Part 5: Accelerated pavement testing on asphalt concrete pavements

Advances in Pavement Design through Full-scale Accelerated Pavement Testing – Jones, Harvey, Mateos & Al-Qadi (Eds.)
 ISBN 978-0-415-62138-0

Accelerated loading, laboratory, and field testing studies to fast-track the implementation of warm mix asphalt in California

D. Jones, R.Z. Wu & B. Tsai
University of California Pavement Research Center, University of California, Davis

C. Barros & J. Peterson
California Department of Transportation

ABSTRACT: The use of Warm-Mix Asphalt (WMA) has increased substantially in recent years and considerable funding has been allocated to research on the topic. Some road authorities have implemented its use based only on results from limited testing, while other states have adopted a more conservative approach. Given the significant differences to Hot-Mix Asphalt (HMA) practice and fears of a moratorium on the use of the technology if unexplained problems occur, the California Department of Transportation decided to follow a more conservative approach, by designing and implementing a phased comprehensive study. Phase 1 investigated rutting behavior of three different WMA technologies against an HMA control in an accelerated loading test with associated laboratory testing assessing rutting and fatigue performance and moisture sensitivity. A number of controlled pilot studies were also constructed during this phase. Phase 2 investigated the effects of the same three WMA technologies on moisture sensitivity in an accelerated loading test. Phase 3 investigated the use of seven different WMA technologies in rubberized asphalt following the same testing program used in Phase 1. The findings have been used to prepare a WMA technology approval process and a framework for statewide implementation that resulted in over one million tonnes of warm-mix asphalt being placed on state highways in the 2011 paving season. This paper provides an overview of the California WMA study and summarizes the results of the accelerated load and laboratory testing completed to date.

1 INTRODUCTION

The California Department of Transportation (Caltrans) has an 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), and to extend the annual paving season. However, the use of a warm-mix asphalt technology requires the addition of additives (including water) into the mix, and changes in production and construction procedures, specifically related to temperature, which could influence performance of the pavement. Therefore, Caltrans and the University of California Pavement Research Center (UCPRC) initiated a phased research study including laboratory testing, accelerated load testing and full-scale field studies to assess concerns related to these changes before statewide implementation of the technology was approved. This is a somewhat more cautious approach compared to some other states, but was implemented to ensure that performance is fully understood and that any future pavement failures on projects using warm-mix asphalt are explainable and do not lead to a moratorium on the use of warm-mix asphalt. History has shown that potentially promising technologies are abandoned simply because of a poor understanding of changed design, production and/or construction procedures. Accelerated pavement testing was an integral component in understanding the effects of long-term truck traffic, and reducing the risk of implementation on routes with high truck volumes. This paper describes the study phases completed to date (Jones, et al., 2008, 2009, 2011a, 2011b), the findings of which have been used to prepare a warm-mix asphalt technology approval process and to guide statewide implementation.

Warm-mix technology names are used in this paper for clarification purposes only. Caltrans and the UCPRC do not endorse the use of any specific warm-mix technology.

2 PROJECT OBJECTIVES

The objectives of the California warm-mix asphalt study are to:

- Determine whether the use of additives (including water), introduced to reduce production and construction temperatures of asphalt concrete, influence mix production processes, construction

procedures, and the short-, medium-, and/or long-term performance of hot-mix asphalt.
- Use research findings to guide the implementation of warm-mix asphalt.

A workplan (Jones, et al., 2007) was prepared for meeting these objectives. Research tasks included monitoring the production of different warm mixes and hot-mix controls; monitoring the construction of test tracks with the mixes including the measurement of emissions; sampling of raw materials during production and specimens from the test tracks for laboratory testing; laboratory testing to assess rutting and fatigue cracking performance, and moisture sensitivity; accelerated load testing to assess rutting and fatigue cracking performance, and moisture sensitivity; monitoring the construction and performance of a series of pilot projects on in-service pavements; and preparing specifications and other documentation required for implementing the use of warm-mix asphalt in California. Research has been undertaken in phases. This paper describes the first three phases, which included:

- *Phase 1:* A laboratory and accelerated load test to assess the performance of three different warm-mixes and a hot-mix control in a conventional dense-graded mix. A test track was built for the study. Laboratory testing on both plant-mixed, field-compacted and laboratory-mixed, laboratory-compacted specimens included assessments of rutting performance, fatigue/reflective cracking performance, and effects on moisture sensitivity. Technologies assessed included *Advera®*, *Evotherm DAT®*, and *Sasobit®*. The test track was constructed at the Graniterock Company's Aromas quarry and asphalt plant.
- *Phase 2:* An accelerated load test to assess moisture sensitivity, using the same test track used in the Phase 1 study.
- *Phase 3:* A laboratory and accelerated load test to assess the performance of seven different warm-mixes against two hot-mix controls in a gap-graded rubberized asphalt mix. A new test track was built for the study. Paving emissions were also measured. Laboratory testing protocols were the same as those followed in Phase 1. Technologies assessed included *Advera®*, *Astec Double-Barrel Green®*, *Cecabase®*, *Evotherm DAT®*, *Gencor Ultrafoam®*, *Rediset WMX®*, and *Sasobit®*. Mixes were produced at two different asphalt plants (Granite Construction's Sacramento plant and George Reed Construction's Marysville plant) to accommodate the two different water injection technologies. Mix designs were prepared for each plant. The test track was constructed at the University of California Pavement Research Center (UCPRC) at the University of California, Davis.

The field testing phase, which was undertaken concurrently with the other phases, is described in another paper. More than 20 test sections were constructed around the state on roads covering a range of traffic volumes and climate regions. Most field studies were on thin overlays including open-graded friction courses. Ongoing research includes studies on binder aging in warm-mix asphalt and the use of warm-mix technologies in mixes containing high percentages of reclaimed asphalt.

3 TESTING PROTOCOLS

3.1 *Laboratory*

Plant-mixed, field-compacted laboratory testing was conducted on specimens sawn or cored from 500 mm × 500 mm slabs sawn from the test track approximately six weeks after construction. Laboratory-mixed, laboratory-compacted specimens were prepared using aggregates and binder collected on the days that the mixes were produced for the test tracks. Tests included shear (AASHTO T-320 [Permanent Shear Strain and Stiffness Test]), beam fatigue (AASHTO T-321 [Flexural Controlled-Deformation Fatigue Test]), and moisture sensitivity (AASHTO T-324 [Hamburg Wheel Track Test] and Caltrans CT-371 [Tensile Strength Retained, similar to AASHTO T-283]). In addition to the above, laboratory-mixed, laboratory-compacted specimens were subjected to an open-graded friction course durability test (Cantabro [ASTM D-7064]). Typical experimental plans used in previous UCPRC studies were adopted for this study to facilitate later comparison of results.

3.2 *Accelerated load testing*

Accelerated pavement testing was undertaken with a Heavy Vehicle Simulator (HVS). The test section layout, test setup, trafficking, and measurements followed standard UCPRC protocols (Jones, 2005). The pavement temperature at 50 mm was maintained at 50°C ± 4°C in all phases to assess rutting potential under typical pavement conditions. Infrared heaters inside a temperature control chamber were used to maintain the pavement temperature. In the moisture sensitivity study, each section was presoaked with water for a period of 14 days prior to testing. A 150 mm high soaking dam was constructed around each test section and a row of 25 mm diameter holes was drilled to the bottom of the upper lift of asphalt (i.e. 60 mm), 250 mm away from the section and 250 mm apart. During testing, a constant flow of preheated water (50°C) was maintained across the section at a rate of 15 L/hour to induce moisture damage.

All trafficking was carried out with a dual-wheel configuration, using radial truck tires (11R22.5- steel belt radial) inflated to a pressure of 720 kPa, in a channelized, unidirectional loading mode. Loads started at 40 kN and were increased to 60 kN after 150,000 load repetitions and to 80 kN after a further 100,000 load repetitions. Load was checked with a portable weigh-in-motion pad at the beginning and end of each test as well as after each load change.

Table 1. Phase 1 and Phase 2 test track data.

Parameter	Control	Advera	Evotherm	Sasobit
Binder content (%)[1]	5.3	5.1	5.2	4.5
Prod temp (°C)	155	120	120	120
Pave temp (°C)[2]	135	105	105	117
Ambient temp (°C)	20	20	20	20
Air voids (%)	5.6	5.4	7.1	7.0

[1]Target 5.2%; [2]Behind screed

Table 2. Phase 3 test track data (Mix Design #1).

Parameter	Control	Gencor	Evotherm	Cecabase
Binder content (%)[1]	7.7	7.9	7.7	7.7
Rubber content (%)	18	18	18	18
Prod temp (°C)	160	140	125	130
Pave temp (°C)[2]	154	128	120	128
Ambient temp (°C)	10	10	10	10
Air voids (%)	4.9	6.3	6.2	6.4
Hveem Stability[3]	27	28	27	27

[1]Target 7.3%; [2]Behind screed; [3]Immediate, no curing

Table 3. Phase 3 test track data (Mix Design #2).

Parameter	Control	Sasobit	Advera	Astec	Rediset
Binder content (%)[1]	7.7	8.0	7.6	8.4	10.0
Rubber content (%)	19	19	19	19	19
Prod temp (°C)	166	149	145	145	140
Pave temp (°C)[2]	137	137	130	125	126
Ambient temp (°C)	10	10	10	10	10
Air voids (%)	11.6	8.5	10.7	9.1	8.4

[1]Target 8.3%; [2]Behind screed

Rutting was measured with a laser profilometer and pavement temperatures were monitored using thermocouples imbedded in the pavement. Dedicated nearby weather stations monitored ambient temperature, rainfall, relative humidity, wind speed and direction, and solar radiation.

4 TEST TRACK DESIGN AND CONSTRUCTION

Test tracks were designed and constructed using conventional techniques and equipment and in conformance to Caltrans specifications. The Phase 1 and 2 test track consisted of two 60-mm asphalt concrete layers, over 300 mm crushed stone base, over 250 mm of crushed stone subbase, over bedrock. The Phase 3 test track consisted of a 60 mm rubberized asphalt concrete layer, over a 60 mm hot-mix asphalt layer, over 400 mm of crushed stone base, over compacted subgrade.

The Phase 1 test track was constructed in late summer with mild ambient temperatures. The Phase 3 test track was constructed in early spring with low ambient temperatures and a cold wind. This was intentional to quantify the potential benefits of using warm-mix asphalt for early season paving.

Haul distance for the Phase 1 test track was approximately 1.0 km and consequently there was no heat loss during the haul. Haul distances from the two asphalt plants for the Phase 3 test track were 60 minutes and 120 minutes respectively. Key data for the asphalt concrete on the two test tracks are provided in Tables 1 through 3.

5 SUMMARY OF LABORATORY TEST RESULTS

5.1 *Air void content*

Air-void contents were higher and more variable on the specimens removed from the test track compared to the specimens prepared in the laboratory. There was a bigger variation in the rubberized mixes compared

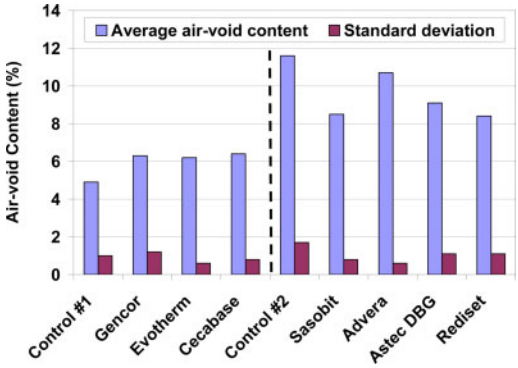

Figure 1. Air void content for Phase 3 test track (Average determined from 65 specimens per mix).

to the dense-graded mixes. This was attributed to a number of reasons including better compaction control and more consistent temperatures in the laboratory compared to the field. The higher air-void contents recorded during construction of Mix Design #2 in the Phase 3 study (Figure 1) were attributed to difficulty with compaction due to higher than expected temperature loss during the longer haul, which resulted in compaction temperatures being lower than optimal. This was expected on the Control section, but should have been better considered by the technology providers when setting production temperatures on the warm-mixes.

5.2 *Rutting performance*

Rutting performance on the specimens removed from the test tracks showed similar trends to the accelerated load test results (discussed in Section 6), with no significant differences between the hot-mix controls and the warm-mixes (example for Phase 1 in Figure 2). Results varied on laboratory prepared specimens, depending on whether the mix was conditioned (four hours at 135°C) prior to specimen preparation or not. On unconditioned specimens, rutting performance on the warm mixes was generally poorer than the controls. This was attributed to less oxidation of the binder and consequent lower initial stiffness of the mixes. On conditioned specimens (typically four hours at compaction temperature), performance was closer to the test track specimens.

5.3 *Fatigue/reflective cracking performance*

There was no significant difference in fatigue cracking performance between the warm-mix and hot-mix specimens in any of the studies, except the *Sasobit* specimens with low binder content from the Phase 1 study, which showed reduced performance, as expected (Figure 3). Laboratory prepared specimens at the correct binder content performed similar to the Control specimens. A limited study to assess small reductions in binder content to counter lower mix stiffness as a

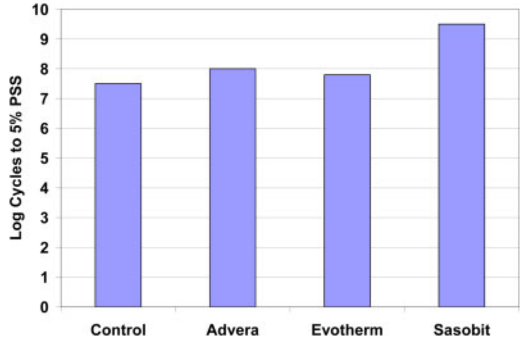

Figure 2. Phase 1 shear test results for specimens removed from test track (PSS = Permanent Shear Strain).

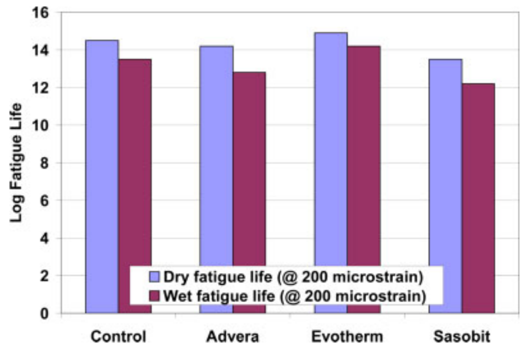

Figure 3. Phase 1 fatigue test results for specimens removed from test track (Tested at 200 microstrain at 20°C).

result of reduced binder aging resulted in a reduction in fatigue performance.

5.4 *Moisture sensitivity*

In the Phase 1 study, Hamburg Wheel Track and tensile strength retained results were generally poor for all mixes (Figure 4), with unconditioned laboratory prepared specimens having lowest performance. In the Phase 3 study, only results for specimens removed from the test track were available at the time of preparing this paper, with results similar for all specimens with little evidence of moisture sensitivity (Figure 5).

5.5 *Open-graded friction course durability*

There was no significant difference in durability between the warm-mix and hot-mix specimens in tests conducted on the Phase 1 aggregates, despite slightly higher drain-down on the warm-mix specimens.

6 SUMMARY OF ACCELERATED LOAD TESTS

6.1 *Phase 1: Early rutting performance on dense-grade*

Testing on the four sections was started in October 2007 and ended in April 2008. The duration of the tests on the four sections varied from 170,000 to 285,000

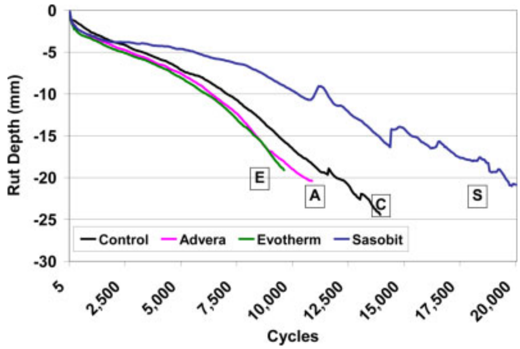

Figure 4. Phase 1 Hamburg Wheel Track test results for specimens removed from test track (C = Control, A = Advera, E = Evotherm, S = Sasobit).

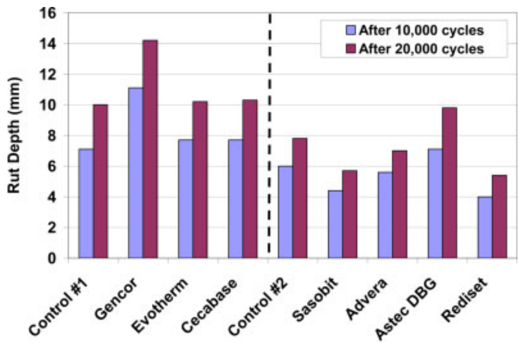

Figure 5. Phase 3 Hamburg Wheel Track test results for specimens removed from test track.

load repetitions. A range of daily average temperatures was experienced; however, the pavement temperatures remained constant throughout HVS trafficking.

Rutting behavior (average maximum rut) for the four sections is compared in Figure 6. The duration of the embedment phases on the *Advera* and *Evotherm* sections were similar to that of the Control; however, the depth of the ruts at the end of the embedment phases on these two sections was slightly higher than the Control. In both instances, this was attributed to less oxidation of the binder during mix production because of the lower plant temperatures and is unlikely to relate to early rutting on in-service pavements with typical California traffic volumes. However, it remains a concern on thick warm-mix pavements with very high truck traffic. Additional binder testing to study effects of the additives and aging at different production temperatures on binder properties is currently being undertaken in Phase 4 to better understand the issue. Rutting behavior on the warm-mix sections followed trends similar to that of the Control in terms of rut rate (rutting per load repetition) after the embedment phase. Note that the performance of the *Sasobit* section cannot be directly compared with the other three sections given that the binder content of this mix was 0.7 percent lower than the other mixes.

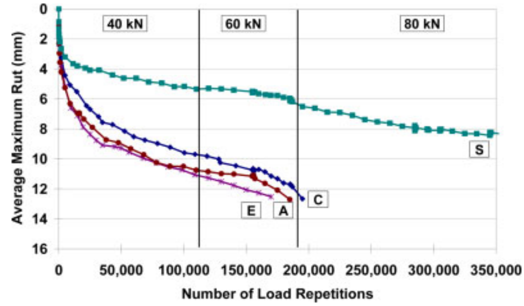

Figure 6. Phase 1 rutting (C = Control, A = Advera, E = Evotherm, S = Sasobit).

6.2 *Phase 2: Moisture sensitivity on dense-grade*

Testing on the four sections was started in June 2008 and ended in May 2009. The duration of the tests on the four sections varied from 352,000 to 620,000 load repetitions. A range of daily average temperatures was experienced during the four seasons of testing; however, the pavement temperatures remained constant throughout HVS trafficking.

Rutting behavior (average maximum rut) for the four sections is compared in Figure 7. The duration of the embedment phases on the warm-mix asphalt sections were shorter than the control, opposite to the behavior in the first phase. Binder extractions and testing is currently being undertaken to better understand this observation. Embedment phases were noted at each load change on all sections.

There was a distinct difference in rutting performance of the *Advera* and *Sasobit* sections compared to the Control and *Evotherm* sections, in that the latter two sections rutted at a notably faster rate than the former two sections. The Control and *Evotherm* sections were predominantly shaded by an adjacent structure for much of the day, while the *Advera* and *Sasobit* sections had sun for most of the day. Binder testing is being undertaken to determine if different aging played a role in this behavior, and the findings will be reported in a separate publication. Trafficking was terminated on the *Advera* and *Sasobit* sections before the failure criterion was met in the interests of completing the study. In forensic investigations undertaken after testing, none of the sections showed any indication of moisture damage, which contradicted the laboratory Hamburg Wheel Track and Tensile Strength Retained test results.

6.3 *Phase 3: Early rutting performance on rubberized asphalt*

This phase was considered as two sub-projects given that mixes came from two different asphalt plants with different mix designs (7.3% binder content on Mix Design #1 compared to 8.3% on Mix Design #2). Load testing was conducted concurrently on both mixes using two Heavy Vehicle Simulators. Testing was started in June 2010 and ended in December 2010.

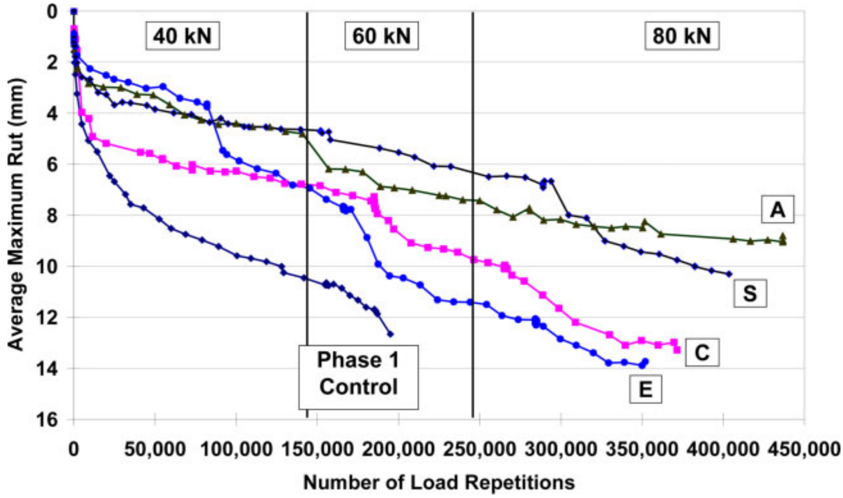

Figure 7. Phase 2 rutting (C = Control, A = Advera, E = Evotherm, S = Sasobit).

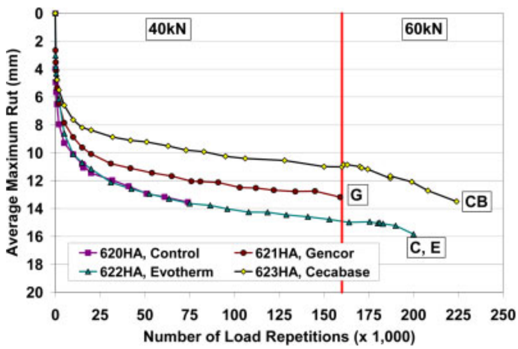

Figure 8. Phase 3, Mix Design #1 rutting (C = Control, E = Evotherm, G = Gencor, CB = Cecabase).

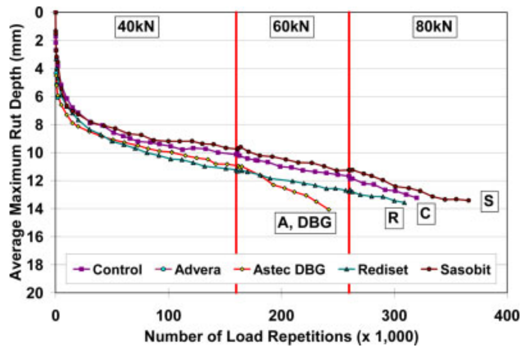

Figure 9. Phase 3, Mix Design #2 rutting (C = Control, A = Advera, DBG = Astec DBG, R = Rediset, S = Sasobit).

On the first project (Control, *Cecabase*, *Evotherm DAT*, and *Gencor UltraFoam*), the duration of the tests varied between 85,000 and 225,000 repetitions; with performance generally better on the warm-mix sections compared to the Control. On the second project (Control, *Advera*, *Astec Double-Barrel Green*, *Rediset*, and *Sasobit*), the duration of the tests varied between 225,000 and 375,000 repetitions with most sections performing in a similar way, but with two sections showing some load sensitivity at higher loads. This behavior was later attributed to subgrade moisture conditions identified during a forensic investigation.

Rutting behavior (average maximum rut) for the two projects is compared in Figures 8 and 9 respectively. In the first project, the embedment phases on two of the warm-mix sections were shorter than the Control. Embedment on the third warm-mix was the same as the Control. In the second project, embedment phases were similar for all mixes.

Differences in performance were related to air-void content, actual binder content, and lift thickness which varied slightly between the mixes. The binder content

Figure 9. Portable flux chamber for measuring emissions during paving.

of the *Rediset* mix was significantly higher than the other mixes (i.e., 1.7 percent higher than the design binder content). Compaction on the second project was generally poor, which was attributed to the longer

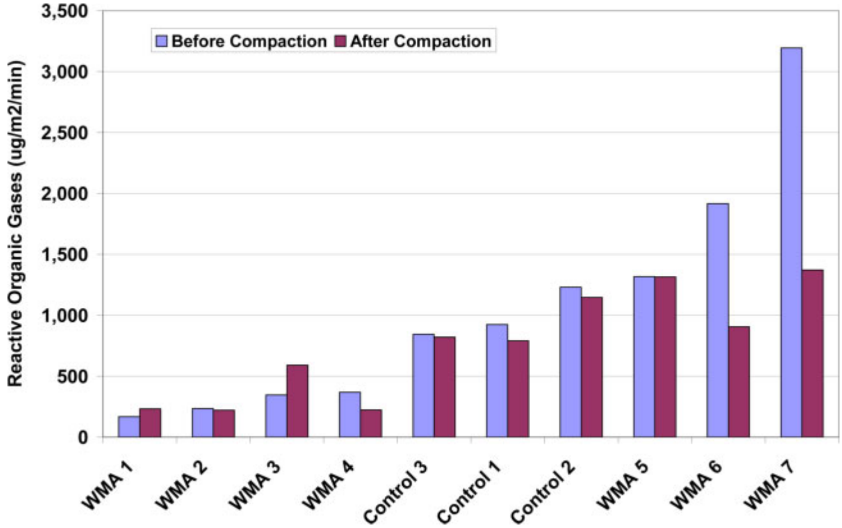

Figure 10. Reactive organic gas emissions during Phase 3 paving.

haul (approximately 2.5 hours) and cold temperatures during placement.

7 EMISSIONS TESTING

The purpose of the emissions study was to develop and assess equipment for accurately measuring surface emissions during hot- or warm-mix asphalt paving operations. A transportable flux chamber (Figure 9) was fabricated to obtain direct measurements of reactive organic gas (ROG) emissions and to estimate the fluxes of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) for different asphalt mixes and production temperatures. A comprehensive validation study was carried out during the Phase 3 study to verify the applicability of the method in characterizing organic compounds in emissions during construction (Farshidi, et al., 2011).

Although trends in emission reduction from the time of placement until after final compaction were similar for all the mixes tested, significant differences were noted in the alkanes' concentration of the emissions from the Control mixes from the two asphalt plants and from the different warm mix technologies (Figure 10). In some instances, the warm mixes had higher concentrations than the control. For example, the second highest emission concentration recorded was on one of the warm-mix sections placed at the lowest temperature recorded of all the sections. Consequently, any generalization with regard to emissions reduction during the placement of asphalt through the use of warm-mix technologies is inappropriate and should be restricted to comparisons of specific WMA technologies against HMA controls.

Preliminary results from this study indicate that the method developed is appropriate for accurately quantifying and characterizing VOC and SVOC emissions during asphalt paving. Based on the results obtained to date, the study is being extended to assess other gaseous and particulate polycyclic aromatic hydrocarbons (PAH) emissions during paving. Collection of PAHs through a fine particulate filter followed by a sorbent-backed filter with further gas chromatographic/mass spectrometric (GC/MS) analysis is being investigated. The results will be used to quantify the potential benefits of using warm-mix asphalt technologies in reducing reactive organic gas emissions, and to more accurately assess the contribution of emissions from asphalt paving to total ROG emissions for specific areas.

8 KEY OBSERVATIONS

The following key observations have been made from the study results to date:

- Smoke and haze typical on construction projects using hot-mix asphalt are significantly reduced on warm-mix projects. However, actual emissions during paving vary between technologies and the temperatures at which they are placed. Consequently, generalizations about reduced emissions from warm-mix asphalt when compared to hot-mix asphalt should not be made.
- Compaction on warm-mix sections is similar to that on hot-mix sections if similar rolling patterns are followed and the temperatures do not drop too low. Warm-mixes cool at a slower rate than hot-mixes and consequently there is a longer time window to complete compaction. However, periods of mix tenderness are also generally longer and breakdown rollers may need to be held back to accommodate this.
- In the Phase 1 experiment, production and compaction temperatures were set. Two of the technologies showed considerable tenderness during

breakdown rolling, indicating that the placement temperatures were on the high side and consequently the breakdown and intermediate rollers were held back until the mix had cooled down to an appropriate level. Contractors may be inclined to reduce the binder content to minimize this problem. This is **NOT** advised; rather the approach of delaying the start of breakdown rolling by a few minutes should be followed. Reduced binder content could lead to a stiffer mix that is more susceptible to raveling and early reflection cracking, especially in thin overlays.
- In the Phase 3 experiment, production and compaction temperatures were set by the individual warm-mix technology provides in discussion with the asphalt plant operator. In certain instances, compaction temperatures may have been a little low, which resulted in poor compaction on some sections. Ambient temperatures and haul time need to be closely monitored in the setting of these temperatures to ensure that adequate compaction can still be achieved. The focus should not be solely on trying to reduce production temperatures.
- Laboratory rutting performance of warm-mix asphalt specimens prepared according to standard procedures with no additional conditioning is generally poorer than hot-mix specimens prepared in the same way, indicating that some early rutting is possible until the binder oxidizes to the same extent as that of hot-mix asphalt. This implies that early rutting is possible in the first few months after construction on thicker warm-mix asphalt projects that carry heavy truck traffic. Longer rut embedment phases on the warm-mix sections compared to the hot-mix section in the Phase 1 accelerated loading study support this observation. No difference in rutting was observed on any of the other accelerated loading tests or on any of the field sections monitored to date, indicating that the problem is probably limited to applications in thicker pavements (the Phase 1 test track was 120 mm thick, whereas all other experiments varied between 38 mm and 50 mm). Reductions in the binder content should not be considered to counter this effect.
- No increase in moisture sensitivity was noted on any of the warm-mix sections assessed in this study. However, measurements at the asphalt plants indicated that the moisture contents of the warm-mixes were generally higher than the hot-mix controls, although all were within Caltrans specification (i.e., 1.0 percent by mass of mix), indicating that the potential for moisture related problems does exist if aggregate moisture contents are not closely monitored.

9 CONCLUSIONS

A comprehensive, phased research study has revealed that warm-mix asphalt will provide equal performance to hot-mix asphalt in most instances. Reduced binder aging as a result of lower production temperatures appears to have a short-term influence on rutting performance, which could result in a faster initial rut rate on thicker pavements under heavy truck traffic for the first few months in hot climates. Accelerated pavement testing was beneficial in understanding this rutting behavior and in assessing the potential for increased moisture sensitivity due to the lower production temperatures. Based on the results and conclusions from the research conducted to date, coupled with training and workshops for district staff, Caltrans is implementing the use of warm-mix asphalt statewide on pavements in all traffic classes, with over a million tons of warm-mix placed in a full spectrum of applications in 2011. Results from the research, and specifically the accelerated pavement testing, were considered a fundamental component in understanding potential risks of implementation, especially on high truck traffic routes and in those areas with moisture sensitive aggregates.

ACKNOWLEDGEMENTS

This paper describes research activities that were requested and sponsored by the California Department of Transportation (Caltrans), Division of Research and Innovation, and the California Department of Resources, Recycling, and Recovery (CalRecycle). Caltrans and CalRecycle sponsorship is gratefully acknowledged. The assistance and interest of the warm-mix technology providers, Graniterock Company, Granite Construction, Teichert Construction, George Reed Construction, and the HVS test crew under the direction of Mr. Peter Miller is also gratefully acknowledged. The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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