Title
Warm-Mix Asphalt Study: Summary Report on Warm-Mix Asphalt Research in California

Author
Jones, D.

Publication Date
2014-06-01

June 2014
Summary Report: UCPRC-SR-2014-02

Warm-Mix Asphalt Study: Summary Report on Warm-Mix Asphalt Research in California

Author:
D. Jones

Partnered Pavement Research Center (PPRC) Contract Strategic Plan Element 4.41.2:
Environmental Impacts and Energy Efficiency of Warm Mix Asphalt

PREPARED FOR:

California Department of Transportation
Division of Research, Innovation and System Information
Office of Materials and Infrastructure

PREPARED BY:

University of California
Pavement Research Center
UC Davis, UC Berkeley

DOCUMENT RETRIEVAL PAGE	**Summary Report: UCPRC-SR-2014-02**

Title: Warm-Mix Asphalt Study: Summary Report on Warm-Mix Asphalt Research in California

Author: D. Jones

Caltrans Technical Lead: C. Barros (Caltrans) and N. Gauff (CalRecycle)

Prepared for: Caltrans and CalRecycle	**FHWA No.:** CA152385B	**Work Submitted:** 06/15/2015	**Date** June 2014
Strategic Plan Element Nos.: 4.18 and 4.41.2	**DRISI Task No.:** 2385	**Status:** Final	**Version No.:** 2

Abstract:

Warm mix asphalt (WMA) is a relatively new technology. It was developed in response to needs for reduced energy consumption and stack emissions during the production of asphalt concrete, improved workability and compaction after long hauls and when using lower placement temperatures, and better working conditions for plant and paving crews. Studies in the United States and Europe indicate that significant reductions in production and placement temperatures, and, potentially, in related emissions are possible. However, concerns exist about how these lower production and placement temperatures could influence asphalt binder aging and, consequently, short- and long-term performance, specifically rutting. The overall objective of this warm mix asphalt study was to determine whether the use of technologies that reduce the production and construction temperatures of asphalt concrete mixes influences performance of the mix.

The testing completed in this warm mix asphalt study provided no results to suggest that warm mix technologies should not be used in conventional, gap-graded asphalt rubber, and open-graded friction course mixes in California, provided that standard specified mix design, construction, and performance limits for hot mix asphalt are met. The use of warm mix asphalt has clear benefits when compared to hot mixes. These include significant reductions in, or even elimination of, smoke and odors, lower emissions, improved workability, better working conditions, and better performance on projects with long hauls or where mixes are placed under cool conditions. The slightly higher costs of using warm mix technologies are outweighed by these benefits.

Based on the findings of this study, the use of warm mix asphalt technologies in asphalt mixes is encouraged, especially on asphalt rubber projects, projects in urban areas, and on projects with long hauls and/or where mixes are placed under cool conditions. Given that warm mix asphalt may be produced at significantly lower temperatures than hot mix asphalt (with associated lower aggregate heating temperatures), moisture sensitivity, especially on water-based warm mix asphalt technologies, should be closely monitored in mix design and quality control/quality assurance testing.

Keywords:
Warm mix asphalt, rubberized warm mix asphalt, asphalt emissions, accelerated pavement testing

Proposals for implementation:
Continue with statewide implementation

Related documents:
UCPRC Research Reports: RR-2008-11, RR-2009-02, RR-2011-02, RR-2011-03, RR-2012-07, RR-2013-02, RR-2013-03

Signatures:

D. Jones **1st Author**	J.T. Harvey **Technical Review**	D. Spinner **Editor**	J.T. Harvey **Principal Investigator**	C. Barros **Caltrans Technical Lead**	T.J. Holland **Caltrans Contract Manager**

DISCLAIMER STATEMENT

PROJECT OBJECTIVE

The objective of the Caltrans/CalRecycle/UCPRC warm mix asphalt study is to determine whether the use of technologies that reduce the production and construction temperatures of asphalt concrete mixes influences performance of the mix.

ACKNOWLEDGEMENTS

The University of California Pavement Research Center acknowledges the assistance and interest of Ms. Cathrina Barros, Mr. Joseph Peterson, Dr. T. Joseph Holland, and Ms. Nahid Hosseinzadeh, (retired) from Caltrans; Mr. Nate Gauff and Mr. Robert Fujii (CalRecycle); Mr. Mike Cook (Graniterock Company); Mr. Tony Limas (Granite Construction); Mr. Jack van Kirk (George Reed Construction); Mr. Chris Barkley and Mr. Bill Clarkson (Teichert Construction); Ms. Annette Smith (PQ Corporation); Dr. Everett Crews (MWV Asphalt Innovations); Dr. Sundaram Logaraj (Akzo Nobel Surface Chemistry); Mr. John Shaw and Mr. Larry Michael (Sasol Wax Americas); Mr. Norm Smith (Astec Industries); Dr. Eric Jorda (Arkema); Mr. Dennis Hunt (Gencor), and the UCPRC Laboratory Staff and Accelerated Pavement Testing Team.

REPORTS FROM THE STUDY

The documents prepared during the warm mix asphalt study document data from test track construction, Heavy Vehicle Simulator (HVS) tests, laboratory performance tests, investigations into emissions and binder aging, and longer-term field studies. This suite of documents includes the following series of first-level analysis reports, a technical memorandum, and this summary report.

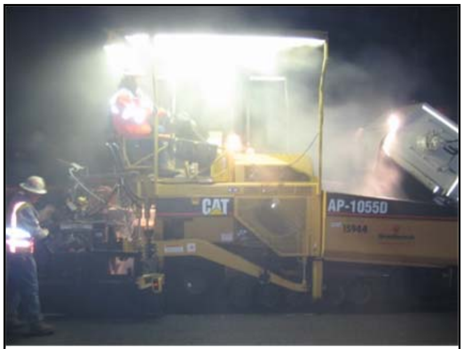
1. Warm-Mix Asphalt Study: Workplan for Comparison of Conventional and Warm-Mix Asphalt Performance Using HVS and Laboratory Testing (UCPRC-WP-2007-01)
2. Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing (UCPRC-RR-2008-11)
3. Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 2 HVS and Laboratory Testing and Phase 1 and Phase 2 Forensic Assessments (UCPRC-RR-2009-02)
4. Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory Prepared Specimens (UCPRC-RR-2012-07)
5. Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1) (UCPRC-RR-2011-02)
6. Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2) (UCPRC-RR-2011-03)
7. Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Binder Aging (UCPRC-RR-2013-02)
8. Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Emissions (UCPRC-RR-2013-03)
9. Warm-Mix Asphalt Study: Field Test Performance Evaluation (UCPRC-TM-2013-08)
10. Warm-Mix Asphalt Study: Summary Report on Rubberized Warm-Mix Asphalt Research (UCPRC-SR-2013-03)
11. Warm-Mix Asphalt Study: Summary Report on Warm-Mix Asphalt Research in California (UCPRC-SR-2014-02)

Blank page

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background


Hot mix asphalt


Warm mix asphalt

Warm mix asphalt (WMA) is a relatively new technology. It was developed in response to demands for reduced energy consumption and stack emissions during the production of asphalt concrete, for better performance after long hauls, lower placement temperatures, improved workability, and better working conditions for plant and paving crews. Studies performed in the United States and in Europe indicate that significant reductions in production and placement temperatures and of potentially related emissions are possible. However, concerns exist about how these lower production and placement temperatures might influence asphalt binder aging and, consequently, both short- and long-term performance, specifically rutting.

The California Department of Transportation (Caltrans) expressed interest in warm mix asphalt with a view to reducing stack emissions at plants, to allow longer haul distances between asphalt plants and construction projects, to improve construction quality (especially during nighttime closures), to improve working conditions during construction, and to extend the annual period for paving. However, the use of warm mix asphalt technologies requires incorporating an additive into the mix, and/or changes in production and construction procedures, specifically related to temperature, which could influence both the short- and long-term performance of the pavement, as well as emissions during production and placement. Consequently, the need for research was identified by Caltrans to address a range of concerns related to these changes before statewide implementation of the technology is approved.

1.2 Project Objective

The research presented in this report is part of Partnered Pavement Research Center Strategic Plan Elements 4.18 and 4.41.2 (PPRC SPE 4.18 and 4.41.2), titled "Warm Mix Asphalt" and "Environmental Impacts and Energy Efficiency of Warm Mix Asphalt," respectively, which were undertaken for Caltrans and the California Department of Resources, Recycling, and Recovery (CalRecycle) by the University of California Pavement Research Center (UCPRC). The overall objective of the warm mix asphalt study was to determine whether the use of technologies that reduce the production and construction temperatures of asphalt concrete mixes influences performance of the mix.

1.3 Structure and Content of This Report

This report presents a summary of all the research on warm mix asphalt carried out in California to date to meet the project objective. Each chapter summarizes a task, as follows:

- Chapter 2: Heavy Vehicle Simulator testing of dense-graded warm mix asphalt (Phase 1: Rutting Performance)
- Chapter 3: Heavy Vehicle Simulator testing of dense-graded warm mix asphalt (Phase 2: Moisture Sensitivity)
- Chapter 4: Laboratory testing of dense-graded warm mix asphalt
- Chapter 5: Heavy Vehicle Simulator testing of gap-graded rubberized warm mix asphalt (Phase 3: Rutting Performance)
- Chapter 6: Laboratory testing of gap-graded rubberized warm mix asphalt
- Chapter 7: Laboratory testing to assess the effect of warm mix asphalt technologies on asphalt binder aging
- Chapter 8: Laboratory testing to assess the effect of warm mix asphalt technologies on emissions during placement
- Chapter 9: Long-term field performance
- Chapter 10: Conclusions and preliminary recommendations

1.4 Terminology

The term “asphalt concrete” is used in this report as a general descriptor for asphalt concrete surfacings. The terms “hot mix asphalt (HMA)” and “warm mix asphalt (WMA)” are used as descriptors to differentiate between the control and warm mixes discussed in this study.

2. HEAVY VEHICLE SIMULATOR TESTING: PHASE 1

2.1 Introduction

Heavy Vehicle Simulator

This phase of the study, which investigated rutting performance on conventional dense-graded asphalt concrete, was based on a workplan approved by Caltrans and included the design and construction of a test track and accelerated load testing using a Heavy Vehicle Simulator (HVS) to assess rutting behavior. A series of laboratory tests on specimens sampled from the test track to assess rutting and fatigue-cracking performance and moisture sensitivity were also undertaken; those results are discussed in Chapter 4.

2.2 Methodology

The study compared the rutting performance of a dense-graded asphalt control mix, which was produced and constructed at conventional hot mix asphalt temperatures (310°F [155°C]), with three warm mixes that were produced and compacted at a temperature 60°F (35°C) lower than the control. The warm mix technologies assessed included *Advera WMA*®, *Evotherm DAT*™, and *Sasobit*®.

2.3 Test Track Construction

The test track was constructed at the Graniterock Company's A.R. Wilson Quarry and Asphalt Plant, near Aromas, California, in September 2007. Design and construction was a cooperative effort between Caltrans, the UCPRC, Graniterock Construction, and the three warm mix technology suppliers. The test track was 262 ft. by 26 ft. (80 m by 8 m) and was divided into four test sections (one control and three warm mixes). The pavement structure consisted of the existing subgrade/subbase material overlying bedrock, with 12 in. (300 mm) of imported aggregate base, and two 2.4 in. (60 mm) lifts of warm mix asphalt concrete. A standard mix design was used and no adjustments were made to accommodate the additives. Target production temperature was set at 310°F (155°C) for the control mix and at 250°F (120°C) for the warm mixes.

2.4 Heavy Vehicle Simulator Testing

HVS testing commenced in October 2007, after a six-week curing period, and was completed in April 2008. This testing compared early rutting performance at elevated temperatures (pavement temperature of

122°F at 2.0 in. [50°C at 50 mm]), using 9,000 lb. and 13,500 lb. (40 kN and 60 kN) loads on a standard dual-wheel configuration and a unidirectional trafficking mode. A total of 835,000 load repetitions, equating to 1.33 million equivalent standard axle loads, were applied over the duration of this phase of the study.

2.5 Observations and Findings

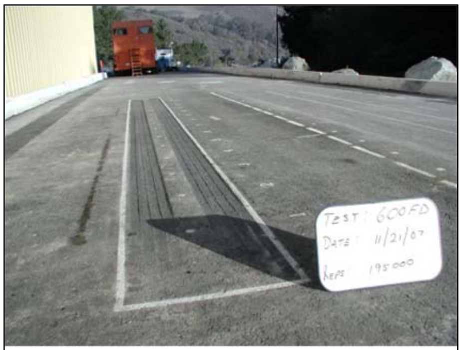
Key observations and findings from the study include the following:

- A consistent base-course was constructed on the test track using materials sourced from the nearby quarry. Thickness and compaction of the base were consistent across the test track.
- Minimal asphalt plant modifications were required to accommodate the warm mix technologies, and the delivery systems were approved under the Caltrans Material Plant Quality Program.
- No problems were noted with producing the asphalt mixes at the lower temperatures. Target mix production temperatures were achieved.
- Although a PG 64-16 asphalt binder was specified in the workplan, subsequent tests by the Federal Highway Administration indicated that the binder was rated as PG 64-22. This did not affect the outcome of the experiment. After mixing Sasobit into the binder, the PG grading changed from PG 64-22 to PG 70-22. The addition of Advera and Evotherm did not alter the PG grade.
- The Control, Advera, and Evotherm mixes met the project mix design requirements. The binder content of the Sasobit mix was 0.72 percent below the target binder content and 0.62 percent below the lowest permissible binder content. This probably influenced performance and was taken into consideration when interpreting the HVS and laboratory test results.
- Graniterock Company did not perform Hveem compaction or stability tests for quality control purposes as there is no protocol for adjusting the standard kneading compaction temperature for mixes with warm mix additives. Instead, Marshall and Superpave Gyratory compaction were performed in the Graniterock laboratory next to the asphalt plant on mix taken from the silo.
- Laboratory quality control tests on the Control mix (specimens compacted with Marshall and Superpave Gyratory compaction) had a higher specific gravity and lower air-void content compared to the mixes with additives. It is not clear whether this was a testing inconsistency or was linked to the lower production and specimen preparation temperatures.
- Moisture contents of the mixes with additives were notably higher than in the Control mix, indicating that potentially less moisture will evaporate from the aggregate at lower production temperatures. All mixes were, however, well within the minimum Caltrans-specified moisture content level (one percent by weight of the mix).
- Construction procedures and final pavement quality did not appear to be influenced by the lower construction temperatures. The Advera mix showed no evidence of tenderness, and acceptable compaction was achieved. Some tenderness was noted on the Evotherm and Sasobit sections, which resulted in shearing under the rollers at various stages of breakdown and/or rubber-tired rolling,


WMA placement

indicating that the compaction temperatures were still higher than optimal. No problems were observed after final rolling at lower temperatures.

- Interviews with the paving crew after construction revealed that no problems were experienced with construction at the lower temperatures. Improved working conditions were identified as an advantage. Tenderness on the Evotherm and Sasobit sections was not considered as being significantly different from that experienced with conventional mixes during normal construction activities.
- Although temperatures at the beginning of compaction on the warm mix sections were considerably lower than the Caltrans-specified limits, the temperatures recorded on completion of compaction were within limits, indicating that the rate of temperature loss in the mixes with additives was lower than that on the Control mix, as expected.
- Some haze/smoke was evident on the Control mix during transfer of the mix from the truck to the paver. No haze or smoke was observed on the mixes with additives.
- Average air-void contents on the Control and Advera sections were 5.6 percent and 5.4 percent respectively. Those on the Evotherm and Sasobit sections, which showed signs of tenderness during rolling, were approximately 7.0 percent, with the caveat that the Sasobit mix binder content was lower than the target while that for the Evotherm sections was not. Based on these observations, it was concluded that adequate compaction can be achieved on warm mixes at the lower temperatures. Optimal compaction temperatures are likely to differ between the different warm mix technologies.
- Skid resistance measurements indicated that the warm mix additives tested do not influence the skid resistance of an asphalt mix.
- HVS trafficking on each of the four sections revealed that the duration of the embedment phases (high early-rutting phase of typical two-phase rutting processes) on the Advera and Evotherm sections were similar to the Control. However, the rut depths at the end of the embedment phases on these two sections were slightly higher than the Control, which was attributed to less oxidation of the binder during mix production at lower temperatures. Rutting behavior on the warm mix sections followed similar trends to the Control after the embedment phase. The performance of the Sasobit section could not be directly compared with the other three sections given that the binder content of the mix was significantly lower.



HVS test section

2.6 Recommendations

HVS test results in this phase showed some differences between the hot and warm mixes in early rutting performance. Consequently, the study recommended that consideration be given to further investigation into the effects of the warm mix asphalt technologies, and their production and placement at lower temperatures, on binder oxidation and aging rates and to performance related to these over the life of the asphalt surfacing. Based on the moisture content of the mixes after production, the study also recommended that aggregate moisture contents would need to be controlled in the stockpiles and that maximum moisture contents may need to be set prior to mix production when using warm mix technologies.

2.7 Reports

The following report was prepared for this phase of the study:

1. JONES, D., Wu, R., Tsai, B., Lu, Q. and Harvey, J. 2008. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2008-11).

3. HEAVY VEHICLE SIMULATOR TESTING: PHASE 2

3.1 Introduction


HVS testing with water

This phase of the study, a continuation of the first phase, involved Heavy Vehicle Simulator (HVS) tests to assess the moisture sensitivity of the mixes and was based on a workplan approved by Caltrans. A series of laboratory tests on specimens prepared with loose mix, sampled and compacted with a rolling-wheel compactor on the day of construction, were also undertaken; those results are discussed in Chapter 4.

3.2 Methodology

HVS testing was carried out on the Control, Advera, Evotherm, and Sasobit sections, adjacent to the sections tested in Phase 1, to assess rutting and cracking performance under water-soaked conditions. Prior to testing, a dam was constructed around each test section and filled with water to a depth of 6 in. (150 mm). Holes were drilled along the length of the section to the bottom of the top lift of asphalt concrete to facilitate soaking. The water level was maintained for 14 days, after which the dam was removed and trafficking started. During testing, a constant water flow of 0.4 gallons (1.5 L) per hour was directed across the section.

3.3 Heavy Vehicle Simulator Testing

HVS testing commenced in August 2008 and was completed in June 2009. This testing compared rutting performance under soaked conditions at elevated temperatures (pavement temperature of 122°F at 2.0 in. [50°C at 50 mm]), using 9,000 lb, 13,000 lb, and 18,000 lb (40 kN, 60 kN, and 80 kN) loads on a standard dual-wheel configuration and a unidirectional trafficking mode. A total of 1.8 million load repetitions, equating to 26.2 million equivalent standard axle loads, were applied over the duration of this phase of the study.

3.4 Observations and Findings

Key observations and findings from the study include the following:

- HVS trafficking on each of the four sections revealed that the duration and rut depths of the embedment phases (high early-rutting phase of typical two-phase rutting processes) on the warm mix sections were approximately half that of the Control, a trend opposite to that observed in

Phase 1. This indicates that the effects of oxidation of the binder at lower production temperatures may only influence performance in the first few months after construction.

- Rutting behavior of the Control and Evotherm sections after the embedment phase was distinctly different from that of the Sasobit and Advera sections. This was attributed to the Control and Evotherm sections being predominantly in the shade of an adjacent shed for most of the day, while the Advera and Sasobit sections were predominantly in the sun for most of the day. It is believed that the rate of aging of the two shaded sections was consequently slower than the other two sections, leading to the difference in performance.


Forensic investigation


Top-down cracking

- The Control and Evotherm tests followed similar trends to each other after the first 80,000 HVS load repetitions and reached the 0.5 in. (12.5 mm) failure point at about 300,000 load repetitions. The Advera and Sasobit tests followed similar trends to the Control after the embedment phase, but with a much slower increase in rut depth. In the interests of completing this phase of the study, the Advera test was terminated after 625,000 load repetitions when the rut depth was 0.45 in. (11.5 mm) repetitions (i.e., before reaching the failure point of 12.5 mm), while the Sasobit test was terminated after 420,000 repetitions when the rut depth was 0.39 in. (9.9 mm).
- A forensic investigation of all the test sections indicated that the rutting was confined to the upper lift of the asphalt concrete. No evidence of moisture damage was noted on any of the sections, although some evidence of debonding between the two lifts of asphalt was noted on the Control section. All sections had some top-down cracking.

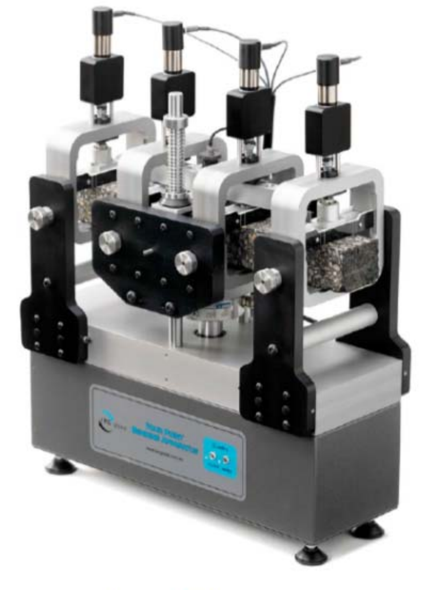
3.5 Reports

The following reports were prepared for this phase of the study:

1. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2009. **Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing and Phase 1 and Phase 2 Forensic Assessments.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2009-02).

4. LABORATORY TESTING: PHASES 1 AND 2

4.1 Introduction


Beam fatigue test

This phase of the study was carried out in conjunction with the accelerated load testing discussed in Chapters 2 and 3 to compare laboratory performance with performance under accelerated loading, and to identify whether the warm mix technologies influenced other performance parameters, such as fatigue cracking and moisture sensitivity. The study was conducted in two phases: the first tested specimens sawn or cored from the test track; the second tested specimens prepared at the test track on the day of construction from loose mix, sampled and compacted with a rolling-wheel compactor (Phase 2a), and specimens prepared in the UCPRC laboratory using aggregate and binder sampled at the asphalt plant on the day of construction (Phase 2b).

4.2 Methodology

The laboratory test program included shear testing, wet and dry fatigue testing, Hamburg Wheel-Track testing, and determination of the wet-to-dry tensile strength ratio.

4.3 Observations and Findings

The laboratory test results indicated that use of the warm mix technologies assessed in this study, which were produced and compacted at lower temperatures, did not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot mix asphalt temperatures. Laboratory test results were influenced by mix production temperatures, actual binder content, specimen air-void content, actual stress and strain levels, and actual test temperature. Variations in these parameters need to be taken into consideration when comparing performance between the different mixes. Specific observations from the laboratory testing include these:

- Moisture sensitivity testing indicated that all the mixes tested were potentially susceptible to moisture damage. There was, however, no difference in the level of moisture sensitivity between the control mix and mixes with warm mix additives.
- All mixes performed significantly better in the Hamburg Wheel-Track Test when subjected to additional curing, indicating that hot and warm mixes are likely to have similar performance on in-

service pavements after a short period of aging (e.g., 6 to 12 months). This finding was consistent with performance on the test track.

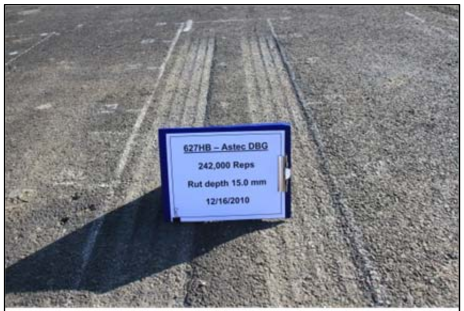
4.4 Reports

The following reports were prepared for this phase of the study:

1. JONES, D., Wu, R., Tsai, B., Lu, Q. and Harvey, J. 2008. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2008-11).
2. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2009. **Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing and Phase 1 and Phase 2 Forensic Assessments.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2009-02).
3. JONES, D. and Tsai, B. 2012. **Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory Prepared Specimens.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2012-07).

5. HEAVY VEHICLE SIMULATOR TESTING: PHASE 3

5.1 Introduction



Phase 3 test section

This phase of the study, which investigated gap-graded rubberized asphalt concrete, was based on a workplan approved by Caltrans that included the design and construction of a test track and accelerated load testing using a Heavy Vehicle Simulator (HVS) to assess rutting behavior. A series of laboratory tests on specimens sampled from the test track to assess rutting and fatigue-cracking performance and moisture sensitivity were also undertaken; those results are discussed in Chapter 6.

5.2 Methodology

The study compared the performance of two gap-graded rubberized asphalt control mixes, which were produced and constructed at conventional hot mix asphalt temperatures (320°F [160°C]), with seven warm mixes, produced and compacted at between 36°F (20°C) and 60°F (35°C) lower than the control. The mixes were produced at two different asphalt plants and are reported as Phase 3a and Phase 3b. Phase 3a included mixes produced at Granite Construction's Bradshaw Plant using *Cecabase RT®*, *Evotherm DAT™*, and *Gencor Ultrafoam GX™* warm mix technologies. Phase 3b included mixes produced at the George Reed Marysville Plant using *Astec Double Barrel Green®*, *Advera WMA®*, *Rediset™*, and *Sasobit®* technologies.

5.3 Test Track Construction

The test track was constructed at the University of California Pavement Research Center (UCPRC) in Davis, California, in April 2010. Design and construction was a cooperative effort between Caltrans, the UCPRC, Granite Construction, George Reed Construction, Teichert Construction, and the seven warm mix technology suppliers. The test track was 360 ft. by 50 ft. (110 m by 15 m) and was divided into nine test sections (two controls and seven warm mixes). The pavement structure consisted of the ripped and recompacted subgrade, 1.3 ft. (400 mm) of imported aggregate base, one 0.2 ft. (60 mm) lift of dense-graded hot mix asphalt, and one 0.2 ft. (60 mm) lift of gap-graded rubberized hot mix (RHMA-G) or warm mix (RWMA-G) asphalt concrete. Each asphalt plant prepared a mix design. No adjustments were made to these mix designs to accommodate the warm mix technologies. Target production temperatures were not set; instead the warm mix technology suppliers set their own temperatures based on experience, ambient temperatures, and haul distance. The production temperature for the Granite Bradshaw RHMA-G Control mix was 320°F (160°C), and 266°F (130°C), 248°F (125°C), and 284°F (140°C) for the Cecabase, Evotherm, and Gencor warm mixes, respectively. Temperatures for the George Reed Marysville RHMA-G Control mix was 335°F (166°C), and 295°F (145°C), 295°F (145°C), 285°F (140°C), and 300°F (149°C) for the Advera, Astec, Rediset, and Sasobit warm mixes, respectively.

5.4 Heavy Vehicle Simulator Testing

HVS testing commenced in June 2010, after a six-week curing period, and was completed in January 2011. Additional testing on three of the sections was conducted in August and September 2011. This testing compared early rutting performance at elevated temperatures (pavement temperature of 122°F at 2.0 in. [50°C at 50 mm]), starting with a 9,000 lb. (40 kN) load on a standard dual-wheel configuration and a unidirectional trafficking mode. A total of 2.2 million load repetitions, equating to 8.1 million equivalent standard axle loads, were applied over the duration of this phase of the study.

5.5 Observations and Findings

Key observations and findings from the study include the following:

- A consistent subgrade was prepared and consistent base-course and underlying dense-graded hot mix asphalt concrete layers were constructed on the test track using materials sourced from a nearby quarry and asphalt plant. Thickness and compaction of the base and bottom layer of asphalt were consistent across the test track.
- Minimal asphalt plant modifications were required to accommodate the warm mix technologies, and the delivery systems were approved under the Caltrans Material Plant Quality Program.
- No problems were noted with producing the asphalt mixes at the lower temperatures. Target mix production temperatures set by the warm mix technology providers were all achieved. There was very little variation in mix properties among the four mixes produced in the Phase 3a study, but there was some variation in binder content among the six mixes produced in Phase 3b due to plant control problems, with the Rediset mix having a significantly higher binder content compared to the design and to the other mixes. Hveem stabilities, determined after three different aging regimes, exceeded the minimum requirement by a considerable margin. Curing did not appear to influence stability. No moisture was measured in the mixes after production.

Test track construction

- Compaction temperatures differed considerably among the mixes and were consistent with production temperatures. The mixes produced at lower temperatures lost heat at a slower rate during transport and placement than the mixes produced at the higher temperatures, as expected. The lower temperatures in the warm mixes did not appear to influence the paving or compaction operations, and interviews with the paving crew after construction revealed that no problems were experienced at the lower temperatures. Improved working conditions were identified as an advantage.

- Smoke and odors were significantly more severe on the control sections compared to the warm mix sections.
- Mix workability, determined through observation of and interviews with the paving crew, was considerably better on the warm mix sections compared to the controls. General consistency of thickness across the track was considered satisfactory and representative of typical construction projects.
- Compaction across the test track appeared to be consistent, confirming that adequate compaction can be achieved on asphalt rubber warm mixes at lower temperatures. Based on observations of the test track construction and interviews with roller operators, optimal compaction temperatures and rolling patterns will differ between the different warm mix technologies. In addition, roller operators will need to consider that there might be differences in roller response between warm mix and conventional hot mixes, and that rolling operations and patterns may need to be adjusted to ensure that optimal compaction is always achieved.


Test track compaction

- HVS trafficking indicated a difference in performance between the mixes from the two asphalt plants:
  + In Phase 3a, HVS trafficking on each of the four sections revealed that the duration of the embedment phases on all sections were similar; however, the depth of the ruts at the end of the embedment phases differed slightly among the sections, with the Gencor (0.26 in. [6.5 mm]) and Cecabase (0.22 in. [5.5 mm]) having less embedment than the Control and Evotherm sections, which had similar embedment (0.31 in. [7.9 mm]). Rut rate (rutting per load repetition) after the embedment phase on the Control and Evotherm sections was almost identical. On the Gencor and Cecabase sections, rut rate was considerably slower than the Control after the embedment phase. The difference in performance between the three warm mix sections is attributed in part to the lower production and paving temperatures of the Evotherm mix compared to the other warm mixes, as well as to the thickness of the asphalt layers (the Evotherm section had thinner asphalt layers than the Control and Cecabase sections). The duration of the tests to terminal rut (0.5 in. [12.5 mm]) on the five sections varied from 42,000 load repetitions on the Evotherm section to 200,000 load repetitions on the Cecabase section.
  + In Phase 3b, HVS trafficking on four of the five sections indicated generally consistent performance among the mixes. Unexpected poor performance was measured on the Advera section (Section 626HA) so additional tests on this section as well as on the Control and Sasobit sections were undertaken to determine the cause and to eliminate possible seasonal and machine-related testing variables. The cause of this poor performance was attributed to a combination of high subgrade moisture content and thinner combined asphalt layers, which were identified during a forensic investigation. The duration of the embedment phases on all sections except the Advera section were similar. Apart from the Advera section, the depth of the ruts at the end of the embedment phases differed only slightly between sections, with the Astec section (0.3 in. [7.5 mm]) having a slightly deeper embedment than the Control, Sasobit, and Rediset sections,

Forensic investigation

which had similar embedment (0.26 in. [6.5 to 6.7 mm]). Rut rate after the embedment phase on the Control and Sasobit sections was almost identical. The rut rate was slightly higher on the Astec and Rediset sections, and was attributed to some moisture in the asphalt layer and subgrade in the Astec section (determined during the forensic investigation), and to the higher binder content on the Rediset section. Although lower production and paving temperatures typically result in less oxidation of the binder, which can influence early rutting performance, differences in production and placement temperatures did not appear to influence performance in this set of tests. The duration of the tests to terminal rut on the five sections varied from 73,500 load repetitions on the Advera section to 365,000 load repetitions on the Sasobit section.

5.6 Recommendations

HVS test results in this and earlier phases showed differences in early rutting performance between conventional and asphalt rubber mixes, between mixes tested after different curing periods, and between pavements subjected to mostly shade and mostly sun, respectively. In line with recommendations from the Phase 1 and Phase 2 studies, this phase of the study also recommended further investigation into the effects of warm mix asphalt technologies, and production and placement of warm mixes at lower temperatures, on binder oxidation and aging rates and to performance related to these over the life of the asphalt surfacing.

5.7 Reports

The following reports were prepared for this phase of the study:

1. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-02).
2. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-03).

6. LABORATORY TESTING: PHASE 3

6.1 Introduction

This phase of the study was carried out in conjunction with the accelerated load testing discussed in Chapter 5 to compare laboratory performance with performance under accelerated loading, and to identify whether the warm mix technologies influenced other performance parameters, such as fatigue cracking and moisture sensitivity.

Hamburg Wheel-Track Test

6.2 Methodology

Specimens were sampled from each section on the test track discussed in Chapter 5 approximately six weeks after construction. The laboratory test program included shear testing, wet and dry fatigue testing, Hamburg Wheel-Track testing, and determination of the wet-to-dry tensile strength ratio.

6.3 Observations and Findings

The laboratory test results indicate that use of the warm mix technologies assessed in this study, which were produced and compacted at lower temperatures, did not significantly influence the performance of the asphalt concrete when compared to control specimens produced and compacted at conventional hot mix asphalt temperatures. Laboratory test results were influenced by mix production temperatures, actual binder content, specimen air-void content, actual stress and strain levels, and actual test temperature. Variations in these parameters need to be taken into consideration when comparing performance between the different mixes. Specific observations from the laboratory testing for the two different mix designs include these:

- Phase 3a
  - Shear performance of the Evotherm and Cecabase mixes did appear to be negatively influenced in part by the lower mix production and construction temperatures, which result in less oxidation of the binder and consequent lower stiffness of the mix. Rutting performance under accelerated load testing (HVS) did not appear to be affected, however. Fatigue performance and moisture sensitivity also did not appear to be affected during the HVS testing.
  - In all the moisture sensitivity tests, the Gencor (water-injection technology) mix appeared to have lower moisture resistance than the other three mixes but in most instances it still met Caltrans-specified performance requirements. This mix was produced at a higher temperature than the other two warm mixes and, like the other mixes, samples taken from the silo contained no moisture.

- Phase 3b
  - Laboratory performance in all the tests appeared to be mostly dependent on air-void content and binder content, as expected, and was less dependent on mix production temperature.
  - The water-based warm mix technology mixes (Advera and Astec) appeared to have lower moisture resistance compared to the other three mixes in all the moisture sensitivity tests.

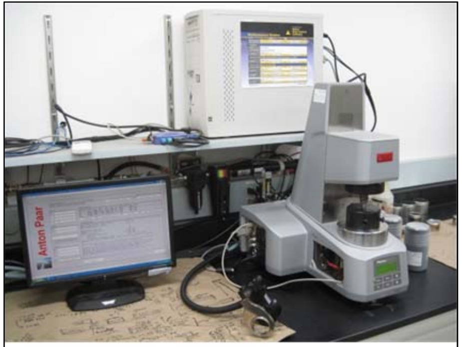
6.4 Reports

The following reports were prepared for this phase of the study:

1. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-02).
2. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-03).

7. LABORATORY TESTING: BINDER AGING

7.1 Introduction



Dynamic shear rheometer

The use of warm mix asphalt technologies allows reduced production temperatures at the plant and during paving and compaction. These reduced temperatures are hypothesized to impact the long-term oxidative aging behavior of the asphalt binder in the mix. This study attempted to quantify these impacts through characterization of field-aged unmodified and asphalt rubber binders extracted and recovered from cores sampled from 13 test sections representing seven different WMA technologies and associated hot mix controls.

7.2 Methodology

A dynamic shear rheometer (DSR) was used to evaluate the binder rheological properties at high temperatures with respect to expected rutting performance. A concentric cylinder geometry testing procedure was assessed as an alternative approach to the conventional parallel plate geometry for testing asphalt rubber binders. A bending beam rheometer (BBR) was used to characterize low-temperature properties.

7.3 Observations and Findings

The following observations and findings were made based on analysis of the results:

- Test results did not appear to be influenced by the warm mix technology chemistry. However, the mix that incorporated an organic wax additive consistently showed better rutting resistance across all the tests, and this was attributed to the residual crystallization wax structure in the binder.
- All the test results appeared to be influenced by production and placement temperatures, indicating that some mixes produced at very low temperatures could be more susceptible to early rutting on pavements that experience high ambient temperatures and high traffic loading.
- Air-void content appeared to have very little effect on the rheological properties of the extracted binder over the aging period assessed, which was not expected.
- Zero shear viscosity (ZSV) was found to be a good indicator of the rheological behavior of asphalt binders with respect to rutting performance, as observed from accelerated load testing. ZSV was also found to be more suitable for describing the rutting performance of asphalt rubber binders than the current Superpave G*/sinδ criterion.
- Viscosity-shear susceptibility was found to be a suitable parameter for understanding the shear sensitivity of asphalt rubber binders. Viscosity-shear susceptibility increased during long-term oxidative aging due to the increased association of polar carbonyl compounds in the binder.

- The nonrecoverable creep compliance and percent recovery parameters obtained from the multiple stress creep recovery test are useful parameters for understanding expected field rutting performance.
- Bending beam rheometer results indicated that the WMA technologies tested did not result in a grade change with respect to thermal cracking properties at low temperatures, with all binders meeting the Superpave criteria at all ages tested. Performance trends for individual binders were consistent with rutting test results.
- The warm mix additives and associated lower production and placement temperatures generally had a limited effect on aging kinetics with respect to long-term field aging, with the exception of the organic wax.
- Laboratory binder aging, specifically in the rolling thin-film oven test, did not always correspond to field aging.

7.4 Reports

The following report was prepared for this phase of the study:

1. FARSHIDI, F., Jones, D. and Harvey, J.T. 2013. **Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Binder Aging.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2013-02).

8. LABORATORY TESTING: EMISSIONS

8.1 Introduction

Emissions testing

The use of warm mix asphalt technologies allows reduced production temperatures at the plant and during paving and compaction. It is believed that their use also reduces emissions from the asphalt. The purpose of this part of the study was to develop and assess equipment for accurately measuring surface emissions during hot or warm mix asphalt paving operations and to quantify any potential environmental benefits during paving operations with respect to the reduction of volatile and semivolatile organic compounds and polycyclic aromatic hydrocarbons. Asphalt plant stack emissions were not assessed as part of this study.

8.2 Methodology

This study developed and assessed equipment for accurately measuring surface emissions during hot and warm mix asphalt paving operations. A transportable flux chamber was fabricated to obtain direct measurements of reactive organic gas emissions and to estimate the fluxes of volatile (VOC) and semi-volatile organic compounds (SVOC) for different asphalt mixes and production temperatures using gas chromatography mass spectrometry. A study to validate the appropriateness of the method was carried out during placement and compaction of the RHMA-G and RWMA-G test sections (three hot mix and seven warm mix, all produced at different temperatures) discussed in Chapter 5. The preliminary results indicated that the method developed was appropriate for accurately quantifying and characterizing VOC and SVOC emissions during asphalt paving. The study was therefore extended to assess other gaseous and particulate polycyclic aromatic hydrocarbon (PAH) emissions from four additional asphalt mixes. Collection of PAHs through a fine particulate filter followed by a sorbent-backed filter with further gas chromatographic/mass spectrometric analysis was investigated. The results were used to quantify the potential benefits of using warm mix asphalt technologies in reducing reactive organic gas emissions.

8.3 Observations and Findings

Based on the results of the study, the following general observations and findings with regard to emissions during asphalt paving were made:

- The developed methodology for characterizing emissions can be used to identify and quantify VOCs, SVOCs, and PAHs in asphalt fumes during production and paving activities.

- In terms of total measured volatile organic compounds, there is a significant difference (a factor of two on average) between emissions concentrations measured from loose mix (e.g., in a truck, windrow, or when tipped into the paver hopper) and those measured from the road surface immediately after compaction.
- The kinetics of emissions over time indicated that the majority of reactive organic gases are volatilized in the first hour after construction.
- Gaseous phase PAH compounds in asphalt fumes are mainly low molecular weight compounds and are present at trace levels. The concentrations varied depending on the temperature of the mix at the time of sampling.
- Particulate phase PAHs were found to be below the detection limit of this study (0.1 ng/µL) for all the mixes (hot and warm) assessed. The results confirmed that the temperature ranges at which the asphalt mixes were produced in this study (123°C to 166°C) were not high enough to initiate significant PAH formation.

The following observations and findings were made with respect to the effect of warm mix asphalt technologies on emissions during paving:

- Alkane emissions consisted of n-hydrocarbons ranging from C8 to C18. Depending on the type of mix and its temperature at the time of sampling, the total alkane emissions from the warm mixes were significantly lower than those measured from the hot mixes (e.g., 117 $\mu g/m^3$ from one of the warm mixes compared to 2,516 $\mu g/m^3$ from the hot mix control).
- In some instances, specific warm mixes had higher alkane concentrations than the hot mix controls. Although these higher concentrations are not a health or safety concern, any generalization with regard to emissions reduction through the use of warm mix asphalt is inappropriate and should be restricted to comparisons of specific warm mix technologies against a hot mix control.
- PAH concentrations correlated with initial mix production temperature, with those warm mixes produced at the lowest temperatures showing the lowest PAH concentrations.

8.4 Recommendations

The use of warm mix asphalt should be considered on any project where emissions are a potential issue (e.g., in urban areas). The reduction (or even elimination) of smoke, haze, and odors, which are common on asphalt rubber projects, are significant when warm mix technologies are used in conjunction with lower production and placement temperatures.

8.5 Reports

The following report was prepared for this phase of the study:

1. FARSHIDI, F., Jones, D. and Harvey, J.T. 2013. **Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Emissions.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2013-03).

9. LONG-TERM FIELD PERFORMANCE

9.1 Introduction


Mendocino field experiment

A number of warm mix asphalt test sections were constructed in California between 2007 and 2010 to assess long-term performance under selected traffic and climate conditions. A range of pavement designs were assessed, but the six projects evaluated in this study focused on open-graded friction courses with polymer-modified (PG 58-34) and asphalt rubber (PG 64-16) binders (three projects each). The main purpose of these experiments was to monitor performance under actual traffic and environmental conditions and to quantify any benefits associated with using warm mix asphalt under specific situations, such as with long hauls, in cool and/or damp conditions, under trafficking by large agricultural equipment, etc. Four of the test sections, which were located near Morro Bay (constructed in May 2008), Point Arena (constructed in September 2008), Orland (constructed in May 2009), and Mendocino (constructed in July 2010), had hot mix controls. Two additional warm mix asphalt projects, located near Marysville (constructed in June 2009) and Auburn (constructed in August 2010), did not include control sections. The warm mix technologies assessed in these projects included Advera, Evotherm, Gencor, Rediset, and Sasobit.

9.2 Methodology

The test sections were monitored biannually from the time they were construction until December 2013. Monitoring included a visual assessment from the shoulder and a photographic record. No physical measurements were taken.

9.3 Observations and Findings

All the sections performed well. On projects with hot mix control sections, the warm mix asphalt sections showed performance equal to the controls. On one project (Interstate 5 near Orland), the warm mix section showed some early minor rutting in the first six months that was not observed on the control. However, after 12 months of trafficking the rut depths on both sections were the same. This early rutting on the warm mix section was attributed to less oxidation of the binder due to the lower production and placement temperatures. Once the rate of oxidation had stabilized (after ± 12 months), rutting performance appeared to be the same, and to progress at the same rate, on both sections. This observation was consistent with observations on earlier accelerated loading experiments and is not considered to be a concern given that rut depths were the same on the control and warm mix sections at the end of the testing/evaluation periods.

Based on the observations in this study, the use of warm mix technologies in open-graded friction course mixes with polymer- and asphalt rubber binders appears to be beneficial, especially on projects that require long hauls and/or placement in cold temperatures. The use of warm mix technologies resulted in improved workability of the mix and better compaction, which should improve durability and prevent early raveling.


Morro Bay field experiment

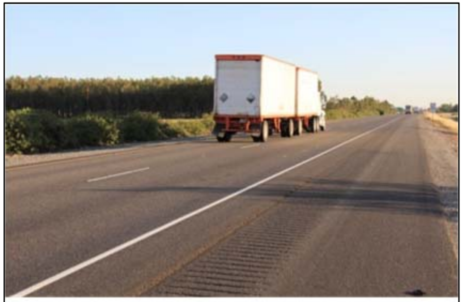
9.4 Reports

The following report was prepared for this phase of the study:

1. JONES, D. 2012. **Warm-Mix Asphalt Study: Field Test Performance Evaluation.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-TM-2013-08).

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions



WMA field experiment

The testing completed in this warm mix asphalt study has provided no results to suggest that warm mix asphalt should not be used in conventional, asphalt rubber, and open-graded friction course mixes in California, provided that standard specified mix design, construction, and performance limits for hot mix asphalt are met. The use of warm mix asphalt technologies in asphalt mixes has clear benefits when compared to hot mixes. These include significant reductions in, or even elimination of, smoke and odors, lower emissions, improved workability, better working conditions, and better performance on projects with long hauls or where mixes are placed under cool conditions. The slightly higher costs of using warm mix technologies are outweighed by these benefits.

10.2 Recommendations

Based on the findings of this study, the use of warm mix asphalt is encouraged, especially on asphalt rubber projects, projects in urban areas, and on those projects with long hauls and/or where mixes are placed under cool conditions. Given that warm mix asphalt may be produced at significantly lower temperatures than hot mix asphalt (with associated lower aggregate heating temperatures), it is recommended that moisture sensitivity, especially with use of water-based warm mix asphalt technologies, be closely monitored in mix design and quality control/quality assurance testing. Care should also be taken on selecting production temperatures for mixes that will be placed on roads with heavy truck traffic in hot climates, as the lower initial oxidation of the binder associated with low production temperatures may lead to early rutting.

Blank page

REFERENCES

1. JONES, D., Wu, R., Tsai, B., Lu, Q. and Harvey, J. 2008. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 1 HVS and Laboratory Testing.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2008-11).
2. JONES, D., Wu, R., Tsai, B., Lu, Q. and Harvey, J. 2008. **Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing, and Phase 1 and Phase 2 Forensic Assessments.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2009-02).
3. JONES, D. and Tsai, B. 2012. **Warm-Mix Asphalt Study: First-Level Analysis of Phase 2b Laboratory Testing on Laboratory Prepared Specimens.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2012-07).
4. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #1).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-02).
5. JONES, D., Wu, R., Tsai, B. and Harvey, J. 2011. **Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing (Rubberized Asphalt, Mix Design #2).** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2011-03).
6. FARSHIDI, F., Jones, D. and Harvey, J.T. 2013. **Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Binder Aging.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2013-02).
7. FARSHIDI, F., Jones, D. and Harvey, J.T. 2013. **Warm-Mix Asphalt Study: Evaluation of Rubberized Hot- and Warm-Mix Asphalt with Respect to Emissions.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-RR-2013-03).
8. JONES, D. 2012. **Warm-Mix Asphalt Study: Field Test Performance Evaluation.** Davis and Berkeley, CA: University of California Pavement Research Center (UCPRC-TM-2013-08).