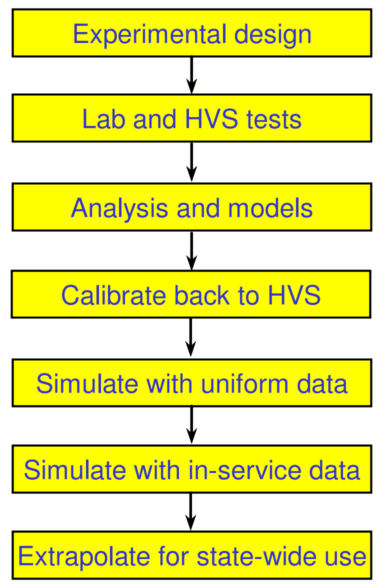
Evaluation of Modified Binder Gap-Graded Mixes for Half-Thickness Reflective Cracking Overlays

The question asked by Caltrans and Industry:
Will gap-graded modified binder (MB-G) mixes provide performance equal to gap-graded rubberized asphalt concrete (RAC-G) mixes in half thickness applications?

Why was this question asked?
MB binders could offer cost savings, and widen the application range for rubberized binders.

How was the question answered?
Caltrans, industry and academia developed a comprehensive plan for laboratory testing, Heavy Vehicle Simulator (HVS) testing, and full-scale testing on in-service highways. The University of California Pavement Research Center (UCPRC), through the Partnered Pavement Research Center program, performed the laboratory and HVS testing. The HVS was used to apply very high traffic loads to 12 uniform rutting and reflective cracking test sections under controlled, matching conditions. A total of more than 15 million load repetitions (about 400 million equivalent standard axles loads) were applied during the study, providing reliable data that was used to develop and calibrate mechanistic models to simulate the performance of similar materials not included in the study, and to extrapolate the results from test sections to other conditions such as different traffic levels, pavement structures, and stages of pavement deterioration.



What is the answer?
The results indicate that gap-graded mixes with MB4, MB4 with 15 percent rubber, and MAC15TR binders will provide superior performance in terms of reflective cracking compared to the same half thickness of RAC-G, when used in thin overlays on cracked asphalt pavements. With regard to rutting performance, conventional dense-graded asphalt concrete was clearly superior to all other mixes, followed by the RAC-G, and then the modified binder mixes. Most of the rutting in the HVS test sections occurred in the DGAC layer below the overlays, and not in the overlay itself.

What are the recommendations?

1. MB4, MB4 with 15 percent rubber, and MAC15TR binders can be used in appropriately designed half-thickness overlay mixes for reflective cracking applications where RAC-G would normally be considered. There is potentially a greater risk of rutting compared to RAC-G if these mixes are used under slow moving, heavy truck traffic in hot climates, hence the current mix designs should not be used in locations with these conditions until proven in pilot projects on in-service highways.
2. The HVS calibrated simulation models should be used to assess the performance of other mixes or changes in binder specifications and to validate future mix and thickness design changes.
3. Long-term performance monitoring (rutting, cracking, forensic coring and assessment of the interactions of underlying pavement and thin overlays) of in-service test sections should be continued to relate long-term performance to the laboratory and HVS findings.

The Test Road

The test road was designed following standard Caltrans procedures and incorporates a 410 mm Class 2 aggregate base (recycled construction waste) on a clay subgrade with a 90 mm dense-graded asphalt concrete (DGAC) surface. Design thickness was based on a subgrade R-value of 5 and a Traffic Index of 7 (~131,000 equivalent standard axle loads, or ESALs). The road was constructed in 2001 by a commercial contractor (selected based on low-bid) using conventional equipment.

This structure was trafficked with the HVS between February 2002 and April 2003 to induce fatigue cracking. A total of approximately 3.3 million load repetitions – equating to about 17.7 million equivalent standard axles (ESALs) using the Caltrans 4.2 exponent – were applied to six sections to induce a minimum of 2.5 m/m^2 fatigue cracking on each section. On completion of the HVS tests, the road was overlaid with six different treatments in June 2003. The thickness for the control DGAC overlay was determined according to Caltrans Test Method 356. The other overlay thicknesses were either the same or half of the DGAC overlay thickness. The treatments included:

- Half-thickness (45 mm) MB4 gap-graded overlay;
- Full-thickness (90 mm) MB4 gap-graded overlay;
- Half-thickness MB4 gap-graded overlay with minimum 15 percent recycled tire rubber;
- Half-thickness MAC15TR gap-graded overlay;
- Half-thickness rubberized asphalt concrete gap-graded overlay (RAC-G), included as a control for performance comparison purposes, and
- Full-thickness (90 mm) AR4000 dense-graded asphalt concrete (DGAC) overlay, included as a control for performance comparison purposes.

HVS Testing on the Overlays

The purpose of the second round of HVS tests was to assess the effectiveness of the overlays in limiting reflective cracking in subsequent HVS testing. The HVS test sections were precisely positioned on top of the sections already trafficked on the underlying pavement. A high-temperature rutting study on sections adjacent to the reflective cracking sections was also carried out to assess the susceptibility of the mixes to early rutting at high pavement temperatures.

Rutting section after trafficking

Cracking section after trafficking

The overlay rutting sections were trafficked with the HVS between September and December 2003 During this period a total of about 80,000 60 kN channelized, unidirectional load repetitions with a dual tire (720 kPa pressure) were applied across the sections, equating to approximately 455,000 ESALs. A temperature chamber was used to maintain the pavement temperature at 50°C±4°C. Measurements taken at regular intervals throughout the test included air and pavement temperatures, in-depth elastic deflection, and surface and in-depth permanent deformation.

HVS trafficking of the overlay reflective cracking sections took place between January 2004 and June 2007. During this period a total of approximately 12.5 million load repetitions at loads varying between 60 kN and 100 kN, depending on the stage in the test plan, were applied across the sections, which equates to about 385 million ESALs. A temperature chamber was used to maintain the pavement temperature on each section at 20°C±4°C for the first one million repetitions, then at 15°C±4°C for the remainder of the test. A dual tire (720 kPa pressure) in a bidirectional loading pattern with lateral wander was used for all experiments. Measurements taken at regular intervals throughout the test included air and pavement temperatures, surface and in-depth elastic deflection, surface and in-depth permanent deformation, and cracking.

Forensic Investigation

A forensic investigation was carried out after HVS testing. This included excavation and assessment of 18 test pits, coring, density and moisture determination, Dynamic Cone Penetrometer (DCP) measurements, and microscope studies of material sampled from the pits. Observations revealed that most of the deformation measured in the rutting study occurred in the underlying DGAC. There was some variation in layer thicknesses over the length of the experiment. DCP measurements and scanning electron microscope studies indicated that the stiffness of the recycled aggregate base varied somewhat between sections due to some re-cementation that occurred after construction. The strongest part of the base was typically between 100 and 250 mm. Studies of the asphalt layers, including fractured cores, showed that cracking in the DGAC and RAC-G overlays had mostly reflected from the underlying DGAC layer. There was no observed cracking on the surface of the MB sections.

Laboratory Study

Laboratory fatigue and shear studies were conducted in parallel with HVS testing. In the cracking study, flexural frequency sweeps (stiffness at different temperatures and period of loading related to traffic speed and climate) and flexural beam tests were carried out to assess cracking resistance of the overlay mixes. In the shear study, stiffnesses at high temperatures and permanent deformation at high temperatures were used to evaluate rutting resistance. Tests were carried out on field-mixed, field-compacted, (shear study only), field-mixed, laboratory-compacted, and laboratory-mixed, laboratory-compacted specimens.

Analyses

Laboratory results were statistically analyzed to identify the significant variables affecting stiffness, fatigue and permanent shear deformation performance. The effects of aggregate gradation, long-term aging, air-void content, mix temperature, and strain/stress level were the focus of the study, with both field- and laboratory-prepared specimens compared. Regression models were developed to portray the effects of the significant variables on the performance-related properties. Test criteria for the shear study included Cycles to 5 Percent Permanent Shear Strain, Permanent Shear Strain at 5,000 Cycles, and Resilient Shear Modulus (G^*). In the fatigue study, test criteria included number of cycles to 50 Percent Loss of Stiffness. Analysis of stiffness-versus-strain repetition curves using three-stage Weibull analysis showed differences in crack initiation and propagation between the DGAC and RAC-G mixes and between the RAC-G and MB mixes, with results indicating that damage may slow during the propagation phase of the RAC-G mix, and even more so for the MB mixes, while it accelerates in the DGAC mix.

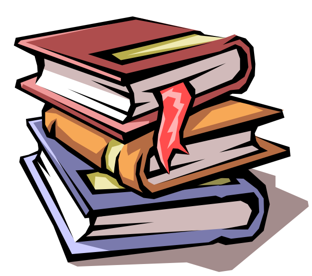
Simulation

Simulation models developed for Caltrans by the UCPRC were used to extrapolate HVS results to identical test and in-service pavement conditions. Two approaches were used:

- A recursive mechanistic-empirical design model for rutting and reflection cracking included in the *CalME* design software. This was used with laboratory shear test results to simulate rutting performance on the HVS sections and then in three climate regions (Desert, Valley, South Coast) at various traffic levels, with two truck traffic speeds (10 and 70 km/h).
- A continuum damage mechanics model using finite element method calculation of strains for simulation of reflection crack initiation and propagation. This was used with laboratory fatigue characterization of the materials to simulate the HVS tests as tested, and then with identical underlying pavement structures and cracking patterns to eliminate differences in as-built conditions and to extrapolate results to other conditions.

Reports

- Construction and first phase of testing
- First-level analysis of the rutting study
- First-level analysis of each fatigue section (six reports)
- First-level analysis of laboratory fatigue and shear studies (two reports)
- Second level analysis report on HVS, laboratory and simulation results
- Forensic investigation
- Summary report



Findings on reflective cracking

Reflective cracking performance of each of the mixes in the HVS, laboratory beam fatigue, and continuum damage mechanics simulation studies are provided in the table below. Rankings are from best to worst. The MB4, MB4 with 15 percent rubber, and MAC15TR mixes performed the best and had similar results to each other. The RAC-G did not perform as well as the MB mixes. The conventional DGAC mix performed worst.

	Rank	Section	Parameter	Finding
HVS	1	45 mm MAC15TR-G	Number of ESALs to 2.5 m/m^2 reflection cracking	None after 91 million
	1	45 mm MB4-G with 15% rubber		None after 88 million
	1	45 mm MB4-G		None after 66 million
	1	90 mm MB4-G		None after 37 million
	5	45 mm RAC-G		60 million
	6	90 mm AR-4000-D (DGAC)		16 million
Lab Fatigue Beam	1	MB4-G	Number of repetitions to 50% loss of stiffness in the beam fatigue test	Laboratory ranking is based on an average of the results from all tests.
	2	MB4-G with 15% rubber		
	2	MAC15TR-G		
	4	RAC-G		
	5	AR-4000-D (DGAC)		
Simulation*	1	45 mm MAC15TR-G	Number of ESALs to 2.5 m/m^2 reflection cracking	153 million
	2	45 mm MB4-G		117 million
	3	45 mm MB4-G with 15% rubber		85 million
	4	45 mm RAC-G		46 million
	5	90 mm AR-4000-D (DGAC)		5 million
	-	90 mm MB4-G		194 million

* All sections simulated with the same pavement structure, underlying cracking pattern and density, climate, & traffic.

Rutting

Rutting performance of each of the mixes in the HVS, laboratory shear, and *CalME* mechanistic simulation studies are provided in the table below. Rankings are from best to worst. Unlike the fatigue cracking performance, the results for rutting were not as consistent across the different evaluation methods. In general, the DGAC mix had clearly superior rutting performance; followed by the RAC-G. The modified mixes had the lowest performance. For the HVS results, it should be noted that most rutting was in the underlying DGAC layer and not in the overlay. Similar results have been recorded in other HVS tests on thin overlays.

	Rank	Section	Parameter	Finding
HVS	1	90 mm AR-4000-D (DGAC)	Number of HVS repetitions to 12.5 mm average maximum rut	8,266
	2	45 mm MB4-G		3,043
	3	45 mm RAC-G		2,324
	4	90 mm MB4-G		1,522
	5	45 mm MB4-G with 15% rubber		914
	6	45 mm MAC15TR		726
Lab shear	1	AR-4000-D (DGAC)	Permanent Shear Strain at 5,000 cycles and Cycles to 5% Permanent Shear Strain	Laboratory ranking is based on an average of the results from all tests.
	2	MAC15TR-G		
	3	RAC-G		
	4	MB4-G		
	5	MB4-G with 15% rubber		
Simulation*	1	90 mm AR-4000-D (DGAC)	Predicted rut (mm) in Central Valley (CV) and Desert (Des) climates, for Traffic Index of 13, & truck speed of 70 km/h	CV 2.8, Des 3.8
	2	45 mm RAC-G		CV 4.8, Des 5.8
	3	45 mm MAC15TR-G		CV 5.3, Des 6.3
	4	90 mm MB4-G		CV 5.6, Des 6.4
	5	45 mm MB4-G		CV 6.4, Des 7.3
	6	45 mm MB4-G with 15% rubber		CV 8.0, Des 8.8

* All sections simulated with the same pavement structure, climate, & traffic. Simulations across various California climate regions and traffic levels provided nearly identical rankings

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