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Investigation of Conditions for Moisture Damage in Asphalt Concrete and Appropriate Laboratory Test Methods: Summary Version

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Investigation of Conditions for Moisture Damage in Asphalt Concrete and Appropriate Laboratory Test Methods:
Summary Report

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Work Conducted as part of Partnered Pavement Research Center Strategic Plan Element No. 4.9: "Investigation of Asphalt Concrete Moisture Damage"

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation

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Abstract:
Moisture damage in asphalt pavements is a complex phenomenon affected by a variety of factors, and has not been fully understood, with major knowledge gaps in three areas: major factors contributing to moisture damage in the field, appropriate laboratory test procedures, and the effectiveness of treatments. Both field and laboratory investigations were performed in this study to provide additional information in these three areas.

Statewide condition survey and field sampling were conducted to identify factors contributing to moisture damage, other than aggregate source. Statistical analysis revealed that air-void content, pavement structure, cumulative rainfall, mix type (DGAC versus RAC-G), use of anti-strip additive (lime or liquid), and pavement age significantly affect the extent of moisture damage. Laboratory experiments revealed that high air-void contents not only allow more moisture to enter mixes, but also significantly reduce the fatigue resistance of mixes in wet conditions. Less than optimum binder contents also reduce the moisture resistance of asphalt mixes under repeated loading.

The effectiveness of the Hamburg Wheel Tracking Device (HWTD) test to determine moisture sensitivity of asphalt mixes was evaluated by testing both laboratory-fabricated specimens and field cores. It was found that the test can correctly identify the effect of anti-strip additives; its results generally correlate with field performance except that the test may sometimes fail mixes that perform well in the field and, in a very few cases, provide false positive results.

A fatigue-based test procedure for evaluating moisture sensitivity was explored in this study based on AASHTO T 321. A test procedure was developed for comparative evaluation of different mixes. Application of the test procedure for use in pavement analysis/design is suggested for expensive projects.

The long-term effectiveness of both hydrated lime and liquid anti-strip agents was evaluated by both the tensile strength ratio (TSR) test and the fatigue beam test. Results showed that both types of treatment are effective in preventing moisture damage for up to one year’s continuous moisture conditioning.

A database with all field and laboratory results has been prepared for Caltrans.

Keywords: Asphalt mixes, moisture damage, stripping, air void content, anti-strip agents, Hamburg Wheel Tracking Test, flexural fatigue response.

Proposals for implementation:

Related documents: *Investigation of Conditions for Moisture Damage in Asphalt Concrete and Appropriate Laboratory Test Methods*, Research Report UCPRC-RR-2005-15, 366 pp; *Moisture Sensitivity Study Database Documentation,* Draft *Technical Memorandum* UCPRC-TM-2006-06, 46 pp.

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PROJECT OBJECTIVES

The goals of this project are to investigate the conditions for moisture damage in asphalt pavements in California and to recommend appropriate test and treatment methods.

These goals were achieved by completion of the following objectives:

1. Perform a statewide field investigation to estimate the effects of different variables on the occurrence and severity of moisture damage and to determine major factors associated with moisture damage in the field, other than aggregate source. To the extent possible with available data, analyze the extent of moisture damage in California.
2. Perform a laboratory investigation to determine the effects of some major factors (air-void content and binder content) on moisture damage. Recommend mitigation measures.
3. Evaluate the effectiveness of the Hamburg wheel tracking device test to determine the moisture sensitivity of asphalt mixes and to predict field performance. To the extent possible with available data, analyze the correlation between lab test results and field performance.
4. Develop and evaluate dynamic loading involved test procedures for determining moisture sensitivity of asphalt mixes. Recommend appropriate conditioning procedures for laboratory tests.
5. Evaluate the effectiveness, especially the long-term effectiveness, of hydrated lime and liquid anti-stripping agents in improving the moisture resistance of hot mix asphalt using both the current and new test procedures.

ACKNOWLEDGEMENTS

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Field data was provided by the Contra Costa County Materials Laboratory and Steve Buckman, and the Washington State Department of Transportation (WSDOT) and Jeff S. Uhlmeyer. Materials were contributed by Graniterock Company in Watsonville, J. F. Shea Co., Inc. in Redding, Syar Industries, Inc. in Solano, Shell Oil Products U.S. in Martinez, Valero Marketing and Supply Company in Pittsburg, Chemical Lime Company, and Akzo Nobel Company.

EXECUTIVE SUMMARY

Moisture damage is the progressive deterioration of asphalt mixes by loss of adhesion between asphalt binder and an aggregate surface and/or loss of cohesion within the binder due to water and water vapor. It is a complex phenomenon affected by a variety of factors. This phenomenon is not fully understood by the pavement engineering community; insufficient knowledge appears to exist in at least three areas: (1) relative significance of factors affecting the damage process in the field; (2) lack of an appropriate laboratory test procedure to assess the effects of moisture on mix response; and (3) the effectiveness of various treatments to reduce moisture damage. Both field and laboratory investigations have been performed in this study to provide additional information in these three areas and have the following objectives:

1. Perform statewide field investigation to estimate the effects of different variables on the occurrence and severity of moisture damage and to determine major factors associated with moisture damage in the field, other than aggregate source. To the extent possible with available data analyze the extent of moisture damage in California.
2. Perform laboratory investigations to determine the effect of some major factors (air-void content and binder content) on moisture damage. Recommend mitigation measures.
3. Evaluate the effectiveness of the Hamburg Wheel Tracking Device test to determine moisture sensitivity of asphalt mixes and to predict field performance. To the extent possible with available data analyze the correlation between lab test results and field performance.
4. Develop and evaluate dynamic loading involved test procedures for determining moisture sensitivity of asphalt mixes. Recommend appropriate conditioning procedures for laboratory tests.
5. Evaluate the effectiveness, especially the long-term effectiveness, of hydrated lime and liquid anti-strip agents in improving the moisture resistance of hot-mix asphalt using both the current and new test procedures.

The field investigation consisted of a general condition survey of nearly 200 California pavement sections, together with data collection on selected projects. Caltrans recommended many of the sections, almost half coming from a list of QC/QA projects statewide and nearly one-fifth chosen by District Materials Engineers or industry professionals in different areas. Nearly one-third of the sections were randomly sampled in Districts 2 and 6 where, historically, moisture damage has occurred. Most of the projects were four to eight years old at the time of the survey. Though not a random sample, the general survey represents pavements encompassing a range of traffic and environmental conditions throughout California.

Based on the general condition survey results, 63 sections were selected for further intensive survey, in which both dry and wet cores were taken near locations of damage and then tested in the laboratory. About 80 percent of these sections were selected because they showed a range of distresses such as raveling and potholes, which might be related to moisture damage. The other 20 percent were termed "control" sections since they did not show any surface distress and were randomly selected. Analysis and subsequent conclusions were based on the information obtained from both the general and the more detailed surveys.

Severe moisture damage was identified in several sections. About 10 percent of pavements with previously undocumented performance in the survey list showed medium or severe moisture damage. This finding cannot be simply extrapolated because it is not based on a random sample. However, it suggests that moisture damage should be a factor to be considered in evaluating asphalt pavement performance in California.

Dry cores revealed that moisture exists in almost every pavement, with values of moisture contents ranging from zero to three percent. In some cases, a significant amount of moisture was observed in pavements that had received little rain for several months.

Air-void content measured from cores was influenced by position in the lane (whether or not in the wheelpath), depth in the pavement, distance from the distressed areas, and construction specifications (whether or not QC/QA project). A strong correlation was determined between moisture content and air-void content with high air-void contents related to high moisture contents. In addition, it was also found that permeability measured on pavements was positively correlated with air-void content.

Statistical analysis, based on an ordered Probit model, was performed on two different data sets: data from cores, and data from all sections in the general condition survey. This model enabled calculation of predicted probabilities for three categories of moisture damage severity as well as marginal effects. These marginal effects indicate how changes in explanatory variables, such as pavement age and traffic, affect the predicted probability that pavements will manifest each moisture damage level. Categories of moisture damage are described in the following table based on visual observation of the sections and cores.

Categories of Moisture Damage in Cores

Moisture Damage Category	Description
Slight stripping or none	Core is intact, integrated without any fines missing
Medium stripping	Core is debonded between two layers. Noticeable quantity of coarse aggregates or fines is missing along the interface or sides or the core. Approximately 10 to 30% bare aggregates exist in cores.
Severe stripping	Core is cracked, or mix is tender or crumbles. Severe loss of materials on sides or interfaces. Over 30% bare aggregates shown in the core.

The Probit model results, based on core data, showed that air-void content, cumulative rainfall, pavement age, the type of underlying layers (PCC or CTB instead of granular), and mix type (DGAC versus RAC-G) were significant at the 90 percent confidence level in affecting moisture damage. The existence of repeated loading (whether or not the core was taken in the wheelpath) had a marginally significant effect but cumulative truck traffic did not appear to be significant. This suggests that simulation of repeated traffic loading should be a factor in assessing moisture damage in the laboratory; however, its existence (but not the total amount) is the significant test parameter. Increases in air-void content, rainfall, and pavement age tend to increase the severity of moisture damage. Based on a limited number of samples, RAC-G mixes did not appear to improve moisture resistance over that for conventional dense-graded mixes.

In contrast, the model results based on the generally surveyed sections showed that additives and pavement age were significant factors. Using additives (hydrated lime or liquid anti-strip agents) tended to reduce the severity of moisture damage. One drawback of the model estimation was that aggregate type was not explicitly included as an independent variable due to the lack of an appropriate method to characterize aggregates. Instead the aggregate was treated as a random effect in the model. It is likely that model estimates would be improved once aggregates can be properly characterized and included.

Case studies on a few severely distressed pavements revealed that in specific cases, one factor or a few may dominate moisture-related damage in pavements. These factors include poor quality aggregate, high air-void content combined with ample source of water, poor pavement drainage design, and inappropriate structural design. High air-void contents were found in the severely distressed pavements in most cases.

The laboratory investigation addressed two issues in detail: (1) evaluation of moisture ingress and retention processes in asphalt mixes and factors affecting these processes, and (2) influence of construction-induced variations on moisture damage.

A soaking-drying test was performed to study the moisture ingress and retention characteristics and influential factors. Results showed that the ingress or evaporation of moisture in the asphalt mixes is not as rapid as expected, and requires a time frame on the order of weeks. The ultimate amount of moisture entering specimens was positively correlated with air-void content, but saturation was insensitive to air-void contents for specimens with seven percent or higher air-void contents. Statistical analysis revealed that air-void content had the strongest influence on the amount of moisture entering asphalt mixes, but aggregate gradation and binder type could also have an influence.

Effect of variations in air-void content and binder content on the moisture sensitivity of asphalt mixes were studied using a flexural beam fatigue test (AASHTO T 321). These two variables, which influence pavement performance, are dependent on construction quality. Results showed that a reduction in the binder content or an increase in the air-void content relative to target values significantly reduced moisture resistance as measured by reduction of the fatigue life of an otherwise good performing mix in a high temperature environment.

The effectiveness of the Hamburg Wheel Tracking Device (HWTD) test to determine moisture sensitivity of asphalt mixes was evaluated using both rolling wheel laboratory prepared specimens and field cores. The test procedure used is similar to that used by most researchers/agencies, such as Aschenbrener et al at the Colorado DOT and Izzo et al at the Texas DOT, with the exception that the water temperature is fixed at 50°C for all mixes. This work was mostly completed prior to publication of AASHTO T 324 (2004), however the equipment is the same and the test procedure is similar. The test procedure correctly identified the effect of anti-strip additives, but underestimated the performance of mixes containing soft binders at a fixed test temperature of 50°C. The correlation between test results and field performance appears to be acceptable with the exception that the test procedure may fail mixes that perform well in the field and, in a very few cases, give false positive results. Further evaluations are necessary to improve the test procedure.

A fatigue-based test procedure for evaluating moisture sensitivity was evaluated. The procedure includes use of the AASHTO T 321 standard and moisture conditioning. The method consisted of evaluation of different mixes using a controlled-strain flexural beam fatigue test performed at 20°C, 10 Hz, and 200με on specimens presaturated using a 635 mm-Hg vacuum for 30 minutes and preconditioned at 60°C for one day. Use of the test procedure for pavement analysis/design was also discussed. The test procedure did distinguish mixes with different moisture sensitivities, and provided a ranking for these mixes consistent with prior field experience. However, variance of the fatigue test results was relatively large. *In the long term this may be a useful test since it has the potential to be incorporated in a mechanistic-empirical pavement design procedure, especially for expensive projects.*

The long-term effectiveness of both hydrated lime and liquid anti-strip agents in improving the moisture resistance of asphalt mixes was evaluated by both the tensile strength ratio (TSR) test and the flexural fatigue beam test. Results showed that both treatments are effective up to one-year of continuous moisture conditioning used in this study.

A database with all field and laboratory results for this project has been prepared for Caltrans.

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1 INTRODUCTION

1.1 Background

While there have been moisture sensitivity problems reported over the years by some Caltrans Districts, e.g., District 2 in the 1980s, it was not until early 2002 that a joint Caltrans/Industry Task Group was formed to address the issue at a statewide level. One of the first actions of this group was to develop a National Seminar on Moisture Sensitivity of Asphalt Pavements under the aegis of the Transportation Research Board of the National Research Council (1). This seminar, funded by Caltrans, was held in San Diego, California during the period February 4-6, 2003. The goals of the seminar were to provide a forum for technology transfer by leading experts in the U.S. and to develop a road map to resolve the problem. It was during this period that Strategic Plan Element, SPE 4.9, was initiated as part of the Partnered Pavement Research Program. The research program, results of which are briefly summarized herein, has utilized the results of the seminar in developing the objectives of this program as described in Section 1.2. This investigation was conducted in the period September 2002 to September 2005.

1.2 Research Objectives

The objectives of this investigation have included the following:

1. Perform a statewide field investigation to estimate the effect of different variables on the occurrence and severity of moisture damage in hot-mix asphalt (HMA), and determine major factors associated with moisture damage in the field, other than aggregate source. To the extent possible with available data, analyze the extent of moisture damage in the State of California highway pavement system.
2. Perform laboratory investigations to determine the effect of some major factors (e.g., air-void content and binder content) on moisture damage in HMA. Recommend mitigation measures.
3. Evaluate the effectiveness of the use of the Hamburg Wheel Tracking Device (HWTD) to determine the moisture sensitivity of HMA and to predict field performance.
4. Develop and evaluate testing procedures involving dynamic loading to determine the moisture sensitivity of HMA. Recommend appropriate conditioning procedures for laboratory tests.
5. Evaluate the effectiveness, especially long-term, of hydrated lime and liquid anti-strip agents in improving the moisture resistance of HMA using both current and new test procedures.

2 STATEWIDE FIELD STUDY TO EVALUATE MOISTURE DAMAGE AND ASSESS CAUSES

2.1 Introduction

The statewide field study included a condition survey of 194 sites, specific project data collection for 63 sections including cores and in-situ permeability tests, and a laboratory test program.

The general condition survey was conducted to provide pavement condition data and to evaluate the extent of possible moisture damage in the pavements so that specific sections could be selected for detailed testing. The locations of the 194 pavement sections are shown in Figure 1(a); the basis for their selection as well as associated mix types and compaction specifications are shown in Table 1 and Table 2. While not a random sample of pavements in California, it does include a range of traffic and environmental conditions. The condition survey was conducted during the period December 2003 to December 2004, with the result that the large majority of the sections evaluated were four to eight years old at the time of the survey.

Table 1: Subdivision of Pavement Sections, Based on Mix Type

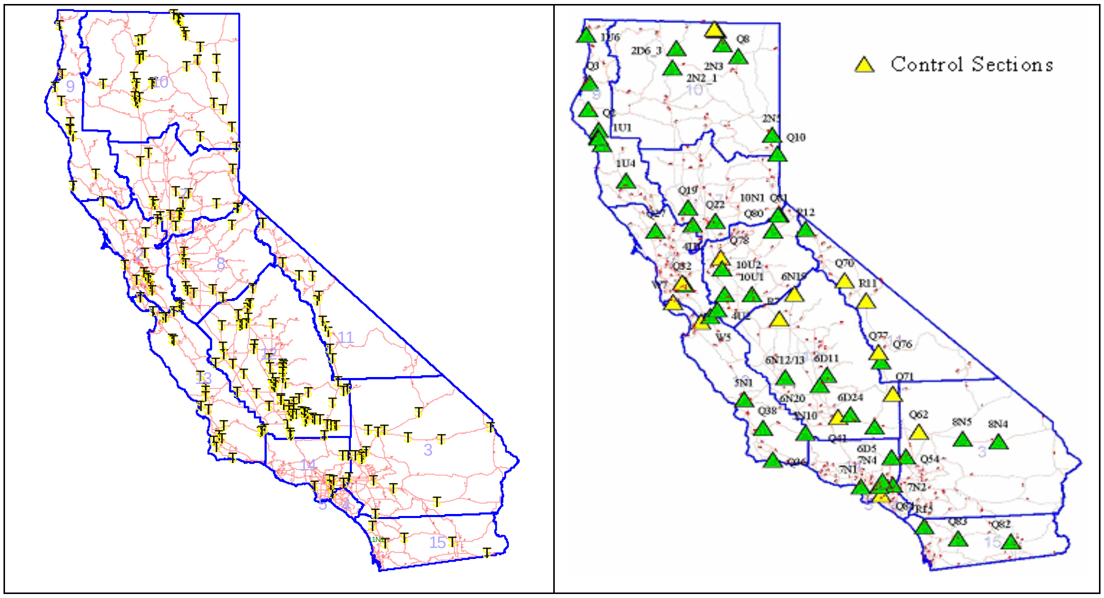
			Mix Type		
			RAC	**DGAC**	**Others**
All 194 projects	Potentially problematic projects 28/26/20*	Recommended by Caltrans, Industry 18/16/12	4/4/4	11/11/8	3/1/0
		Discovered by UCPRC 10/10/8	1/1/1	9/9/7	0/0/0
	Prior performance unknown projects 166/37/14	With visually observed distress 84/24/12	7/3/2	75/21/10	2/0/0
		Without visually observed distress 82/13/2	0/0/0	80/13/2	2/0/0
Total			12/8/7	175/54/27	7/1/0

* Note: The first number represents the number of projects in each category; the second number represents the number of projects that were cored; the third number represents the number of projects that showed moisture damage.

Table 2: Subdivision of Pavement Sections, Based on Construction Specifications

			Construction Specification		
			QC/QA	**Non-QC/QA**	**Unknown**
All 194 projects	Potentially problematic projects 28/26/20*	Recommended by Caltrans, Industry 18/16/12	3/3/2	4/4/3	11/9/7
		Discovered by UCPRC 10/10/8	6/6/5	3/3/3	1/1/0
	Prior performance unknown projects 166/37/14	With visually observed distress 84/24/12	16/1/0	57/20/9	11/3/3
		Without visually observed distress 82/13/2	65/13/2	6/0/0	11/0/0
Total			90/23/9	70/27 /15	34/13/10

* Note: The first number represents the number of projects in each category; the second number represents the number of projects that were cored; the third number represents the number of projects that showed moisture damage.



(a) Condition survey sites **(b) Core sites**

Figure 1: Condition survey and core sites.

2.2 Project Data Collection and Laboratory Tests on Field Cores

Condition surveys were performed at the 194 sites using a field condition survey form included in Reference (2). The extent and severity of all observed surface distress such as cracking, rutting, potholes, segregation, raveling, bleeding, and patching, were carefully recorded and photographed. Geometries and drainage conditions of each of the pavement section were also recorded.

Historical project data including mix design, pavement structure, and construction records, were obtained from Caltrans District Materials Engineers' offices as well as other District pavement design and maintenance offices. Lack of data in some of the District offices limited the number of sections used for analysis.

Traffic information, primarily the annual average daily truck traffic (AADTT), was extracted from traffic information contained in the Caltrans Pavement Management System (PMS) database for the period 1980 to 1997 in the design lane, using the truck lane distribution factors developed from Caltrans Weigh-in-Motion (WIM) data (3). A uniform three percent compound growth rate was assumed for all sections to estimate the cumulative truck traffic to the date of the evaluations.

Climate data, including annual rainfall, freeze-thaw cycles, and degree-days greater than 30°C, were estimated from weather stations in California, Nevada, Oregon, and Arizona contained in the *Climate Data for Integrated Model* (CDIM) software (4). Interpolation of the weather station data was necessary to estimate the climate data at some locations.

Based on the condition survey data, 63 sections were selected for intensive survey, at the locations shown in Figure 1(b). About 80 percent of the sections were selected because they had shown different types of distress, such as potholes, raveling, cracking, rutting, and bleeding, some of which might be related to moisture damage. Pavements showing strong indications of moisture damage (such as frequent potholes and irregular rutting) were also included. The other 20 percent of sections, termed "control" sections, had no observable surface distress. Cores were generally obtained near locations where damage was more advanced. The sampling program was biased toward distressed pavement sections rather than being a random process since the purpose of the study was to estimate the relative contributions of different factors to moisture damage.

Most sections were cored in either the June-to-September or March-to-April periods. At each section, both dry and wet cores were taken in the truck lane at 10 to 20 meter distances from the most advanced surface manifestation of distress. When each core was extracted from the pavement it was quickly labeled, photographed, and sealed in a heavy-duty plastic bag to retain the in-situ moisture content. Close to the coring positions, pavement permeability was measured with the falling-head permeameter (Figure 2).

Figure 2: Falling-head permeameter used in the field.

2.3 Summary of Results

Evaluation of the data obtained from the field study provided the following results.

To obtain a relationship between moisture damage and surface distress, data obtained from dry cores for 49[1] of the 63 pavement sections were used to develop a model making use of an artificial neural network (ANN). This model was then used to estimate potential moisture pavement damage in other sections which had not been cored. Out of the 166 sections with unknown performance before the survey was conducted, analysis of the core

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[1] Some sections were excluded due to limited data.

data showed that 14 sections had appreciable moisture damage, and the ANN estimate revealed another 8 sections that had the potential for significant moisture damage. In other words, about 8 to 13 percent of the randomly selected pavement sections in this study suffered moisture-related problems. Although this does not necessarily reflect the statewide extent of moisture damage due to the fact that the sections used in this study were not completely randomly sampled, it does suggest that consideration of the potential for moisture damage should not be neglected in designing asphalt pavements in California.

An ordered Probit model was selected to examine the influence of material characteristics, pavement structure, and traffic and climate factors on the severity of moisture damage. (The ordered Probit model approach has been used to build discrete deterioration models in infrastructure management in civil engineering [6]). This model enables calculation of predicted probabilities for each category of moisture damage as well as marginal effects. The Probit model was applied twice: to core data from 63 of the 194 projects cored; and, to data from 139 of the 194 sections subjected to condition survey for which relatively complete data sets could be obtained. The model parameters and the marginal effects of independent variables were used.

The model estimates based on sections that were cored showed that air-void content, pavement structure (whether or not underlying PCC or CTB exists), cumulative rainfall (since time of construction), pavement age, and mix type (DGAC or RAC-G) are significant at the 90 percent confidence level in affecting moisture damage. Existence of repeated loading (based on whether or not the core was taken in the wheelpath) has a marginally significant effect but cumulative truck traffic does not appear to be significant. That is, repeated loading from trucks has an effect on the extent of moisture damage, but the intensity of repeated loading, once it exists, does not appear to make a significant difference. Increase in air-void content, rainfall, and pavement age tends to increase the severity of moisture damage. The presence of PCC or CTB instead of granular underlying layers, and use of DGAC mixes instead of RAC-G are associated with decreased damage severity. Limited data suggest that use of RAC-G mixes does not improve moisture resistance any more than use of conventional dense-graded graded mixes.

Model estimates based on the data from the 139 condition survey sections showed that additive and pavement age are significant factors. (These factors did not show as significant in the model based on the core data, likely due to the limited amount of data). Using additives (hydrated lime or liquid anti-strip agents) tends to reduce the severity of moisture damage.

Estimates from both models may be improved by explicitly including the aggregate effect. Unfortunately, an appropriate method to characterize aggregate type was not available during this investigation. Raw aggregate samples were also not available. SMARA (Surface Mining and Reclamation Act of 1975) numbers for aggregate sources were recorded in the database for this project where they were available.

Case studies on a few severely distressed sections revealed that in a specific case, one or a few factors may dominate moisture-related damage in pavements. In these studies, factors included: poor quality aggregate, high air-void content combined with an ample source of water, poor pavement drainage design, and inappropriate structural design. High air-void contents were found in the severely distressed pavements in most cases.

Findings and recommendations to mitigate damage in asphalt from the field studies are summarized as follows:

1. Air-void content should be controlled more strictly during construction to reduce both the average value and standard deviation. For the samples tested in the study, the average air-void content in sections showing little or no moisture damage was about 7 percent; the average air-void content in the sections showing medium or severe damage was 1 to 1.5 percent higher. The standard deviation of air-void content was also greater in sections showing medium or severe damage, indicating greater variability of compaction in sections with problems. It is desirable to reduce the required air-void content of dense-graded mixes to 7 percent during construction.
2. Additives (hydrated lime or liquids) can be used to increase the resistance of asphalt mixes to moisture damage.
3. The pavement drainage system should be well designed and maintained to ensure quick removal of water both on top of and inside the pavement during rain. Since the amount of rainfall has a significant effect on moisture damage and rainfall cannot be controlled by design, it is necessary to have an efficient drainage system to reduce the chance of water getting into and residing in pavements.
4. For RAC-G mixes, further research on their moisture sensitivity should be conducted. At the current stage, the compaction effort during construction may need to be increased to reduce air-void content.
5. From a pavement structure perspective, designs that include a layer with a high air-void content between two layers with low air-void contents should be avoided, especially in areas where high temperatures and heavy traffic exist.

In this study the Probit model was estimated based on 235 core samples or 139 pavement sections, which is relatively small in size. In addition, the lack of complete information of the explanatory variables (e.g., aggregate properties) also limited the applicability of the estimated model. The proposed methodology, however, is appropriate for modeling moisture damage in asphalt pavements. It has the potential to be used as part of pavement management to predict the moisture damage probability in asphalt pavements at any age and to establish possible correlations between laboratory test results and field performance. If moisture sensitivity test results (e.g., tensile strength ratio) are available for the field mixes and included in the model, the model can provide guidelines to determine the acceptance criterion for these test results for pavements in different traffic and environmental conditions.

All data from the field study have been included in a relational database that has been delivered to Caltrans. (5)

3 MATERIALS USED FOR LABORATORY PREPARED TEST SPECIMENS

This section describes the materials used for the laboratory prepared specimens in the studies described in Sections 4, 5, 6, and 7. Also included in this section are some test results for the materials together with a summary of the mix designs and specimen compaction procedures.

3.1 Aggregates

From an evaluation of five potential aggregate sources, two were selected for use in the laboratory experiments. One, termed Aggregate A, was a quarried material from central California; the other, termed Aggregate B, was obtained from a gravel source south of Redding, California. Laboratory tests, including the Texas boiling water test (BWT) (ASTM D 3625-96) and the indirect tensile strength ratio (TSR) test (CTM 371), suggest that Aggregate A has poor compatibility with asphalt. No severe moisture damage, however, has been observed in pavements containing this aggregate. Aggregate B exhibited good compatibility in the BWT. Conventional test properties for the two materials are summarized in Table 3.

Table 3: Aggregate Properties

Aggregate Property		Test Method	Aggregate A	Aggregate B
Specific Gravity	Coarse	CTM 206	2.86	2.63
	Fine	CTM 208	2.74	2.71
Los Angeles Abrasion Tests (% Loss)	100 rev.	CTM 211	8	4
	500 rev.	CTM 211	30	18
Crushed Particles (%)	Coarse	CTM 205	100	100
	Fine	CTM 205	100	100
	Combined	CTM 205	100	100
Sand Equivalent	Combined	CTM 217	76	58
Water Absorption (%)	Coarse	CTM 206	0.94	1.32
Methylene Blue Test (mg/g)	Fine	Ohio DOT Supplement 1052	8.0	4.8
			7.5	4.1
			7.3	4.0

3.2 Asphalts

The two asphalts used were an AR-4000 asphalt cement (PG64-10) and PBA-6 polymer modified binder (PG 58-34M). The AR-4000 asphalt was supplied by Shell Oil Products US, Martinez, California, while the PBA-6a by Valero Marketing and Supply Company, Pittsburg, California. Both asphalts have been used extensively in California; at times the PBA-6a binder has been used to reduce moisture damage in some regions of the state. The basic binder properties were provided by the material suppliers, and are included in Reference (2). *(N.B. The binders were supplied prior to the introduction of the PG grading systems in California [i.e., 2003–04]; the PG grades shown are estimates]*.

3.3 Anti-Strip Treatments

Three additives were used in this project: hydrated lime, supplied by the Chemical Lime Company, used in the amount 1.4 percent by weight of aggregate; and two liquid anti-strip agents, anonymous proprietary products coded “A” and “B″ at an amount 0.75 percent by weight of asphalt (according to the supplier, “A” would be expected to perform better than “B”). This amount of anti-strip additive is higher than normally used (0.25 to 0.5 percent); however, binder tests suggested that the potential softening of the binders resulting from this proportion, other than improving moisture resistance, would not influence the test results.

3.4 Specimen Preparation and Mix Designs

Laboratory specimens prepared included: cylindrical specimens 101.6 mm in diameter by 63.5 mm high for Stabilometer (CTM 366) and TSR (CTM 371) tests; cylindrical specimens 152.4 in diameter by 50.8 mm high for repeated load simple shear tests at constant height (RSST-CH) (AASHTO TP 7-94)[2]; prismatic specimens 63.5 mm wide, 50.8 mm high, and 381 mm long for controlled-strain repeated load flexural fatigue tests (AASHTO T-321); and prismatic specimens 241.3 mm wide, 76.2 mm high, and 330.2 mm long for Hamburg Wheel Tracking Device (HWTD) tests. The Stabilometer and TSR test specimens were compacted using the Triaxial Institute (California) compactor (CTM 304). All other specimens were prepared by rolling wheel (RW) compaction; these specimens were obtained by coring and sawing to shapes noted above (2).

Two aggregate gradations were used, 19 mm medium and coarse (Section 39, California Standard Specifications). Figure 3 shows the gradations plotted on the Superpave grading chart (7).

Mixes containing the two gradations were used for the moisture ingress/egress studies described in Section 4. All other laboratory prepared specimens contained the medium gradation. Details of the specimen preparation procedures are described in Reference (2).

Mix designs, i.e., binder content selection (according to CTM 367), were developed for mixes containing aggregates A and B using the medium gradation and the AR-4000 binder. The resulting binder contents, 5.0 percent for Aggregate A, and 6.0 percent for Aggregate B (mass of aggregate basis) were then used for all laboratory compacted specimens.

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[2] A discussion of the results of the RSST-CH tests has not been included in this summary report. Reference (2) does include these data as well as some discussion of the potential future use of this test to assess the influence of moisture on mix rutting performance.

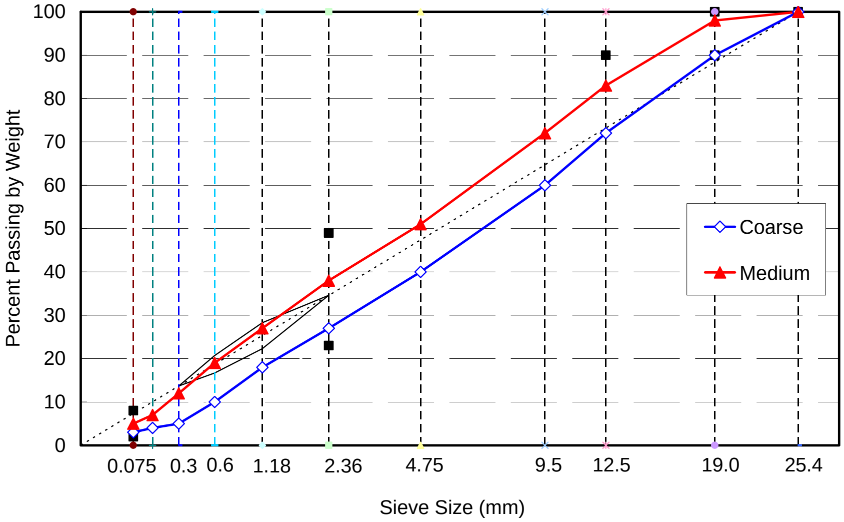


Figure 3: Aggregate gradations (sieve sizes raised to 0.45 power).

4 LABORATORY STUDY TO ASSESS FACTORS ASSOCIATED WITH MOISTURE DAMAGE

The laboratory study described in this section investigated two aspects of moisture damage in detail: (1) the characteristics of moisture ingress and retention processes in asphalt concrete including factors affecting these processes, and (2) the effect of construction-induced variations on moisture damage. An understanding of the first can assist in the design of less water-absorbent mixtures while knowledge of the second provides an indication of the importance of construction quality control for some of the mix parameters.

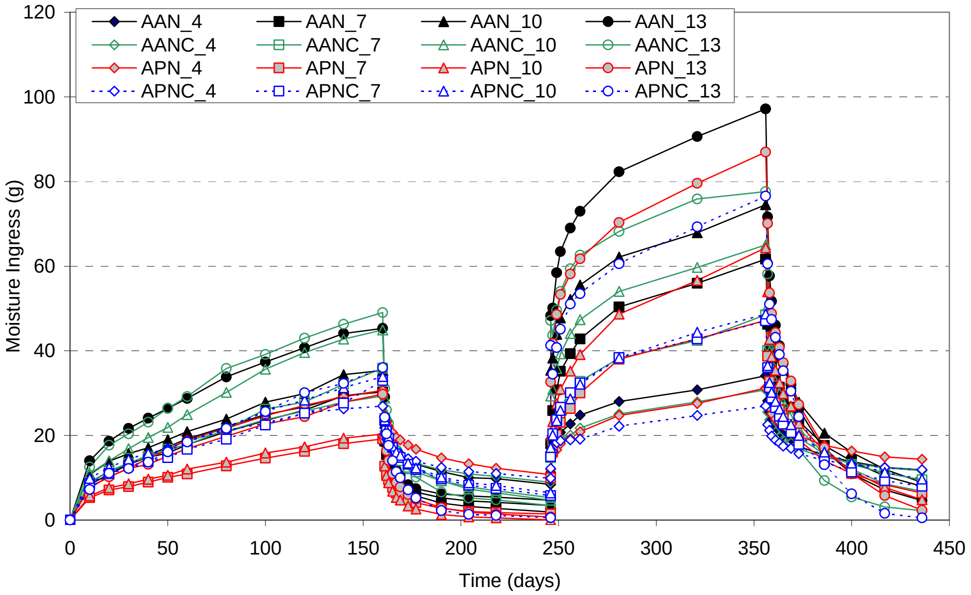
4.1 Moisture Ingress and Retention

Moisture enters the pavement structure in both liquid and vapor form. Liquid water can enter the asphalt mix through the surface or side from precipitation and irrigation by gravity and hydraulic pressure or from the subgrade by capillary action. Moisture vapor, primarily coming from unbound granular layers and the subgrade, moves upward and may be entrapped by the asphalt mix. A laboratory experiment was designed to simulate the movement of both forms of water.

For the moisture vapor study, specimens were first dried to constant mass at 50°C; then placed in a 100 percent relative humidity (RH) environment at 25°C for vapor conditioning. The mass of each of these specimens was weighed periodically until the mass reached a constant value. This process required about four months. The specimens were then placed in an environment at 20°C with an RH in the range 20 to 60 percent for drying after moisture conditioning. The mass of each specimen was then measured periodically until it reached a constant value, which required about three months. This study was intended to simulate in situ conditions with little rainfall but abundant water in the subgrade system.

To simulate the condition of a frequent and ample source of water on the surface or sides of the asphalt mix, the following procedure was followed. Specimens were first submerged in water at 25°C. When the mass of the specimen stabilized, requiring about three months, it was then placed in the same drying environment as used in the vapor conditioning test sequence. Reaching a constant mass for these specimens also required about three months.

Figure 4 illustrates the development of wetting and drying as a function of time. Cylindrical specimens prepared by RW compaction were used for this study. Mixes containing both binders and the medium and coarse gradations were prepared at four levels of air-void content (3-5, 6-8, 9-11, and 12-14 percent) covering the range observed from the field studies. With two replicates, a total of 32 specimens were tested.



In the legend on the figure, the first letter represents Aggregate A; the second letter represents binder type (A, AR-4000; P, PBA-6a); the third letter indicates anti-strip treatment (N, none, LA for liquid A, LB for liquid B, M for lime); the fourth letter represents gradation type (nil, medium gradation; C, coarse gradation); and the last number represents air-void content level as percent air-voids.

Figure 4: Average moisture ingress and retention process (moisture mass).

The moisture ingress process in vapor conditioning was characterized by the Mitscherlich model (8), while the moisture ingress in the soaking and moisture evaporation phases was fitted by a two-segment curve. A nonlinear mixed effect model was then applied for statistical analyses of the relative influence of binder type, aggregate gradation, and air-void content.

As seen in Figure 4, ingress and evaporation of moisture in the asphalt mixes required time to reach equilibrium (3 to 4 months). The ingress rate was higher during the first two weeks than during the later period. The amount of moisture ingress or evaporation during this period was generally comparable to the amount occurring in the first two weeks. This indicates that a good drainage system which can quickly remove water from an HMA pavement surface and intercept rising moisture vapor or capillary water from underneath can significantly reduce the amount of water entering asphalt pavements, even in a region with heavy rainfall.

The ultimate amount of moisture in specimens, estimated from the curve-fitting was found to be generally positively correlated with air-void content during vapor conditioning or soaking and insensitive to the air-void content during drying. Saturation, however, is insensitive to air-void contents for specimens with 7 percent or higher air-void contents in all conditioning processes. During vapor conditioning, around 30 to 40 percent saturation was reached by specimens with 7 to 13 percent air-void content, while specimens with 4 percent air-void content attained a higher saturation level, around 80 percent. During the soaking conditioning, approximately 50 to 80 percent saturation occurred in specimens with 7 to 13 percent air-void content, while specimens with 4 percent air-void content had about 80 to 90 percent saturation. In the drying process, after vapor conditioning or soaking, the asymptotic residual saturation was reduced to about 30 percent for specimens with 4 percent air-void voids, but less than 15 percent for specimens with higher air-void contents. The above observations suggest that it is reasonable to specify the same saturation range (e.g., 50 to 80 percent) in a moisture sensitivity test for specimens with different air-void contents (greater than 5 percent). For specimens with air-void contents less than 5 percent, it may be more appropriate to directly specify a higher level of the order of 80 to 90 percent.

Statistical analysis revealed that air-void content has the strongest influence on the amount of moisture entering asphalt mixes, but aggregate gradation and binder type also have an effect. Under the same conditions, mixes containing the AR-4000 binder absorbed more moisture than mixes containing the PBA-6a binder. The effect of aggregate gradation differed with different conditions. To reduce the potential for moisture ingress as well as the actual quantity of moisture entering the asphalt concrete, air-void content should be strictly controlled to as low a level as practical during construction.

4.2 Effect of Construction-Induced Variations in Mixes

There are a number of construction-related factors that can influence the performance of asphalt concrete. For example, in the field study summarized in Section 2, standard deviations in air-void contents for the cores from individual sections varied from 1 to 3.5 percent. This investigation has been limited to evaluation of mix performance resulting from variations in air-void content and asphalt content relative to specific target values.

For this phase of the investigation, a flexural fatigue test procedure (described in detail in Reference [2]) was utilized. Two test series were conducted: the first to simulate the field condition where a large amount of moisture exists in the pavement for a short period at a mild temperature; and the second to simulate the field condition where pavements contain abundant moisture for a long period or at a high temperature, with the assumption that higher temperatures accelerate damage in the same manner as extended exposure periods. For these two test series only the mix containing Aggregate B and AR-4000 asphalt cement, the medium grading, and without anti-strip treatment (BAN) was used.

In the first test series, three air-void contents (4, 7, and 10 percent), two binder contents (optimum, 6 percent and low, 5.5 percent), and two preconditioning procedures, dry and wet, were utilized. For dry preconditioning, beam specimens were not conditioned with water and were stored in a 20°C room before testing. For each beam specimen, wet preconditioning included partial saturation in a vacuum of 16 kPa absolute pressure (635 mm-Hg vacuum) for 30 minutes, and then immersion in a 25°C water bath for 24 hours. Two replicates were tested at each combination of factor levels, requiring a total of 24 specimens.

In the second series, mixes with three air-void contents (5, 8, and 11 percent[3]) and three binder contents (6, 5.5, and 5 percent) were included. The water bath temperature in the wet preconditioning procedure was changed from 25°C to 60°C, while the other preconditioning steps remained the same as in the first series. Because mix materials (aggregate and binder) were depleted after the first experiment and were re-obtained from the suppliers a few months later, additional specimens were also tested in the dry condition to eliminate the influence of material variations. Thus, a full factorial, 36 specimens, was tested.

The Strategic Highway Research Program (SHRP) developed four-point flexural fatigue controlled-strain test was used (AASHTO T-321). Test conditions included: temperature, 20°C; strain level, 200με; and loading frequency, 10 Hz. The equipment for saturation and testing are shown in Figure 5. When the beams were moisture conditioned, they were immediately wrapped with Parafilm prior to placement in the fatigue test unit.

The major findings from the two experiments are:

1. In both moisture conditioning procedures, moisture reduced the stiffness of the HMA. However, the reduction is not significantly affected by the variation in air-void content or the binder content.
2. In the controlled-strain flexural beam fatigue test, when moisture was present for a short period of time at a mild temperature in a mix with relatively good moisture resistance, the fatigue performance of the mix at a given strain level was improved rather than compromised. This results from the fact that in a controlled strain test reduced stiffness results in a lower stress level; hence a longer fatigue life. Variation in air-void content or in binder content did not significantly change the adverse effect of moisture. However, this does not mean that fatigue life would necessarily be increased in an actual pavement structure. Stiffness reduction induced by moisture would lead to larger strains and therefore may lead to a reduced fatigue life of the pavement.
3. At high conditioning temperatures, however, the fatigue response of a mix was reduced by the presence of moisture, especially at a binder content 0.5 percent or more lower than the optimum binder content, or at an air-void content equal to or higher than 11 percent, or a combination of both conditions.

Both experiments have demonstrated that the control mix (BAN) exhibited good resistance to moisture damage at its optimum binder content and design air-void content (7 to 8 percent). Increased air-void content led to reduced stiffness and fatigue life. In addition, a reduction in the binder content or an increase in the air-void content produced a significant reduction in the moisture resistance of the mix in repeated loading at a fixed strain level. This was demonstrated by the high temperature conditioning test series. These data emphasize the

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[3] Because of a limited amount of material available, specimens containing slightly higher air-void contents were used.

importance of quality control during construction; i.e., insuring adherence to target values (e.g., binder content and air-void content) together with uniformity (low standard deviations) in these parameters.

For the mix used in the study, it is also important to note that considering only the reduction in mix stiffness did not show the adverse effects of variation in binder content and air-void content on moisture resistance of the mix. This suggests that caution must be exercised in the use of test procedures that do not include repeated loading to evaluate or predict moisture damage in asphalt mixes.

(a) Beam vacuum saturation equipment.

(b) Four-point beam fatigue test unit.

(c) Fatigue test system

Figure 5: Moisture conditioning and flexural fatigue test equipment.

4.3 Summary

The laboratory study for moisture ingress and retention revealed that air-void content is by far the most important factor influencing the amount of moisture entering asphalt mixes. Binder type and aggregate gradation also have an effect but to a much lesser extent. The laboratory study to evaluate some effects of construction-induced variation demonstrated that a reduction in binder content or an increase in the air-void content will significantly reduce the moisture resistance of a good performing mix under repeated loading in an unfavorable environment (i.e., high temperatures).

Both the field and laboratory investigations have conclusively demonstrated that the air-void content of a mix is a very important factor affecting moisture damage in asphalt pavements. Higher air-void contents not only allow more moisture to enter pavements, especially in areas with heavy rainfall, but also significantly reduce the fatigue resistance of mixes in wet conditions. It is necessary to strictly control air-void content during construction, preferably to a level of 7 percent or lower. A good pavement drainage system is also necessary to mitigate moisture damage, even for mixes with low air-void contents.

5 EVALUATION OF HAMBURG WHEEL TRACKING DEVICE (HWTD)

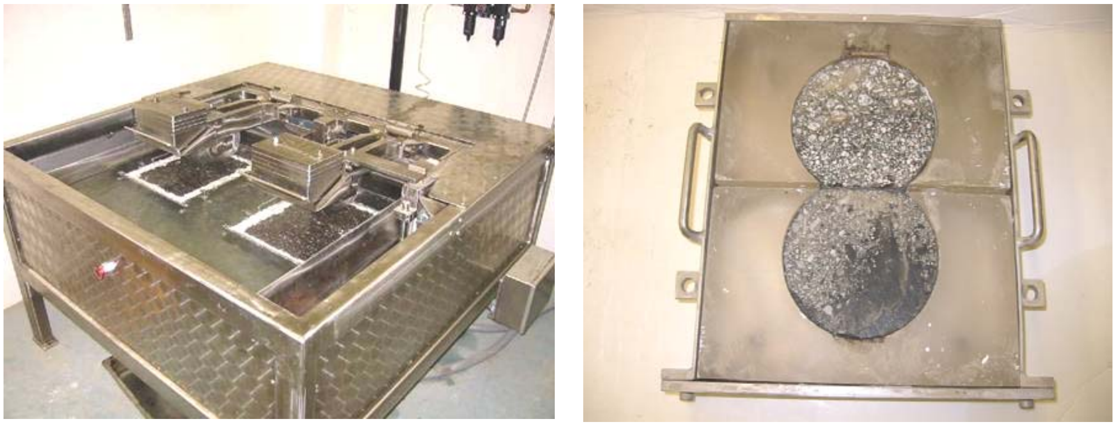
The Hamburg Wheel Tracking Device (HWTD) was introduced into the U.S. in the early 1990s by pavement officials and engineers after a scanning tour of European countries (9). Some research has been conducted into validating the effectiveness of the test and correlating the test results with field performance, and the findings seemed to be promising (9, 10). In order to consider the HWTD as a potential near-future substitute for the TSR test, more research is needed to verify its effectiveness for a broad range of material types and field conditions, particularly in areas such as California where the test has not been evaluated. This section describes an investigation in which a common HWTD test procedure was evaluated using laboratory-fabricated specimens and cores from in-service asphalt pavements as described in previous sections.

5.1 Hamburg Wheel Tracking Device, Equipment, and Specimens

The Hamburg Wheel Tracking Device used in this study was manufactured by the Precision Machine & Welding Company located in Wichita, Kansas. The device can test two specimens simultaneously using two reciprocating steel wheels. Each wheel has a diameter of 0.2 m and a width of 0.047 m. The weight of each wheel is fixed at 72 kg, producing an average contact stress of about 0.7 MPa. Specimens are tested under water and the temperature is adjustable from 5°C to 80°C; in this investigation a temperature of 50°C was used. Rut depth at the specimen surface is measured by a linear variable displacement transducer (LVDT) on each wheel with a range of measurement of deformation 0 to 30 mm, ±0.01 mm. Measurements are taken along the length of the slab at 11 equally spaced points, including the center point. The machine is capable of running up to 200,000 cycles. A test is stopped when a specified number of cycles or limiting deformation is reached, e.g., 20,000. If one sample reaches the preset deformation, the wheel rises, and the other sample continues until the test is complete. A maximum of about nine hours is required for a test.

Test specimens may be either prismatic (typically 0.26 m wide, 0.32 m long, and 0.076 m thick) or cylindrical (0.15 m diameter and 0.076 m high) and may be laboratory prepared- or field cores. In this study both RW-compacted prismatic specimens and field cores were tested. Laboratory prepared mixes were aged at 135°C for four hours (2). It should be noted that at this time there is no standard specimen preparation or test procedure in use (2). The test procedure used in this study is described in Reference (2). Figure 6 shows the test equipment and the specimen holder when cylindrical specimens (cores or laboratory prepared) are used.

Figure 7 illustrates a typical rut depth progression curve of a mix during the test. Several characteristics of the relation are defined, including the creep slope, stripping slope, and stripping inflection point. The creep slope is related to rutting from plastic flow, the stripping slope to moisture damage, and the stripping inflection point to the number of passes at which an abrupt increase in slope occurs.



(a) Test equipment **(b) Core specimen holder**

Figure 6: Hamburg Wheel Tracking Device and cylindrical specimen holder.

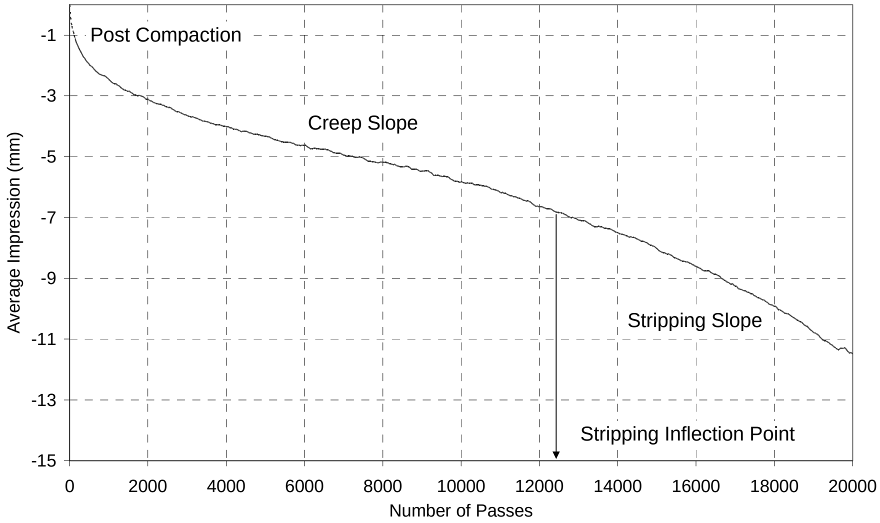


Figure 7: Representative HWTD test results.

The factors included in the laboratory evaluation were as follows: two aggregate types: A and B; two binder types: AR-4000 and PBA-6a; three additive conditions: nil, hydrated lime (1.4 percent by weight of dry aggregates), and liquid anti-strip Agent A (0.75 percent by weight of asphalt).

As stated in Section 3: based on laboratory test data, Aggregate B exhibited better compatibility with asphalt than Aggregate A; based on field performance data, mixes containing a PBA-6a binder exhibited better moisture resistance than mixes containing an AR-4000 binder; and based on both laboratory tests and field performance data, treated mixes demonstrated better moisture resistance than untreated mixes. A full factorial design was used for the study. For the three factors listed above and two replicates a total of 24 specimens were required. Mixes containing the medium gradation were compacted to air-void contents of 7± 1 percent, a range now considered typical for newly constructed pavements in the field.

Core testing in the HWTD used four of the eight wet cores (0.15 m in diameter) taken from each of the pavement sections described in Section 3, two from between the wheelpaths and two in the wheelpath. In a few cases where wet cores were only taken from between the wheelpaths, four rather than two were tested. Two cores from the same location (i.e., either in the wheelpath or between the wheelpaths) were combined to form one test specimen, Figure 6(b). A total of 210 cores (105 specimens) were tested from 57 of the 63 pavement locations.

It should be noted that cores from in-service pavements have not been tested to date elsewhere in the HWTD; rather, the use of this test has been limited to laboratory-mixed, laboratory-compacted specimens (LMLC), or laboratory-compacted specimens made from newly-placed field mix (FMLC). Cores from in-service pavements have usually experienced traffic and environmental conditioning prior to testing; thus their response may be different from that of the fresh mixes. Accordingly, the tests on the cores in this study should be considered as an initial study that potentially might be used for HWTD validation in the future.

5.2 Analyses of Test Results

Rut depths at 10,000 and 20,000 wheel passes were extracted from test results for the laboratory test specimens from the factorial with the three mix variables. The rut depth at 20,000 passes was obtained by linear extrapolation for specimens where testing was terminated before reaching 20,000 passes. It was observed that mixes containing the two binders showed significantly different responses in the HWTD test. No moisture damage was evidenced in the mixes containing the AR-4000 binder, with the exception of the untreated mix containing Aggregate A; i.e., for these mixes, the stripping inflection point occurred at more than 20,000 passes and rut depths at 20,000 passes were all smaller than 10 mm. On the other hand, poor results were observed in the majority of mixes containing the PBA-6a binder. Rut depths at 20,000 wheel passes were generally significantly larger than 10 mm and a significant amount of fines appeared at the top surface of the specimens. These results suggest that mixes containing the PBA-6a binder would be more susceptible to moisture damage than mixes containing the AR-4000 binder. This is contrary, however, to the information discussed in Section 2; i.e., mixes containing the PBA-6a binder have been used as one of the measures to reduce moisture damage in mixes in some regions of California. One possible reason for the result in the HWTD test is that mixes containing the PBA-6a binder have a lower stiffness than mixes containing the AR-4000 binder for the temperature and loading conditions used in this investigation. This likely contributed to the plastic flow and deep ruts obtained in these specimens and may not necessarily be related to moisture damage.

Analysis of variance (ANOVA) was used to evaluate the capability of the HWTD to distinguish aggregates and treatments with different moisture sensitivities. Rut depths at 10,000 and 20,000 passes were selected as the response variables. Inferences obtained from the results for both sets of measured rut depths were the same.

Aggregate type was not considered significant. Mixes treated with hydrated lime showed smaller rut depths than mixes treated with the liquid anti-strip agent and both had smaller rut depths than those for the untreated mixes. Mixes containing AR-4000 binder showed much smaller rut depths than mixes containing PBA-6a binder.

For the field cores, performance of the pavement sections tested in the HWTD was determined from the pavement condition survey and visual inspection of dry cores The performance was evaluated on a scale of ordered discrete values with the emphasis placed on moisture related distresses (e.g., stripping) as shown in the following table:

Table 4: Performance Rating System for Cores from Field Survey

	Condition
1 (Good)	Pavement has no distress. Core is intact.
2 (Fair)	Pavement has slight raveling, cracking, or segregation. Core is debonded, but only slight stripping exists on the debonded interfaces, or slight amount of fines missing along the core sides.
3 (Poor)	Pavement has significant distress. Mix is weak, with severe loss of coarse aggregates in the cores. Core is cracked into more than one piece and shows 40 to 60 percent stripping.
4 (Very Poor)	Pavement has severe distress. Core is totally disintegrated with over 60 percent stripping.

Although two replicates were tested for each pavement section, generally one sample was from between the wheelpaths and the other from the wheelpath. Since the two samples might produce different test results because they had been subjected to different traffic loading, test results for both were compared to evaluate the difference. For this comparison, stripping inflection points greater than 20,000 repetitions were all reported as 20,000, and nonexistent stripping slopes reported as zero. Test results showed that there was no significant difference between specimens tested from both locations based on the stripping inflection point or stripping slope. However, specimens from between the wheelpaths exhibited smaller rut depths than those from the wheelpath. It is likely that specimens from between the wheelpaths received significantly less traffic than those from the wheelpath. Test results for specimens from between the wheelpaths were used for further analysis since their condition was considered to be more representative of newly placed mixes.

From the initial analysis, using test data from specimens between the wheelpaths, the following observations were noted:

- For all the sections with good field performance, satisfactory HWTD results were obtained.
- For the sections with fair field performance, HWTD results were also reasonable because those fair sections that failed in the test were generally four to eight years old and may show unacceptable moisture damage in a few years.
- For some of the poor or very poor field sections, performance was overestimated by the HWTD.

Since the pavement sections tested contained different mixes with different aggregate gradations, binder types, and in-situ air-void contents, such differences could have a significant effect on the test results. Accordingly, the original data set was reduced and split to exclude possible confounding effects of these factors. Most of the pavement sections sampled contained mixes with dense-graded aggregates (a few contained gap-graded aggregates). Further analysis focused on the sections containing mixes with dense-graded aggregates. Air-void contents of field cores ranged from 3 to13 percent; however, no clear correlation was obtained from the test results; thus no adjustment was made for this factor.

Data from tests on laboratory-prepared specimens suggested that binder type significantly affected the HWTD test results. To exclude its potential confounding effect, the test data on the cores were divided into two subsets—sections containing conventional binders and sections containing polymer-modified binders. For a limiting rut depth criterion of 10.0 mm at 20,000 passes, of the four sections in the poor or very poor categories that contained the conventional binders, two sections exhibited a rut depth smaller than 10 mm. This suggests that the HWTD test can overestimate the performance of mixes containing conventional binders and produce false positive results.

For the mixes containing the polymer-modified binders, the correlation between test results and field performance was better. If 10-mm rut depth at 20,000 passes is used as the pass/fail criterion, three good sections would all pass and four poor or very poor sections would all fail.

Based on the test data obtained in this study, the test parameters shown in Table 5 provide preliminary pass/fail criteria which could be use as a starting point to evaluate newly placed mixes in California with the HWTD.

Table 5: Suggested Performance Criteria for HWTD Test Results on Cores

Characteristic Variable	Mixes Containing Conventional Binders	Mixes Containing Polymer Modified Binders
Stripping Inflection Point, passes	6,000	10,000
Stripping Slope (mm/1000 passes)	1.0	0.8
Rut Depth at 20,000 passes (mm)	12.0	11.0

In summary, the common HWTD test procedure performed on field cores gives satisfactory results for mixes with good performance, but may produce false negative results for mixes with fair performance. For mixes with poor or very poor performance, the test procedure can fail most of them, but may produce false positive results in a few particular cases.

One potential weakness of the field evaluation is that samples were taken from in-service pavements instead of newly constructed ones, which may add variations to the mix properties resulting from environmental effects (e.g., aging) and traffic loading. In this study, the traffic loading effect was reduced by analyzing results of specimens obtained from between the wheelpaths. However, the influence of binder aging was not considered in the analysis. Aging of materials may improve the moisture resistance of mixes, but it is unlikely to significantly change the moisture sensitivities of mixes (i.e., change a moisture sensitive mix to a moisture insensitive mix). Accordingly, conclusions of this field evaluation should likely remain valid.

5.3 Summary

The purpose of this investigation has been to evaluate the effectiveness of an HWTD test procedure using both laboratory-fabricated specimens and field cores. It was found that the procedure can correctly identify the effect of anti-strip additives, but may underestimate the performance of mixes containing soft binders at the fixed test temperature 50°C. The correlation between test results and field performance seems acceptable except that the test procedure may fail mixes that perform well in the field (false negative) and, in a very few cases, give false positive results. It has to be mentioned that the above correlation is limited to testing with in-service field cores. Air-void contents and prior environmental and traffic conditioning were all uncontrollable in the field cores and inevitably increase the variability of the test results. In retrospect, making the following changes to the test procedure might improve the moisture damage results:

1. Use various water temperatures for different binder grades based on the environmental regions where the mixes are used. For mixes with low stiffness, such as those containing the PBA-6a binder, a temperature lower than 50°C may be used so that the excess plastic flow not related to moisture damage can be reduced. This approach has been suggested by some researchers and documented in some state test procedures (e.g., Colorado).
2. Run the HWTD test in dry condition when poor results are obtained from the regular test. By this approach, the confounding effects of aggregate structure, binder stiffness, and others can be minimized, and the effect of moisture can be clearly defined by a ratio or a difference of the test results under both conditions. This requires that the HWTD be capable of maintaining a high air temperature during the test, which can be achieved by adding an air-heating system and an environmental chamber to the device. The potential problem of steel wheels picking up mixes during the test may also need to be solved.

6 DEVELOPMENT OF PERFORMANCE-BASED TEST PROCEDURE TO MEASURE MOISTURE DAMAGE

The investigation summarized in this section briefly describes a flexural fatigue-based test procedure to evaluate the moisture sensitivity of asphalt mixes. Current test procedures to evaluate this mix performance characteristic are not well calibrated to in-situ performance and cannot be used as a part of mechanistic-empirical (ME) pavement design procedures. Thus, the results of a test, such as the repeated flexural fatigue test, which simulates field conditions, can potentially be incorporated as a mix parameter in an ME pavement design procedure with the potential to incorporate moisture effects on asphalt mixes directly in a pavement analysis.

Included in this section are a description of both test and preconditioning parameters together with a comparison of results from the flexural fatigue-based test with those from both the TSR and HWTD tests. Use of this procedure as a part of an ME pavement design process is also briefly discussed.

6.1 Materials, Mixes, and Mix Preconditioning and Flexural Fatigue Test Procedures

Material used for this phase of the investigation included: Aggregates A and B; and the AR-4000 and PBA-6a binders. Mixes were prepared with the two binders, with and without the hydrated lime anti-strip additive, using the medium aggregate gradation. Beam specimens were obtained from slabs prepared by rolling wheel compaction to air-void contents in the range of 6 to 8.5 percent.

Based on the test results presented in Section 2 (Field Mix Study) and Section 4 (Laboratory Mix Study), and a moisture-conditioning duration study using the four mixes noted in the previous paragraph, the following preconditioning procedure was selected: beam specimens were saturated in a 635-mm Hg vacuum for 30 minutes (equipment shown in Section 4) and then placed in a water bath at 60°C for 24 hours. At the conclusion of the soaking period, the beams were cooled to 20°C and wrapped in Parafilm^{TM} which remained on the specimens during the fatigue tests.

The flexural fatigue tests were conducted in the controlled-strain mode of loading using a frequency of loading of 10 Hz and at a temperature of 20°C. This temperature is a representative value for temperature conditions during the rainy season in California, which occurs during the period October to April. Strain levels were 200 and 400$\mu\varepsilon$ for the AR-4000 and PBA-6a mixes respectively (Section 4). Tests were performed on dry as well as the moisture preconditioned specimens. No Parafilm was used for the dry specimens since a study showed its effect on specimen behavior to be negligible.

6.2 Test Data Analyses

Statistical analyses were performed to assess the influence of the parameters used in this study. As reported earlier, mixes containing the PBA-6a binder had significantly lower stiffness than mixes containing the AR4000 binder. Addition of hydrated lime increased mix stiffness, while moisture conditioning generally reduced stiffness. Mixes containing Aggregate A were more affected by moisture than mixes containing Aggregate B. Less stiffness reduction occurred in mixes with PBA-6a binder than those with the AR4000 binder; also, less stiffness reduction occurred in the mixes treated with hydrated lime than in the untreated mixes. These results are consistent with expected field experience; that is, mixes containing the Aggregate B, PBA-6a binder, or hydrated lime would be expected to be more resistant to moisture damage than mixes containing the Aggregate A, AR4000 binder, or no treatment. The initial stiffness ratio (ISR), defined as the moisture-conditioned initial stiffness divided by the initial stiffness without moisture conditioning is shown in Table 6 for all mixes tested.

With fatigue life as the response variable, the relative ranking of mixes based upon a fatigue life ratio (FLR) is still reasonable. FLR is defined as the moisture-conditioned fatigue life divided by the fatigue life without moisture conditioning. As seen in Table 6, mix AAN exhibited an FLR about 0.28, much less than that of the other mixes. This is consistent with the fact that mix AAN, as seen earlier, is sensitive to moisture. The FLR for mix BAN was higher than that of mix AAN; mixes treated with hydrated lime, AAM, and BAM had higher FLRs than the untreated mixes AAN and BAN. Improvement of the FLR with the addition of hydrated lime was more significant for mix AAN than for mix BAN. For mixes containing the PBA-6a binder, a direct examination of the stiffness deterioration curves revealed that, except for mix APN, moisture showed little influence on stiffness deterioration with repeated loading.

Results from the CTM 371 and HWTD test are also shown in Table 6. TSR values were as follows: (1) mixes with Aggregate B, higher than mixes containing Aggregate A; (2) mixes containing the PBA-6a, significantly higher than mixes with AR4000; and, (3) mixes treated with hydrated lime, significantly higher than untreated mixes. Hydrated lime treatment improved the TSR value more in mixes containing Aggregate A than in mixes with Aggregate B. These results are generally consistent with the results from the flexural beam fatigue test, especially when the initial stiffness is used as the response variable.

Table 6: Normalized Fatigue Test Results (FLR), TSR, HWTD Test Results

Mix Type	Preconditioning Temperature 25°C		Preconditioning Temperature 60°C		Tensile Strength Ratio (%)	Rut Depth after 20,000 Passes (mm)
	ISR	FLR	ISR	FLR		
AAN	0.88	0.30	0.63	0.28	29	6.62
AAM	0.91	1.60	0.83	2.13	85	6.82
BAN	0.93	1.31	0.78	0.66	52	7.84
BAM	0.91	1.74	0.86	1.54	91	6.94
APN	0.85	-	0.77	-	47	42.3
APM	1.00	-	1.16	-	86	10.17
BPN	0.94	-	1.06	-	85	56.40
BPM	1.02	-	1.05	-	100	13.73

In Table 6, rut depths greater than 25 mm in the HWTD test were obtained by extrapolation from test data since the test was terminated when the rut depth reached 25 mm. Other response variables, including stripping inflection point and stripping slope, are also included in the table. For the four mixes containing the AR4000 binder, the final rut depths were all very small. In fact, no stripping inflection point had occurred in the test for these mixes except AAN, which showed a very small stripping slope. On the other hand, the four mixes containing PBA-6a binder all showed large rut depth in the test and their stripping inflection points occurred early. As stated earlier, these results may not be necessarily related to moisture sensitivity, but may rather be attributed to the fact that the mixes containing PBA-6a binder have much lower stiffness than the mixes containing AR4000 binder. The data also show that hydrated lime was effective in reducing permanent deformation (rut depth), especially for mixes containing the PBA-6a binder.

6.3 Summary

The test results suggest that the controlled-strain flexural beam fatigue test has the potential for use in evaluating the moisture sensitivity of asphalt concrete mixtures. The initial stiffness ratio (ISR) produced a similar trend to that of the tensile strength ratio (TSR) test and field experience in terms of the relative ranking of various mixes. The relative ranking of mixes based upon the fatigue life ratio (FLR) was generally reasonable in terms of aggregate and treatment types.

An unexpected observation from the fatigue test is that for mixes with relatively good field performance the fatigue life was increased instead of decreased when moisture existed in the mixes. Several reasons might contribute to this result. First, the increased specimen flexibility due to moisture, as reflected by the lower initial stiffness, led to a lower stress level in the controlled-strain test. Second, since the fatigue life was defined as the number of repetitions to *50 percent reduction of the initial stiffness*, a lower initial stiffness also led to a lower final stiffness as the stopping point of the test, which corresponded to more repetitions. Third, for the mixes treated with hydrated lime, lime might further react with asphalt and aggregate and form a stronger bond among the mix components during the preconditioning. Whether the extension of fatigue life due to moisture can occur in the field is uncertain. For the same mix in the pavement, a lower stiffness will lead to higher stress and strain levels under the same wheel load, which may counteract the beneficial effect of moisture. Caution should be paid before extending the laboratory results to the field.

The fatigue test results are not consistent with the HWTD test results, except that both tests revealed the beneficial effect of hydrated lime on the moisture resistance of HMA. In the HWTD test, the binder type tended to significantly influence test results; mixes with PBA-6a binder generally showed a large amount of rutting while those containing AR4000 generally exhibited much less. This is inconsistent, as stated in Section 5, with field experience.

7 EVALUATION OF THE LONG-TERM EFFECT OF ADDITIVES

This section summarizes an evaluation of the effectiveness of anti-strip additives under extended moisture conditioning (up to 12 months) on mix performance. Three conditioning procedures have been used. A measure of their equivalency was obtained from comparisons of their effects on mix performance as measured by changes in tensile strength and fatigue response with time.

7.1 Experiment Design

The two test methods used herein to examine the long-term effectiveness of anti-strip additives are CTM 371 (TSR) and the flexural beam fatigue test procedure (Sections 4 and 6). The mix containing Aggregate A, the AR-4000 binder, and the medium aggregate grading were selected for this evaluation. Anti-strip additives included hydrated lime and both liquid additives, A and B. For the TSR test program, specimens were compacted using kneading compaction to an air-void content of about 6.5 percent. For the fatigue tests, specimens were obtained from slabs compacted by rolling wheel compaction to air-void contents in the range of 6 to 8 percent. Four conditioning periods were used: 0, 4, 8, and 12 months.

For the TSR tests, specimens were conditioned using three procedures:

- "Dry," in which dry specimens were stored in a room at a controlled temperature of 20°C until testing;
- "25°C," in which specimens were first submerged in water under a vacuum of 50 kPa absolute pressure (381 mm-Hg vacuum) for three minutes and then stored in a humid room at 25°C and 100 percent relative humidity (RH) until tested; and
- "CTM 371," which followed same conditioning procedure used in "25°C," followed by a freeze-thaw cycle of 16 hours at -18°C and then 24 hours at 60°C.

Only liquid anti-strip Agent A was used in the TSR program resulting in a total of 108 specimens.

In the fatigue test series, specimens were conditioned Dry (same as TSR tests) or "Wet", in which they were subjected to saturation in a vacuum at 16 kPa absolute pressure (635 mm Hg vacuum) for 30 minutes, and then wrapped in Parafilm, and stored in the same humid room as the "25°C" TSR specimens.

7.2 Summary of Test Results

Measurements for the TSR test series included: indirect tensile strength (ITS), and inspection of the split faces for stripping and broken aggregates. For the fatigue test series measurements included: initial stiffness, fatigue life, and inspection of the split faces, as for the TSR test series. Results of the analyses can be summarized as follows.

Both hydrated lime and liquid anti-strip agents improved the moisture resistance of the control mix (AAN). Mix properties—including indirect tensile strength, flexural stiffness, and fatigue life—were least affected by moisture for the mix treated with hydrated lime (AAM), most affected by moisture for the untreated mix (AAN), and moderately affected by moisture for the mixes treated with liquid anti-strip agents AALA and AALB, with the former mix performing somewhat better than the latter.. These anti-strip agents did not significantly change the mix properties in the dry condition. Hydrated lime did not significantly change the indirect tensile strength or fatigue response, but significantly increased the flexural stiffness in the dry condition.

For a conditioning period as long as one year, both hydrated lime and liquid anti-strip agents were effective in improving the moisture resistance of asphalt mixes. The effectiveness of the hydrated lime and liquid anti-strip agents did not decrease during the 12-months conditioning time used in this study.

There appears to be a reasonable equivalency between the two conditioning procedures, CTM 371 and long-term moisture conditioning using the 25°C procedure. This equivalency provides support for using the CTM 371 conditioning procedure in the laboratory to test the moisture sensitivity of asphalt mixes.

Moisture damage develops with time on a nonlinear scale. At a mild temperature (25°C), damage evolves significantly in the first four months. For the untreated mix, moisture damage continues to develop at a slower rate after four months; for treated mixes, however, no further damage tends to occur after four months.

When moisture remains in the mix for a short period, neither indirect tensile strength nor the flexural initial stiffness can discriminate between mixes with and without treatments. However, fatigue life may show a difference between the untreated and treated mixes. Thus the fatigue life ratio has the potential to be used as the index of moisture sensitivity.

Moisture may reduce or extend the fatigue life of asphalt mixes. For moisture-sensitive mixes, the fatigue life is reduced whenever moisture exists in the mixes. For moisture-insensitive mixes the fatigue life may be extended by moisture. However, as noted earlier, this does not insure longer pavement performance since mix stiffness is likely reduced with the possibility that pavement damage will be increased.

Both visual inspection of stripping and examination of the number of broken aggregates on the split faces can be used as supplementary indices of the moisture resistance of asphalt mixes.

8 SUMMARY

The investigation summarized herein was performed during the three year period from September 2002 to September 2005. It included the following elements: (1) investigation of the factors contributing to moisture damage in asphalt mixes using field and laboratory data; (2) evaluation of the effectiveness of the Hamburg Wheel Tracking Device (HWTD) test for predicting mix performance in terms of moisture damage; (3) comparison of various conditioning procedures for use with the HWTD, California Method CTM 371, and the SHRP-developed flexural beam fatigue test; (4) evaluation of the effect of moisture on flexural stiffness and fatigue responses to provide a fatigue-based test procedure that can be used in a mechanistic-empirical pavement analysis procedure to estimate the influence of moisture on pavement performance; and (5) evaluation of the longer-term (up to one year) effectiveness of anti-strip additives. A brief summary of the findings of these studies include the following:

1. Severe moisture damage existed in some asphalt pavements in California. About 10 percent of pavements with previously unknown performance in the field survey showed appreciable moisture damage. Although this does not necessarily reflect the statewide extent of moisture damage due to the incompletely random sampling used in this study, it does emphasize that consideration of moisture damage should not be neglected in mix design and pavement design and rehabilitation methodologies for asphalt pavements.
2. Substantial knowledge has been gained in terms of the effects of a variety of factors on the occurrence and severity of moisture damage in asphalt pavements. Based on statistical analyses of the data the following factors have a high significance: (1) air-void content of the asphalt mix; (2) pavement structure (whether or not underlying PCC or CTB exists); (3) cumulative rainfall; (4) mix type (DGAC or RAC-G); (5) use of additives; and (6) pavement age (an indicator of long-term exposure to the climate conditions). High air-void contents not only allow more moisture to enter pavements, but they also significantly reduce the fatigue resistance of mixes in wet conditions. Dry cores indicated that substantial amounts of moisture exist in many pavements even several months after rain; moreover, the amount of moisture present in cores is positively correlated with the air-void content. Air-void contents of conventional dense-graded asphalt mixes cored from about 50 sites ranged from 2 percent to 14 percent with a mean of about 7 percent. Based on the information presented herein, improved compaction control during construction to reduce both the mean and variance of air-void contents in pavements definitely would reduce the risk of moisture damage. Reducing the binder content also significantly reduces the moisture resistance of asphalt mixes under repeated loading in terms of fatigue performance and should therefore be closely controlled at the mix design target value.
3. Based on a limited number of samples, RAC-G mixes did not show an apparent advantage in improving moisture resistance as compared to dense-graded mixes with conventional asphalt binders. Severe

stripping has been observed in a few pavement sections using the RAC-G mixes. Higher air-void contents in a number of these mixes compared to the air-void contents of QC/QA dense-graded mixes may be one of the reasons leading to this observed moisture damage.

4. Increased annual rainfall and/or pavement age also increase the probability of moisture damage.
5. Occurrence of repeated loading (whether or not in the wheelpath) had a marginally significant effect on moisture damage but cumulative truck traffic did not appear to be a significant factor. This suggests that simulation of repeated traffic loading should be a factor in assessing moisture damage in the laboratory; however, its existence and not the total number of repetitions is the significant test parameter.
6. The HWTD test procedure used in this study can correctly identify the effect of anti-strip additives, but may underestimate the performance of mixes containing soft binders at the fixed test temperature of 50°C used in this study. The correlation between laboratory test results and field performance seems acceptable except that the test procedure may fail mixes that perform well in the field and, in a very few cases, give false positive results. Improvement of the prediction accuracy of the HWTD test may be obtained by the following two changes to the test procedure: (1) use of a test temperature that is appropriate to the environment where the mix is placed; and (2) running the test in dry condition when poor results are obtained from the regular wet test. Relative to the first suggested change, it would seem more reasonable to determine the temperature based on the seven-day high air temperature instead of the designated high temperature for the PG grade. For the second recommended change, selection criteria proposed in the Colorado DOT Laboratory Procedure 5112 (9) can be followed. With this approach, the confounding effects of aggregate structure, binder stiffness, and others can be minimized, and the effect of moisture clearly identified.
7. Fatigue-based test results (i.e., fatigue life) can identify mixes with different moisture sensitivities, and provide a ranking of mixes consistent with field experience. Initial stiffness measured in the fatigue beam test, however, is not as discriminative as fatigue life. The TSR test results are consistent with fatigue test results and field experience, while the HWTD test results are not with respect to aggregate type and binder type.
8. Moisture has a complex influence on the fatigue response of asphalt mixes in the controlled-strain flexural beam fatigue test. It may extend or reduce laboratory-measured fatigue life depending on the conditioning procedure. At higher conditioning temperatures moisture damage is significantly increased, especially in untreated mixes; whereas, moisture content and conditioning duration have less effect.
9. A performance-based test procedure has been suggested for comparative evaluation of different mixes: controlled-strain flexural beam fatigue test performed at 20°C, 10 Hz, and 200με on specimens presaturated under a 635 mm-Hg vacuum for 30 minutes and preconditioned at 60°C for one day. This procedure can distinguish mixes with different moisture sensitivities and provide a ranking of mixes

consistent with prior engineering experience; however test variance is relatively high. With further evaluation it could become a part of asphalt pavement analysis and design approach to explicitly include the moisture effect.

10. Both hydrated lime and liquid anti-strip agents can improve the moisture resistance of asphalt mixes, as evidenced by the results from both field and laboratory data. Mix properties, including indirect tensile strength, flexural stiffness, and fatigue life are least affected by moisture for mixes treated with hydrated lime and only moderately affected for mixes treated with liquid anti-strip agents. Different liquid anti-strip agents have different degrees of effectiveness. Addition of liquid anti-strip agents does not significantly change the mix properties in the dry condition. Similarly, addition of hydrated lime does not have much influence on indirect tensile strength or fatigue response in the dry condition but does produce an increase in flexural stiffness.
11. For a conditioning period as long as one year, both hydrated lime and liquid anti-strip agents are effective in improving the moisture resistance of asphalt mixes. In this investigation the effectiveness of hydrated lime did not diminish within the time frame investigated and in some cases resulted in continued improvement during the one year period. Effectiveness of the liquid anti-strip agents generally remained constant over the one-year period.
12. There appears to be an equivalency between the following two conditioning procedures: a short-term freeze-thaw cycle and long-term moisture conditioning at the 25°C temperature.
13. Moisture damage develops with time on a nonlinear scale. At a mild temperature, the damage evolves significantly in the first four months, and then levels off.
14. When moisture exists in the mix for a short period, neither indirect tensile strength nor the flexural initial stiffness can discriminate between mixes with and without treatments. However, the fatigue life can show sufficiently the difference between untreated and treated mixes. It is more discriminative to use the fatigue life ratio as the index of moisture sensitivity if very short conditioning periods are used.

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