

---

# Research findings on the use of Rubberized Warm-Mix Asphalt in California

David Jones<sup>1</sup>, Rongzong Wu<sup>1</sup>, Cathrina Barros<sup>2</sup>, and Joseph Peterson<sup>2</sup>

<sup>1</sup>University of California Pavement Research Center, USA  
UC Davis, 1 Shields Ave, Davis, CA, USA

<sup>2</sup>California Department of Transportation, USA  
Address

[djjones@ucdavis.edu](mailto:djjones@ucdavis.edu)

---

**ABSTRACT.** The University of California Pavement Research Center (UCPRC), on behalf of the California Department of Transportation initiated a comprehensive, phased research study into the use of warm-mix asphalt, involving laboratory and accelerated load testing, and full-scale field experiments. The objective of this study was to determine whether warm-mix asphalt performs equal to or better than conventional hot-mix asphalt. The third phase of the study covered rubberized asphalt. Caltrans is mandated by law to use rubber recycled from scrap tires in at least 35% of all asphalt placed in the state. Although the benefits of rubberized asphalt are well documented, it has numerous limitations that are often not considered in research, including higher production and placement temperatures that have environmental and health constraints, and restrictions on long hauls and early and late season paving. Observations during rubberized warm-mix experiments indicated an absence of smoke and odour and significantly better workability compared to the hot-mix controls. Similar compaction levels were recorded on hot-mix control and warm-mix sections and on experiments in remote locations, rubberized mixes could be hauled for up to four hours, placed with ease whilst still achieving the required compaction. Equal or better performance has been observed over four years. Based on these research results, Caltrans placed more than one million tons of rubberized warm-mix during the 2011 paving season.

**KEYWORDS:** rubberized warm-mix asphalt, accelerated pavement testing

---

## 1. Introduction

The California Department of Transportation (Caltrans) is mandated by law to use crumb rubber recycled from scrap tires in at least 35 percent of all asphalt placed in the state. Although the benefits of rubberized asphalt in terms of improved fatigue and reflection cracking resistance are well documented, it has a number of limitations in terms of production and placement that are often not considered in the research and consequently restrict its use on construction projects. Firstly, it is typically produced at temperatures around 170°C, 25°C higher than conventional asphalt. This requires more energy to produce and results in higher emissions and odors from the plant stacks, which are strictly controlled in California. Consequently, rubberized mixes can often not be produced and placed in urban areas. Secondly, rubberized asphalt (R-HMA) needs to be placed at higher temperatures than conventional asphalt, leading to health and safety problems for workers and resulting in excessive smoke and odors, a problem for the travelling public and adjacent residential and commercial properties. Thirdly, rubberized asphalt cannot be used in remote areas that require longer hauls because of heat loss during transport, and lastly, it cannot be used at the beginning and end of the paving season due to the lower ambient temperatures, especially during night work.

Caltrans has an interest in all applications of warm-mix asphalt (WMA) 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 night-time 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. The University of California Pavement Research Center (UCPRC), on behalf of Caltrans, initiated a comprehensive, phased research study into the use of warm-mix asphalt, involving laboratory and accelerated load testing, and full-scale field experiments to assess these potential influences [1-5]. The objective of this study was to determine whether warm-mix asphalt performs equal to or better than conventional hot-mix asphalt. The third phase of the study, also sponsored in part by the California Department of Resources Recycling and Recovery (CalRecycle), and subject of this paper, covered the use of warm-mix in rubberized asphalt (R-WMA) to determine whether its use could alleviate any or all of the issues listed above [3,4]. Very little research on the use of warm-mix rubberized asphalt (R-WMA) had been undertaken in the USA at the time of undertaking this research [6]. The Caltrans approach to warm-mix asphalt is somewhat more cautious compared to some other states in the USA, but was followed to ensure that performance is fully understood and that any future pavement failures on projects using warm-mix asphalt are fully understood and do not lead to a moratorium on its use in the state. History has shown that potentially promising technologies are often abandoned simply because of a poor understanding of changed design, production and/or construction procedures.

This paper provides an overview of the research undertaken and a summary of the results that were used to support implementation of warm-mix technologies on rubberized asphalt projects in California. Warm-mix technology names are used in this paper for clarification purposes only in line with other publications on the subject. Caltrans, CalRecycle and the UCPRC do not endorse the use of any specific warm-mix technology.

## 2. Rubberized Warm-Mix Asphalt Study Objectives

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

- Determine whether the use of additives (including water), introduced to reduce production and construction temperatures of rubberized asphalt concrete, influence mix production processes, construction procedures, and the short-, medium-, and/or long-term performance of rubberized hot-mix asphalt.
- Use research findings to guide the implementation of rubberized warm-mix asphalt in California.

The study workplan [6] was updated to meet these objectives. Research included:

- Monitoring the production of seven different warm mixes and two hot-mix controls (all using a 12.5 mm gap-graded mix). Two different water injection technologies were assessed, which required that the warm mixes and associated controls be produced at two different plants. The warm-mix technologies assessed included Advera<sup>®</sup>, Astec Double-Barrel Green<sup>®</sup>, Cecabase<sup>®</sup>, Evotherm DAT<sup>®</sup>, Gencor Ultrafoam<sup>®</sup>, Rediset WMX<sup>®</sup>, and Sasobit<sup>®</sup>.
- Monitoring the construction of a 110 m x 15 m test track using the nine different mixes including the measurement of emissions behind the paver and after compaction;
- Sampling of raw materials during production and sampling of specimens from the test track for laboratory testing;
- Laboratory testing to assess rutting and fatigue cracking performance, moisture sensitivity, and binder aging properties over time;
- 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 with both gap-graded and open-graded mix designs;
- Preparing specifications and other documentation required for implementing the use of warm-mix asphalt in California.

### **3. Testing Protocols**

#### ***3.1 Laboratory***

Slabs (for fatigue beam specimens) and cores (for shear and moisture sensitivity tests) were removed from the test track approximately six weeks after construction. 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 AASHTO T-283 [Tensile Strength Retained]). Typical experimental plans used in previous UCPRC studies [1,2] were adopted for this study to facilitate later comparison of results.

#### ***3.2 Accelerated Loading***

Accelerated pavement testing was undertaken with a Heavy Vehicle Simulator (HVS). The test section layout, test setup, trafficking, and measurements followed standard UCPRC protocols [7]. The pavement temperature at 50 mm depth was maintained at  $50^{\circ}\text{C}\pm 4^{\circ}\text{C}$  to assess rutting potential under typical pavement conditions. Infrared heaters inside a temperature control chamber were used to maintain the pavement temperature. 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. Load was checked with a portable weigh-in-motion pad at the beginning of each test and after each load change.

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

#### ***3.3 Field Tests***

Field test assessments included documentation of construction and a visual assessment of performance at six-monthly intervals. Rutting was measured with a two-metre straightedge. Since all experiments were relatively thin open-graded friction courses (25 mm to 30 mm), no structural testing (e.g., deflection) was carried out.

## **4. Test Track Mix Design, Mix Production and Construction**

### ***4.1 Test Track Design***

The test track was designed to represent a relatively low-volume road structure that would fail under trafficking within a reasonable space of time. The structure consisted of a 400 mm aggregate base over a compacted silty-clay subgrade. A 60 mm thick conventional hot-mix asphalt layer (i.e., no rubber) was placed on top of the aggregate base. The 60 mm gap-graded rubberized warm-mix asphalt layer was placed on top of the conventional hot-mix asphalt layer (the warm-mix overlays were placed approximately eight months after placing the hot-mix asphalt layer).

### ***4.2 Mix Design***

Two different water injection (or foaming) technologies were assessed in this study. Consequently, the two mixes needed to be produced at two different asphalt plants (referred to as Mix Design #1 and Mix Design #2 in this paper). Mix production with the remaining five additive technologies were split between the two plants. Separate mix designs for the 12.5 mm gap-graded mix were developed by each plant using different aggregate sources, and consequently direct comparisons of performance between the two mixes is not attempted in this paper. Target binder contents for the two mixes were 7.3 percent and 8.3 percent respectively for the two plants. Crumb rubber content was 19 percent by mass of binder. Warm-mix technologies were not included in the mix designs and the mix designs were not adjusted to accommodate the warm-mix technologies.

### ***4.3 Mix Production and Placement***

Mixes were produced and placed over two days (one day per plant). Production and placement temperatures were decided by the warm-mix technology provider and the paving contractor, and varied considerably between the different mixes. Ambient temperatures ranged between 8°C and 12°C on both days with a cold wind adding a chill factor. These conditions represented typical early or late paving season conditions over much of California. Haul time from the two asphalt plants were between 60 and 80 minutes for Mix Design #1 and 120 and 140 minutes for Mix Design #2. Key attributes of the construction of each mix are summarized in Table 1 and Table 2.

Mix production at asphalt plant #1 was generally consistent across all four mixes. Binder contents ranged between 7.7 percent and 7.9 percent, all slightly above the target binder content of 7.3 percent. Construction was also consistent across all four mixes, although higher air void contents (determined from cores) were recorded on the warm-mix sections. This was attributed to slight differences

in the way that warm mixes compact compared to hot mixes, specifically with regard to dealing with periods of mix tenderness.

**Table 1. R-WMA Test Track Data (Mix Design #1)**

Parameter	Warm-Mix Technology (in order of production)			
	Control	Gencor	Evotherm	Cecabase
Binder content (%) <sup>1</sup>	7.7	7.9	7.7	7.7
Prod Temp (°C)	160	140	125	130
Pave Temp (°C) <sup>2</sup>	154	128	120	128
Air voids (%)	4.9	6.3	6.2	6.4
Hveem Stability <sup>3</sup>	27	28	27	27

<sup>1</sup> Target 7.3%

<sup>2</sup> Behind screed

<sup>3</sup> Immediate, No curing

**Table 2. R-WMA Test Track Data (Mix Design #2)**

Parameter	Warm-Mix Technology (in order of production)				
	Control	Sasobit	Advera	Astec	Rediset
Binder content (%) <sup>1</sup>	7.7	8.0	7.6	8.4	10.0
Prod Temp (°C)	166	149	145	145	140
Pave Temp <sup>2</sup> (°C)	137	137	130	125	126
Air voids (%)	11.6	8.5	10.7	9.1	8.4

<sup>1</sup> Target 8.3%

<sup>2</sup> Behind screed

Mix production at asphalt plant #2 was less consistent with binder contents ranging between 7.6 percent and 10.0 percent. Three of the mixes were below the target binder content, one was close to the target binder content and the other significantly higher than the target. Construction was also less consistent, with a relatively large variation in air void content. Better compaction was achieved on the warm-mix sections compared to the control, although air void contents were still considered high. This was attributed to the long haul and cold ambient conditions, under which the warm mixes were expected to perform better than the Control.

During construction, smoke and odours were significantly lower or absent on the warm-mix sections compared to the hot-mix controls (Figure 1). Workability of the mix, specifically with regard to raking, was significantly better on the warm mix sections, despite the lower mix temperatures.

#### 4.4 Emissions Testing

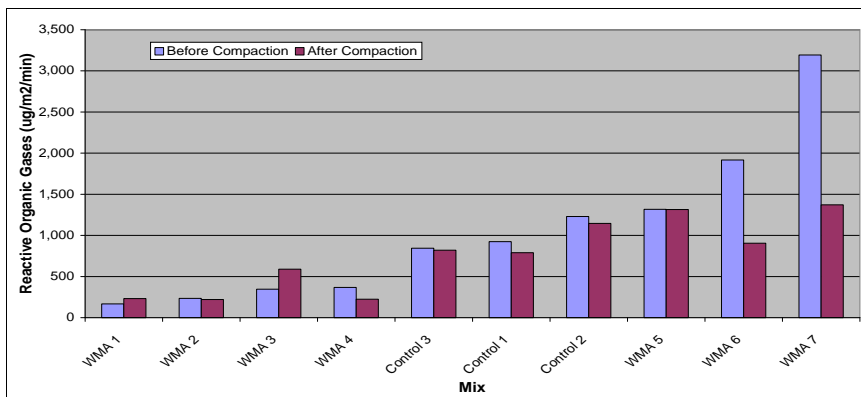
The purpose of the emissions study was to develop and assess equipment for accurately measuring surface emissions during hot- or warm-mix asphalt paving operations. A transportable flux chamber was fabricated to obtain direct measurements of reactive organic gas (ROG) emissions and to estimate the fluxes 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 R-WMA study to verify the applicability of the method in characterizing organic compounds in emissions during construction [8].



**Figure 1.** Comparison of hot- and warm-mix asphalt test track construction.

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 2). 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.



**Figure 2.** Reactive Organic Gas emissions from test track construction.

Preliminary results from this emissions 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.

## 5. Summary of Laboratory Test Results

### 5.1 Air Void Content

Average air void contents are summarized in Figure 3 (based on 65 specimens per mix, total of 585 specimens). Average air-void contents of the warm-mix specimens from Mix Design #1 were about 1.5 percent higher than the Control. There was very little variation along the length of each test track section, or between the three warm mixes, indicating consistent construction. On the Mix Design #2 specimens, air void contents were lower than the Control, indicating better compaction in the relatively cold temperatures after the longer haul. There was some variation between the different mixes, mostly related to mix compaction temperature, but little variation within each section. The Control mix had the highest variation, as expected.

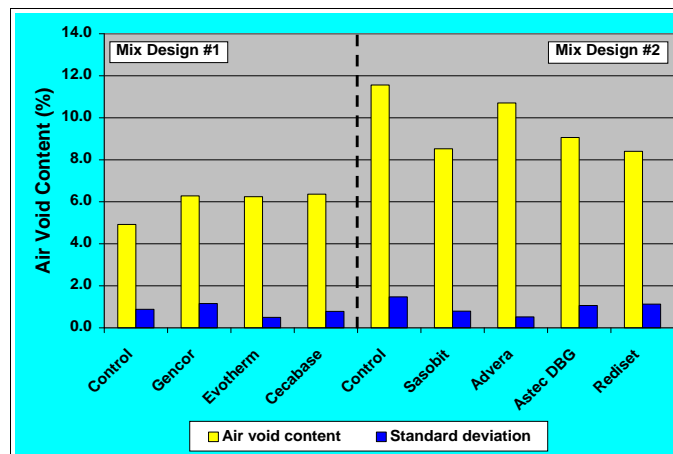


Figure 3. Average specimen air void content.



Based on these results and those from previous phases, the use of warm-mix technologies does not appear to negatively influence compaction, provided that mixes are compacted at realistic compaction temperatures and that paving crews understand the potential differences in mix tenderness between hot and warm mixes.

### **5.2 Rutting Performance (Shear Test)**

Shear test results were highly variable for the different mixes for both mix designs. This is common for a repeated load test at relatively high strains and the results are not presented in this paper. Hamburg Wheel Track Test results, discussed in Section 5.4 below, provided more consistent results for these mixes.

### **5.3 Fatigue/Reflective Cracking Performance**

Fatigue life results were also variable, but generally linked to air void content of the actual specimen being tested. Variability of results is a common observation in repeated load fatigue tests involving relatively low testing strains and temperatures (i.e., 200 and 400 microstrain at 10°C and 20°C). Fatigue life on specimens from Mix Design #1 was generally low compared to that on specimens from Mix Design #2, but there was more variability on specimens from the second experiment. Average results for dry and wet beam fatigue tests at 400 microstrain and 20°C are shown in Figure 4. Based on these results and results from earlier phases of testing, the use of warm-mix technologies is not considered to influence the fatigue performance of asphalt concrete, despite lower oxidation of the binder associated with lower production and placement temperatures.

### **5.4 Moisture Sensitivity**

The warm-mix specimens showed slightly higher moisture sensitivity than the Control on two of the three mixes for Mix Design #1 in the Hamburg Wheel Track Test. The third mix (water injection technology) was notably higher (Figure 5), despite having similar air void contents. For Mix Design #2, three of the warm-mixes exhibited slightly lower moisture sensitivity compared to the Control and one of the mixes (the water injection technology) showed similar performance to the Control. There was less variability in the Tensile Strength Retained test results (Figure 6), with results generally influenced by air void content of the individual specimen, as expected. Mixes from both plants have historically not been moisture sensitive. Results from this and previous phases indicate that moisture sensitivity is only likely to be influenced by warm-mix technologies if recommended moisture contents after production (typically a maximum of one percent by mass of the mix) are exceeded. That is, the warm-mix technology by itself is unlikely to influence moisture sensitivity, but rather that problems are likely to be attributed to aggregate management (i.e., using wet aggregates), mix production (i.e., high post production moisture contents), and construction quality (i.e., high air void contents).

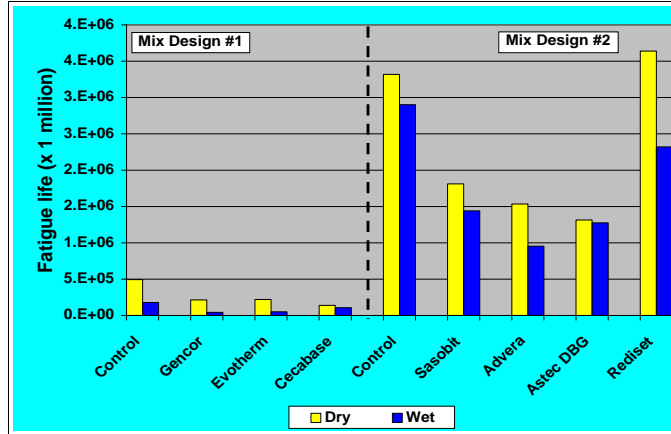


Figure 4. Fatigue life test results (testing at 400 $\mu$ strain and 20°C).

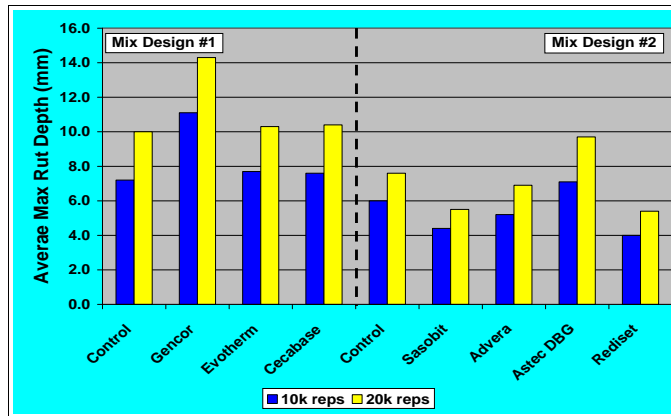


Figure 5. Hamburg Wheel Track test results (testing at 50°C)..

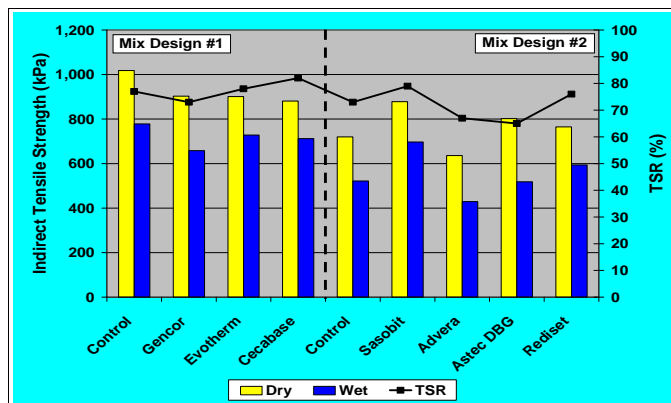
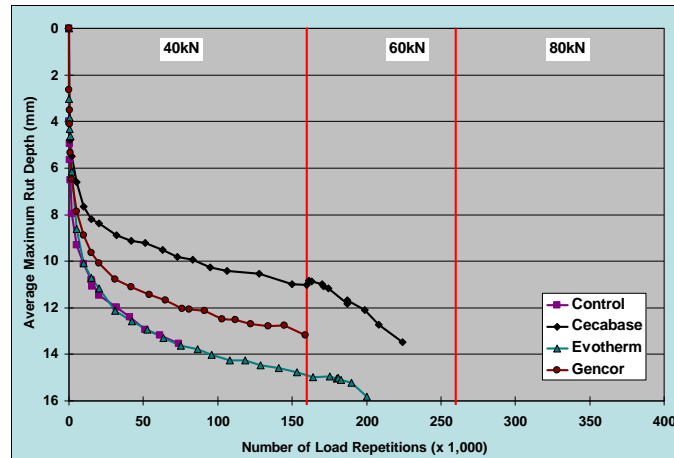


Figure 6. Tensile Strength Retained test results.

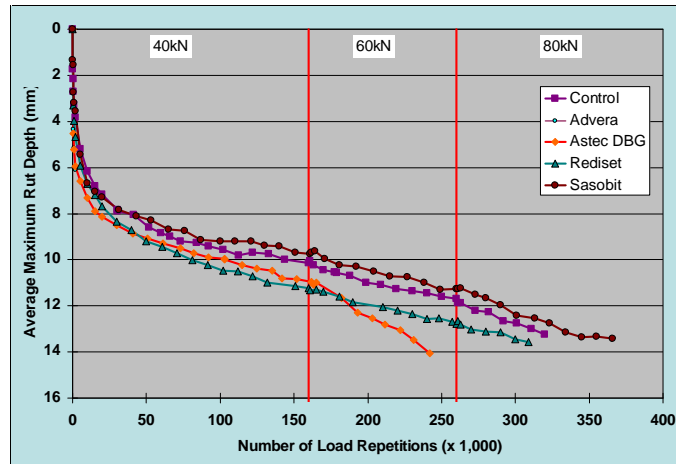
## 6. Summary of Accelerated Load Testing Results

Accelerated load testing was conducted concurrently on both mixes using two Heavy Vehicle Simulators (HVS). Testing was started in June 2010 and ended in December 2010. On the Mix Design #1 project (Control, Cecabase, Evotherm DAT, and Gencor UltraFoam), the duration of the tests varied between 85,000 and 225,000 load repetitions; with performance on the warm-mix sections generally equal to or better than the Control. On the Mix Design #2 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, with one showing some load sensitivity at higher loads.

Rutting behaviour (average maximum rut) for the two projects is compared in Figure 7 and Figure 8 respectively. In the first project, the embedment phases (an indication of the potential for early rutting) on two of the warm-mix sections were shorter than the Control, indicating potentially slightly better rutting performance despite higher air void contents. Embedment on the third warm-mix section was the same as the Control. In the second project, embedment phases were similar for all mixes. These results differ from other warm-mix experiments where embedment phase characteristics have typically indicated the potential for slightly deeper ruts in the early stages of trafficking compared to hot-mix asphalt sections, attributed to less oxidation of the binder during production and placement.



**Figure 7.** R-WMA Test Results (Mix Design #1).



**Figure 8.** *R-WMA Test Results (Mix Design #2).*

Aging studies are currently being undertaken on the binders sampled during production to determine whether the addition of crumb rubber positively influences early rutting performance of warm mixes. Results will be published on completion of the study.

Differences in rutting performance appear to be related to air-void content and actual binder content, both of which varied between the mixes. Compaction on the second project was generally poor, which was attributed to the long haul (approximately 2.5 hours) and cold temperatures during placement. Forensic investigations (Falling Weight Deflectometer testing, test observations, density and moisture content tests, and Dynamic Cone Penetrometer tests) after all testing was completed supported these observations. High subgrade moisture contents on the Advera and Astec Double-Barrel Green sections accounted for higher rut rates and sensitivity to load increases on these sections. The forensic investigations did not reveal any other factors that might have influenced the results.

## 7. Summary of Full-Scale Field Experiments

Ten rubberized open-grade friction course experiments continue to be monitored in various parts of California, with the first experiments being constructed in 2008. The experiments were selected to cover a wide range of climate, traffic, and haul distance variables. Climatic conditions varied between cool and wet coastal areas, through hot Central Valley areas to mountainous cool regions. Traffic covered both relatively low volumes on rural roads ( $\pm 10,000$  AADT) and high volumes on Interstate Highways ( $> 40,000$  AADT), with some experiments including a high percentage of heavy agricultural equipment in the

traffic counts. Haul distances varied between 30 minutes and four hours. A range of the warm-mix technologies used in the test track was used in the different field experiments. Performance on the warm-mix sections was equal to or better than the hot-mix control in all instances. On the long hauls, some ravelling was noted on the hot-mix controls within a year of construction, especially in the cool, moist coastal areas. This is typical for open-graded mixes under these conditions and is attributed to poor compaction as a result of the low mix temperatures when they arrive at the construction site. No ravelling was noted on any of the warm-mix sections. A slightly higher rut rate compared to the Control was noted in the very early stages of one warm-mix experiment on an Interstate Highway with very high truck traffic. However, similar rut depths were measured on both the Control and warm-mix sections after 12 months, and thereafter, rut rate was the same on both sections. Similar early embedment trends were noted on the earlier accelerated pavement tests and were attributed to the lower oxidation of the binder in the warm mixes.

## 8. Key Observations from the Study

The following key observations have been made from the rubberized warm-mix asphalt 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. Roller operators need to be aware of the differences in behaviour between hot and warm mixes.
- During construction of warm-mix asphalt projects, additional mix tenderness is often experienced during breakdown rolling. Discussions with warm-mix technology providers revealed that placement temperatures were probably on the high side in these instances and consequently the breakdown and intermediate rollers should be held back for a few minutes until the mix has 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 and changing rolling patterns to suit should be followed. Reduced binder content could lead to a stiffer mix that is more susceptible to ravelling and early reflection cracking, especially in thin overlays.

- Warm-mix production temperatures should be based on ambient temperatures and haul time to ensure that adequate compaction can still be achieved. Production temperatures should not be set according to the lowest possible temperature advertised by the technology provider.
- 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 some early rutting is possible in the first few months after construction on thicker warm-mix asphalt projects that carry heavy truck traffic. Reductions in the binder content should not be considered to counter this effect. Field performance monitoring indicates that the rut rates of hot and warm mixes is equal after between about nine and 12 months.
- 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 specification, indicating that the potential for moisture related problems does exist if aggregate moisture contents are not closely monitored.
- Laboratory testing on a range of mixes has indicated that the use of warm-mix technologies does not influence fatigue or reflective cracking performance despite less initial binder oxidation and consequent lower stiffness. No difference in reflective cracking performance was noted on hot- and warm-mix sections during four years of field performance monitoring.

## 9. Conclusions

The University of California Pavement Research Center (UCPRC), on behalf of the California Department of Transportation (Caltrans) initiated a comprehensive, phased research study into the use of warm-mix asphalt, involving laboratory and accelerated load testing, and full-scale field experiments. The objective of this study was to determine whether warm-mix asphalt performs equal to or better than conventional hot-mix asphalt. The third phase of the study covered the use of warm-mix in rubberized asphalt. Observations of production and construction of a number of rubberized warm-mix experiments, including intensive assessment of the construction of an accelerated pavement testing track with seven different warm-mix technologies and two hot-mix controls, indicated:

- An almost total absence of smoke and odor and significantly better workability.
- Lower emissions were recorded behind the paver compared to the hot-mix controls.

- Similar compaction levels were recorded on the hot-mix control and warm-mix sections.
- Field experiments indicated that rubberized mixes could be hauled for between three and four hours to remote locations, placed with ease whilst still achieving the required compaction. Night and early and late season paving was also feasible.

Laboratory, accelerated load testing, and field performance results from this study all indicate that equal, and in some instances, better performance can be expected from the use of warm-mix asphalt when compared to hot-mix asphalt. Better performance is certainly achieved on projects that require a long haul, or are constructed during marginal weather conditions. Based on these results, Caltrans placed more than one million tons of rubberized warm-mix asphalt in the state during the 2011 paving season. Use is expected to grow in future years.

## 10. 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, assistance and interest are gratefully acknowledged, as is the support of the warm-mix technology providers used in the studies, Granite Construction, George Reed Construction, and Teichert Construction. 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. The UCPRC laboratory staff and Heavy Vehicle Simulator crew are also acknowledged.

## 11. Bibliography

1. JONES, D., Wu, R., Tsai, B.W., Lu, Q. and Harvey, J.T. 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. (RR-2008-11).
2. JONES, D., Wu, R., Tsai, B.W., and Harvey, J.T. 2009. *Warm-Mix Asphalt Study: First-Level Analysis of Phase 2 HVS and Laboratory Testing and Forensic Investigation*. Davis and Berkeley, CA: University of California Pavement Research Center. (RR-2009-02).
3. JONES, D., Wu, R., Tsai, B.W., and Harvey, J.T. 2011. *Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3a HVS and Laboratory Testing, and Forensic Assessment. (Mix Design #1)*. Davis and Berkeley, CA: University of California Pavement Research Center. (RR-2011-02).

4. JONES, D., Wu, R., Tsai, B.W., and Harvey, J.T. 2011. *Warm-Mix Asphalt Study: Test Track Construction and First-Level Analysis of Phase 3b HVS and Laboratory Testing, and Forensic Assessment. (Mix Design #2)*. Davis and Berkeley, CA: University of California Pavement Research Center. (RR-2011-03).
5. JONES, D., Wu, R., Tsai, BW, Barros, C., and Peterson, J. 2011. Key Results from a Comprehensive Accelerated Loading, Laboratory, and Field Testing Study on Warm-Mix Asphalt In California. *Proceedings 2nd International Conference on Warm-Mix Asphalt*. St Louis, MO.
6. JONES, D. and Harvey, J. 2007. Warm-Mix Asphalt Study: *Workplan for Comparison of Conventional and Warm-Mix Asphalt Performance using HVS and Laboratory Testing*. Davis and Berkeley, CA: University of California Pavement Research Center. (WP-2007-01).
7. JONES, D. 2005. *Quality Management System for Site Establishment, Daily Operations, Instrumentation, Data Collection and Data Storage for APT Experiments*. Pretoria, South Africa: CSIR Transportek. (Contract Report CR-2004/67-v2).
8. FASHIDI, F. and Jones, D. 2011. Direct Measurements of Volatile and Semi-Volatile Organic Compounds from Hot- and Warm-Mix Asphalt. *Transportation Research Record, Journal of the Transportation Research Board, No 2207*. Washington, DC: National Academy of Sciences.