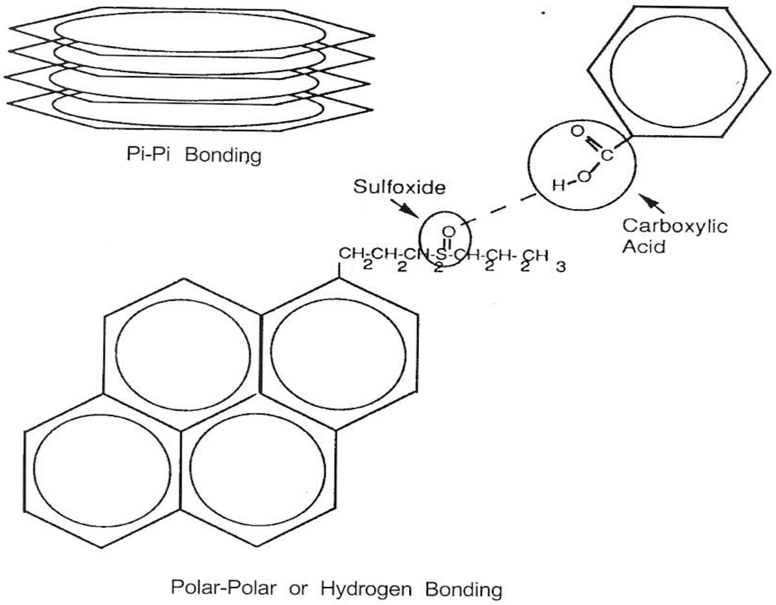


FIGURE 6 Types of intermolecular asphalt bonds. (After Jones 1992.)

Nonpolar molecules do not interact strongly enough to form networks, but they do substantially influence asphalt performance. The molecular weight of nonpolar molecules is related to low temperature performance (Jones 1992). A preponderance of high-molecular-weight nonpolar molecules will lead to asphalts that stiffen and perform poorly at low service temperatures. If nonpolars are waxy, they will crystallize at low temperatures and become crack susceptible.

Nonpolar and polar molecules must interact in an acceptable manner or be "compatible." If polar and nonpolar molecules are relatively similar in chemistry, they will be compatible; however, if they are very different, the polar network will not stay in solution, and phase separation can be a substantial problem.

Asphalt Model

Jones (1992) explains the history of development of an asphalt model. He describes how analytical techniques including size exclusion chromatography and ion exchange chromatography have led to viewing asphalt as a two-phase system. The polar molecules interact with each other through polar–polar or hydrogen bonding. These bonds form associations that create a network within the nonpolar solvent molecules. However, as explained by Jones, both phases make a significant contribution to asphalt performance. Figure 7 illustrates the model described by Jones (1992)—the Strategic Highway Research Program (SHRP) model.

The associations of polar molecules are due to polar sites on the asphalt through hydrogen bonding. Other interactions take place through pi–pi bonding and Van der Waals bonding. These interactions provide the major contribution to viscoelastic properties of the asphalt. Actually, the term phase is not accurate in the description of polar versus nonpolar components because the mixture is homogeneous and the bonds between the polar molecules are rather weak and form and break constantly.

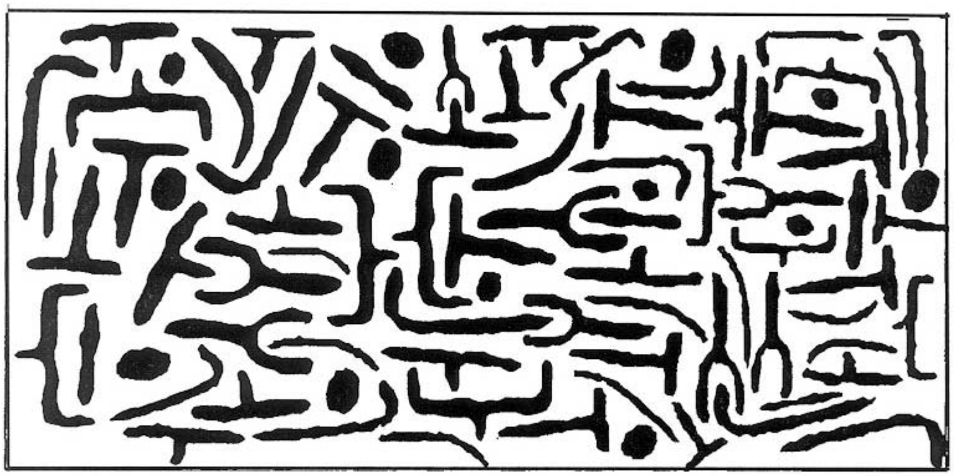


FIGURE 7 SHRP asphalt model. (After Jones 1992.)

Multifunctional Organic Molecules

Data show that having two or more functional groups on the same molecule makes it possible to form chains of weak polar–polar interactions. According to Jones (1992), these chains are the foundation of the polar networks. An example of a multifunctional organic molecule is one with both a carboxylic acid (R-COOH) and a sulfoxide (S=O) on the same molecule. Figure 8 is an example of two multifunctional organic molecules. The first one contains three heteroatoms in its structure: a phenol group (O-H), a sulfoxide (S=O), and a ketone (C=O). The second example is a linear chain molecule that contains a carboxylic acid (R-COOH) and a mercaptan (SH) group.

Multifunctional organic molecules have a major impact on aging. This is because for polar molecules to generate significant physical changes, it is necessary for them to interact in chainlike structures or form networks. Figures 9 and 10 illustrate how oxidation of molecules with a single active site results in a "quenching" of the effect of oxidation, while the oxidation of molecules with multiple active sites develops a continuous network.

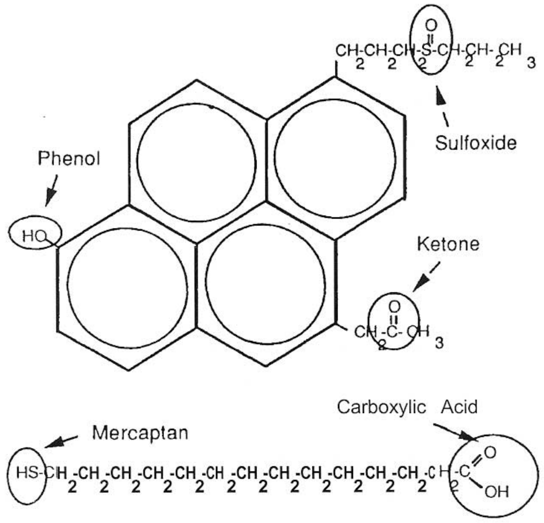


FIGURE 8 Types of multifunctional organic molecules. (After Jones 1992.)

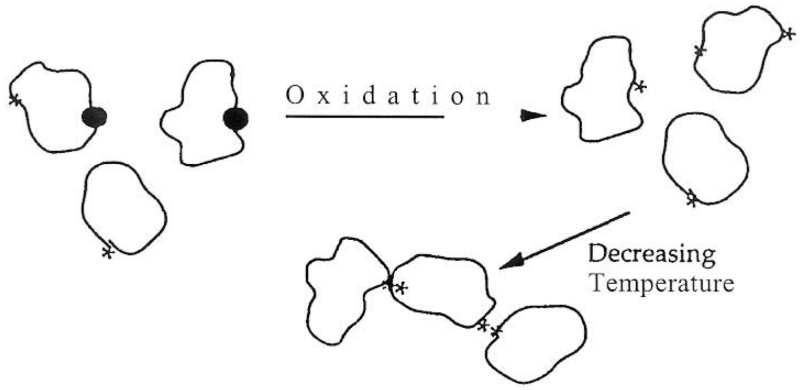


FIGURE 9 Asphalt with simple active sites. (After Jones 1992.)

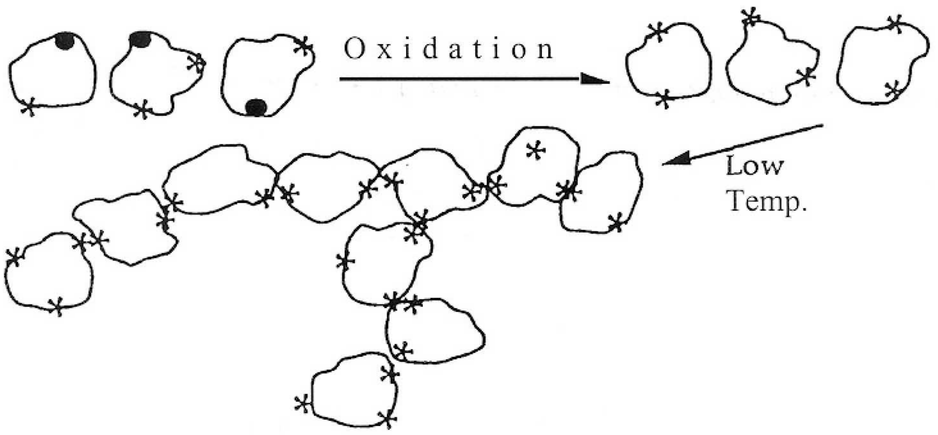


FIGURE 10 Asphalt with multiple active sites. (After Jones 1992.)

Asphalt Chemistry and Adhesion
Polarity or separation of charge within the organic molecules promotes attraction of polar asphalt components to the polar surfaces of aggregates. Although neither asphalt nor aggregate has a net charge, components of both have nonuniform charge distributions, and both behave as if they have charges that attract the opposite charge of the other material. Curtis et al. (1992) have shown that aggregates vary widely in terms of surface charge and are influenced by environmental changes. Robertson (2000) points out that adhesion between asphalt and aggregate arises between the polars of the asphalt and the polar surface of the aggregate. He also points out that polarity alone in asphalt is not sufficient to achieve good adhesion in pavements because asphalt is affected by the environment. Robertson (2000) further states that asphalt has the capability of incorporating and transporting water. Absorption of water varies with asphalt composition and changes further as asphalt is oxidized. Cheng et al. (2002), as discussed previously, have shown that a substantial quantity of water can diffuse through and be retained in a film of asphalt cement or an asphalt mastic, substantially changing the rheology of the binder. Robertson (2000) states that at the molecular level in asphalt, basic nitrogen compounds (pyridines) tend to adhere to aggregate surfaces tenaciously. Carboxylic acids are easily removed from aggregate in the presence of water if the acids form a monovalent salt by interaction at the aggregate surface, but divalent (calcium) salts of acids are much more resistant to the action of water.

Curtis (1992) ranked the affinity of various asphalt functional groups to bond to aggregate surfaces by using adsorption isotherms (UV adsorption spectroscopy). In general she found acidic groups, carboxylic acids, and sulfoxides to have the highest adsorptions, while ketone and nonbasic nitrogen groups had the least. However, the sulfoxide and carboxylic acids were more susceptible to desorption in the presence of water. According to Curtis (1992), the general trend of desorption potential of polar groups from aggregate surfaces is sulfoxide > carboxylic acid > nonbasic nitrogen ≥ ketone > basic nitrogen > phenol.

Effect of Aggregate Properties on Adhesion

A number of aggregate properties affect the adhesive bond between asphalt and aggregate: size and shape of aggregate, pore volume and size, surface area, chemical constituents at the surface, acidity and alkalinity, adsorption size surface density, and surface charge or polarity.

Pore Volume and Surface Area

Yoon and Tarrer (1988) investigated five aggregates (granite, dolomite, chert gravel, quartz gravel, and limestone). They measured pore volume, surface area, average pore size, and percentage coating after boiling. Their study showed that stripping resistance is defined by the level of physical bond that is achieved between the asphalt and aggregate, and this is, in turn, defined by surface area, pore volume, and pore size. The optimal resistance to stripping was developed in aggregates that provide a large surface area for bonding as well as a favorable pore size for adequate (deep) asphalt penetration. This is probably because when asphalt cement coats a rough surface with fine pores, air is trapped and the asphalt has difficulty penetrating the fine pores (Yoon and Tarrer 1988). However, the penetration of asphalt cement into pores is synergistically dependent not only on the pore structure but also on the viscosity of the asphalt cement at mixing temperatures.

Yoon and Tarrer (1988) also determined that aggregates with approximately equal physical properties (e.g., pore volume and structure and surface area) can have very different properties depending on their basic chemistry and mineralogy, which define surface activity. Yoon and Tarrer found substantially higher bonding power for limestone than for quartz gravel even though both had similar physical surface structures. The results of Cheng et al. (2002) were very similar; they found that a certain granite aggregate has a much higher surface energy per unit area than a certain limestone, but when bonding energy was computed in terms of unit mass instead of unit surface area (incorporating effects of surface area), the limestone was predicted to have a much greater potential to resist damage in repeated loading tests of asphalt samples at 85% saturation.

pH of Contacting Water

Hughes et al. (1960) and Scott (1978) reported that adhesion between asphalt cement and aggregate in the presence of water became weakened when the pH of the buffer solution was increased from 7.0 to 9.0 (Scott 1978). Yoon and Tarrer (1988) showed that if different aggregate powders (chert gravel, quartz sand, quartz gravel, granite, limestone, and dolomite) were added to water and allowed to react with water for up to about 30 minutes, the pH of the blend will increase to some asymptotic value (Figure 11). Even granite, known to be acidic, showed an increase in pH over time to about 8.8. The granite reaction in water, which leads to this gradual pH increase, is, according to Yoon and Tarrer, due to the silicate lattice reaction with the water to impart excess hydroxyl ions as follows:

$$\begin{array}{cccccccccccccc} & | & & & & & | & & & & & & & \\ - & S & - & O & - & Na & + & H_2O & \rightarrow & -SiOH & + & Na^{+} & + & OH^{-} \\ & | & & & & & | & & & & & & & \end{array} \qquad (1)$$

This is a typical hydrolytic reaction of the salt of a weak acid.

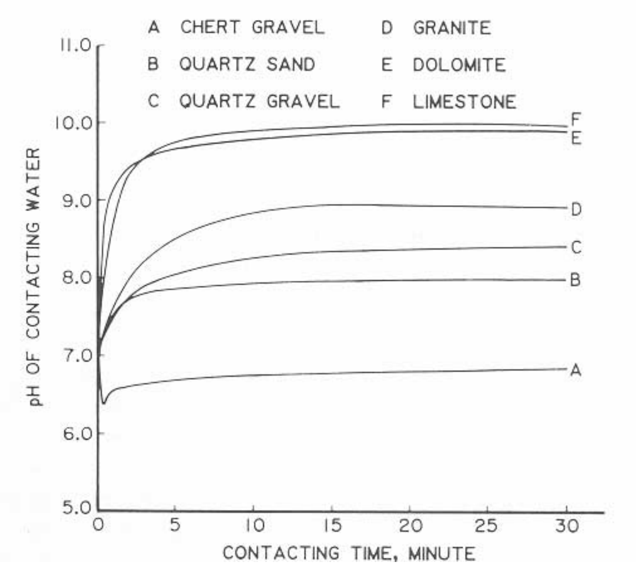


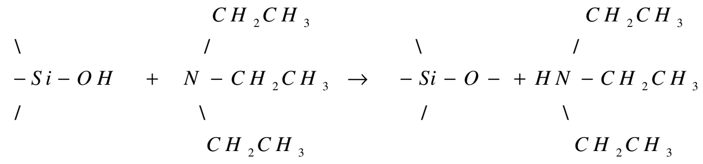
FIGURE 11 Changes in pH of water in which aggregates were immersed. (After Yoon and Tarrer 1988.)

Yoon and Tarrer (1988) assessed the sensitivity of stripping to changes in pH of water in contact with the aggregate surface. They performed boiling stripping tests to verify the sensitivity. The pH of the water was modified by using a solution of HCl or NaOH. The stripping became more severe as the pH increased. Yoon and Tarrer explain that when an aggregate is being coated with asphalt, the aggregate selectively adsorbs some components of the asphalt—the more polar compounds and hydrogen bonds or salt links are formed. Obviously, the type and quantities of the adsorbed components affect the degree of adhesion. Yoon and Tarrer state that the presence of ketones and phenolics is thought to improve stripping resistance, whereas carboxylic acids, anhydrides, and 2-quinolenes are thought to increase stripping sensitivity because of the substantial water susceptibility of the associated bonds.

According to Yoon and Tarrer (1988), the water susceptibility of the hydrogen bonds and salt links between the adsorbed asphalt components and the aggregate surface would increase as the pH of the water at the aggregate surface increases. Therefore, it seems reasonable to conclude that stripping sensitivity will increase as the pH of the water increases. Experimental results of Yoon and Tarrer (1988) substantiate this hypothesis. However, they warn that other surface aggregate properties also play a role. Different types of metal ions affect stripping potential. For example, alkaline earth metals in limestone associate strongly with the asphalt components in carboxylic acids to form alkaline earth salts, and the bonds formed are not dissociated easily in water even at a high pH. In other words, the adsorption is strong because of the insolubility of the alkaline earth salts formed between the limestone and the bitumen acids.

The addition of hydrated lime offers a mechanism to tie up carboxylic acids and 2-quinolenes so they cannot interact with hydrogen bonding functionalities on the aggregate surface to produce moisture-sensitive bonds. Thomas (2002) points out that the interaction of lime with components in the asphalt not only prevents the formation of moisture-sensitive bonds but also subsequently allows more resistant bonds (e.g., with nitrogen compounds from the asphalt) to proliferate. He points out that an additional benefit of the use of lime is to react with or adsorb compounds that can be further oxidized and enhance the increase in viscosity as a result of oxidation. In fact, experiments at Western Research Institute (2002) show a substantial improvement in moisture resistance after severe freeze–thaw experiments when lime is added directly to the bitumen and before the bitumen is coated on the aggregate. Western Research Institute is currently studying the effect of bonds between the aggregate surface and bitumen components including sulfonic acids, ketones, and 2-hydroquinolines on moisture damage.

In a manner similar to the reaction between acidic compounds such as carboxylic acids in asphalt and alkaline aggregate or with lime, an amine compound either if present in asphalt or added in the form of an antistripping additive will react with acidic surfaces as in the case of siliceous aggregates to form a surface compound. Evidence of the formation of such a surface compound between siliceous surfaces and amine compounds was demonstrated by Titova et al. (1987).

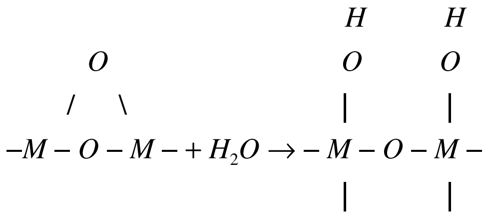


$$\underset{/}{\overset{\backslash}{-Si-OH}} \;+\; \underset{\underset{CH_2CH_3}{\backslash}}{\overset{\overset{CH_2CH_3}{/}}{N}}-CH_2CH_3 \rightarrow \underset{/}{\overset{\backslash}{-Si-O-}} \;+\; \underset{\underset{CH_2CH_3}{\backslash}}{\overset{\overset{CH_2CH_3}{/}}{HN}}-CH_2CH_3$$

Silica,Triethylamine compound
Stable > 900°F in Vacuum

Surface Potential

Interfacial activity between asphalt cement and the aggregate surface is fundamentally important in assessing stripping potential. Yoon and Tarrer state that the functional groups of asphalt that are adsorbed on the aggregate surface come mainly from the acid fraction of the asphalt. Yoon and Tarrer offer the example of carboxylic acid (R-COOH), which in the presence of water separates into the carboxylate anion ($R\text{-}COO^-$) and the proton (H^+). This causes the asphalt surface to have a negative polarity at the interface. Aggregates with water present are negatively charged, and as a result, a repulsive force develops between the negatively charged aggregate surface and the negatively charged asphalt surface at the interface. Payatakis (1975) states that solid surfaces in contact with water usually acquire changes through chemical reactions at the solid surface and adsorption of complex ions from the solution. For example, metal oxide surfaces in water hydrolyze to form hydroxyl groups:



$$-\overset{\overset{O}{/\quad\backslash}}{M-O-M}- + H_2O \rightarrow -\underset{|}{\overset{\overset{\overset{H}{O}}{|}}{M}}-O-\underset{|}{\overset{\overset{\overset{H}{O}}{|}}{M}}- \qquad (2)$$

which subsequently dissociate as

$$-M-OH \leftrightarrow -M^{+} + {}^{-}OH \quad (3)$$

A high pH value of the water in contact with the mineral surface will cause the surface to be more negatively charged.

Yoon and Tarrer (1988) report that the intensity of the repulsion developed between the asphalt and aggregate depends on the surface charge of both the asphalt and aggregate. They used zeta potential as a method to measure aggregate surface charge and found a general trend that aggregates that have a relatively high surface potential in water are more susceptible to stripping (see Figure 12).

SHRP Research on Aggregate Surface Chemistry

General

Labib (1991) confirmed the existence of a range of acid–base types among various SHRP aggregates using zeta potential measurements and electrophoretic mobility. He reported that it is significant that the initial pH of aggregates was greater than 9.0, irrespective of aggregate type. This would neutralize the bitumen carboxylic acids at the interface and cause hydrolysis of bitumen–aggregate bonds. The high pH was attributed to basic soluble salts even in acidic aggregates.

Labib (1991) documented the sensitivity of the bitumen–aggregate bond to pH. He identified three pH regions. At pHs above about 8.5 (Region 3), dissolution of the surface silica occurred in quartz or silica aggregates. In carbonate-based aggregates at pHs between about 1 and 6 (Region 1), calcium ion dissolution occurred, and the presence of carboxylic acids enhanced stripping in this region through cohesive failure in the aggregate. Podoll et al. (1991)

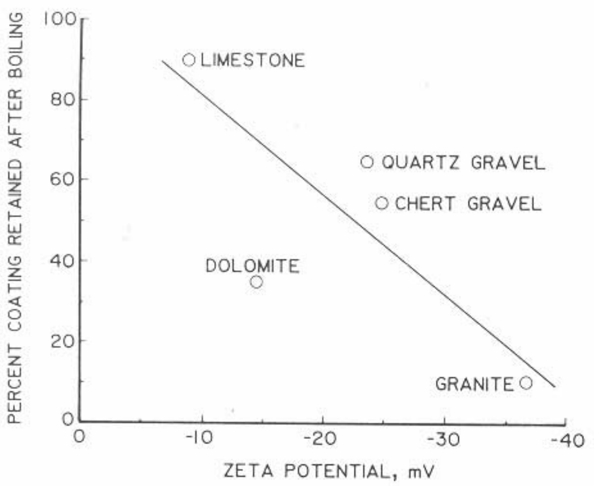


FIGURE 12 Comparison of aggregate surface potential and stripping propensity as determined by the boiling water tests. (After Yoon and Tarrer 1988.)

used surface analysis by laser ionization to confirm that bitumen–aggregate bond disruption occurs within the aggregate and not at the interface. They found notably less sodium, potassium, and calcium in the top monolayer of aggregate in stripped areas than in unstripped areas. This indicates that dissolution of the cations was greater where bitumen had been stripped away. Scott's (1978) work on bitumen-coated glass slides supports Podoll et al. He found that debonding occurred in the more water-soluble glasses and not in the more stable opal glasses.

Jamieson et al. (1995) conclude that net adsorption of bitumen on aggregate is a function of five aggregate variables: potassium oxide, surface area, calcium oxide, zeta potential, and sodium oxide. Alkali earth metals (sodium and potassium) are detrimental to adhesion. Higher surface area provides more active sites per unit mass for interaction. Calcium forms water-resistant bonds, and aggregates with a more negative surface charge may provide more potential for adsorption.

SHRP Adhesion Model

The SHRP adhesion model concludes that aggregate properties have a greater impact on adhesion than do various binder properties. Adhesion is achieved mainly by polar constituents in the bitumen bonding with active aggregate sites through hydrogen bonding, Van der Waals interaction, or electrostatic forces. The general trend is that sulfoxides and carboxylic acids have the greatest affinity for aggregates. However, in the presence of water, sulfoxides and carboxylic acid groups are more susceptible to debonding, whereas phenolic groups and nitrogen bases are more effective in providing a durable bond (Jamieson et al. 1995). It is also apparent that aromatic hydrocarbons have much less affinity for aggregate surfaces than the polar groups.

SHRP Stripping Model

The SHRP view is that stripping is controlled by cohesive failure within the aggregate rather than at the bitumen–aggregate interface (Jamieson et al. 1995). Surfaces rich in alkali metals are more susceptible to debonding than surfaces rich in alkaline earth metals because the latter form water-insoluble salts with acid and other groups with the bitumen.

Podoll et al. (1991) state that stripping of siliceous aggregate may be associated with the presence of water-soluble cations and aluminosilicates. The mechanism is probably dissolution of salts, dissociation of silica due to the high pH environment generated by solubilization of alkaline earth cations, electrostatic repulsion between negatively charged aggregates and ionic components of the bitumen at the surface, and dissolution of soaps formed between acid anions on the bitumen surface and alkali metal cations on the aggregate surface.

The superior stripping resistance of some limestones is due to the formation of water-insoluble (covalent) bonds between calcium sites on the aggregate and bitumen constituents, but stripping of calcareous aggregate can occur where their water solubility is high.

WAYS TO IMPROVE ADHESION

Interaction of Acidic Aggregates and Asphalt with Alkaline Amine Compounds

Amines have a long hydrocarbon chain. The chain is compatible in asphalt cement, and, in the presence of water, the amine is ionized to form an amine ion, $R\text{-}NH_3$, which has a positive charge (cationic). The physical properties of fatty amines can be altered by changing the nature of the hydrocarbon chain while the chemical nature can be altered by changing the number of amine groups and their positions in the molecule (Porubszky et al. 1969). Taken together, the chain length and number of amine groups greatly influence the adhesion of the asphalt. Optimum performance is typically achieved with 14 to 18 carbon chain amines with one or two amine groups (Porubszky et al. 1969; Tarrer and Wagh 1991).

Fatty amines enable asphalt to wet aggregate surfaces. The amine group reacts with the aggregate surface while the hydrophobic hydrocarbon chain of the fatty amine is anchored in the asphalt. The net effect (Tarrer and Wagh) is that the long hydrocarbon chain acts as a bridge between the hydrophilic aggregate and the hydrophobic bitumen surface, encouraging a strong bond.

Effect of Hydrated Lime on Adhesive Bond

Plancher et al. (1977) hypothesized that hydrated lime improved binder–aggregate adhesion by interacting with carboxylic acids in the asphalt and forming insoluble salts that are readily adsorbed at the aggregate surface. This is an important reaction because hydroxyl (OH) groups are found on the surfaces of siliceous aggregates. These SiOH groups form hydrogen bonds with carboxylic acid groups from asphalt and strongly affect the adhesion between the asphalt and aggregate (Hicks 1991). But this hydrogen bond is quickly broken in the presence of water, and the two groups dissociate and reassociate with water molecules through hydrogen bonding. This means that the hydrogen bonding between the water molecules and the SiOH group and between the water molecule and the COOH group is preferred over the bond between SiOH and COOH.

When lime is added, some dissociation of the $Ca(OH)_2$ molecule occurs, resulting in calcium ions (Ca^{++}). These ions interact with the carboxylic acids (COOH) and 2-quinolenes (Petersen et al. 1987) to form rather insoluble calcium organic salts. This leaves the SiOH molecule free to bond with nitrogen groups in the asphalt (Petersen et al. 1987). These bonds are strong and contribute to adhesion. Figure 13 illustrates some of the important functional groups in asphalt.

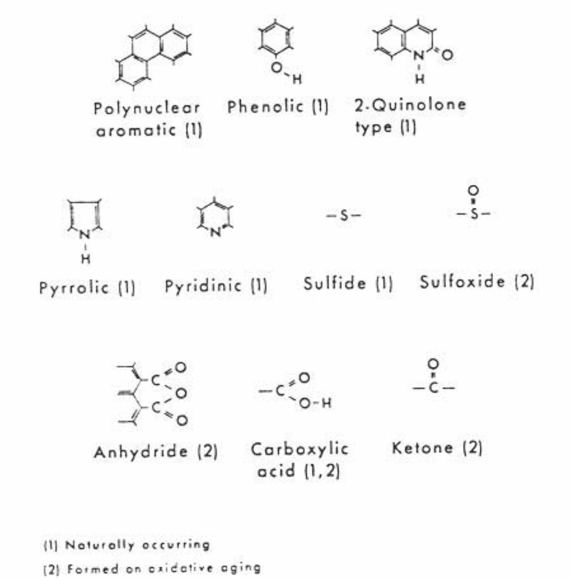


FIGURE 13 Chemical functionalities of importance in asphalt polarity and that contribute in the reaction with calcium. (After Petersen et al. 1987.)

Schmidt and Graf (1972) state that the effectiveness of hydrated lime as an antistripping agent cannot be completely explained by the reaction between calcium from lime and the acids in the asphalt. They state that lime provides calcium ions that migrate to the aggregate surface and replace hydrogen, sodium, potassium, or other cations.

In 1997 the Western Research Institute provided an excellent explanation of the hypothesized aggregate–asphalt interaction.

> Susceptibility to water stripping depends, at least in part, on the water solubility of organic salts formed from the reaction of carboxylic acids in the bitumen with carbonates in the aggregates. High molecular weight magnesium and calcium salts are relatively hydrophobic and not very soluble in water. Sodium salts, being more soluble, lead to stripping. Further, it was found in SHRP research that carboxylic acids in bitumen hydrogen bond very strongly with hydroxyl groups on siliceous aggregates, these being highly concentrated on the aggregate surface. However, this hydrogen bond is highly sensitive to disruption by water, thus accounting, at least in part, for the high moisture sensitivity to moisture damage of pavement mixtures containing siliceous aggregates. Conversion of carboxylic acids to insoluble salts (e.g., calcium salts) prior to use in pavement mixtures could prevent adsorption of water-sensitive free acids on the aggregate in the first place. When pavement containing surface active materials is wet and is subjected to mechanical action of traffic, it is predictable that the surface activity of the sodium carboxylates (soaps) in the bitumen will help scrub the oil (bitumen) away from the rock. . . . The practical, perhaps conservative, solution to the historical problem of stripping is to convert all acidic materials in asphalt to water-insensitive (non-surface active) calcium salts at the time of production. This would require lime treatment at the refinery. Some refineries do this today (SHRP bitumen AAG). The recommendation here is that conversion of acids to calcium salts be made a universal requirement. The process recommended here reduces moisture susceptibility of the whole asphalt rather than just at the interface. Lime treatment of the aggregate will be desirable.

Yoon and Tarrer (1988) discuss the effect of water pH on stripping potential in asphalt mixtures with respect to antistripping additives. Their analysis showed that as the pH of the water increases, the adsorptive bonds between amine-type additives and aggregate surfaces are weakened. As a result, water can more easily displace asphalt from the aggregate surface. They point out that this is not the case with hydrated lime, where the resistance to stripping is independent of the pH of the contacting water. However, other research has shown that normally pHs as high as 10 will not dislodge amines from the aggregate, and pHs greater than 10 are very unusual. The effectiveness of the polyamine additives increases with curing time in studies by Yoon and Tarrer (1988). They found that by storing asphalt–aggregate mixtures for a few hours at 300°F, the effectiveness of some additives improved considerably even at a high pH value of contacting water. Yoon and Tarrer (1988) hypothesize that the reason for the improved performance with curing might be the development of a film of polymerized asphalt.

Other Chemical Treatments

Jamieson et al. (1995) describe three possible treatments to improve adhesion: addition of cations to the aggregate surface, addition of antistripping agents to the bitumen, and aggregate pretreatment with organosilanes. Jamieson et al. (1995) point to research that shows that enhanced bonding is associated with relatively large concentrations of iron, calcium, magnesium, and aluminum at the aggregate surface. Jamieson et al. describe that the principal role of antistripping agents is to trigger the dissociation of aggregations of bitumen components, thereby increasing the availability of bitumen functional groups for active sites on the aggregate surface. Bonding energy measurements indicate that the effectiveness of aggregate pretreatment with modifiers is dependent on aggregate type, probably because antistrip agents are usually amines with relatively similar properties, whereas aggregates vary widely (Jamieson et al. 1995). Organosilane pretreatment of aggregate increases the number of polar adsorption sites on the aggregate surface (DiVito and Morris 1982; Graf 1986). Research during SHRP ranked the overall performance of organosilane treatments as a function of hydrophobic bonding enhancements and determined the order of ranking to be amino > hydrocarbon > thiol.

DUSTY AND DIRTY AGGREGATES

General Mechanisms of Bond Disruption with Dirty or Dusty Aggregates

Dusty aggregates may generally be referred to as aggregates coated with materials smaller than 75 µm. This may cause a problem in developing an acceptable bond between fine and coarse aggregate because the asphalt binder tends to coat the dust and not the aggregate, leading to a greater probability for bond interruption and hence displacement.

Dirty aggregates normally refer to aggregates coated with clay mineral fines. While clay-sized materials are soil particles smaller than 2 µm, true clays are not only very small particles but also have a unique mineralogy and morphology. Clay minerals are made up of alternating layers of silca and alumina, which comprise particles that have a great affinity to adsorb water. This is why clay fines are plastic in nature and have a large plasticity index [range of moisture content between the plastic limit (where the soil acts as a plastic semisolid) and the liquid limit (where the soil acts as a liquid)]. The presence of clay particles on the aggregate surface is similar to that of dust. The asphalt bond with the fine and coarse aggregate is disrupted by the presence of the dust of clay. In fact, the situation is worse with clay fines because these particles have a tendency to swell when they take on water, and this swelling mechanism can break or disrupt an existing bond with asphalt. Furthermore, clay is more active than other soil particles. This can lead to other complex reactions between asphalt, water, and the clays, including emulsification. Clay particles adsorb cations because of their strong negative surface charge and their enormous specific surface area. The amount and nature of the cations adsorbed can affect bond interactions and emulsification potential.

In summary, aggregates coated with dust or clay disrupt the asphalt–aggregate bond and can also lead to more complex reactions among water, asphalt, and aggregate, such as emulsification.

Kandhal et al. (1998) evaluated aggregate tests to assess the potential for aggregate fines to cause stripping in asphalt mixtures. They considered the sand equivalent test, the plasticity index test, and the methylene blue test. They evaluated a set of 10 asphalt mixtures using a common coarse limestone aggregate but with different fine aggregates. They used two validation tests to assess moisture damage: American Association of State Highway and Transportation

Officials T283 and the Hamburg wheel-tracking test. After a careful statistical analysis of results, they found that the methylene blue test did the best job of identifying moisture sensitivity of the mixtures.

Modification of Dusty and Dirty Aggregates to Improve Asphalt–Aggregate Interaction

Hydrated lime has been used to treat dusty and dirty aggregates. The mechanism is partially because hydrated lime reacts with clay to change its properties. Two basic mechanisms are involved: cation exchange or molecular crowding of calcium hydroxide molecules at the surface of the clay and pozzolanic reaction.

Cation exchange or calcium hydroxide crowding provides an abundance of divalent calcium ions, which, because of their high concentration and divalent nature, replace the normally available cations in the clay environment. This leads to a substantial reduction in clay plasticity (Little et al. 1995) and causes clay colloids to flocculate into larger aggregates (Little et al. 1995). However, the most important reaction is the pozzolanic reaction, where caustic calcium hydroxide raises the pH of the lime-water-clay system to more than 12. At this high pH, clay minerals are attacked and the silica and alumina solubilize. Soluble silica and alumina then combine with free calcium cations to form calcium silicate and calcium aluminate hydrates, further reducing plasticity, stabilizing the clay, and forming more well-cemented agglomerates (Little et al. 1995). One might expect that the lime-modified clay coatings will "peal" from the aggregates and no longer remain as coatings but as "cemented" small aggregates of flocculated clay that can be separately coated with asphalt.

CONCLUSIONS

Although several separate mechanisms have been identified to explain the process of moisture damage in asphalt pavements, it is more likely that most asphalt pavements suffer moisture damage as a result of a synergy of several processes. From a chemical standpoint, the literature is clear that neither asphalt nor aggregate has a net charge, but components of both have nonuniform charge distributions, and both behave as if they have charges that attract the opposite charge of the other material. Researchers point out that certain polar asphalt compounds develop more tenacious and moisture-resistant bonds with the aggregate surface than others and that the development of the more tenacious and long-lasting bonds can be promoted by treatment of the asphalt mixtures with additives. The most durable bonds appear to be formed by interaction of phenolic groups and nitrogen bases from the bitumen. These form insoluble salts. While sulfoxides and carboxylic acids have a greater affinity for the aggregate surfaces, they are most susceptible to dissolution on water.

The asphalt–aggregate bond is affected by aggregate mineralogy, adsorbed cations on the aggregate surface, and the surface texture and porosity. Favorable chemical bonding between asphalt and aggregate alone will not optimize the adhesive bond and minimize moisture damage. The bond is part physical, and, therefore, the asphalt must be able to wet and permeate the aggregate surface. This process is dependent on asphalt rheology at mixing temperatures and the nature of the aggregate surface, pore size, pore shape, and aggregate mineralogy. To complicate matters somewhat, the ability to bond asphalt to aggregate is dynamic and changes with time. This is largely affected by the shift in pH at the aggregate–water interface, which can be triggered by dissociation of aggregate minerals near the surface or by the nature of the pore water (cation type and concentration).

Moisture damage is certainly not limited to adhesive failure, but weakening of the cohesive strength of the mastic due to moisture infiltration is equally important. Recent research has shown that water can diffuse into asphalt of mastics and that each can hold an appreciable amount of water. Research over many years has clearly shown that this water can weaken the asphalt mixture, making it more susceptible to damage. Thus the logical view is that the deleterious effects of moisture on the adhesive and cohesive properties, both of which influence asphalt mixture performance, must be considered. In fact, recent work at Texas A&M University points out that the propensity for either adhesive or cohesive failure in an asphalt mixture is dependent on the thickness of mastic cover. Since the distribution varies considerably within the mixture, the statistical distribution will determine which mechanism controls.

ACKNOWLEDGMENTS

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TOPIC 2

Questions and Answers

DALLAS LITTLE
Texas A&M University, Speaker

Q1—Alan James, Akzo Nobel
As far as I understand the presentation, the asphalt contains good and bad players as far as the adhesion is concerned. Carboxylic acids are bad players and nitrogen compounds are good players. Can the surface energy measurements distinguish between good and bad players or do both contribute to the surface energy numbers?

A—Dallas Little
In a sense surface energy measurements can differentiate, but perhaps not with the precision you imply in your question. Surface energy can differentiate between acid–base and Lifshitz–Van der Waals interactions, for example, but they cannot directly differentiate between, say, carboxylic acids and carbonyls or between carboxylic acids and nitrogen compounds. But the fact is that surface energy can give us a "global" sense of bond energy, and this is perhaps where we need to begin. Although I did not present it in this paper, we look at the impact of surface energy on moisture damage as sort of a two-step process. In the first part, the adhesive bond formed between the asphalt and the aggregate protects against damage. We obviously want this value to be high. In the second step, the bond energy or Gibbs free energy between the asphalt and aggregate demonstrates a preference of the aggregate to bond with water rather than asphalt. This free energy value turns out to be negative, which indicates a reduction in energy as water replaces asphalt at the aggregate surface, and hence this is a favored process. If the absolute value of this number is large, then the rate of debonding will be high; if it is smaller, then the rate of damage due to debonding will be lower. Therefore, we seek a large bond energy directly between the asphalt and aggregate (impeding bond interruption in the first place) and a less negative value of bond energy between the asphalt and aggregate in the presence of water (slowing the rate of debonding if water gets to the interface).

Q2—John Harvey, University of California at Davis
With the long-term chemical and pH changes that could occur in the field over a period of a few years, could benefits of treatment diminish? Most treatment benefits have been laboratory tested with accelerated tests lasting several weeks. Are you aware of any long-term testing confirming the benefits identified with short-term tests?

A—Ray Robertson, Western Research Institute
To answer your question, John, we have some field sites that several different states have very kindly put in for us where the comparison is among asphalts that are used. In other words, the principal variable at each site is the asphalt. We are looking at differences in the long-term performance characteristics of those asphalts. That, to me, is the gold standard measuring stick. While I'm up, can I make a comment on what was asked over here on surface energy measurements? You really don't want to measure surface energy of individual components. The

real advantage of the method is to measure the positive and negative effects together. For any of you who weren't around the day after TRB, we had a pretty lively discussion on that subject for a while. Really, the surface energy measurement is to get the summation of the effects of all of the components of the asphalt. Can I make one more comment? To continue with what you have heard quoted here on carboxylic acids, one of the things we are going to have to watch more carefully is what happens with aging of asphalts, what kinds of new materials are formed. Again, to pick on Dr. Ken Thomas, he has identified some components from aging that cause substantially greater moisture sensitivity than carboxylic acids. How one treats these materials to "get them out of the way" is a subject we will probably discuss quite a bit more tomorrow.

A—Dallas Little
I really like the comment, Ray. I use the term global; you use the term summation effect. But the fact is we need something to simplify what we are looking at because, otherwise, the complexity of the interaction can be overpowering. So, if you can come up with a tool, even though it may be somewhat limited because you can't differentiate among the species, if it gives you this overall summation or global effect then it is valuable. It is kind of an unbiased measure of the bonding propensity between the asphalt mastic and the aggregate. That is what we are really looking at and see promise in.

Q3—Gayle King, Koch Pavement Solutions
Dallas, I am intrigued by your compression test, which applied multiple loads to a submerged specimen. I assume you are trying to create the pore pressures that we once hoped to simulate with the environmental conditioning system, but maybe missed. Best guess! Are you creating higher pore pressures than observed with the ECS, and how might it compare with the Hamburg WTD or other mechanical wheel-tracking devices? Any feel for whether you are creating the same kind of damage that the Texas Department of Transportation has seen in problem mixes where static immersion tests did not pick up moisture problems?

A—Dallas Little
Gayle, that's a very, very insightful question. I would have to say that, unfortunately, we haven't measured the pore pressures in the experiment. We brought the system to about 85% saturation pretty much without confinement prior to running the repeated low compression experiment. So we really don't have a handle on what those pore pressures are, but that is something that should be done. That is a very important part of the puzzle.

Q4—Barry Baughman, Ultra Pave
Dr. Little, have you looked at using polymeric aggregate treatments to protect the aggregate from the moisture while improving the adhesion to the asphalt?

A—Dallas Little
No, we haven't looked at it. Our research to this point has looked at basic aggregates, and I use the term "basic" to refer to natural, or unaltered, aggregate. We looked at just the basic aggregates and the bitumen. However, we do have a study under way with the International Center for Aggregate Research that is looking at different coating or modification effects on the aggregate to see how they might affect surface energy and how that might affect the resistance to damage.

Q5—Robin Graves, Vulcan Materials Co.
Looking at the difference between a lime mitigation situation, adding lime to the aggregate versus to the bitumen. Have you looked at the solubility of calcium hydroxide in the bitumen system and do you know how soluble the calcium is and whether there are any pH changes in that system?

A—Dallas Little
I have not done that, Robin. That is a good question. You know, this thing about adding lime to the bitumen is intriguing because over the years we have looked at adding it, not as an antistrip, but considering it as a filler to the bitumen. Today I showed you one slide where the amount of damage that an asphalt sample can handle before failure is strongly affected by the filler. This is because the filler acts to mitigate the damage by absorbing energy, redirecting microcracks, crack pinning, and all those mechanisms. Over the years, we've found that the impact of hydrated lime as filler is bitumen-dependent: it works better in some than it does in others. We have referred, in past publications, to lime as an interactive filler with some bitumens while it acts as an inert filler with others. This is probably because the surface of the lime forms an interactive layer or buffer region because of absorption of polars in some bitumens. For example, hydrated lime in SHRP asphalt AAD is much more effective than it is when mixed with AAM. Didier Lesueur with LCPC in Nantes, France, and I presented a paper in 1999 (Effect of Hydrated Lime on Rheology, Fracture, and Aging of Bitumen, *Transportation Research Record: Journal of the Transportation Research Board, No. 1661*, pp. 93–105) concerning this interactive effect. This goes all the way back to the work of Claine Petersen, Hank Plancher, and others who state that this interactive effect is due to functionalities such as carboxylic acids interacting with the surface of the lime. So all that is really interesting, but we have not at this point in time looked at the ionization potential of the lime within the asphalt, and that would be something we would need to do.

Q6—Joe Button, Texas Transportation Institute
Dallas, would you answer this question in the short term and the long term? Do you see the surface energy measurement process as a specification test in the future?

A—Dallas Little
Yes, I do. I think it will be a specification test. There is a project under negotiation right now where we are trying to look at it as a specification test, and I certainly see the potential for doing that. I see the potential for shortening the time period for the surface energy measurement on the aggregate. We can then use the bond energy between the aggregate and bitumen as a basis to specify aggregates and bitumens on the basis of compatibility with one another. The short answer is yes; the long answer is we've got a little bit of work to do to get there. We also have to keep in mind that it's not just surface energy that affects the response of the asphalt mixtures. Other factors do as well. Mixture properties such as mixture compliance, the time effects on compliance, and so forth affect the ability of the mixture to resist damage. The surface energy characteristics can also help us define crack potential. Not just bonding potential; they can help us define the potential of the mixture to crack. Dick Schapery in 1974 developed a viscoelastic fracture model, which says essentially that the energy you put into the system is balanced by the surface energy that is created on crack surfaces as they develop. So, there is a fundamental relationship between surface energy and crack growth and crack healing, as Schapery predicted

in the mid-1970s. If you can develop a mixture that is resistant to the propagation of cracks and enhances the healing of microcracks, then certainly you are reducing the damage potential. Systems that crack more and have more crack damage have a greater propensity for moisture damage because the moisture can migrate into the damaged crack areas. So surface energy is not just related to the bonding effect; it is also related to the propagation of damage through microcracking.

Q7—Roger Smith, Consultant
We've heard that certain fine fillers, such as hydrated lime, can be a benefit. I'd like to hear your thoughts on the general effect of high dust (P 200) on moisture sensitivity.

A—Dallas Little
I think I have tried to limit the discussion to what would be the appropriate amount of filler in the constraints of the overall mix design. If the appropriate amount of filler is present to pin the cracks, absorb some of the energy, and make the mixture more resistant to damage, then you are in good shape. Obviously, you can abuse that and add too much, and then you get into a whole line of other problems. You could develop a mix that is too dry, a mix that is so dry that you alter the adhesive bond between the mastic and the aggregate surface, and then you go down another route that might cause more damage than good for sure. So you know, asphalt is a very humbling material. It is a material that keeps us all in check and often surprised.

Q8—Bill Maupin, Virginia Transportation Research Council
Dallas, have you looked at time dependency effect on bond strength? In other words, could you initially have a strong bond that may become weak over time with certain asphalt–aggregate additive systems?

A—Dallas Little
I think you could, Bill, and we have not looked at that. I think that some research indicates that if you have some environmentally induced shifts in pH and so forth, certain types of additives or certain systems make a difference. We haven't looked at that, but it is certainly something important to look at.

TOPIC 3

Test Methods to Predict Moisture Sensitivity of Hot-Mix Asphalt Pavements

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Test Methods to Predict Moisture Sensitivity of Hot-Mix Asphalt Pavements

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The work conducted through the years toward development of moisture damage tests is summarized in this paper. Moisture damage has been a major concern to asphalt technologists for many years. Attempts to develop laboratory tests to distinguish between good- and poor-performing mixes in regard to stripping date back to the 1920s.

The tests for identifying the moisture damage potential of an asphalt–aggregate mixture can be classified into two major categories: those on loose mixtures and those on compacted mixtures. The static immersion and the boil test, both conducted on loose mixtures, were among the first tests introduced to the paving industry. This was followed by introduction of the immersion–compression test in the late 1940s. This test was conducted on compacted specimens and was the first test to become an ASTM standard in the mid-1950s. Research in the 1960s brought considerable awareness to asphalt pavement technologists of the significant effects of climate and traffic on moisture damage. The significance of these factors was emphasized through the work of researchers such as Johnson (1969), Schmidt and Graf (1972), Jiminez (1974), and Lottman (1978).

The work by Jiminez resulted in a laboratory test simulating the effect of repeated water pressure on the behavior of saturated hot-mix asphalt. Extensive work by Lottman resulted in the laboratory test that currently has the widest acceptance in the paving industry. This test was further modified through the work of Tunnicliff and Root (1982). Wheel tracking of asphalt mixes submerged under water gained popularity for determination of moisture damage in the 1990s. The Hamburg wheel-tracking device and the asphalt pavement analyzer are among the tests of this type. It was also during this period that the environmental conditioning system was introduced to the industry at the completion of the Strategic Highway Research Program (SHRP) in 1993.

The Superpave system, the product of SHRP, adopted the standard test method AASHTO T283 as the required test for determination of the risk of moisture damage. This test procedure is similar to the Lottman test procedure with some modification. With the Superpave system being adopted by most state highway agencies, AASHTO T283 became the most widely used test procedure within the industry. Some agencies have reported problems with this test in terms of correlation between the laboratory results and field observations.

Today, it remains a challenge to asphalt pavement technologists to develop a highly reliable and practical test procedure for determination of moisture damage. An important consideration in development and acceptance of a test procedure for moisture damage should be calibration of the test to the conditions for which it will be applied. Some tests have been calibrated and implemented on a local basis (a region within a state). No test has been successfully calibrated and implemented across a wide spectrum of conditions. Reasons for this have been lack of correlation with field performance, a lack of good field performance databases, and problems with the tests such as variability and difficulty of operation.

INTRODUCTION

Historical Development

The performance of hot-mix asphalt (HMA) in the presence of water is a complex issue and has been the subject of numerous research studies during the past six decades. During this period, asphalt technologists and state highway agencies have been in pursuit of a reliable laboratory test protocol to predict the asphalt pavement behavior in the field with regard to moisture sensitivity. The facts that the adhesion between asphalt and aggregate is reduced in the presence of water (stripping) and that the cohesion within the asphalt binder itself deteriorates have been known to practitioners for a long time and date back to at least the 1920s. Early work on this problem was performed by Nicholson (1932), Riedel and Weber (1934), McLeod (1937), Hubbard (1938), Powers (1938), Winterkorn et al. (1937), Saville and Axon (1937), Winterkorn (1937; 1938; 1939), Krchma and Nevitt (1942), Krchma and Loomis (1943), and Hveem (1943), among others. An extensive bibliography covering work performed prior to 1959 is given by Rice (1958).

Examination of the 1937 *Proceedings* of the Association of Asphalt Paving Technologists (AAPT) shows two papers on asphalt–aggregate adhesion and problems with moisture sensitivity and references to previous work. For example, a paper by Saville and Axon discusses the search for a usable laboratory test and presents results from boiling tests and soaking tests and compares them with the field stripping performance of mixes with different types of aggregate. That paper also contains photographs of stripped mixes that would all be recognized from pavements today (as a note, this indicates that stripping problems did not begin because of changes in asphalt composition in the early 1980s). In an update on asphalt test development in the 1943 AAPT *Proceedings*, Hveem commented on the problem and stated:

> A complete solution to this entire problem may readily appear from another source. That is to say, that there are now many methods of treatment being advocated or in process of development which should improve the capacity of any asphalt to stick to virtually all aggregates under the most adverse conditions. When an agent is commercially available that can be added to the asphalt at the refinery, this entire problem may largely disappear, although it is likely that accurate test methods will always be needed in order to compare the effectiveness of competing forms of treatment.

The immersion–compression test was introduced in 1950s as the first moisture damage test on compacted specimens under ASTM standard. In that decade, some work was also conducted on the surface energy of asphalt and aggregate and its relationship to bonding properties (Thelen 1958). Andersland and Goetz (1956) also introduced the sonic test for evaluation of stripping resistance in compacted bituminous mixtures.

More recent attempts toward development of tests to predict asphalt mixture moisture sensitivity started in the 1960s and 1970s with the work of Johnson (1969), Schmidt and Graf (1972), Jimenez (1974), and Lottman (1978). All recognized the importance of simulating field conditions through accelerating test conditioning in the laboratory. Jimenez used vacuum saturation followed by cyclic pore pressure application to achieve this purpose, while Lottman used vacuum saturation followed by freezing and hot water bath conditioning.

Lottman's laboratory test protocol, presented to the industry in 1978, was a breakthrough in regard to a coherent test procedure for predicting moisture-induced damage to asphalt concrete. The protocol introduced by Lottman was later modified and standardized as AASHTO Test Procedure T283. Root and Tunnicliff presented their version of the Lottman procedure in the early 1980s during an extensive evaluation of antistripping additives.

At the same time, Kennedy, Roberts, Anagnos, and Lee at the University of Texas at Austin introduced two test procedures to the industry: Texas freeze–thaw pedestal test (1982) and Texas boiling test (1984). The boiling test was developed on the basis of work that had been conducted in departments of transportation in Louisiana, Texas, and Virginia between 1975 and 1980 and is very similar to the test used by Saville and Axon in 1937. The freeze–thaw pedestal test was a modification of the procedure introduced earlier by Plancher et al. (1980) at the Western Research Institute.

Ensley et al. (1984) worked toward development of techniques for measuring the bonding energy of the asphalt–aggregate system. This was also a time for some researchers to evaluate the test methods available for moisture damage. As example is the work by Gharaybeh (1987).

Afterwards, there was no significant development in moisture damage test procedures until the Strategic Highway Research Program (SHRP) sponsored research toward development of new moisture sensitivity tests. The result of this research was the environmental conditioning system (ECS) (Al-Swailmi and Terrel 1992). At the same time, the Hamburg wheel-tracking device (HWTD) was introduced into the United States (Aschenbrener and Currier 1993). Colorado, Texas, and Utah were among the first states to explore the HWTD (Aschenbrener 1995).

The search for new reliable test procedures for determination of moisture sensitivity continues. Western Research Institute (WRI) has undertaken in-depth research on asphalt chemistry and its relationship to moisture damage. WRI has determined that displacement of asphalt polars from aggregate by water varies by asphalt source. Currently, WRI is developing a rapid centrifugation method to simulate displacement of polars by water. The hypothesis being tested is the following: asphalt–aggregate mixtures that form insoluble calcium salts of asphalt components are the least prone to moisture damage. On another front, the concept of surface energy has reemerged as a potential tool for determining the adhesion of asphalt–aggregate systems.

While these recent research developments can contribute significantly toward determination of compatible and moisture-resistant asphalt–aggregate mixtures, they do not address the effect of the interaction between traffic and water on moisture damage in pavements. Hence, a new test procedure on compacted samples is being investigated under National

Cooperative Highway Research Program (NCHRP) Project 9-34 aimed at proper simulation of environment/traffic factors in regard to moisture damage.

Types of Moisture Sensitivity Tests

In general, the tests that have been developed can be divided into two main categories: qualitative and quantitative. Qualitative tests provide a subjective evaluation of the stripping potential and include

- Boiling water test,
- Freeze–thaw pedestal test,
- Quick bottle test,
- Rolling bottle method, and
- Many others.

The quantitative tests provide a value for a specific parameter such as strength before and after conditioning. These tests include

- Immersion–compression test,
- Indirect tensile test,
- Marshall immersion test,
- Double punch method,
- Resilient modulus tests, and
- Many others.

Alternatively, the tests can be categorized into those aimed at checking the compatibility between aggregate and asphalt on the basis of conditioning of the loose mix and those used to determine moisture sensitivity of the compacted mix structure. The latter can be divided into those that look at water conditioning and those that include the interaction of traffic and water. The first type of test helps to determine whether an asphalt–aggregate system is compatible and whether it is resistant enough against debonding in the presence of water without any attempt to evaluate the mechanical behavior of the mixture under applied loads and water. In the second group of tests, attempts are made to take the effect of the compacted mix structure as well as traffic and environment into consideration when the mix behavior is evaluated in the presence of water. These tests typically give a result that is interpreted as pass or does not pass. At this time, none of these tests provide information that can be used in a mechanistic-empirical design framework by providing information on the effect of water on stiffness, and fatigue and rutting transfer functions.

The complexity of developing test methods to predict moisture damage in the field is evident from the variables that interact in this phenomenon, including the following:

- The great number of aggregate sources and their highly varied mineralogies, crystal structures, and surface textures;
- The numerous types of unmodified and modified asphalt binders used across the United States; and
- The varied environmental conditions, traffic, and construction practices.

It has remained a challenge to the pavement industry to improve the current moisture damage tests to provide a more reliable distinction between poor and good performers and to relate the numbers from any test to performance on a given project with its unique combination of variables.

For a moisture susceptibility test procedure to be successful for mix design and field quality control, certain criteria must be satisfied:

1. It must be representative of the mechanisms that cause moisture damage in the field and produce results that match those occurring in the field under similar conditions, or it must measure some property that determines the performance of the mix in the field without actually simulating field conditions in the laboratory.
2. It must be capable of discriminating between poor and good performers in regard to stripping. If the first criterion (above) cannot be satisfied, then some discriminator of this type is useful; however, the results must still be tied to field performance.
3. It must be repeatable and reproducible, with the allowable variance depending on the constraint of the fourth criterion.
4. It must be feasible, practical, and economical enough that it can be included in routine mix design practice.

These four criteria are the key items to the success of any test procedure selected for identification of asphalt concrete moisture susceptibility.

SIGNIFICANCE OF MOISTURE-SENSITIVITY TESTS

Implementation of any laboratory test for moisture sensitivity or stripping will always require calibration of the results that the test generates with observed field performance. If the test results are not calibrated with field performance, the test runs a larger risk of eliminating mixes that would perform well in the field or permitting mixes that have a high probability of having a shortened life due to moisture damage.

Review of the literature, including laboratory experiments and field studies, indicates that while moisture damage susceptibility is highly correlated with aggregate source, other variables can significantly increase or decrease the risk of moisture susceptibility for a given mix used on a given project. These variables include (Harvey et al. 2002)

- Drainage and the condition of the drainage system;
- Pavement structure, including lack of bonding between asphalt concrete layers, which can permit lateral movement of water; the presence of cracks, which permit water to enter; the presence of open-graded or seal coat materials below the surface, which can trap water below the surface; and the presence of fabrics or interlayers that can trap water below the surface;
- Mix design, including binder content, gradation, and dust-to-asphalt ratio, which can determine the film thickness on the aggregates and the permeability of the mix; binder selection, which determines the stiffness of the binder and the susceptibility to penetration of the asphalt film by water; and the use of additives, which can reduce the overall susceptibility of the mix;
- Construction variability, including segregation, which can create areas with high air void contents and low binder contents, which permit water to enter and are more susceptible to moisture damage; variance from the job mix formula, which can create susceptible areas with

less dense gradation and lower binder contents; and compaction, which can create areas with high air voids and therefore high permeability and low strength;

- Climate, which determines the presence of water (unless there is a nearby irrigation or sprinkler system that is creating an artificial climate), the amount of freeze–thaw action, and the temperature of the asphalt and the water when it is being subjected to traffic; and
- Traffic, which applies stresses to the mix while it is in a weakened condition from moisture and has been shown in several studies to determine whether moisture damage and stripping occur by comparison of cores from the wheelpath with those from outside the wheelpath.

The interactions of these variables and the different level of interaction at which laboratory test methods can measure relevant properties or simulated performance are shown in Figure 1.

With regard to the last item in the list, the influence of traffic loading on moisture damage was recognized early when a forensic analysis was conducted after one of the loading cycles at the Penn State Test Track. The HMA in the base course was completely stripped of binder in the wheel tracks but was undamaged between the wheel tracks, as reported by Anderson and Shamon (1984). Bejarano and Harvey (2002) found that an asphalt-treated permeable base material stripped completely in the wheelpath in a full-scale pavement subjected to subsurface water infiltration under heavy vehicle simulator loading but had no stripping just outside the wheelpath. Some reduction in stiffness and strength was observed in the material outside the wheelpath.

The preceding list of variables suggests that a “one size fits all” approach in terms of passing and failing results from laboratory tests will be difficult to implement because a given mix may perform well under one set of circumstances and poorly under a different set. Implementation of laboratory tests will be less difficult and the risk of eliminating usable mixes and permitting susceptible mixes will be reduced if the field calibration is as comprehensive as possible in terms of consideration of these variables. This should be achieved in the light of a common test calibrated to local conditions. Some researchers such as Philips and Marek (1986) have emphasized the need for a moisture damage test via a common procedure.

There are three primary difficulties in performing a comprehensive field calibration:

- Obtaining comprehensive data for the independent variables listed above;
- Quantifying the dependent variable, performance; and
- Relating results from laboratory- and field-compacted test specimens.

In regard to obtaining comprehensive data for the independent variables, most states have a great deal of difficulty in compiling good data for the independent variables listed above to relate to observed field performance. In particular, only a few state pavement management system databases include mix information, construction quality data, or information on the underlying pavement structure. Very few agencies have information on maintenance activities that have been performed, which may significantly affect the performance of the pavement with respect to moisture sensitivity and stripping. The most recent comprehensive efforts at field calibration have typically included fewer than 25 test sections (Aschenbrener et al. 1995; Busching et al. 1986) and have not considered the full range of variables shown above. Solaimanian et al. (1993) evaluated long-term stripping performance of 46 test sections on 9

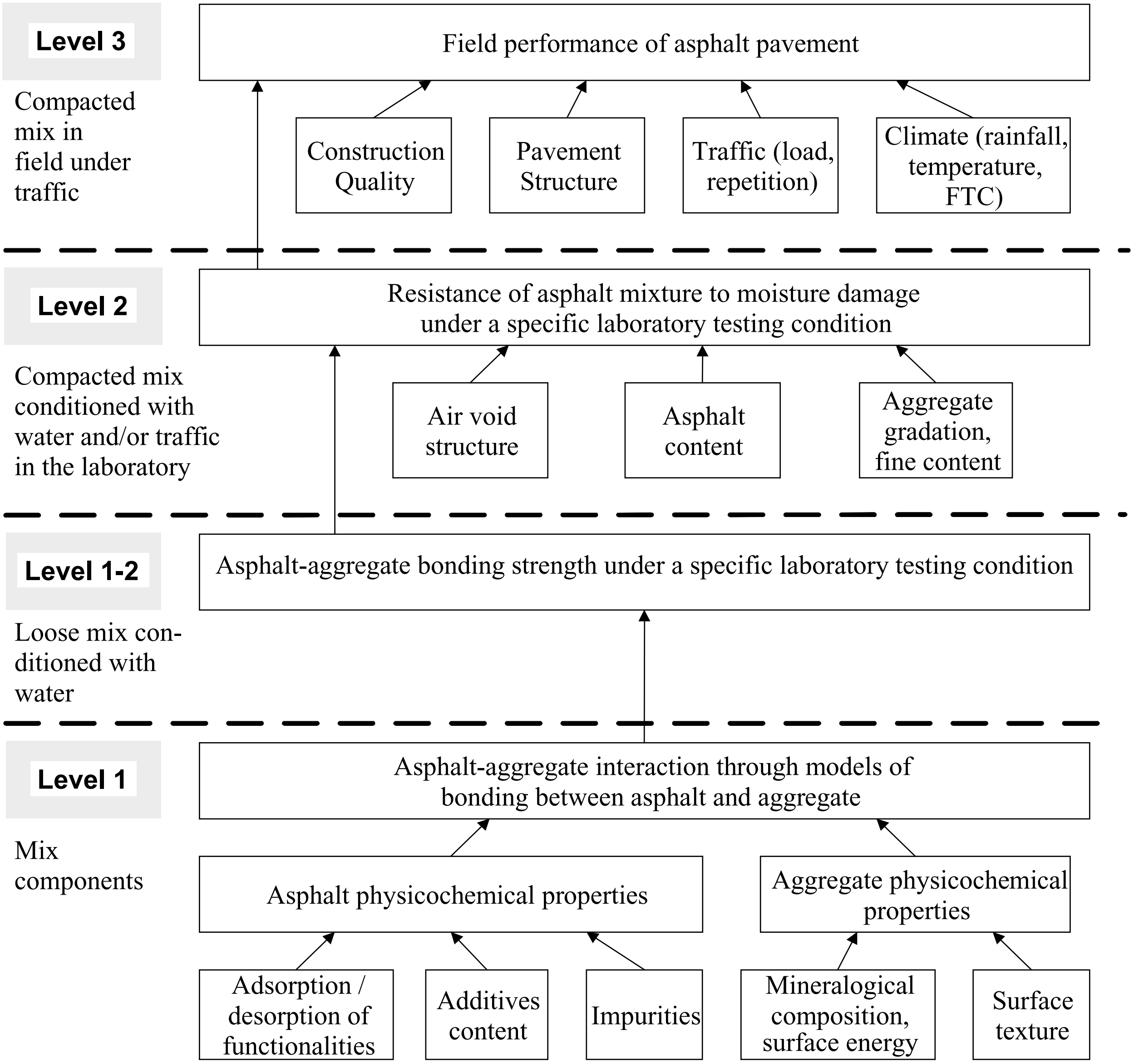


FIGURE 1 Factors influencing moisture damage of asphalt pavements (after Lu 2003).

roads for a period of 6 years and found no clear relationship between laboratory results and field performance.

In addition, the conditions under which moisture damage and stripping occur may not be the same in different locations. This indicates that calibration data sets must include the climate regions and traffic conditions in which the test results will be used. For example, Aschenbrener identified that all of the test sections compared with test results in Colorado had most of their precipitation during the hottest months of the year. The pass/fail values developed in Colorado may not be applicable to northeastern California, where the hottest months have little or no rainfall. The Long-Term Pavement Performance database has not been mined for moisture sensitivity/stripping information, but it has had difficulty in providing comprehensive data for many of its test sections. A recent database of hot-mix asphalt concrete data developed by White et al. (2002) that is comprehensive in terms of the variables listed above may provide a valuable source of information for calibration in the future. Development of better databases for calibration of laboratory results with field data is vital for development of better laboratory tests for moisture sensitivity/stripping and other distress mechanisms.

With regard to quantifying performance, identification of stripping can be difficult without coring if it occurs below the surface, and moisture damage that does not proceed to stripping is very difficult to identify without information about mix performance in the absence of water. For example, Aschenbrener et al. (1995) identified pavements as being “good,” “high maintenance,” “complete rehabilitation,” or “disintegrators.” Pavements were placed in these categories on the basis of years to failure versus design life and coring to find stripping. Other researchers use different criteria for all but the “good” pavements. Stripping is seldom formally identified and entered into a database on field projects when they fail, and the stripping itself is visually identified and therefore somewhat subjective unless most of the asphalt has disappeared from the aggregate. This is also the case for laboratory tests that rely on visual identification.

Pavements that do not exhibit significant visible stripping may have their performance significantly reduced and fail by fatigue cracking, raveling, or rutting, without being identified in the field as having moisture damage. This makes it difficult to set thresholds for laboratory test results to minimize moisture damage for mixes that exhibit little observable stripping. Some laboratory tests also submit the mix to conditions that will not result in stripping but that do cause significant moisture damage, measured as reduction in strength or stiffness. These tests are particularly difficult to calibrate with field results because field measurements of stiffness and strength are difficult to obtain. Mixes lose strength and stiffness when wet but regain these properties when dried (Figure 2). A faster damage rate occurs under loading when the mix is wet, but if properties are measured when dry the effects of water may not be apparent.

With regard to the difficulty in relating field and laboratory results, the primary problems are differences between field and laboratory test specimen air void contents, size of voids, permeability, and aging. Many of the test methods summarized in this document require that specimens be prepared to a predetermined air void content. Laboratory studies have shown that air void content has a significant effect on test results, and difficulty should be expected in

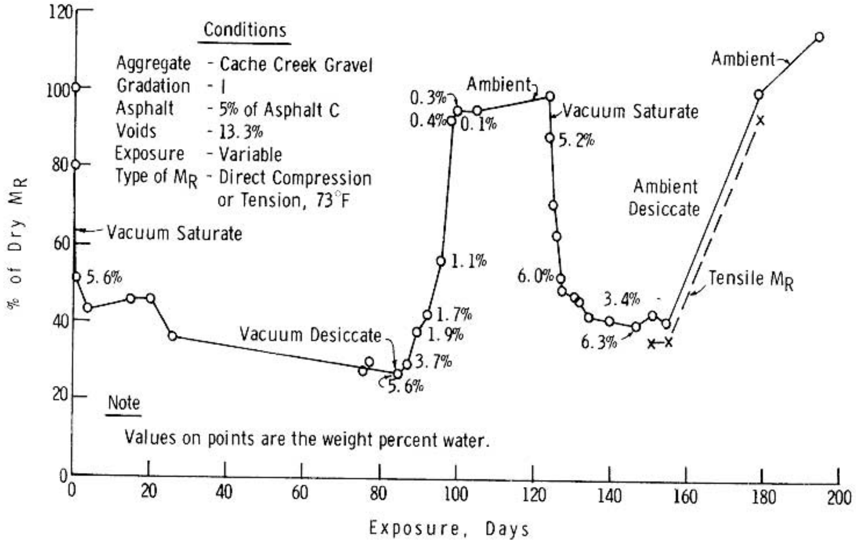


FIGURE 2 Effect of moisture on resilient modulus may be reversible (after Schmidt and Graf 1972).

correlating laboratory test results with field performance if laboratory specimens are not compacted to the same air void contents as occurred or are expected to occur in the field for a given project. Even when air void contents are matched between the laboratory and field, the results may vary between the two for the reasons described above, as was identified by Aschenbrener (1995). These differences will largely depend on the laboratory compaction device used, because different compaction methods can create very different aggregate and void structures in the specimen even though the total air void content is the same. The results also depend on the laboratory aging procedures used.

If a method can be calibrated with field results, the next criteria it must pass to be implementable concern repeatability and reproducibility and cost in terms of staff, time, materials, and equipment. To some degree, inherent higher variance can be overcome with additional replicate specimens. However, bias and variance caused by differences among operators and laboratories are difficult to overcome with more replicates because the ability to "tweak" the results is placed in doubt, whether intentionally or unintentionally. These factors must be considered and be acceptable for a test to be implementable. However, it can be argued that having a test that is easy and inexpensive to perform but that cannot be calibrated with field results is of no use.

In addition to an ability to correlate with field performance, laboratory tests are often required to be able to measure the effects of moisture sensitivity mitigation measures, particularly additives and modified binders. The effects of mitigation must be correlated with field performance. Again, the mechanism used in the laboratory to evaluate a mix and its relation to the mechanism that causes moisture susceptibility/stripping in the field may not be the same, and as noted previously the field mechanism may vary between different projects.

MOISTURE SENSITIVITY TESTS

Tests used to estimate moisture sensitivity of HMA can be classified into two general types: tests on loose mixtures and tests on compacted mixtures. Tables 1 and 2 summarize the tests for moisture sensitivity on loose and compacted mixtures, respectively.

TABLE 1 Moisture Sensitivity Tests on Loose Samples

Test	ASTM	AASHTO	Other
Methylene blue			Technical Bulletin 145, International Slurry Seal Association
Film stripping			(California Test 302)
Static immersion	D1664*	T182	
Dynamic immersion			
Chemical immersion			Standard Method TMH1 (Road Research Laboratory 1986, England)
Surface reaction			Ford et al. (1974)
Quick bottle			Virginia Highway and Transportation Research Council (Maupin 1980)
Boiling	D3625		Tex 530-C Kennedy et al. 1984
Rolling bottle			Isacsson and Jorgensen, Sweden, 1987
Net adsorption			SHRP A-341 (Curtis et al. 1993)
Surface energy			Thelen 1958, HRB Bulletin 192 Cheng et al., AAPT 2002
Pneumatic pull-off			Youtcheff and Aurilio (1997)

* No longer available as ASTM standard.

TABLE 2 Moisture Sensitivity Tests on Compacted Specimens

Test	ASTM	AASHTO	Other
Moisture vapor susceptibility			California Test 307 Developed in late 1940s
Immersion–compression	D1075	T165	ASTM STP 252 (Goode 1959)
Marshal immersion			Stuart 1986
Freeze–thaw pedestal test			Kennedy et al. 1982
Original Lottman indirect tension			NCHRP Report 246 (Lottman 1982); Transportation Research Record 515 (1974)
Modified Lottman indirect tension		T 283	NCHRP Report 274 (Tunnicliff and Root 1984), Tex 531-C
Tunnicliff–Root	D 4867		NCHRP Report 274 (Tunnicliff and Root 1984)
ECS with resilient modulus			SHRP-A-403 (Al-Swailmi and Terrel 1994)
Hamburg wheel tracking			1993 Tex-242-F
Asphalt pavement analyzer			
ECS/SPT			NCHRP 9-34 2002-03
Multiple freeze–thaw			

The third category is tests for surface treatments and chip seals.

The following sections provide detail on these tests and their limitations.

Tests on Loose Mixtures

These are the tests conducted on asphalt-coated aggregates in the presence of water. Examples include boil, film strip, and static/dynamic immersion tests. One advantage of these tests is that they are simpler and less costly to run than tests conducted on compacted specimens. Another advantage is that they require simpler equipment and procedures.

The major disadvantage is that the tests are not capable of taking the pore pressure, traffic action, and mix mechanical properties into account. The results are mostly qualitative, and interpretation of the results becomes a subjective matter depending on the evaluator's experience and judgment. There is also not much evidence correlating results from these tests to field performance of hot-mix asphalt concrete.

Loose mixture tests are best used for comparison between different aggregate–asphalt mixtures in terms of compatibility, strength of adhesion, and stripping. Mixtures failing in these tests, on the basis of some established criterion, have the potential to strip and should be avoided. However, good results should not mean that a mix can be used, since the effects of the other contributing factors are not considered in these tests. Defining a pass/fail criterion is not an easy task for most of these tests. For example, visual evaluation is used in the static immersion test to determine the degree of stripping below or above 95 percent, a criterion that is not very repeatable between different operators and different laboratories.

Methylene Blue Test

The methylene blue test attempts to identify the harmful clays and dust available in the fine aggregate. This test does not directly provide a measure of stripping since no asphalt is used.

However, the results can be used to decide whether potential for stripping exists because if aggregates are coated with montmorillonite-type clay, proper coating will not take place between the aggregate and asphalt.

The methylene blue test was developed in France and was recommended by the International Slurry Seal Association (ISSA) to quantify the amount of harmful clays of the smectite (montmorillonite) group, organic matter and iron hydroxides present in fine aggregates. The test method titled "Determination of Methylene Blue Adsorption Value (MBV) of Mineral Aggregate Fillers and Fines" was contained in Technical Bulletin 145 of ISSA (1989). In the test, methylene blue (MB) is dissolved in distilled water with a known concentration. A known weight of the filler finer than 75 microns is also uniformly stirred and dispersed in a separate beaker. Drops of MB solution, 0.5 mL each, are added to the solution with a burette one at a time while stirring. After each drop of MB, one drop of the solution is removed using a stirring rod and placed on filter paper. The test is continued until a light blue halo is formed around the drop. The absorption of MB by clay is used to determine the amount of harmful clay, with greater absorption indicating larger amounts of harmful clays. Research by Kandhal et al. (1998) has indicated that larger MB values correspond to lower tensile strength ratios from AASHTO T283.

Film Stripping Test (California Test 302)

This is a modified version of test procedure AASHTO T182 (Coating and Stripping of Bitumen–Aggregate Mixtures). In California Test 302, a 60-g mass of aggregate coated with asphalt is placed in a 60°C oven for 15 to 18 h. The sample is then cooled to room temperature and placed in a jar with about 175 mL of distilled water. The jar is securely capped and placed in the testing apparatus, which rotates at a rate of about 35 rpm for 15 min (Figure 3). The sample is removed and the percentage of stripping is estimated when the jar is viewed under fluorescent light. The results are reported in terms of the percent total aggregate surface stripped.

Static Immersion Test (AASHTO T182)

Although this test is still continued as a standard method under AASHTO, it is no longer available as an ASTM standard (originally ASTM Standard Practice D1664). The asphalt–aggregate mixture is cured for 2 h at 60°C and cooled to room temperature. It is then placed in a glass jar and covered with 600 mL of distilled water. The jar is capped and placed in a 25°C water bath and left undisturbed for 16 to 18 h. The amount of stripping is visually estimated on

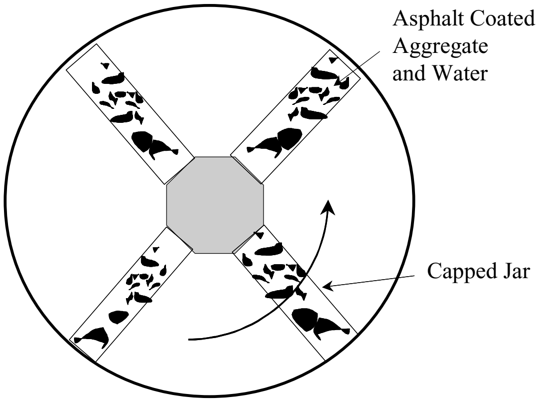


FIGURE 3 Rotating asphalt–aggregate mixture in a sealed jar for film stripping test.

the basis of the established criteria. The total visible area of the aggregate is estimated as either less than or greater than 95%. This is a major limitation of the test because the results are decided purely on the basis of a subjective estimate of less than or greater than 95%. Test results have indicated that placing samples at 60° C bath rather than 25° C for 18 h increases the amount of stripping.

Dynamic Immersion Test

The dynamic immersion test is used to accelerate the stripping effect compared with the static immersion test. The test has not been standardized and is not widely used. Samples of asphalt–aggregate mixtures are prepared the same way as for the static immersion test but are subjected to 4 h of agitation. As the period of agitation increases, the degree of stripping increases. Both static and dynamic immersion tests, however, fail to take into account the pore pressure effect and traffic action, as is the case for all tests on loose mixtures.

Chemical Immersion Test

The chemical immersion test method covers the determination of the adhesion of bitumen to stone aggregate by means of boiling asphalt-coated aggregate successively in distilled water. Increasing concentrations of sodium carbonate (Na_2CO_3) are used, numbered 0 to 9 and referred to as the Riedel and Weber (R&W) number. Zero refers to distilled water, 1 implies 0.41 g of sodium carbonate in 1 L of water, and 9 refers to the highest concentration, which is 106 g of Na_2CO_3 in 1 L of water. Between 1 and 9, for every doubling of concentration the R&W number is increased by one. The number of the concentration at which the bitumen strips to such an extent that it is no longer a film but only specks or droplets is called the stripping value.

An asphalt–aggregate test sample of 100 g is dried in an oven at 110°C. The aggregate is mixed with binder at high temperature and left to cool to room temperature. Solutions of sodium carbonate in distilled water are prepared at different concentrations. About 50 mL of distilled water is brought to boiling in a 200-mL glass beaker. Afterwards, 10 g of the prepared aggregate–binder mix is placed into the boiling water. After 1 min of boiling, the water is drained and the sample is placed on filter paper. The sample is examined for stripping after it is dry. The stripping value of the aggregate is the R&W number of the lowest concentration at which stripping occurs. If the sample does not strip at number 9, a stripping value of 10 is given to the aggregate. If no stripping is observed, the procedure is repeated, starting with the weakest concentration of sodium carbonate.

Surface Reaction Test

Test procedures have been developed at different times to quantify the level of stripping for loose asphalt–aggregate mixtures. Quantifying the degree of stripping eliminates problems encountered with visual rating. One of these procedures, developed by Ford et al. (1974), is called the surface reaction test. This test is based on the principle that calcareous or siliceous minerals will react with a suitable reagent and create a gas as part of the chemical reaction products. This generated gas, in a sealed container, will create a certain pressure that can be considered proportional to the mineral surface area exposed to the reagent. The reagent is typically an acid. The test is conducted on the asphalt–aggregate mixture after it has been subjected to the stripping effects of water. Different levels of stripping result in different exposed surface areas of aggregate particles. A larger exposed surface area will generate higher gas pressure. The advantages of the test are that it is simple and reproducible and takes less than 10 min to perform. A disadvantage is that the test requires use of highly corrosive and toxic acids.

Texas Boiling Test

The Texas boiling test procedure was developed by Kennedy et al. (1982; 1984) on the basis of the earlier work. The procedure requires adding asphalt–aggregate mixture to boiling water and bringing the water back to boiling after this addition. After 10 min, the mixture is allowed to cool while the stripped asphalt is skimmed away. The water is drained, and the wet mixture is placed on a paper towel and allowed to dry. Visual rating is conducted to assess the level of stripping. This test procedure is a quick method for evaluating the moisture sensitivity of an asphalt–aggregate mixture. However, it does not account for mechanical properties of the mix, and it does not include the effects of traffic action. The test is also subjective and qualitative, and results are judged on the basis of a visual rating. A useful application of the test could be for quick evaluation of various asphalt–aggregate combinations as a relative measure of the bond quality and stripping resistance. The procedure has been standardized as ASTM D3625 (Effect of Water on Bituminous-Coated Aggregate Using Boiling Water).

Rolling Bottle Test

The test was developed by Isacsson and Jorgensen of Sweden (1987). Aggregate chips are coated with binder and covered with water in glass jars. The jars are rotated so that the contents are agitated. Periodically, the coating of the stones is estimated visually.

Net Adsorption Test

The net adsorption test (NAT) was developed under SHRP in the early 1990s and is documented in SHRP Report A-341 (Curtis et al. 1993). The test is used to determine the affinity and compatibility of an asphalt–aggregate pair and the sensitivity of the system to water. Therefore, it can be considered a screening test.

The test comprises two steps. First, asphalt is adsorbed onto aggregate from a toluene solution, the amount of asphalt remaining in solution is measured, and the amount of asphalt adsorbed to the aggregate is determined. Second, water is introduced into the system, asphalt is desorbed from the aggregate surface, the asphalt present in the solution is measured, and the amount remaining on the aggregate surface is calculated. The amount of asphalt remaining on the surface after desorption is termed net adsorption.

The net adsorption test offers a direct means of comparing the affinity of different asphalt–aggregate pairs. The test is relatively fast and easily performed. However, SHRP Report A-341 provides mixed conclusions in terms of correlation between NAT results and moisture sensitivity results from indirect tension tests on compacted specimens. The NAT procedure was modified by researchers at the University of Nevada at Reno, and the test results were correlated with the ECS (Scholz et al. 1994). The study by Scholz et al. (SHRP-A-402, 1994) indicates that predictions of the water sensitivity of the binder as proposed by NAT show little or no correlation to wheel-tracking tests on the mixes.

Wilhelmy Plate Test and Universal Sorption Device for Surface Free Energy

In recent years, asphalt technologists have performed research into the relationship between surface free energy and moisture damage potential. Most of the surface energy research for asphalt–aggregate mixture combinations has been conducted at Texas A&M University (Elphingstone 1997; Cheng et al. 2001; Cheng et al. 2002).

The principle behind using the concept of surface free energy is that the cohesive bonding within asphalt and the adhesive bonding between asphalt and aggregate are related to the surface free energy of the asphalt and aggregate. Researchers at Texas A&M University demonstrated the effectiveness of this concept by using three different aggregates (one granite and two limestone aggregates) and two of the SHRP asphalts (AAM and AAD). The permanent deformation on compacted specimens using compressive testing correlated well with measured values of surface free energy of the asphalts and aggregates used in the research when tested in dry and wet conditions. The asphalt surface free energy is determined by using a Wilhelmy plate test, where the dynamic contact angle between asphalt and a liquid solvent is measured. The surface free energy of aggregate is measured by using a universal sorption device developed at Texas A&M University.

Pneumatic Pull-Off Test

The pneumatic pull-off test provides a rapid and reproducible means of evaluating moisture susceptibility of asphalt binders. The experimental procedure measures the tensile and bonding strength of asphalt binder applied to a glass plate as a function of time while exposed to water. Asphalt binder, containing 1.0% by weight of glass beads, is applied to a porous disk, which is then pressed onto a glass plate. The glass beads are used to control the thickness of the asphalt film and do not appear to have any effect on the results. The pressure necessary to debond the conditioned specimen at 25°C is measured with a pneumatic adhesion tester. The typical pulling rate is about 66 kPa/s, and asphalt film thickness is around 200 microns. The test has indicated that, as expected, soak time is an important factor. This means that longer exposure to water increases stripping damage if the mixture is susceptible to debonding. A study by Youtcheff and Aurilio (1997) has indicated that the viscosity building structure provided by asphaltenes is disrupted by the presence of water, and the resistance to moisture damage of the binder appears to depend on the properties of the maltenes.

Tests on Compacted Mixtures

These tests are conducted on laboratory-compacted specimens or field cores or slabs. Examples include indirect tensile freeze–thaw cyclic with modulus and strength measurement, immersion–compression, abrasion weight loss, and sonic vibration tests. This last test is also conducted on loose mixtures and is currently under investigation by the Western Research Institute. The major advantage of these tests is that the mix physical and mechanical properties, water/traffic action, and pore pressure effects can be taken into account. The results can be measured quantitatively, which minimizes subjective evaluation of test results. The drawback of these tests is that more elaborate testing equipment, longer testing times, and more laborious test procedures are needed.

Immersion–Compression Test ASTM D1075 (1949 and 1954) and AASHTO T165-55 (Effect of Water on Compressive Strength of Compacted Bituminous Mixtures)

The immersion–compression procedure was originally published as ASTM D1075-49. Therefore, the test is among the first to be used for evaluation of moisture sensitivity. Revisions were made to the procedure in 1996. Goode (1959) explains the test in detail in *ASTM Special Technical Publication 252*.

Two groups of compacted specimens are used in this test method. One group is submerged in a 120° F water bath for 4 days for conditioning, and the other group is maintained dry. An alternative approach to conditioning is to immerse the test specimens in water for 24 h at 140° F. Compressive strength is measured on specimens of both groups at 77° F at a deformation rate of 0.05 in./min per inch of height. For a 4-in.-tall specimen, the rate would be 0.2 in./min. The average strength of conditioned specimens over that of dry specimens is used as a measure of moisture sensitivity of the mix. Most agencies have used a 70% ratio as a passing limit.

Marshall Immersion Test

The conditioning phase of this test is identical to the one used for the immersion–compression test. However, Marshall stability is used as a strength parameter rather than compressive strength.

Moisture Vapor Susceptibility

The moisture vapor susceptibility procedure was developed and has been used by the California Department of Transportation (California Test Method 307). Two specimens are prepared and compacted using the kneading compactor, as for mix design testing, except that they are prepared in stainless steel molds. The compacted surface of each specimen is covered with an aluminum seal cap, and a silicone sealant is applied around the edges to prevent the escape of moisture vapor. An assembly with a felt pad, seal cap, and strip wick is prepared to make water vapor available to the specimen by placing the free ends of the strip wick in water. After the assembly is left in an oven at 60° C with the assembly suspended over water for 75 h, the specimen is removed and tested immediately in the Hveem stabilometer. A minimum Hveem stabilometer value is required, which is less than that required for the dry specimens used for mix design.

Repeated Pore Water Pressure Stressing and Double-Punch Method

This test procedure was developed by Jimenez at the University of Arizona (1974). The test falls in the category of those that include measurement of mix mechanical properties and those that take traffic dynamic loading into account. To capture the water pore pressure effect, compacted specimens undergo a cyclic stressing under water. The load is not directly in contact with the specimen. This stressing is accomplished through generating cyclic pressure within water at a rate of 580 rpm. The generated water pressure is between 35 and 217 kPa, which, according to Jimenez, is within a range comparable with pressure expected in saturated pavements under traffic. Once cyclic water pressure inducement is complete, the tensile strength of the specimens is determined by using the double-punch equipment. Compacted specimens are tested through steel rods placed at either end of the specimen in a punching configuration. Jimenez demonstrated the severity of this test by comparing predictions on similar mixtures using the immersion–compression test.

Original Lottman Indirect Tension Test

The original Lottman procedure was developed by Lottman at the University of Idaho in the late 1970s (Lottman 1978). The procedure requires one group of dry specimens and one group of conditioned specimens. The specimens are 4 in. in diameter and about 2.5 in. thick. Conditioning includes vacuum saturation of specimens under 26 in. of mercury vacuum for 30 min followed by 30 min at atmospheric pressure. The partially saturated specimens are frozen at 0° F for 15 h followed by 24 h in a 140° F water bath. This is considered accelerated freeze–thaw conditioning.

Lottman proposed thermal cyclic conditioning as an alternative. For each cycle, after 4 h of freeze at 0°F, the temperature is changed to 120°F and maintained for 4 h before being changed back to 0°F. Therefore, a complete thermal cycle lasts 8 h. The specimens go through 18 thermal cycles of this type. Lottman concluded that thermal cycling was somewhat more severe than the accelerated freeze–thaw conditioning with water bath. Conditioned and dry specimens are both tested for tensile resilient modulus and tensile strength using indirect tensile equipment. The loading rate is 0.065 in./min for testing at 55°F or 0.150 in./min for testing at 73°F. The severity of moisture sensitivity is judged on the basis of the ratio of test values for conditioned and dry specimens.

AASHTO T283 (Modified Lottman Indirect Tension Test Procedure)

The AASHTO Standard Method of Test T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage," is one of the most commonly used procedures for determining HMA moisture susceptibility. The test is similar to the original Lottman with a few exceptions. One of the modifications is that the vacuum saturation is continued until a saturation level between 70% and 80% is achieved, compared with the original Lottman procedure that required a set time of 30 min. Another change is in the test temperature and loading rate for the strength test. The modified procedure requires a rate of 2 in./min at 77°F rather than 0.065 in./min at 55°F. A higher rate of loading and a higher temperature were selected to allow testing of specimens with a Marshall stability tester, available in most asphalt laboratories. The higher temperature also eliminates the need for a cooling system.

Briefly, the test includes curing loose mixtures for 16 h at 60°C, followed by a 2-h aging period at 135°C. At least six specimens are prepared and compacted. The compacted specimens should have air void contents between 6.5% and 7.5%. Half of the compacted specimens are conditioned through a freeze (optional) cycle followed by a water bath. First, vacuum is applied to partially saturate specimens to a level between 55% and 80%. Vacuum-saturated samples are kept in a –18°C freezer for 16 h and then placed in a 60°C water bath for 24 h. After this period the specimens are considered conditioned. The other three samples remain unconditioned. All of the samples are brought to a constant temperature, and the indirect tensile strength is measured on both dry (unconditioned) and conditioned specimens (Figure 4).

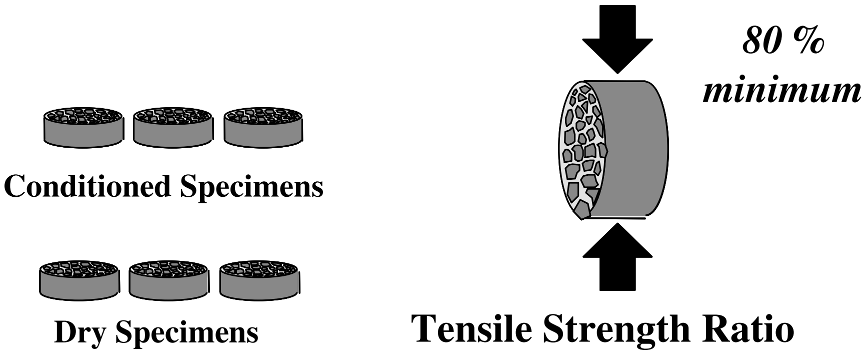


FIGURE 4 Indirect tensile test used for dry and conditioned specimens for AASHTO T283.

State highway agencies report mixed success with this method. Several research projects have dealt with the method's shortcomings, resulting in suggested "fixes," but the test remains empirical and liable to give either false positives or false negatives in the prediction of moisture susceptibility. Major concerns with this test are its reproducibility and its ability to predict moisture susceptibility with reasonable confidence (Solaimanian and Kennedy 2000a).

AASHTO T283 was adopted by the Superpave system as the required test for determination of moisture damage. Following this adoption, state highway agencies made this test the most widely used procedure for determination of moisture damage potential. Later, Epps et al. (2000) investigated this test extensively under NCHRP Project 9-13. The project, "Evaluation of Water Sensitivity Tests," was completed in 1999 and provided recommended changes to AASHTO T283 to better accommodate its use in the Superpave system. The researchers investigated the effect of a number of factors on the test results, including different compaction types, diameter of the specimen, degree of saturation, and the freeze–thaw cycle. They used five aggregates, two considered good performers in terms of moisture resistance and the other three considered to have low to moderate resistance to moisture damage. Binders were specific to each mix and included PG 58-28, 64-22, 64-28, and 70-22. In summary, the following conclusions were drawn from that study, as reported by Epps et al. (2000):

- In general, resilient modulus had no effect on tensile strength of dry specimens, conditioned specimens with no freeze–thaw, or conditioned specimens with freeze–thaw.
- Dry strength of 100-mm-diameter Superpave gyratory compactor (SGC) specimens and 100-mm Hveem specimens was larger than that of 150-mm SGC specimens.
- Dry strength of 100-mm Marshall specimens was the same as that of the 150-mm SGC specimens.
- Dry strength of 100-mm-diameter SGC specimens was similar to the dry strength of 100-mm Hveem specimens.
- Dry strength increased as the aging time for the loose mix increased.
- The freeze–thaw tensile strength was the same as the no freeze–thaw tensile strength.
- The level of saturation had little effect on the no freeze–thaw and freeze–thaw tensile strengths. The levels of saturation used in the study were 50%, 75%, and 95%.
- The tensile strength ratio of 150-mm SGC specimens was larger than the tensile strength ratio of 100-mm-diameter SGC specimens or 100-mm Hveem specimens.
- The tensile strength ratio of 150-mm SGC specimens was similar to the tensile strength ratio of 100-mm Marshall specimens.

The results obtained in this study indicated that the water sensitivities of the mixtures as described by the state departments of transportation did not satisfactorily match the observed behavior of the mixtures for a number of data groups.

ASTM D4867 (Tunnicliff–Root Test Procedure)

ASTM D4867, "Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures," is comparable with AASHTO T283. In both methods, the freeze cycle is optional. However, curing of the loose mixture in a 60°C oven for 16 h is eliminated in the ASTM D4867 procedure.

Texas Freeze–Thaw Pedestal Test

The Texas freeze–thaw pedestal test was proposed by Kennedy et al. (1982) as a modification of the water susceptibility test procedure proposed by Plancher et al. (1980) at the Western Research Institute. The test is in the category of those evaluating the compatibility between asphalt binder and aggregate and the corresponding adhesiveness.

The test is designed to minimize the effect of mechanical properties of the mix by using a uniform-sized aggregate. It prescribes the preparation of hot mix using a fine fraction of aggregate [passing the No. 20 (0.85-mm) and retained on the No. 35 (0.50-mm) sieve] and asphalt at a temperature of 150°C. The hot mix so prepared is kept in the oven at 150° C for 2 h and stirred for uniformity of temperature every hour. At the end of 2 h, the mix is removed from the oven and cooled to room temperature, reheated to 150°C, and compacted with a load of about 28 kN for 15 min to form a briquette 41 mm in diameter by 19 mm in height (the procedure does not prescribe any tolerance for the dimensions). The briquette is cured for 3 days at room temperature and placed on a pedestal in a covered jar of distilled water (Figure 5). It is then subjected to thermal cycling of 15 h at –12° C, followed by 9 h at 49° C. After each cycle, the briquette surface is checked for cracks. The number of cycles required to induce cracking is a measure of water susceptibility (typically 10 freeze–thaw cycles).

Pedestal test specimens are prepared from a narrow range of uniformly sized aggregate particles coated with 5% asphalt. This formulation reduces aggregate particle interactions in the mixture matrix, and the thin asphalt coating between aggregate particles produces a test specimen that is highly permeable and thus allows easy penetration of water into the interstices found between aggregate particles. Therefore, moisture-induced damage in the specimen can easily arise either from bond failure at the asphalt–aggregate interface region (stripping) or from the fracture of the thin asphalt–cement films bonding aggregate particles (cohesive failure) by formation of ice crystals.

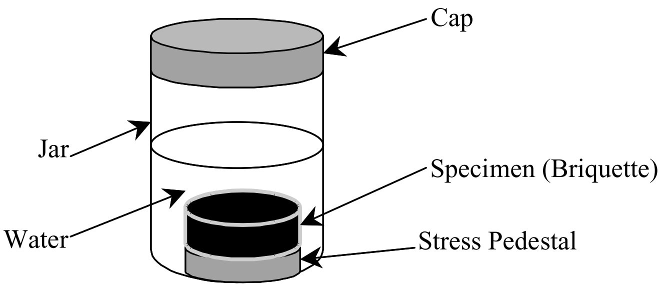


FIGURE 5 Freeze–thaw pedestal test: compacted specimen in a water jar ready for thermal cycling.

Hamburg Wheel-Tracking Device

The HWTD was developed by Esso A.G. in the 1970s in Hamburg, Germany (Romero and Stuart 1998). This device measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of an asphalt concrete specimen that is immersed in hot water. The wheel rolls back and forth on the submerged specimen. Originally, a pair of cubical or beam test specimens were used. However, with the increasing use of the SGC, the Texas Department of Transportation (TxDOT) and others have adopted a testing protocol using cylindrical specimens compacted in the SGC (Figure 6). Typically, gyratory-compacted specimens are arranged in a series to provide the required path length for the wheels. Each steel wheel passes 20,000 times or until 20 mm of deformation is reached. The measurements are customarily reported versus wheel passes.

The results from the HWTD are the postcompaction consolidation, creep slope, stripping slope, and stripping inflection point (Figure 7). The postcompaction consolidation is the deformation measured at 1,000 passes, assuming that the wheel is densifying the mixture within the first 1,000 wheel passes. The creep slope is the number of repetitions or wheel passes to create a 1-mm rut depth due to viscous flow. The stripping slope is represented by the inverse of the rate of deformation in the linear region of the deformation curve, after stripping begins and until the end of the test. The stripping slope can be quantified as the number of passes required 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. It represents the moisture damage resistance of the HMA and is assumed to be the initiation of stripping (Aschenbrener and Currier 1993).

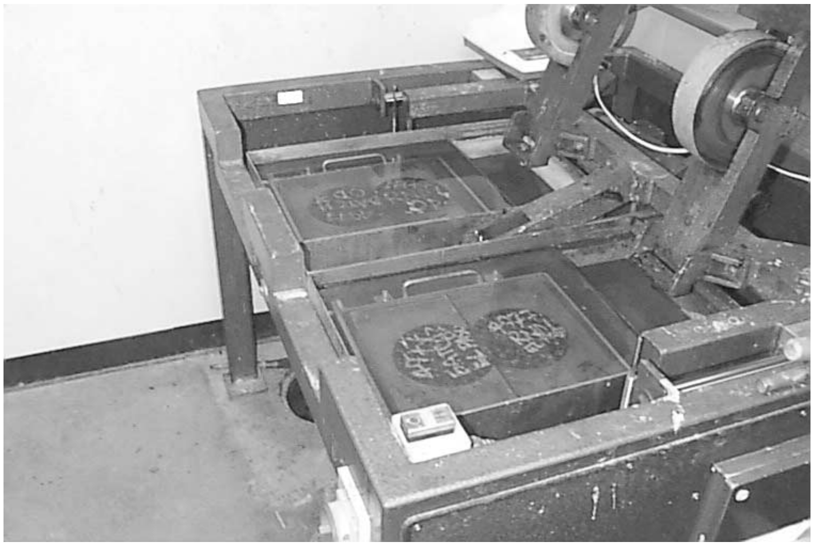


FIGURE 6 HWTD with cylindrical specimens.

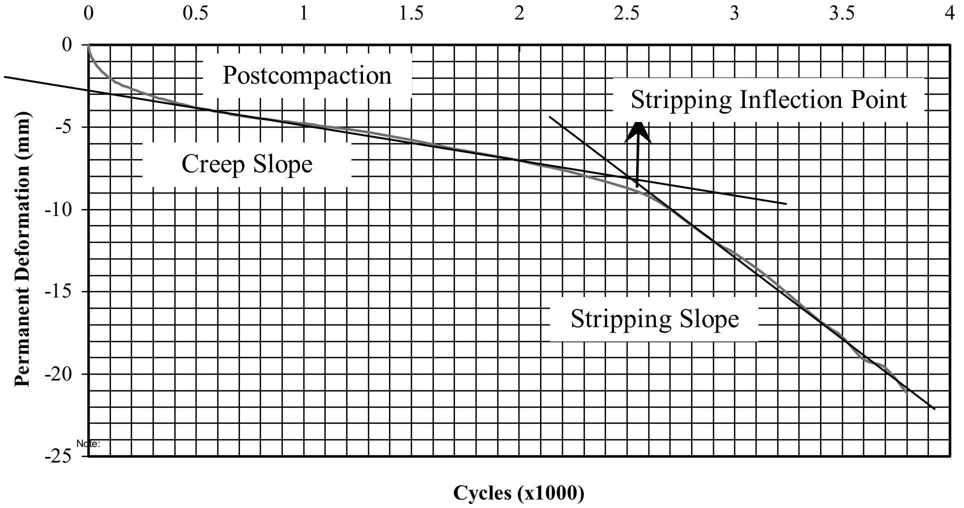


FIGURE 7 Results from testing with the HWTD.

This device has been researched extensively through a series of projects (Aschenbrener and Currier 1993; Aschenbrener 1995; Stuart and Izzo 1995; Stuart and Mogawer 1995; Aschenbrener et al. 1995; Stuart and Mogawer 1997). The Federal Highway Administration (FHWA) has been involved in several research projects using the HWTD. Stuart and Izzo (1995) worked on finding a correlation between binder stiffness and rutting susceptibility using the HWTD. They found that a stiffer binder would provide a mixture with lower rutting susceptibility. Stuart and Mogawer (1995), using different binders, concluded that the creep slopes should be used for evaluating rutting susceptibility. The researchers also demonstrated that decreasing the coarse aggregate content from 80% to 60% had no significant effect on the rutting performance of the mixtures.

Stuart and Mogawer (1997) also performed a study to evaluate the validity of laboratory wheel-tracking devices on the basis of pavement performance results. They concluded that the increase in nominal maximum size from 19 mm to 37.5 mm, and an associated 0.85% decrease in optimum binder content, decreased rutting susceptibility on actual pavements. However, none of the wheel-tracking devices tested, including the HWTD, adequately predicted a decrease in rutting susceptibility with increased nominal maximum aggregate size.

The Colorado Department of Transportation (CDOT) has performed extensive research evaluating HMA with the HWTD. Aschenbrener (1995) evaluated factors that influence the results from the HWTD. He found that there was an excellent correlation between stripping observed in laboratory tests and the moisture damage of pavements with known field performance. There was also an excellent correlation between stripping inflection point and known stripping performance.

It was found that for good pavements, the stripping inflection point was higher than 10,000 passes, and for pavements that lasted 1 year, the stripping inflection point was less than 3,000 passes. It was also found that the results from the HWTD were sensitive to aggregate properties such as dust coating on the aggregates, clay content, and high dust-to-asphalt ratios. One other finding was that as the short-term aging time increases, samples become more resistant to moisture damage. This is in agreement with other research that shows that higher mix stiffness for conventional binders generally gives better stripping results (because water penetration will be more difficult). Aschenbrener recommended that testing temperatures for the HWTD be selected on the basis of the high temperature environment the pavement will experience.

Although it is used in the asphalt industry primarily as a screening test for moisture sensitivity, the HWTD test has also shown promise in providing information on aggregate properties (Solaimanian and Kennedy 2000b). In spite of its utility as a screening test, a disadvantage is that this test does not provide a fundamental property that can be used for modeling purposes. Recommended values for specific climates and traffic levels are also not available. The test also simulates the stripping mechanism that takes place when rainfall occurs during the hot time of the year, hence Aschenbrener's recommendation that test temperatures should be selected from the hottest time of the year. This recommendation may not be applicable to locations where water primarily enters the asphalt concrete during the cooler time of the year.

Environmental Conditioning System

As part of the SHRP Asphalt Research Program, the mechanisms responsible for moisture damage were extensively investigated, and a new system for predicting the moisture susceptibility of HMA was developed (Al-Swailmi and Terrel 1992). The ECS test procedure was developed at Oregon State University (OSU) as a part of the Asphalt Research Program. The procedure (originally designated as AASHTO TP34, "Determining Moisture Sensitivity of Compacted Bituminous Mixtures Subjected to Hot and Cold Climate Conditions") was designed to determine the moisture susceptibility of compacted HMA specimens under conditions of temperature, moisture saturation, and dynamic loading similar to those found in pavements. A schematic diagram of the ECS is shown in Figure 8.

In this procedure, a membrane-encapsulated specimen is subjected to cycles of temperature, repeated loading, and moisture conditioning. The specimens used in the ECS procedure are 102 ± 4 mm in diameter and 102 ± 4 mm in height. The air void content of the test specimens must be in the range of 7.5% ± 0.5% (note that AASHTO T283 requires 7.0% ± 0.5%). The loose asphalt concrete mixtures are prepared following AASHTO TP4-93, Edition 1B, and are short-term aged in accordance with AASHTO PP2-94, first edition. The short-term

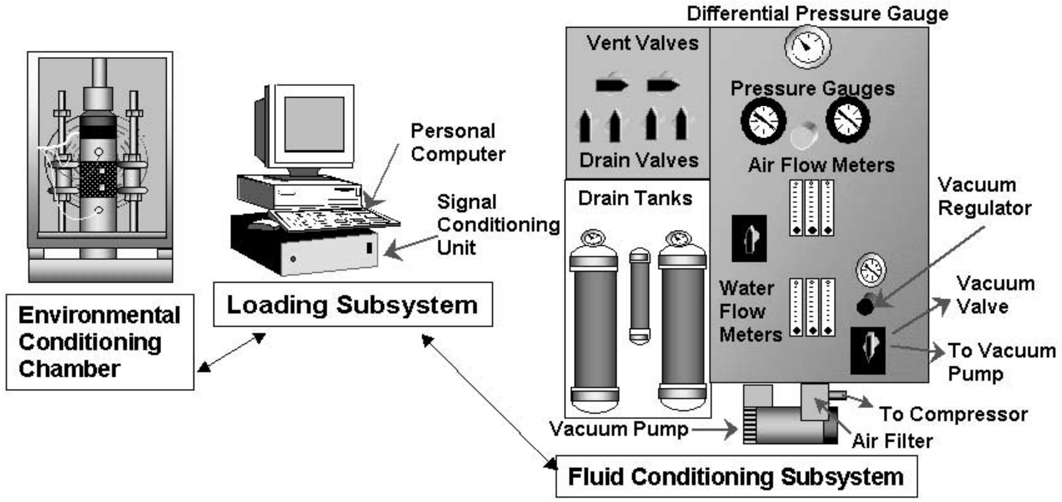


FIGURE 8 Schematic diagram of the ECS test.

aged mixtures are compacted using an SGC per AASHTO TP4-93. The compacted specimens are left at room temperature overnight to cool to room temperature. Afterwards, a latex membrane is placed around the specimen and sealed with a silicone sealant. The specimens are then set aside for a minimum of 15 h to dry.

The air permeability and dry resilient modulus (M_R) of the specimen are determined after it is placed inside the ECS load frame. The air permeability is determined by flowing air through the specimen at a vacuum level of 68 kPa. The resilient modulus is determined by applying a load in the form of a haversine wave with a loading period of 0.1 s and a rest period of 0.9 s. Pulling deaired distilled water through it at a vacuum level of 68 kPa then saturates the specimen. In the next step, the water permeability of the specimen is determined.

The saturated specimen is subjected to a "hot cycle," that is, the temperature of the specimen is elevated to 60°C for 6 h while it is subjected to the haversine loading. The specimen is cooled to a temperature of 25° C for at least 2 h. At the end of the 8 h, the conditioned M_R and the water permeability are determined. The process is repeated for two more cycles (i.e., 6 h of loading and heating at 60°C followed by 2 h of cooling). If the ratio of the conditioned M_R to the unconditioned M_R falls below 0.7, the mixture is considered as moisture susceptible; if the ratio is greater than 0.70 the mixture is considered acceptable. Needless to say, this procedure is too long and complicated and must be shortened and simplified before it can be adopted for routine mixture design or quality control testing.

One advantage of the ECS is that it includes the influence of traffic loading and the resulting effect of pore water pressure, a significant consideration if the mechanism that causes moisture damage in the pavement is to be simulated.

The ECS showed promise when it was introduced to the industry. One of the main advantages of the system was its capability of simulating field conditions within the laboratory to some extent. The test setup had the capability of applying load while the specimen was at elevated temperature and saturated. Lottman (1971), Majidzadeh and Brovold (1966), Anderson and Shamon (1984), Hallberg (1950), and Jimenez (1974) have suggested that one of the mechanisms of stripping is the inducement of pore pressure within the air voids of HMA due to traffic and temperature loads. They proposed that pore water pressure could exceed the adhesive strength of the binder aggregate surface and break the adhesive bonds. The researchers at OSU tried to simulate this mechanism by applying a repeated load on the specimen while the saturated specimen was heated. However, the visual stripping, permeability, and modulus measurements from AASHTO TP34 did not provide a better relationship with field observations than what was obtained from AASHTO T283. In addition, the test was more complex and expensive than the other tests existing at the time.

One of the first studies in which the ECS and the HWTD were evaluated includes the work conducted by Aschenbrener et al. (1994). The researchers compared the results from the ECS and the HWTD for 20 pavement sites with known histories of performance with respect to moisture damage. Performance of the sites was categorized as good, high maintenance, complete rehabilitation, or disintegrator. Their conclusion was that the HWTD is a very severe test, especially for the sites with good field performance. The researchers concluded that, with some modification, the HWTD results correlated well with field performance of the pavements for which the tests were conducted. With regard to the ECS, the conclusion was that the samples were only mildly conditioned. Only 3 of the 13 sites with poor field performance failed in the laboratory.

Tandon et al. (1997), in a study sponsored by TxDOT, performed a comprehensive evaluation of the ECS in which special emphasis was placed on the accuracy and precision of the system. Researchers identified numerous problems with the resilient modulus measurement systems and conditioning procedures. The original ECS system as proposed by the SHRP researchers consisted of a pneumatic loading system placed inside a conditioning chamber. The chamber had the capability of maintaining temperature at 60° C. However, water at room temperature was supplied to the specimen (for maintaining saturation). This reduced the temperature of the specimen to 40°C. This cooling of the specimen might affect the proper conditioning of the specimen. Diverting the flow of water through a heating system before it reaches the specimen could eliminate this problem. To maintain saturation, water is continuously pulled through the specimen by using a vacuum. The vacuum also induces confinement to the specimen and reduces the possibility of specimen bulging during the conditioning phase.

A coefficient of variation of more than 30% was observed during the preliminary evaluation of the original ECS using 15 HMA specimens (3 types of mixes with 5 specimens of each mix). To identify causes of variability, the resilient modulus of a synthetic specimen was measured nine times by dismantling and reassembling the specimen in the test setup. The observed coefficient of variation was similar to that of the HMA mix, indicating that the problem was with the test setup. The rigidity of the test setup, vibrations in the measurement system, and the precision of the strain measurement device were evaluated. Researchers noted that the system lacked rigidity and had to be replaced with a rigid loading system. The loading system was placed inside the chamber on a flexible support, contributing to excessive system compliance and allowing vibrations (due to loading) to be transferred to the strain measurement system. This resulted in reduction of the precision of the strain measurement system. In addition, the strain measurement system consisted of yoke assembly and linear variable differential transformer (LVDT). Researchers ascertained that the yoke assembly significantly affected the repeatability of the system and needed to be replaced by a more robust strain measurement system.

On the basis of the evaluation and recommendations of the researchers, Alam (1997) modified the system and proposed the following procedure:

> The ECS system consists of a fluid conditioning subsystem, an environmental conditioning subsystem and a loading subsystem. The fluid conditioning subsystem maintains a constant flow of water and supply of vacuum to the specimen. The environmental conditioning subsystem, which houses the loading subsystem, can maintain a desired temperature and humidity. The loading subsystem can simulate traffic conditions by applying a repeated half-sine loading on the specimen throughout the conditioning phase. The same subsystem is also used for measuring the resilient modulus of the specimen.
>
> The specimen to be tested is prepared at an air void content of between 7% and 8% with a height of 4 ± 0.15 in. (102 ± 4 mm). The prepared specimen is removed from the mold and cooled at room temperature for one hour. The specimen is then subjected to static immersion saturation for five minutes, enclosed within a membrane, and placed between the top and bottom end platens of the resilient modulus (MR) test setup. After this step, water at room temperature is circulated through the specimen for one hour. After one hour of waiting, the water flow is stopped, the vacuum is released, and the reference resilient modulus is measured.

> The specimen is then conditioned either for six or eighteen hours. During the conditioning, a flow of water at 140°F (60° C) is maintained while a cyclic load is applied to the specimen. After six hours of conditioning, the chamber door is opened, conditioning is stopped and the circumference of the specimen is measured. If the circumference of the specimen increases by more than 2%, the material will be considered as moisture-susceptible. At this point, the conditioning process is stopped, and the specimen is removed from the setup. Otherwise, the specimen is conditioned for twelve additional hours. After the specimen is cooled, the resilient modulus of the specimen is measured again and is considered as the conditioned resilient modulus. If the MR ratio (ratio of the conditioned and unconditioned resilient moduli) falls below 0.8, the mixture will be considered as marginal. If the MR ratio is equal to or above 0.8, the mixture will be considered as a well-performing mix.

Tandon and Nazarian (2001) tested three different types of mixes with the ECS: well performing, poor performing, and marginal performing. The new test setup and protocol were evaluated by using blind mixes (Tandon and Nazarian 2001). The predicted behavior from the modified ECS procedure matched field performance in some cases, and in other cases it did not. A postmortem study indicated that the gradation used in specimen production did not consistently match the job mix formula. New specimens were prepared as per job mix formula, and the results matched the anticipated field performance.

This validation study indicates one of the limitations of any moisture susceptibility laboratory test that relies on mechanical properties. Since the modulus or strength of a material is dependent on parameters such as the gradation, asphalt concrete content, and air void content, any deviation from the job mix formula during construction or laboratory testing may favorably or unfavorably affect the moisture susceptibility of the mixture.

Flexural Fatigue Beams Test with Moisture Conditioning

To evaluate the effects of moisture damage on the fatigue cracking performance of asphalt concrete mixes, experimentation on moisture conditioning of flexural fatigue beams was done by Shatnawi et al. (1995). Fatigue beams were cut from field sections that had exhibited different levels of moisture-related damage. Raw materials from these projects were also used to create laboratory-compacted fatigue beams, including some with lime treatment added.

The conditioned beams were partially saturated to 60% to 80% by using a vacuum and then subjected to three repeated 5-h cycles of 60° C followed by 4 h at 25° C while remaining submerged, and one 5-h cycle at –18° C. They were then removed from the water bath and tested for fatigue following AASHTO TP-8. The results showed that the conditioning had a significant effect on the initial stiffness and on the fatigue performance in the laboratory. For the laboratory-compacted specimens asphalt content and air void content were not independently controlled, and the results showed that binder contents reduced by 0.5% produced higher air void contents under standard compaction, which together increased the moisture susceptibility of both initial stiffness and fatigue life.

Some of the specimens obtained from the field had air void contents greater than 12%, which indicated that their moisture susceptibility in the field was highly related to construction compaction control. The results also showed that lime marination treatment improved the performance of the fatigue beams. Two potential reasons for the benefits of the lime treatment could not be separated in the experiment design: the lime increased the fines content of the mixes, which resulted in lower air void contents under a standard laboratory compaction effort, and it was assumed that there was a chemically induced benefit as well.

ECS/Simple Performance Tests Procedure

New test procedures such as simple performance tests (SPTs) are emerging as a result of NCHRP Projects 9-19, 9-29, and 1-37. These tests will fill the gap for the Superpave design system, which currently lacks mechanical tests as part of the design procedure. The proposed tests are dynamic modulus, repeated axial load, and static axial creep tests. NCHRP Project 9-34, currently in progress, is using these tests with the ECS to develop new test procedures for evaluation of moisture sensitivity (Figures 9 and 10). It is anticipated that modifications to the current conditioning are required to obtain the most reliable procedure. Below is a brief description of the three SPTs under evaluation for moisture sensitivity.

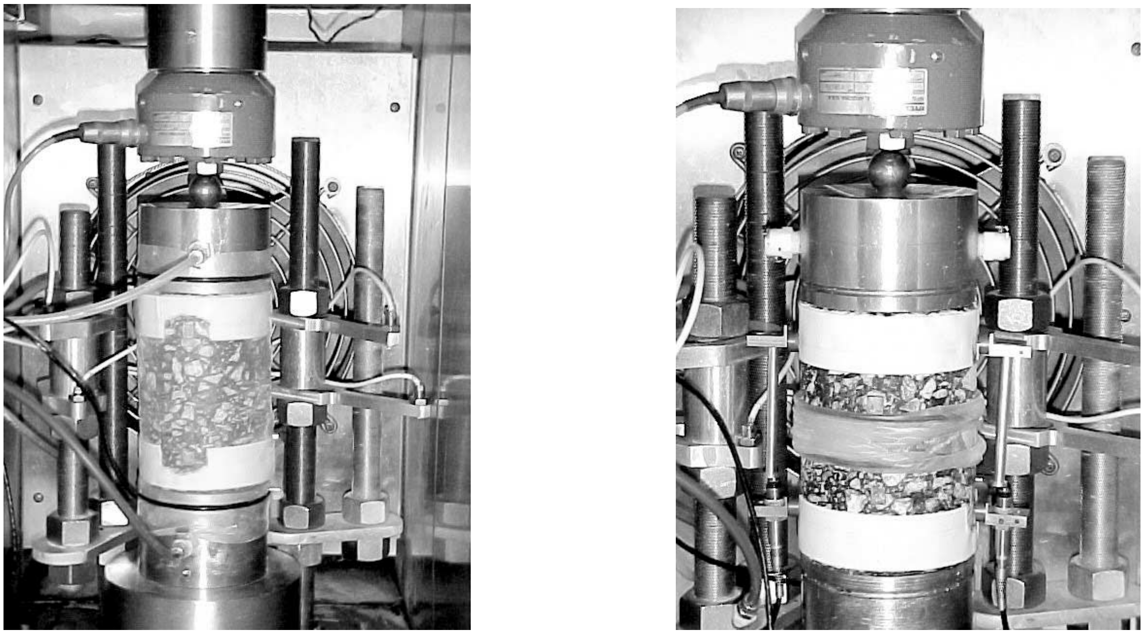
Dynamic Modulus To measure dynamic modulus, sinusoidal loads are applied to the specimen at different test temperatures and test frequencies. A sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The applied stress and the resulting recoverable axial strain response of the specimen are measured and used to calculate the dynamic modulus and phase angle.

In this procedure, a 150- by 150-mm specimen is prepared using an SGC and is cored in the center to obtain a 100-mm (diameter) by 150-mm (height) specimen. The cored specimen is sawed at the ends to make leveled specimens. The gauge length for measuring axial deformations is 101.6 mm ± 1 mm. The specimen is placed in the environmental chamber and allowed to equilibrate to the specified testing temperature ±1°C. A contact load (P_{min}) equal to 5% of the dynamic load is applied to the specimen. Sinusoidal loading ($P_{dynamic}$) is applied to the specimen in a cyclic manner. The dynamic load is adjusted to obtain axial strains between 50 and 150 microstrain.

The recommended test series for the development of master curves for use in pavement response and performance analysis consists of testing at –10°C, 4.4°C, 21.1°C, 37.8°C, and 54.4°C at loading frequencies of 0.1, 0.5, 1.0, 5, 10, and 25 Hz at each temperature. Testing at a given temperature begins with the highest frequency of loading and proceeds to the lowest. At the beginning of testing, the specimen is preconditioned with 200 cycles at 25 Hz. A typical rest time period between each frequency run is 2 min. This rest period shall not exceed 30 min for any two-frequency runs.

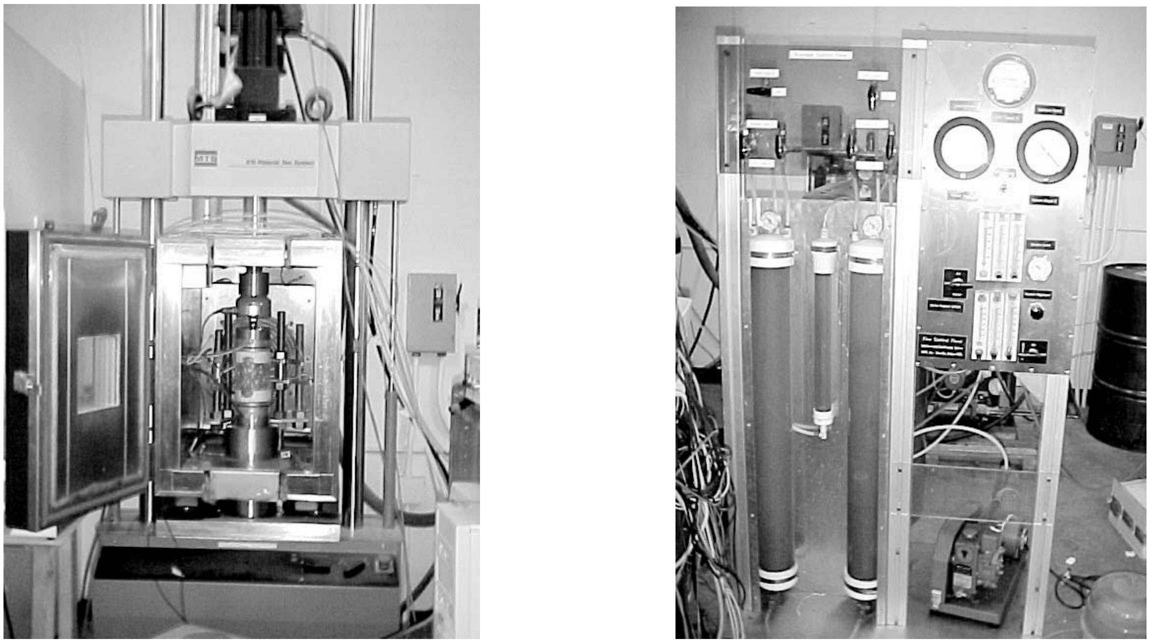
The suggested procedure includes conditioning requirements modified from those of the NCHRP Project 9-34 study. Since it is difficult to perform dynamic modulus testing at every single temperature, one test temperature is selected for the tests conducted at all frequencies.

Flow Number In this test, a cylindrical sample of asphalt concrete mixture is subjected to a haversine axial load. The load is applied for a duration of 0.1 s with a rest period of 0.9 s. The rest period has a load equivalent to the seating load. The test can be performed without confinement, or else a confining pressure is applied to better simulate in situ stress conditions. Cumulative permanent axial and radial strains are recorded throughout the test. In addition, the number of repetitions at which shear deformation, under constant volume, starts is defined as the flow number.



(a) (b)

FIGURE 9 Specimen setup for (*a*) conditioning and (*b*) testing.



(a) (b)

FIGURE 10 (*a*) Testing chamber and (*b*) environmental conditioning subsystem for ECS/SPT setup.

The specimen preparation, size requirements, and placement in the machine are similar to those of the dynamic modulus test. The only difference is that radial LVDTs are also attached to the specimen.

The recommended test protocol for the SPT for use in the Superpave volumetric mix design consists of testing the asphalt mix at one effective pavement temperature T_{eff} and one design stress level selected by the design engineer. The effective pavement temperature T_{eff} covers approximately the temperature range of 25°C to 60° C. The design stress levels cover the range from 69 to 207 kPa for the unconfined tests and from 483 to 966 kPa for the confined tests. Typical confinement levels range between 35 and 207 kPa. For the NCHRP Project 9-34 research, the test temperature and required stress level are selected within the range specified by the test procedure.

Flow Time In this test, a cylindrical sample of asphalt concrete mixture is subjected to a static axial load. The test can be performed without confinement, or a confining pressure may be applied to better simulate in situ stress conditions. The flow time is defined as the postulated time when shear deformation, under constant volume, starts. The applied stress and the resulting permanent or axial strain response of the specimen are measured and used to calculate the flow time.

Tests Methods to Evaluate Asphalt–Aggregate Adhesion for Surface Treatments and Chip Seals

Several tests are used particularly to evaluate the adhesion between aggregates and binder in a chip seal or surface treatment application. The immersion tray, plate, and sand mix tests are examples.

Immersion Tray Test

In the immersion tray test, a film of binder is placed in a shallow tray and covered with water. Afterwards, aggregate chips are pressed into the surface of the binder. The chips are removed after a specified time, and the coverage of the face in contact with binder is estimated visually. The test provides a general and rough estimate of adhesion strength between asphalt and aggregate. The rate and magnitude of pressing and pulling force can affect the results.

Plate Methods

In the plate method test, a film of binder is placed on a metal plate. Wet or dry aggregate chips are pressed or rolled into the surface. The plate may be immersed in water. The adhesion of the chips is determined by blows to the back of the plate. Chips that fall off are weighed or counted, or the chips are removed by pliers and the coating determined. The use of wet chips gives a measure of active adhesion.

Sand Mix Method

Wet sand is mixed or shaken with a solution of binder in solvent. The color and cohesion of the sand are determined. A black agglomerated sand is a positive result.

Extent of Use of Various Moisture Sensitivity Tests by State Departments of Transportation

Various versions of AASHTO T283 and ASTM D4867 tests are the most commonly used procedures within various agencies. A survey by Hicks (1991) showed that almost half of the 44 agencies surveyed were using these procedures before developments made by SHRP (Table 3). The rating in the table is based on a 0 to 9 scaling, with 9 referring to 100% effectiveness of the method. A recent survey of 55 agencies (including 50 states) compiled by Aschenbrener indicates that more agencies have moved toward using these two procedures or their modified versions after SHRP. Table 4 shows that more than 80% of the agencies that use a moisture sensitivity test procedure favor AASHTO T283 and ASTM D4867 or a similar procedure. Seven agencies have reported that they do not use any moisture sensitivity test for design.

In 1988, Kiggundu and Roberts quantified the effectiveness of several tests, on the basis of test data from various researches, as shown in Table 5.

The success/failure ratings, as established by Kiggundu and Roberts and presented in Table 5, are based on comparing the laboratory predictions with the field performance ratings. A higher percent success implies a larger number of "correct" predictions.

TABLE 3 Agencies Using Different Moisture Sensitivity Tests Before SHRP (Hicks 1991)

Test Method	No. of Agencies Using	Average Rating	
		Number	Description of Effectiveness
Boiling water (ASTM D3625)	9	5	Slight to moderate
Static immersion (AASHTO T182)	3	4	Slight
Lottman (NCHRP 246)	3	7.5	High
Tunnicliff and Root (ASTM D4867)	9	5	Slight to moderate
Modified Lottman (AASHTO T283)	9	7.5	High
Immersion–compression (AASHTO T165)	11	5	Slight to moderate

TABLE 4 Agencies Using Different Moisture Sensitivity Tests After SHRP

Test Method	No. of Agencies Using
Boiling water (ASTM D3625)	0
Static immersion (AASHTO T182)	0
Lottman (NCHRP 246)	3
Tunnicliff and Root (ASTM D4867)	6
Modified Lottman (AASHTO T283)	30
Immersion–compression (AASHTO T165)	5
Wheel tracking	2

SOURCE: R. G. Hicks, L. Santucci, and T. Aschenbrener, "Introduction and Seminar Objectives" (Topic 1 of this seminar).

TABLE 5 Success Rates of Test Methods (Kiggundu and Roberts 1988)

Test Method	Minimum Test Criteria	% Success
Modified Lottman (AASHTO T283)	TSR = 70%	67
	TSR = 80%	76
Tunnicliff–Root (ASTM D4867)	TSR = 70%	60
	TSR = 80%	67
	TSR = 70%–80%	67
10-minute boil test	Retained coating 85%–90%	58
Immersion–compression (AASHTO T165)	Retained strength 75%	47

NOTE: TSR = tensile strength ratio.

SUMMARY

Moisture damage has been a topic of great interest to asphalt pavement technologists and state highway agencies for many years. Over the past 70 years, the industry has witnessed development of a considerable number of tests by many researchers and agencies.

The tests developed fall into general categories: those that are conducted on loose asphalt–aggregate mixtures and those that are conducted on compacted mixes. Most of the tests of the first group provide an estimate of the asphalt–aggregate compatibility and stripping potential. Most of the tests in the second group attempt to take the mix properties, water action, and traffic into account in different ways. Some of the tests of the second group provide moisture sensitivity of the mix on the basis of a mix parameter such as strength or modulus before and after conditioning. Others provide some measure of damage such as permanent deformation to the mix while being conditioned under combined load and water actions.

Some tests have been calibrated and implemented on a local basis (a region within a state). No test has been successfully calibrated and implemented across a wide spectrum of conditions. Reasons for the lack of widespread calibration with field performance include the limitations of the tests in including all of the effects causing moisture damage, lack of accessible field performance data, and difficulties with the tests such as variability and difficulty of operation.

Many variables in the field make field correlation difficult, but development of such a correlation remains absolutely necessary. This has been a major shortcoming in the development of effective laboratory tests that can provide quantitative results used in specifications and design across a wide range of conditions.

Mechanisms of moisture susceptibility/stripping may be different because of the different variables, but tests and their calibration must take into account materials, construction, traffic, and climate. The result will be that a given mix will have different risks depending on where and how it will be used, and these factors must be accounted for in test development, test evaluation and calibration, and test implementation.

Databases that include the required variables and sufficient numbers of projects do not exist at this time and are very difficult to develop. However, databases of this type are necessary for effective calibration of laboratory tests for moisture susceptibility and stripping.

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TOPIC 3

Questions and Answers

MANSOUR SOLAIMANIAN
Pennsylvania State University, Speaker

Q1—John D'Angelo, Federal Highway Administration
I will agree with you. I think one of the big things we have to do in any of this testing is try and simulate what's happening in the field. But as I went through all the testing you showed here, you always talked about making specimens in the 7% range, plus or minus. I am really a believer that we're not even close to what's going on in the field. I think a lot of what we see in the field is actually much higher air voids, and that's a big problem in that it's not being recognized yet. How can we get a lab test to correlate to the field when the lab voids aren't even close to what's going on in the field? Have you looked at all at trying to address some of these issues, particularly about what's really happening in the field and what level of compaction we really have out there? I'll let you go from there.

A—Mansour Solaimanian
Thank you, John. I do agree with you. The construction air void has a major effect, and that needs to be looked at very closely. It's not just a matter of stripping when you talk about the air void effect. It's also considering the effect of air voids on rutting. You do your mix design, and then you make your specimens at 7% air voids, for example, for performance testing. Then you make your prediction of the performance of the mix and you wonder how this correlates with the field air voids. So that is a very general question. It's not just for stripping, it's for rutting and fatigue and other properties that you try to simulate or predict in the laboratory. So as part of this project, one of the things that we plan to do is to consider the air void effects in these tests and get them to the typical acceptable levels in the field. I think most states don't accept a mix if the density is under 90%. Maybe we should take the air voids to the lowest acceptable level even though a penalty might be applied. We should then see how the results compare in terms of your failure and success with a 7% or any other air void level we are currently working on. Right now, we have only been looking at a typical level of air voids that has been used in T283 and other test procedures.

Q2—Dale Rand, Texas Department of Transportation
On the slide that showed the percentage of success, can you elaborate on the criteria used on the percentage of success? Was that an opinion or was that based on something else? It kind of implies that the test correlates with something.

A—Mansour Solaimanian
You notice that at the bottom of the slide, I had Kiggundu and Roberts. I took the data directly from their interpretation of failure and success, and I believe they looked at the mixes that had stripped and the mixes that did not strip or were considered good. I do not know what exactly their criteria have been on deciding which one had been a stripping mix in the field and which one not. They looked at the laboratory results and made a comparison against the field data.

They decided which ones correlated well with the stripping ones and which ones did not. This way, they came up with percentages to indicate rate of success in prediction. For example, if a material is stripped in the field, and the lab criterion is 70% on TSR while we get 60%, then we consider this a successful prediction. On the other hand, if a mix had stripped and we had a TSR of 90%, then the prediction was not successful.

Q3—Gayle King, Koch Pavement Solutions
Mansour, great presentation. I find it interesting that you emphasize the methylene blue test but don't talk about sand equivalency. My own prejudice lies in that same direction. A French sabbatical gave me a strong appreciation for the surface activity of fines, particularly as related to moisture damage in mixes. Of course methylene blue is now part of ISSA microsurfacing specifications, because fines also have a strong impact on emulsion break. Studies by Tim Aschenbrener and Ken Kandhal showed similar correlations between methylene blue and Hamburg. Although correlations weren't perfect, Hamburg consistently failed when methylene blue was high. The entire experimental scatter fell in the region where methylene blue was low, because mixes will strip in the Hamburg for reasons other than surface-active fines. The message was clear, mixes consistently stripped when methylene blue was high. Do we get that same information from sand equivalency? Or should we replace sand equivalency with methylene blue?

A—Mansour Solaimanian
I am not sure I can answer your question but I will try. I do agree with you that methylene blue is a very good test. In terms of how good the r^2 was in every case, I was just reporting what I noticed from Ken's work. I suppose the r^2 values were around 70%. But again, this is just based on his data. On replacing SE with MB, I am not sure you will be capturing the same thing because when you do the methylene blue, you are doing it on –200 material in the mix, and when you do your sand equivalency, you are basically doing it on material passing the No. 4 sieve. You do have an amount of fines in your mix that you need to watch out, regardless of your testing. You might have 4% of –200 material, but you should watch out that this material might contain a lot of bad clay. You still need to look at your sand equivalency to make sure your material passing the No. 4 sieve is OK. I may not have answered your question very clearly.

Q4—Jack Van Kirk, Basic Resources, Inc.
I have two questions. One is that after SHRP, you said a lot of the states switched over, and a total of 30 are now using T283. The first question is, Why did a lot of those states change over? What convinced them? The second question is, How much variability is in the parameters or the criteria they are using to run the test? Everything from voids in the specimens to saturation levels to compaction method can introduce differences between states and variability within a state.

A—Mansour Solaimanian
Why so many states picked it up, you want to answer that, Gary? I don't know. I guess because it became a part of the Superpave Design System. With regard to your second question on variability, there is variability between technicians in a given state, and between different states depending on where you are in terms of your air voids and your testing procedures. It is a big deal.

Q5—Dick Root, Root Pavement Technology, Inc.
Maybe a couple of comments on the procedure itself and maybe why it was adopted indirectly. I was a little bit confused by a couple of your comments, so maybe you can help clear me up on this. First of all, T283 and ASTM D4867 are the same test. One was performed or put together by a research team, and the other was put together by a committee, so they got a little bit deviant in the committee aspect of it. The control of air voids and saturation levels, you made an indication, or at least I perceive, that would affect the test results or maybe cause errors in it. There were several studies done during the original research and follow-up studies by Irv Dukatz at Vulcan Materials that showed that with a range of air voids at 6–8 and with the saturation levels of 55–80, you essentially get the same results for a ratio of strengths, not individual strength. Obviously, the PSI would be different at 6% voids than 8%, but when you start looking at ratios, that narrowed the data down to very, very close. I think the reason for the adoption of it is simple. It can be run in the field and it was reasonably an advancement over what we were running previous to that, boiling water tests and emergent compression tests.

A—Mansour Solaimanian
Yes, ASTM D4876 and AASHTO T283 I think are essentially the same, but if you look at the procedures, there is a 16-hour curing in AASHTO T283 that does not exist in ASTM D4867. Other than that, you are right. Curing is very different between the two procedures. I would be interested in seeing that data that you mentioned in terms of essentially getting the same ratio and see how big the database or what kind of data has been used in there.

Q6—Carl Monismith, University of California, Berkeley
I think that your answer why T283 was adopted is correct because many states, immediately after the completion of SHRP, adopted the Superpave method of mix design, and T283 is a part of the methodology. The other thing I wanted to mention is this matter of the sand equivalent and methylene blue tests. The sand equivalent test was developed circa 1950; information regarding the test was published by the Highway (now Transportation) Research Board by F. N. Hveem in 1952. The primary purpose of the test is to eliminate the potential for detrimental clay coatings on aggregate particles, coatings that could result from improper processing of aggregates obtained from alluvial deposits. I would argue that it would be extremely imprudent to replace the sand equivalent test with the methylene blue test; the sand equivalent test is a very important test for the control of fines. If pavement technologists want to look at the nature of these fines, methylene blue is a useful additional test. As noted above, to replace one with the other would be unwise.

A—Mansour Solaimanian
I agree, Carl.

TOPIC 4

Treatments

TOPIC 4

Treatments

JON EPPS
Granite Construction

ERIC BERGER
Chemical Lime Co.

JAMES N. ANAGNOS
Akzo Nobel Asphalt Applications, Inc.

In the presence of water, asphalt-aggregate mixtures can experience a loss of bond between the asphalt binder and the aggregate (adhesion). In addition, the asphalt binder may experience changes in properties (strength, stiffness, viscosity, etc.) when water is present (cohesion). Loss of bond or changes, or both, in the properties of the asphalt binder can result in significant engineering property changes in hot-mix asphalt mixtures and premature distress in pavements.

A number of premature pavement performance problems were experienced in the United States in the middle and late 1970s and into the 1980s. This distress resulted in significant expenditures for rehabilitation and maintenance. Raveling, rutting, alligator cracking, bleeding, longitudinal cracking, and transverse cracking were some of the forms of pavement distress experienced during that period. Rutting was a relatively common form of premature distress during this period. The relatively large number of pavements experiencing some form of premature distress was in part responsible for the Strategic Highway Research Program (SHRP) and the resulting Superpave™ binder specification and mixture design method.

CAUSES OF PREMATURE DISTRESS

Premature pavement distress during this period of time has been attributed to several factors, including

1. Increase in truck traffic volumes,
2. Increase in truck weights,
3. Increase in tire pressure,
4. Changes in asphalt binder properties (both chemical and physical),
5. Changes in aggregate properties,
6. Construction practices,
7. Pavement design considerations, and
8. Moisture sensitivity.

Other factors have been identified by various authors but are not included in the list.

Truck traffic volume has increased significantly on our nation’s highways. Increases in commerce as well as a shift from rail transport to highway transport are among the major driving forces. Truck weights in some states have increased and, in part, contribute to the premature distress. Truck tire pressures increased from approximately 70 psi in the 1960s to an average of 100 psi by the late 1970s. Tires are used in Europe and Asia with inflation pressures of 135 psi and above. The types of truck tires also changed during that period.

The oil embargo, which started in late 1973, resulted in a different slate of crude oil being used in a number of refineries throughout the United States. Asphalt binders produced by some refineries changed significantly during that period.

Aggregate sources are continually changing, and in some cases the quality of aggregates has declined. Aggregate quality and type are related to water sensitivity problems in hot-mix asphalt.

The quality of construction has improved since the mid-1980s as quality control and quality assurance types of specifications have been used by more states. Improvements in in-place air voids, joint density, and general quality control associated with asphalt binder content, aggregate gradation, and segregation have occurred since the early 1980s.

The more widespread use of open-graded friction courses, and in some areas interlayers constructed with chip seals or fabrics, resulted in hot mixes subjected to increased moisture contents over longer periods of time. The use of these types of materials caused premature distress in some pavements during the 1970s and 1980s.

MOISTURE SENSITIVITY AND PREMATURE DISTRESS

Moisture sensitivity was identified as a major contributor to premature distress on several pavements in the Intermountain West and the Southeastern United States in the late 1970s. Research programs on water sensitivity were initiated by NCHRP and several states in the middle and late 1970s. Field experimental projects were conducted in the early 1980s. Significant amounts of research were conducted in the 1980s and early 1990s. A renewed interest in moisture sensitivity and in particular the relationship between laboratory testing and field performance started in the late 1990s and continues today.

Raveling, rutting, alligator cracking, and bleeding are forms of hot-mix asphalt pavement distress that can be caused in part by moisture sensitivity problems. Raveling, or the loss of aggregate from the surface of the pavement, is generally associated with water sensitivity, aging of the asphalt binder, and low asphalt binder contents, among other factors. Raveling is a common form of pavement distress in the Intermountain West. Some areas of the Intermountain West experience nearly 300 air freeze–thaw cycles annually. A significant number of these freeze–thaw cycles occur in the presence of moisture.

Rutting has been related to moisture sensitivity in hot-mix asphalt as a result of the loss of strength due to the presence of moisture. Often the rutting is associated with some bleeding of the asphalt surface, and raveling can also be present. Several pavements in the Southeastern United States experienced rutting that was associated with high pavement temperature and moisture. Rutting in other areas of the United States has been related to moisture, particularly when chip seals, interlayers, and open-graded friction courses are used without high-quality hot-mix asphalt.

Fatigue is associated with load repetitions and is experienced in those pavements with relatively high stresses or strains due to traffic. A reduction in the stiffness of the hot-mix asphalt (resilient modulus or dynamic modulus) in a pavement can result in stresses and strains in the hot-mix asphalt that exceed the fatigue capacity of the hot mix. Moisture can contribute a reduction in the stiffness of the hot-mix asphalt.

TREATMENTS FOR MOISTURE SENSITIVITY PROBLEM

The potential for a hot-mix asphalt to have moisture sensitivity problems is related to the properties of the asphalt binder, properties of the aggregate, hot-mix asphalt characteristics, climate, traffic, construction practices, and pavement design considerations. For a particular project, the climate and traffic volumes cannot be controlled. Construction practices and pavement design considerations can be controlled to a limited extent. From a practical standpoint, the selection of the asphalt binder and aggregate for a particular project is based largely on availability and economics. Mixture designs can be developed with moisture sensitivity as one of the controlling factors.

For most projects, an asphalt binder and aggregate are selected and the mixture design is developed. The mixture is then tested for moisture sensitivity and, if not accepted, a "treatment" of some type is selected based on experience and laboratory testing. The hot-mix asphalt is judged to be acceptable if it meets certain laboratory test criteria. Some public agencies require all hot-mix asphalt mixtures to be treated for moisture sensitivity. Other public agencies require that the field-produced hot-mix asphalt meet certain laboratory test criteria as part of the test strip process or during production of the hot-mix asphalt for the project, or both.

A survey conducted by Aschenbrener in August 2002 indicated that 25 states use a liquid antistripping agent, 13 states use hydrated lime, and 7 states use either a liquid or hydrated lime (*1*).

A variety of treatments are available to improve the water sensitivity of a particular hot-mix asphalt. These treatments can be conveniently grouped into those that are added or applied to the asphalt binder and those that are applied to the aggregate. Although the treatments are typically added or applied to the asphalt binder and the aggregate, their physicochemical effect is on both the asphalt binder and aggregate.

Treatments Added to the Asphalt Binders

A variety of chemicals are being used to reduce the moisture sensitivity of hot-mix asphalt. The majority of chemicals presently used are alkyl amines and are sold under a variety of brand names. These chemicals are added directly to the asphalt binder either at the refinery or asphalt terminal, or at the contractor's asphalt facility during production of the mix with an in-line blending system. These types of chemical additives are generally referred to as "liquid antistrip agents or adhesion agents." Liquid antistrip agents are not only used in hot-mix asphalt but are commonly used in cold-applied, asphalt-bound patching materials, in asphalt binders used for chip seals, and in the binder used for precoating the aggregates in chip seals.

There is evidence that some polymers can act as antistrip agents. Polymers are typically blended with the asphalt binder at the refinery or terminal and supplied to the hot-mix asphalt producer.

The physicochemical properties of the liquid antistrip agents and the polymers that are added to the asphalt binders are discussed elsewhere in these conference proceedings. The physicochemical interaction between these types of antistrip agents and the asphalt binder and aggregate is also discussed elsewhere in these conference proceedings.

Treatments Applied to the Aggregates

Hydrated lime, portland cement, fly ash, flue dust, and polymers have been added to aggregates to provide resistance to moisture in hot-mix asphalt mixtures. Typically, these materials are added to the aggregate and mixed before the introduction of the asphalt binder in the hot-mix asphalt production process. In some cases, hydrated lime or portland cement has been added in the drum mixing operation at the point of entry of the asphalt binder to the heated aggregate.

Hydrated lime is currently the most commonly used treatment for aggregates. Portland cement was used by a number of states (for example, Arizona and Nevada); however, most public agencies no longer use portland cement. Fly ash, flue dust, and polymers are infrequently used currently. The properties of the fly ash and flue dust must be determined to establish if these materials are suitable for use in hot-mix asphalt as antistrip agents. A limited amount of research and field installations have been performed with polymer additions to aggregates.

The physicochemical properties of these types of antistrip agents that are added to the aggregates are discussed elsewhere in these conference proceedings. The physicochemical interaction between these types of antistrip agents and the asphalt binder and aggregate is also discussed elsewhere in these conference proceedings.

Currently, most public agencies use either a liquid antistrip agent and add the liquid to the asphalt binder or use hydrated lime and add the lime to the aggregate. Because these materials are most commonly used, the majority of this synthesis of information will be directed toward the use of liquid antistrip agents added to asphalt binders and the use of hydrated lime added to aggregate before the introduction of the asphalt binder.

LABORATORY TEST METHODS

Laboratory tests are commonly used to determine the effectiveness of different types of antistrip treatments. A brief review of test methods frequently used by public agencies is provided. These test methods are further defined and compared in other papers presented at this conference. The effectiveness of various types of antistrip treatments is determined by the use of these tests described later in this synthesis of information.

A number of test methods have been developed to determine the moisture sensitivity of hot-mix asphalt mixtures. Most of the tests developed are suggested for use during the mixture design process and not for quality control or quality assurance testing. For the most part, extensive data are not available that allow for a good correlation to be established between the laboratory test and field performance.

Laboratory tests to evaluate water sensitivity can be grouped into three categories:

1. Loose mixtures,
2. Representative mixtures, and
3. Compacted mixtures.

Tests that can be placed into each of these categories, and which are subsequently used in this synthesis, are presented below.

Loose Mixture Tests

A variety of loose mixture tests have been developed and continue to be used by some public agencies. Soaking and boiling tests on loose mixtures of asphalt binders and aggregates were used by a number of states in the 1950s and 1960s. The length of soaking, temperature, and method of evaluating the degree of bond loss vary among the techniques used.

The Texas DOT boiling test and ASTM D3625 are examples of these types of tests. In the Texas test, the hot-mix asphalt is soaked and boiled for 10 min. Water sensitivity of the hot-mix asphalt is judged by visually determining the amount of bond loss between the asphalt binder and the aggregate. Samples of mixtures or photographs of mixtures with different percentages of bond loss have been used to assist in the determination of the percent bond loss of the sample.

Representative Mixture Test

The freeze–thaw pedestal test developed at Western Research Institute on the University of Wyoming campus, and further developed at the University of Texas, selects a portion of the fine, one-sized aggregate for testing. The aggregate is coated with asphalt, compacted, placed on a pedestal, and subjected to alternating freeze–thaw cycles until fracture is observed.

The selected fine aggregate fraction and asphalt binder are compacted into a 1.5-in. diameter by ¾-in. sample and immersed in water and alternately frozen and thawed until failure occurs. Research was reported in the 1980s using this test technique to evaluate the effectiveness of various antistrip agents.

Compacted Mixtures

The immersion–compression (ASTM D1075), Chevron, Tunnicliff-Root, and the Lottman tests are examples of compacted mixture tests. All of these tests use the project asphalt binder and the project aggregate. The materials are mixed and compacted for testing. The immersion–compression test has been used extensively by several state DOTs, the U.S. Army Corps of Engineers, and the Federal Aviation Administration. Arizona DOT has modified the test method so that the air voids of the compacted mixture are in the range of 6% to 8%, rather than a typical value of 3% to 5%.

Chevron Asphalt developed a test in the 1960s using compacted hot-mix asphalt. The compacted hot-mix asphalt was subjected to water saturation by vacuum, and the resilient modulus was measured before and after the introduction of water. Lottman and coworkers at the University of Idaho further developed the test method and added freeze–thaw cycles (*2*, *3*) to the test procedure. The developed test procedure was standardized as AASHTO T283, and the freeze–thaw cycles reduced to one.

Tunnicliff and Root (*4*) performed research using similar techniques for NCHRP. Their research resulted in the development of ASTM D4867, which is similar to the Lottman test without the freeze–thaw cycle required. Tensile strength of conditioned and unconditioned samples is measured by the indirect tension test procedure. Tensile strength ratios (TSRs) are often reported for the mixtures tested.

Nevada DOT made further improvements in the Lottman test procedure and tested for both resilient modulus and indirect tensile strength. In addition to testing for TSR, Nevada specifies a minimum dry tensile strength.

The SHRP research program developed a test method that is capable of applying a repeated load while introducing moisture into the sample. The temperature can be cycled to produce freeze–thaw conditions. Texas DOT and the University of Texas at El Paso have continued to perform some developmental work on the test procedure.

Wheel-tracking tests such as the Hamburg and the Purdue University laboratory rut tester are examples of tests used in the United States in the 1990s to today. Laboratory or field compacted samples are subjected to repeated wheel loading in the presence of water, and rut depths are measured.

The immersion–compression, Chevron, Lottman, Tunnicliff and Root, Nevada DOT, and SHRP tests, and the rutting types of tests are all examples of water sensitivity tests performed on compacted mixtures produced from asphalt binders and aggregates used on the paving projects. Those tests that compact samples to relatively high air void contents (6% to 8%), subject the samples to high levels of water saturation, and perform freeze–thaw cycles are the most severe indicators of water sensitivity in hot-mix asphalt. Additional details on these and other test methods can be found in these conference proceedings.

TREATMENTS ADDED TO THE ASPHALT BINDERS

As discussed, liquid antistrip additives have been used effectively and extensively in the United States to reduce the moisture sensitivity of hot-mix asphalt materials. Liquid antistrip agents can affect the engineering properties of the asphalt binder and the engineering properties of the hot-mix asphalt mixture. The effectiveness of the liquid antistrip on the water sensitivity of the hot-mix asphalt mixture depends on the physicochemical properties of the asphalt binder and the aggregate, as well as on the amount of liquid antistrip agent used. Liquid antistrip materials can be added to the asphalt binder at a number of locations and by various methods. The long-term effectiveness of antistrip agents is demonstrated by Tunnicliff and Root (*5*). A summary of information on asphalt binder properties, hot-mix asphalt mixture properties, and construction operations associated with the use of liquid antistrip agents is presented below.

Asphalt Binder Properties

The properties of the combined asphalt binder and liquid antistrip agent depend on the chemistry of the asphalt binder, the chemistry of the liquid antistrip, the concentration level of the liquid antistrip, and the types of carrier or dispersant used with the liquid antistrip, among other factors. The combined binder properties can also depend on the time and temperature of storage of the asphalt binder–liquid antistrip material.

Some of the low-performance liquid antistrip agents use oil-type carriers or dispersants, which can change the physical properties of the asphalt binders. High-performance liquid antistrip agents contain very little dispersants. In the early and middle 1980s, diesel oil was used as a dispersant, a practice long since discarded even in low-performance liquid agents. However, some early testing of liquid antistrip agents was performed with additives containing diesel oil. Table 1 shows the magnitude of the viscosity change at 140°F resulting from the addition of a liquid antistrip on three different asphalt binders. The magnitude of the viscosity change depends on the type of additive, concentration of the additive, and type and source of asphalt binder (*6*).

The degree of aging of an asphalt binder may also be altered by the presence of liquid antistrip agents, as shown in Table 2 (*6*). The viscosity at 140° F of the aged asphalts with liquid antistrip may be lower than that of the control asphalt binder, but the ratio of its viscosity increase (treated sample viscosity after aging to viscosity of treated sample before aging) may be larger. A laboratory aging test was performed to generate the data shown in Table 2.

The penetration of the asphalt cement can also be affected by the presence of a liquid antistrip agent. The magnitude of the penetration change depends on the type of additive, additive concentration, and type and source of the asphalt binder, as shown in Figure 1 (*7*). Figure 2 shows the change in penetration of aged asphalt binders with various concentrations of liquid antistrip agents. Changes in penetration (ratio basis) are shown for three types of asphalt binders and four concentrations of liquid antistrip agents (*8*).

The effect of a liquid antistrip agent’s concentration on viscosity is shown in Figure 3 (*7*). The amount of change depends on the asphalt cement type and source. A 30% change in viscosity at 140°F is possible at 1% concentrations of liquid antistrip. Figure 4 shows that the viscosities of treated asphalt binders are reduced in comparison with the aged properties of the original asphalt binders (*7*).

Some Superpave binder testing has been performed on asphalt binders containing various high-performance liquid antistripping agents. Figure 5 shows the changes associated with the parameter G* sin delta ("Adhesion Promoters," Technical Bulletin, Akzo Nobel). Additional G* sin delta data for a variety of asphalt binders and dosage amounts are shown in Figures 6 to 10 (*9*).

In addition, when high-performance liquids are used, they may exhibit little or no change when measured for SHRP asphalt binder properties, as shown in Table 3 (*10*). It should be noted that for the high-performance liquid Agent A, Source B binder would require the addition of 10% of the additive to create a drastic change in the G* sin delta parameter binder property.

The G* sin delta parameter used in Superpave binder specifications is reported to be an indication of fatigue resistance of the binder. Currently, the upper specification limit is 5,000 kPa. Considerable discussion is occurring in the technical community relative to the validity of this parameter for fatigue.

Hot-Mix Asphalt Properties

A South Carolina Department of Highways research program determined the indirect tensile strength of samples subjected to the Tunnicliff–Root test, without freeze thaw cycle (ASTM D3625) (*11*). Figures 11 to 13 show the indirect tensile strengths before and after exposure to water for aggregates from Sources A, B and C. Comparisons are made with control samples (without antistrip treatment) and for samples of hot-mix asphalt made with liquids and lime as antistrip additives.

The South Carolina Department of Highways also conducted studies to investigate the effect of sample storage time on water sensitivity test results (*11*). Figures 14 to 17 show the effect of sample storage time on the moisture-conditioned properties of mixtures subjected to the Tunnicliff Root procedure. Test results from three aggregate sources are shown on these figures for samples stored 24 h and 60 days before testing. The codes used to identify the types of antistrip additives are provided as follows:

0—control (no antistrip additive);
1—liquid antistrip;
2—hydrated lime;
3—liquid antistrip; and
4—liquid antistrips.

Storage times of 60 days increased the dry tensile strength while only slightly altering the tensile strength after the samples had been exposed to a water sensitivity test.

Boil tests performed in South Carolina are shown in Figure 18 (*11*). Three aggregates were used. Results from control samples as well as samples treated with a liquid antistrip and hydrated lime are shown.

Results of the Lottman tests (AASHTO T283 with a freeze–thaw cycle) are shown in Figures 19 to 26 for aggregate samples obtained from California, Florida, Georgia, Mississippi, Missouri, South Carolina, and Utah (*12*). These results were obtained on asphalt binders treated with different dosage levels of amidoamine, polyamine, and lime antistrip agents. In general, it appears that the optimum liquid additive dosage ranged from 0.5% to 0.75% by weight of the binder, whereas the TSR values ranged from 0.95 to 1.05. Hydrated lime was applied at a rate of 1.0% on the basis of the weight of the aggregate. It should be noted that the values for the liquid antistrip agents mirrored the hydrated lime values of TSR.

Texas DOT reported on a study containing several aggregates obtained near the Houston area. Table 4 contains a summary of the results of this study, which used different types of liquid antistrip agents. The results obtained from AASHTO T283 tests indicate that the specification limits of 70% retained strengths could be obtained with various percentages of liquid antistrip agents (*13*).

Figure 27 (*14*) illustrates the relative improvement that may be obtained in the Hamburg rut depth test with the use of various liquid agents. Three different aggregate sources, three binder sources (all modified binders) ranging from PG70-22 to PG76-22, and four liquid agents were used in the study. A rut depth of 12.5 mm for a surface layer is considered unsatisfactory. It can be seen that Liquids A and B performed well.

A Colorado study (*15*) provides TSR data after AASHTO T283 conditioning on hot-mix asphalt mixtures from 20 different projects (Figure 28). The effectiveness of the liquid antistrip materials used on these projects as measured by the TSR value is shown, with one of the conclusions being that "neither lime nor anti-stripping agents are a panacea for moisture damage."

In 1995, Maupin (*16*) reported that considerable stripping was evident in field cores from Virginia projects 3 to 4 years old that contain liquid antistripping agents. One of the conclusions of this study was that hydrated lime appeared to perform better than liquid antistrip agents. Owing to the concerns raised by these findings, another field study was initiated on projects placed in 1991 and 1992 after more stringent specifications were introduced for liquid antistrip agents.

Maupin (*17*) reported in 1997 that the results of this latter study did not validate the previous study conclusion relative to the behavior of liquid antistrip agents and hydrated lime. One conclusion from the 1997 study indicated that hydrated lime and chemical antistrip additives performed at an equal level. It was believed that chemical additive suppliers improved their product to meet specification.

TSR data for 12 Virginia projects are shown in Figure 29 ("Tensile Strength Ratio—Virginia," provided by Akzo Nobel), and with only one exception, the TSR values for liquid antistrip agents and hydrated lime appeared to coincide.

A field evaluation study by Tunnicliff and Root concerning antistripping additives in asphaltic concrete mixtures is presented in *NCHRP Report 373* (*5*). Nineteen test sections were constructed in eight states with and without antistripping additives. Tunnicliff and Root concluded that during the 6- to 8-year study, eight of the nine additives performed satisfactorily, and ASTM Method D4867 correctly predicted the performance of 16 of the 19 experimental sections.

Indirect tensile stiffness modulus values for a base course treated with various dosages of liquid antistrip agent are shown in Figure 30 (*Adhesion Promoters*, Technical Bulletin, Akzo Nobel). Limited data are presented for various soak times, ranging from 0 to 30 days, and they show a much improved modulus with the use of a high-quality liquid.

Several types of liquid antistripping agents, hydrated lime, and a combination of hydrated lime and liquid antistrip agent were used in a Louisiana laboratory and field evaluation study (*18*). The project was constructed in fall 1990, and to date little distress is evident other than some longitudinal cracking in one area. Boil, Ross count, and an AASHTO T283 type of test with 10 multiple freeze–thaw cycles were conducted on project plant run mix. Results of these tests are shown in Figures 31 to 36. The dosage rate for all of the liquids was 0.8%, based on the weight of the asphalt binder, and the rate for hydrated lime was 1.4%, based on the weight of the aggregate. In addition, one test section contained a combination of hydrated lime at 1.4% and a liquid at 0.8%.

In summary, the boil test (Figure 31) does not show a substantial difference between additives; however, when conducting AASHTO T283 with multiples of 1, 3, 5, and 10 freeze–thaw cycles, differences occur with the use of various additives (Figure 33). With the addition of multiple conditioning cycles (Figure 33), a reduction of tensile strength values is noted. Figures 32 and 34 depict the loss of TSR with regard to an increase in air voids and a decrease in wet tensile strength with freeze–thaw cycles. It should be noted that the high-performance Liquid A generally outperformed the other additives in the laboratory phase.

Results from the freeze–thaw pedestal test conducted on an aggregate treated with different types of liquid antistrip agents are shown in Figure 37 (*19*). The number of freeze–thaw cycles to failure is shown. Comparisons with a control sample, hydrated lime, pyridine, and multiple chemical additives added at an unusually low dosage rate of 0.25% are shown in this laboratory study.

Construction Operations

Liquid antistrip agents can be added at the contractor's hot-mix asphalt production facility. The liquid antistrip agent is typically added to the asphalt binder by means of an in-line injection system just before the asphalt binder's entering the drum dryer or batch mixer. The liquid antistrip agent can also be added to the asphalt binder storage tank and circulated before use.

Cost-Effectiveness

The material cost of liquid antistrip agents typically ranges from $0.45 to $0.75 per pound of liquid antistrip. This equates to a cost of $6.75 to $11.25 per ton of asphalt binder for a treatment concentration of 0.75%. Thus, the typical increase in the cost per ton of hot-mix asphalt concrete is from $0.30 to $0.70 for the liquid antistrip agent. The cost for in-line blending equipment installed at the contractor's plant ranges from $10,000 to $25,000. Typically, the in-line blending equipment is amortized over a 5-year period. The total price increase in using a liquid antistrip agent is typically in the range of $0.50 to $0.81 per ton of hot-mix asphalt.

TREATMENTS ADDED TO THE AGGREGATES

As described previously, several treatments have been added to aggregates in an attempt to alter the moisture sensitivity of hot-mix asphalt. Hydrated lime, portland cement, fly ash, flue dust, and polymers are among the materials used. Hydrated lime is currently the most popular treatment used on aggregates, and most of the discussion will center on its use in hot-mix asphalt.

Before a discussion of lime, some of the available information on the use of the other additives will be presented. This limited review includes information on portland cement, flue dust, and polymers.

Two research projects conducted in Nevada provide limited information on the effectiveness of portland cement, fly ash, and lime (*20*, *21*). Figures 38 to 40 illustrate the effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate. The use of portland cement and lime together was not as effective as the use of relatively high percentages of hydrated lime alone on this aggregate. Figure 41 presents research results from a Nevada DOT study, which evaluated mixtures in the laboratory as well as placed sections in the field in a climate subjected to numerous freeze–thaw cycles (*20*, *21*).

Figure 42 illustrates the relative effectiveness of portland cement and hydrated lime based on available data in 1991 (*22*). Lime in general has proven to be a more effective antistrip additive than portland cement over a wide range of aggregate and asphalt binder types.

Polymeric Aggregate Treatment

The use of a polymeric aggregate treatment system provides a protective barrier on the aggregate, which repels water and waterproofs the aggregate while providing an improved bonding with the asphalt. When properly applied, the polymeric aggregate treatment will turn a hydrophilic aggregate into a hydrophobic aggregate, increasing the water resistance of the hot-mix asphalt.

One of the additional benefits observed by using polymeric aggregate in this system of treatment is that the amount of asphalt required in the mixture may be lowered, resulting in cost savings for the hot-mix contractor (*23*, *24*). As the polymer coats the porous aggregate, less asphalt is needed to fully coat the surface.

Western Research Institute conducted a study on the effect of antistrip treatments on asphalt–aggregate systems (*25*). In this study, an environmental scanning electron microscope (ESEM) was used to observe how the asphalt–aggregate interface changes with sequential freeze–thaw cycling under water and to evaluate the effectiveness of antistrip additives. The untreated control samples displayed separation at the asphalt–aggregate interface after only one freeze–thaw cycle. Amine-treated asphalt samples and lime-treated aggregates showed varying degrees of separation after freeze–thaw cycles, whereas the polymeric aggregate–treated samples showed no separation after 10 freeze–thaw cycles.

Asphalt Binder Properties

While the polymeric aggregate treatment is added to the aggregate, there is an interaction at the interface between the aggregate coating and the asphalt. This interaction results in an improved mechanical and chemical bond. The polymer used is specially selected to have compatibility with the asphalt and to enhance the aggregate-coating-asphalt bonding.

Hot-Mix Asphalt Properties

A Florida study investigated various amounts of SBR latex and lime (*26*). The solids concentration of polymer ranged from 0.05% to 0.1%, whereas 1% to 1.5% of lime was used. The amount of amine used was based on the percent asphalt (0.5%). Samples were prepared according to the supplier’s recommended procedures. Ratios of the conditioned treated mixtures over the unconditioned untreated mixtures were calculated. SBR-treated mixtures displayed the highest TSR of the various treatments. As more SBR was added, the TSR increased, suggesting that with this aggregate there is a concentration dependency (see Figure 43). The SBR-treated samples show a somewhat higher wet tensile strength than do the samples treated with other antistripping agents and the untreated samples (see Figure 44).

In a Texas study (*27*), aggregates from different regions of Texas were evaluated and both the TSR and Texas boil test were performed. Aggregates from four different districts in Texas were selected and used to evaluate the effectiveness of SBR and lime in preventing moisture damage. The polymer treatment system reduced the percent uncoated aggregate for all the mixtures tested. In Texas, a minimum TSR of 80% is required. None of the aggregates passed the AASHTO T283 test untreated, which means they are all highly moisture sensitive mixtures. The lime treatment worked better with the aggregate from the Pharr District than the SBR treatment did. Because the aggregates are made up of a variety of minerals, the chemical composition and texture of the surface are important variables in the performance of SBR. With the use of the SBR, the aggregates from Atlanta, Amarillo, and El Paso all passed the TSR requirement (see Figure 45). For the Atlanta District, the 0.1% polymer treatment produced much higher dry and wet tensile strengths than did the lime, again indicating an enhancement of the mixture strength (see Figure 46).

Aggregates from two locations in Nevada were also studied (*23*). In both cases, the highest level of SBR performed as well as or better than the lime-treated mixtures (Figures 47 and 48). The SBR-treated samples also showed higher dry and wet tensile strength when compared with no additive and lime. On the basis of these results, SBR treatment is an excellent replacement ASA for lime with these aggregates.

A reduction in the optimum asphalt binder content can be associated with polymer treatment. When the polymer aggregate treatment was used with two marginal aggregates, reductions in binder contents of 0.85% to 0.40% were noted.

Aggregates from four locations in Colorado were studied (*24*). The study was performed to investigate the effectiveness of the polymer aggregate treatment system on four aggregate sources.

The results of the study suggest that the polymer aggregate treatment process should be an acceptable alternative to hydrated lime. Generally, with the polymer aggregate treatment process, the optimum oil contents are lower, and the Lottman TSR values are still acceptable (Figures 49 to 53). This study's results are site specific (Figures 49 to 53). Other sources of aggregate, even though they may be similar, need to be evaluated individually.

Construction Operations

SBR latex concentrate is delivered to the job site and must be diluted to 15% solids before use. This is accomplished automatically when using an approved application unit. The latex is then applied to the aggregate stream. Approved application units have two pumps that proportion the latex and water at the correct ratio. The pumps discharge through a line to the aggregate feed belt. A valve is provided in the combined discharge line to permit sampling of the final blend.

At the hot-mix plant, the latex should be applied to the aggregate stream just before entry into the dryer drum. Very little mechanical agitation of the aggregate is required to properly disperse the SBR latex emulsion, owing to the osmotic characteristic of the SBR latex. Simple devices may be used to introduce mechanical agitation on the belt and disperse the polymer on the aggregate before it enters the heated drum, if desired. The application system is nontoxic, nonflammable, noncorrosive, and easy to clean.

Cost-Effectiveness of Polymeric Aggregate Treatment

The material cost of polymeric aggregate treatment depends on the concentration needed to achieve the desired results. Generally, a range of 0.5 to 1.5 lb solid polymer per ton of aggregate is evaluated to determine the optimum rate, with 1.0 lb being typical. The cost for the application system installed at the contractor's plant ranges from $10,000 to $18,000, depending on the degree of automation required. The material cost increase using the polymeric treatment system varies, depending on the usage rate and pricing of the SBR latex.

Lime Treatments

Hydrated lime [$Ca(OH)_2$] is a fine, highly alkaline inorganic powder that has many industrial and environmental applications throughout the world. It first appeared in about 1910 as an asphalt stiffener in a proprietary product. Lime disappeared for a few decades, was used in the 1950s and 1960s in the Southwest, and began to reappear nationally during the search for solutions to the moisture sensitivity problems that arose in the 1970s. Researchers observed that the addition of hydrated lime to asphalt mixtures improved the adhesive bond between the aggregate and bitumen, substantially reducing the occurrence of stripping. Further research identified chemical reactions that occurred between lime and many bitumens that reduced their affinity for water, in turn reducing the mixtures' tendencies to strip. In addition, when aggregates are coated with clays, hydrated lime can react pozzolanically to remove those deleterious materials that would otherwise damage the mixture. States in those regions where stripping was most prevalent began to add hydrated lime to their mixtures, and word of its benefits spread through the Southeastern states and the Intermountain West.

The decades since hydrated lime was first identified as an antistripping additive have produced dozens of research papers and thousands of field projects expanding the general knowledge of its mechanisms for mitigating moisture damage. In the 1970s, research performed by Plancher et al. (*28*) at the Western Research Institute demonstrated that hydrated lime reacted with carboxylic acid and 2-quinolene groups in asphalts to form insoluble products that were no longer sensitive to moisture. One result of those reactions was an improvement in the cohesive strength of the binder, which was better able to resist the absorption of water. In addition, Petersen asserted that the reactions facilitated strong bonding between asphalt basic nitrogen groups and the aggregate surface. That initial work has been built on by additional studies at Western Research Institute highlighting other contributions that hydrated lime makes to asphalt mixtures—contributions that synergistically reduce the mixtures' susceptibility to moisture.

In addition to chemically reacting with many commonly used bitumens, hydrated lime alters the surface chemistry of aggregates that are susceptible to moisture. For many years, it was hypothesized that the highly alkaline hydrated lime coated the surface of acidic aggregates, facilitating the development of strong bonds between the aggregates and acidic bitumens. With the development of new analytical tools and a deeper understanding of micromechanics, that hypothesis is being more thoroughly investigated by Lytton, Little, and others who are studying the surface energies of bitumens and aggregates. Their work suggests that a hydrated lime wash may alter the surface energy of aggregates, enabling them to bond more strongly with bitumens to withstand the intrusion of water. Further investigations are under way to quantify the extent of that improvement over a broad array of aggregates.

Hydrated lime helps to mitigate moisture sensitivity of asphalt mixes in mechanical ways as well as chemical. Lesueur and Little (*29*) demonstrated that hydrated lime significantly increases $G^*/\sin\delta$ without significantly increasing the brittleness of the binder. As an extremely fine, active filler (characteristically 50% smaller than 10 μm), the hydrated lime helps to stiffen the mixture, often increasing the PG rating of the binder by a full grade with the addition of only 1% lime by weight of the aggregate (*30*). By stiffening the mix, the lime increases its resistance to rutting and fatigue cracking, reducing the ability of water to enter the system.

For many bitumens, hydrated lime also reduces the rate of oxidative aging, which extends the resiliency of the mix, in turn reducing the incidence of cracking, which also provides pathways for water to enter the pavement. This reduction in the rate of aging is a function of the reactions between the calcium hydroxide and polar acids in the bitumens that react with the environment, forming brittle compounds. In other words, when hydrated lime reacts chemically with bitumens, it often both eliminates components that facilitate the progression of water through the mix and removes compounds that contribute to oxidative aging.

The addition of hydrated lime to asphalt mixtures commonly results in a complex array of interactions that all contribute to a reduction in moisture sensitivity. The lime reacts chemically with both bitumen and aggregate to remove undesirable chemical compounds on the one hand, and to improve the surface energy and acidity balance on the other. At the same time, the dispersion of fine hydrated lime particles throughout the mastic helps to stiffen the mix, making it more resistant to mechanical failures from rutting and fatigue cracking. The contributions are synergistic, as is appropriate in a complex system such as asphalt cement, contributing interactively to the mitigation of moisture sensitivity in the mixtures.

Asphalt Binder Properties

Laboratory and field research has indicated that benefits of using lime in hot-mix asphalt are not restricted to improving the resistance to water sensitivity. Lime also acts as a mineral filler, can reduce the plastic index if clays are present, and can reduce oxidation of the asphalt binder.

Figures 54 to 56 illustrate the mineral filler effect on asphalt binders. The addition of lime increases the viscosity (see Figure 54) (*9)*, the stiffness of the binder as measured by the rutting parameter ($G^*/\sin \delta$) in the Superpave binder specification (Figure 55) (*31*), and the stiffness of the binder as measured by the fatigue parameter (G^* sin delta) in the Superpave binder specification (Figure 56) (*9*). Increases in viscosity with the addition of lime to asphalt binders have been documented elsewhere.

Lime is a well-known stabilizer for clay soils. The lime changes the physicochemical properties of the clay minerals and reduces the plastic limit as well as changing the structure of the clay mineral. Lime is effective in reducing the plastic index of marginal quality granular base courses as well as reducing the plastic index of clays present in some aggregates used for the production of hot-mix asphalt.

Petersen et al. (*32*) investigated the effect of lime on the hardening properties of asphalt binders. Several asphalt binders were used in the study, as were several lime contents. A number of physical properties of the asphalt binders were tested before and after a laboratory aging test. Figure 57 illustrates the reduction in aging resulting from the presence of lime in the asphalt binders.

Jones (*33*) conducted research on Utah pavements that indicated that hardening of the asphalt binder can be reduced by the use of lime in hot-mix asphalt (Figure 58).

Hot-Mix Asphalt Properties

Lime is available in several forms, including high-calcium quick lime, dolomitic quick lime, high-calcium hydrated lime, normal hydrated dolomitic quick lime, and pressure hydrated dolomitic quick lime. High-calcium hydrated lime is by far the most commonly used lime in the United States. Figure 59 (internal data set, Materials and Test Division, Nevada DOT, 1998) and Figure 60 (*34*) indicate the resilient modulus before and after the addition of various types of lime. The hydrated limes used in the study offered the most improvement to moisture sensitivity. The hot-mix asphalt mixture, which used quick lime, did not have a measurable resilient modulus after exposure to water and a freeze–thaw cycle.

Figures 61 and 62 (*35*) indicate that the addition of hydrated lime to a hot-mix asphalt will increase the stiffness of the mixture. Comparison of resilient modulus values at 0%, 1%, and

2% lime indicate that the stiffness is increased on the dry or unconditioned mixtures with the addition of lime (mineral filler effect). Similar trends in the data are noted when tensile strength values are measured. It should also be noted that the conditioned or wet resilient modulus and tensile strength values will also increase with the addition of hydrated lime (improvement in moisture sensitivity of the mixtures).

Research conducted at Oregon State University (*36*) indicates that the permanent deformation or rutting characteristics of hot-mix asphalt will improve in both the dry and wet conditioned states with the addition of lime. Figure 63 indicates the benefit of using hydrated lime to prevent rutting. Data in Figure 64 (*30*) summarize a Texas rutting study on rut depth. The Hamburg wheel-tracking device was used to predict the rutting behavior of hot-mix asphalt mixtures treated with different types of antistrip agents.

Figure 65 (*36*), based on Oregon State University data, also indicates an improvement in fatigue life with the addition of hydrated lime in both the dry and wet conditioned state. Figure 66 (*37*) also indicates that rutting can be reduced by the addition of lime to hot-mix asphalt.

Research has indicated that the amount of hydrated lime needed to improve the moisture sensitivity of a hot-mix asphalt is of the order of 1% to 2% by dry weight of aggregate. Some mixture may require lime contents as high as 2.5% to achieve the desired results (*35*). The amount of lime in a hot mix to reduce oxidative hardening is below 0.5% by dry weight of aggregate.

Asphalt binder contents in hydrated lime–treated hot-mix asphalt often increase slightly (0.1% to 0.3% by dry weight of aggregate) (*35*). Some hot-mix asphalt mixtures may require less asphalt binder with the addition of lime or remain unchanged as compared with mixtures without lime addition.

Construction Operations

Several methods are commonly used to introduce hydrated lime into the asphalt mixture, each of them producing beneficial attributes for moisture sensitivity mitigation. On the basis of the observations earlier in this paper, it might be surmised that each of the methods of addition optimizes different contributions to the rheological and physical attributes of the mixture, but little research has been done to quantify those differences. Suffice it to say that asphalt mixtures benefit from the addition of hydrated lime, no matter how it is introduced into the mix. Following are descriptions of the addition methods most commonly used throughout the country.

Dry Lime on Dry Aggregate This method of adding hydrated lime is arguably the simplest, requiring only the addition of a storage silo and a metering system to an existing asphalt plant. The lime is metered onto the belt or auger that transports the fines into the mixing drum and is added along with the fines. Because some of the fines are usually drawn from the baghouse, any lime that is lost from the mix is recycled through that system. The fines are usually added to the mix immediately before the introduction of the binder. Consequently, the hydrated lime is distributed throughout the binder, some of it coming into direct contact with the aggregate while another fraction is available to react with the bitumen performing as a chemically active filler in the mastic. Because of the small investment required to add dry hydrated lime into the mix, the cost of this method is nominal, generally amounting to approximately $1.00 per ton of hot mix.

Dry Lime on Damp Aggregate A second common method for adding hydrated lime to asphalt mixes is to apply the dry lime to damp aggregate, generally from 1% to 3% above the saturated surface dry condition. The aggregate is then run through a pug mill to mix the lime and the aggregate together, ensuring that the aggregate is coated with lime. The lime/aggregate composite is then either fed directly into the plant (most common) or allowed to marinate in stockpile to allow time for the lime to react with clay or other coatings and contaminants that are present in the aggregate. The dry lime/damp aggregate method has the benefit of visually coating the aggregate before its introduction into the drum or batch mixer, while at the same time providing some free hydrated lime particles to migrate throughout the mastic. Because of the addition of a pug mill to the plant setup, and the addition of free water that must be dried off in the mixing process, this method is more expensive than the dry process, generally costing about $1.50 to $2.00 per ton of mix.

Lime Slurry on Dry Aggregate The addition of hydrated lime slurry to the aggregate arguably provides the best aggregate coating of all the methods, but it presents several challenges to hot-mix producers. The slurried lime is metered onto the aggregates, sometimes using different application rates, depending on the size fraction, and it is run through a pug mill to ensure thorough coating. After mixing in the pug mill, the aggregate is either fed directly into the plant or stockpiled and marinated for some period of time to allow the lime to react with the surface of the stone or any coatings or contaminants in the aggregate. Although this method of hydrated lime addition clearly provides the best aggregate coverage, it presents some problems to users, because the aggregates may contain substantial amounts of water that must be dried off during the mixing. In addition, when the aggregates are stockpiled for marination, yard space is needed, and additional material handling is required. This application method requires equipment for making the lime slurry and metering it onto the aggregate. Consequently, it is the most expensive method for adding lime to the asphalt mixture, often costing about $3.00 to $4.00 per ton to implement.

Figure 60 (*34*) and Figures 67 to 72 provide some laboratory and field evidence of the benefits obtained by adding lime, through the various methods presented as follows. Some data indicate that lime slurry applications are better than the use of dry lime on damp aggregate and dry lime on dry aggregate [see Figure 60 (*34*) and Figure 69 (*38*)], whereas other data, depending on the aggregate, indicate that nearly equal benefits can be obtained by any of the common methods used today (see Figure 69) (*38*).

Marination after the treatment with lime is frequently used in a number of Western states. Figures 67 and 68 (*39*), Figures 70 and 71 (*40*), and Figure 72 (*41*) indicate that some benefit can be obtained from the stockpiling or marination method. The benefits obtained by the use of marination depend on the aggregate, according to some information collected in Nevada.

Figure 73 indicates that treatment of only a fraction of the total aggregate used in a hot-mix asphalt can be effective in improving the moisture sensitivity of the mixture (*42*). Additional studies are needed with a wider range of aggregate types.

Figure 72 (*41*) and Figure 74 (R. E. Graves, "Lime in Sand for Hot-mix Asphalt: Test Project Summary," internal memorandum, Chemical Lime Group, Dec. 1992) indicate that lime-treated aggregates can be stockpiled for periods in excess of 60 days. The length of time allowed for stockpiling of treated aggregates remains an issue in several states.

Cost-Effectiveness of Hydrated Lime

As for any product that has been used successfully for decades, considerable anecdotal evidence exists attesting to the long-term benefits of adding hydrated lime to hot-mix asphalt. In the past

2 years, both the state of Nevada and the National Lime Association (NLA) have quantified the cost-effectiveness of using hydrated lime. A study performed by the University of Nevada–Reno for Nevada DOT (*43*, *44*) compared equivalent sections of lime-treated and nontreated highways that had been constructed between 1987 and 1994. Laboratory tests of field cores and data from the state's pavement maintenance system were both used in the analysis, which concluded that the addition of hydrated lime increased the expected pavement life by an average of 3 years. The 38% increase in life compared favorably with the 12% increase in the original cost of the lime-treated hot-mix asphalt.

In addition, in 2001, NLA commissioned a national study of the cost-effectiveness of hydrated lime, along with the development of a life-cycle cost analysis modeling tool that engineers could use to compare pavement alternatives (*45*). That effort, which included participation from 10 state DOTs and 10 paving contractors (Figure 75) (*45*), concluded that hydrated lime can save from 9% to 20% of a pavement's cost over the course of its life cycle. The actual saving depends on the strategies and activities selected by the agency, of course. The NLA model is based on the widely used FHWA model and is available for free.

SUMMARY

As the composition and quality of asphalt binders and aggregates continue to change and as the demands being placed on hot-mix asphalt pavements continue to increase, it is likely that more and more asphalt mixtures will require the addition of treatments to mitigate moisture sensitivity. Moisture sensitivity problems in hot-mix asphalt mixtures are related to one or more of the following:

- Properties of the asphalt binder,
- Properties of the aggregate,
- Design and characteristics of the hot-mix asphalt,
- Climate,
- Traffic,
- Construction practices, and
- Pavement design considerations.

A variety of treatments are available to improve the water sensitivity of particular hot-mix asphalt. These treatments can be conveniently grouped into those that are added or applied to the asphalt binder and those that are applied to the aggregate. Although the treatments are typically applied to only the asphalt binder or aggregate, their physicochemical effect is on both the asphalt binder and the aggregate.

A variety of chemicals are being incorporated into asphalt binder to reduce the moisture sensitivity of hot-mix asphalt mixtures. The majority of these chemicals presently used are alkyl amines and are sold under a variety of brand names. These types of chemicals are generally referred to as liquid antistrip agents or adhesion agents. Liquid antistrip agents are typically added to the asphalt binders at the contractor's hot-mix asphalt plant or at the refinery.

Hydrated lime, portland cement, fly ash, flue dust, and polymers have been added to aggregates to provide resistance to moisture in hot-mix asphalt mixtures. Of the products identified previously, hydrated lime is the most common addition to aggregates. Typically, hydrated lime is added to the aggregate and mixed before the introduction of the asphalt binder into the hot-mix asphalt mixing plant.

Liquid antistrip agents and hydrated lime are presently the most common types of antistrip agents used in the United States. The information contained in this report illustrates the behavior of these two types of antistrip agents on asphalt binder properties as well as on hot-mix asphalt mixtures.

Results obtained on laboratory-prepared samples and testing in the laboratory indicate that both liquid antistrip agents and hydrated lime can improve the moisture sensitivity of hot-mix asphalt. In addition, these antistrip agents can influence the behavior of hot-mix asphalt mixtures and thus pavement behavior relative to rutting, fatigue, raveling, and so forth. The magnitude of improvement offered by these antistrip chemicals as illustrated by laboratory tests depends on the laboratory test method used to evaluate moisture sensitivity as well as the asphalt binder source, aggregate type, antistrip concentration, and other aspects.

Few research reports are available that define the behavior of antistrip agents on field-produced mixtures and define the performance of pavements with and without antistrip agents. Thus, life-cycle cost information associated with the use of these antistrip chemicals is limited.

Research continues to improve the understanding of asphalt binders and aggregates and to develop fundamental tests that will enable engineers to confidently evaluate and predict the performance of hot-mix asphalt and pavements. Research to improve available antistrip agents is also under way. The growing understanding of the basic science and fundamental engineering principals, including surface energy and fracture mechanics, will allow the development of improved methodologies to reduce moisture sensitivity.

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TABLE 1 Viscosity Change in Different Asphalt Binders as a Result of Addition of an Antistrip Agent

Liquid Antistrip Additives
Original Asphalt Viscosity, 140° F

Asphalt	Control	Additive A	Additive B
A	1980	1760	1810
B	2250	2060	2070
C	1430	1300	1340

Source: Anderson et al. (*6*).

TABLE 2 Viscosity Change in Different Aged Asphalt Binders as a Result of Addition of an Antistrip Agent

Liquid Antistrip Additives
Aged Asphalt Viscosity, 140°F

Asphalt	Control	Additive A	Additive B
A	3680 (1.28)	3570 (1.41)	3220 (1.54)
B	5770 (1.31)	5160 (1.43)	4620 (1.52)
C	4070 (1.23)	3660 (1.39)	3390 (1.49)

Source: Anderson et al. (*6*).

TABLE 3 G*Sin(delta) Values for Binders with Various Liquid Antistrips

Binder Source	Liquid Antistrip Agent	Additive, %	Test Temp, °C	G*/sin d kPa
A	None	----	64	1.35
A	A	1.0	64	1.36
B	None	---	64	1.44
B	A	1.0	64	1.34
B	A	10.0	64	0.38
B	B	1.0	64	1.17

Source: PaveTex Engineering and Testing, Inc. (*10*).

TABLE 4 Texas DOT Liquid Antistrip Study

Type of Mixture	Liquid Additive, Percent			
	0	0.5	1.0	1.5
Surface	5* (21)**	74 (23)	63 (30)	
Leveling	17 (24)	100 (7)	68 (15)	
Base	13 (8)	71 (7)	67 (15)	29 (7)

Source: Ho (*13*).

* Percentage of projects passing 0.70 TSR requirement for AASHTO T283 (with freeze–thaw).

** Number of samples.

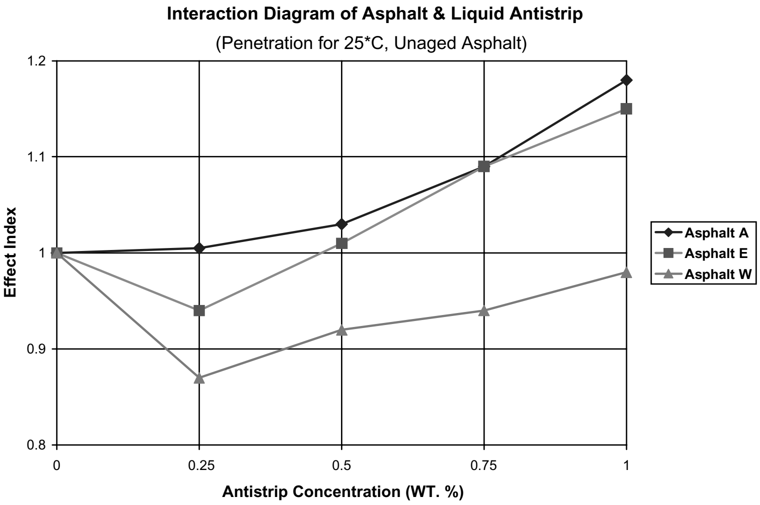

FIGURE 1 Penetration of asphalt binders as a function of antistrip agent concentration (*7*).

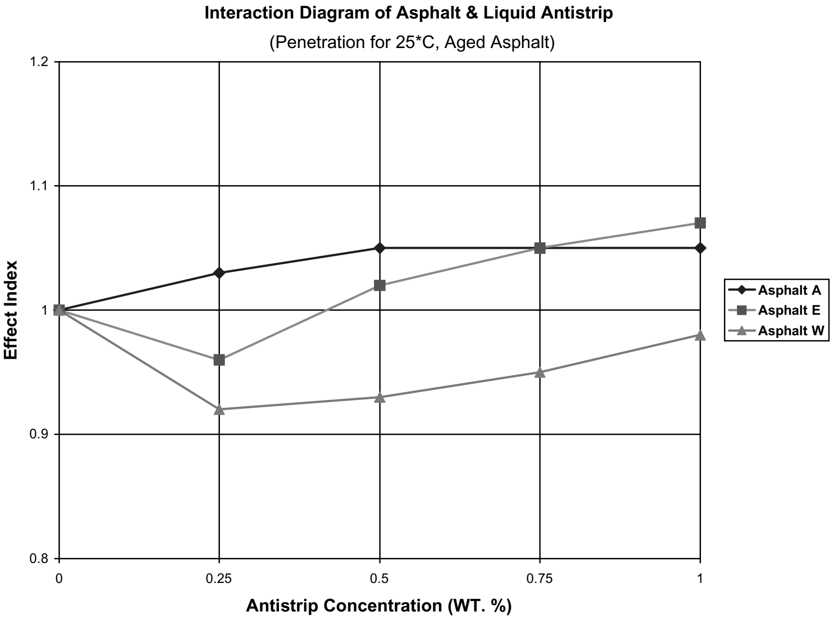

FIGURE 2 Penetration of aged asphalt binders as a function of antistrip agent concentration (*8*).

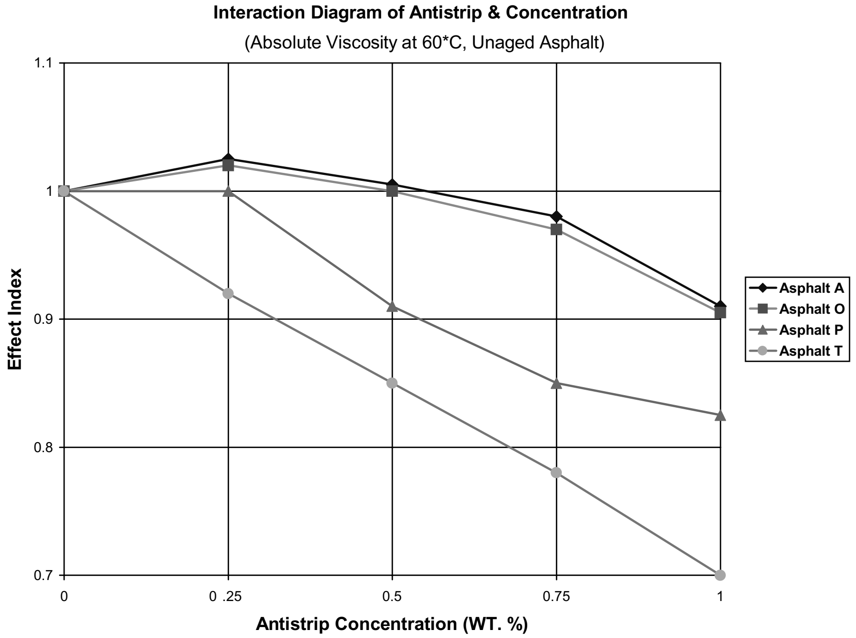

FIGURE 3 Absolute viscosity of asphalt binders as a function of antistrip agent concentration (*7*).

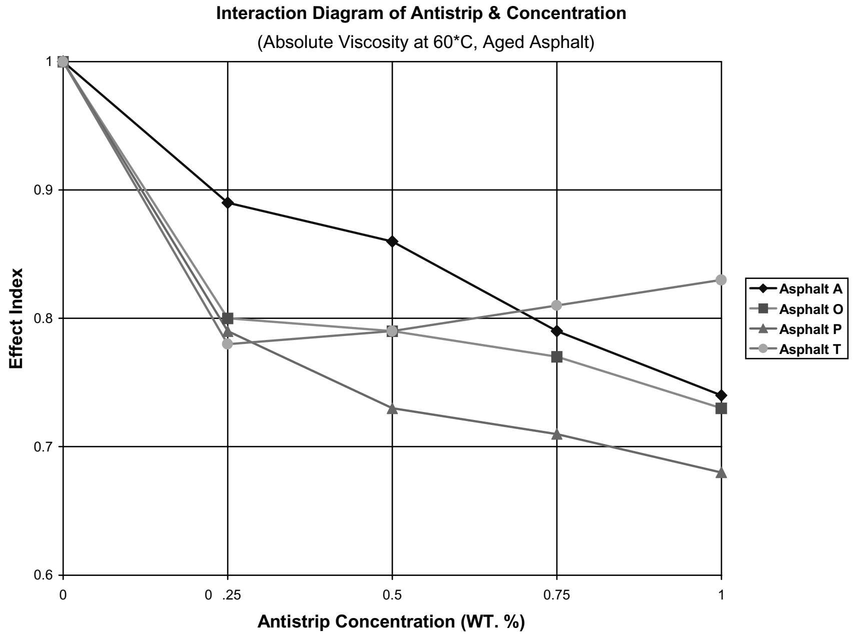

FIGURE 4 Absolute viscosity of aged asphalt binders as a function of antistrip agent concentration (*7*).

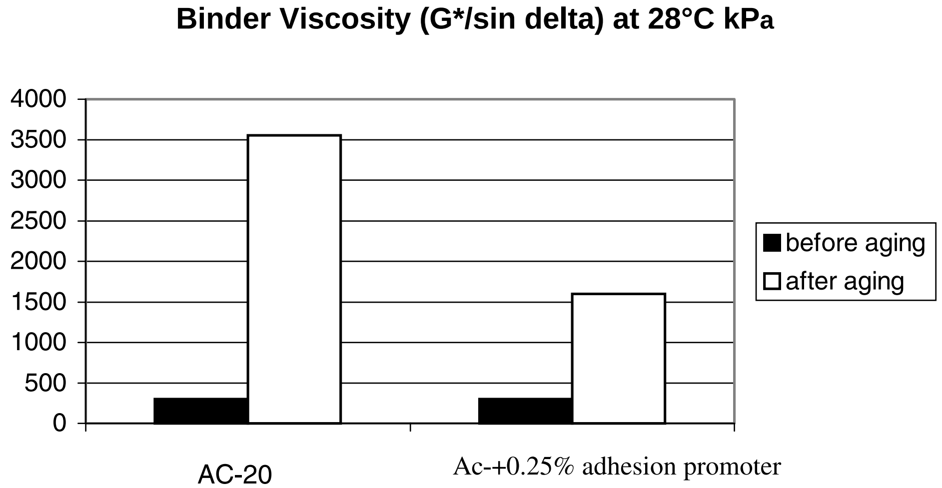

FIGURE 5 Binder stiffness and aging after PAV ("Adhesion Promoters," Akzo Nobel).

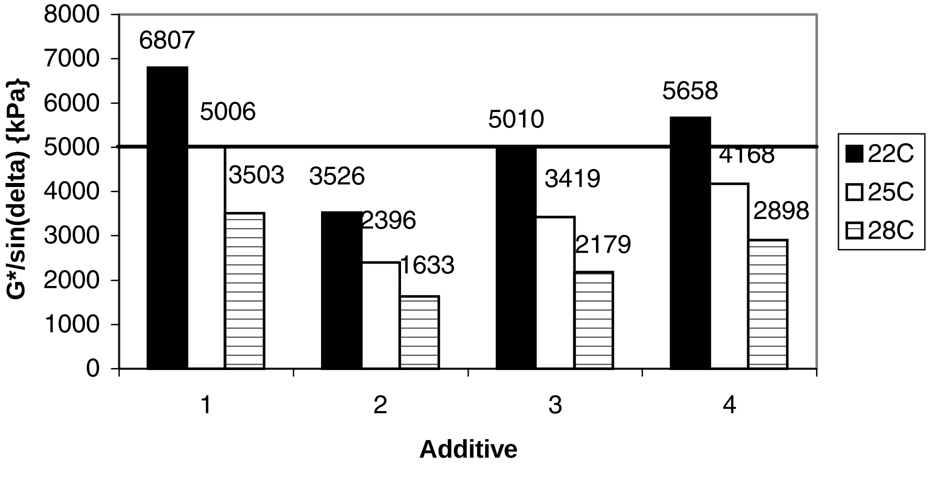

FIGURE 6 Effect of various additives on fatigue cracking West Texas sour crude (*9*).

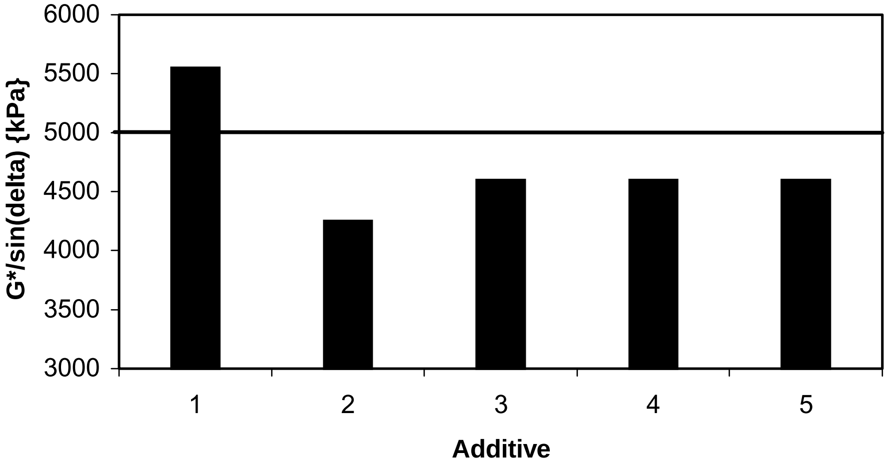

FIGURE 7 Effect of LAS on fatigue cracking of AC-20 (*9*).

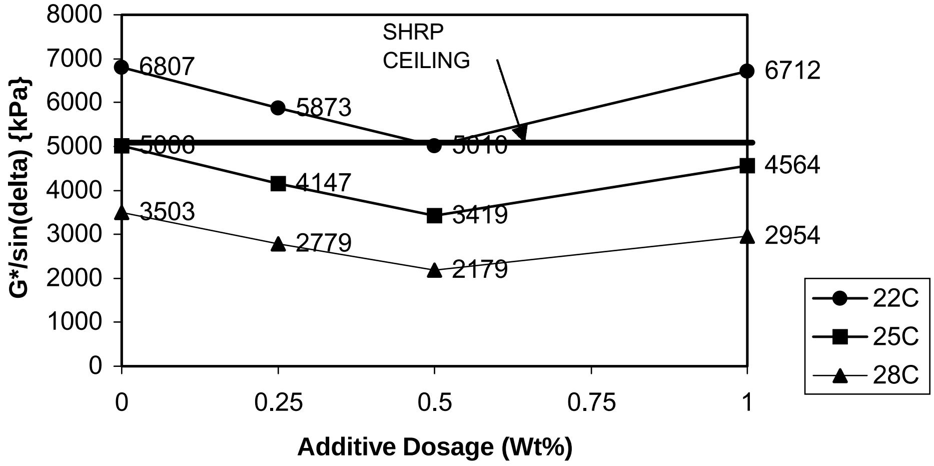

FIGURE 8 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

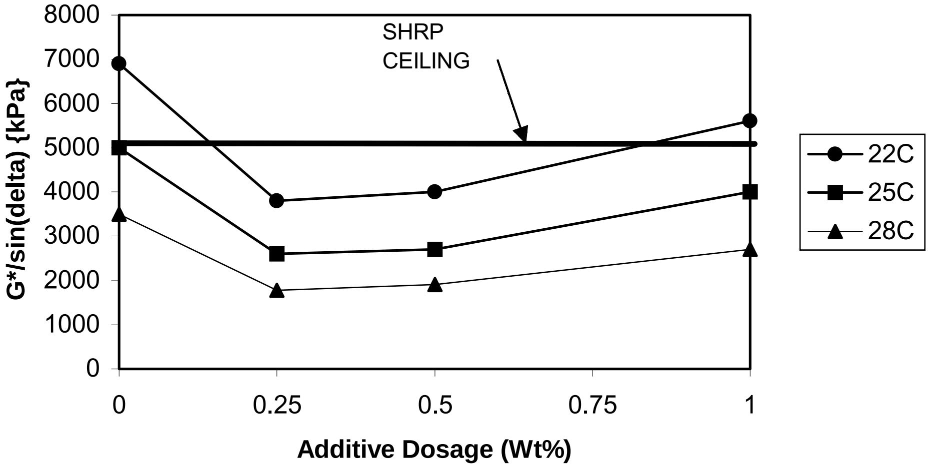

FIGURE 9 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

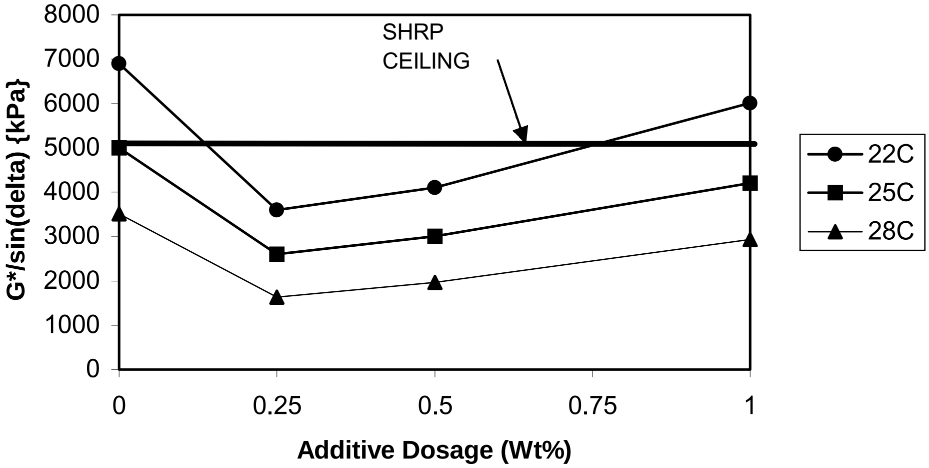

FIGURE 10 Effect of dosage of an antistrip additive on fatigue cracking West Texas sour crude (*9*).

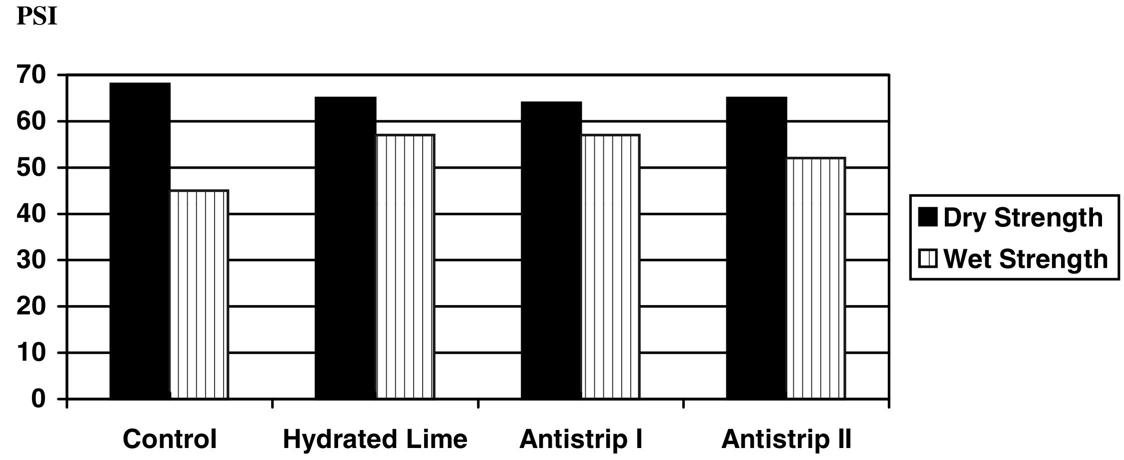

FIGURE 11 Indirect tensile strength of Aggregate A as a function of antistrip before and after exposure to water (*11*).

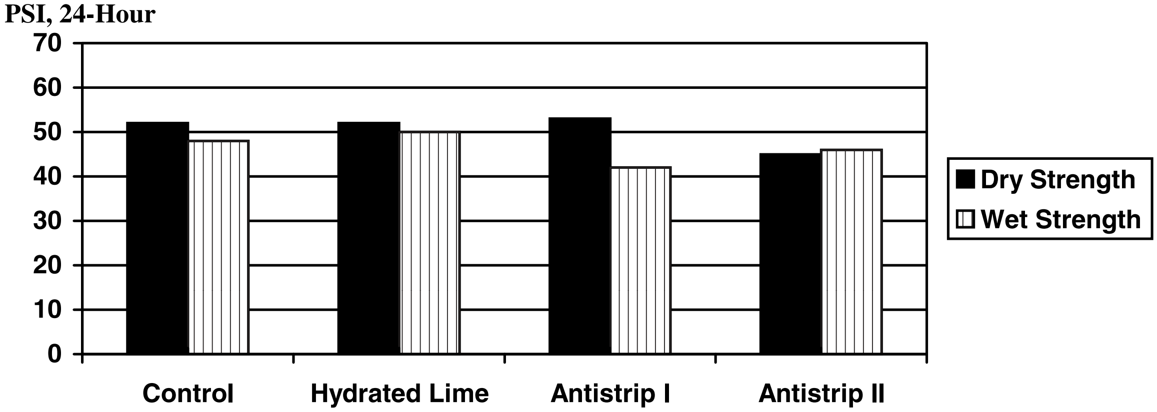

FIGURE 12 Indirect tensile strength of Aggregate B as a function of antistrip before and after exposure to water (*11*).

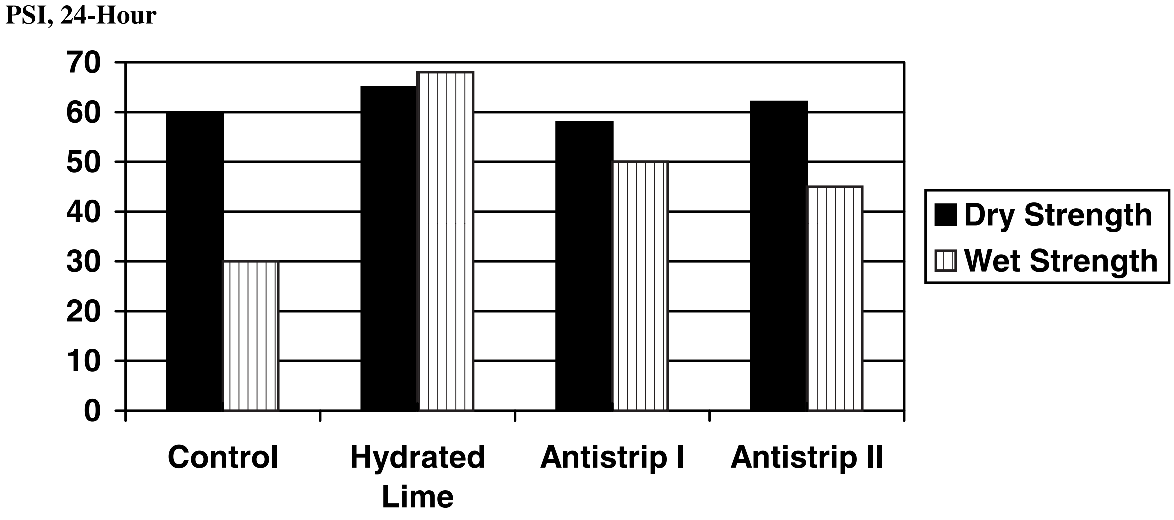

FIGURE 13 Indirect tensile strength of Aggregate C as a function of antistrip before and after exposure to water (*11*).

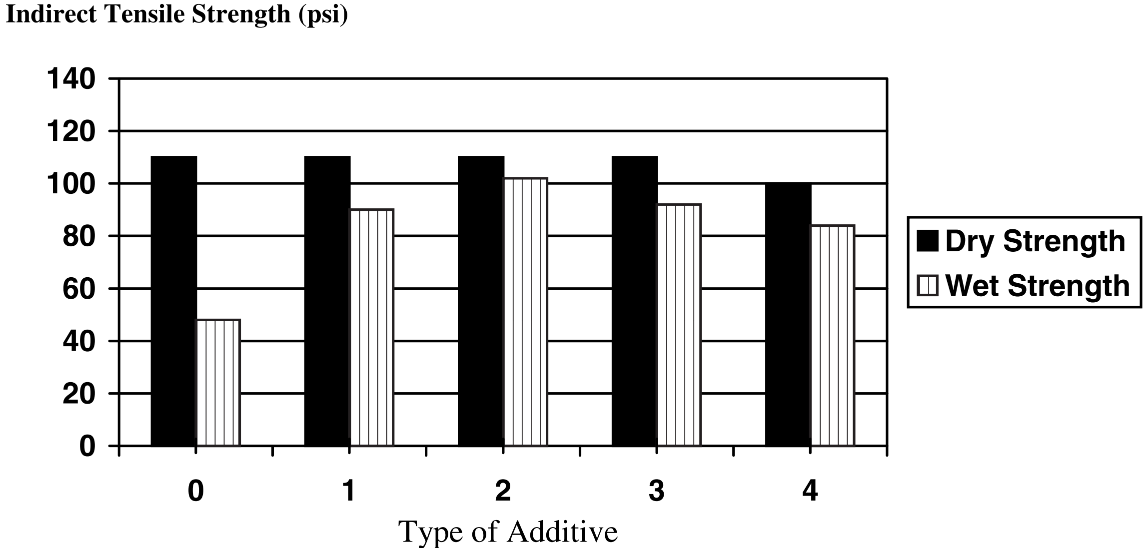

FIGURE 14 Indirect tensile strength as a function of antistrip before and after 24 h of moisture conditioning (*11*).

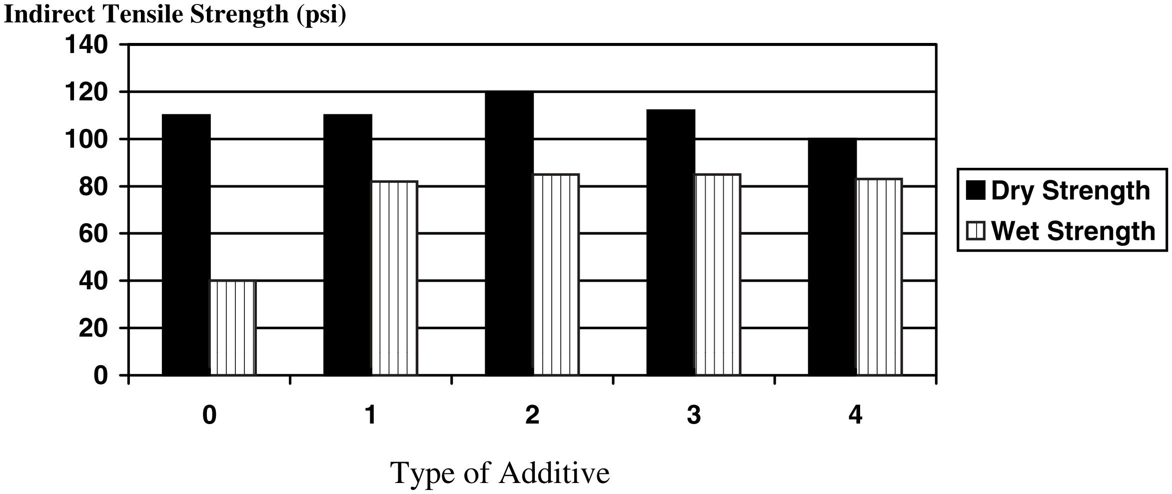

FIGURE 15 Indirect tensile strength as a function of antistrip before and after 24 h of moisture conditioning (*11*).

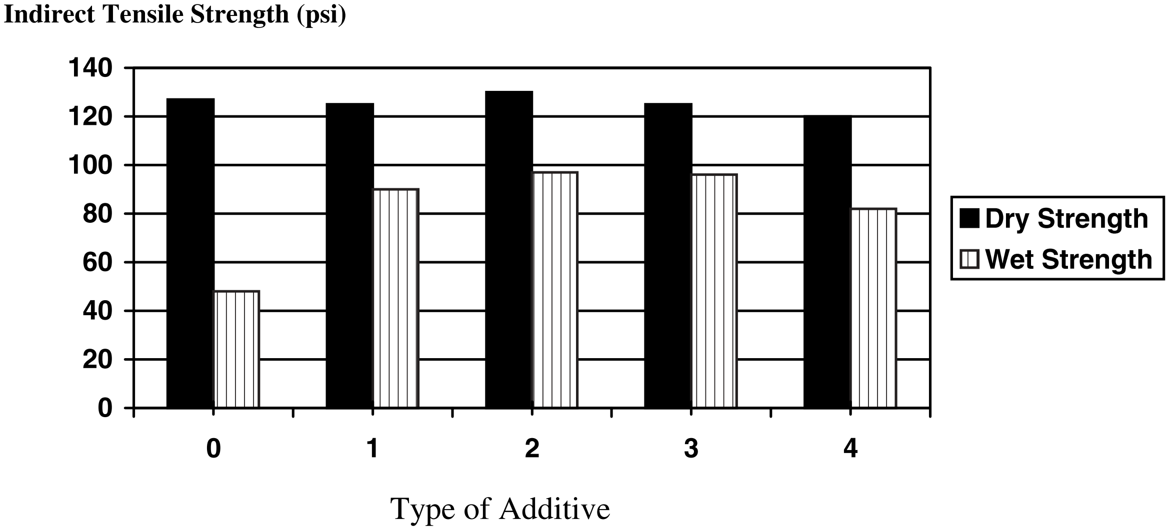

FIGURE 16 Indirect tensile strength as a function of antistrip before and after 60 days of moisture conditioning (*11*).

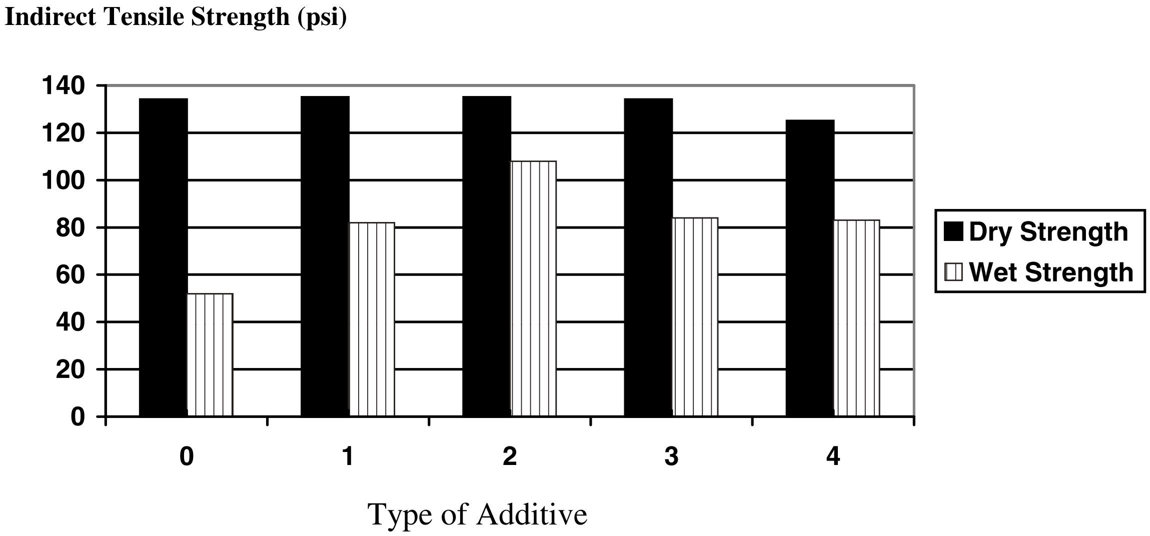

FIGURE 17 Indirect tensile strength as a function of antistrip before and after 60 days of moisture conditioning (*11*).

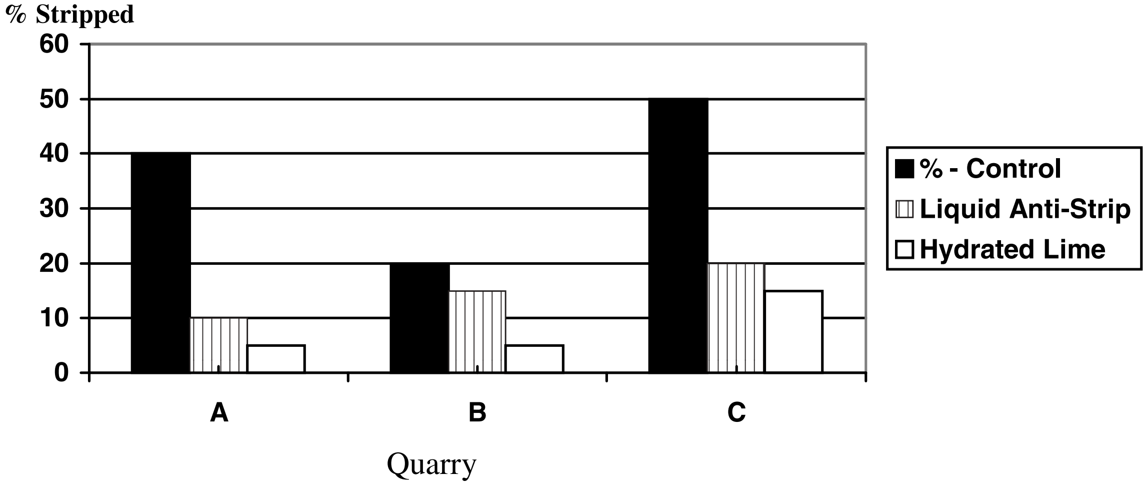

FIGURE 18 Boil test results as a function of antistrip agent and quarry (*11*).

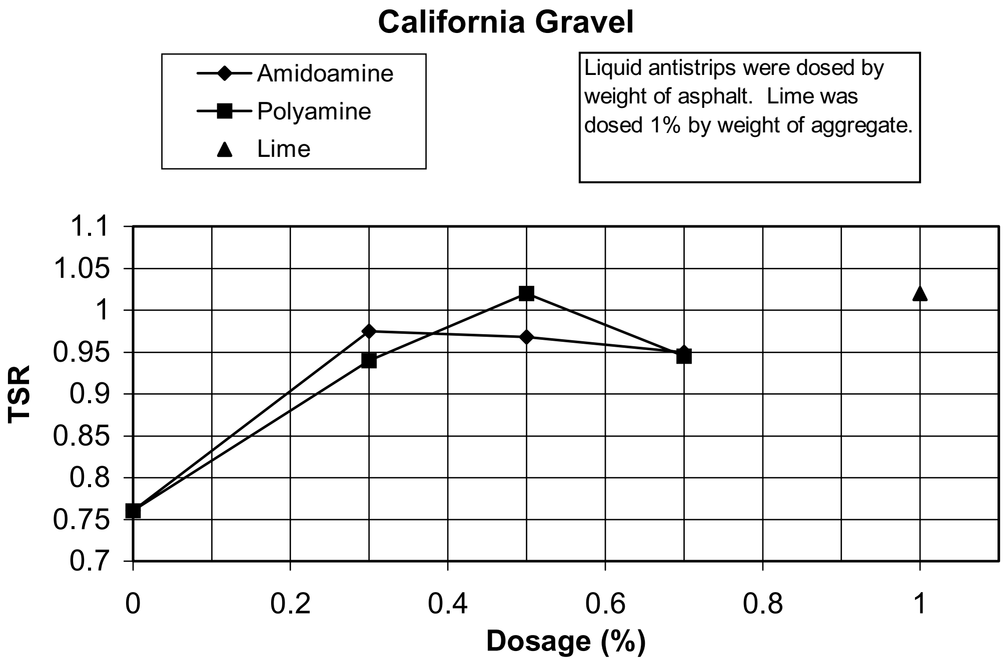

FIGURE 19 Results of Lottman tests for aggregates treated with different antistrip agents in California (*12*).

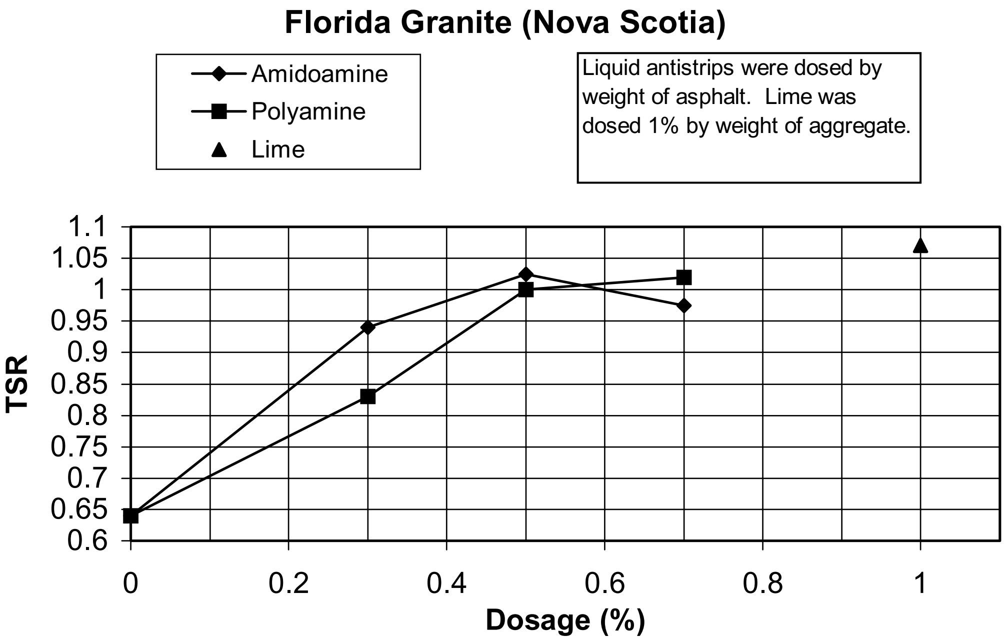

FIGURE 20 Results of Lottman tests for aggregates treated with different antistrip agents in Florida (*12*).

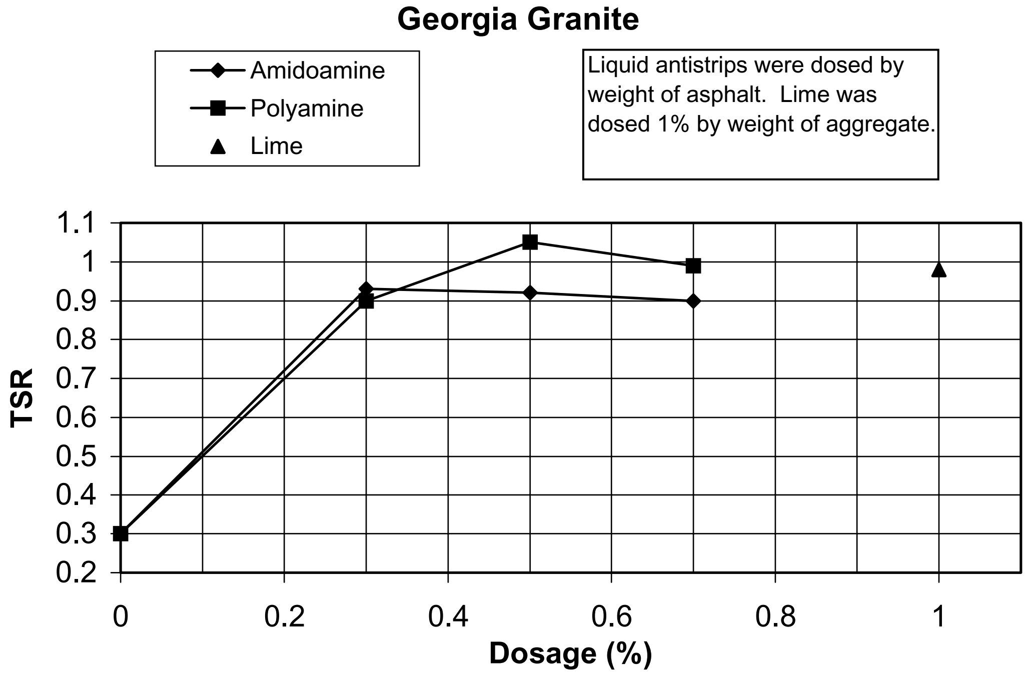

FIGURE 21 Results of Lottman tests for aggregates treated with different antistrip agents in Georgia (*12*).

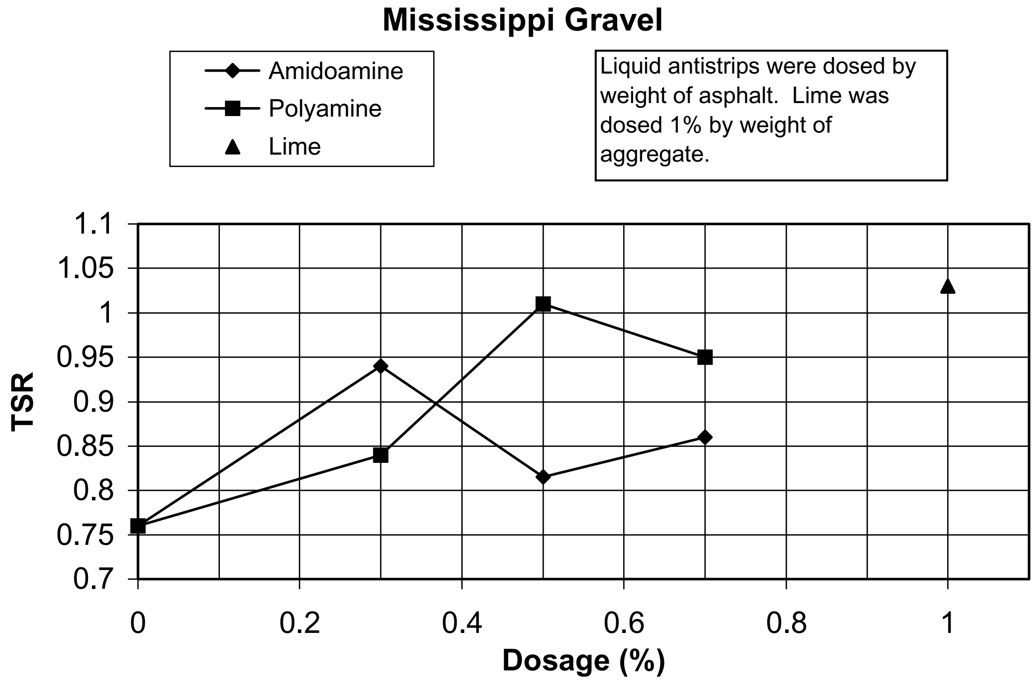

FIGURE 22 Results of Lottman tests for aggregates treated with different antistrip agents in Mississippi (gravel) (*12*).

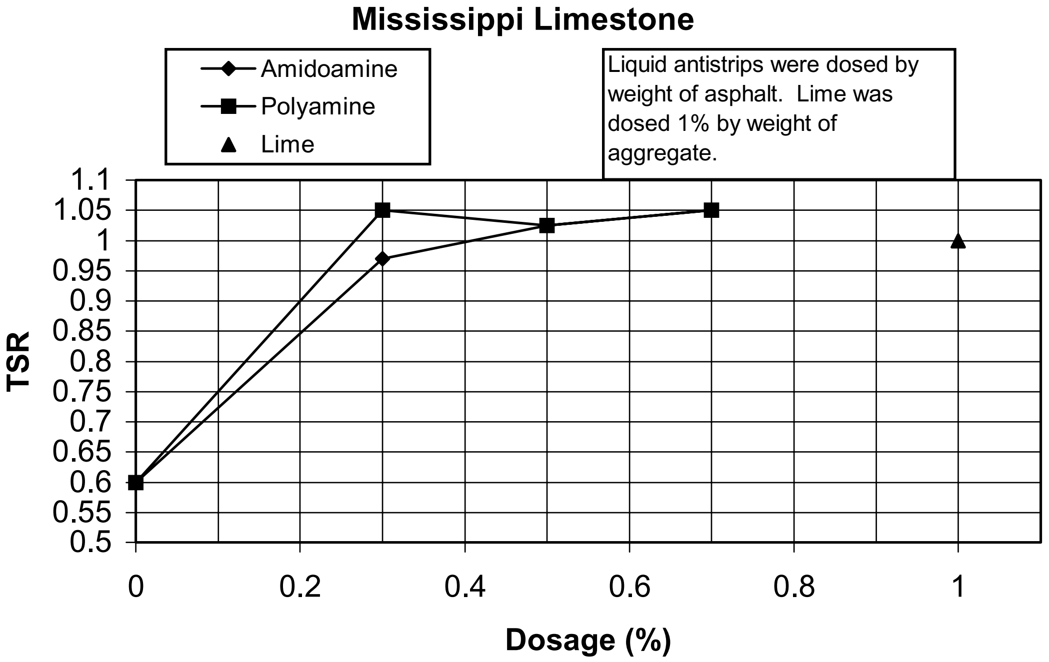

FIGURE 23 Results of Lottman tests for aggregates treated with different antistrip agents in Mississippi (limestone) (*12*).

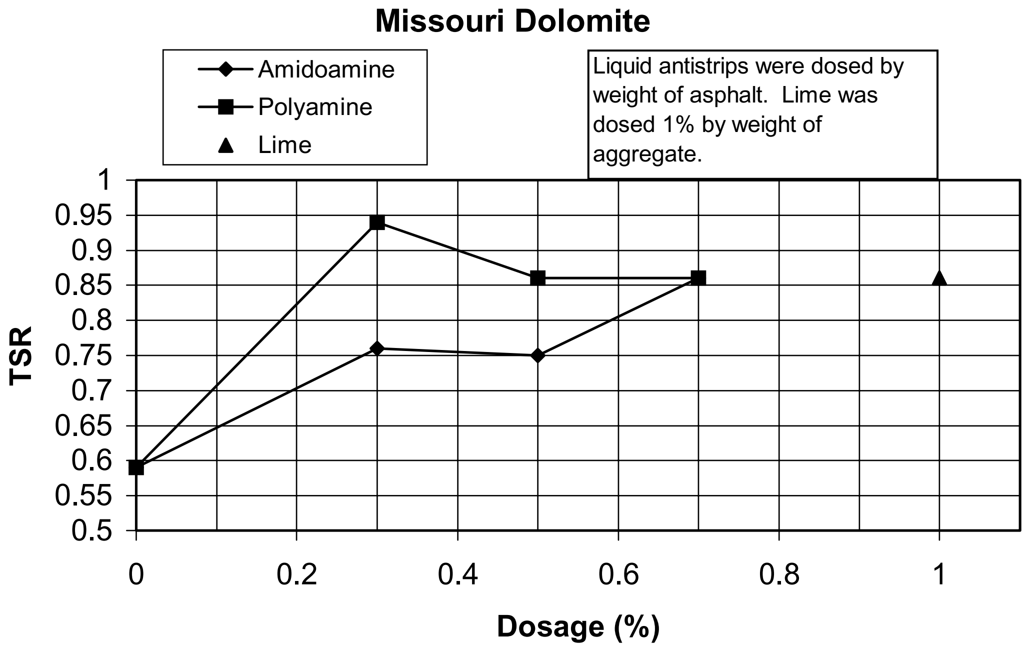

FIGURE 24 Results of Lottman tests for aggregates treated with different antistrip agents in Missouri (*12*).

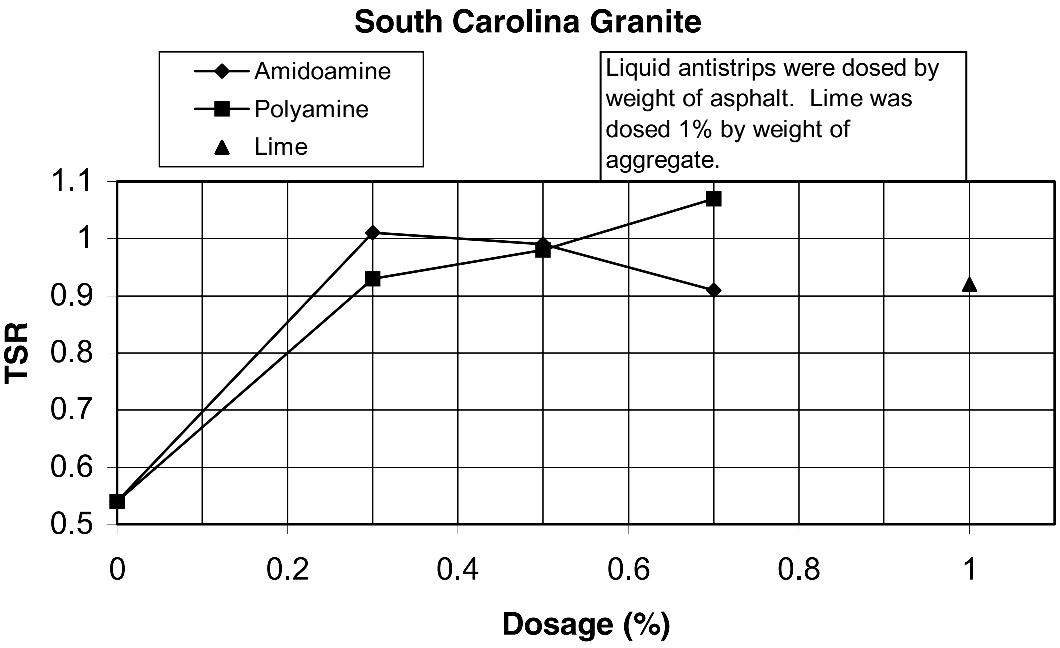

FIGURE 25 Results of Lottman tests for aggregates treated with different antistrip agents in South Carolina (*12*).

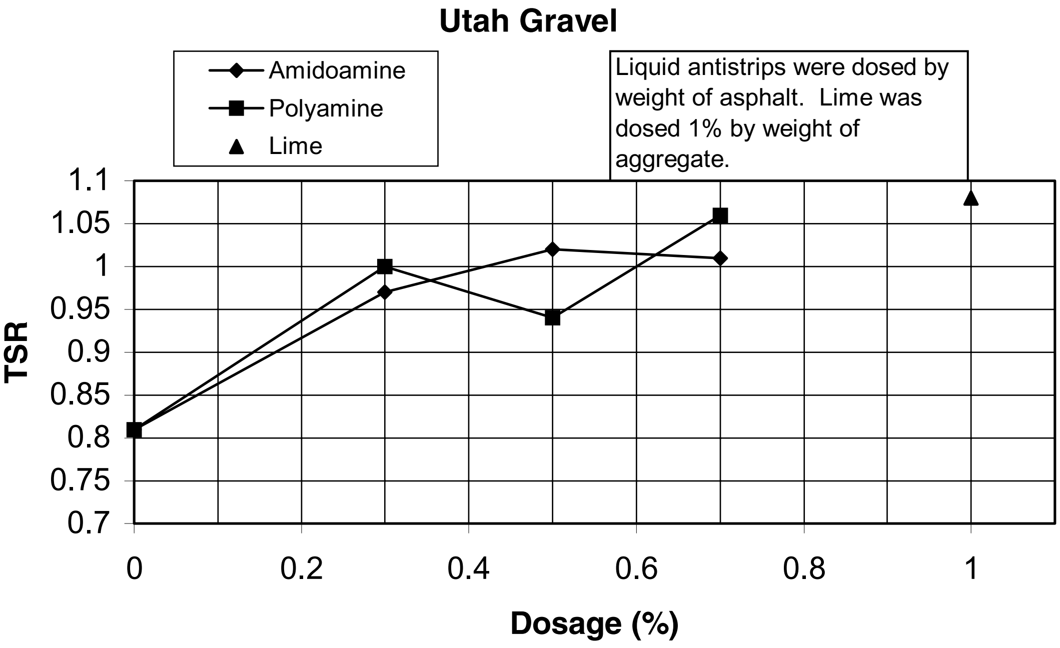

FIGURE 26 Results of Lottman tests for aggregates treated with different antistrip agents in Utah (*12*).

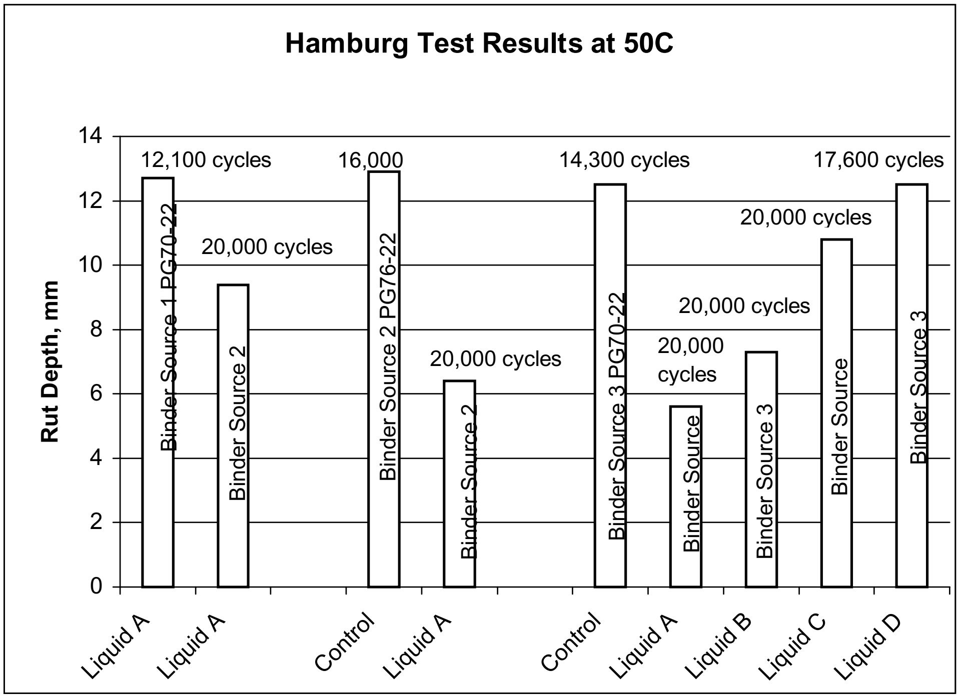

FIGURE 27 Hamburg rut test results for mixtures using various liquid antistrips and asphalt binders (*14*).

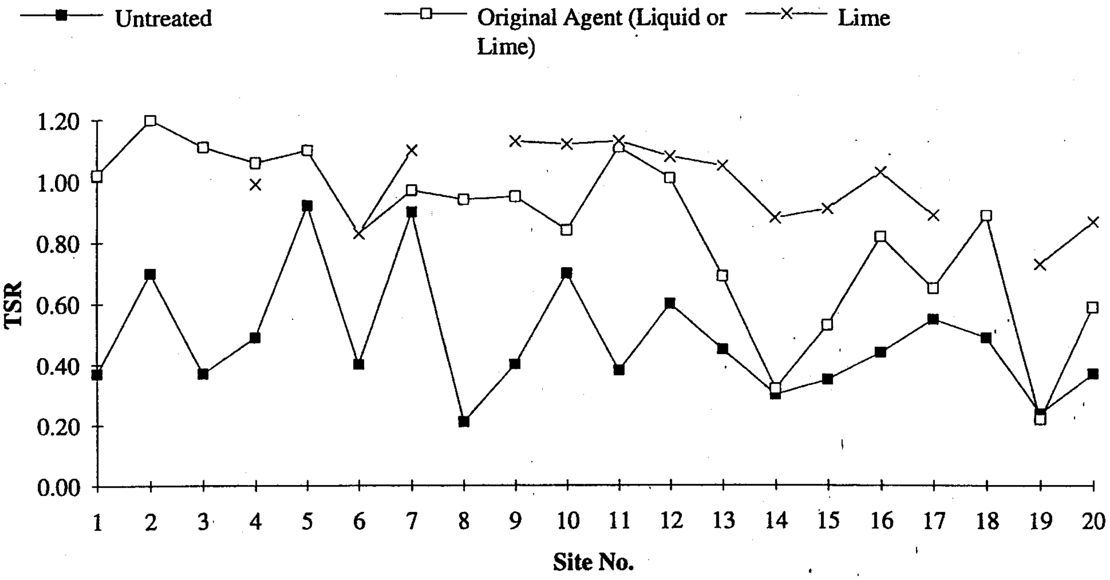

FIGURE 28 Effect of liquid antistrip on tensile strength ratio for various projects in Colorado (*15*).

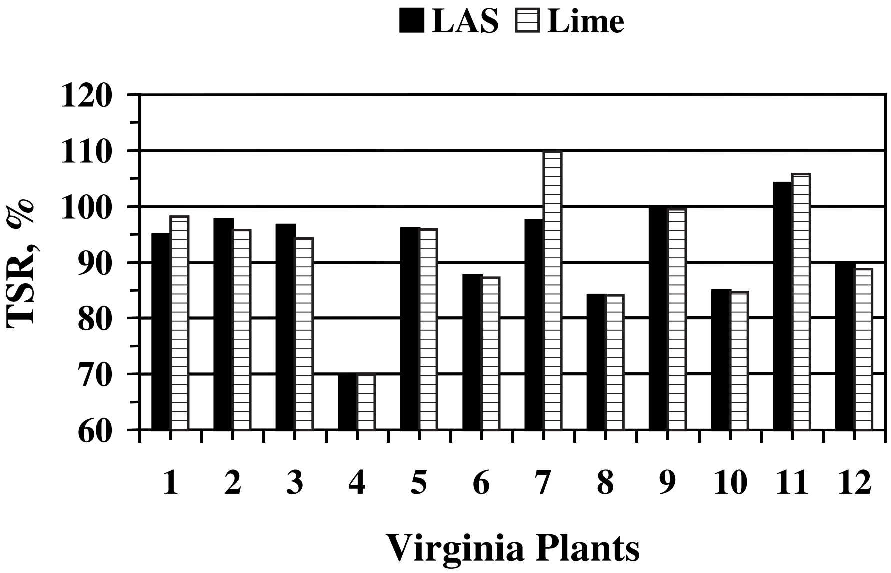

FIGURE 29 Comparison of tensile strength ratios for various projects in Virginia using liquid antistrip agents and lime ("Tensile Strength Ratio—Virginia," provided by Akzo Nobel).

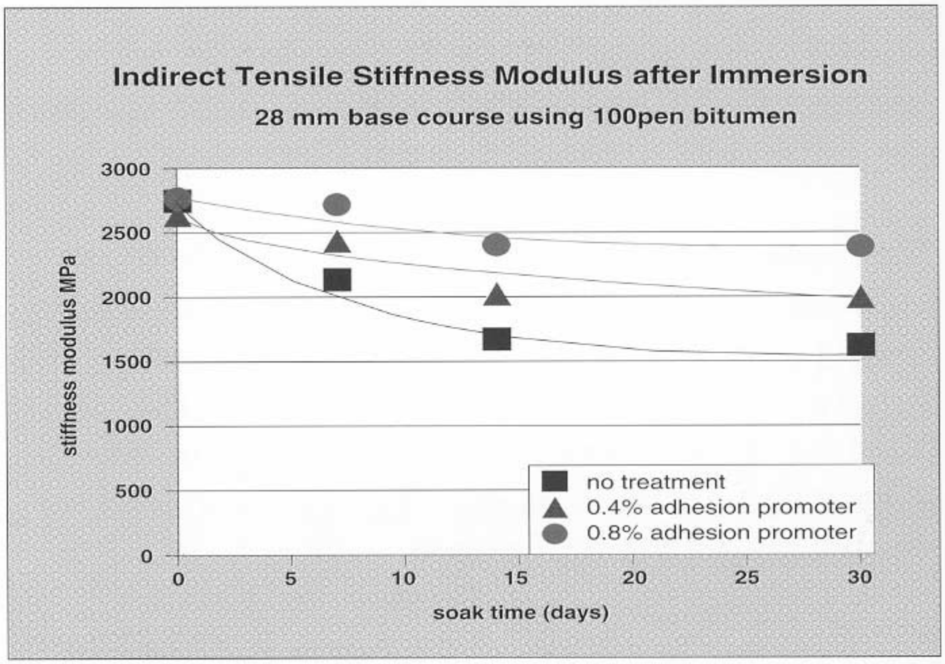

FIGURE 30 Indirect tensile stiffness modulus values for a base course treated with various dosages of liquid antistrip (*Adhesion Promoters*, technical bulletin, Akzo Nobel).

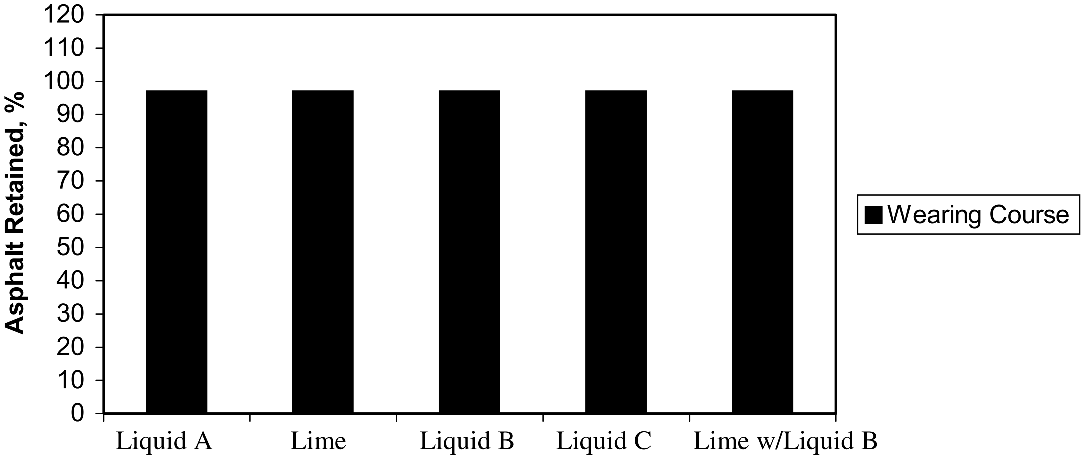

FIGURE 31 Louisiana boil test results using various antistrip agents in mixtures in Louisiana (*18*).

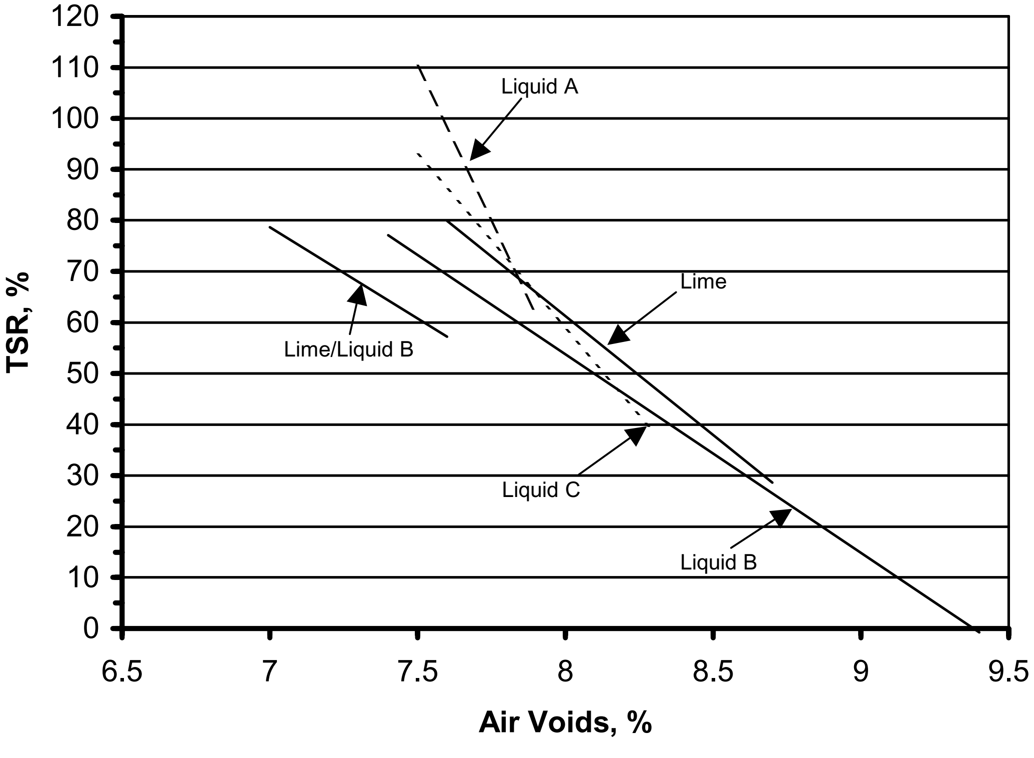

FIGURE 32 Tensile strength ratio test results using various antistrip agents in mixtures in Louisiana (*18*).

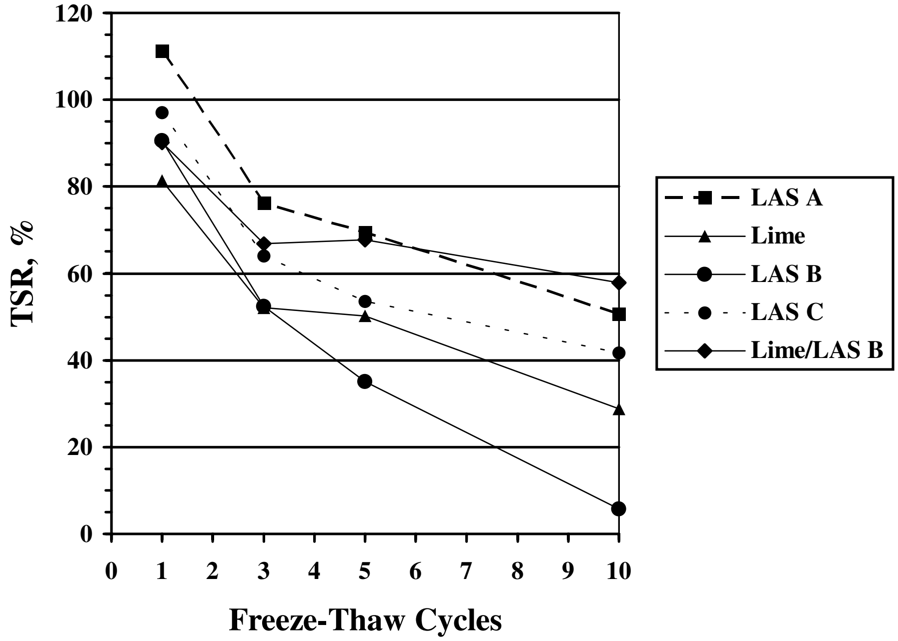

FIGURE 33 Tensile strength ratio test results as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

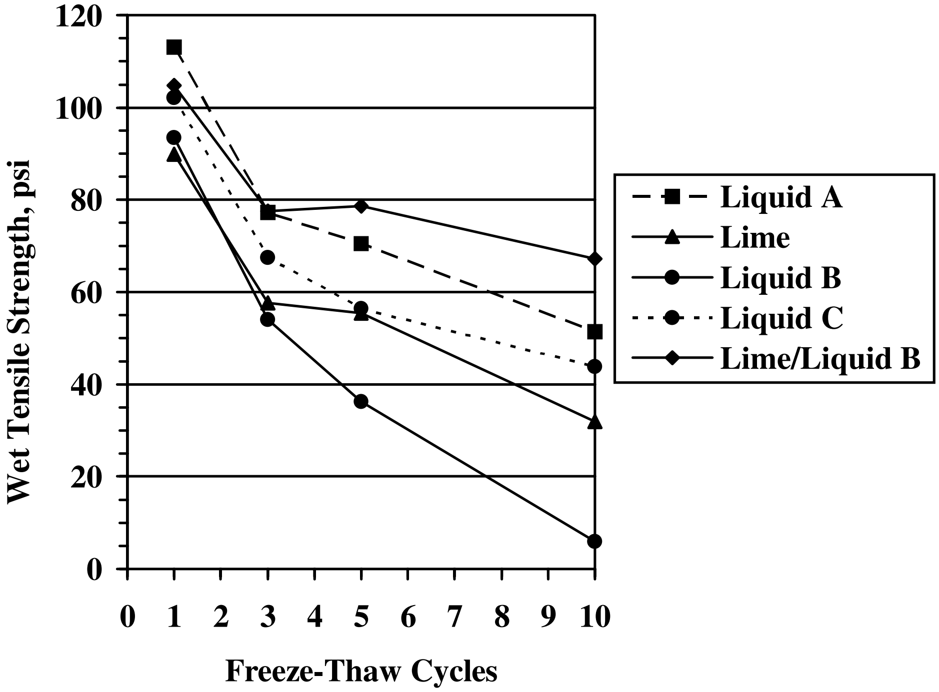

FIGURE 34 Wet tensile strength results as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

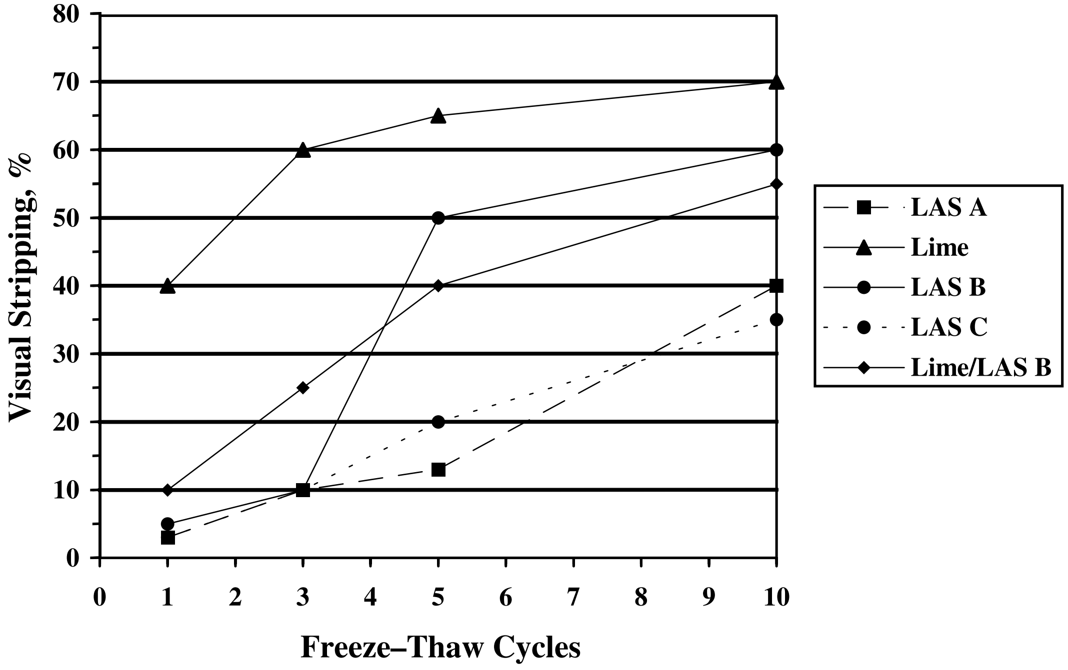

FIGURE 35 Visual stripping percentage as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

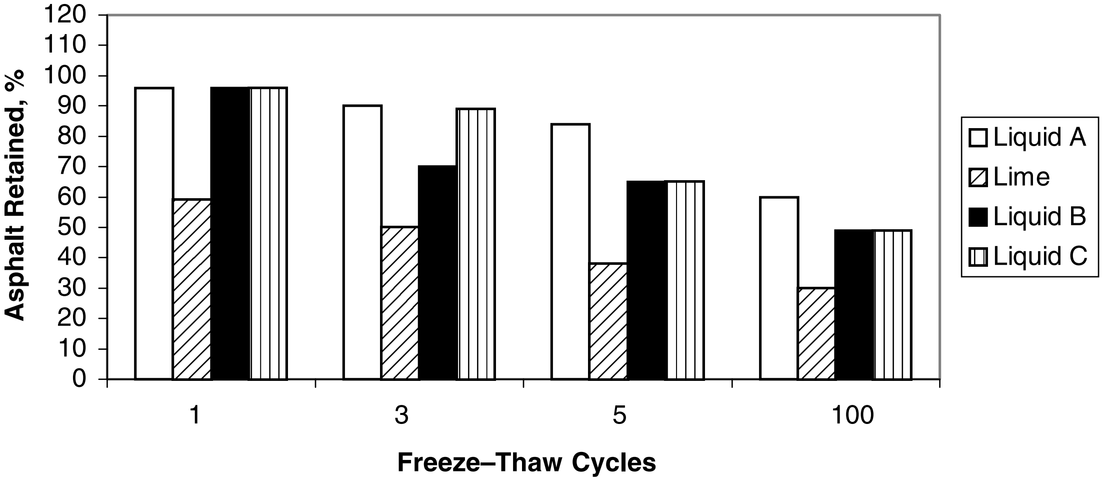

FIGURE 36 Asphalt retained percentage as a function of freeze–thaw cycles for various antistrip agents in mixtures in Louisiana (*18*).

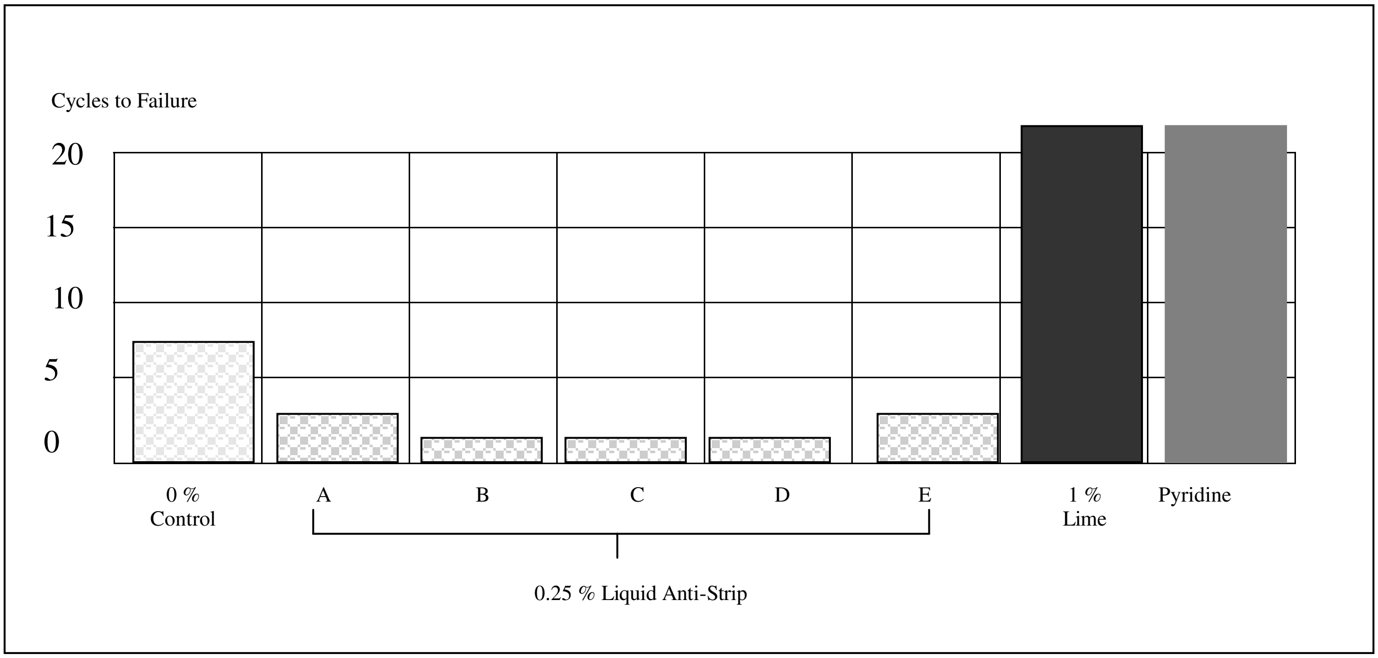

FIGURE 37 Effect of selected modifiers on moisture damage freeze–thaw pedestal test (*19*).

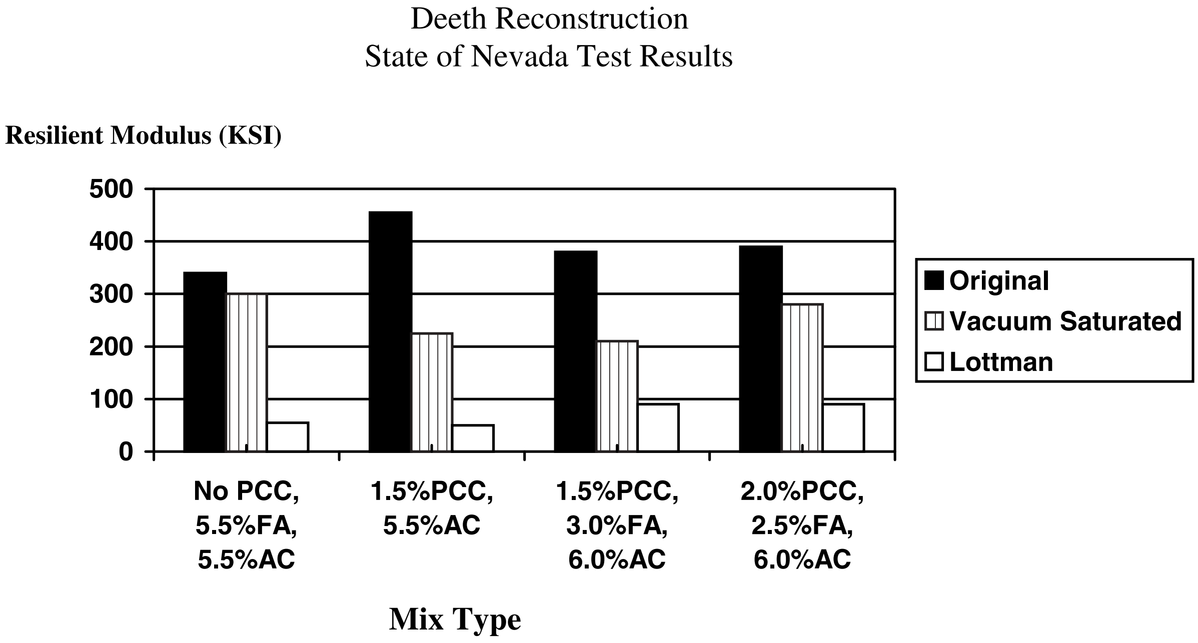

FIGURE 38 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

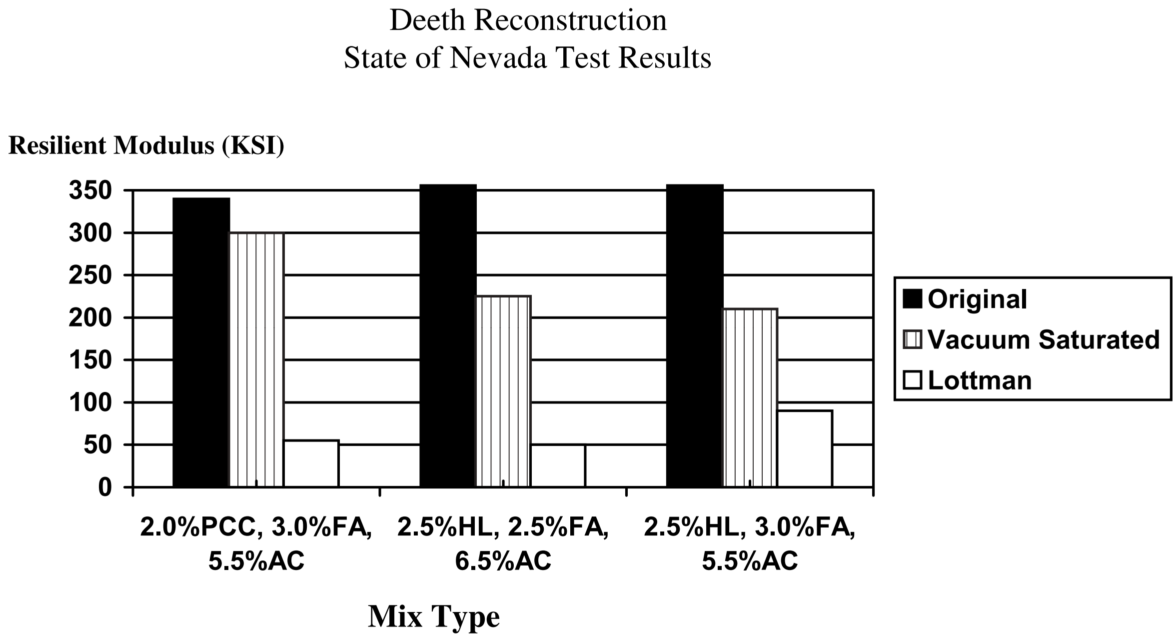
Deeth Reconstruction
State of Nevada Test Results

FIGURE 39 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

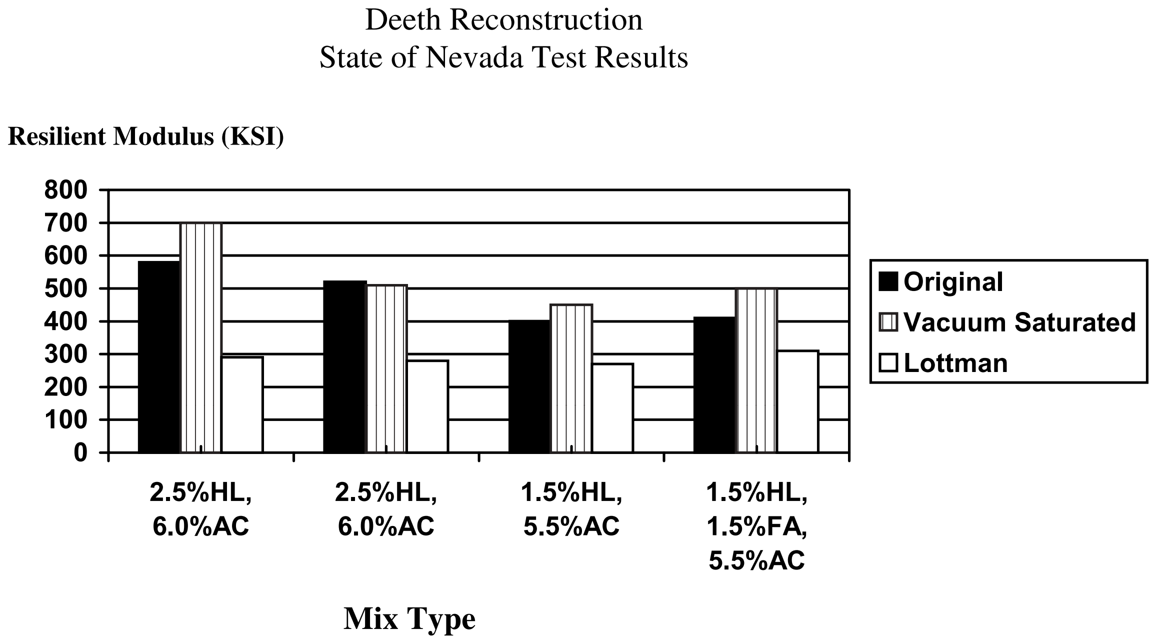
Deeth Reconstruction
State of Nevada Test Results

FIGURE 40 Effectiveness of fly ash, portland cement, and hydrated lime on the moisture sensitivity of a single aggregate (*20*, *21*).

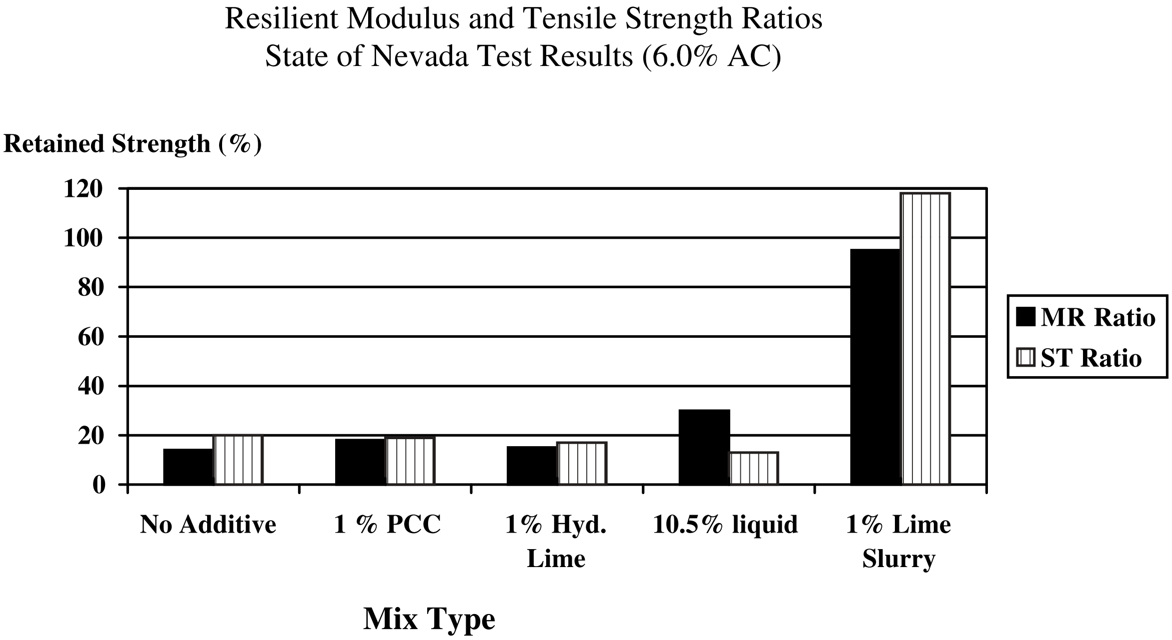

FIGURE 41 Resilient modulus and tensile strength ratios of various mixtures evaluated in Nevada (6.0% AC) (*20*, *21*).

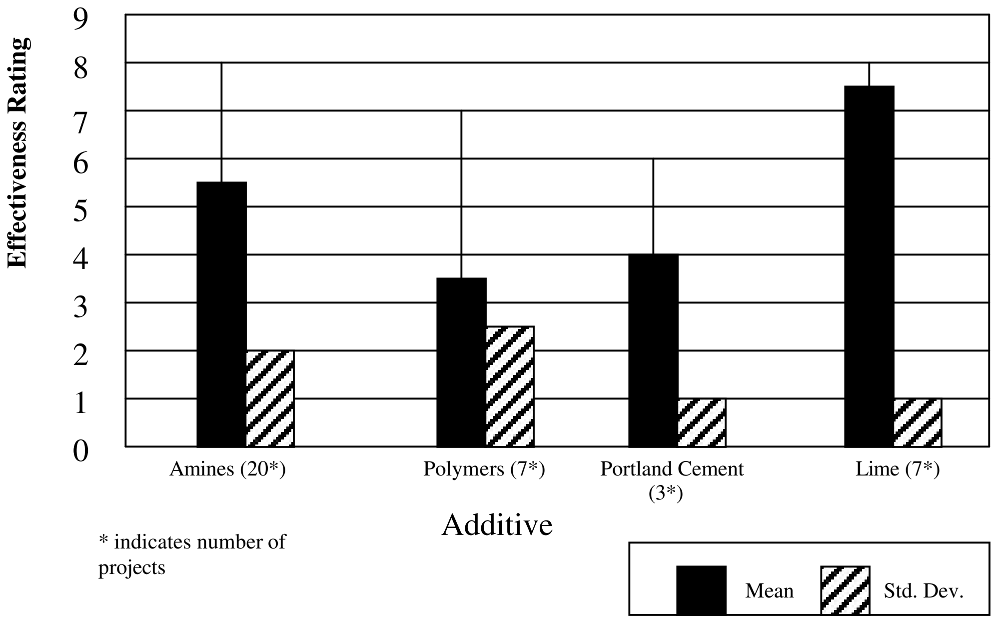

FIGURE 42 Relative effectiveness of additives in eliminating or reducing moisture problem (*22*).

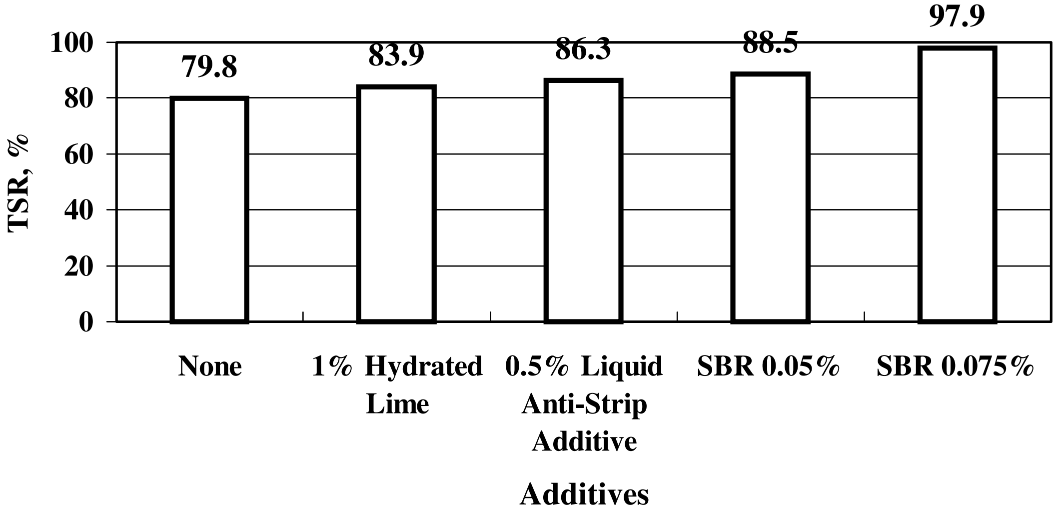

FIGURE 43 Florida study: tensile strength ratios with various antistrip agents with Florida granite (*26*).

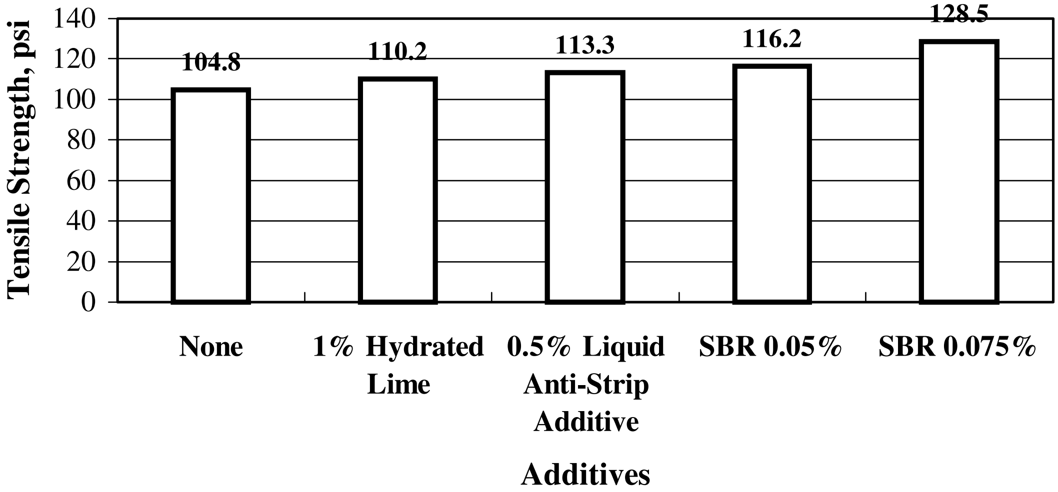

FIGURE 44 Florida study: wet tensile strength with various antistrip agents with Florida granite (*26*).

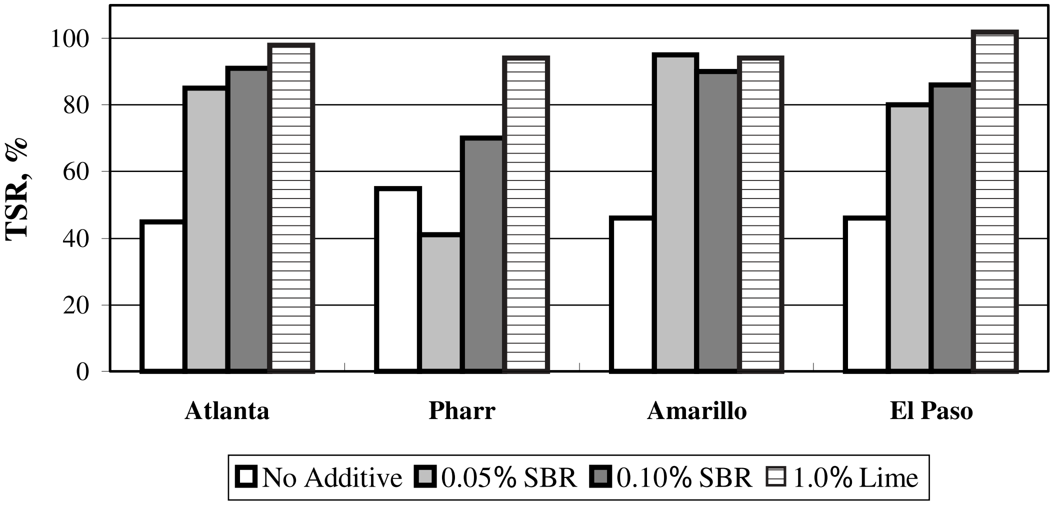

FIGURE 45 Texas study: tensile strength ratios with various antistrip agents with various Texas aggregates (*27*).

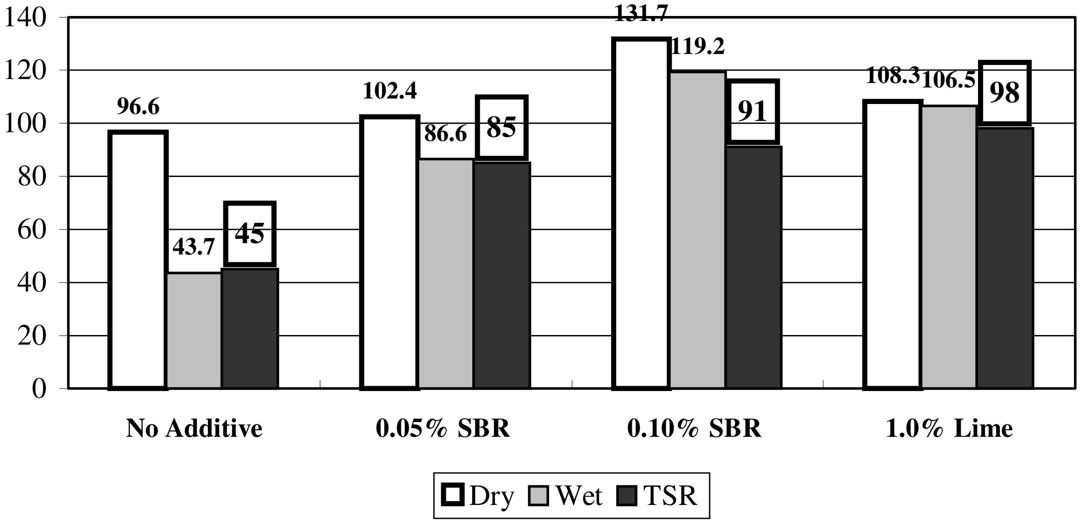

FIGURE 46 Texas study: tensile strength versus tensile strength ratio with various antistrip agents with Atlanta District aggegate (*27*).

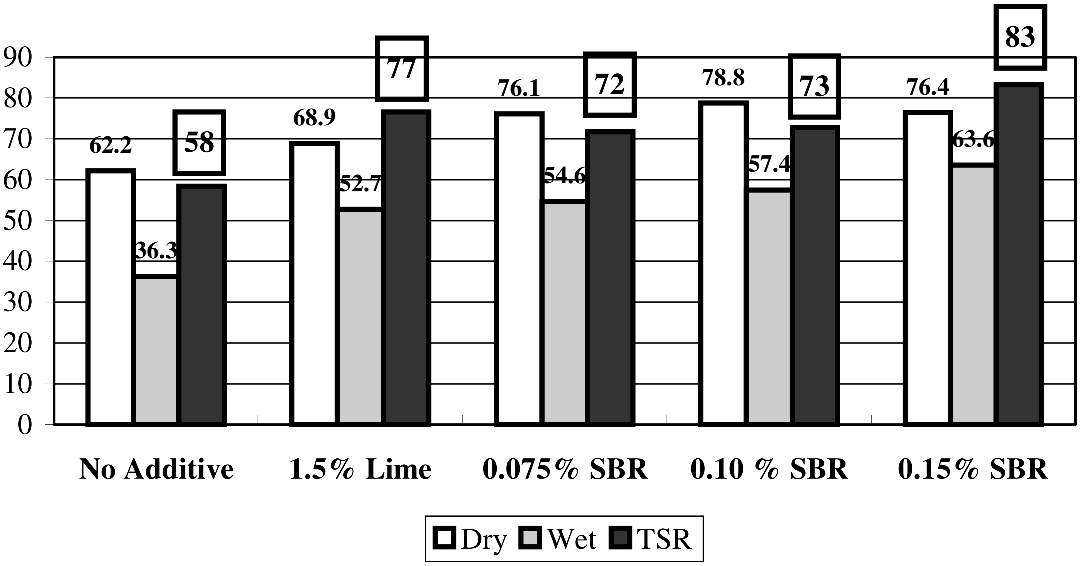

FIGURE 47 Nevada study: tensile strength versus tensile strength ratio with various antistrip agents with Elko aggregate (*23*).

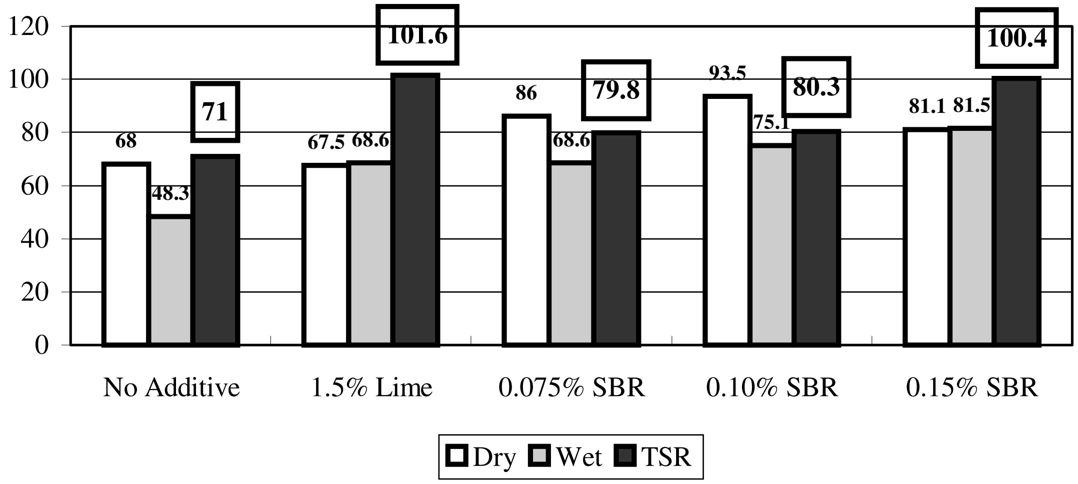

FIGURE 48 Nevada study: tensile strength versus tensile strength ratio with various antistrip agents with Lockwood aggregate (*23*).

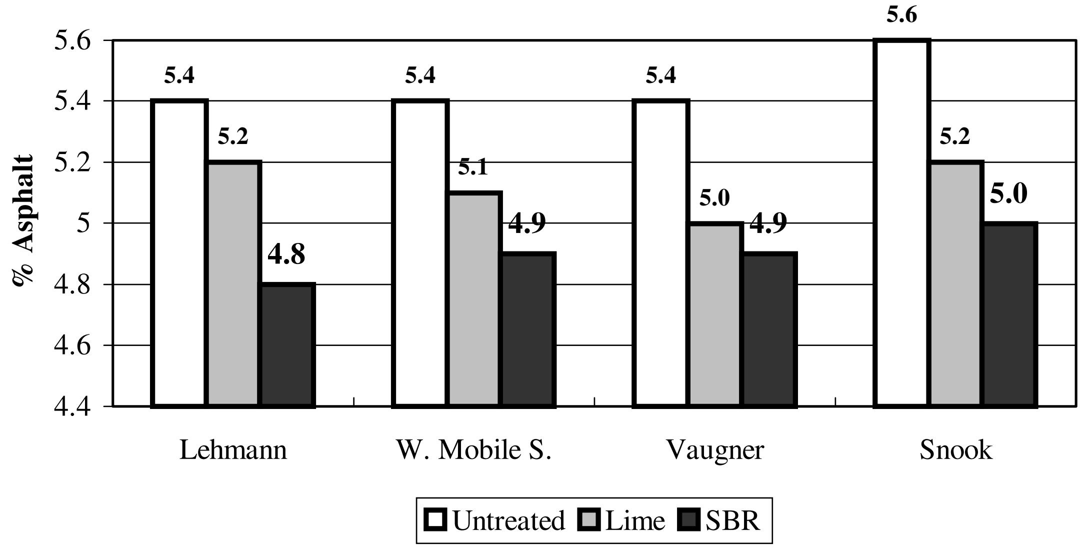

FIGURE 49 Colorado study: optimum oil content with various antistrip agents with Colorado aggregates (*24*).

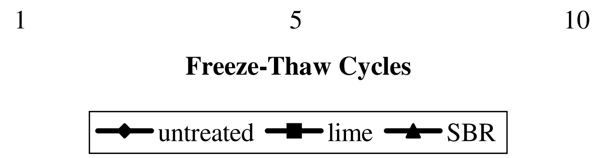

FIGURE 50 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Western Mobile South aggregate (*24*).

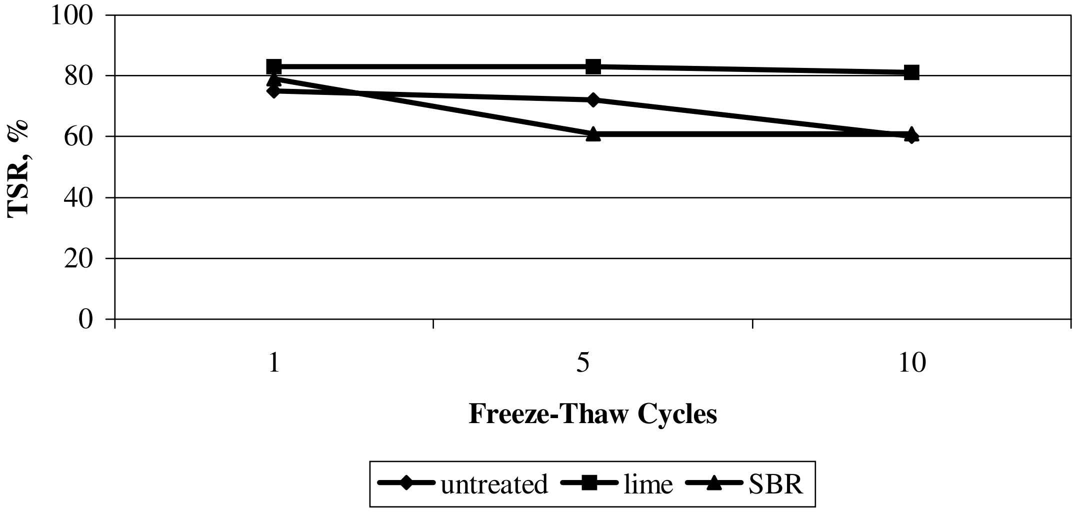

FIGURE 51 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Lehmann aggregate (*24*).

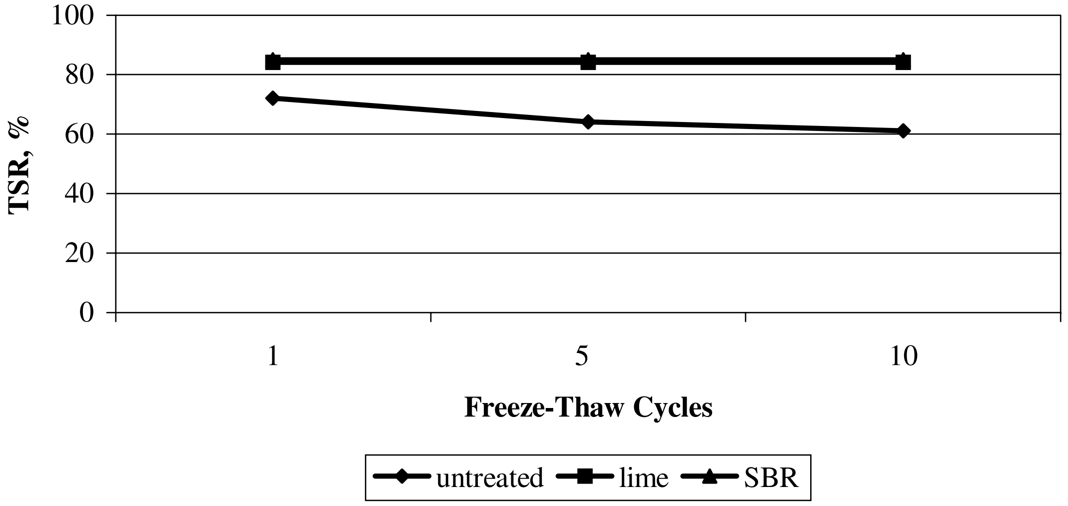

FIGURE 52 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Vaugner aggregate (*24*).

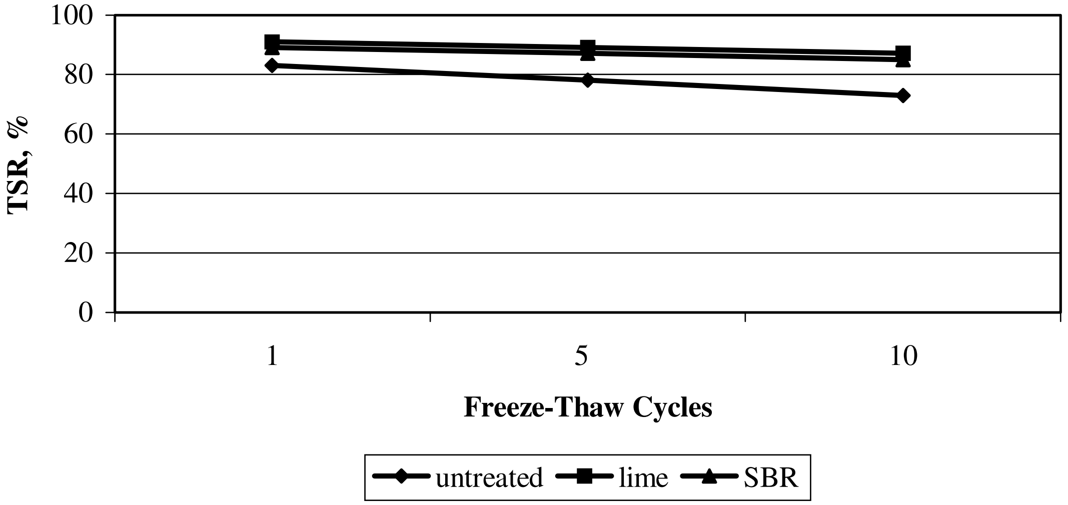

FIGURE 53 Colorado study: tensile strength ratio test as a function of freeze–thaw cycles for antistrip agents in mixes of Colorado Snook aggregate (*24*).

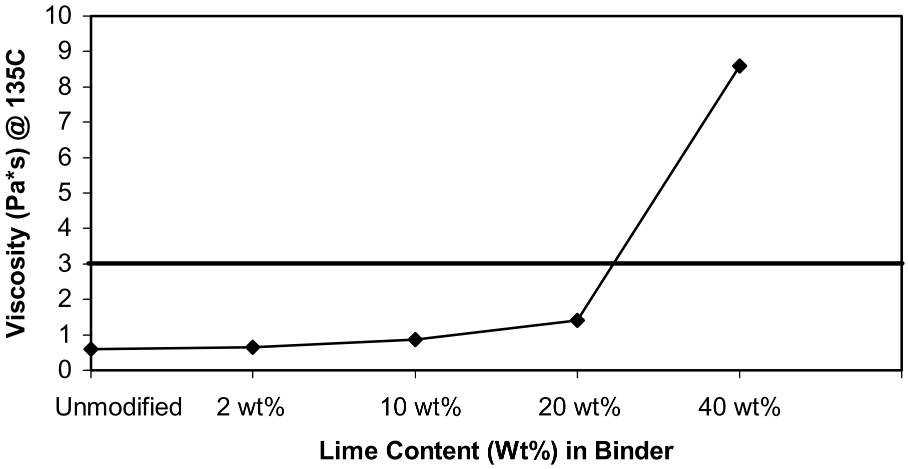

FIGURE 54 Effect of lime dosage on binder viscosity (*9*).

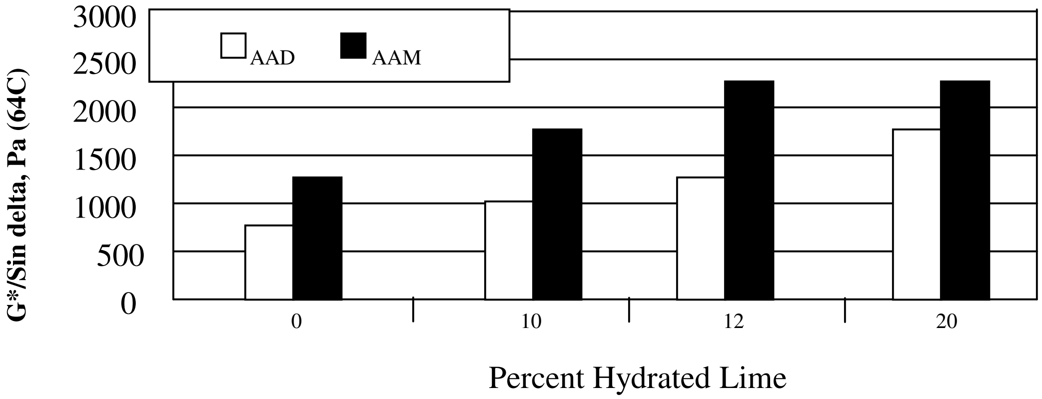

FIGURE 55 Effect of the addition of hydrated lime on asphalt binder rheology, G*/sin(delta) (*31*).

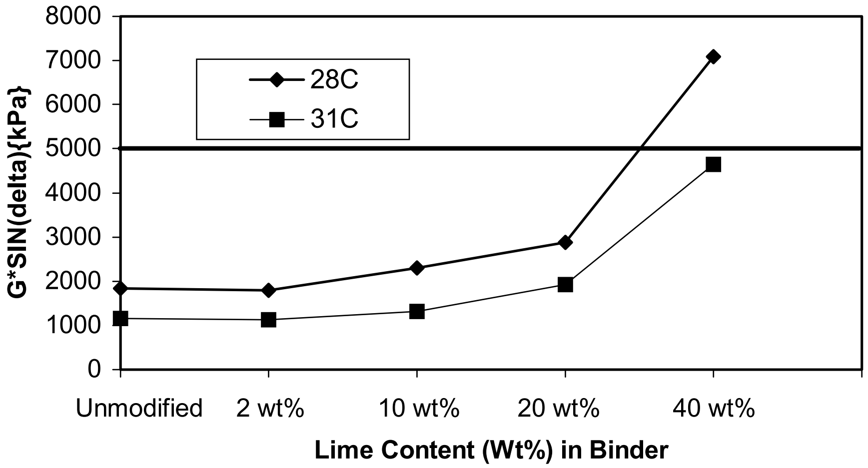

FIGURE 56 Effect of lime dosage on binder viscosity (*9*).

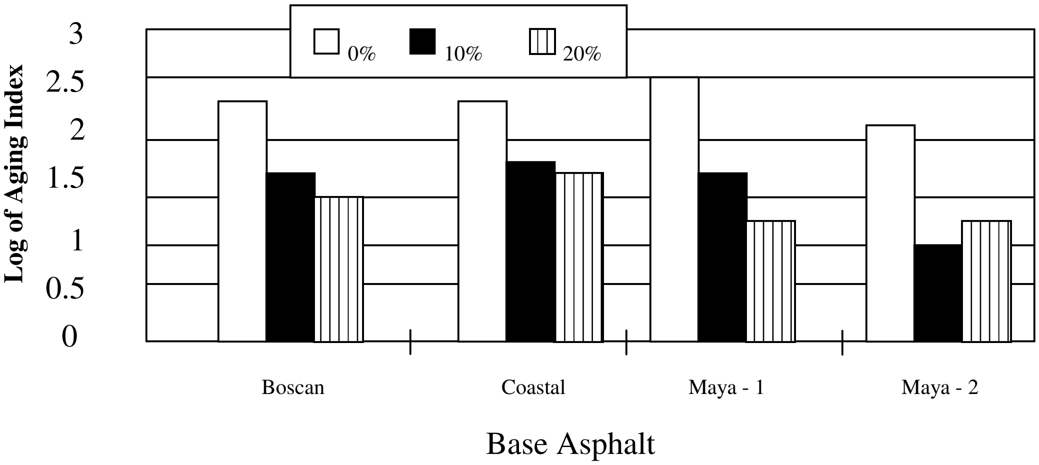

FIGURE 57 Effect of hydrated lime in reducing the aging of asphalt binders (*32*).

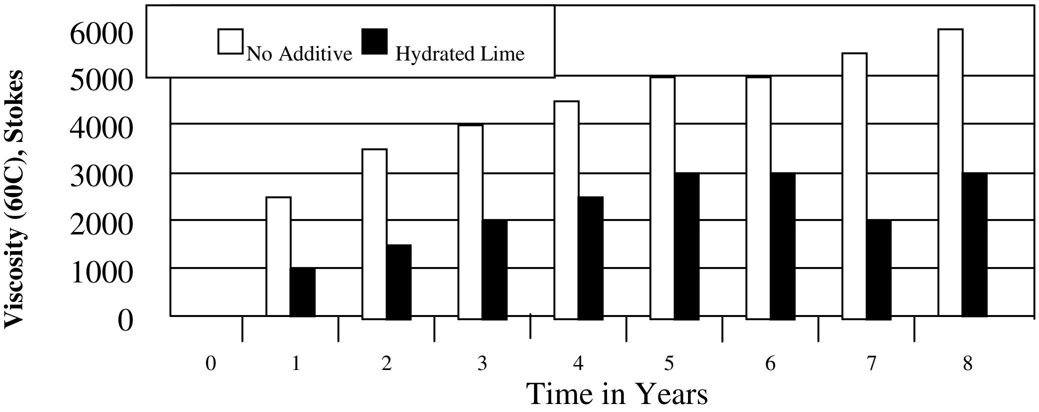

FIGURE 58 Field data demonstrating the effect of hydrated lime on the hardening of asphalt binder based on Utah data (*33*).

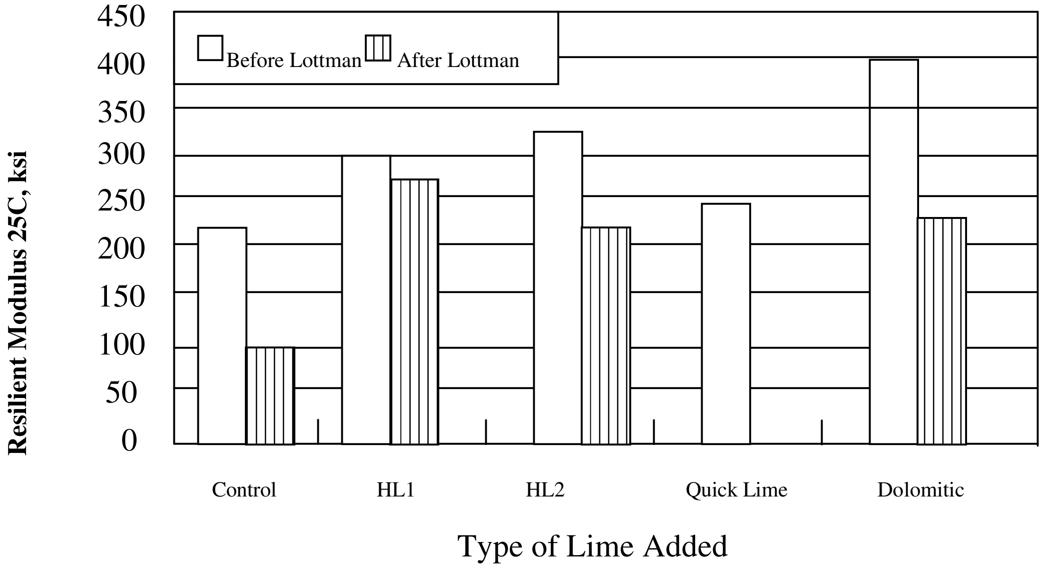

FIGURE 59 Effect of type of lime added to dry aggregate on the resilient modulus (internal data set, Materials and Test Division, Nevada DOT, 1998).

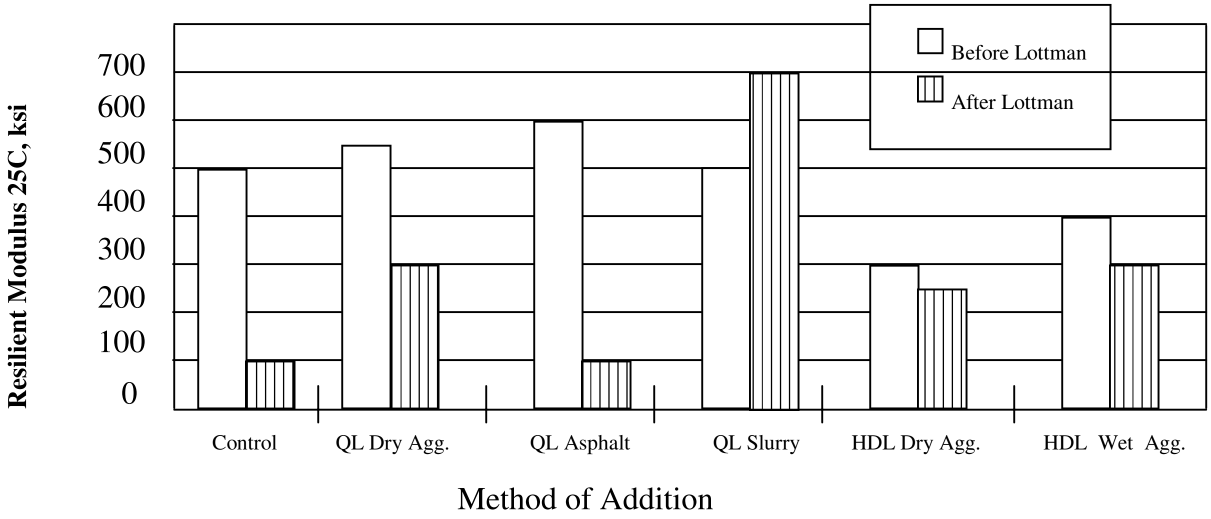

FIGURE 60 Effect of the method of hydrated lime addition on the restrained resilient modulus after Lottman conditioning (*34*).

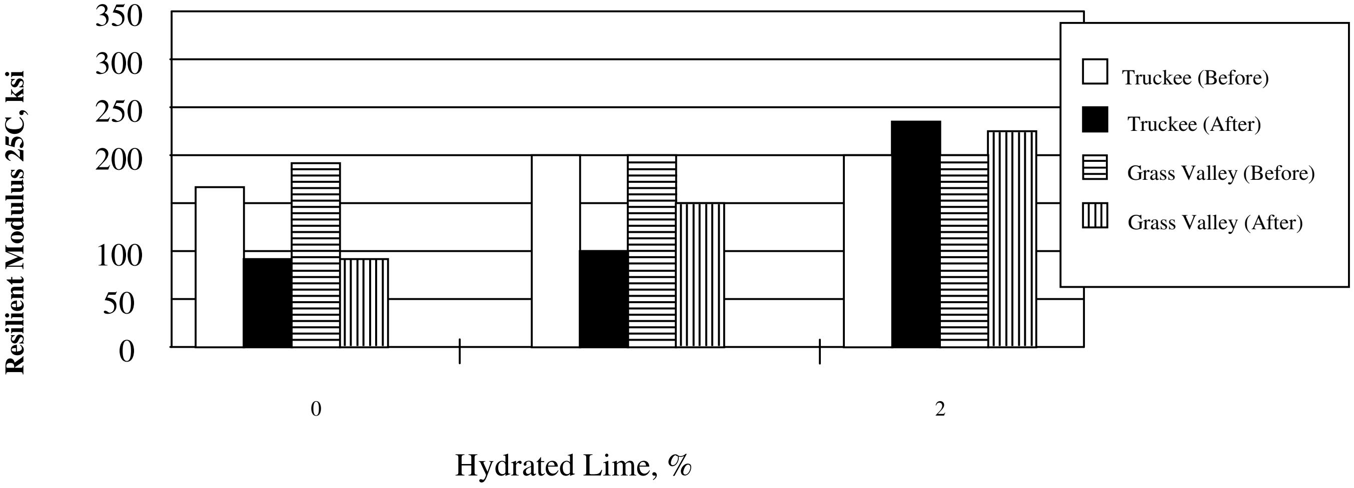

FIGURE 61 Effect of hydrated lime on the resilient moduli before and following Lottman conditioning for Truckee and Grass Valley, California, mixtures (*35*).

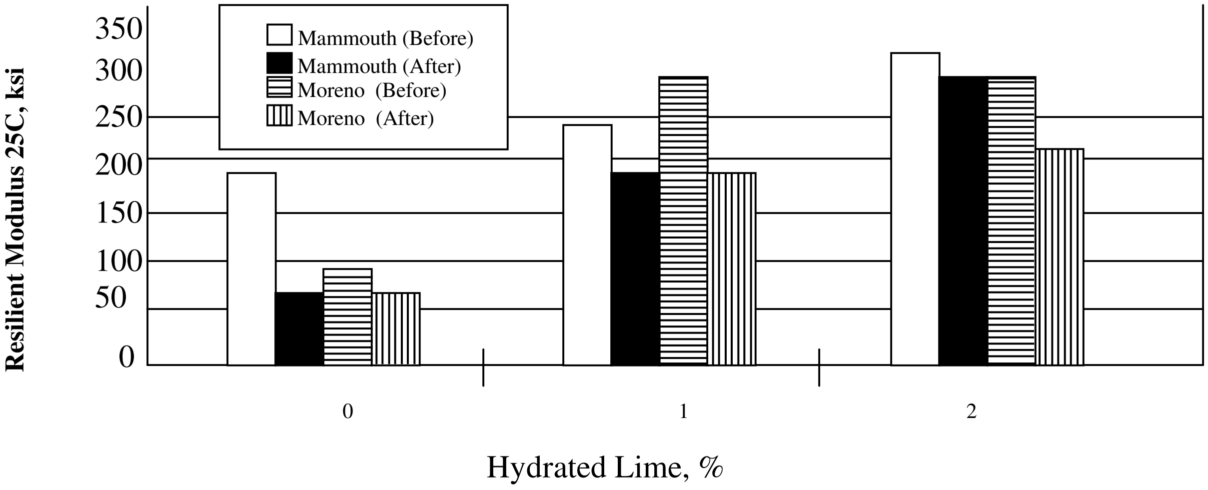

FIGURE 62 Effect of hydrated lime addition on the resilient moduli before and following Lottman conditioning for Mammouth and Moreno, California, mixtures (*35*).

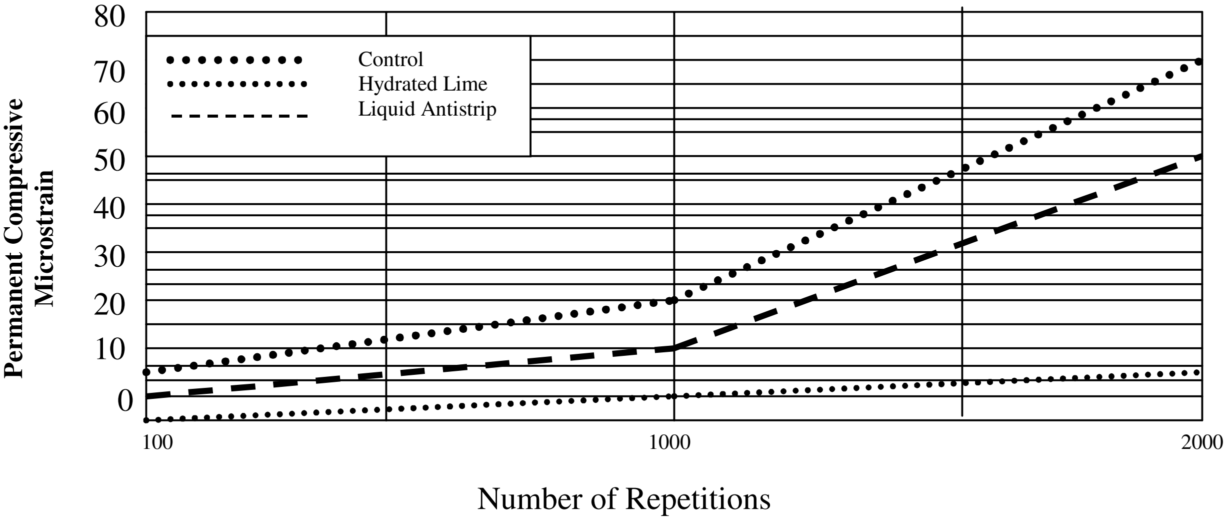

FIGURE 63 Effect of additives (with moisture) on permanent deformation: Oregon Department of Highways field study (*36*).

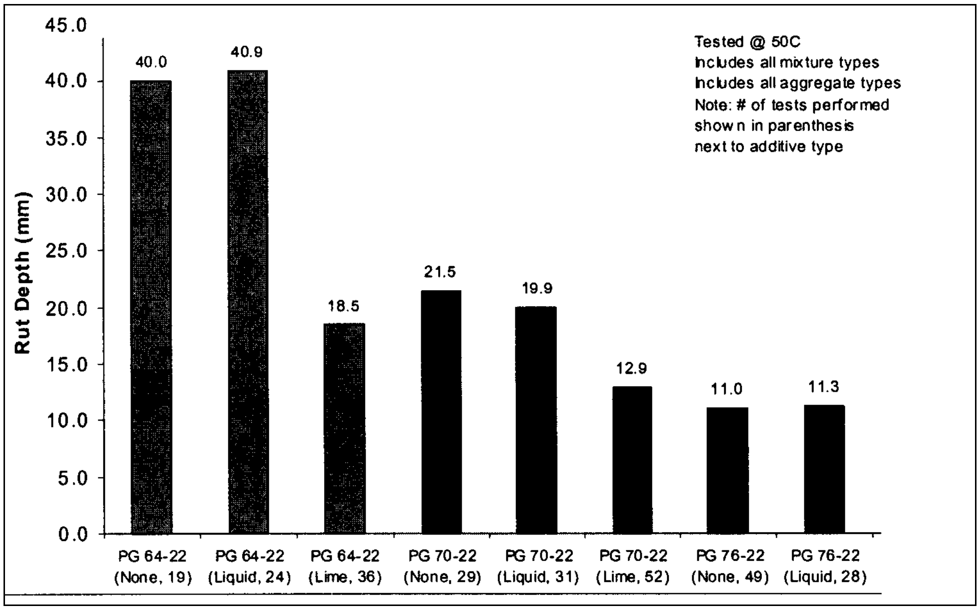

FIGURE 64 Effect of binder grade and additive type (*30*).

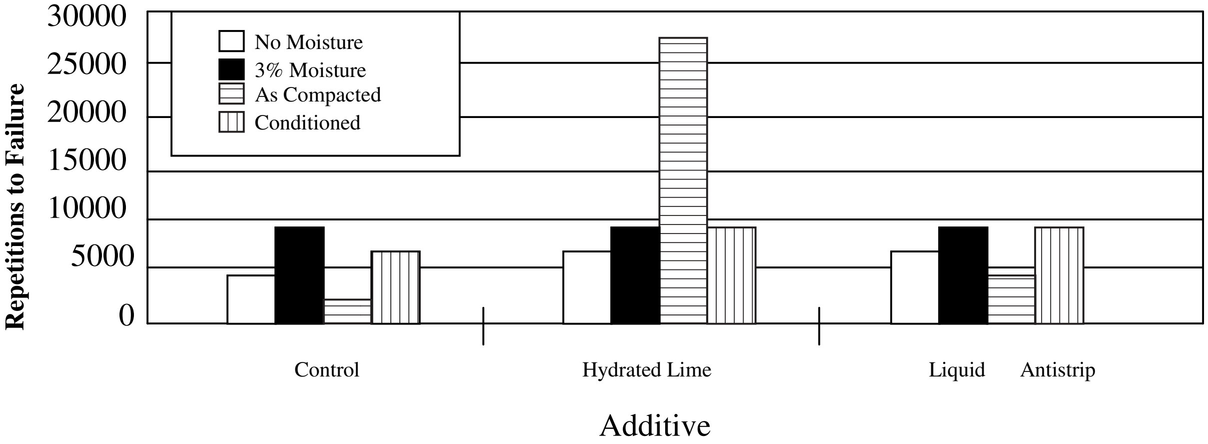

FIGURE 65 Effect of additives on fatigue life: Oregon Department of Highways field study (*36*).

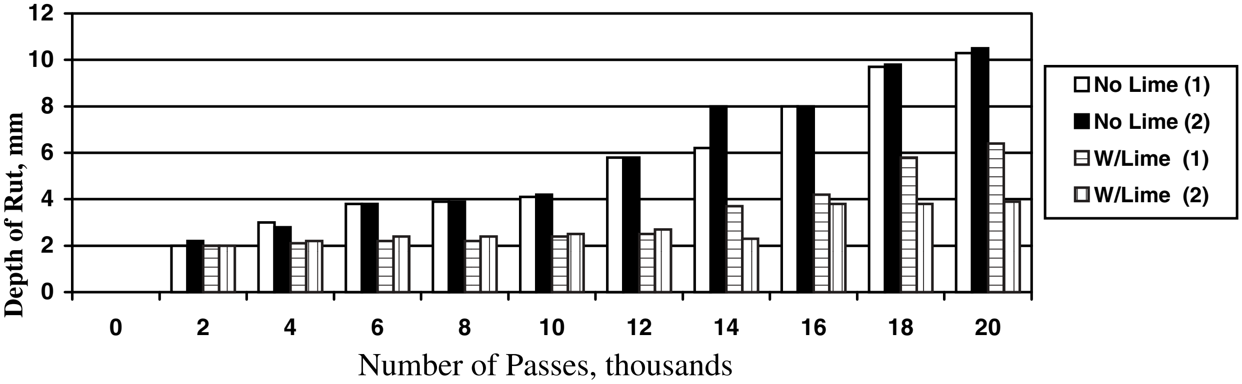

FIGURE 66 Results of rut tracking tests from Wuppertal-Dornap, Germany (*37*).

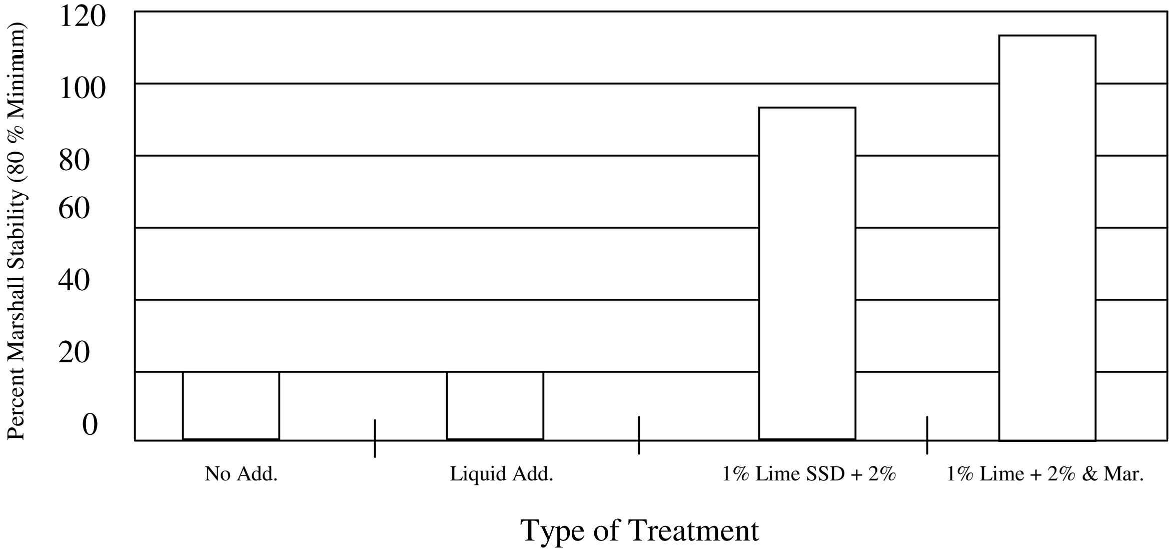

FIGURE 67 Effect of the type of additive and method of addition on the retained tensile strength of materials from SR-50, Millard County Line to Salina, Utah (*39*).

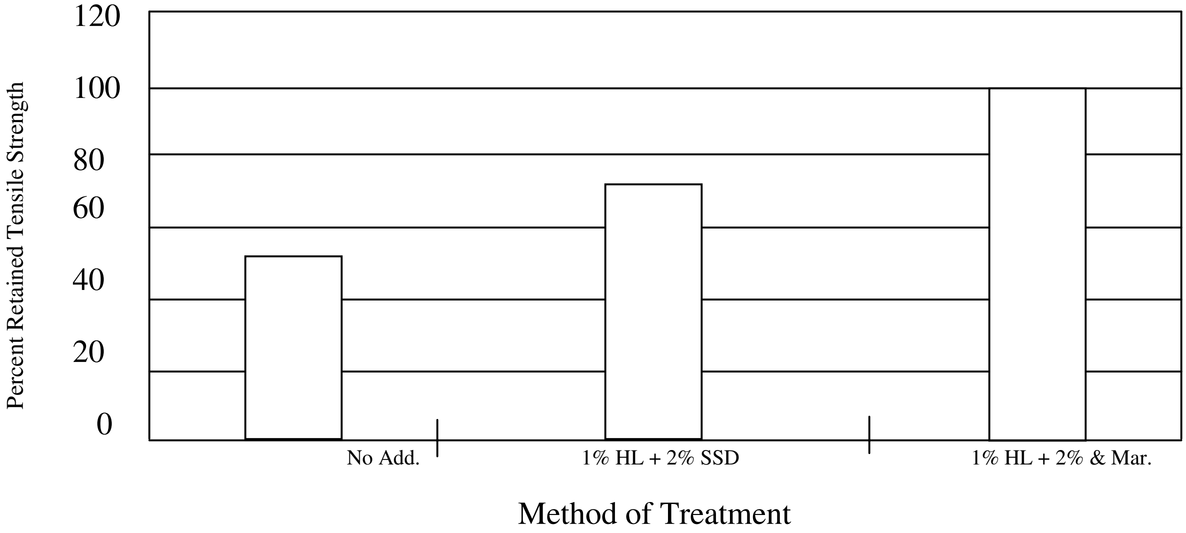

FIGURE 68 Effect of lime addition on tensile strength ratio for materials from I-70 Wetwater to Colorado Line, Utah DOT (*39*).

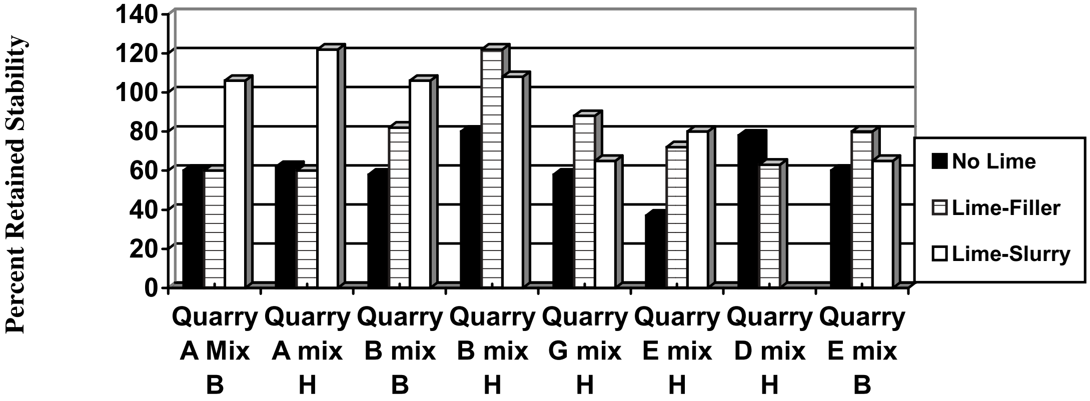

FIGURE 69 Effect of the addition of lime and method of addition on the retained stability for Georgia DOT mixtures (*38*).

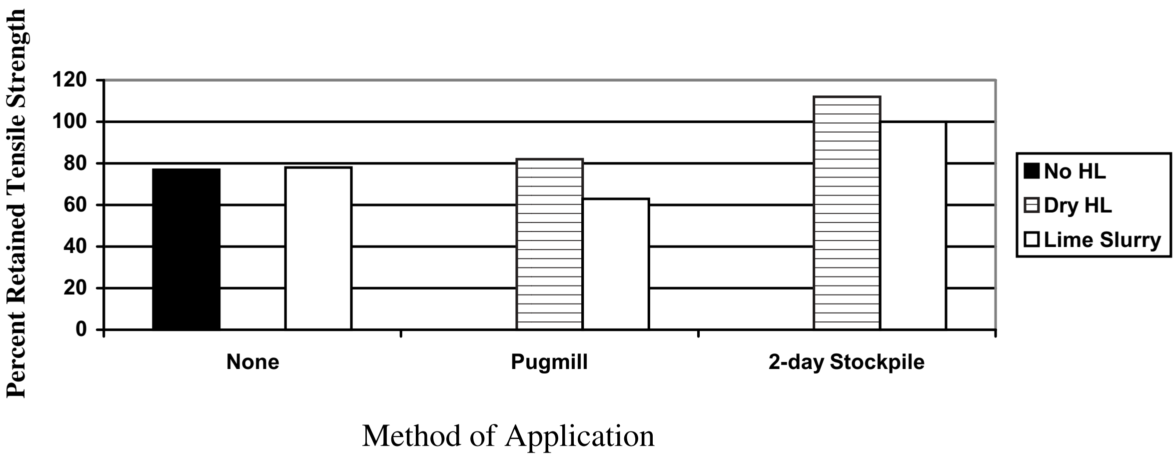

FIGURE 70 Effect of the method of application on retained tensile strengths of batch plant operations in Texas (*40*).

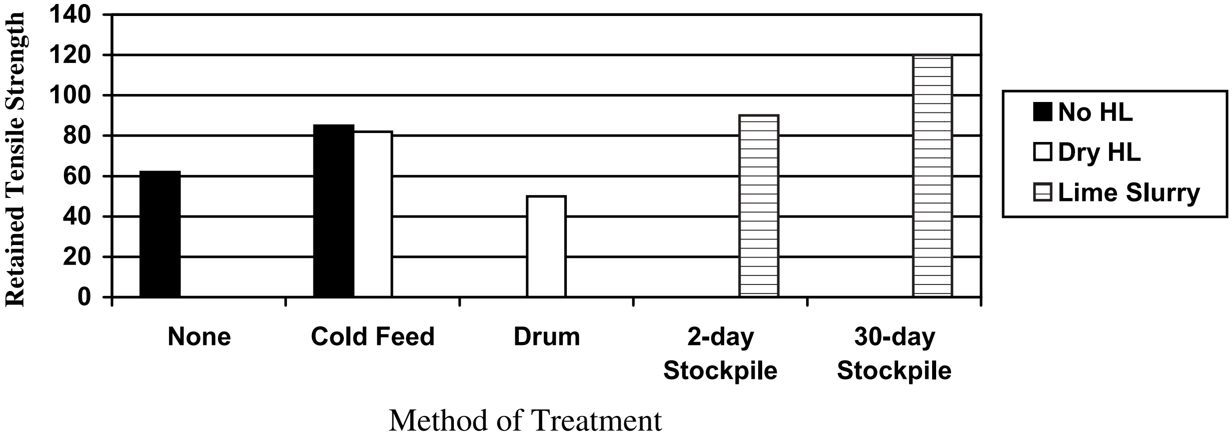

FIGURE 71 Effect of addition of lime to drum plant operations (*40*).

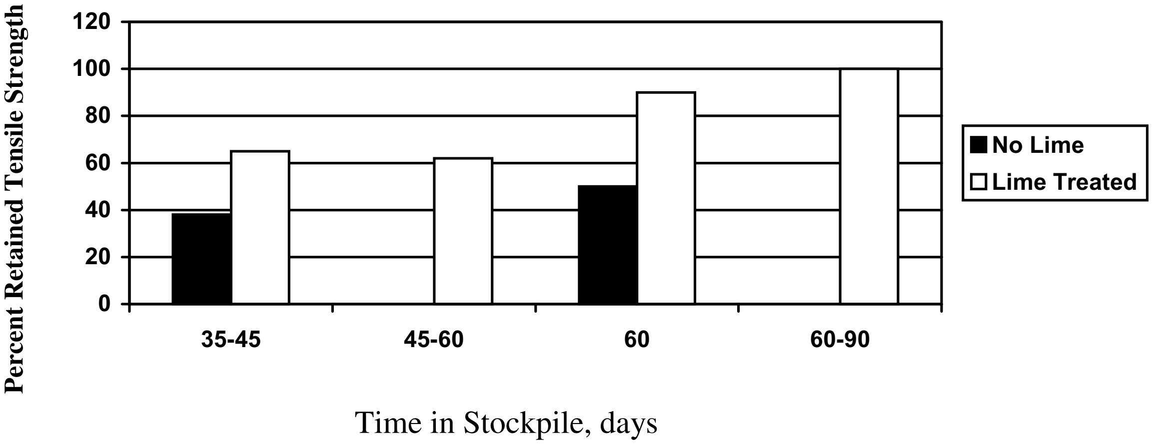

FIGURE 72 Effect of addition of lime to drum plant operations (*41*).

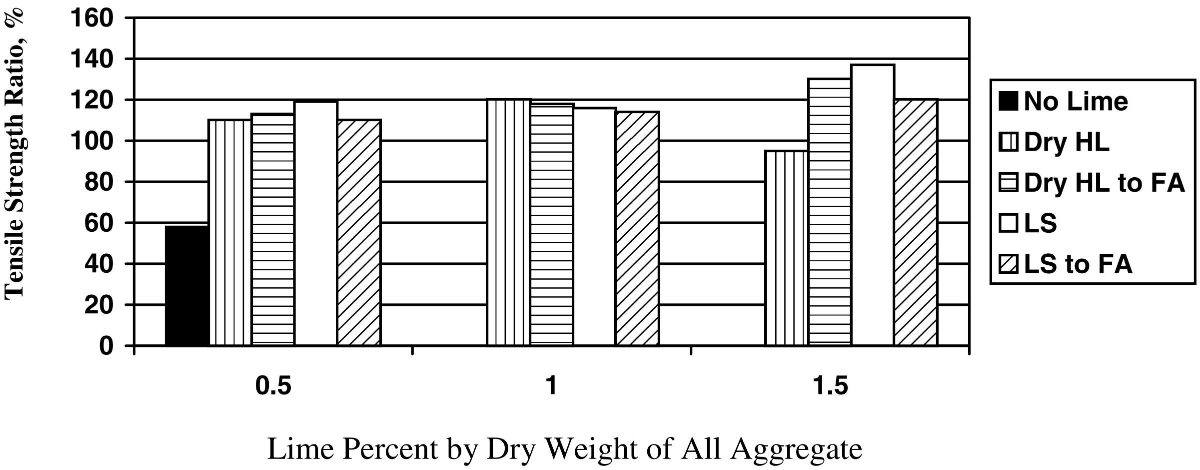

FIGURE 73 Effect of method of lime marination and percent lime added to granite aggregate (*42*).

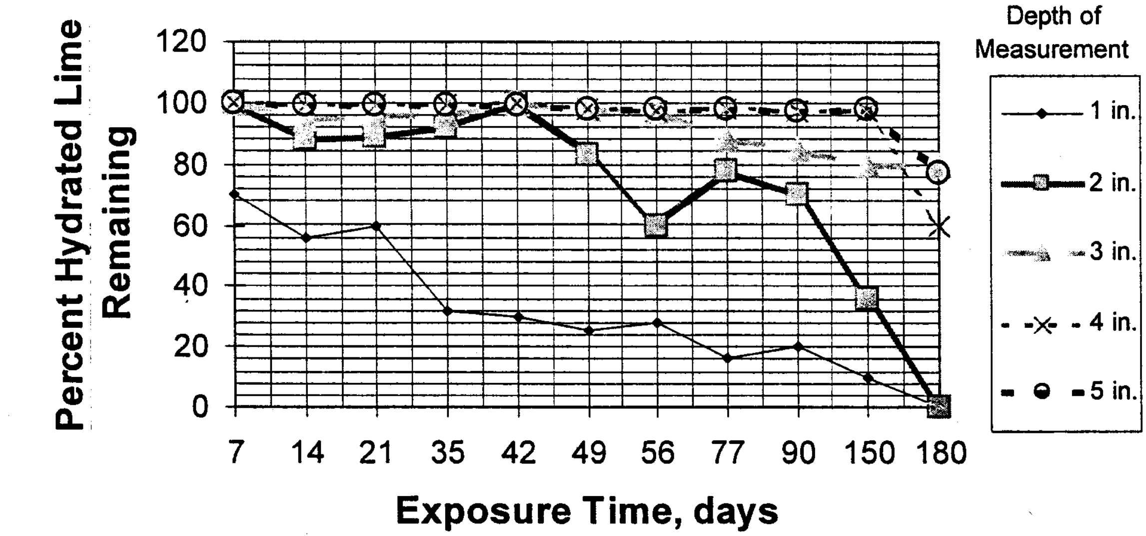

FIGURE 74 Effect of exposure time and stockpile carbonation on the active $Ca(OH)_2$ remaining (E. R. Graves, "Lime in Sand for Hot-Mix Asphalt: Test Project Summary," internal memorandum, Chemical Lime Group, Dec. 1992).

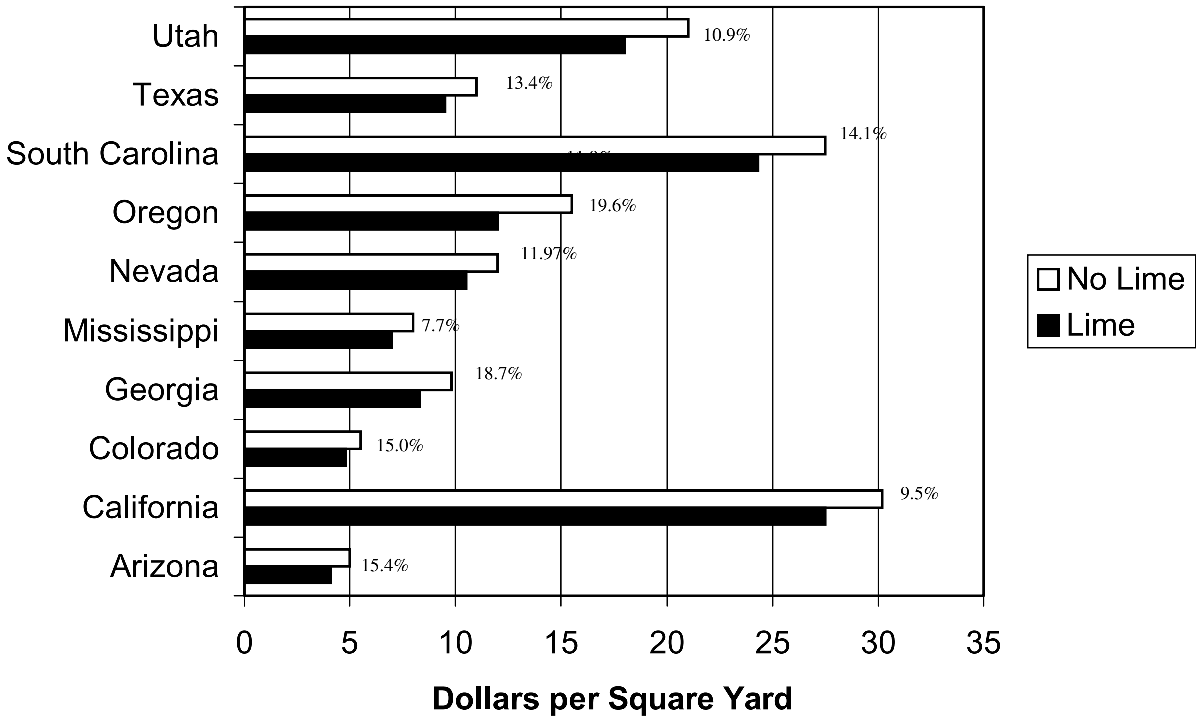

FIGURE 75 Life-cycle cost analysis of using lime for various states (*45*).

TOPIC 4

Questions and Answers

JON EPPS
Granite Construction, Speaker

ERIC BERGER
Chemical Lime, Speaker

JAMES ANAGNOS
Akzo Nobel Asphalt, Speaker

Q1—Pat Lavin, Arr-Maz
What is the purpose of marinating the lime?

A—Eric Berger
Most commonly, it is used to react with the undesirable surface stuff, surface coatings, be they fine particles that it can often carbonate or clay with which it can react pozzolanically. In the case of granitic and other quarried stones, it just seems to provide better performance in some circumstances. The state of Nevada did quite a bit of work on this several years ago, and I think you did quite a bit of it, didn't you, Jon, where they compared by testing behind the paver whether marination of a dry lime on damp aggregate process, not a slurried process, improved the performance? They concluded that yes, indeed, it did. In a later study that Peter Sebaaly did comparing the different application methods, NDOT decided that they'd stick to the marination method that worked best for them. But the study noted that in about 80% of the circumstances, the data indicated it didn't really matter that much whether you marinated or didn't marinate.

Q2—Pat Lavin, Arr-Maz
So the different time frames like 30 days or 3 weeks or 6 weeks are really indifferent?

A—Eric Berger
For how long you could leave it in stockpile?

Q3—Pat Lavin, Arr-Maz
For how long are you supposed to marinate it before you can use it?

A—Eric Berger
Usually that's 24 to 48 hours before you can put it in the plant. That varies by the state that requires marination. In terms of leaving it in the stockpile, there have been a couple of studies done. Dallas Little did one in Mississippi a good number of years ago. Dr. Robin Graves, who's in the audience here, did one probably 10 years ago or so. They discovered that in stockpile, it could remain active; the calcium hydroxide will remain chemically active for months.

A—Jon Epps
Those data are contained in the paper, too, about the stockpile. The carbonation takes place in the stockpile from the outside in and shows the depths of carbonation for various lengths of storage time that Robin Graves did. The other thing I might mention, and Dean can speak up if he wants. The most effective use of the marination process seems to be with those aggregates that contain some clay in them and gave enough time for the ion exchange to take place, which is pretty instantaneous if you can get the clay to the lime and then maybe it will have a pozzolanic reaction. And a little water.

Q4—Larry Santucci, University of California, Berkeley
This is a question for Eric and maybe a question some folks here from Caltrans might ask. On the chart that you showed toward the end of your presentation on cost savings using lime, could you explain why California is spending $30 per square yard while Colorado appears to be spending only $5 per square yard on projects?

A—Eric Berger
I don't even have to bother Gary, the author of that study, with that because I worked for the state of Washington for a decade or 15 years, and the differences depend upon which costs are captured in a state's reconstruction or maintenance activities. Wouldn't you say that that's true and different states report very differently, which is one of the reasons why it is so hard to transfer a PMS program from one state to another? I am sure that is what the cost difference is.

Q5—Larry Santucci
So this is not an apples-to-apples comparison of costs?

A—Eric Berger
It is data generated by each state for each state. But if you wanted to compare South Carolina with Colorado, it probably would be inappropriate because there are guardrails in one and shoulder widening in the other.

Q6—Gayle King, Koch Pavement Solutions
Based upon research by Bishara and Fager at Kansas DOT and reports from Ludo Zanzotto at Calgary, there appear to be serious incompatibilities between certain asphalt modifiers. In particular, one might boost a binder's PG grade with acidic materials while at the same time adding basic components to the mix as antistripping agents. The problem is primarily communication. The binder supplier modifies the PG grade, but the contractor chooses the antistrip solution. In response to problems observed in Oklahoma and elsewhere, Nebraska just published a specification that requires binder suppliers to add liquid amines at their terminal before the binder is graded, so that grade fallback and modifier incompatibility can be avoided. Any thoughts on whether that's an appropriate solution, or are there other ways to avoid compatibility problems?

A—Jon Epps
Is that a question, Gayle, or a statement?

Q7—Gayle King
I'd like to hear what others might suggest as a solution. How should we handle such incompatibility issues?

A—Jon Epps
I'll just start out by saying that some public agencies require sampling the asphalt binder in the feed line to the mixing chamber, and so whatever goes on before that is the contractor's and supplier's responsibility. That forces the issue just like you are suggesting. Jim, do you have a comment? Eric?

A—Eric Berger
My response to that is one test is worth a thousand expert opinions.

A—Jim Anagnos
I think so far we have had this occur several times in the state of Texas with particular suppliers and basically the liquids are added at the contractor's point in that state, at the contractor on site. The thing that he has addressed, the problem at that point, he has changed suppliers of the binder. I'm not saying that is the solution to it, but those are some of the things that have been done. I guess the biggest solution to it would be to have it added at the refinery and allow the folks at the refinery to have that worked in. Sometimes you can add concentrated amounts of amines, particular kinds of amines; it is my understanding that will combat that. You're going to ask me how much that is. I can't answer. I don't know.

Q8—Pat Lavin, Arr-Maz
I think what Gayle is specifically talking about is the state of Kansas has developed a specification where they don't like the idea of using phosphoric acid to bump the grade of their asphalt binders. So what they are doing is they are requiring the asphalt supplier to prequalify their binder with amine antistrip additive as a way to test for the presence of phosphoric acid in the asphalt. What we've found out is it is also crude sensitive. In other words, one supplier will knock it down a grade and another supplier won't.

Q9—Bob Humer, Asphalt Institute
Jon, in one of your slides, there is a polymeric treatment of aggregates and it says 1 pound per ton, which is like 5/100th of a percent. In what form is that and how do you really treat that entire aggregate surface with 1 pound of polymeric materials? Just give me a picture of how this works.

A—Jon Epps
Very carefully, obviously, is the answer to that. Peter, do you want to respond to that? Peter Sebaaly is in the audience and he was the everyday person on that study.

A—Peter Sebaaly, University of Nevada, Reno
Yes, the 1 pound per ton is a true figure. You dilute the material. It is a very thin material and you dilute it with water and very, very, very carefully you mix it in the lab. That's all I can say.

Q10—Bob Humer, Asphalt Institute
Just a comment, Eric. You said that mixing lime with asphalt is still in kind of a trial stage. On reservoirs, such as for drinking water, we like to see a coating of mastic, which is specified as a blend of paving grade asphalt and 70% by weight lime. Sometimes that is a little hard to blend, so they drop off to 60% lime. So we are at pretty high concentrations of blending lime in with asphalt for those mastic coatings. Just that you are aware of that. A good example is the MWD Devil's Canyon Afterbay reservoir near San Bernardino.

A—Eric Berger
One of the problems that we've had, and this is being worked on both here in the U.S. as well as in Europe, is the volume that we can blend in at the time just as you described. Dallas Little and Chemical Lime and the Arizona DOT are sort of struggling their way to a field trial of this very thing. But it certainly would simplify matters for everyone and do a world of good for a lot of bitumens, I think.

Q11—Barry Baughman, Ultrapave
I'd like to address the polymer issue. It is 1 pound of dry polymer per ton of aggregate. Basically, the material is supplied as a latex, which has very small particles and very large surface areas. They are applied on the belt as the aggregate goes down into the drum dryer. During the first few feet in the drum dryer, they get dispersed throughout the aggregate. They form a waterproof coating onto the aggregate. Basically, the aggregate (which is water loving) becomes water repelling. The material we use is also a hydrocarbon polymer; therefore, it has an attraction to the asphalt and improves or enhances the bond to the asphalt. If anyone has any questions, they can see me.

Q12—Ron Sekhon, Caltrans
What is the chemical composition of these liquid antistrips? With lime we have some sort of information how the reaction takes place with the clay particles and so forth. I was interested in knowing how the liquid antistrip works.

A—Jim Anagnos
If you want the chemical composition, you're not going to get that from me because I don't know what it is. You might have to ask the chemists who are involved like companies like Arr-Maz, Akzo Nobel, Unichem, Rohm & Haas. Those chemists might be able to divulge that kind of information. I cannot.

Q13—Jack Van Kirk, Basic Resources, Inc.
One of the things that we're really toiling with in California, we have for many years, is liquids versus lime. There have been a lot of studies done, and I know in the early years certain types of liquids came out that were used and weren't quite as effective. Later on, I guess a new line of liquids came out and one of the things that is very difficult for a lot of us in the audience to do when we look at these studies is you look at the lime folks and they show the lime is great and the liquid is not. You look the other way and you find the liquid is just as good as the lime in different ways. One of the things that would be very helpful to us is to look at some type of study that you showed earlier and I think it indicates that when you use a liquid it makes a big difference in the kind of liquid you use on the type of aggregate you have. So, the question is,

when the lime studies were done, are we looking at apples and oranges? Are we looking at the same types of things that they are looking at today—like you talked about a high-quality liquid as opposed to some of the things that were looked at early on? It is like the white industry versus the black industry when it comes to pavements. It is the same thing for lime versus liquids. If we are going to be able to move forward with this in an equal type of evaluation, we have to be looking at the same types of products in both cases and we all know that lime works very well. The bottom-line question is, is there a difference today with the liquids that are being done that are going to give us the same type of performance as maybe dry lime to wet aggregate or even the lime slurrying in some cases and were they different in some of the cases that were done in the lime industry?

A—Jim Anagnos
I know, for example, for some of the experimental work we did at the University of Texas between 1970 up to 1990 that I was involved with—I know at that time we used an awful lot of liquids that were not very good performers. And I suspect, I don't have absolute data on it, I just know from my own experience that we used additives that were not good performers. I don't know what the studies would have shown back then if you had used a high-performance additive and whether they were available at that time. I can't answer. I don't know. But I have a feeling that a lot of the studies were done with inferior products. For example, in Virginia, I think Bill Maupin looked at a study early on in the early 1990s of some projects that were placed and he found that the liquid did not perform well. So, he raised his specifications, his requirements, and he went back out and looked at projects under the new requirements and found that they were not any different. He could not see any discernible difference between the liquids and the hydrated lime. What I am leading up to is I guess you have to have some sort of testing process to look at these things. This is a very complicated situation. I didn't get to say this earlier, but I don't think that you have an elixir of an additive that can be added to anything and everything and have it accomplish everything under the sun. I don't think that's possible. I don't think you're going to ever find it. I don't know that you're ever going to find a particular test that's going to be 100% positive each time. I say positive, that it will relate to field performance. When you look at field performance you have many other issues involved besides "what kind of additive did you put in," so that's a very hard correlation to make.

A—Jon Epps
Just an observation from reviewing the literature once again, Jack. It's not an answer to your question. The various types of additives that we've talked about today are certainly asphalt binder dependents. It's been said already they're aggregate dependent, their concentration dependent, and they are also test method dependent in terms of how good they show up to be. That's as a minimum that I found out.

Q14—Mike Cook, Caltrans
Two quick questions. We had some discussion about marination of lime-treated aggregate and the maximum marination period allowed. Does environment like rain affect that maximum marination period? My second question is how do we know what a high-quality liquid antistrip is? Is there any ASTM or AASHTO designation or a reference to differentiate between antistrips that perform well and those that perform poorly?

A—Eric Berger
The answer is that I don't remember in Robin Graves' study, but I do remember in the study that Dallas Little did in Mississippi that during the 6 months or so that the material sat in stockpile, it rained at least 8 inches. What happened was that the carbonation, which for those of you who don't know is the retransformation of the calcium hydroxide into calcium carbonate or limestone, proceeded from the outside surface of the stockpile just a couple of inches into the stockpile. The calcium hydroxide was active on the inside of the stockpile. It seems to me Robin's study went at least that long, and did it rain much in that study?

A—Robin Graves
Yes.

A—Eric Berger
He said yes.

A—Jon Epps
And it was for over 120 days, Robin, or something like that?

A—Robin Graves
About 6 months.

A—Jon Epps
Jim, can you answer the next question, which dealt with how do you tell the liquid antistrips that perform well from those that perform poorly?

A—Jim Anagnos
The only way I know to do it is by doing some additional testing. For example, you might use a Hamburg-type test, you might use a PG grading-type SHRP-type test to see what that additive is doing to your neat binder. But I think it all comes down to what you are doing for testing. Is there something in AASHTO or ASTM that this qualifies one as being a "good one or a bad one"? I don't know of any.

TOPIC 5

Material Production, Mix Design, and Pavement Design Effects on Moisture Damage

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Material Production, Mix Design, and Pavement Design Effects on Moisture Damage

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Moisture damage has caused many pavement failures throughout the United States. Moisture damage is loss of bond between the asphalt and aggregate or in some cases the loss of cohesive strength of the asphalt. Moisture damage can manifest itself though various failure mechanisms. These include rutting, fatigue cracking, raveling, and potholes. In Colorado, several sections of I-70 failed in just a few short months after placement. A moisture-damage-susceptible mix was placed with high air voids. It was subjected to high rains just before being covered with a plant mix seal and then opened to traffic. This created a section where the moisture was trapped in the high air void mix, covered with a seal that would not let the moisture escape, and then subjected to scour created by high traffic. The open intermediate layer quickly stripped, leaving uncoated aggregate covered by a thin plant mix seal, which quickly disintegrated. This type of failure costs precious dollars to repair, which are needed to improve and upgrade the infrastructure system.

Researchers have been trying to define the causes for moisture damage since the first hot-mix asphalt (HMA) pavements were placed and began to fail. There are many causes of moisture damage. The intent of this paper is to discuss the effects of material production, mixture design, and pavement design on moisture damage. The basic characteristics of materials can change depending on how they are produced. For asphalts, there are many different refining processes, all of which will change its properties and can affect moisture damage. This is also true of the aggregate production process. How the aggregates are crushed and processed will change how they will react to asphalt and water.

The mix design will also affect moisture damage. A coarse-graded mixture and a fine-graded mixture may react differently. Volumetric proportioning will affect compaction, which in turn will affect moisture damage. The relationship between mixture design and structural layers has an effect on moisture damage. Sealing an open layer between two dense layers is likely to trap water and cause moisture damage.

REFINING EFFECTS ON MOISTURE DAMAGE

HMA for paving is produced by combining asphalt binder and aggregates. The chemical interaction between the binder and the aggregate is key to understanding the ability of HMA to resist moisture damage. Understanding this interaction requires an understanding of the production process for the materials.

Asphalt binders are the product of the petroleum crude oil refining process. Two basic items drive the physical and chemical properties of asphalt binders: the crude oil source and the refining process used to produce the asphalt (*1*). Crude oil pumped from the ground typically contains water, salts, clays, and a variety of mineral mater. Most of these materials are damaging to the refinery and are typically removed before the crude oil is processed. Most of these materials are also detrimental to the moisture performance characteristics of the asphalt binder and should be removed to prevent their inclusion in the final product.

Salts act as emulsifiers (*2*) and if left in the crude oil will end up in the asphalt binder. The water and salts in the crude oil often create emulsions, which have to be removed before the crude oil can be refined. The water and salts can cause significant problems with corrosion in the plumbing of refineries. The salts are typically removed by adding additional water to the crude at an elevated temperature to dissolve them. The water and salts are then separated from the crude by either chemical or electrostatic methods (*1*). This is done in settling tanks just before the refining process.

Crude oil is also acid. These acidic crude oils can also be corrosive to the plumbing in the refinery. To reduce the acid concentration, caustic soda or pulverized limestone is sometimes added to the crude oil. As with the natural salts that are in the crude when it is pumped from the ground, these acid neutralizers must be removed from the crude oil before refining. Salts from caustic soda are strong emulsifying agents and are very corrosive to aluminum tanks.

A diagram of a typical crude oil processing system is shown as Figure 1. The crude oil desalting is done before the crude is heated and sent to the distillation tower. The desalting is typically, but not always, done at the refinery. Some refineries do not desalt. In these cases, very harmful matter can go through the refining process and end up in the residue, which is the asphalt binder.

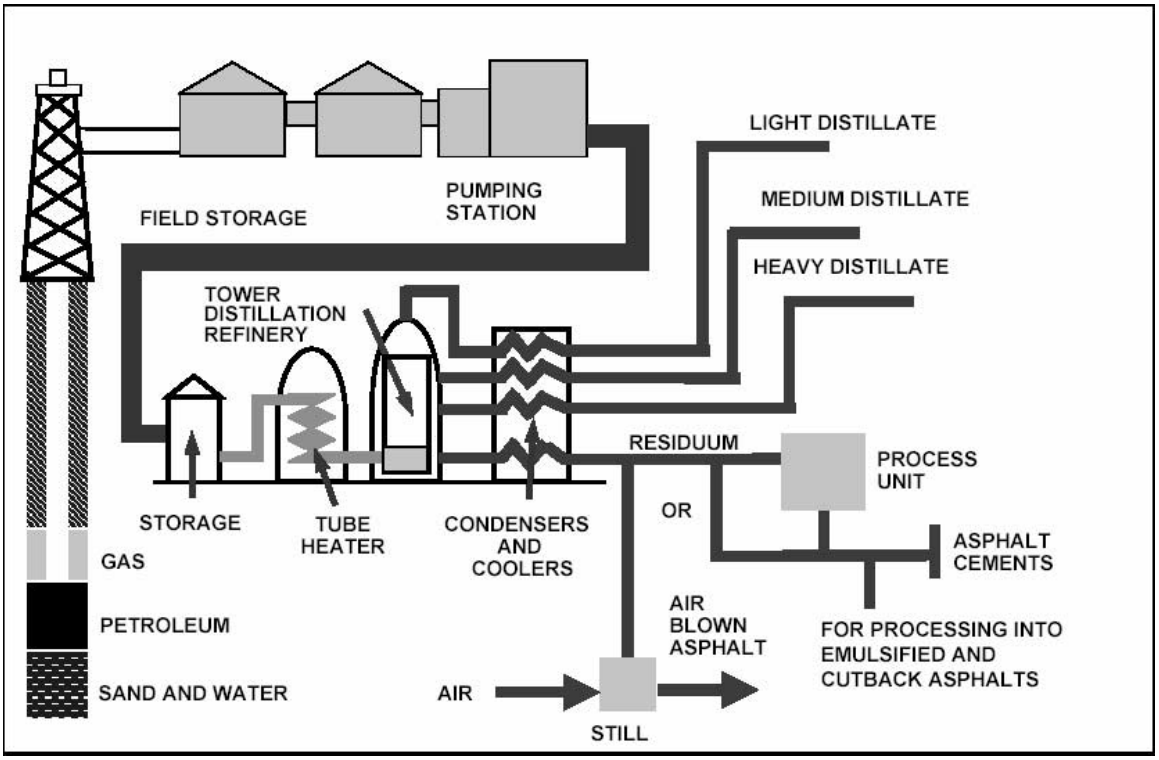


FIGURE 1 Diagram of a typical refining process for the production of asphalt binders.

Acids

The asphalt binder produced during the refining process can be modified in many different ways to meet the specifying agency's specifications. These different modification methods will change the moisture sensitivity of the binder. Such changes can be for the better, but in some cases the changes can be detrimental to the moisture sensitivity of the binder.

Air blowing is one method of modifying asphalt binders. Air blowing is a chemical modification of the binder (*1*). Air blowing involves percolating air through the asphalt binder in a large tank for several hours. Passing air through the binder will change the molecular structure and chemical makeup of the binder. Air blowing will change the average molecular size of the binder and increase its stiffness. Air blowing will also cause some oxidation of the binder. This oxidation can create increased amounts of carboxylic acids and sulfoxides (*3*). During HMA production, the carboxylic acids and sulfoxides will attach themselves to the surface of the aggregate and prevent nitrogen compounds from bonding. The carboxylic acids and sulfoxides are also easily displaced from the surface of the aggregate by water, causing moisture damage (*2–4*), as shown in Figure 2. The extent of this problem will vary significantly depending on the properties of the base asphalt binder and the amount of oxidation that occurs during the air-blowing process. Air blowing is not inherently bad. If the base asphalt is low in acid content, the resultant binder will likely be low in acid content.

As noted, there are many methods for modifying binders. Acid compounds have also been used to modify the asphalt binders and extend the temperature range at which they will perform. The most prominent of these is polyphosphoric acid. The addition of polyphosphoric acid will increase the high temperature stiffness of the binder, thereby increasing the high temperature grade. The one concern with acid modification is that in some cases it can be reversible.

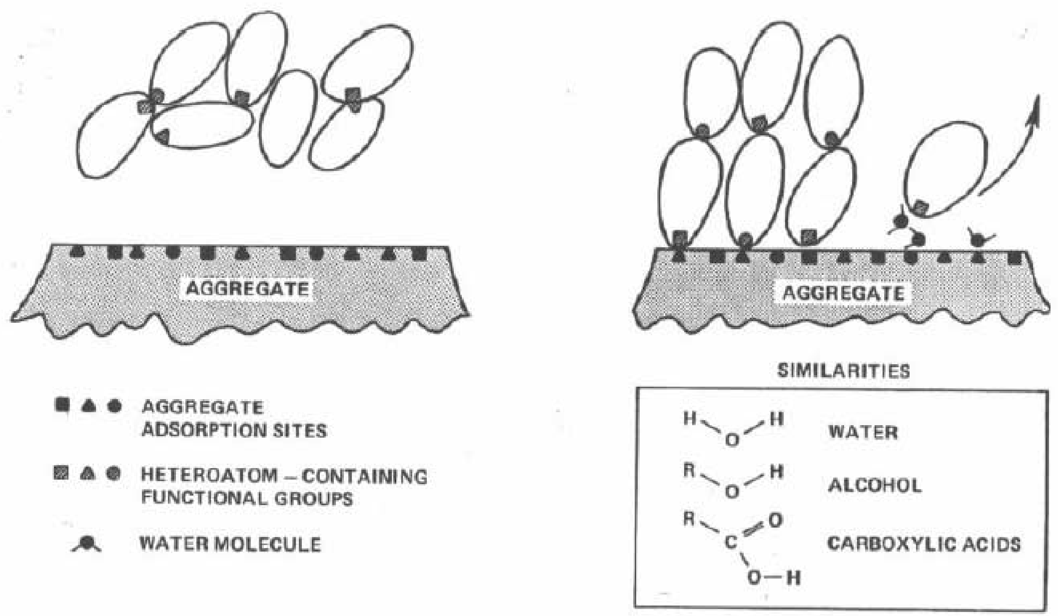


FIGURE 2 Molecular bonding sites of asphalt on aggregates being displaced by water (*4*).

In field applications, there have been occasions in which the acid modification process has been reversible (*5–7*). On several projects in which acid was used as a modifier and an amine antistripping agent was added at the plant site, dramatic changes took place. The amine neutralized the acid, resulting in a softening of the binder. Additionally, the amine antistripping agent was neutralized, which allowed stripping damage to occur in the mix.

During the past 2 years, extensive studies have been done to evaluate acid modification. Several have indicated that the acid modification process is reversible. In these studies, binders modified with acid would revert to the base asphalt binder properties when amine antistripping agents were added. Several other studies indicated that when small amounts of acid, 0.5% by weight of binder, were used to act as stabilizers in polymer-modified asphalts, the changes were not reversible even when hydrated lime was added to the binder as an antistripping agent.

Caustics

Caustics used in the refining process will also cause problems with moisture damage. As noted, most crude oils are acidic. The amount of acidity varies depending on the source of the crude oil. In some locations, sodium hydroxide has been used to lower the pH of the crude, to reduce corrosion of the plumbing at the refinery. Sodium hydroxide is a salt highly soluble in water and one known to act as a strong emulsifier in asphalt binder. If the crude oil is not desalted after the caustic treatment, these salts will remain in the crude oil and end up in the asphalt binder (*4*).

Caustics have also been used to increase the high temperature grade of the binder (*8*). Sodium hydroxide has been used as an agent to create large polar molecules to modify asphalt binder and increase stiffness. When sodium hydroxide is used as a stiffening agent, the caustic salts are left in the asphalt. As noted, these salts are strong emulsifiers and have caused stripping in asphalt mixtures. The use of this type of system to modify asphalt has been discontinued because of extensive problems with corrosion of aluminum tanks.

AGGREGATE PRODUCTION

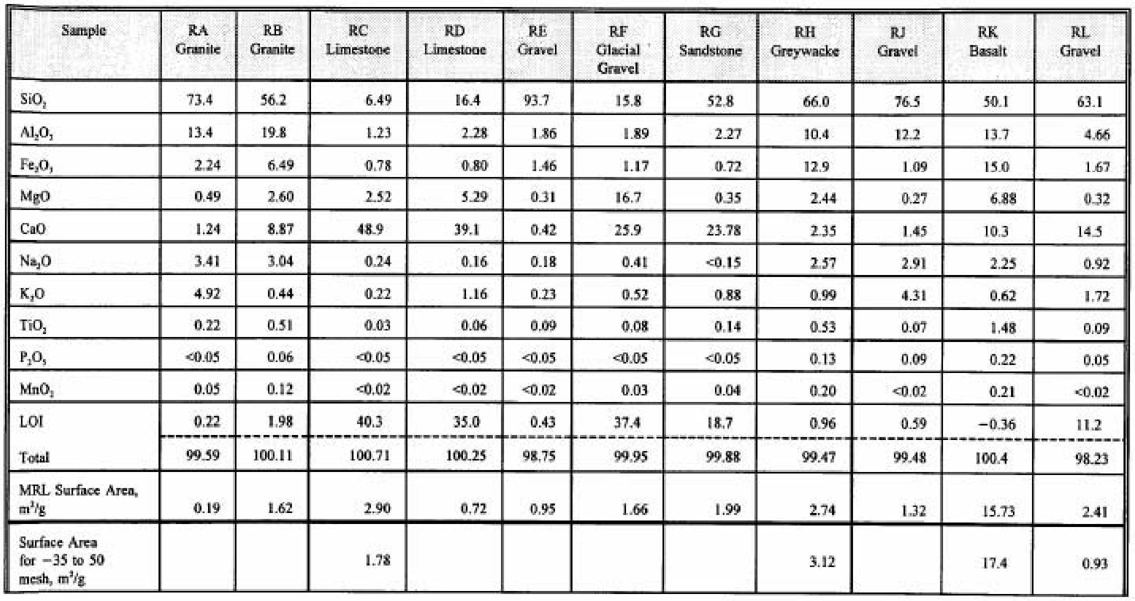
Minerals

The chemical makeup of aggregates is as complex as that of asphalt. This is demonstrated in Table 1 (*9*). The chemical composition of several aggregates used in the SHRP research is listed along with surface area determinations. These aggregates cover a wide variety of mineralogical composition representing many of the aggregates used across the country.

Depending on the source of aggregate, there is a predominate compound that makes up that aggregate. Silicon dioxide or calcium carbonate is the predominant compound found in most aggregates. As seen in Table 1, one or the other of these compounds makes up a major portion of the aggregate. Those aggregates that are primarily made up of silicon dioxide are typically acid, and those that are primarily calcium carbonate are typically basic. Figure 3 graphically shows the acid-base makeup of typical aggregate used in the United States.

The bonding of the asphalt acid-based molecules to the base molecules of the aggregate has been put forward as the primary form of adhesion for hot-mix asphalt (*10*). However, this acid-base bonding of asphalt to aggregate is not the only important factor in moisture damage (*1*, *2*). The physical properties of the aggregate are also important in the asphalt-aggregate bond. The porosity and surface texture will affect the mechanical bond between the asphalt and aggregate (*1*, *11*). Aggregates with rough surface texture or a high amount of surface pores, or

TABLE 1 Mineral Composition of the MRL Aggregate Used in SHRP Research (*9*)



Sample	RA Granite	RB Granite	RC Limestone	RD Limestone	RE Gravel	RF Glacial Gravel	RG Sandstone	RH Greywacke	RJ Gravel	RK Basalt	RL Gravel
SiO_2	73.4	56.2	6.49	16.4	93.7	15.8	52.8	66.0	76.5	50.1	63.1
Al_2O_3	13.4	19.8	1.23	2.28	1.86	1.89	2.27	10.4	12.2	13.7	4.66
Fe_2O_3	2.24	6.49	0.78	0.80	1.46	1.17	0.72	12.9	1.09	15.0	1.67
MgO	0.49	2.60	2.52	5.29	0.31	16.7	0.35	2.44	0.27	6.88	0.32
CaO	1.24	8.87	48.9	39.1	0.42	25.9	23.78	2.35	1.45	10.3	14.5
Na_2O	3.41	3.04	0.24	0.16	0.18	0.41	<0.15	2.57	2.91	2.25	0.92
K_2O	4.92	0.44	0.22	1.16	0.23	0.52	0.88	0.99	4.31	0.62	1.72
TiO_2	0.22	0.51	0.03	0.06	0.09	0.08	0.14	0.53	0.07	1.48	0.09
P_2O_5	<0.05	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	0.13	0.09	0.22	0.05
MnO_2	0.05	0.12	<0.02	<0.02	<0.02	0.03	0.04	0.20	<0.02	0.21	<0.02
LOI	0.22	1.98	40.3	35.0	0.43	37.4	18.7	0.96	0.59	−0.36	11.2
Total	99.59	100.11	100.71	100.25	98.75	99.95	99.88	99.47	99.48	100.4	98.23
MRL Surface Area, m^2/g	0.19	1.62	2.90	0.72	0.95	1.66	1.99	2.74	1.32	15.73	2.41
Surface Area for −35 to 50 mesh, m^2/g			1.78					3.12		17.4	0.93

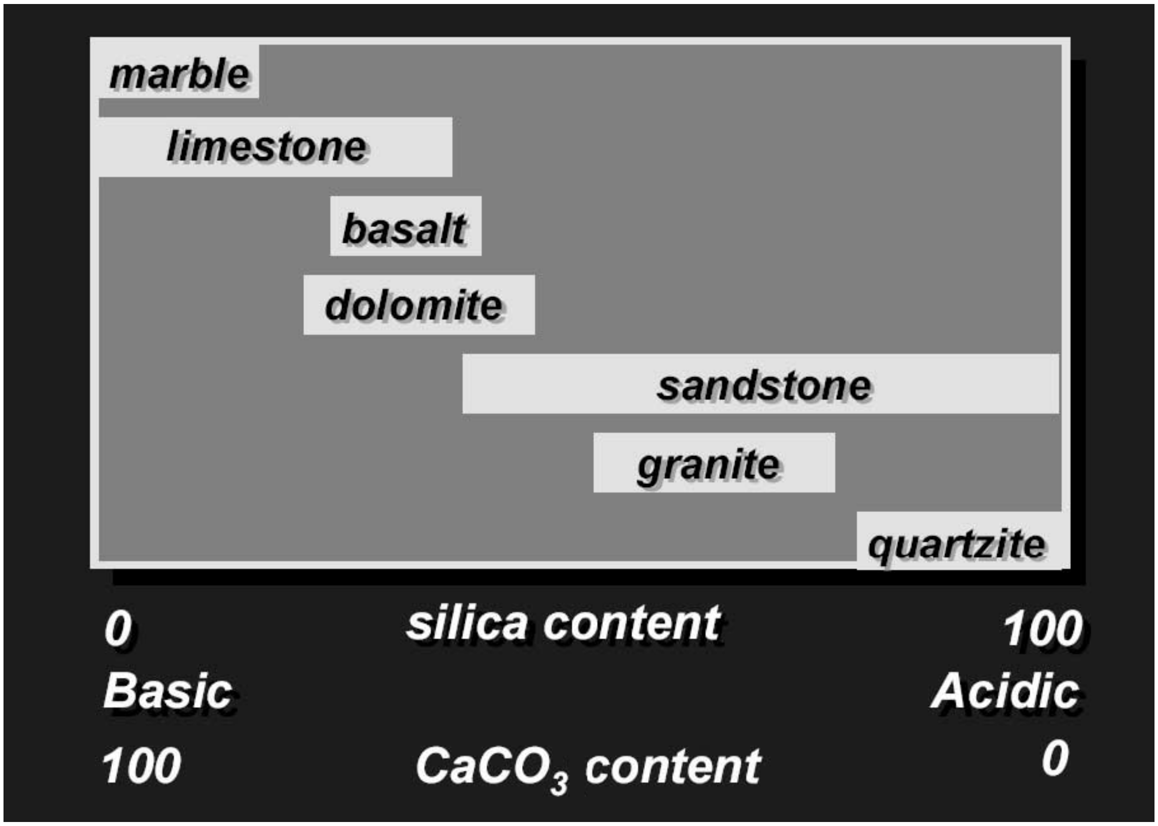


FIGURE 3 Acid-base composition of typical aggregates (*10*).

both, will increase the moisture damage resistance of the asphalt mixture. Aggregates with rough surfaces and high voids provide more surface area for the asphalt to bond to.

Many of the silicate aggregates have low porosity or smooth surface texture, but this is not always the case. Some granites do have very high surface texture and can create good mechanical bonding, but those factors may not be enough to overcome problems with chemical bonds. Not all limestone aggregates have good chemical sites or texture for bonding to the asphalt. Some limestones contain high amounts of calcite. The calcite locks up the calcium carbonate so it is not available for bonding to the asphalt (*4*) and can reduce the aggregate surface area.

Dirty Aggregate

There are many factors that affect the bond between asphalt and aggregate. Chemical bonding, as well as mechanical bonding, has been shown to be important to moisture damage resistance, but it is not the only type of bonding that affects moisture damage. In the crushing process, dust is generated. The nature and extent of the dust can have a major effect on the moisture damage potential of the hot mix.

Dusty and dirty aggregate can promote moisture damage. Dust coating on the aggregate can prevent the asphalt binder from bonding directly to the surface of the aggregate. Asphalt by osmosis does allow water to pass through it (*8*, *10*). Consequently, water can get between the binder and the surface of the stone, stripping the asphalt from the aggregate surface.

The production process for HMA is affected by dust on the aggregate. In a hot-mix drum plant, the aggregate is heated and dried as it passes through the drum-dryer. Aggregate that is coated with dust will slow the process of allowing the water to escape from the center of the aggregate. In these cases, the asphalt is prevented from bonding well to the surface of the stone by the dust, and then the moisture in the aggregate weakens the bond as it escapes slowly from the mix, a situation shown in Figure 4. This problem is only significant when large amounts of dust are covering the aggregate. All processed aggregate will have some amount of dust, but only when it is caked on does the dust create a real problem with moisture damage.

There are cases when even small amounts of dust can cause a problem. This happens when the dust is made up of small claylike particles. Clay can actually act as an emulsifier (*2*, *3*). Clay will expand in the presence of water, and the expanded clay can lift the asphalt off the surface of the aggregate. If this is combined with the action of traffic, the clay will emulsify the asphalt in the mix and cause severe stripping. This is why it is critical that clay not be allowed in the mix. In some cases, clay is generated in the crushing process. Gravel aggregate may have shale mixed in. When crushed, the shale can break down, reverting to clay and getting into the mix. Figure 5 shows a gravel deposit with large amounts of shale mixed in.

MIXTURE TYPE AND DESIGN CONSIDERATIONS

In addition to materials (aggregates and asphalt binder), the selection of the type of asphalt mixture that will be used on a given project may have an influence on the moisture susceptibility of the asphalt mixture. The three general categories of mixture types are dense graded, gap graded, and open graded.

The most commonly used asphalt mixture type in the United States is the dense-graded asphalt mixture. The *HMA Pavement Mix Type Selection Guide* (*12*) notes that dense-graded asphalt mixtures are “considered the workhorse of HMA, since they may be used effectively in

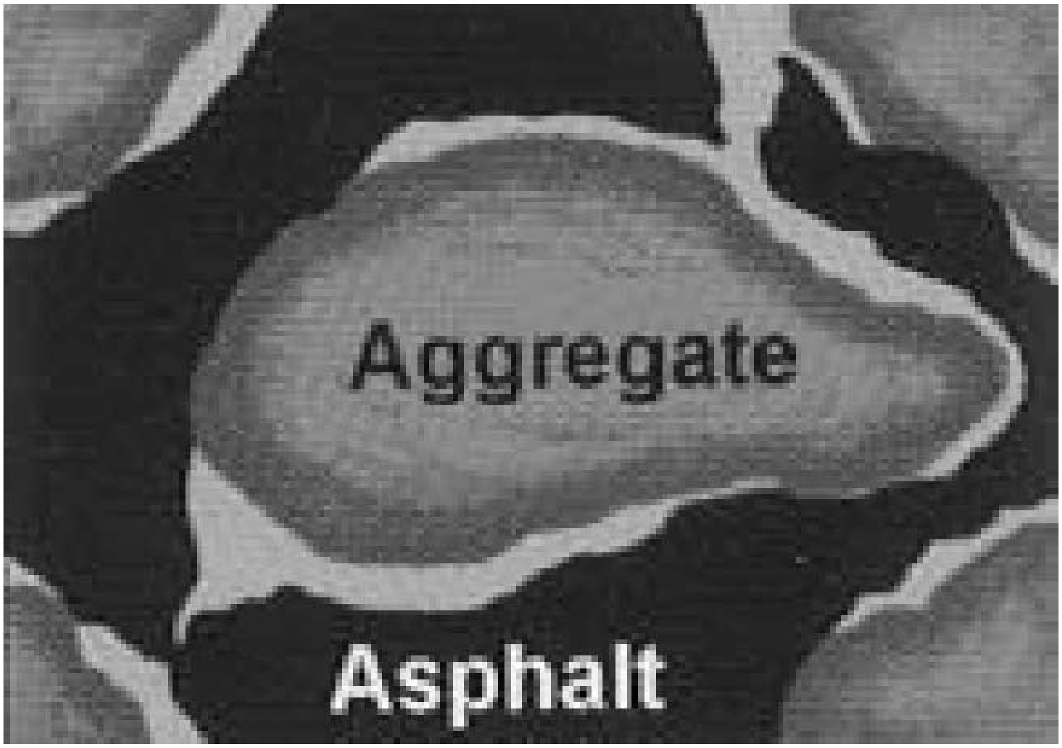


FIGURE 4 Asphalt separated from the surface of the aggregate.

FIGURE 5 Gravel aggregate with large quantities of shale.

all pavement layers, for all traffic conditions." Dense-graded mixtures may be classified generally as either fine or coarse mixtures, with the definition based on the percentage of the combined gradation on the 2.36-mm sieve (or 4.75-mm sieve for mixtures with a nominal maximum aggregate size of 25 mm or 37.5 mm) compared with the defined maximum density line. Generally, mixtures with a gradation having a higher percentage passing the 2.36-mm sieve than the maximum density line are considered fine-graded mixtures. These mixtures are usually well graded with a continuous distribution of particle sizes. Figures 6 and 7 are examples of dense-graded mixtures that are considered fine and coarse, respectively.

Stone matrix asphalt (SMA) is a type of gap-graded asphalt mixture that is used most often as a premium surface (wearing) course mixture for high-volume roadways. By definition, gap-graded mixtures do not maintain a continuous grading (like dense-graded mixtures), but have a "gap" in the gradation where there is a predominance of single-sized material (material retained on one or two sieves). As shown in Figure 8, this SMA gradation has over 50% of its combined aggregate pass the 12.5-mm sieve, but it is retained on the 4.75-mm sieve. Another characteristic of the SMA is the high dust content compared with those of the dense-graded mixtures. The high dust content allows the matrix (manufactured sand, mineral filler, asphalt binder, and additives) to be stiff, thereby assisting in the rutting resistance of the asphalt mixture.

The last general category of asphalt mixture type is the open-graded asphalt mixture. The open-graded friction course (OGFC) is the most common open-graded mixture type used in the United States for surface courses (*12*). The asphalt-treated permeable base (ATPB) is an open-graded mixture that is used as a base course to assist with drainage of water from below the pavement surface. The OGFC is a permeable layer that allows water to quickly pass through the pavement surface for drainage. The ATPB also allows water to be quickly drained from the pavement structure.

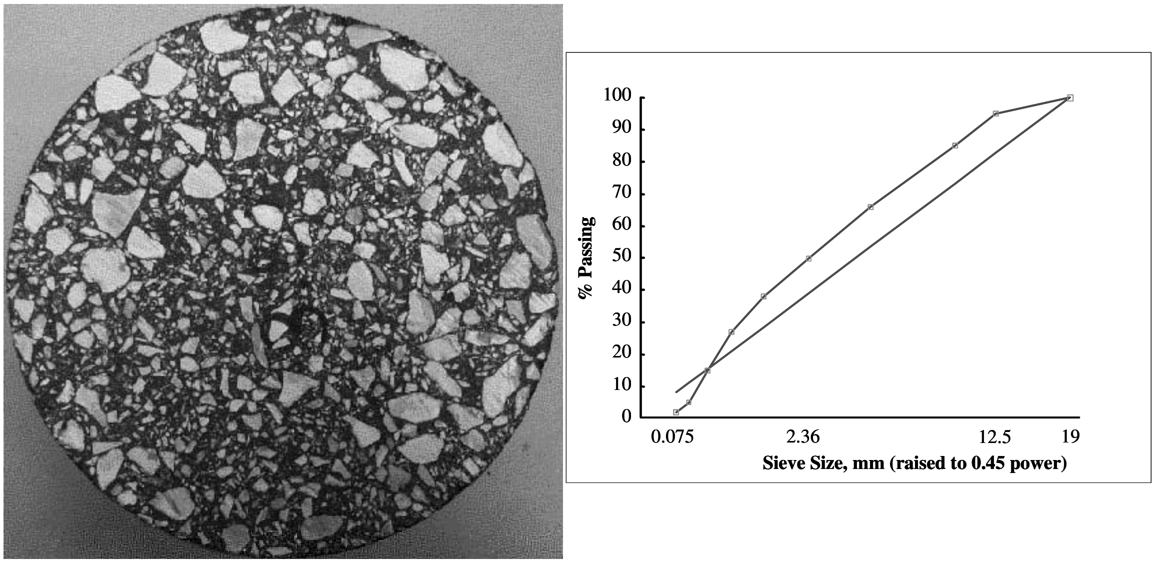


FIGURE 6 Dense-graded asphalt mixture (12.5-mm fine).

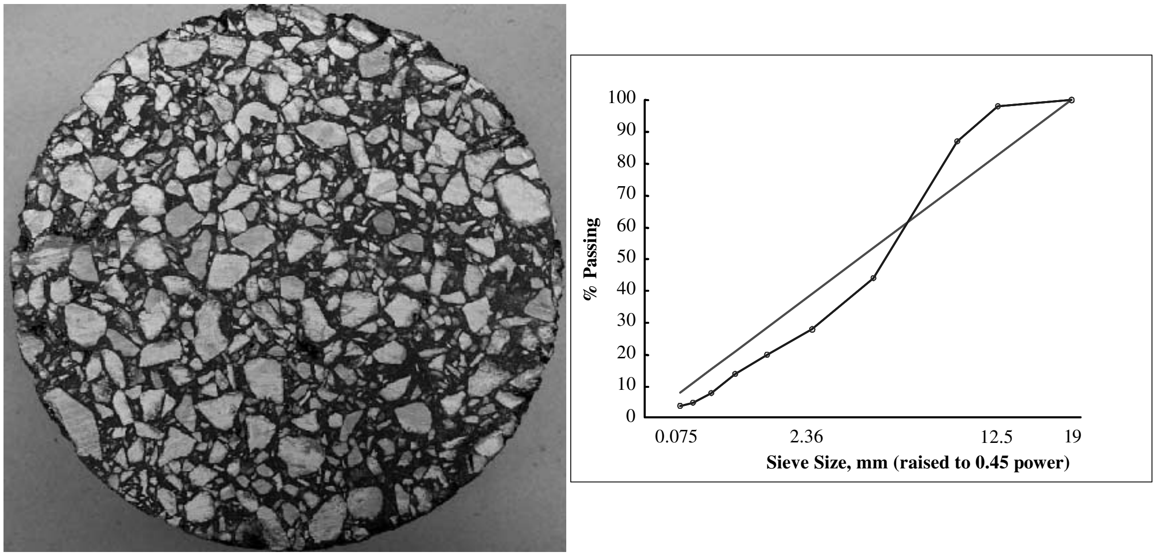


FIGURE 7 Dense-graded asphalt mixture (12.5-mm coarse).

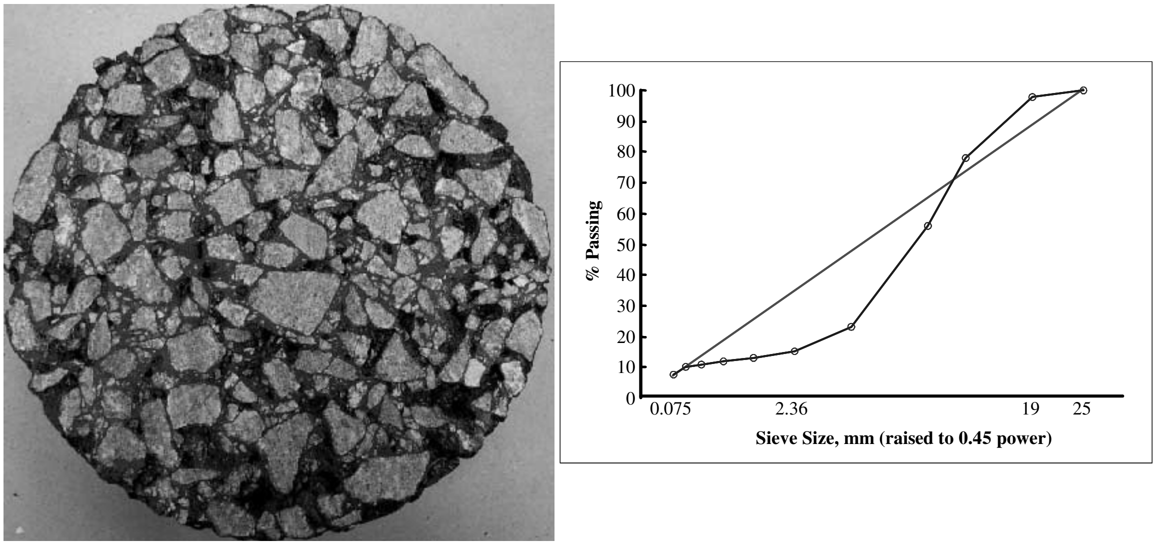


FIGURE 8 Gap-graded asphalt mixture (19-mm SMA).

Of the three major mixture types (dense-graded, SMA, and OGFC), moisture damage is least likely to be associated with SMA for several reasons that will be outlined in the following section. Even though dense-graded and OGFC mixtures may be more likely, in general, to be associated with stripping problems than SMA mixtures are, it does not mean that these mixtures cannot be effectively used without exhibiting moisture damage.

Causes of Stripping Related to Mixture Design

The selection of material—aggregates and asphalt binder—has a large impact on the stripping potential of an asphalt mixture. Likewise, the type of asphalt mixture required by the project influences the material selection. Because it is considered a premium mixture for high-volume roadways, the SMA mixture uses high-quality crushed aggregate for both the coarse and fine portions of the mixture. The crushed fine aggregate is combined with mineral filler and, if required, fibers to produce a stiff matrix. In many cases, user agencies will also increase the grade of the asphalt binder to compensate for the high traffic loading. This may result in a premium asphalt binder, such as a polymer-modified asphalt, being used in the mixture. The combination of high-quality crushed aggregate and premium asphalt binder grade helps lessen the possibility of stripping problems in SMA mixtures compared with other mixture types.

Another potential cause of stripping related to mixture design is excess dust coating of the aggregates. Both the National Asphalt Pavement Association (NAPA) and Asphalt Institute (AI) recognize that dust coating of the aggregates can inhibit the adhesion of the asphalt binder, thereby allowing water to penetrate to the aggregate surface (*13*, *14*). This is a problem most associated with dense-graded mixtures using crushed aggregates (particularly limestone).

Although SMA mixtures have a much higher total dust content than dense-graded mixtures do, they are not expected to experience this same problem as dense-graded mixtures. The principal reason that high dust content could negatively affect dense-graded mixtures, but not SMA mixtures, is that the SMA mixture, being gap graded, has a high percentage of voids in the mineral aggregate compared with the dense-graded mixtures. Usually high dust content reduces the void space in the combined aggregate. This void space, identified as the percentage of voids in the mineral aggregate or VMA, is the total volume in a combined aggregate that is available for air voids and asphalt binder. A mixture that is expected to perform adequately in service must balance the volume of air voids and the volume of asphalt binder for rutting resistance and durability.

Because of the gap-graded nature of an SMA, the VMA remains high even though the dust content is high. Assuming that the percentage of air voids stays the same in both SMA and dense-graded mixtures, the SMA mixture will have a higher volume of asphalt binder, or a thicker film coating on the aggregates compared with the dense-graded mixture. This reduces the potential of water penetrating the asphalt film.

By contrast, a high dust content in a dense-graded mixture typically reduces the VMA of the mixture. At the same percentage of air voids, the dense-graded mixture will have a lower volume of asphalt binder (thinner film coating on the aggregates) than will an SMA mixture. This increases the potential of water penetrating the asphalt film.

Because VMA is the total volume of void space in the aggregate structure, it changes based on the compaction effort used. At high compaction levels, such as those used to simulate heavy traffic loading, the aggregates are packed together more tightly, leaving less room for air voids and asphalt binder. Because the percentage of air voids is usually fixed, the volume of asphalt binder used in the mixture must decrease as the compaction effort increases, to maintain the same VMA.

Not all mix design methods use the same compaction effort for mixtures. For instance, a mixture designed using the Marshall mix design procedure for heavy traffic requires 75 blows per side of the specimen with the Marshall compaction hammer (*15*). The same mix designed for medium traffic only requires 50 blows per side. Assuming that both mixes are designed at the same percentage of air voids and VMA, the mix designed using 50 blows will have a higher volume of asphalt binder (asphalt binder content) than the same mix designed using 75 blows. Similarly, mixes designed by the Superpave® mix design method using 75 gyrations will have a higher asphalt binder content than the same mix designed using 125 gyrations (again, assuming the same percentage of air voids and VMA). In both cases, the mixes with the lower asphalt binder content will have a lower film thickness, plus an increased potential for water penetrating the asphalt film to the aggregate surface. Excess dust on the aggregates and in the mixture can exacerbate this condition.

Causes of Stripping Related to Construction

The major construction variable that can increase the stripping potential of an asphalt mixture in service is compaction (*13*). It is generally accepted from various studies that air voids are not interconnected when there are less than 4% to 5% air voids in the mixture. This value depends somewhat on the type of mixture, because the connectivity of the air voids in a fine dense-graded mixture may be different than in a coarse dense-graded mixture.

Generally, user agencies specify that the compacted asphalt mixture must have at least 8% air voids in place immediately after construction. The mixture is then assumed to densify normally under traffic to its final percentage of air voids (approximately 4%) after a few years of traffic loading.

The SHRP A-003A researchers at Oregon State University proposed the concept of a "pessimum" (defined as the opposite of "optimum") voids content in an asphalt mixture that relates to its stripping potential (*16*). At low percentages of air voids (less than 4% to 5%), the voids are not connected and the potential for water intrusion and stripping is low. At high percentages of air voids (greater than 15% to 20%), the voids are interconnected such that the mixture is free draining. In between these percentages of air voids (greater than 5% and less than 15%) is the pessimum range, where some of the air voids are interconnected and water may become trapped in the mixture, thereby increasing its stripping potential. This concept is illustrated in Figure 9.

Unfortunately, most mixtures are constructed near the middle of this pessimum range, causing an increase in stripping potential early in the pavement life. After several years of traffic, the mix is assumed to densify normally to the impermeable range (4% to 5%). However, if the mixture does not densify as expected, the mixture will be left with high enough air voids to still be in the pessimum range. This lack of expected densification can be caused by several factors including the following:

- The asphalt binder is too stiff (or modified) to allow normal densification for the climate and traffic.
- The laboratory compaction effort is too high for the traffic loading, resulting in a "harsh" mixture (low asphalt binder content).

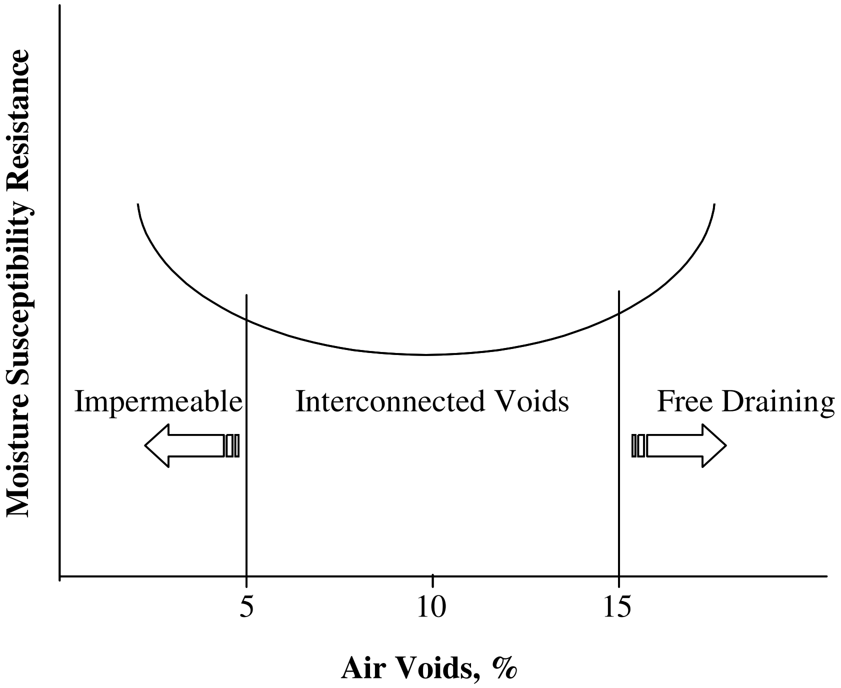


FIGURE 9 SHRP A-003A research concept of pessimum air voids.

Thus, proper selection of materials and mix design procedures in the design phase has an important impact on the percentage of air voids after initial compaction and densification under traffic.

For all mixture types, adequate compaction is important. However, by nature, SMA mixtures are often tighter (have lower air voids in place) and impervious immediately after compaction than are typical dense-graded mixtures. By contrast, OGFC mixtures have a much higher percentage of air voids in place to permit adequate drainage. In either case, the SMA and OGFC mixtures are more likely to be outside of the pessimum air voids range suggested by the SHRP A-003A researchers than are dense-graded mixtures.

Another variable that may have an impact on the stripping resistance of a mixture is residual moisture in the aggregate after being processed through the mixing facility. Aggregates with moisture retained after passing through the dryer may affect the adhesion of the asphalt binder to the surface of the aggregate.

PAVEMENT DESIGN CONSIDERATIONS

The most important pavement design variable that affects the moisture damage potential of an asphalt mixture is pavement drainage. The conclusion to AI's ES-10, *Cause and Prevention of Stripping in Asphalt Pavements*, treats the stripping problem quite simply as "water is the culprit causing stripping. Anything that allows it to stay around long enough to damage the pavement is an accomplice" (*14*). This same publication notes that "It has been observed that asphalt pavements over untreated granular bases *with well-designed and properly operating drainage* have not stripped, even when made with aggregates that are prone to stripping." NAPA's QIP 119, *Moisture Susceptibility of HMA Mixes: Identification of Problem and Recommended Solutions*, notes that "Kandhal et. al. (*17*) have reported case histories where the stripping was not a general phenomenon occurring on the entire project, but rather a localized phenomenon in areas of the project over-saturated with water and/or water vapor due to inadequate subsurface drainage conditions" (*13*).

More recently, NCHRP published the key findings from the NCHRP 1-34 project, *Research Results Digest No. 268: Performance of Subsurface Pavement Drainage*. This research summarized the effects of subsurface drainage on flexible pavements. In one conclusion, it was stated, "The inability to drain a permeable layer leads to increased fatigue cracking and rutting; increased stripping may also result" (*18*).

Because water and water vapor may move in both vertical directions—down by gravity and up by capillary action—it is important that designers be aware of these concerns when selecting mix types. For instance, it may be advantageous to use an ATPB (a type of open-graded mixture used as a base course) as the bottom layer in a pavement structure. This permeable layer may allow water to escape from the pavement structure more quickly than does a conventional unbound dense aggregate base.

OGFC mixtures, likewise, should be selected in conjunction with the underlying mixture types. Because the OGFC allows water to pass down through the surface to the underlying mixture, it is important that the lower layer mixture be well compacted and impermeable. Otherwise, the OGFC mixture may simply channel water into the semipermeable mixture, and, following the repeated loading of traffic, allow the water to rapidly scour the lower layer mixture, resulting in stripping. By contrast, the use of seal coats on the surface may create an impermeable barrier, trapping water in the underlying layers.

The pavement designer should be aware of these potential problems of trapping moisture when selecting mixture types for the project. After all, it seems logical that the simple truth stated from the first paragraph in this section is the most important: do not let the water stay in the pavement system and the potential for moisture damage will be greatly reduced.

CONCLUSIONS AND RECOMMENDATIONS

Moisture damage can be a significant problem that severely shortens a pavement's life. The causes of moisture damage are many and varied, ranging from the basic materials to the design and construction process. Thus, it is critical that each aspect of the production process be managed properly.

Asphalt binders are produced from crude oils that contain materials that can cause moisture damage problems. These are natural salts that, when exposed to water and mechanical action such as traffic, can cause the asphalt to emulsify and strip from the aggregate.

Asphalt modification, depending on how it is done, can also aggravate moisture damage problems. Acids and caustics have been used to stiffen the binder to improve high temperature rut resistance. Depending on the nature of the crude and the extent of the modification, these methods can be effective in improving the binder or can create binders that may react with other additives to cause stripping.

To avoid such situations, it is very important that the binder be tested with all additives in it, including binder modifiers for performance and any antistripping agents. If there is an interaction between the different modifiers, the only way to identify it is through testing with all additives included.

Even more critical in determining if the mix is susceptible to moisture damage is evaluating the binder aggregate combination. The only way to determine if the aggregate will provide good bonding sites for the binder is to measure the mixture properties. Even limestone aggregate can have problems with moisture damage if the calcium carbonate is locked up by calcite.

Tests for clay should be performed on the crushed aggregate as it is to be used in the mix. Clay can come from many sources, and the only way to ensure that it does not get into the mix is to test for its presence in the combined aggregate as it is delivered to the plant site.

Asphalt technologists should be aware of the potential effects of mixture type on stripping potential in a pavement structure. Judicious selection of appropriate mix types for the project can help minimize the potential for moisture damage in the pavement structure.

Finally, adequate compaction and pavement drainage are needed to ensure that water entering the pavement structure will have an opportunity to leave before causing significant damage.

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TOPIC 5

Questions and Answers

JOHN D'ANGELO
FHWA, Speaker

Q1—Gayle King, Koch Pavement Solutions
John, excellent presentation! You've addressed a lot of important issues. Your point regarding inappropriate application of chip seals to seal moisture into the pavement brings back some particularly unpleasant learning experiences from the past. More importantly, you've really captured some of the pressing binder chemistry issues we don't handle well as an industry. I've followed four projects in which surface mixes failed due to stripping within 8 months, and each was caused by specific binder chemistry problems. In each case, good performance was achievable when other binders of similar grade were substituted for the problem material. Although each failure was related to binder chemistry, the causes were different. One was an acid/amine compatibility problem, one was a crude source problem, one was caused by the addition of absurdly high concentrations of emulsifiers, and the fourth is still under investigation. Three of these projects were built using the current AASHTO T283 or agency equivalents thereof. One was CDOT's project on Copper Mountain, with more recent failures about 2 years ago in Oklahoma and last year in Nebraska. In all cases, Hamburg wheel tracking indicated disintegrator mixes, and the binder always showed some signs of reemulsification. To make an emulsion, one needs asphalt, an emulsifier (chemical salt, surface active clay), water, heat, and mechanical energy. In mixes, mechanical energy creates pore pressure, and the resulting shear stresses cause the binder to strip/emulsify. No mechanical energy, no emulsion. We are consistently missing such stripping mechanisms with T283. Wet wheel-tracking tests can predict these problems. For example, when clay acts as the asphalt emulsifier, Hamburg tends to cause much more damage than might be presumed from static immersion tests. Aschenbrener's and Kandahl's Hamburg/methylene blue studies emphasize this point. I apologize for the long comment, but I believe we are missing critical stripping mechanisms by relying on laboratory tests that do not create damage caused by pore pressure.

A—John D'Angelo
Thank you, Gayle. I'll have to sort of agree with you. I agree that the existing AASHTO T283 doesn't have any mechanical action per se and it doesn't cause the problem where you can get reemulsification of the asphalt. Also, the pore pressures cause some of the separations of asphalt from the aggregate even if it's not emulsification. I think it's critical to have the mechanical action. I'm not a big fan of the Hamburg, though, because I think it's too severe a test. If it passes with the Hamburg test, you've probably got a pretty indestructible mix. I'll grant you that one, but it might be a little too severe. That's why I'm holding great hopes for the NCHRP 9-34 procedure.

Q2—Bill Bailey, Rock Binders
I've always wondered over the years—you had an excellent slide here, by the way—why the ratios of the tensile strength numbers being high didn't really relate to the control, on the control

being 800 tensile strength and then the ratio failing but the failing tensile strength would be 800 or higher because the original in that failing sample would be higher. Nobody's ever really addressed that. I'm just a kind of dumb old country boy who doesn't understand a lot of this so I appreciate your letting me be here. I do understand mathematically that if you take the square feet of a ton of mix and measure it for the area, 5 microns will cover that substantially. But anyway, I'd like answers to the other questions.

A—John D'Angelo
In the development of the tensile strengths ratio, that was one of the things that was a relatively easy test, the indirect tensile strength of a mix. You can do it with some very simple equipment and you get a result. One of the best ways to look at the response of the material between an unconditioned and a conditioned was to evaluate the ratio between the strengths. The next issue is how do you then add the effect of the overall total strength of the mixture. To do this, it becomes a lot more complicated. Some states have put minimum strength requirements on the mix, so that if you don't get a minimum strength, you won't pass the test. No one has figured out how to really address that issue of total strength, unless you go into some of the other criteria. You're looking at things like modulus, which then makes the test much more difficult to run.

Q3—Dick Root, Root Pavement Technology
Just a quick comment. When we start fooling around with allowing a reasonable level of air voids to work with and you start taking absolute tensile strengths, then if you did have 6% air voids versus 8%, you had noncomparable results. So we ignored absolute tensile strength and looked at the ratios for that very reason.

Q4—Bob Humer, Asphalt Institute
First of all, John, thank you very much for an excellent paper. I really appreciate your stressing some of the very basic points as a first line of defense against moisture sensitivity. If we can't do those basic things right, then maybe after that there is some chemical stuff we can look at. Especially stressing good mix design, good compaction, and proper lift thickness to get compaction. One of your slides shows the minimum lift thickness and a maximum lift thickness. The minimum we've talked about, so we don't have to argue about the three times the nominal maximum aggregate size. But you have a maximum lift thickness there of five times the nominal maximum aggregate size. Where does that come from, and why is there such a maximum limit, other than for compaction energy? Why would there be such a tight limit on the maximum lift thickness?

A—John D'Angelo
On the maximum of five times the nominal aggregate size, that's typically the relationship for coarser-graded mixes. What you have there is when there is a lot more of the stone or the stone content as a larger percentage of the materials, you have to be careful. When the lift thicknesses for coarse-graded mixes get a little bit too high, they'll have a tendency to push around some. It's almost like pessimum voids with permeability. If you get too much lift thickness in these very coarse-graded mixes, they'll have a tendency to shove around significantly and even uncompact themselves, so you have to be careful with that. Again, it depends on the type of mixtures you have. I know the French typically use a dense-graded mix in a lot of the work that they do. They actually go up to seven times the normal maximum aggregate size. However, they don't usually use these very coarse-graded mixes. The contractors won't want to work in France,

because I guarantee you, as contractors, you'd hate it. The French will tell you exactly the lift thickness, the type of roller you'll have, how many passes to make to compact the mix, and then they'll hold you to the compaction.

Q5—Don Goss, Valero
Thank you, John, for your presentation. I thought you included a lot of good information. I just have a couple comments to make. One, earlier in the presentation you mentioned asphalt as the bottom of the barrel of the crude, and you implied that maybe it was waste material, and that hurt, John!

A—John D'Angelo
I would never really consider it waste.

Q6—Don Goss, Valero
Just for the record, there are other uses for the material—as a base oil in marine fuel, of course, in roofing products, and as coker feed, which would create a higher fuel yield from the barrel of crude. So, I just wanted to make that comment, and say that with the development of a lot of the recent tests that reflect the fundamental engineering properties of the binder, many of us who produce asphalt consider it no longer as a by-product but as an engineered product in its own right, and we think it's a very valuable material. I guess on a little bit more serious note, with respect to testing the binder with everything in it, I think you make a good point in respect to grading the binder. With respect to reflecting moisture sensitivity, I just want to comment that I think it is important that we test the mix because the binder may not contain everything that's going to impact moisture sensitivity. Thank you for allowing me to comment.

A—John D'Angelo
I agree with you wholeheartedly. Basically, I tried to stress through the whole presentation that you want to test all the products, and more important than anything it's the final product, the hot-mix asphalt on the roads, that's key to test. You've got to look at the details of the components, but most important of all, you have to look at how they go together and what the product looks like as it's going to be used.

Q7—Dale Rand, Texas Department of Transportation
Two quick comments. We've seen over the last couple of years a problem with the TSR, particularly with the polymer-modified asphalts. For example, you can have a wet strength that is 150 psi and yet the mix still fails the tensile strength ratio. This has been a big problem and a big frustration. I know from the industry side and from the TxDOT side trying to get tests that pass when we are at the same time pushing the use of more and more polymer-modified asphalts in the applications for high-traffic areas. When you take a test that's got 25% variability and you start adding all these polymers and lime to it and all these other additives, it's been a big frustration for us. So for whatever it's worth, we made the decision never to run that test again and we had zero opposition from industry or TxDOT. We were waiting for somebody to say, "Wait, you are doing the wrong thing." The other comment I wanted to make was on your concern about the Hamburg being too severe a test. I'd go back to what you said about one size does not fit all. With the Hamburg and what we are doing now, one criterion does not fit all also.

You really have to look at it based on the PG grade of the asphalt. Anyway, I just wanted to comment on it.

A—John D'Angelo
Thank you, Dale. I'm not trying to attack the Hamburg. I used tensile strength for the slides because that's the data we have for the most part. Though I'm not a fan of the Hamburg test, I don't think that the TSR is the answer, but it's what's being used today predominantly because we have a lot of data on it. The ultimate test will have some kind of mechanical action. You've elected to use the Hamburg and work with it. That test has its problems, too; that's why I want to continue to look for something new. Of course, my thing is that I'm sort of into research and technology transfer. I'm always looking for something new; nothing is good enough for me. I always have to find something new. Otherwise, I'd be out of a job or I'd be bored.

Q8—Gayle King, Koch Pavement Solutions
Run your 1.2% acids through the Hamburg. I predict you won't like the results.

A—John D'Angelo
I'm not saying they are good or bad. Go ahead, Tim.

Q9—Tim Aschenbrener, Colorado Department of Transportation
I had a question regarding the pavement design, and I didn't see it covered in this area, but I think it's really critical. I was wondering if you could make a few comments on the importance of an aggregate base course.

A—John D'Angelo
Are you talking about just the general graded aggregate base?

Q10—Tim Aschenbrener, Colorado Department of Transportation
Yes. Our asphalt industry conducted a survey of the 10 best-performing asphalt pavements in Colorado and came up with a series of lessons learned. One of the common features in all those pavements was the existence of an aggregate base course between the subgrade and the asphalt pavement. In areas where we constructed full depth asphalt on the subgrade, we continuously found severe moisture damage at that interface. Where aggregate base course existed, it did not. So when repair is needed to the full depth asphalt, it is extremely expensive. So I think one area that is critical in the pavement design is to ensure that good-quality aggregate base course is in place.

A—John D'Angelo
There has been a lot of discussion on specifically base type and moisture damage. Should the pavement be full depth asphalt with a black base or a thinner asphalt layer with an aggregate base? To address the problem with moisture, an asphalt permeable base that's the drainage layer to make sure you don't have the moisture that's being brought up from the subgrade, which causes significant problems, was developed. That's one of the approaches taken to address that problem. Then again, even with aggregate bases, you run into problems with drainage. You have to be sure you have a good drainage layer to get that water out of that base or it can cause significant problems, either full depth asphalt or aggregate. There are different ways to tackle any one of these issues. I don't know if the issue is if it's good to have an aggregate base. I think

it's better to not have a lot of moisture sitting in a layer that has high stresses, and if you are at the bottom of that asphalt layer, that's where the stresses start to develop. Probably some of the aggregate bases are reasonable in making sure that layer doesn't stay saturated continuously, I would guess.

Q11—Bob Rea, Nebraska Department of Roads
We use a lot of liquid antistrips and plan on using them a lot more in the future also, but we also agree with your concern that early on we saw a lot of the tensile strength ratios get much tighter with the liquid antistrips, but at the same time they were lowering the tensile strength of the mix. Just wondered if there are some threshold values that one would look at for a minimum tensile strength and then use a ratio from there or anything like that.

A—John D'Angelo
Well, there is not really a minimum ratio. I think Jim Anagnos sort of talked about that. Originally, a lot of these liquid antistrips would soften the asphalt and you would get better ratios, but they actually softened the asphalt, and that is part of what caused the problem with lower tensile strengths. That's why if you are going to use liquid antistrips, it is critical that you test the binder for the binder properties to make sure it meets specs with the liquid antistrip in it, to make sure you didn't soften the binder. He showed several slides earlier where the newer materials don't do that anymore, but that's based on a limited study. I would imagine there are some suppliers out there that are supplying things that will cause problems. To avoid that kind of problem involves more than just setting a minimum value for a tensile strength ratio. It is to make sure that binder you are testing to meet a certain stiffness value has the amine in it to make sure it's really not reducing that strength.

TOPIC 6

Production and Construction Issues for Moisture Sensitivity of Hot-Mix Asphalt Pavements

TOPIC 6

Production and Construction Issues for Moisture Sensitivity of Hot-Mix Asphalt Pavements

JIM ST. MARTIN
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Today we are demanding more from our pavements than ever before. As we continue our efforts to design and construct hot-mix asphalt (HMA) pavements that perform better and last longer, we must consider all of the factors involved in the ultimate performance of the pavement. Moisture-induced damage within HMA has been described as a national issue leading to the decreased life of our nation's roadways. As we consider the nature of materials and specifications across the country, it is important to understand the impact that both material production and construction can have on the ultimate performance of the HMA pavement in the field.

During the design of most HMA mixtures, tests to evaluate the potential for moisture-induced damage are conducted. For most states in the United States, AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage," or a modified version, is used for this purpose. If a designed mix meets the requirements of this test, it is assumed that the mix will perform in the field with respect to resistance to moisture damage. However, if the designed mix is not produced and constructed properly, moisture damage can still occur as a result of construction deficiencies.

There are a number of production- and construction-related issues that can affect the ability of an HMA pavement to resist moisture damage. Factors from the handling of stockpiles through placement and compaction of the HMA on the roadway can affect the potential for moisture damage in the field. In fact, mixes that are marginal with respect to resistance to moisture damage that are well constructed on the roadway may perform better than mixes with a low potential for moisture damage that are poorly constructed. Therefore, the proper production and construction of HMA pavements is vital to providing roadways that will perform up to and beyond their design lives.

CAUSES OF MOISTURE DAMAGE

Before discussing the production and construction factors that can affect the resistance of HMA to moisture damage, the mechanisms that cause moisture damage must first be defined. There are two primary modes of moisture damage: adhesive and cohesive failure. Adhesive failures occur when the asphalt binder separates from the aggregate, typically in the presence of water. Cohesive failures occur because of a weakening within the asphalt binder film coating the aggregate, generally owing to moisture effects. The literature describes five primary mechanisms that lead to either of these failure modes: detachment, displacement, pore pressures, hydraulic scouring, and spontaneous emulsification (*1*, *2*).

Detachment is described by a microscopic separation of the asphalt film from the aggregate by a thin layer of water without any obvious breaks in the film (*2–4*). Detachment is believed to be caused by incomplete drying of the aggregate during plant production. Excessive moisture not removed from the aggregate can later migrate within the interstitial pores of an aggregate and lead to detachment of the asphalt film.

Displacement is described as the preferential removal of the asphalt film from the aggregate surface by water (*1–3*). This occurs when water is absorbed into an aggregate through a break in the asphalt film, owing to incomplete coating of the aggregate, rupture of the asphalt film, or loss of dust coatings around the aggregates. Rupture of the asphalt film can occur as a result of fracturing of the aggregates during field compaction, in-service traffic, or environmental action such as freeze–thaw (*1*). Displacement occurs because the aggregate has a higher affinity for water than for the asphalt binder. Therefore, the water displaces the asphalt binder around the aggregate.

The pore pressure mechanism occurs from the presence of water in the interconnected voids of the HMA (*5*). Densification of the HMA under traffic causes the interconnected voids to become isolated (no longer interconnected), and the water is trapped within these isolated voids. As traffic passes over the HMA, pore pressures increase and then decrease again after the load passes. This continuous increase–decrease of pore pressures can rupture the asphalt film and lead to displacement or hydraulic scour.

Hydraulic scour occurs in surface mixes from the application of vehicle tires on a saturated HMA (*1*, *2*). Water is compressed into the pavement in front of the tire, resulting in a compressive stress within the interconnected void structure. Once the tire passes, a vacuum forms, pulling water back out of the interconnected voids. This compression–tension cycle occurs every time a vehicle passes over the pavement and can lead to moisture damage due to displacement or spontaneous emulsification.

Spontaneous emulsification occurs when an inverted phase emulsion (water suspended within asphalt) forms within the HMA (*1*, *2*). Unlike the previously mentioned mechanisms, which result in adhesive failures, this mechanism leads to cohesive failures. In the field, spontaneous emulsification failures can be difficult to detect because no loss of asphalt coating can be observed.

In describing the production and construction factors that can affect moisture damage, each of the aforementioned mechanisms of failure can occur. It is, however, important to note that for any of the five mechanisms to occur, generally, water must be present either within the aggregate or within the pavement. Sufficient drying of the aggregates and constructing the pavement in such a way that the pavement is impermeable will help ensure that moisture damage will not occur.

For the purposes of this paper, production factors shall include the handling of materials once at the HMA facility through completion of the mixing process within the plant. Construction factors shall include the loading of produced mixture through compaction of the roadway. In addition, we have assumed that a mix has been designed and approved to comply with all applicable specifications.

OBJECTIVE OF THE PAPER

The objective of this paper was to highlight various production and construction issues that can increase the potential for moisture-induced damage in HMA pavements. Also, good production and construction practices are discussed to help decrease the potential for moisture damage in HMA pavements.

MATERIAL PRODUCTION ISSUES

For the purposes of this paper, the production of HMA begins with the stockpiling of aggregates on the HMA plant site. Once the stockpiles have been placed, the aggregate must travel through the cold feed system (no matter the plant type) to be heated and combined with the liquid asphalt binder. After the mixing of the aggregates and binder has been completed, the mixture must be loaded for transportation to the roadway. In this paper, material production encompasses all of the activities up to loading of the trucks for transportation. Within this section, the various steps of HMA production and their potential effect on moisture-induced damage are discussed. As will be seen throughout this section, two recurring issues are related to moisture-induced damage: segregation and the moisture content of the aggregates. Segregation prevents the HMA from being produced to meet the job mix formula. If the mix does not meet the job mix formula, then the results of moisture susceptibility testing during mix design are not applicable. Moisture remaining in the aggregate after the asphalt binder has coated the aggregate can lead to detachment of the binder film during service life.

Stockpile Handling

It is well known that the quality control of the HMA product, regardless of plant type, begins with the aggregate stockpiles. This also includes recycled asphalt pavement stockpiles. The goal is to produce a mix that is as close to the mix design target values as possible and to consistently provide that material to the paving train for placement in the field. The equipment used for production purposes can blend the various stockpiles to be used in the HMA consistently, but it cannot control the gradation of the individual stockpiles. Therefore, it is important to provide consistent and uniform aggregates to be blended. That is, even the most accurate production facility, when provided with aggregates that are highly variable in gradation or moisture content, cannot provide a consistent material at the design target values.

The foundation for aggregate stockpiles should be stable, clean, and dry (*6*). Stable foundations are needed so that the construction equipment can efficiently build the stockpiles and remove material from the stockpiles. Clean foundations ensure that foreign materials, such as roots, soil, or grass, are not picked up with the aggregates. Foundations should be constructed such that water does not pond underneath the stockpile, thus increasing the moisture content of the aggregates near the bottom of the stockpile.

Aggregate stockpiles should be built to minimize segregation of the coarser particles. This can be done by using sound stockpile building practices (*7*). It is also important that there is sufficient space between the stockpiles so that cross-contamination between stockpiles does not occur. Stockpiles should also be built to be free draining, to ensure that the moisture content within the stockpile stays as low and consistent as possible. A method of preventing water from infiltrating into the stockpile is to cover the stockpile using some type of a roof structure (Figure 1). Tarps are generally not recommended for covering stockpiles because moisture tends to collect under the tarp.

Proper handling techniques should be used to minimize segregation. Excessive handling of the aggregates can also cause degradation of the aggregates, which causes a change in the gradation of the stockpile.

With regard to the various methods of treatment for moisture sensitivity, the lime slurry marination (LSM) procedure does affect the aggregate stockpiles. Some states require the aggregate stockpiles to be treated with lime slurry and then allowed to marinate for a minimum specified time. Typically, there is a minimum time limit for this procedure and a maximum time limit after which the stockpile is deemed to be unsatisfactory for use in the product. Again, the consistency and uniformity of the stockpiles and their treatment are extremely important factors in the material production process. Possible factors for consideration for the LSM process are as follows:

- Adequate stockpile area for the maximum anticipated production or marination period,
- Overhead protection of stockpiles in case of inclement weather (rain),
- Positive control of water runoff from stockpiles (many states have specific requirements concerning storm water runoff),
- Control and regulation of marinated materials (i.e., first in, first out), and
- Monitoring and control of moisture content of stockpiles.

Again, the material producer should employ the best available practices for its specific conditions and location to control the quality of the aggregates and supply a consistent and uniform material to the production facility.

FIGURE 1 Covered aggregate stockpiles and cold feed bins.

Cold Feed System

The cold feed system includes cold feed bins, collecting conveyor, and charging conveyor. To produce a uniform, high-quality HMA, it is imperative that the entire cold feed system be properly calibrated. Aggregates from the stockpiles are placed in the cold feed bins by front-end loaders. The use of bulkheads with the cold feed bins is generally sound practice to prevent aggregate from overflowing from one bin to another. Commingling of different stockpiles within the cold feed bins can alter the design gradation (*6*). Aggregate is discharged from the bottom of the cold feed bin onto a feeder belt. This belt then takes the aggregate to the collecting conveyor. The aggregates then generally pass through a scalping screen, to remove oversized aggregates or deleterious materials, and fall onto the charging conveyor, which takes the aggregate to the drum for heating.

In a number of states, hydrated lime is required as an antistripping additive; it is added either between the collecting and charging conveyors or on the charging conveyor. In adding hydrated lime, it is important to understand that the purpose of the hydrated lime is to change the chemical charges of the aggregates so that the asphalt binder adheres better to the aggregate. Therefore, the aggregates and hydrated lime must be completely mixed. Hydrated lime may be mixed with the aggregates by falling through the scalping screen; some states require a pug mill between the collecting and charging conveyors. Regardless of the method by which the hydrated lime is introduced, some moisture is required for the chemical reaction to occur. Also, for best results, the hydrated lime needs to be evenly distributed within the aggregate.

Drying and Mixing Process

The goals of the drying and mixing process are the same no matter the plant type used:

1. Completely dry the aggregates.
2. Add the proper proportions of asphalt binder and aggregates.
3. Produce properly coated HMA meeting the job mix formula.

Aggregates not properly coated with asphalt binder lead to a higher potential for moisture damage, owing to displacement. A good, sound quality control/quality assurance program will ensure that the two latter goals are met. However, depending on the gradation and moisture content of the aggregates, the amount of drying within the drying process can change. Aggregate blends that contain a large percentage of coarse aggregates (e.g., coarse-graded Superpave®, stone matrix asphalt) may require more drying time than do blends with a higher fraction of fine aggregates. Regardless, the moisture content of the aggregates should be monitored during production. At least two moisture contents should be obtained per day, and more if the moisture conditions change during the day (e.g., rain) (*6*).

Complete drying of the aggregate can be achieved, no matter the plant type, by maintaining a steady rate of HMA production. The rate of production should match the paving operation on the roadway. If the rate of production is too high, the aggregates are not exposed to the heat within the drum long enough to become dry. Proper maintenance of the flights within the drying drum is also vital to achieving the proper aggregate veil within the drum to ensure drying. In addition, the angle of the drum can be decreased slightly to keep the aggregate in the drying zone longer.

Quality Control and Assurance

Modern HMA production facilities are capable of producing large quantities of materials. To ensure success, the plants should be calibrated frequently to verify that all of the components of the facility are working within acceptable tolerances. Some states have a certification procedure that requires each facility desiring to manufacture material for the agency to verify its operational accuracy, to maintain its certification. If the state or local agency does not have such a requirement, it is highly desirable that the plant operator perform a similar procedure to ensure that the plant is operating within its expected tolerances.

The proper control of each of the mix design components is critical to produce a mix that is as close to the design target values as possible. Some of the issues for consideration during the production process are as follows:

- Control and monitoring of moisture content (particularly with the LSM process; additional moisture content can reduce plant production capacity);
- Control of introduction of antistrip treatment material;
- Adequate mixing of the aggregates with lime (dry or slurry);
- Proper introduction of liquid antistrip into the mix or binder (some agencies allow the addition at the refinery or terminal; others require the addition at the HMA production facility);
- Proper drying of the aggregates;
- Proper handling of baghouse fines; and
- Proper charging of silos.

As in any production process, quality control is an integral and necessary component. The proper control of the various aggregate sizes, their moisture content, the binder, the antistrip treatment material, baghouse fines, mix moisture, mix temperature, and other critical components is very important to the production of a consistent, uniform material meeting the design target values. The continuous testing, monitoring, and adjustment of the plant are vital in supplying a mix to the HMA paving train that meets all of the design requirements.

MATERIAL CONSTRUCTION ISSUES

Once mixture is produced in the HMA facility, it must be loaded into trucks, transported, placed, and compacted to provide the final riding surface. As will be discussed in this section, segregation will again be a major contributor to increase potential for moisture damage. However, unlike the physical segregation within the production process, segregation can also take the form of thermal nonuniformity. Maybe the most important issue related to the construction process is low density. Areas of low pavement density can be permeable to water. If pavements are constructed to be impermeable, then the potential for moisture damage is greatly decreased. The following sections discuss the effect of construction on moisture damage.

Loading of Mixture

During loading of the mix into trucks, the primary mode for increasing the potential for moisture damage is improper charging of the truck bed. Improper charging of the truck bed can lead to segregation on the roadway. Brown et al. (*8*) have shown that segregation can lead to increased permeability within the completed pavement. In turn, greater permeability allows water to more easily penetrate the pavement and bring about moisture damage by any of the five mechanisms of failure.

Transportation of Mixture

The next phase of the construction process is the transportation of the HMA to the project site. An area of concern during transportation is the draindown of asphalt binder from the coarse aggregate. This usually only occurs for mixes having very thick binder films, especially coarse-graded mixes like open-graded friction courses (OGFC) or stone matrix asphalt (SMA). This draining of the asphalt binder from the coarse aggregate structure can be translated to segregation on the roadway. As a result of the draindown, the coarser aggregates are not coated with sufficient asphalt binder, and therefore moisture damage can occur owing to displacement, detachment, or hydraulic scour in the presence of water.

Another potential problem during the transportation of HMA to a job site is excessive cooling of the mix. If the HMA mix has cooled below a certain temperature, which is asphalt binder and mix specific, it will be difficult to achieve proper density on the roadway. Insufficient density allows water to permeate into the pavement.

Paver Operations

Once at the project, the HMA must be loaded into the paver. It is important that there be coordination between the plant and paving train. Enough mixture must be supplied to the paving train to prevent the paver from stopping. However, the supply of mix to the paving train should not be such that there are an excessive number of trucks waiting to empty. As the trucks wait, the mixture cools.

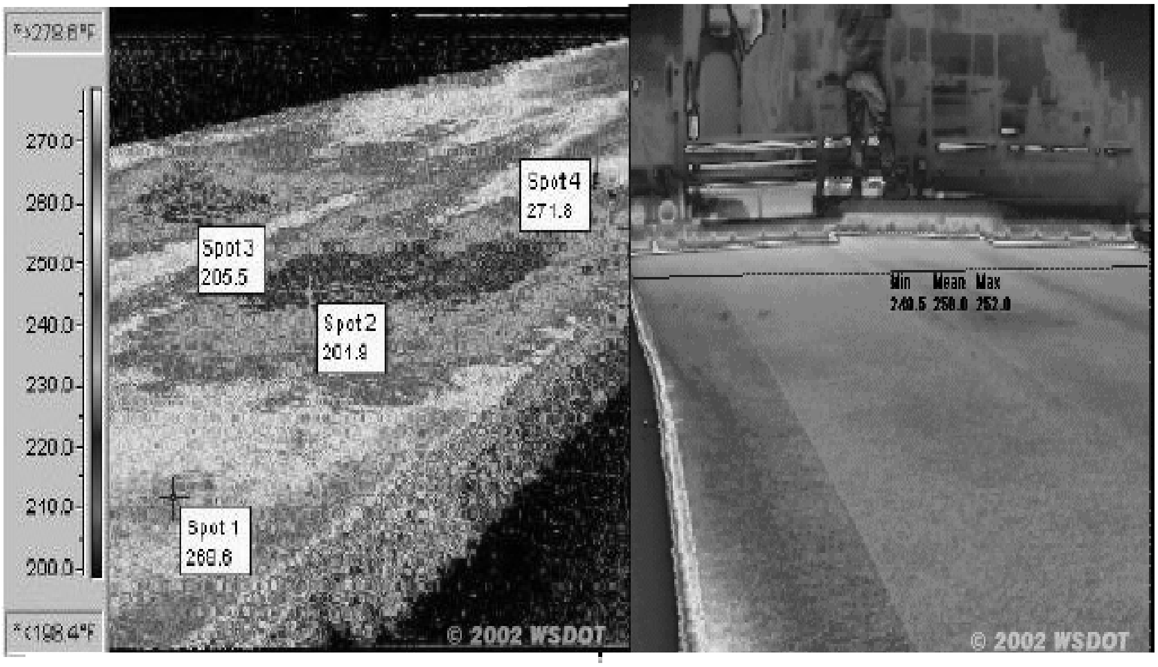
There are numerous methods for loading pavers. Depending on the type of truck transporting the HMA—end dump, bottom dumps, or flow boys—the exact method of charging the paver can be different. The existence of a material transfer vehicle can also affect how HMA is charged to the hopper of a paver. The primary problem related to charging a paver is segregation, whether physical or thermal. As stated previously, physical segregation results in some aggregates not being properly coated with asphalt binder. An example of physical segregation is found in Figure 2. This figure shows a thermal image of a pavement with the telltale signs of end-truck segregation. The segregated areas (lighter color) shown in the figure are more prone to moisture damage as a result of displacement, detachment, or hydraulic scour because this type of segregation leads to thinner asphalt binder films.

Thermal segregation has been around for many years; however, the thermal imaging cameras have only recently identified this potential problem. Thermal segregation occurs during the transportation of mix to a project site. During transportation, the mix cools within the back of trucks, unevenly leaving a crust of cooler mix on top. This crust travels through the paver and leads to cool spots interspersed within warmer spots (see Figure 3*a*). The cooler spots of mix are more difficult to compact under the roller and in some cases will cause the roller to bridge over the warmer mix. This situation will lead to locations with lower density and, thus, potential permeability problems. A possible solution to this thermal segregation is to use a material transfer vehicle, or other suitable device, that remixes the HMA before going into the hopper of the paver. Another option would be to use insulated trucks that help prevent temperature loss. Figure 3*b* shows the thermal properties of a pavement when proper remixing is accomplished.

Compaction of HMA

Once placed on the roadway, the mix is rolled to achieve a desirable in-place density. This step in the construction of a properly designed and produced HMA is likely the most important in obtaining a pavement that will resist moisture damage. For dense-graded mixes, numerous

FIGURE 2 Thermal image of pavement with end-truck segregation.



(a) (b)

FIGURE 3 Thermal images of pavement: (*a*) with thermal segregation; (*b*) without thermal segregation.

studies have shown that initial in-place air void content should not be below approximately 3% or above approximately 8%. Low in-place air voids have been shown to result in rutting, bleeding, and shoving, while high air voids lead to permeability problems such as moisture damage or excessive oxidation of the asphalt binder. (It should be noted that some of the "rich bottom" mixes that are being used as fatigue-resistant layers at the bottom of structural sections have very low air voids by design. Because of their location in the designed structure, they are not subject to shoving, rutting, or bleeding.) From a moisture damage standpoint, permeable pavements allow water to infiltrate into the pavement and lead to moisture damage by any of the five mechanisms discussed previously.

The permeability of HMA pavements has become a continuing issue discussed in the HMA community, especially with the introduction of Superpave and SMA mixes in the 1990s. A survey by Brown et al. (*9*) suggested that coarse-graded Superpave mixes seem to be more permeable than conventional dense-graded mixes (Marshall or Hveem designed) at similar in-place air void contents. Work by Westerman (*10*) and Choubane et al. (*11*) using a laboratory permeability device showed that coarse-graded Superpave mixes became permeable when in-place air void contents were more than 6%. The National Center for Asphalt Technology has several reports on the effect of in-place air voids on permeability (*12–14*).

There are several factors influencing the interconnectivity of the air voids, and hence permeability, in compacted HMA pavements. Work by Mallick et al. (*15*) and Cooley et al. (*14*) showed that nominal maximum aggregate size (NMAS) (Superpave definition) has a great influence on the permeability characteristics of a pavement, at a given in-place void content (see Figure 4). By an increase in the NMAS, the size of the individual air voids increases, which results in a higher potential for interconnected air voids. Hainin and Cooley (*16*) have investigated the effect of lift thickness on permeability (see Figure 5). The results suggested that as lift thickness increases, permeability decreases for a given mix and in-place air void content. A thicker lift reduces the chance of interconnected voids.

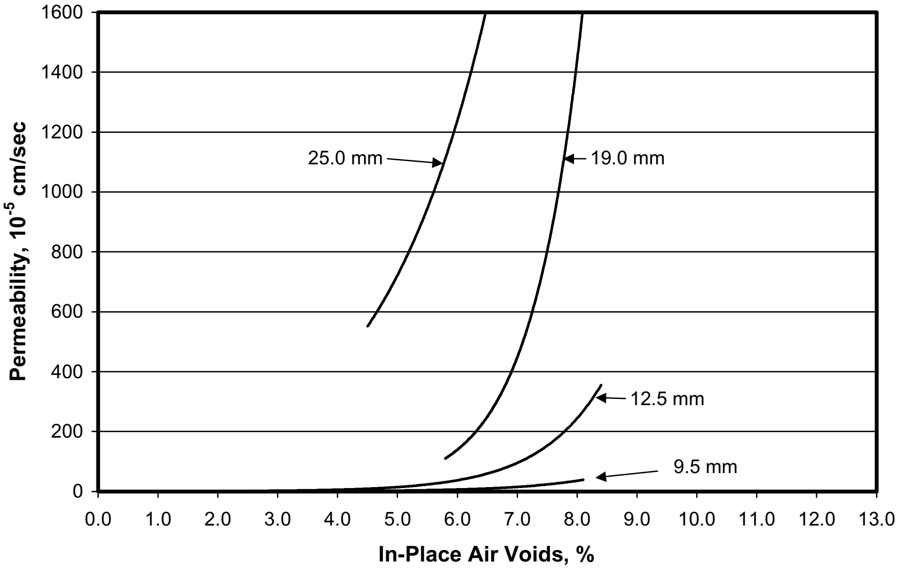


FIGURE 4 Impact of nominal maximum aggregate size on permeability (*15*).

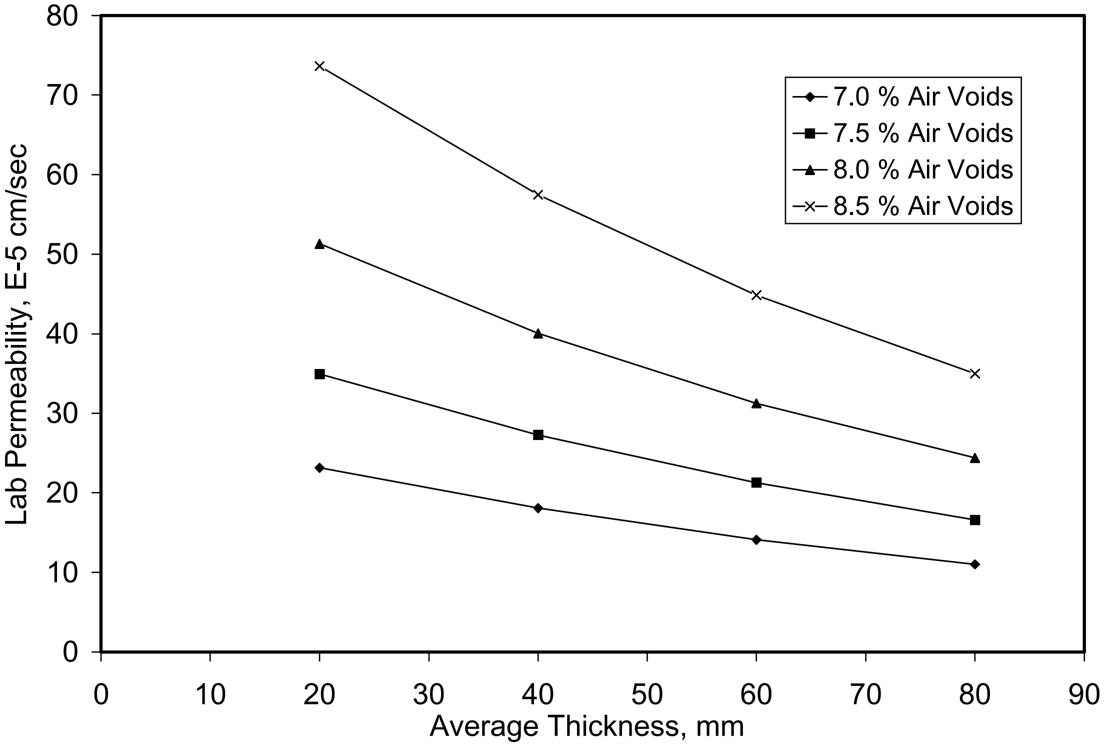


FIGURE 5 Effect of lift thickness on permeability (*16*).

In a recent study at the National Center for Asphalt Technology (*16*), 42 ongoing HMA construction projects were investigated with respect to permeability. A total of 354 cores were obtained from the 42 different Superpave projects. Of the 42 projects, 13 projects used a 9.5-mm NMAS gradation, 26 projects used a 12.5-mm NMAS gradation, and 3 projects used a 19.0-mm NMAS gradation. Laboratory permeability tests were conducted on each core in accordance with ASTM PS 129-01, Standard Provisional Test Method for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter. This method uses a falling head approach in measuring permeability.

The results indicated that in-place void content was the most significant factor affecting the permeability of Superpave pavements (see Figure 6). Other factors having a significant impact on permeability were percent coarse aggregate in blend (i.e., fine- or coarse-graded), percent passing 12.5-mm sieve (defining NMAS in data set), percent passing 1.18-mm sieve, design compactive effort (N_{des}), and lift thickness. As the values of percent coarse aggregate in the blend, percent passing 12.5- and 1.18-mm sieves, and N_{des} increased, permeability increased. For coarse-graded Superpave designed mixes, as the coarse aggregate ratio (ratio of coarse aggregate to fine aggregate as defined by the 4.75-mm sieve) approached 1.0 or higher, permeability increased significantly. Also, permeability decreased as lift thickness increased.

From a moisture damage standpoint, it is obvious that a permeable pavement increases the potential for stripping (unless the pavement is designed to be permeable like OGFC). A pavement that is permeable allows the water to penetrate into the pavement. Once the water

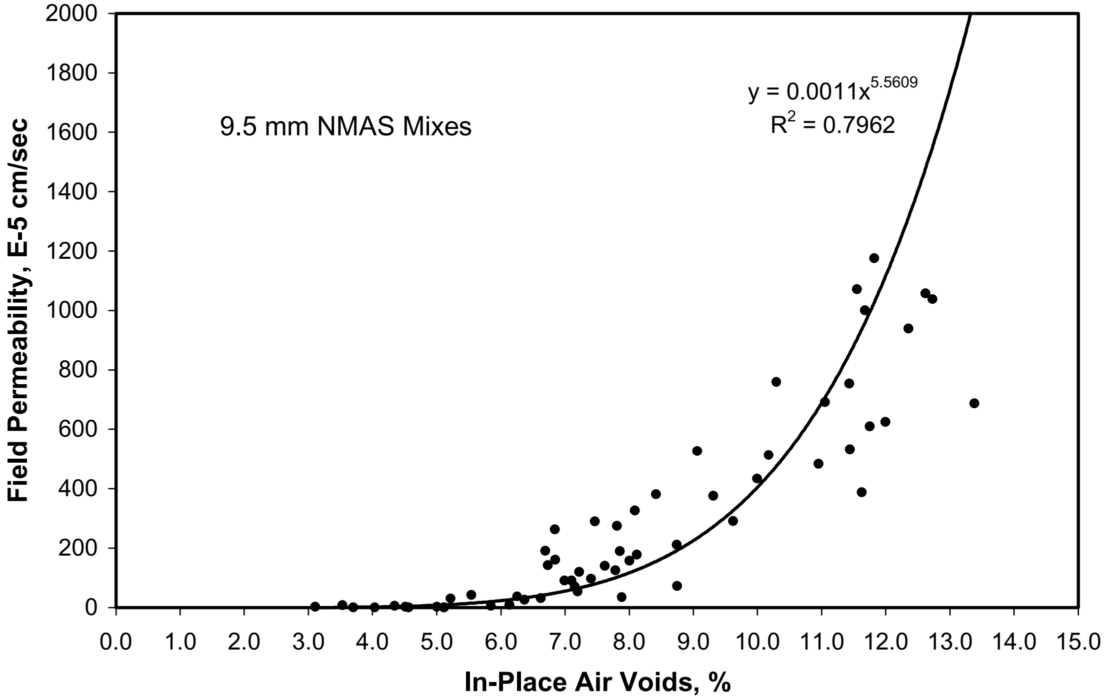


FIGURE 6 Relationship between permeability and in-place air voids (*14*).

penetrates into the pavement, moisture damage can occur from any of the five mechanisms of failure.

The area of the pavement that is likely the most susceptible to allowing water into the pavement structure is a longitudinal joint. Allowing water to penetrate into the pavement can prematurely distress the pavement at longitudinal joints (see Figure 7). Some unpublished work conducted at the Virginia Transportation Research Council used a field permeability device to track the changes in permeability across the joint. Field permeability tests were conducted 18 in. on either side of the joint, 6 in. on either side of the joint, and over the longitudinal joint. Figure 8 illustrates how permeability changed across the joint. Typically, longitudinal joints are constructed to a lower density than is the mainline pavement. This lower density at the joints is a result of compacting unconfined edges, not properly pinching the joint with the roller, and so forth. Figure 8 clearly illustrates that the mainline roadway (18 in. on either side of joint) had much lower permeability—hence, higher density—than at the joint. At 6 in. on either side of the longitudinal joint, the permeability is also higher than within the mainline. This region of low density near the joint is the primary area where water can infiltrate into a pavement.

Another factor related to moisture damage when compacting HMA is excessive rolling or the use of rollers that are too heavy. Either factor may cause fracturing of the aggregate. Again, in the presence of water, the fractured aggregate can absorb water and lead to displacement of the asphalt film.

FIGURE 7 Distressed longitudinal joint.

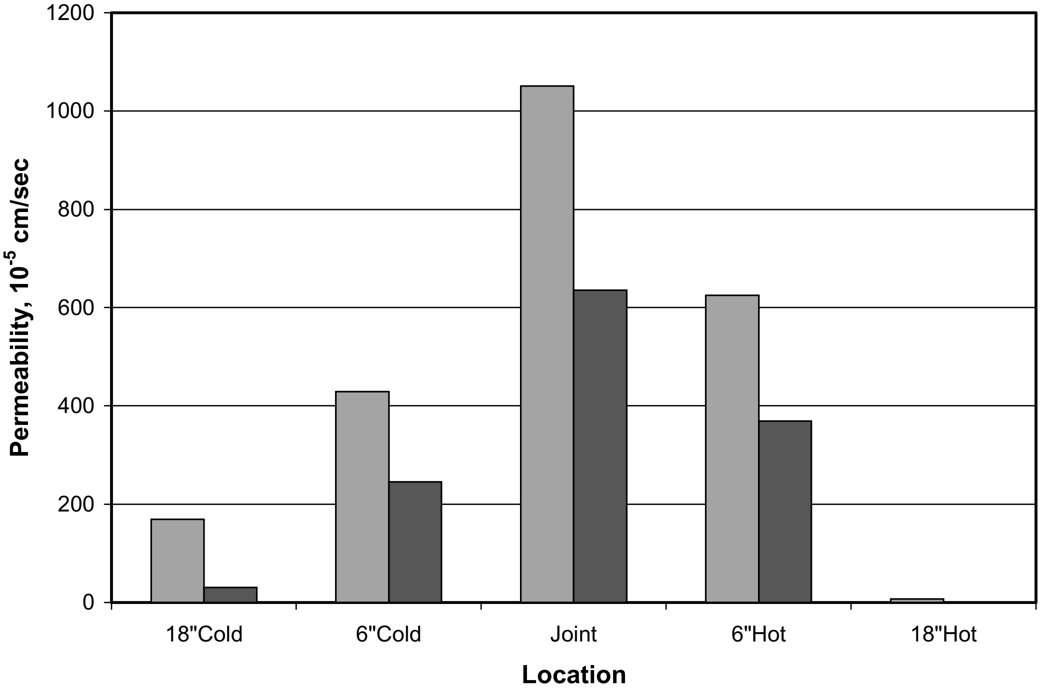


FIGURE 8 Change in permeability across a longitudinal joint.

Other Construction Issues

Several other construction issues warrant discussion. With regard to paving conditions, factors such as ambient and base temperature should be monitored. If either is too low, obtaining the proper density may be difficult.

Pavements should always be constructed on stable bases. A stable platform is needed so that the compaction energy provided by rollers is provided to the HMA layer being compacted.

Next, pavements should maintain a sufficient cross slope to ensure that water does not pond on the surface. If water does not flow off the pavement, there is a greater potential for the water to infiltrate the pavement, increasing the potential for moisture damage.

SUMMARY

The construction and production processes for HMA can have a profound effect on how a pavement will perform with respect to moisture damage. During production, a number of issues should be carefully controlled to help ensure an HMA that is resistant to moisture damage. Aggregate stockpiles must be properly built and maintained to prevent segregation. The plant operator must account for the moisture content of the aggregate stockpiles. If the moisture content is too high, then the production process should be slowed to allow for complete drying of the aggregates. Moisture left in the interstitial pores of the aggregates creates a potential for detachment of the asphalt binder film. Also during production, close control of the materials should be conducted. It is also important during the production process to ensure that all aggregate particles are properly coated with asphalt binder. Aggregates not properly coated can absorb water and thus lead to an increased potential for moisture damage. As always, good production practices with a good quality control program should always be used to ensure that a high-quality HMA reaches the roadway.

From a construction standpoint, there are two primary issues that must be closely controlled. First, segregation of the mix should be minimized. This includes both physical and thermal segregation. Numerous studies have shown that segregation can reduce the anticipated life of a pavement. The use of equipment that remixes the HMA before charging the paver hopper helps to minimize both physical and thermal segregation. The second construction issue is the proper compaction of the mix on the roadway. Compaction should be conducted in such a way that the mixture reaches the desired density and the aggregates within the mix are not excessively fractured. Longitudinal joints must be closely monitored to ensure that they are compacted properly.

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TOPIC 6

Questions and Answers

L. ALLEN COOLEY, JR.
National Center for Asphalt Technology, Speaker

Q1—Steve Healow, Federal Highway Administration, California Division
I have a question on your infrared images. They look like they were from Washington State and I find them compelling. I wonder if you can elaborate on the first slide and the third slide. The first slide was where you had the heterogeneous mat; there was thermal segregation all over the place, whereas on the third slide, there was no thermal segregation. It looked pretty homogeneous for the entire mat. What was different about those two processes? Was it the same contractor and was his level of effort different between those two images? What was the contractor doing in the first image to maximize his thermal segregation and what was done in the third image to minimize thermal segregation?

A—Allen Cooley
I don't know a good answer. Those slides were from a NAPA training presentation. My guess, knowing a little bit about what's going on with the thermal imaging, is that the first slide was a worst-case scenario, long haul distance, no material transfer vehicle, and so forth—all those types of things. And the last slide was probably where the material transfer vehicle that remixed the mix was used. That way you are getting a more uniform temperature within the mat.

Q2—Carl Monismith, University of California, Berkeley
Allen, I noted that neither John D'Angelo's presentation nor yours included anything about the actual mixing process, the mix production. It seems to me that this could be a problem also. Again, I'll show my age. I grew up in an era when batch plants were generally the way to produce hot mixes; moisture content in batch mixes was controlled to less than ½%. I am wondering if part of our problem, at times, comes about because there may be less control of the moisture in the aggregate at the time of production in the widely used drum plants. This certainly could lead to moisture sensitivity problems. Thus, I would hope that people might discuss this in the breakout session concerned with production.

A—Allen Cooley
I agree 100% and that's a little bit my fault, because when I saw the title of John's presentation, I thought he was going to cover it, and he probably thought I was going to cover it. In our paper, we do discuss moisture contents of the aggregates. We know if you leave the moisture in the aggregate, there is a higher potential for the displacement of the film, which can lead to moisture damage. That is contained in our paper.

Q3—Dave Newcomb, National Asphalt Pavement Association
On your distribution of air voids on projects, it is really like you said, disheartening to see such low densities, and low density is a precursor to distresses. Has anybody followed up to actually quantify how many of those pavements or what the condition of those pavements actually are?

A—Allen Cooley
We are in the process of doing that. As part of NCHRP 9-9 (1), which is the research study to evaluate the design gyration levels within Superpave, we are actually going back and coring each one of the 40 projects. Obviously, we got density at the time of construction, but we are also obtaining cores after 3 months, 6 months, 12 months, and 24 months. At 24 months, we are doing a performance evaluation. There's talk with the project panel that we may also obtain 4-year cores to take a look at densification, which is what we need for the design gyration level stuff. But at that time period, if it's extended to the fourth year as well, we will do another performance evaluation and have that type of information.

Q4—Roger Smith, Consultant
We often hear the term "first line of defense" applied to density and achieving density in our mat. I think that maybe that's the second line of defense once you're out there paving. One thing I've seen from my experience, especially in private work and especially at city/county level, is overlay work done without regard to reestablishing cross slope on the surface of the pavement so the water drains off the pavement. I think it's very important for the agencies, whether it be the state or the local agencies, as part of their overlay design and project, to really ensure that they are taking that opportunity of the overlay to reestablish cross slope.

A—Allen Cooley
That's a very good comment, thank you. Any more questions?

Q5—Gerry Huber, Heritage Research Group
A couple of comments, Allen. The one thought that went through my mind when you showed the tapered longitudinal joint, I thought right back to your comments about permeability. I know one of the concerns of some of the folks who are using those is getting density into them and that you end up with a 12-inch-wide strip that's very low on density. Just a comment.

A—Allen Cooley
I wasn't pushing that particular method. What I was doing was saying there's new technology. I think you're absolutely right. There is some low-density stuff. Besides the notched wedge, there are different materials that you can put on the joint to try and limit some of the permeability issues and stuff like that. I was solely saying there are some new technologies but we need to go farther as well.

Q6—Gerry Huber, Heritage Research Group
That's pretty much what I thought you were saying. I just thought I'd raise it as a point for the audience. Then the last thing is dealing with the pictures of the thermal segregation. One of the things I've trained myself to do whenever I see those pictures is immediately look at the scale on the side of the picture, because the tighter the range on the scale, the more blotchy it ends up looking. The botchy slide has a bottom end of 200 degrees and the other slide has a bottom end of 80 degrees. That may be the reason why the second and third slides may have ended up disguising some of the blotchiness, or the first one enhanced it either way.

A—Allen Cooley
May have.

Q7—Mansour Solaimanian, Pennsylvania State University
Good presentation, Allen. I think what you talked about in terms of permeability is very important. What you mentioned was that you could have basically the same air void and different nominal maximum sizes and get different permeabilities. I think that is probably one of the reasons why we cannot find a good match between our laboratory results and pavement performance. We always emphasize that you must get your air void level within the given range in the laboratory and conduct your partial vacuum saturation and you get 50% to 60% or whatever saturation level for the same air void level for two different mixes. We then conduct the test and we come up with either pass or fail. Now we put those mixes in the field and we see totally different behavior even at the same level of voids, because they have different void sizes and permeabilities. So I think any test method that works with the laboratory air voids in terms of establishing criteria should really look at permeability as one of the factors that contributes. That is one of the things that we are going to look at in Phase 2 of NCHRP 9-34. Rather than just emphasizing that you should get a specific air void level and do your test, maybe we should say because of different void structures, you should look at the permeability and go from there.

A—Allen Cooley
I agree wholeheartedly. Just as another comment on that, Kevin Hall had a paper a couple of years ago. He came up with a test to evaluate the air void pathway within samples. If I remember right, when he looked at lab samples, basically what he found is all of the flow is coming out the side of the sample. When you looked at field samples, all the flow was going through the samples. What we're seeing is the density gradient within the lab-compacted samples. That's another piece of the puzzle along with the permeability. We need to take a look at both of them at the same time when we look at a laboratory moisture damage test.

TOPIC 7

Field Experiences

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).

Proposed Environmental Risk Region Map 2002

Risk
Red = High
Yellow = Moderate
Green = Low

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).

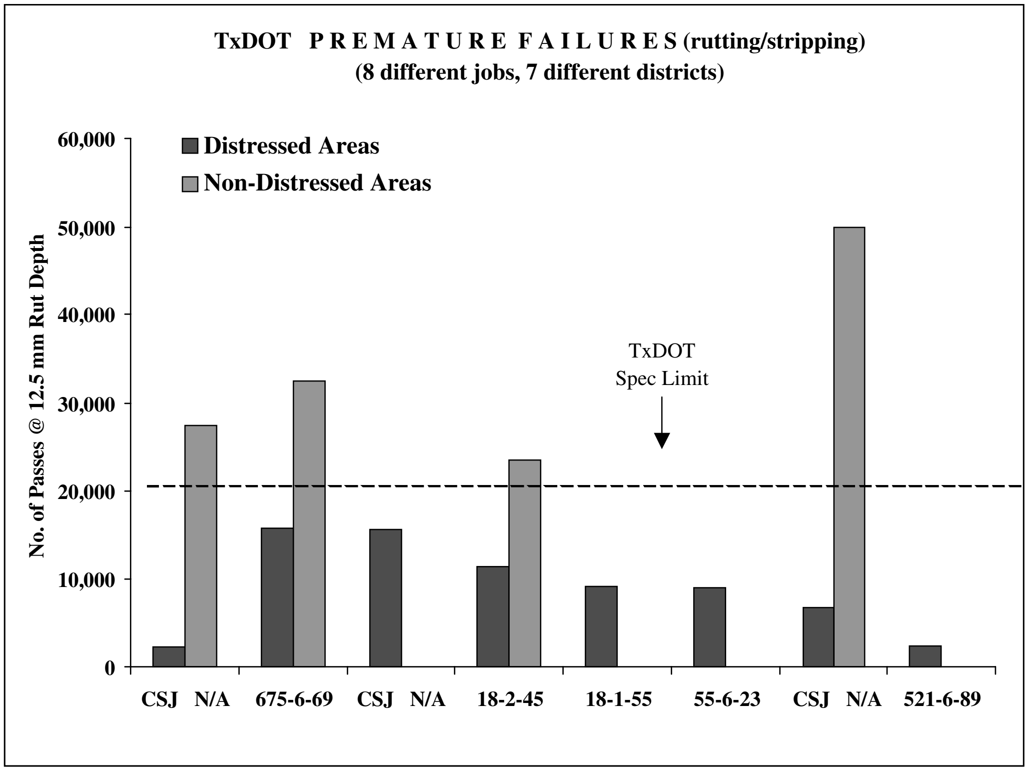

FIGURE 2 TxDOT premature failures predicted by the HWTD.

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.

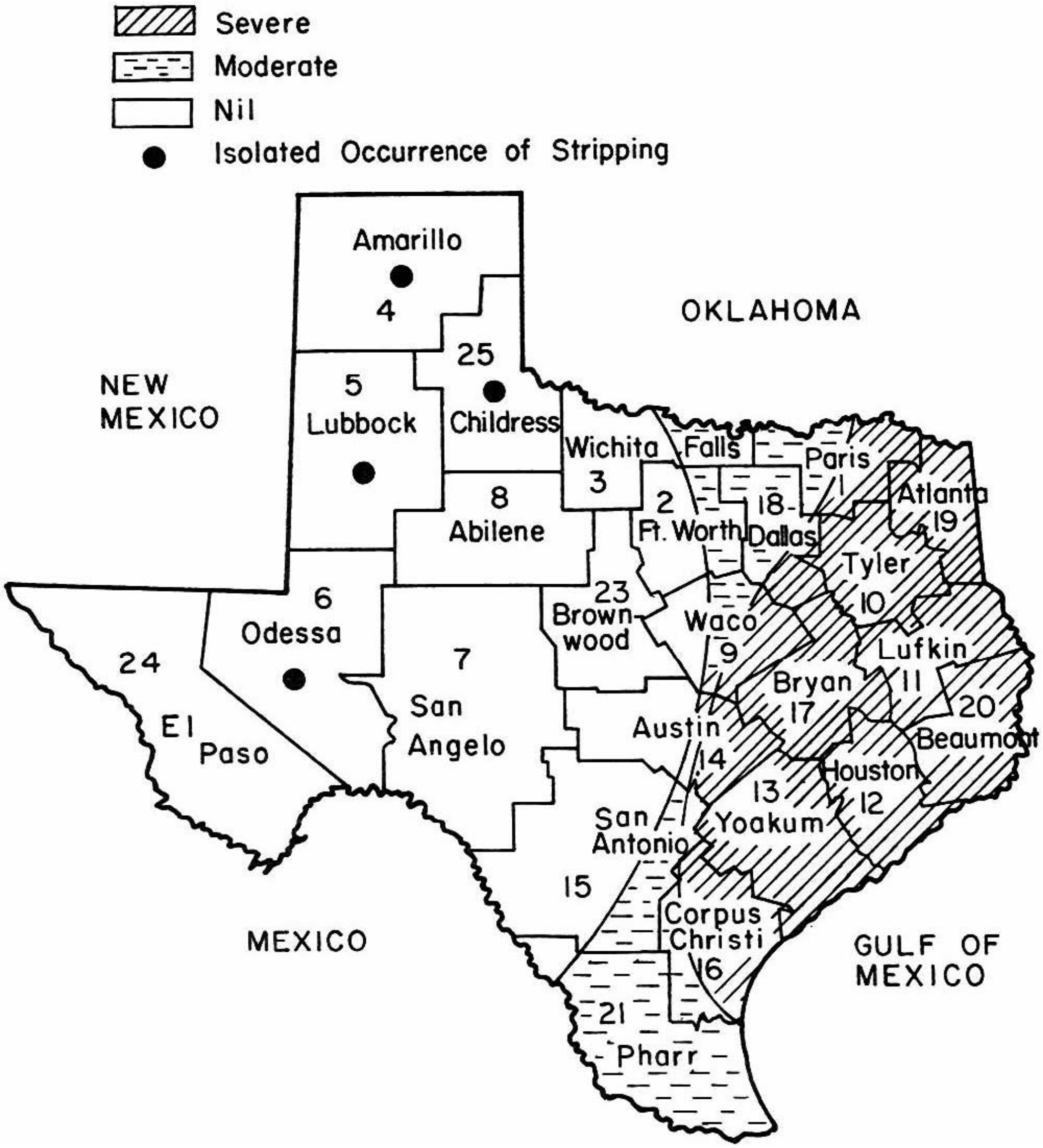

FIGURE 3 Extent of moisture damage in Texas (*11*).

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*)

	Boiling Test	Lottman Test
Stripping Potential of Mix	Uncoated Aggregate Surface	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^{0}C to 0.5-in. Rut Depth
PG 64	10,000
PG 70	15,000
≥ 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

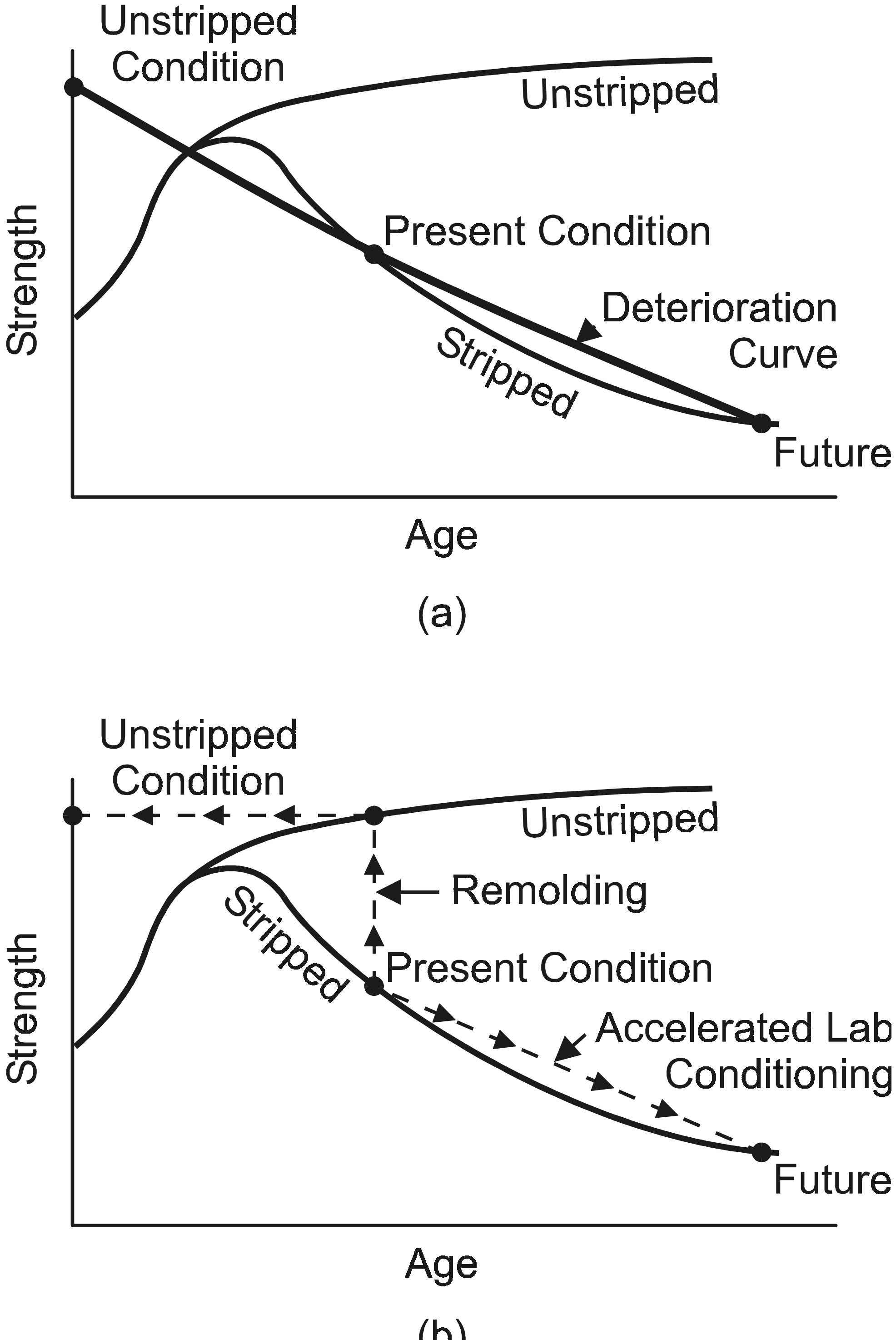

FIGURE 5 Development of the VDOT deterioration curve.

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.

TOPIC 8

Specifications to Control Moisture Sensitivity Problems in Asphalt Pavements

TOPIC 8

Specifications to Control Moisture Sensitivity Problems in Asphalt Pavements

Rita B. Leahy
MACTEC (formerly Law Crandall)

Michael C. Cook
California Department of Transportation

[Editor's note: the final paper from this presentation was not available for publication.]

TOPIC 9

Implementation and Strategic Plan

TOPIC 9

Implementation and Strategic Plan

JAMES S. MOULTHROP
Fugro-BRE, Inc.

JOE W. BUTTON
Texas Transportation Institute

FREDERICK D. HEJL
Transportation Research Board

Moisture sensitivity of hot-mix asphalt (HMA) paving mixtures is one of the leading pavement performance-related issues facing highway agencies. Most agree that the current test protocols for identifying moisture sensitive mixtures do not accurately predict actual field performance. It appears desirable to assemble a group of knowledgeable and experienced personnel from highway agencies, academia, and industry, and to conduct a workshop to develop a strategic plan to address this issue.

Clearly, one of the most important aspects of any study or effort is disseminating the results to practitioners. The objective of this seminar is no different. A number of different agencies will be represented at the seminar, and the goals of disseminating the findings are to

1. Emerge from the meeting with an understanding of the best practices for identifying moisture sensitive asphalt mixtures currently being used in the United States,
2. Understand the barriers that exist in eliminating the moisture damage problem,
3. Identify relevant research needs so that knowledge gaps can be studied and conquered, and
4. Develop a strategic plan for administering the required research and implementing the findings.

BEST PRACTICES

A survey dated August 2002 (*1*) of 50 state departments of transportation, 3 FHWA federal lands offices, the Washington, D.C., Department of Transportation, and 1 Canadian province indicates that 45 of these agencies have identified a potential moisture damage problem with their flexible pavements and specify some type of treatment to mitigate the problem. More than one-half use a liquid antistrip material, 30% use lime, and the remainder use one or the other.

Forty-eight of the 55 agencies responded that they perform tests on the mix at some point in the mix design and construction process to determine the need for and suitability of the antistrip material. The types of testing include tensile test (AASHTO T283, ASTM D4867, or similar), compressive test (AASHTO T165 or similar), retained stability, and wheel tracking in combination with tensile testing. Sixty-two percent test for moisture damage during the mix design phase only, whereas 38% test during the mix design and during construction.

This review indicates that considerable effort is expended in attempting to control or eliminate moisture damage, but it also illustrates the number of different approaches to solving the problem. One might ask this question: Has any agency solved the problem with the approach it has taken? The identification of procedures and processes that are successful, so that others may implement them, is an essential outcome of this meeting and the first goal of the seminar. Specific test methods, specifications, and protocols that work need to be identified and documented so that the final report contains this information. Also, the Asphalt Institute is developing a document on best practices to help deal with the problem of moisture sensitivity.

IDENTIFY GAPS IN KNOWLEDGE: BARRIERS

Although 45 agencies perform some type of testing during the mix design and production processes, 11 agencies are performing some type of research to better understand the phenomenon of moisture damage. Specific projects target

- Understanding the chemical nature of the problem,
- Refining existing procedures,
- Developing an improved procedure, and
- Correlating laboratory testing to field performance.

This finding suggests that there are agencies that acknowledge that existing procedures have not been successful or do not meet the agencies' expectations. This is also true at the national level, where both FHWA and NCHRP are sponsoring work to better understand the important design and construction issues as well as methods for eliminating the problem.

Are these gaps in knowledge the result of a lack of understanding of the phenomena, or the result of inability to actually accomplish the process or procedure? The second goal of the workshop is to identify gaps in knowledge of moisture damage and to prepare plans to fill in these gaps with studies that will help us better understand the process and develop and implement procedures to solve the problem. The activity should be done by using or developing proven test methods that identify those factors that lead to moisture damage.

IDENTIFY RESEARCH NEEDS

In June 2001, a number of practitioners representing state highway agencies, academia, and industry met in Sacramento, California, to discuss research needs in the area of pavement preservation (*2*). Although not specifically identified as a research need, moisture damage was considered as part of the overall performance of pavement preservation treatments.

TRB committees A2D03, Characteristics of Bituminous-Aggregate Combinations to Meet Surface Requirements, and A2D05, General Issues in Asphalt Technology, have solicited problem statements from committee members and others, and they currently have statements dealing with moisture damage in the queue to obtain some type of funding.

The third goal of the seminar is recognizing that there are gaps in the knowledge of moisture damage that exist and to identify research required to understand the problems and provide solutions.

In the approach to research needs, consideration should be given to new, promising methods, such as surface energy measurements. Some of these new methods may be quicker and less variable than some of the current tests being used. Further evaluation of torture tests may hold some promise. Performance-based tests that are repeatable and reliable are needed.

The effects of design, production, and construction practices, including quality control, may be a practical issue to address at the seminar. Many pavements are constructed and accepted with air void levels that significantly exceed specified limiting values. Moisture may weaken the asphalt aggregate bond in these pavement layers and expose them to successive damage by moisture, even though they are subsequently compacted to acceptable air void levels by traffic. With the advent of vibratory rollers, many have abandoned the use of pneumatic rollers, which may do a better job of sealing the surface of a compacted HMA mat.

The fourth goal of the seminar is, once these items have been identified, to ask participants to prepare problem statements in standard TRB format (*3*) for each issue and include them in each breakout session strategic plan.

CHALLENGES AND EXPECTATIONS

Challenges for Seminar Participants

There are several challenges to the seminar participants. They include the following:

- Is it reasonable to expect that the moisture damage problem can be solved? Since the late 1970s, a number of studies have been carried out in an attempt to define, understand, evaluate, and mitigate moisture damage. Two of the most notable studies were carried out under the sponsorship of NCHRP and resulted in the publication of NCHRP Reports 192, 246, 274, and 373 (*4–7*). In Report 246, the author recommended the use of a test procedure that is currently known as AASHTO T283. As noted, at least four different test methods are currently being used by agencies to aid them in predicting moisture damage. This indicates that there is no universally accepted method for the determination of moisture damage.
- Can a strategic plan be developed to solve the problem? Like any focused endeavor, a strategic plan for solutions of the moisture damage problem appears to be the most effective approach. Developing a plan that concentrates on the desired outcome, incorporates all the known variables, and attracts the most talented people to undertake the effort seems advisable. A well-designed experimental plan should be part of any plan, so that it will have a successful outcome.
- If the answer is yes to the two foregoing questions, then what is expected from the breakout sessions? After pondering those two important questions, and presuming that the answer is “yes,” the breakout groups will be challenged to discuss the issues relating to specific moisture damage topics, debate the pros and cons of various approaches, and prepare a strategic plan on how best to evaluate and solve the moisture damage problem.

Charges to Breakout Session Participants

Specific charges to the breakout participants include the following:

- Be proactive and participate in the discussions. To attack and solve the moisture damage problem, the best ideas are necessary. Come prepared to discuss the pertinent problems and offer your opinions on how best to solve them.
- Think “outside the box” for solutions. Using strategies from other industries or experiences can be very helpful in taking a nontraditional approach to problem solving.

- Respect others' opinions even though you do not agree with them. This is an essential component of the democratic process. Synthesizing the best ideas can happen only when all ideas are on the table.
- Begin with an objective and establish goals. Most effective plans begin with an objective that provides a beacon to direct our undertaking. Goals provide the mileposts during the planning process to keep us on target and permit us to measure our accomplishments. A fundamental research approach is required to understand the physical and chemical phenomena that contribute to moisture damage and to lead to a viable solution to the problem. If the fundamental test protocols require expensive test equipment and highly specialized experts to interpret resulting data, they may be unsuitable for routine specification testing. But gaining a fundamental understanding of the problem is essential for developing a practical specification test and acceptance criteria.
- Prepare an action plan to accomplish goals and objectives. The overall objective of the breakout sessions is to provide the contract team with sufficient information to prioritize problem statements and research areas. The ultimate goal is to obtain funding to complete the necessary studies to solve the HMA moisture damage problem.

FRAMEWORK FOR CONDUCT OF THE BREAKOUT SESSIONS

Four concurrent breakout sessions will be held. They are Fundamentals, Testing and Treatments, Design and Specifications, and Construction and Field Performance. Each session will have a facilitator and note takers, whose challenge will be to direct and focus the discussion and prepare a record of the salient discussions.

Expectations from the Breakout Sessions

Each facilitator should encourage discussions that address the following deliverables of the seminar:

- Identify best practices.
- Identify gaps in knowledge and barriers to progress.
- Identify research needs.
- Prepare a strategic plan for the future.

Adequate facilities and aids will be provided to assist the facilitator and note takers. It is expected that each breakout session will be somewhat different in style but the final outcome of the discussions will be in the same format to facilitate the preparation of a final summary of the seminar.

Specific Questions

Specific questions that need to be discussed at each session were noted earlier in the "Introduction and Seminar Objectives" presentation, but they are repeated here for convenience. These questions are meant to help focus discussion and are not intended to be all-inclusive. It is critical that the facilitators set the boundaries, or scope, of each session. With limited time, it is important to minimize overlap and use the time available most efficiently.

- Session 1: Fundamentals
  - What are the mechanisms causing moisture-related distress?

  - Are there procedures available for identifying moisture sensitive aggregates and asphalts?
  - What are the major gaps in the knowledge?
  - What fundamental issues still need to be addressed?
- Session 2: Testing and Treatments
  - What test method is best for identifying moisture-related problems? What relates to field performance?
  - Are improvements still needed to existing test methods?
  - How effective are the various additives, and processes for adding them, in minimizing the effects of moisture?
  - Is there documented evidence on how they affect pavement life? If not, why not?
  - What issues still need to be addressed?
- Session 3: Design (mix and pavement) and Specifications
  - What mix design procedures and properties are most effective for controlling moisture-related problems?
  - What items in the specifications should be controlled to minimize problems?
  - Are we considering all the major factors in design and specifications? If not, what additional factors need to be considered to minimize the effects of water on the asphalt pavement?
- Session 4: Construction and Field Performance
  - How do we distinguish moisture-related distress from distress related to construction problems?
  - What construction issues need to be controlled to reduce moisture problems?
  - What has worked and what has not worked in the field?
  - What information is needed to make better decisions when it comes to preventing moisture-related distress?
  - Should permeability be a consideration?

CONCLUSIONS AND RECOMMENDATIONS

Summary of Breakout Sessions

At the conclusion of the seminar, each of the facilitators will make a presentation summarizing the discussions of each workshop using the format presented in the attachments section at the end of this paper.

Strategic Plan for the Future

As a result of the seminar, a strategic plan will be developed by the project team and will consist of the following essential elements. It is envisioned that this plan will be directed to FHWA, TRB, NCHRP, and AASHTO for consideration for future research and development funding. Elements of the plan are as follows:

- Introduction
- Objectives and goals of the national seminar
- Organization of the seminar and breakout sessions
- Summaries of the breakout sessions

  - Best practices
  - Knowledge gaps and barriers to progress
  - Research needs
- Identification and prioritization of significant needs from each breakout session
- Discussion of resources needed to address these needs, along with research problem statements that can be readily used in the research community
- Time line with milestones to track the progress of solving these needs
- Conclusions

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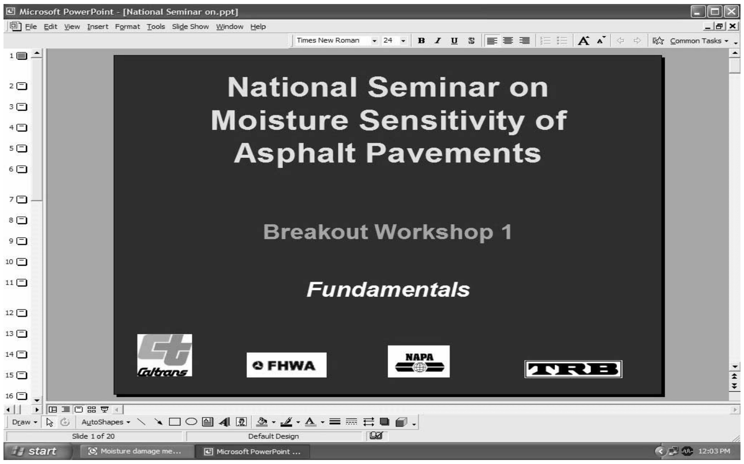
ATTACHMENTS

Presentation Format

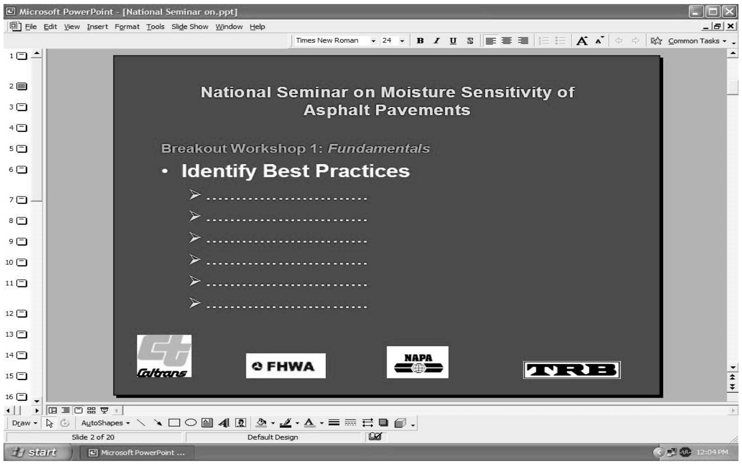
The following PowerPoint slide formats will be used during the final seminar session so that the presentations will be easier to follow and the development of the strategic plan will be more uniform.



National Seminar on
Moisture Sensitivity of
Asphalt Pavements

Breakout Workshop 1

Fundamentals



National Seminar on Moisture Sensitivity of Asphalt Pavements

Breakout Workshop 1: *Fundamentals*

- Identify Best Practices
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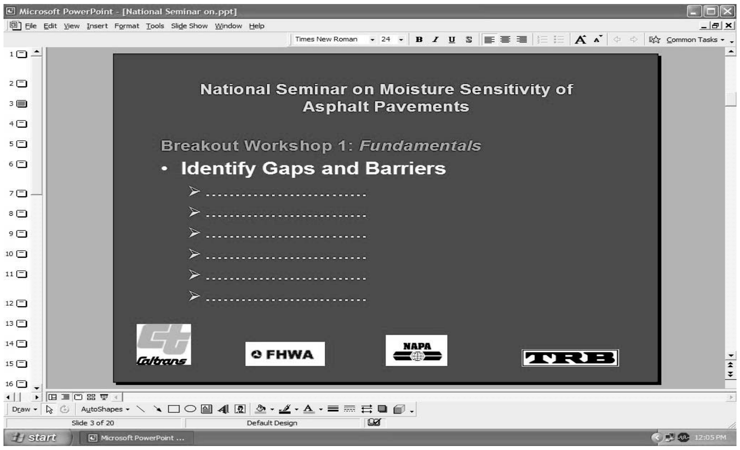

National Seminar on Moisture Sensitivity of Asphalt Pavements

Breakout Workshop 1: *Fundamentals*

- Identify Gaps and Barriers
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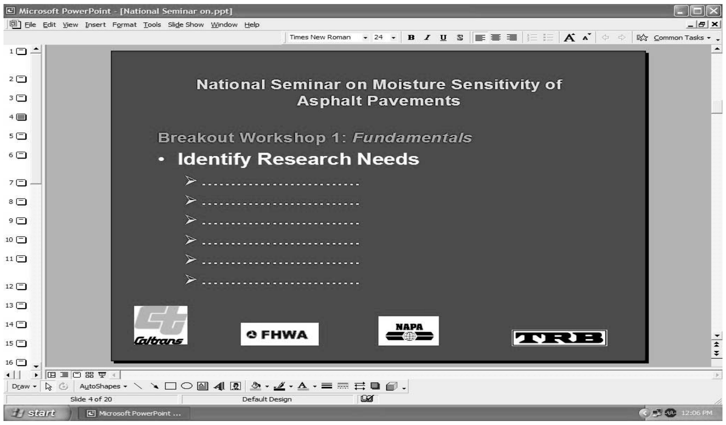

National Seminar on Moisture Sensitivity of Asphalt Pavements

Breakout Workshop 1: *Fundamentals*

- Identify Research Needs
  - ➢ ....
  - ➢ ....
  - ➢ ....
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  - ➢ ....
  - ➢ ....

Problem Statement Format

Problem statements that are developed by the workshop participants should use the following format followed by TRB standing committees.

I. PROBLEM TITLE

A suggested title, in as few words as possible.

II. RESEARCH PROBLEM STATEMENT

A statement of general problem or need—one or more paragraphs explaining the reason for research. Be explicit about how the intended research product will be used and by whom.

Note: A TRIS online literature search (ntl.bts.gov/tris) is encouraged to avoid duplication with existing or past research. If a literature search is performed, general comments on the results should be provided.

III. RESEARCH OBJECTIVE

A statement of the specific research objective, defined in regard to the expected final product, that relates to the general problem statement. Define specific tasks necessary to achieve the objective.

IV. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding

An estimate of the funds necessary to accomplish the objectives. As a general guideline, the present cost for research usually averages between $150,000 and $200,000 for 100% of a professional employee's time per year. Such an amount represents a fully loaded professional rate that would include an individual's direct salary and benefits and an agency's overhead or indirect costs. Average rates for supporting staff might be approximately one-half those of professionals. Depending on the type of research, the estimate should be modified for any unique expenses, such as the purchase of materials, extensive physical testing or computer time, and extraordinary travel.

Research Period

An estimate of the number of months of research effort, including 3 months for preparation of a draft final report, necessary to the accomplishment of the objectives as mentioned.

V. URGENCY, PAYOFF POTENTIAL, AND IMPLEMENTATION

Statements concerning the urgency of this particular research in relation to highway transportation needs in general and the potential for payoff (couched in benefit/cost terms if at all possible) from achievement of project objectives should be given.

A statement should be included that further describes the anticipated products from the research (e.g., recommended specification language, new instrumentation, or recommended test methods). The anticipated steps necessary for implementation of the research product should also be delineated.

Will an industry group have to adopt a new test method or revise its current practices or equipment? This information should be as specific as possible, noting particular documents that may be affected or techniques or equipment that may be made obsolete. Any institutional or political barriers to implementation of the anticipated research products should also be identified.

Example Problem Statement

I. PROBLEM TITLE

Minimizing Transportation Agencies' Liability Associated with Use of Contaminated Property

II. RESEARCH PROBLEM STATEMENT

Historically, transportation agencies have avoided using contaminated properties for project construction. Major concerns have been (*a*) increased costs and delays due to regulatory compliance requirements and, more significantly, (*b*) uncertainty about future liability. Recently, the federal government and state governments have initiated legal or administrative changes, or both, to encourage the cleanup and redevelopment of contaminated property (brownfield redevelopment). As the private and public sectors remediate abandoned, polluted properties and restore them to the economic mainstream, transportation agencies will be expected to play a cooperative role in providing access to these revitalized areas. The use of contaminated sites may offer transportation agencies the opportunity to acquire property at reduced costs. Technological advances and lesser remediation requirements reduce cleanup costs. However, despite changes in the regulatory climate and potential decreases in costs of cleanup, transportation agencies remain wary about the uncertainties of liability for future cleanup, for third-party suits, or for deposition of excavated construction materials. Guidance will help planners and design engineers determine the risk and opportunities of using brownfields.

III. RESEARCH OBJECTIVE

The objectives of this research project are to (*a*) define the degree of protection available to public transportation agencies under federal and state laws; (*b*) assess responsibility and defenses to third-party liability; (*c*) identify procedures to minimize liability when using contaminated property, such as engineering, land use, or other institutional controls; and (*d*) prepare a findings report that includes detailed examples of the most feasible methods for state departments of transportation and recommendations for transportation agency staff, including both legal and design professionals.

The following tasks will be performed:

1. Literature search. A review of current literature on these topics will be conducted with the awareness that changes in law are happening quickly enough that juried academic journals are likely to be somewhat behind the development of new government policies on such issues as natural attenuation of contaminated media.
2. Survey of agencies. A survey will be conducted, using written forms and interviews, to identify examples of current and anticipated lawsuits, policy development, and guidance documents that describe issues related to the use of contaminated property. Included in the survey will be questions on how agencies are handling the construction of utility trenches or other structures through contaminated media that may create preferential pathways for migration of contamination onto other properties.
3. Identification of methods to assess and minimize liability. Methods that are determined to be potentially successful, as revealed in the literature search and survey, will be identified. Steps will be evaluated and described, including (*a*) engineering controls, (*b*) land use restrictions or other institutional controls, and (*c*) risk assessment methods for evaluation of alternatives.
4. Preparation of report. A summary of findings will be prepared for the use of public transportation agency professionals. The report will include an assessment of the degree of variability of different states' laws that affect the usefulness of the information gathered.

IV. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Cost: $225,000. Duration: 18 months.

V. URGENCY, PAYOFF POTENTIAL, AND IMPLEMENTATION

Recent change in federal policy and in some states' policies encouraging use of brownfield contaminated properties makes it important that this study of liability be initiated immediately so that appropriate measures can be undertaken before contaminated properties are acquired or construction is initiated on them. Although it is difficult to estimate dollar savings, new policies would make it important that risks be defined and accounted for to avoid losses in the future.

TOPIC 9

Questions and Answers

JAMES MOULTHROP
Fugro-BRE, Speaker

Q1—Gayle King, Koch Pavement Solutions
One might perceive a division here into pro-Hamburg and pro-T283 camps. I hope everyone will read Tim Aschenbrener's CDOT reports and remember how he has used both tests in tandem. Tim has made great use of the Hamburg as a research tool to understand materials, as a forensic tool to evaluate premature stripping failures, and as a performance tool to award project bonuses. However, he has adapted T283 for daily specification control and relies on methylene blue to control clay. Of course, Dale Rand has taken the very big step of adopting Hamburg for all hot-mix specifications, but only after testing some 1,500 mixes to set performance limits and understand local materials. Let's put their findings and actions into perspective as it relates to Caltrans. The key decisions: $4.00 a ton to slurry lime, $2.00 a ton to use dry lime, $0.50 a ton for liquid antistrip or no additive for moisture resistance. That's up to $10 million to be spent on somewhat arbitrary decisions lacking best available information. If clay is the bad actor, methylene blue and Hamburg should be part of the decision process as to best practice, as Aschenbrener so clearly demonstrated when he used both to locate clay seams in a problem aggregate pit. If high clay content is the only reason to slurry lime, then methylene blue could serve as the single specification control to make that decision once relative damage risk is understood in the Hamburg. One other valuable reason to bring a Hamburg into Caltrans labs may be more political than scientific. Categorize this idea as a picture worth a thousand words. When a contractor is required to employ a more expensive alternative than a competitor's, serious heartburn ensues. Watching his favorite mix fall apart under the Hamburg wheel leaves an image that causes him not only to understand the problem, but makes him want to do better. Most important, he now has a tool, which enables him to isolate and resolve his own quality problems. There are many things that Caltrans can learn from the Hamburg that don't require changing specifications. Let's try not to divide into two camps, but recognize where both T283 and wet wheel-tracking tests can provide best value.

Q2—Tim Aschenbrener, Colorado Department of Transportation
A couple of comments. One, it would be a value to me, very soon if possible, if I could get a copy of the presentations that were done this morning. I don't know if that's something you can e-mail out to all the participants, because that is something I can start taking a look at and sharing with the folks back in Colorado right away.

A—Gary Hicks, MACTEC
I've instructed Dr. Leahy to get those out so they'll be out either tomorrow or early next week, depending on what else she has to do.

Q3—Tim Aschenbrener, Colorado Department of Transportation
A second thing: you mentioned a survey. I am wondering who the target audience for that survey would be. One audience might be all the states in the country 6 to 8 months from now. I'm not sure if that would really be the right audience. I might be curious if we surveyed all the people here, not just the people from Caltrans, but everybody here 1 year from now. Have you done anything differently? Changed a specification? Written a research problem statement? What have you done differently in the last year as a result of this? It wouldn't have to be a meeting. It could be a simple survey, and I'd be interested in one or two paragraphs or one or two pages written up about some of the things that happened as a result.

A—Jim Moulthrop
That is very doable and I think it is a very good idea.

Q4—Carl Monismith, University of California, Berkeley
I would like to just make a comment about Gayle King's comment. I don't believe that the discussions that took place will lead people to select this camp or that. If they have the information, they will make their own judgments. For example, the discussions we had yesterday in the session on tests and treatments were very healthy, particularly those related to tests. I would hope that Eric Berger, the cochairman of the session, would agree with me on this assessment.

SUMMARY REPORT:
BREAKOUT SESSION 1

Fundamentals

SUMMARY REPORT: BREAKOUT SESSION 1

Fundamentals

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Breakout Session 1 started at 10:00 a.m. with self-introductions and circulation of an attendance sheet (see the list at the end of this report). Brief technical presentations were scheduled. The facilitators proposed three primary modes of moisture damage to get the participants thinking:

- Chemical—bond/debond;
- Physical—rugosity, surface area, and absorption; and
- Mechanical—stone breaking and scrubbing, hydrostatic pressure.

The facilitators reminded the working group of its charge to accomplish the following tasks by the end of the day:

- Identify best practices.
- Identify gaps in knowledge and barriers to research and implementation.
- Identify research needs.
- Develop the strategic plan.

The following mechanisms and causes of moisture-related distress were identified by group brainstorming:

- Adhesive failure;
- Cohesive failure—asphalt weakens, aggregate dissolves;
- Binder aging—by oven, in-place over time, thermodynamic effects;
- Asphalt aggregate interface—changes over time, molecular reorientation;
- Binder stiffness—viscosity effect, use of modifiers;
- Trapped moisture in the pavement structure;
- Binder "film thickness";
- Asphalt emulsification—regular [asphalt cement (AC) in H_2O] and invert (H_2O in AC) (chemistry or mechanical working or both);

- Aggregate aging mechanisms? time frames from crushing to use in HMA? Highly siliceous aggregates may improve by aging;
- Lime aging—carbonation onto aggregate surface;
- Aging of moisture treatments in general;
- Salt in the binder—effects of sodium, calcium, potassium, and other mineral salts;
- Diffusion of moisture into asphalt binder;
- Mastic failure—sheds minus No. 200 and migrates;
- Filler (minus No. 200) issues;
- Clay and dust;
- Aggregate type/binder type—compatibility;
- Aggregate morphology—rugosity, shape, and so forth;
- Environmental effects—moisture, temperature, temperature differential, kinetics;
- Drainage—surface and subsurface;
- Water transport, including permeability;
- Mixture aging; and
- Modifier effects, including compatibility.

Issues identified during the discussion of each item listed above include the following:

- Multiple mechanisms: Moisture damage is often a result of multiple mechanisms rather than a single cause.
- Components versus system—Effects of incorporation into the mixture on component properties/behavior.
- Durability.
- False positives: Attributing problems to moisture damage that result from other causes, such as poor construction or durability issues. Can also apply to test results that indicate opposite result to that which occurs in service.
- Definitions.

Presentations and related discussions followed.

PRESENTATION 1

Ken Thomas, Western Research Institute

Ken reported on emulsion work at Western Research Institute (WRI) performed for FHWA, which addressed chemical effects of asphalt aging. When RTFO- or PAV-aged AC is dissolved in toluene and hand shaken with water, some asphalts form an emulsion and the pH of the water turns highly acidic. Aging AC at 80°C for 20 day ys changes sulfur components, increasing the concentration of alkyl sulfides. Ken reported a correlation of more than 90% between concentrations of sulfur/alkyl sulfide and strong acid in such asphalts, as detected by nonaqueous potentiometric titration. The sulfonic acids produced are organic analogs of sulfuric acid that attack and change the AC and dissolve aggregates.

Ken reported that the Strategic Highway Research Program asphalts and aggregates were tested for moisture resistance by coating a particular size fraction of each aggregate with 5% AC by weight. Researchers developed a matrix of selected materials treated with DBSA, a detergent compound containing sulfonic acid that lowers AC pH and acts as an emulsifier. DBSA reportedly artificially ages AC by adding sulfonic acid, which appears to promote moisture damage, owing to strong surfactant effects that are more pronounced than those of carboxylic acid. Lime may deactivate the acid by forming a nonionic compound, which might slightly offset the lime's effectiveness in resisting stripping. Ken suggested that on the basis of limited data at high acid concentrations, it may be the properties of aged AC that determine the moisture susceptibility of asphalt pavements.

PRESENTATION 2

Jack Youtcheff, FHWA, Turner–Fairbank Highway Research Center

Jack talked about work on permeability, solubility, water transport through an AC film, and the utility of the pneumatic pull-off test, which was developed on the basis of an adhesion coatings test apparatus. Test parameters were developed by Marek. The pull-off test starts by applying a thin (200-micron) film of AC mixed with 1% glass beads by volume (to act as spacers for load platen) to a smooth glass plate that is subsequently submerged in 25°C water. Cohesive failure occurs when both the plate and load platen remain coated. A series of tests was performed at varying soak times to develop a plot of pull-off strength (psi) versus soak time (hours). One straight run AC from Venezuelan crude was formulated with nine different modifiers to meet the same PG grade. Maltene content was evaluated. Typical plots of pull-off results showed a steep initial slope and then the strength leveled off. The binder modified with Elvaloy performed best in the pull-off test. The following conclusions were presented:

1. Stiffer binders have greater resistance to moisture damage due to decreased permeability, so oxidation tends to improve moisture sensitivity to a point. However, stiffening due to excessive aging may be detrimental to field performance.
2. Asphalts with high maltene concentration (stiffer, more viscous) are less sensitive to moisture damage. Asphalts that are high in asphaltenes appear more sensitive to moisture damage.
3. Mode of modification can affect moisture sensitivity.

Jack then discussed effects of lime and clay on asphalt moisture sensitivity. Montmorillonite clay was the worst tested; lime was no help. Lime is not a cure-all and is not always effective. He recommended use of the pull-off test to screen binders, but he cautioned that the findings are limited to the test conditions.

The group broke for lunch at noon and reconvened at 1:30 p.m.

PRESENTATION 3

Gayle King, Koch Pavement Solutions

Gayle talked about moisture damage to mastics and presented two conditions for such:

1. Binder being sensitive to moisture
2. Passing No. 200 material—"the hidden emulsifiers."

In mechanical stripping, the minus No. 200 particles on the surface are loosened, the mastic pumps up and comes apart, and the mixture matrix disintegrates. Mixes that fail in this manner reportedly often meet T283 requirements, but they fail in service and during Hamburg testing. Whether the fines are generated by pulverization of larger stones under the wheel or consist simply of the existing minus No. 200 is not well documented. Gayle cautioned against overpreparing specimens for moisture susceptibility testing. He recommended limiting cure time in the oven to 2 hours, possibly less if short hauls are anticipated. He pointed out the discrepancy with earlier advice to use aged asphalts for evaluating moisture sensitivity and stated that sulfonation is substantially offset by the stiffening effects of aging. He cited Hamburg definitions developed by Tim Aschenbrener of Colorado DOT during study of the Colorado "disintegrator" mixes. Modifiers can have good or bad effects, and Gayle believes that the Hamburg test can be used to distinguish between them. He reported that the Hamburg test shows whether clay is present very early in the test procedure. Sand equivalent is typically used to identify the presence of clay, but it does not characterize the plastic fines. The methylene blue test is considered quantitative because it identifies surface active fines and surface energy may also be used. Another screening test for AC binders is Branthaver's separatory funnel, in which the water that has been mixed with the AC settles out and its pH can be measured to determine acidity. He cited an incident in Oklahoma in which amines (antistrip) added to a phosphoric acid–treated AC binder reacted to form salts, which increased moisture sensitivity and caused the pavement to fail. Recommendations included the following:

- Confirm PG grade after amine addition.
- Use the separatory funnel test to check acidity.
- Minimize conditioning loose mixture samples before testing for moisture susceptibility.

PRESENTATION 4

Sundaram Logaraj, Akzo Nobel

Sundaram spoke about adhesion and active adhesion, and the effects of organic acids and bases. He defined active adhesion as coating and formation of chemical bonds in water. He presented a table excerpted from the *Shell Bitumen Industrial Handbook* (Shell Bitumen, Surrey, United Kingdom, 1995) that showed acid and base values in milligrams of potassium hydroxide (KOH) per gram for naphthenic and paraffinic asphalts. He stated that AC is generally weakly acidic and that siliceous aggregates may also have acidic surfaces. He recommended using tests that address both adhesion and cohesion, such as Lottman and wheel tracking, to evaluate potential for moisture damage.

MECHANISMS OF MOISTURE DAMAGE

Next, the facilitators referred the group back to the list of mechanisms and causes of moisture-related distress identified at the beginning of the breakout session. After considerable discussion, the group categorized these items with respect to the three primary modes of moisture damage that the facilitators had first presented, and then ranked the items within each category in order of importance.

1. Chemical
    - Bonding/debonding
    - Adhesive/cohesive
    - Asphalt or aggregate

Included are clay/dust/filler, mastic failure, salt in binder, aggregate aging, and molecular orientation over time.

2. Physical
   - Rugosity
   - Surface area
   - Absorption

Included are water transport and permeability, environment, aggregate morphology and absorptivity, diffusion of moisture, stiffening viscosity diffusivity, and stiffening aging.

3. Mechanical/construction
   - Stone breaking
   - Scrubbing

Included are density issues, drainage, film thickness, trapped moisture, and mechanical working, including cracking under compaction and hydrostatic pressure in service.

However, there were considerable overlap and interrelationships among these categories. With further discussion, the group decided that regardless of the mode of damage (chemical, physical, or mechanical), all of the items listed could also be classified according to the following three primary mechanisms of moisture damage that the group had identified earlier:

1. Emulsification—includes clay, dust, filler, salts in asphalt, hydrostatic pressure by mechanical working, and so forth.
2. Adhesive failure—includes aggregate morphology, absorptivity and aging, molecular orientation at interface, permeability, and so forth.
3. Cohesive failure—includes water absorption, molecular orientation, mastic, aggregate, and so forth.

Many participants felt that these three mechanisms provided a better frame of reference for addressing the pertinent issues. The next step was to proceed with the charge to identify existing best practices for addressing these mechanisms.

EXISTING BEST PRACTICES FOR TESTING AND SPECIFICATIONS

The following are the best practices identified by members in attendance:

- Use Hamburg test to screen HMA mixtures; it addresses all three moisture damage mechanisms, although may yield false negatives. There was considerable discussion about listing T283 here and some of the group felt strongly that it should be. Instead it is considered as an item that needs more research.
- Use aggregate screening tests:
  - Methylene blue (washed),
  - Hydrometer,
  - Soundness,
  - Sand equivalent (washed), and
  - Plasticity index.

- Verify PG grading of binder after additive addition.

EXISTING BEST PRACTICES FOR PREVENTION OF MOISTURE DAMAGE

The following are the best practices identified by members in attendance:

- Achieve adequate compaction/density during construction.
- Provide adequate drainage of the pavement structure.
- Avoid marginal material combinations.
- Have an appropriate mixture design, including additives (such as binder modifiers, fibers, or other fillers, lime, liquid antistrip), based on sound volumetric principles.
- Use quality control and quality assurance for mixture production, placement, and compaction, including sampling behind the paver.

The group decided to combine the charges to identify gaps in knowledge and needed research, and it included consideration of barriers to implementation.

RESEARCH TO ADDRESS GAPS AND BARRIERS

- Hamburg—optimize/standardize test methods for HMA mixtures
- Identifying new and existing test methods for research, including T283 and screening tests for components and systems
- Emulsification
  - Methylene blue—optimize/standardize test method for screening aggregates
  - Establishing aggregate testing protocol
  - Emulsifiability of asphalt
    - Standardizing separatory funnel test
    - Bitumatic (shake or mixing test)
    - Salts—APT, ICP

    Pessimum voids and pore pressure
- Adhesive failure
  - Developing and standardizing surface energy measurement method
  - Molecular orientation at asphalt aggregate interface
- Cohesive failure, bitumen or mastic
  - Heithaus
  - Pull-off
  - Water absorption and diffusion test
- Aggregate
  - ECS
  - ICP
  - Atomic absorption
  - Solubility and X-ray diffraction of solution

The final charge was to develop a strategic plan for addressing the issues and needs identified by the Fundamentals working group.

STRATEGIC PLAN

- Circulate the results of the seminar and breakout sessions for comments and suggestions.
- Establish technical working groups to address issues and research needs.
- Develop a new TRB synthesis pertaining to moisture damage of asphalt pavements.
- Identify or construct field sections for validation of research findings.
- Perform forensics on existing hot-mix asphalt mixtures and materials.
- Present research needs and problem statements to AASHTO.
- Conduct TRB or ASTM symposia on moisture damage of asphalt pavements.
- Do additional technology transfer through white papers and short courses.

The Fundamentals Breakout Session adjourned at about 5:00 p.m. The facilitators and note keeper stayed to prepare the required summary PowerPoint presentation for Thursday morning. Gaylon Baumgardner of Paragon Technical Services helped prepare the slides and his assistance was greatly appreciated.

BREAKOUT SESSION ON FUNDAMENTALS: ATTENDEES

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SUMMARY REPORT:
BREAKOUT SESSION 2

Testing and Treatments

SUMMARY REPORT: BREAKOUT SESSION 2

Testing and Treatments

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INTRODUCTION

Breakout Session 2 on Testing and Treatments was called to order at 10:00 a.m. on February 5, 2003, by session cochairs Eric Berger and Carl L. Monismith. Ground rules for the session were established. Essentially it was agreed that with the 6 h available, about 3 h would be devoted to testing, and 2 h to treatments. The first topic would be testing. Also, a limited time was allowed for presentations. Two participants, Gayle King and Ronald Terrel, had requested the opportunity to make brief presentations. It was emphasized that the session had the following objectives:

1. Identify best practices.
2. Identify gaps and barriers.
3. Identify research needs.
4. Suggest elements for a strategic plan, if possible.

In addition, some questions were posed.

In testing, key issues to be considered include the following:

- Screening versus fundamental property tests;
- Use of torture tests versus those that measure fundamental properties;
- Test reproducibility and repeatability;
- Cost and length of time to perform a test, practicality;
- Design or production test, or both;
- Best test method to identify moisture-related problems (does it relate to field performance?); and

- Improvements needed in existing test methods.

Also to be considered in the deliberations for mix testing were the following requirements, among others:

- Temperature (hot, cold),
- Loading (simulating traffic),
- Aggregate structure in mix representative of field compaction,
- Degree of saturation of specimen at time of test, and
- Water properties (e.g., pH).

The question was also posed, If good mix design, pavement design, and construction practices are followed, is a moisture sensitivity test required?

For treatments, key issues to be addressed include the following:

- Effectiveness of various additives,
- Best way to introduce additives,
- Cost-effectiveness,
- Environmental and worker safety issues,
- Documented evidence of impact on pavement life,
- Field performance and comparable data, and
- Performance over time and possibility of diminished effects.

Before the presentations, the following statements by Bill Maupin were introduced (he had been assigned to another session):

- Testing
  - Must be practical (if contractor is responsible for testing, it should be simple enough to be used as a design and production test).
  - Must indicate long-term performance (do some additives lose effectiveness over time?).
- Treatments: Do some polymer-modified asphalts react with antistrip additives to make them ineffective?

A list of the participants in this session, the majority of whom remained in attendance throughout the session, appears at the end of this report.

PRESENTATIONS

Gayle King

Gayle King, in his presentation, raised the issue of the mastic's [binder plus fines (minus No. 200 material)] role in mix stripping. He argued that the mastic might be responsible for a number of failures related to moisture; that is, the mastic is disintegrating in the presence of water and traffic. He stated that there is evidence of this situation from observations of performance in the wheelpaths of some in-service pavements. The sequence is the appearance at the surface first of light-colored material (filler), then asphalt. Eventually potholes form, resulting from absence of the binder. His studies using the Hamburg wheel-tracking device (HWTD) have shown this for a number of mixes. King stated that linear kneading compaction is used to prepare slabs for his tests. Only short-term oven aging (2 h) is used; otherwise, one might not observe this response in the HWTD.

A question was raised in this regard, based on the presentation by Dale Rand, that the Texas experience with HWTD indicated that stiffening of the binder (which would come about because of longer aging) reduced the likelihood of failure. King stated that this may be true, but it may also depend on how the stiffness increase in the binder is obtained. The performance of mixes containing modified binders in the HWTD may not always follow the Texas findings of improved performance with increase in stiffness (as measured in the PG system).

Ronald Terrel

Ron Terrel discussed the "pessimum voids" concept first presented by him during his Strategic Highway Research Program (SHRP) research, which resulted in the moisture sensitivity test—the Environmental Conditioning System (ECS). He argued that most dense-graded mixes are constructed in this range (approximately 6% to 10% air voids), whereby water can readily enter the mix but is slow to evaporate. This raises both design and construction issues.

DISCUSSION OF TESTING

Initially, the discussion was directed to an examination of a screening (loose mix or surface energy) test versus a test on compacted mix subjected to moisture action. Many agreed that a screening test would be useful to material suppliers and contractors if one is using new materials, or if one is doing a process control test. On the other hand, many felt that a moisture sensitivity test on the compacted mix should be included in the mix design process, and that a relatively quick field test on the compacted field mix for quality control and quality assurance purposes is also desirable.

Attention was then directed to existing tests, including AASHTO T283, the HWTD, the SHRP-developed ECS (and modifications), and various loose mix tests.

AASHTO T283

Although AASHTO T283 is a standard test, it was stated that there are variations of the test in use by various states. Differences include degree of saturation and specimen compaction procedure. Application of too high a vacuum during the saturation process can result in damage to the specimen. Differences in permeability resulting from different aggregate gradings (e.g., coarse versus fine Superpave® gradings) will influence performance. Density gradients both horizontal and vertical, produced by gyratory compaction, can also influence test results. It was emphasized that a quality assurance program is imperative to obtain reliable and reproducible test results. That is, both testers and laboratories must be certified.

Based on the results of NCHRP 9-13 (*NCHRP Report 444: Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design*) prepared by University of Nevada at Reno staff, modifications have been incorporated into AASHTO T283 in the 2002 version of the test. These changes should assist in reducing variability in test results. There is the concern, however, that favorable test results do not guarantee good field performance, nor do poor results necessarily mean that the mix will fail in service.

Hamburg Wheel-Tracking Device

Many participants felt that some form of repeated loading of the mix in the saturated condition is essential and is a plus for the HWTD. (Note: It was mentioned by a number of discussants that the Asphalt Paving Analyzer with its standard loading configuration does not meet this requirement.) To date, the HWTD has exhibited poor repeatability, indicating the necessity for standardization. Individual agencies that use the HWTD extensively have developed their own protocols for its use. However, no generally accepted method has been adopted that could provide guidance nationwide. Applicability of the HWTD for field testing was also questioned. It was observed that failure in the HWTD should not be attributed to moisture sensitivity unless "fines" appear in the water covering the specimen.

Environmental Conditioning System

The results of the discussion of this test methodology were that it is a very promising approach but is not yet ready for widespread use as a laboratory mix evaluation procedure for moisture sensitivity.

Loose Mix Tests

Many in the group felt that tests on loose mix do not provide in-service performance information. Rather their role is for screening purposes. In this regard, it was noted that an ultrasonic test on loose mix might serve as a quick test.

Permeability Tests

Some discussion was devoted to the role of mix permeability in moisture sensitivity evaluation. It was observed that in the pessimum voids range, there is not a definitive relationship between permeability and calculated air void content. This situation is likely related to different degrees of interconnectivity of voids—for example, as a function of aggregate gradation. It was suggested that porosity (a measure of accessible air voids) might be a better measure of accessibility of water to the laboratory test.

Discussion was also devoted to the use of air permeability to measure the propensity for ingress of water into the mix. This has been used for compaction control of mixes in the field (e.g., Washington Department of Transportation as early as the 1960s). Air permeability is relatively easy to measure and may serve as a useful part of moisture sensitivity testing.

Summary

Many agreed that the tests being used today do not measure fundamental properties. Nevertheless, the tests, such as AASHTO T283 and the HWTD, may be useful in the near term so long as they use standard procedures and are calibrated to local conditions. An important issue not addressed in these discussions is the impact of long-term aging of the binder on the effects of moisture on asphalt mixes. There is some evidence that aging of the asphalt binder may increase the moisture sensitivity of mixes. However, this could be one of the needed research activities.

Current Practices: Testing

Rather than using the designation "best practices," the group agreed to use the term "current practices." Members of the group identified three existing tests, which can be used in some manner to assist in mitigating moisture sensitivity in asphalt mixes:

1. AASHTO T283-02,
2. HWTD, and
3. Loose mix testing.

That the use of one or more of these tests can produce mixes with at least short-term resistance to moisture is predicated on the assumptions that the mixes are well designed and produced, and that they are properly constructed. In addition, it is assumed that one or more can be used for initial mix design and production control.

For the AASHTO T283-02 methodology, a number of issues to address are as follows:

1. It is essential that successful modifications to the procedure be incorporated and that a standard procedure be followed. Presumably, the T283-02 procedure reflects many of these developments.
2. Reproducibility and repeatability of the method are crucial to ensure successful application. For example, the successful use of the procedure by the Colorado Department of Transportation has resulted from its program of certification of both testers and laboratories, and their proficiency evaluation program.
3. Specimen preparation should be standardized; this includes both the specimen compaction procedure and strict control of the degree of saturation of the resulting test specimen.
4. A standard procedure for air void determination is essential.
5. Because mix permeability varies as a function of aggregate gradation, determination of the degree of saturation based on calculated air void content might be misleading at times. Therefore, consideration should be given to other procedures to define the degree of saturation.
6. The procedure must be calibrated for local conditions.
7. A disadvantage of the procedure is the lack of repeated loading to simulate the effects of traffic.

For the HWTD, a positive feature of the test is that it includes repeated loading. In addition, stripping can be identified by transport of fines from the mix being loaded into the surrounding water. Issues to be addressed include the following:

1. Test conditions and criteria should be established for the specific environment in which the mix will be used, and they depend on mix characteristics.
2. A standard method of specimen preparation including specimen size and compaction procedure is required.
3. Improvements in equipment are required, for example, where rut depth is measured.
4. A standardized procedure that can provide guidance nationwide is lacking.
5. Repeatability and reproducibility are concerns.
6. No precision and bias data are available.

Loose Mix

This testing is recommended primarily for screening purposes. Potential procedures include

1. Static boiling,
2. Use of a rolling bottle (to input mechanical energy to coarse mix in water), and

3. Ultrasonic testing of coarse mix in water.

Gaps in Current Knowledge

Major gaps identified include the following:

1. Lack of criteria and procedures for local calibration of test methods,
2. Test correlation with failure mode, and
3. Lack of well-documented field performance data.

The third item is a particularly severe deficiency in the moisture sensitivity area. It is extremely important that data be collected that can be related to field performance—performance that can be directly attributed to moisture sensitivity, not to improper mix design, poor control of mix production, or inadequate mix compaction.

Research Needs

Many agreed that it is important to complete the ECS research, which includes provision for simulated traffic loading, and therefore its influence on pore water pressure effects on mix performance; measurement of dynamic modulus as influenced by moisture (significant mix characteristic used in AASHTO 200X pavement design and rehabilitation procedure); and considerations of water quality, for example, as measured by pH. Other needs include defining the effects of long-term aging on moisture sensitivity characteristics and continuing the development of tests that measure fundamental properties related to the moisture sensitivity of mixes.

DISCUSSION OF TREATMENTS

In addition to the key issues listed in the introductory remarks, three items were identified:

1. The need to verify whether treatment is in the product (binder or mix),
2. Potential incompatibility of binder and additive, and
3. Mix design procedure if treatment (additive) is incorporated.

In considering first the mix design methodology, it was observed that if a mix design is accomplished without some form of treatment and the additive is incorporated subsequently, some agencies may not evaluate the treated mix. Many participants felt that the final mix design should be done with the treatment/additive included. For example, the Oregon Department of Transportation (ODOT) contract documents state that if the aggregate is to be lime treated, the mix design is performed with lime incorporated in the mix. It was also noted that ODOT requires that if lime is added later, the original design is redone with lime added.

For lime treatment, a number of participants indicated that dry lime on wet aggregate was very effective. Nevada reported that this form of lime addition worked well in the laboratory but that, in participants' experience, marinating was required in the field. The cost of marinating is high. Thus, it was noted that if the requirement that the plant mix pass the test is enforced, then the contractor will take the necessary steps to introduce the lime properly. It was suggested that one way to improve the dry lime on wet aggregate option is to conduct the mixing in an enclosed pug mill before the aggregate is mixed with the asphalt.

The question was raised about the addition of lime to the asphalt. Since this is under investigation, it was recommended that this be listed as a research topic.

Discussion of liquid antistrip additives produced a number of useful recommendations. Considering addition at the refinery versus at the hot-mix plant site, there was agreement that on-site addition is preferred.

The issue of softening of the binder by the additive was raised. It was noted that the majority of high-quality antistrip additives in use today do not reduce binder stiffness. Nevertheless, the binder should be required to meet the specification after the addition of the antistrip material.

Other treatments were also discussed, including the use of cement (versus lime), polymer coating on aggregate, and polymer modification of the binder. It was noted by Arizona that although cement had been permitted for a number of years, lime treatment has now substantially replaced it for aggregate treatment.

Polymer coating of aggregate is being evaluated. Currently, the quantity of polymer added is about 1 lb per ton of aggregate. Compatibility with a specific aggregate must be checked. It was reported that the material serves to waterproof the aggregate surface (very thin applied film) and is compatible with the asphalt.

Verifying the amount of additive in the mix is still a problem. It was noted, however, that there is a device that can be used to determine the amount of liquid antistrip additive in the binder by measuring its change in pH.

There are worker safety issues and environmental concerns in hot-mix production using various treatments. For example, dust may be a safety problem in the use of dry lime on wet aggregate, and there may be fumes associated with the use of liquid antistrip materials. Because government agencies and contractors both are aware of the safety and environmental issues associated with the currently used treatments, the decision was made to not include this aspect in the recommendations.

Relative to the impact of type of treatment on pavement life, Nevada indicated [on the basis of a study of eight projects, [Sebaaly et al. 2003 (*1*)] that lime treatment extended pavement life by an average of 3 years. It was also noted that in Oregon lime treatment increased pavement life by about 2 years. Many in the group believed, however, that there is little documented information in this area and that an effort should be made to document field performance on a more widespread basis.

The necessity for studies of the comparative performance of pavements in specific environments with different treatments was discussed. An example of this type that is under way in South Dakota was reported by P. Sebaaly. The study, in two locations of the state, includes comparisons of the untreated mix with mixes treated using different methods for lime addition and liquid antistrip material. The project has been under way for less than 3 years, and no differences in field performance have been observed thus far. Many agreed that studies of this type are important.

The question of potential reduction in effectiveness of treatment with time was discussed. Because little, if any, information is available, this should be an area of proposed research.

The incompatibility of some modified asphalts and liquid antistrip additives was briefly discussed. One example was presented in which an asphalt modified with phosphoric acid was blended with liquid antistrip, with the result that the effects of both the modification and antistrip were negated. This should be considered a gap in knowledge.

Best Practices: Treatments

Best practices identified by members in attendance are the following:

- To ensure that the proper additive (both type and amount) is used, mix design should be performed incorporating the specific additive planned for use. It was observed that some material specifications, for example, aggregate gradations, might not reflect the potential for additives such as lime. Thus, some modification in requirements may be required for these conditions.
- Recommended best practice for the addition of lime is dry lime on wet aggregate. Associated with this is the requirement that acceptance of the mix be based on mix production data. Consideration should also be given to a method specification for incorporation of lime, for example, closed twin-shaft pug mill mixing of lime with aggregate before mixing with asphalt/binder. In some circumstances, coated aggregate with plastic (high plasticity index) fines should include a period of marination before mixing with asphalt/binder.
- The best practice for incorporation of liquid antistrip with the binder is on site where the mix is being produced. Acceptance should be based on certification of product type and amount. Binders with liquid antistrip additives should be tested after the antistrip has been added to ensure that the material meets the specification requirements.

Gaps in Current Knowledge

The following gaps were identified:

1. Lack of a standard method to verify the quantity of additive, particularly lime, in the mix.
2. Lack of documented field performance data for mixes containing the different treatments and additives for a range of environmental and traffic loading conditions. The performance data should include comparable mixes without treatment to assist in life-cycle cost analysis.
3. Lack of documentation of compatibility of various additives with conventional asphalts and modified binders.

Research Needs

Identified research needs include the following:

1. Development of a field test to determine uniformity of distribution of an additive (e.g., lime) in the mix.
2. Documented field performance data of side-by-side comparisons of mixes containing a range in treatments/additives for different environments and traffic loading conditions (e.g., similar to the South Dakota experiment referred to earlier).
3. Evaluation of aging of aggregates in stockpiles.
4. Evaluation of the characteristics of asphalt in which lime is blended before mixing with aggregate, for example, at the refinery or on site.
5. Evaluation of common moisture sensitivity mitigation treatments to determine whether there is any deterioration in their performance over time in pavements experiencing different environments and traffic loading conditions. Development of documented field performance data is required to determine whether, in fact, such behavior actually occurs.

ACKNOWLEDGMENTS

The cochairs thank all of the participants in the session. Participants' willingness to share their extensive experiences with the group contributed significantly to achieving the goals of the breakout session. The cochairs also gratefully acknowledge the efforts of the two recorders for the session, Jennifer Kwong of Caltrans and Julie Nodes of the Arizona Department of Transportation. Their extensive notes were most helpful in preparing this report.

REFERENCE

1. Sebaaly, P. E., E. Hitti, and D. Weitzel. Effectiveness of Lime in Hot-Mix Asphalt Pavements. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1832*, TRB, National Research Council, Washington, D.C., 2003, pp. 34–41.

BREAKOUT SESSION ON TESTING AND TREATMENTS: ATTENDEES

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SUMMARY REPORT:
BREAKOUT SESSION 3

Design and Specifications

SUMMARY REPORT: BREAKOUT SESSION 3

Design and Specifications

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The list of participants follows this report.

- Jimmy Brumfield pointed out aspects of Mississippi Department of Transportation experience related to using lime-based additives.
  - Mississippi has one local source of aggregates; the rest are imported from outside the state.
  - In the early 1990s, projects were using 1% to 1.5% lime, and they encountered some stripping problems.
  - Since 1992, lime is added to 100% of projects regardless of material, and no stripping problems were observed.
  - In Mississippi state projects, no marination was used.
  - Lime is incorporated on damp aggregates on the cold feed.
  - Mississippi often adds liquid antistrip along with lime.
  - Mixing same grade asphalts from different sources will not give a final asphalt with the same grade that the initial components had; therefore, a modified Lottman test is applied on the final product.
  - Allow for lime in voids in mineral aggregate/mix design.
  - Use of boil test to track compatibility problems.
- Rita Leahy emphasized that when talking about specifications, it is important to distinguish among
  - Materials specifications,
  - Construction specifications, and
  - Design specifications.

BEST PRACTICES

The following best practices were identified by members in attendance.

Materials Specifications

Aggregates

- Nominal maximum aggregate size (NMAS): Use the current AASHTO Superpave® recommendations.
- Coarse versus fine aggregates: The effects of mix type in relation to compaction and permeability must be considered when selecting aggregate.
- Clean aggregates: Tony Limas (Granite Construction) mentioned the cleanliness value as a way to account for coarse aggregate cleanliness.
- Mineral filler is important. All fillers supplied as an independent product should come with a manufacturer certification of compliance.
- There are tests currently used and considered to be the best practice: sand equivalent test as a standard specification test to evaluate the amount of clay. In addition, there are two other tests. They are the plasticity index (currently used by the Nevada Department of Transportation) and the methylene blue test used by Texas that can assist in identifying how sensitive the material is to water.
- Perform "washed" sieve analysis.
- Limit natural sands. Texas uses a 15% limit on natural sand content, and Mississippi uses 10%.
- The shape of aggregates is important. It is desirable to use well-crushed aggregates (angular aggregates) that have a good effect on mix performance overall. Coarse aggregate angularity and fine aggregate angularity are available tests.

Binder and Additives

- Modified binder: Does it improve moisture performance or have no effect? Pros and cons were presented. Texas results from a large forensic study show that sections with modified binder had no stripping problems, whereas the nonmodified binder sections did. Nevada experience shows the contrary: modified binder does not improve stripping properties. Worth noting is that Nevada has important problems with getting the aggregates clean of clay.
- Asphalt rubber: Does it improve moisture performance or not? From practice, some participants emphasized that stripping problems were encountered with asphalt rubber.
- Modified binders: They improve the resistance to moisture damage because of an increased asphalt film thickness.
- Additives: They improve the resistance to moisture damage. Nevada combines the polymer and the lime to mitigate stripping problems. Utah uses modifiers to meet PG specifications. Lime is then added on all mixes to address stripping. According to Utah's experience, the combination of lime and polymer or even rubber improves resistance to moisture damage. Nebraska uses liquid antistrip combined with the binder and points out that when mixing binder with additives, there are interactions that change the overall properties of the mix. A test of the combined mix (binder and additive) needs to be performed to check whether the PG grade requirements are still met. What was observed is that the combination binder and liquid antistrip reduces the PG grade.

Dick Root gave a short presentation on "Mix Design Issues with Lime" and emphasized the importance of not specifying a restrictive gradation about the maximum density line and of specifying a minimum voids in mineral aggregate (VMA) to allow room for lime and asphalt.

Mix Design Specifications

- For a moisture test to be performed on the final mix (binder + aggregates + additives) is considered important.
- VMA specifications for mix design are considered critical. It was considered important to restate the factors affecting VMA: gradation, shape, and texture.
- Dick Root's presentation brought out that is important not to use overly restrictive gradation bands.
- Account for baghouse dust in the design.
- Conduct field (plant) mix verification for volumetric and moisture testing.

Structural Design Specifications

- The surface layer should be designed with smaller NMAS to reduce permeability and better protect from moisture damage.
- From Mississippi's experience, layer permeability is important. It is good practice to ensure that the highest permeability is in the surface layer and that each succeeding layer is less permeable than the underlying one, except when open-graded friction courses (OGFCs) are placed on the surface, and the bottom layer should have low permeability. This observation led to consideration of the following topics in the structural design:
  - Ensure there is a good drainage at the subgrade level before sealing (for rehab and overlay jobs, redo the cross slope, if necessary). If good drainage conditions are met, seal the subgrade with a prime coat or cut back before placing a treated permeable base, for example, ATPB, or before placing aggregate base (AB). Also seal the top of AB. Sealing the top of ATPB is not required (see Figure 1).

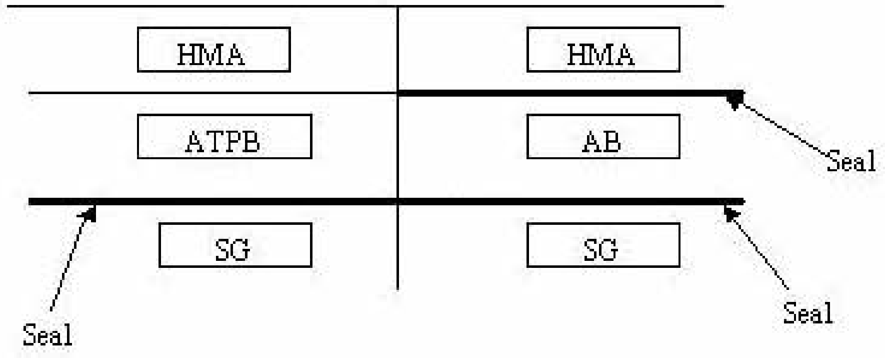

FIGURE 1 Layer permeability.

  - For regions with a wet environment, consider using internal drainage (e.g., ATPB).
  - Do not overlay OGFC. This should be removed before any overlays are placed. It is important to have a permeability test.
  - Higher traffic areas justify stricter adherence to the recommendations as given.
  - Follow National Asphalt Pavement Association–FHWA publication mix type selection guide recommendations regarding lift thickness versus NMAS.

Construction Specifications

- Construction specifications should include mix volumetric and compaction based on air voids.
- Use percentage of the maximum theoretical density varied according to the mix type; coarser mixes have higher density requirements.
- Use material transfer device to eliminate temperature segregation problems.
- Joints proved to be weak points where moisture sensitivity problems initiate (joints are usually more permeable than mainline pavement). It was considered important to have joint density specifications (e.g., minimum 91% of maximum theoretical density or within a relative compaction of 3% of the main line).
- Joint seal type materials and heaters can be used to reduce permeability of joints.
- If additives are added in the field (e.g., lime, liquid antistrip), it is good practice to test the final product at the plant (in production) to make sure it meets the specifications (both PG grade and TSR).
- Adopt and reference in the specifications the *Hot-Mix Asphalt Paving Handbook* as best practices.
- The optimum quantity of liquid antistrip should not be specified, but should be determined through laboratory testing.

GAPS IN KNOWLEDGE

- Tests that correlate to field performance,
- Gap in defining what are the failure mechanisms,
- Gap in documenting and sharing the information on successful projects, and
- No diagnostic tools for moisture damage.

RESEARCH NEEDED

- Look at the long-term effect of additives.
- Consider the aging effects of additives on the mix in relation to moisture damage performance.
- Standardize terms defining and related to moisture damage.
- Develop a data format to be used by everybody involved in the study of moisture damage and maybe a Web-based database that will make it easy to document and share information for research purposes (forensic procedure).

- Publish a synthesis on existing test procedures, mechanisms they address, their shortcomings, and so forth.
- Look at the side effects of additives (lime, LS, LAS) on fatigue, rutting, and so forth.

BREAKOUT SESSION ON DESIGN AND SPECIFICATIONS: ATTENDEES

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SUMMARY REPORT
BREAKOUT SESSION 4

Construction and Field Performance

SUMMARY REPORT: BREAKOUT SESSION 4

Construction and Field Performance

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This session was convened by facilitators Bill Maupin and Joe Peterson, with Steve Healow as recorder. After 30 minutes of enumerating discussion topics, the group began preparing its presentation in earnest by focusing on best construction practices that experience has shown will help control moisture problems. We also wanted to focus on the real-time information that is useful for making better decisions during construction that are effective in preventing moisture-related distress. Similarly, we reviewed best practices at the hot-mix plant, which could preclude moisture damage.

The following assumptions were adopted to exert some control on our free-ranging discussions:

- Good contract administration practices (by the agency and contractor and producer) are in place.
- We have a good asphalt concrete mix design.
- Our materials meet specifications (i.e., good, clean aggregates and good binder).
- Our supplier has good quarry practices.
- We have a good performance-based testing program in place.

BEST PRACTICES

The following best practices for minimizing moisture sensitivity during construction were identified by members in attendance:

- Training: All team members (agency and contractor) need standardized training. This is discussed later in the section on identifying gaps and barriers and is a milestone in the strategic plan.
- Materials handling: Aggregate moisture content, aggregate segregation, and temperature segregation are the most critical elements. If they can be controlled, then materials handling will be all but eliminated as a contributing factor.

- Production balance and control: For hot-mix plants with continuous drum mixers, the plant operator must adjust for moisture in the aggregate. Out on the grade, we must adjust for some balance between plant production, the speed of the paver, the roller pattern to achieve target density, the number of trucks, the haul distance, and other critical factors.
- Uniform optimum mat and joint density: If we could consistently accomplish this, most of our moisture sensitivity problems would go away.
- Proper drainage at the surface and subsurface: Let's not ignore the fact that years after new construction, we have additional opportunities to restore proper surface drainage, that is, with maintenance treatments and rehabilitation projects.
- Preplanning: Before construction begins, it is important to assign responsibilities, establish who is responsible for what, and clearly define roles and avenues of communication.

IDENTIFY GAPS AND BARRIERS

The only items standing between us and resolving of the moisture sensitivity problem are these issues:

- We are in crisis mode for training as a result of personnel turnover in agencies and industry. Thus, inviting a mix of agency and industry people to our training sessions takes on new significance. With similar backgrounds, all are more likely to emerge with a cooperative spirit, which will pay dividends by resolving construction issues at the local level. We help ourselves by taking advantage of this valuable opportunity to foster networking.
- Many of us struggle with a time lag in process control. Timely results from materials testing are invaluable to the owner and contractor. However, their value diminishes rapidly over time.
- Lack of continuous test results means lapses occur in our process control. It is like dozing off during an exam.
- In regard to complexity of project logistics, our construction projects tend to succeed when our materials suppliers deliver the goods, within specified limits, when and where they are needed, regardless of whether or not the materials are time sensitive. Our successful contractors cope every day with a maelstrom of risks and resources to construct the final products as specified. Why can't all suppliers and contractors succeed? How is it that some are consistently successful and make it appear easy?
- We will need accurate density measurements to achieve target density in a cost-effective manner.
- Equipment constraints, which are often overlooked, contribute significantly to a design that is constructible and a project free of delays, change orders, and cost overruns due to rejected work.
- Agency managers' note: Project control by funding is a recipe for disaster. The practice of downsizing projects in final design or after they have gone to construction is a recipe for failure.

IDENTIFY RESEARCH NEEDS

- Continuous measurements of density or stiffness would provide the roller operators with continuous feedback on the sufficiency of their rolling pattern.

- Real-time automated plant control is an idea whose time came long ago, but which our industry has only partially embraced. Consider the Boeing 747. Life is much easier for the pilots as a result of the higher degree of automation at the controls. They choose to fly hands-on at takeoff and landing, although the aircraft avionics and programmable navigation systems have been sophisticated enough for decades to proceed hands-off from gate to gate. Our hot-mix plant operators deserve more of that type of automation, in which the menial tasks are automated, leaving them free to monitor and adjust as necessary.
- Similarly, our people and projects will benefit immeasurably from automated paver control and feedback.
- What are the effects of temperature on adhesion and, in turn, on the potential for moisture damage?
- What is the relationship between permeability and performance?

ELEMENTS OF A STRATEGIC PLAN

- Development and implementation of joint training courses with the following features: self-directed learning, understanding basic materials, and virtual training for equipment operators
- Preconstruction partnering in which roles are defined, responsibilities are assigned, and authority is delegated
- Construction activities that focus on control of segregation
  - Adopt standard definition of segregation (i.e., NCHRP)
  - Adopt accurate measurement standards
  - Adopt specifications with incentives and disincentives to achieve desired results
- Balance construction activities
  - Implement best practices
  - Submit productivity plan
  - Implement productivity plan
- Obtain uniform optimum density
  - Optimize joint density
  - Adopt accurate measurement tool
  - Adopt incentives and disincentives to obtain desired results

BREAKOUT SESSION ON CONSTRUCTION AND FIELD PERFORMANCE: ATTENDEES

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Conference Summary

CONFERENCE SUMMARY

National Seminar on Moisture Sensitivity of Asphalt Pavements

February 4–6, 2003

LARRY SANTUCCI
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I am honored to have the opportunity to give a brief summary of this seminar on moisture sensitivity. It has been exciting to see the seminar unfold. I applaud Caltrans for hosting this effort along with the enthusiastic participation of industry and the support and encouragement of the Transportation Research Board and the Federal Highway Administration.

Although I have been away from a direct involvement in asphalt research for a few years, this subject has always been dear to my heart. I believe that the detrimental effects of moisture on pavement performance are underestimated. I feel that by instituting sound engineering judgment in the selection of materials, design considerations, and construction practices, we can significantly extend pavement life once we understand and address these moisture-related effects.

Let's take a moment and briefly review what was covered earlier this week. On Tuesday morning, you heard a series of lectures that started out with an introduction by Gary Hicks that identified the extent of the moisture sensitivity problem throughout the nation. Gary defined the purpose of the seminar and provided some examples and definitions of moisture-related problems. He challenged the group to come up with implementable solutions to help mitigate moisture-related distress in asphalt pavements.

Dallas Little provided valuable information on the chemical and mechanical processes associated with moisture-related distress. Dallas, in his presentation, captured the numerous theories that have evolved over the years to help explain the problem. He pointed out that not only the nature of the aggregate and the asphalt binder is important, but also the manner and environment in which these materials are combined are also critical. He noted that surface energy measurements can serve as a tool for screening asphalt–aggregate compatibility. In addition, asphalt must be able to wet the aggregate and penetrate surface voids, to provide a strong mechanical bond. Dallas also pointed out that moisture resistance is derived not only from bond strength but also from mastic strength. This paper provides an excellent resource for researchers and practitioners who continue to seek ways to minimize the detrimental effects of moisture on pavement performance.

Mansour Solaimanian reviewed the historical development of test methods, dating back to the 1930s, that have been proposed to predict moisture sensitivity of asphalt pavements. In all, approximately 25 tests on loose mixtures or compacted specimens have evolved. The link between predictions from laboratory tests and actual field performance has been somewhat elusive. The most widely used test to predict moisture sensitivity seems to be some form of retained strength test, such as AASHTO T283, with a growing interest in some version of a wheel-tracking test. Mansour identified the key elements of a successful test as one that is repeatable and reproducible; feasible, practical, and economical; serves as a good discriminator; and simulates field mechanisms.

On Tuesday afternoon, Jon Epps, Jim Anagnos, and Eric Berger informed us of the various types of treatments available to reduce the moisture sensitivity of asphalt mixtures. We learned that the most widely used treatments are amine-based liquid additives applied to the asphalt binder and lime applied in various ways to primarily the aggregate. The benefits and effectiveness of each additive type were presented. It was pointed out that the effectiveness of any treatment is dependent on such factors as the asphalt binder type, the aggregate used, the concentration level, the age of the mix, and the test method used to evaluate moisture resistance.

John D'Angelo focused on material production issues, including different crude oil sources, crude oil refining, and asphalt binder modification. He identified certain acids present in asphalt binders that may be susceptible to moisture damage. He pointed out that the practice of caustic treating asphalt to increase stiffness can create soluble salts that may emulsify in the presence of water. The chemical nature of aggregates and aggregate production concerns such as the presence of clay and dirty aggregate that affect the adhesion of the binder to the aggregate were discussed. Mix design and pavement design considerations, including the selection of mix types (dense versus coarse versus gap graded mixes) for specific applications, aggregate size relative to lift thickness, and the potential of trapping moisture in lower pavement layers, were covered in John's presentation.

Allen Cooley gave the presentation on construction issues and focused on minimizing segregation, both thermal and mechanically induced, during loading of the mix, transportation of the mix to the job site, and charging of the paver. Relative to compaction, Allen suggested the use of permeability measurements as a way to achieve proper field densities. He emphasized that all air voids are not created equal and showed variations in the permeability–air voids relationship with changes in nominal maximum size aggregate. Allen also covered improved techniques to construct longitudinal joints to help reduce the permeability at this potentially sensitive area in the pavement to water infiltration.

Amy Epps Martin led a tag team of presenters who provided a historical perspective of their experiences with moisture sensitivity in the states of California, Nevada, Texas, and Virginia. Summarizing these efforts, Amy identified the need for an improved test or tests and criteria to predict moisture sensitivity. She also suggested that testing needs to be done on the combination of materials coupled with other design considerations such as proper drainage of the entire pavement structure. Amy's recommendations included a plea to better understand the mechanisms contributing to moisture sensitivity, and she encouraged all present to continue to share experiences to reach a common goal of moisture-resistant pavements.

On Wednesday morning, Rita Leahy (in a presentation not included in this proceedings) identified a number of factors that need to be considered in specifications to mitigate the effects of moisture sensitivity. Some factors we can control, whereas others we need to accommodate. We control fairly well the design, materials, and construction factors. However, we must accommodate factors such as traffic, the environment, and sometimes materials. Rita proposed that specification possibilities may be either fundamental or mechanical. She suggested that by implementing what we know now, by using sound design methods, good mix production and construction practices, and proper selection of materials, we could go a long way toward minimizing moisture-related damage.

Jim Moulthrop closed the lecture series by outlining the challenges and expectations of the breakout sessions. Jim pointed out that the primary goal of the seminar was to identify, in regard to best practices, what works now and can be used immediately to mitigate moisture sensitivity problems. He also requested that participants identify what we do not know in terms of knowledge gaps and what we need to address with additional research. Another goal of the breakout sessions was to develop strategic plans or a road map for the future. Jim concluded by providing templates for the facilitators to use as a guide in the various breakout sessions.

Some of the recurring themes that surfaced over the course of the lecture presentations included the fact that chemical and physical properties of both the aggregate and the asphalt binder are very important in obtaining good adhesion. We heard about the importance of good compaction practices to reduce the air voids or permeability of the pavement and hence its susceptibility to moisture. We also heard about the need for a test or series of tests that relate to field performance. The concept of refining and enforcing existing specifications and good practices to minimize moisture sensitivity was presented.

Armed with this information, each participant attended one or more of the breakout sessions: Fundamentals, Testing and Treatments, Design and Specifications, and Construction and Field Performance. The results of participants' hard work was reported earlier by the facilitators assigned to the sessions. I commend all participants for their efforts and I was especially pleased to see that the major part of their deliberations focused on developing best practices that could be used now to help reduce moisture sensitivity problems.

When we examine possible accomplishments of this 2½-day seminar, several items come to mind. Certainly, one major accomplishment was bringing together the vast array of talent from around the country that is in this room, and I give that credit to our seminar leader, Gary Hicks. Other accomplishments include the dissemination of knowledge in the lecture presentations and the exchange and sharing of ideas in the breakout sessions. From these activities, action plans were developed that identified best practices, gaps in knowledge, and research needs. And finally, a future accomplishment will be the documentation of these seminar findings in a Transportation Research Board publication.

How might we measure the success of our efforts over the past few days? One measure might be how well we transfer the technology through training of the people on the front lines dealing with the issue of moisture sensitivity. Plans are being made by Caltrans to conduct 1-day training sessions this fall throughout the districts, using the information that comes out of this seminar and the results from ongoing joint industry–Caltrans task forces. Implementation of task force recommendations is expected to follow in early 2004. Another measure of success could be a systematic documentation of field results that demonstrates the benefits of using certain best practices to reduce moisture sensitivity. Changes in state practices as a result of efforts here in the form of improved specifications, tests, or protocols would be a measure of success. Of course, the ultimate goal would be to realize a significant drop-off in moisture-related problems. Over the longer term, a measure of success would be funded research that originated from recommendations of this seminar.

Road Map for Mitigating National Moisture Sensitivity Concerns in Hot-Mix Pavements

Road Map for Mitigating National Moisture Sensitivity Concerns in Hot-Mix Pavements

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One of the charges of the seminar on moisture sensitivity was to develop an outline for a road map for addressing the national concern of moisture sensitivity. That road map is presented in this paper. Implementation of the findings, best practices, and research needs presented in the road map are expected to be discussed by various materials and research committees within the transportation community.

There cannot be a road map to address the national issues related to moisture sensitivity in hot-mix asphalt (HMA) pavements without a vision, a mission, goals, and associated work tasks. Members of the national seminar steering committee have developed the following descriptions for these items:

- Vision: Eliminate moisture sensitivity distresses in HMA pavements.
- Mission: Provide the necessary tools to practitioners that can be used to eliminate moisture sensitivity in HMA pavements.
- Tasks: Identify the best practices, gaps in knowledge, and research needs to address moisture sensitivity in HMA pavements.

NEED FOR A ROAD MAP

Moisture sensitivity in HMA pavements is one of the leading pavement performance–related issues facing highway agencies. Most agree that the current test protocols for identifying moisture-sensitive mixtures do not accurately predict field performance.

A survey dated August 2002 of the state highway agencies, the FHWA federal lands offices, and selected Canadian provinces indicated that 45 of the 55 agencies responding identified a moisture-related problem in their HMA pavements, and they specify some type of treatment to mitigate the problem. More than 50% use a liquid antistrip agent, 30% use lime, and the remainder use one or the other.

Forty-eight of the 55 agencies perform a test on the mix at some stage of the mix design and construction process to determine the need for an antistrip agent. The types of tests include indirect tensile tests (AASHTO T283, ASTM D4867), compressive strength tests (AASHTO T165), and wheel tracking in combination with the tensile test. Slightly more than 60% test for moisture damage during the mix design phase, while the remainder test during the mix design or construction phases of the project.

Though considerable work has been done over the past 50 years to solve the problem of moisture sensitivity in HMA pavements, there is still no agreement on a solution for mitigating the problem. As a result, the road map that is presented in this document is expected to provide direction to the pavement community in solving the moisture sensitivity problem.

ROAD MAP OBJECTIVE, GOALS, AND TASKS REMAINING

Objectives

The following are the objectives to be achieved with this road map:

- Identify existing best practices to mitigate moisture damage.
- Determine gaps in knowledge, both short and long term.
- Identify research needs in the following areas:
  - Fundamental material properties,
  - Testing and treatment procedures,
  - Design (pavement and mix) and specifications, and
  - Construction and field performance.
- Identify a process and timeline to accomplish these tasks.

Goals

The steps that have been used to accomplish these objectives include the following:

- Conduct a national seminar of leading experts to focus on the issue. The seminar was held in San Diego on February 4–6, 2003. The California Department of Transportation initiated the seminar to bring about a better understanding of how to deal with a moisture sensitivity issue (or problem) that had developed in northern parts of the state in the early 1990s.
- Present papers on various subjects to stimulate discussion on the important issues and their solution. Peer-reviewed papers were presented at the seminar.
- Develop reports on best practices, gaps in knowledge, and research needs in the following areas:
  - Fundamentals,
  - Testing and treatments,
  - Design and specifications, and
  - Construction and field performance.

A summary of the results of these reports is included in this road map.

Tasks Remaining

Tasks that remain to be completed include the following:

- Prioritize research needs
  - Short-term
  - Long-term
- Prepare research problem statements
- Identify funding sources
- Obtain funding and conduct the research

It is expected that the committees in the Bituminous Section of the Transportation Research Board will be able to prioritize the identified research needs and develop the appropriate research problem statements. In the meantime, it will be necessary to identify appropriate funding sources to accomplish the needed work.

MAJOR FINDINGS OF THE SEMINAR

The major findings from the seminar came partly from the papers and the subsequent discussion, but they were more fully developed in the breakout sessions. Findings are presented in terms of best practices, gaps in knowledge, and research needs.

Best Practices

For each of the breakout sessions, best practices were identified and summarized. Table 1 summarizes the best practices for the fundamentals breakout group. The best practices are presented in two broad categories: testing/specification and prevention. In terms of testing and specifications, the following were developed:

- Use test methods (as designed) to verify acceptable resistance to moisture damage.
- Use the Hamburg test to screen HMA mixtures because it addresses the major mechanisms of moisture damage. AASHTO T283 still needs work to quantify its relationship to field performance.
- Use improved aggregate tests to screen good from bad performers. These include tests such as the cleanness value to indicate the type of claylike materials clinging to the aggregate, the sand equivalent test to indicate the amount of claylike material on the fine aggregate, and the plasticity index or methylene blue tests to determine the sensitivity of clay to moisture. In addition, a wash and sieve analysis should be performed during design and construction, and natural sands should be limited in their use.
- Verify the effect of the liquid antistrip agent on the grading of the asphalt after it has been added and mixed.

In terms of prevention, the following good construction practices were identified:

- Treat mixtures as necessary to mitigate moisture damage when identified by mix testing.
- Achieve good compaction and provide adequate drainage.
- Avoid marginal material combinations.

TABLE 1 Summary of Best Practices: Fundamentals

TESTING AND SPECIFICATIONS	PREVENTION
• Use Hamburg device	• Achieve good density and drainage
• Include aggregate tests ○ Methylene blue ○ Hydrometer ○ Soundness ○ Sand equivalent	• Avoid marginal materials
	• Include additives in mix design
• Grade binder after additives	• Practice good QC/QA, including sampling behind paver

- Use sound mix design practices, including volumetrics and additives in the mix design process.
- Practice good quality control/quality assurance (QC/QA) for mixture production, placement, and compaction.

Table 2 summarizes the best practices resulting from the breakout group on testing and treatments. They include the following areas:

- Testing: Three test procedures could be used to mitigate moisture damage. The tests included AASHTO T283, the Hamburg wheel-tracking test, and a loose mix test. However, issues such as sample preparation, repeatability and reproducibility, relationship to field performance, and the need for standardized test procedures were all expressed as concerns that need to be addressed.
- Treatments: Several items were identified as important:
  - Verify that the antistrip material is in the mix.
  - Identify any incompatibility between the binder and the additive.
  - Ensure that the additive was included in the mix design process.
  - Acceptance of the mix should be based on mix production data.

TABLE 2 Summary of Best Practices: Testing and Treatments

CURRENT TESTING PRACTICES	TREATMENTS	APPLICATION OF ANTISTRIP AGENTS
AASHTO T283	Mix design should include additives	Use dry lime on wet aggregate or add liquids to the binder at the job site
Hamburg wheel-tracking device	Test binder with additives	Accept on the basis of production data
Loose mix—consider screening tests such as static boiling, rolling bottle, or ultrasonic	Certification that correct product is used and of product quality	Use method specification for incorporating lime

- Incorporating additive into the mix: With respect to a method of adding lime, the use of dry lime on wet aggregate was identified as the best practice. Lime slurry is also good, but it costs more because of the additional handling of the materials. For liquid antistrip agents, the additive should be mixed with the asphalt on the construction site.

Table 3 summarizes the best practices identified by the group on design and specifications. They include the following:

- Materials issues: Use clean aggregates and improved aggregate tests to identify problem aggregates. Limit the natural sands to about 15% and use angular aggregates. Use additives such as lime or liquid antistrip agents to mitigate moisture damage problems.
- Mix design: It is essential that a test be performed on the mix to identify its potential for moisture damage, and the test should be performed as a part of the mix design process. The use of voids in the mineral aggregate in the mix design process is considered critical. All additives, including any baghouse fines, should be included in the mix design process.
- Structural design: Use of permeability to evaluate the compaction of the finished product is considered an important step to minimize moisture damage. Practice good drainage design in all pavements, both at the surface and in the underlying layers. Do not overlay open-graded mixes; they should be removed prior to an overlay.
- Construction specifications: Emphasis was placed on the use of clean aggregates. Tests such as the sand equivalent, plasticity index, or methylene blue can be used to identify dirty aggregates. Both modified binders and antistrip agents help reduce the potential for moisture damage. The use of good compaction, improved joint designs, and testing of plant-mixed products for moisture sensitivity are all good practices.

Table 4 summarizes the best practices identified by the construction and field performance group. They include the following:

- Training: Training of agency and contractor personnel should be a high priority in mitigating moisture damage.
- Materials handling: Aggregate moisture content and segregation from aggregate handling or from temperature variations need to be controlled.
- Production balance and control: If the hot-mix production is not in balance with the paving or the compaction equipment, it is difficult to achieve uniform mixes and uniform densities.
- Improved mat and joint density: If only this were accomplished, most of the moisture problems could be eliminated.
- Good surface and subsurface drainage: Emphasize the need to follow good practices to restore drainage during maintenance and rehabilitation operations.

TABLE 3 Summary of Best Practices: Design and Specifications

MIX DESIGN	STRUCTURAL DESIGN	SPECIFICATIONS
▪ Include moisture test ▪ Include volumetrics in mix design process ▪ Include all additives in design—replicate production process ▪ Use baghouse fines in design	▪ Permeability test ▪ Good drainage practices	▪ Material aggregates (baghouse fines, binders, etc.) ▪ Construction including joint density ▪ Verify presence of additives by mix verification moisture test

TABLE 4 Summary of Best Practices: Construction and Field Performance

TRAINING	MATERIAL HANDLING	UNIFORM MAT AND JOINT DENSITY
▪ Joint training with agency and contractor personnel ▪ Need to develop cooperative spirit in solving problems	▪ Control aggregate moisture content ▪ Minimize aggregate segregation ▪ Minimize temperature segregation	▪ Need for improved compaction ▪ Control permeability for mix ▪ Control drainage characteristics of mix

Gaps in Knowledge

A number of gaps in the knowledge were identified. The major gaps are summarized in Table 5. For example, the fundamentals group identified the following gaps in knowledge that need to be addressed:

- Standardize existing test procedures. Many test methods, including the Hamburg wheel-tracking device, do not have standard procedures. There is a need to optimize the procedure and then standardize it as an AASHTO/ASTM test procedure.
- Identify new test methods for mixes and screening tests for components.
- Develop tests to evaluate the emulsifiability of the asphalt binder.
- Develop a better understanding of the mechanisms of failure, including both adhesive and cohesive failures.

The group on testing and treatments identified the following gaps:

- Lack of criteria and procedures for calibration of test methods,
- Correlation of the test with a specific failure mode,
- Lack of well-documented field performance data,
- Need to verify that an additive is present, and

- Need to establish the compatibility of the additive with the binder.

All of these gaps are important if a test method is to be developed that correlates with field performance. At present, none of the test methods relate well to field performance.

The group on design and specifications identified the following gaps in knowledge:

- Laboratory tests that correlate with field performance,
- Identification of moisture damage in the field and the mechanisms causing the damage,
- Documentation of information on successful projects and the sharing of this information, and
- Diagnostic tools to identify moisture damage.

The group on construction and field performance identified the following gaps:

- Joint training with agency and contractor personnel to cope with personnel turnover.
- Timely test results: Lack of continuous test results means lapses in process control.
- Coping with complex project logistics: Some contractors are good at this and others are not.
- Achieving good density continuously in the mat and at the joints. It is important to achieve density in a cost-effective manner.
- Equipment constraints: These can contribute to project delays, change orders, and overruns due to rejected work.
- Project control by funding: The practice of downsizing a project in final design or after it goes to construction is a recipe for disaster.

Research Needs

The last item solicited from the breakout sessions was the identification of research needs. Table 6 summarizes the needs identified by the various groups. As can be seen, there is redundancy in the recommended research needs. Although needs were identified, research needs statements were not developed. This task remains to be completed by research and materials committees in the transportation community.

GENERAL DISCUSSION OF THE ROAD MAP

The findings from the breakout session suggested that the following items be included as part of the road map:

- Develop a presentation for the AASHTO Subcommittee on Materials on the findings from the seminar.
- Circulate the proceedings of the seminar for comments and suggestions.
- Establish technical working groups to address research needs and develop problem statements.
- Initiate an NCHRP synthesis on moisture sensitivity as soon as possible. The last one was done in the early 1990s.
- Conduct a follow-up TRB/ASTM symposium on moisture sensitivity.

- Provide additional technology transfer or training on the subject. This could include
  - Basic materials understanding,
  - Self-directed training, and
  - Virtual training.
- Develop guidelines for preconstruction partnering that would include
  - Roles defined,

TABLE 5 Gaps in Knowledge

FUNDAMENTALS	• Standardization of Hamburg device • Testing protocol for aggregates • Need to identify emulsifiability of binder • Need to understand the mechanisms for adhesion and cohesive failures • Aggregate properties that contribute to failure mechanisms
TESTING AND TREATMENTS	• Testing – AASHTO T283 – Update precision and bias – Specimen preparation-compaction and degree of saturation – Air void determination – Calibrate for local conditions – Need for repeated load – Porosity/permeability – Standardization and certification – Hamburg device ▪ No standard procedure • Test conditions for environment and mixture • Sample preparation and compaction ▪ Equipment improvements ▪ No precision and bias – Loose mix ▪ Criteria/protocols for local calibration ▪ Data collection that relates to field performance • Treatments – Verify quantity of additive in mixture – Field performance of various additives over time – Compatibility of additives with bitumen, polymers, and so forth
DESIGN AND SPECIFICATIONS	• Develop tests that correlate to field performance • Identify the real failure mechanisms • Document field performance
CONSTRUCTION AND FIELD PERFORMANCE	• Need for training • Time lag of process control/lack of continuous test results • Complexity of project logistics • Inaccurate density measurements • Equipment constraints • Project control by funding

TABLE 6 Research Needs

FUNDAMENTALS

- Standardize Hamburg device and test method.
- Identify needed test methods for mixes and for components.
- Develop tests to identify the emulsifiability of a binder.
- Adhesion failures: Evaluate surface energy measurement method and molecular orientation at the asphalt–aggregate interface.
- Cohesive failures—for both the bitumen and mastic. This could include an evaluation of the Hiethaus procedure, pull-off tests, and water absorption and diffusion tests.
- Develop improved aggregate tests such as the environmental conditioning system (ECS) or inductively coupled plasma procedures to evaluate solubility.

TESTING AND TREATMENTS

- Testing
  - Develop fundamental property tests
  - Evaluate effects of long-term aging on moisture susceptibility of mixes
  - Develop a rapid QC test
  - Complete the ECS research initiated under SHRP
    - Dynamic modulus/fundamental properties
    - Traffic impacts on pore pressure
    - pH of water
- Treatments
  - Develop a field test to determine uniform distribution of additive to mix
  - Document field performance of additives over time
  - Evaluate aging of aggregates in the stockpile
  - Evaluate the potential of placing the lime directly into the bitumen
  - Evaluate whether there is diminished performance with the various treatments over time

DESIGN AND SPECIFICATIONS

- Develop diagnostic tools for identifying moisture damage
  - Standardization of terms
  - Evaluation techniques
  - Testing data format
  - Forensic procedures
- Evaluate long-term effects of treatments on aging, moisture, and pavement performance
- Evaluate the side effects of additive use on mix properties (fatigue, rutting, and the like)
- Develop a synthesis of test procedures
  - What mechanisms are measured per test?
  - Variations used for each test
  - Pros and cons of each test
  - Standardization of terms

CONSTRUCTION AND FIELD PERFORMANCE

- Develop continuous density/stiffness measurement equipment.
- Develop real-time automated plant control and automated paver control/feedback.
- Evaluate the effects of temperature on adhesion.
- Develop a relationship between permeability and performance.

    - Responsibility assigned, and
    - Authority delegated.
- Develop improved mixture and construction guides for mitigating moisture sensitivity problems in the following areas:
    - Identification/mitigation of moisture-sensitive mixes
        - Laboratory testing
        - Correct treatment to address the problem
    - Minimization of segregation
        - Implementation of standard definition of segregation (NCHRP)
        - Development of an accurate measurement tool
        - Development of incentive/disincentive payments standards
    - Implement best practices in construction
        - Submit and implement a productivity plan
        - Optimize joint density
        - Use accurate density measurement tools
        - Use improved incentive/disincentive payments for density
- Construct field sections for validation of any new theories.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Conclusions of the authors of this paper from the seminar are summarized briefly below; details are discussed in the text of the paper.

- Current test methods for assessing moisture susceptibility of HMA mixes do not relate well to documented field performance and are not standardized.
- The industry does not currently have a clear understanding of the fundamental mechanisms that affect moisture damage in HMA.
- There is a deficiency of well-documented field performance data for pavements that experience moisture damage.
- Training of agency and contractor personnel is essential and should be given high priority. It is felt that many of the moisture-related problems could be eliminated through understanding of good construction practices.
- Current construction specifications should be enforced or modified (and enforced) to ensure adequate mat and joint density. If only this were accomplished, moisture-related problems in HMA would likely be greatly reduced.
- Proper surface and subsurface drainage practices need to be implemented during pavement construction, rehabilitation, and maintenance operations.
- Significant research needs were identified. Needs statements should be prepared by research and materials committees and submitted to appropriate agencies.

Recommendations

Following are the authors’ recommendations resulting from the seminar:

- Present the findings of this seminar to the AASHTO Subcommittee on Materials at its August 2003 meeting and request its support in initiating and promoting research needs related to moisture susceptibility in HMA.
- Prioritize a list of research needs and develop an accompanying estimated budget and timeline.
- Initiate development of an NCHRP synthesis on moisture susceptibility of HMA paving mixtures.
- Develop improved guidelines for identifying moisture-sensitive mixes as well as for mixture design and construction to mitigate moisture sensitivity problems.
- Set a realistic timetable to accomplish the items identified above.
- Conduct a follow-up symposium on moisture susceptibility in HMA pavements at a future TRB-, ASTM-, or AASHTO-sponsored event.

RESOURCES

Aschenbrener, T. *Results of Survey on Moisture Damage of Hot-Mix Asphalt Pavements*. Colorado Department of Transportation, August 2002.

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Terrel, R. L., and J. W. Shute. *Summary Report on Water Sensitivity*. SHRP-A/IR-89-003. Strategic Highway Research Program, Washington, D.C., 1989.

Tunnicliff, D. G., and R. E. Root. *NCHRP Report 274: Use of Antistripping Additives in Asphaltic Concrete Mixtures*. TRB, National Research Council, Washington, D.C., 1984.

Tunnicliff, D. G., and R. E. Root. *NCHRP Report 373: Use of Antistripping Additives in Asphaltic Concrete Mixtures: Field Evaluation*. TRB, National Research Council, Washington, D.C., 1995.

APPENDIX A

Conference Program

NATIONAL MOISTURE SENSITIVITY SEMINAR

February 4–6, 2003

PROGRAM

Seminar Description

Moisture damage in asphalt pavements is a ***national concern.*** Correctly identifying the problem and isolating the contributing factors—materials and construction—are equally challenging. The goals of this national seminar are twofold: technology transfer from leading experts, and a road map to solving this problem. Topics to be addressed include the following:

- **Identifying the problem—distinguishing between materials-induced versus construction-related factors**
- **Fundamental concepts—binder and aggregate considerations; failure mechanisms**
- **Test methods—laboratory and field**
- **Remediation—additives and construction practices**
- **Field performance and case studies**
- **Specifications—shortcomings**
- **Environmental and health issues**

Time Line

The national seminar will be held at the Radisson La Jolla in San Diego, California, February 4–6, 2003. It is being planned by a steering committee made up of agency personnel (state and federal), industry, and academia. The national seminar will be an invited-only session, so the steering committee will also identify potential guests who can contribute to the subject.

Tentative Program

February 3, 2003

5:00 p.m. – 7:00 p.m.	*Steering Committee Meeting*
5:30 p.m. – 7:00 p.m.	*Registration*
7:00 p.m. – 9:00 p.m.	Working Dinner with Presenters, Moderators, Facilitators, and Note Keepers

February 4, 2003

7:30 a.m. – 8:00 a.m.	*Continental Breakfast and Registration*
8:00 a.m. – Noon	*Session 1 (Moderator—David Newcomb)*
■ Welcome –	Anne Mayer (Caltrans) and Gary Hamby (FHWA)
■ Lecture 1 –	Introduction and Seminar Objectives (Gary Hicks)
■ *Break*	
■ Lecture 2 –	Chemistry and Mechanisms (Dallas Little)
■ Lecture 3 –	Test Methods (Mansour Solaimanian)
Noon – 1:30 p.m.	*Lunch (on your own)*
1:30 p.m. – 5:30 p.m.	*Session 2 (Moderator—Brandon Milar)*
■ Lecture 4 –	Treatments (Jon Epps)
■ Lecture 5 –	Design and Production Processes (John D'Angelo)
■ *Break*	
■ Lecture 6 –	Construction Issues (Jim St. Martin)
■ Lecture 7 –	Field Experiences (Dale Rand/Amy Epps-Martin)
6:00 p.m. – 7:00 p.m.	*Hosted Reception*

February 5, 2003

7:30 a.m. – 8:00 a.m.	*Continental Breakfast*
8:00 a.m. – 10:00 a.m.	*Session 3 (Moderator—Terrie Bressette)*
■ Lecture 8 –	Specifications (Rita Leahy)
■ Lecture 9 –	Implementation (Jim Moulthrop)

10:00 a.m. – 10:30 a.m.	*Break*
10:30 a.m. – Noon	*Parallel Breakout Sessions*
■ Breakout 1	Fundamentals
1. Facilitators	Dave Jones and Alan James
2. Note Keeper	Anne Stonex
■ Breakout 2	Testing and Treatments
1. Facilitators	Carl Monismith and Eric Berger
2. Note Keeper	Jennifer Kwong
■ Breakout 3	Design and Specifications
1. Facilitators	John D'Angelo and Mike Cook
2. Note Keeper	Lorina Popescu
■ Breakout 4	Construction and Field Performance
1. Facilitators	Joe Peterson and Bill Maupin
2. Note Keeper	Steve Healow
Noon – 1:30 p.m.	*Lunch (on your own)*
1:30 p.m. – 5:30 p.m.	*Parallel Breakout Sessions (Continued)*
■ Breakout 1	Fundamentals
1. Facilitators	Dave Jones and Alan James
2. Note Keeper	Anne Stonex
■ Breakout 2	Testing and Treatments
1. Facilitators	Carl Monismith and Eric Berger
2. Note Keeper	Jennifer Kwong
■ Breakout 3	Design and Specifications
1. Facilitators	John D'Angelo and Mike Cook
2. Note Keeper	Lorina Popescu
■ Breakout 4	Construction and Field Performance
1. Facilitators	Joe Peterson and Bill Maupin
2. Note Keeper	Steve Healow
6:00 p.m. – 7:00 p.m.	*Hosted Reception*
7:00 p.m. – 10:00 p.m.	*Working Dinner for Facilitators / Note Keepers*

February 6, 2003

7:30 a.m. – 8:00 a.m. *Continental Breakfast*

8:00 a.m. – Noon *Session Wrap-Up (Moderator—Mike Anderson)*

- Summary of Breakout Sessions and Discussions
    1. David Jones and Alan James
    2. Carl Monismith and Eric Berger
    3. John D'Angelo and Mike Cook
    4. Joe Peterson and Bill Maupin

- Break

- Road Map for the Future and Discussion—Jim Moulthrop and Joe Button
    1. Best Practices
    2. Gaps in Knowledge
    3. Implementation and Research Needs

- Conference Summary—Larry Santucci

- Closing Remarks—Phil Stolarski (Caltrans)

APPENDIX B

Final List of Participants

APPENDIX B

National Moisture Sensitivity Seminar

February 4–6, 2003

La Jolla, California

Final List of Participants

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The **Transportation Research Board** is a division of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation through research. In an objective and interdisciplinary setting, the Board facilitates the sharing of information on transportation practice and policy by researchers and practitioners; stimulates research and offers research management services that promote technical excellence; provides expert advice on transportation policy and programs; and disseminates research results broadly and encourages their implementation. The Board's varied activities annually engage more than 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

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