

OVERVIEW OF AN ACCELERATED PAVEMENT TESTING STUDY TO ASSESS THE PERFORMANCE OF MODIFIED BINDERS IN ASPHALT CONCRETE OVERLAYS

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ABSTRACT

A comprehensive laboratory and accelerated pavement testing study on the use of terminal blend modified binders to limit reflective cracking in thin asphalt concrete overlays has recently been completed at the University of California Pavement Research Center. The experiment entailed the construction of a 90 m test road consisting of compacted clay subgrade, a 410 mm aggregate base and 90 mm dense graded asphalt concrete surface. A Heavy Vehicle Simulator (HVS) was used to induce fatigue cracking on six, eight-by-one metre sections. Trafficking on each section was stopped when crack density exceeded 2.5 m/m². Six different overlays, including dense graded asphalt concrete (DGAC) and rubberized asphalt concrete (RAC-G) control sections, and three different terminal blend rubber modified binder sections, were then placed on the road. The original six section locations were precisely mapped onto the overlays and the HVS used to assess reflective cracking in each. Pavement temperatures were controlled in a temperature chamber. Separate rutting studies were also carried out on the overlays in separate HVS experiments adjacent to the fatigue experiments. In conjunction with the HVS testing, laboratory shear and fatigue testing was carried out on field mixed/field compacted, field mixed/laboratory compacted, and laboratory mixed/laboratory compacted specimens. The findings have shown a good relationship between HVS and laboratory results. The results indicate that gap-graded mixes with between seven and fifteen percent recycled tire rubber provided superior performance in terms of reflection cracking compared to the DGAC and RAC-G mixes, when used in thin overlays on cracked asphalt pavements. With regard to rutting performance, conventional DGAC 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. This paper provides an overview of the experiment and summary of the results.

Keywords: Accelerated pavement testing, Reflection cracking, Modified binder

Conference Topic selected: Pavement materials

INTRODUCTION

California, like most other states in the USA, has a mature road network that requires ongoing maintenance and rehabilitation. On that part of the network surfaced with asphalt concrete, fatigue cracking is a common distress, which is typically maintained by placing a thin overlay of dense-graded asphalt concrete (DGAC) or gap-graded rubberized asphalt concrete (RAC-G). Milling of the upper 50 mm to 100 mm of the old wearing course may be carried out prior to overlaying to maintain the existing surface elevation. The life of these overlays depends in large part on the extent of fatigue cracking in the original surface, and the support provided by the underlying layers. With a view to extending the life of overlays, a study comprising accelerated pavement testing and associated laboratory testing was initiated by the California Department of Transportation (Caltrans) and the University of California Pavement Research Center (UCPRC) to evaluate the reflection cracking and early rutting performance of asphalt mixes used in the state (Caltrans, 2005).

The main objective of this investigation was to compare the performance of three maintenance overlays using modified binder (MB) mixes against two control maintenance overlay mixes (DGAC and RAC-G), essentially asking the question "*Will gap-graded modified binder (MB-G) mixes provide performance equal to gap-graded rubberized asphalt concrete (RAC-G) mixes in half-thickness applications?*" (UCPRC 2003). MB binders are asphalt binders modified with polymers and recycled tire rubber and blended at the refinery (terminal blend) meeting a Caltrans performance related specification. This study, termed the MB-Road study, is part of a larger study to develop

improved rehabilitation designs for reflection cracking for California. The objectives of the MB-Road study will have been met after completion of four tasks:

1. Develop improved mechanistic models of reflection cracking in California
2. Calibrate and verify these models using laboratory and HVS testing
3. Evaluate the most effective strategies for reflection cracking
4. Provide recommendations for reflection cracking strategies

This paper describes part of the work undertaken to complete Task 2 and includes a summary of the project experimental design, accelerated pavement testing, laboratory testing, and preliminary findings. Results of the other tasks are described in other reports and papers.

TEST SUMMARY

The MB-Road study was divided into three phases (Jones, et al, 2007a):

- Phase 1 covered construction of a uniform test pavement, demarcating six uniform test sections, trafficking these sections with a Heavy Vehicle Simulator (HVS) to induce fatigue cracking on the asphalt concrete layer, then overlaying the test track with the following six overlays (Figure 1). The "MB" specification is Caltrans specific and is currently being changed to be compatible with the PG system.
 - Half-thickness (45 mm) MB4 gap-graded overlay (7 percent recycled tire rubber);
 - Full-thickness (90 mm) MB4 gap-graded overlay;
 - Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber, termed MB15-G in this paper;
 - Half-thickness (45 mm) MAC15TR gap-graded overlay, termed MAC15-G in this paper (15 percent recycled tire rubber);
 - Half-thickness (45 mm) rubberized asphalt concrete gap-graded overlay (RAC-G), included as a control for performance comparison purposes, and
 - Full-thickness (90 mm) dense-graded asphalt concrete (DGAC) overlay, included as a control for performance comparison purposes. The binder used was AR-4000, approximately equivalent to PG64-16.
- Phase 2 included HVS and laboratory testing:
 - 12 HVS tests, including six reflection cracking tests at moderate temperature on sections positioned precisely over the cracked original six Phase 1 tests on the underlying DGAC, and six rutting tests at high temperature on sections adjacent to the reflective cracking sections.
 - A comprehensive laboratory investigation to relate laboratory rutting and fatigue performance to performance under the HVS. Experiments were conducted on cores removed from the road, on field-mix/laboratory-compacted (FMLC) samples, and on laboratory-mixed/laboratory-compacted (LMLC) samples.
- Phase 3 entailed a detailed second-level analysis of the laboratory and HVS data, and included performance modeling and simulation of the various mixes using models calibrated with data from the primary elements listed above.

Instrumentation

Instrumentation of the test sections consisted of the following:

- Multi-Depth Deflectometers (MDD): used to measure elastic vertical deflections and permanent vertical deformations at various levels in the pavement structure, relative to a reference depth located in the subgrade.
- Road Surface Deflectometer (RSD): used to measure elastic vertical deflections at the surface of the pavement.
- Laser Profilometer: used to measure the transverse profile of the pavement surface to determine surface rutting.
- Thermocouples used to measure temperatures at various depths in the asphalt bound materials.
- Time Domain Reflectometer: used to monitor the changes in water content in the unbound layers just outside the trafficked area during testing of the section

The following testing was also undertaken:

- Digital Crack Imaging: used to measure surface cracking.

- Falling Weight Deflectometer (FWD): used to measure elastic vertical deflections at the surface of the pavement before and after HVS testing and on areas not trafficked to monitor asphalt aging and seasonal changes in unbound layer moduli.
- Dynamic Cone Penetrometer (DCP): used to measure the relative shear resistance of unbound layers.
- Trenching: To determine final rut depths in each layer and assess final condition of the pavement layers after completion of HVS trafficking.

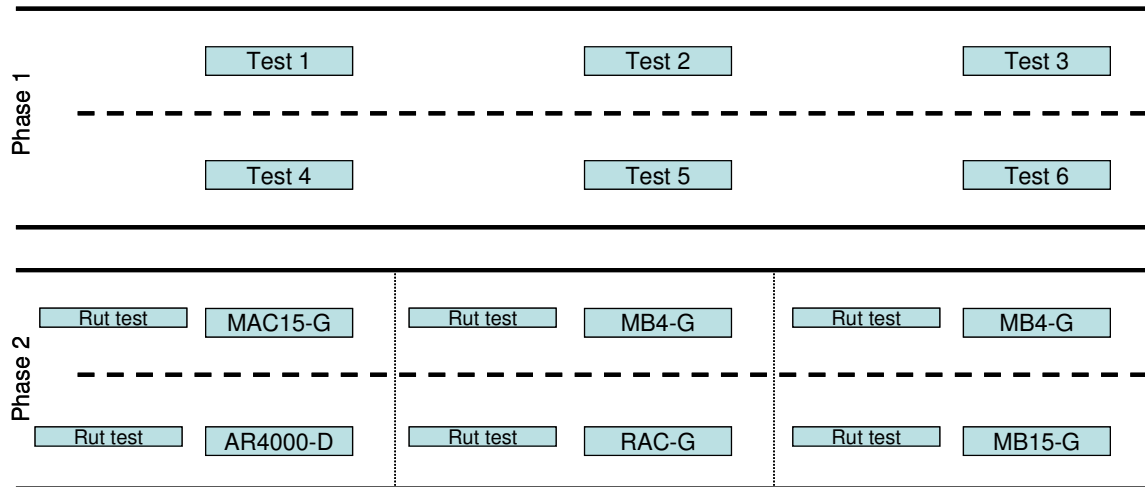


FIGURE 1: MB-Road layout

PHASE 1: CONSTRUCTION, INITIAL HVS TRAFFICKING, AND OVERLAY PLACEMENT

The test road was designed following standard Caltrans procedures and incorporated 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 California 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.

Six sections (Section numbers 567RF - 569RF and 571 - 573RF on this structure were 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 the six sections to induce a minimum of 2.5 m/m² fatigue cracking on each section (Jones, et al, 2007a). The fatigue cracking measured on the sections is shown in Figure 2 (at the end of the paper). In June 2003, the road was overlaid with six different treatments. The thickness for the control DGAC (using an AR4000 binder approximately equivalent to PG64-16) overlay was determined according to Caltrans Test Method 356. The other overlay thicknesses were either the same or half of the DGAC overlay thickness.

PHASE 2: HVS RUTTING AND REFLECTIVE CRACKING TESTS

The second phase of HVS tests consisted of two sub-phases. In the first, a rutting study on sections adjacent to the reflective cracking sections was carried out to assess the susceptibility of the mixes to early rutting at high pavement temperatures (50°C at 50 mm pavement depth). In the second, a reflective cracking study was carried out to assess the effectiveness of the overlays in limiting reflective cracking at moderate temperatures (20°C then 15°C at 50 mm pavement depth). These sections were precisely positioned on top of the sections already trafficked on the underlying pavement during Phase 1 (see Figure 1).

Rutting Study

The overlay rutting sections were trafficked with the HVS between September and December 2003 on sections next to the demarcated fatigue sections on each overlay, and over a part of the underlying pavement that had not been trafficked during Phase 1. 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 at 50 mm depth. Measurements taken at regular intervals throughout the test included air and pavement temperatures, in-depth elastic

deflection, and surface and in-depth permanent deformation. An average maximum rut of 12.5 mm was set as the failure criterion. Findings and observations based on the data collected during the Phase 2 HVS rutting study include (Steven, et al, 2007):

- An aggressive loading regime (60 kN wheel load at 50°C pavement temperature) was followed to induce failure.
- The number of repetitions required to reach the failure criterion of 12.5 mm average maximum rut depth varied between 726 repetitions for the MAC15-G mix and 8,266 repetitions for the AR4000-D mix. Results are listed in Table 1, which includes ranking from best to worst, the number of load repetitions to reach an average maximum rut depth of 12.5 mm, and the average maximum rut depth and the average deformation measured after completion of testing. The ranking is shown graphically in Figure 3.

TABLE 1: Phase 2 HVS Rutting Study Results

Rank	Overlay	Repetitions to 12.5 mm	Average Maximum Rut (mm)	Average Deformation (mm)
1	AR4000-D	8,266	15.6	8.1
2	MB4-G (45 mm)	3,043	31.3	9.7
3	RAC-G	2,324	22.7	10.3
4	MB4-G (90 mm)	1,522	23.3	11.9
5	MB15-G	914	18.8	7.1
6	MAC15-G	726	23.5	7.7

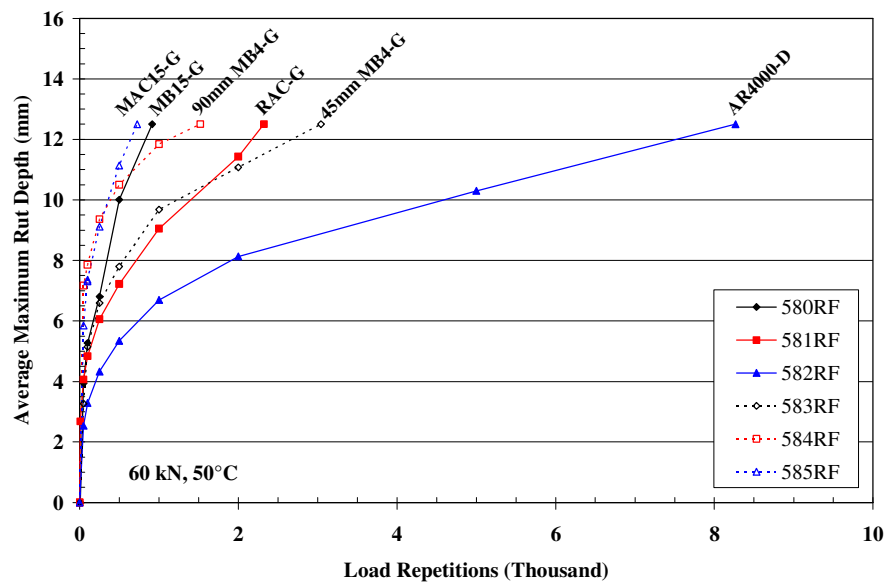


FIGURE 3: Progression of average maximum rut depth to 12.5 mm failure criteria.

- Analysis of surface profiles and test pit observations during a forensic investigation (Jones, et al, 2007) indicate that most of the permanent deformation occurred in the underlying DGAC surfacing layer (Figure 4). The deformation along each section was reasonably uniform, with the exception of the 90-mm MB4-G, where more severe rutting and heaving occurred at one end of the test section compared to the other. All of the sections showed some heaving at the sides of the trafficked area, with heights varying between 5 mm and 16 mm. Further investigations are currently being carried out to determine the reason for this rutting behavior.

Reflective Cracking Study

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

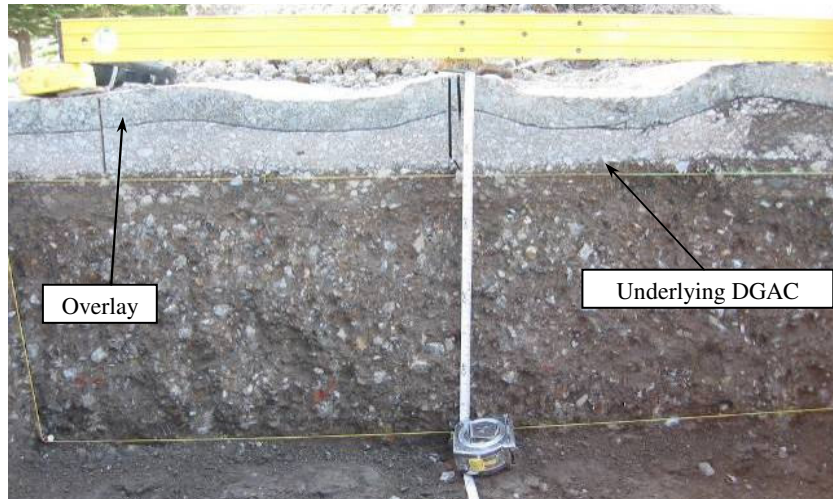


FIGURE 4: Rutting in the underlying DGAC on the 45-mm MB4-G Section.

TABLE 2: Phase 2 HVS Fatigue Cracking Study Results.

Rank	Section	ESALs to 2.5 m/m ² reflection cracking
1	45 mm MAC15-G	No cracking after 91 million
1	45 mm MB15-G	No cracking after 88 million
1	45 mm MB4-G	No cracking after 66 million
1	90 mm MB4-G	No cracking after 37 million
5	45 mm RAC-G	60 million
6	90 mm AR-4000 DGAC	16 million

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. A crack density of 2.5 m/m² was set as the failure criteria. FWD measurements were taken before and after each HVS tests. Figure 5 (at the end of the paper) shows the outcome of the fatigue experiments. Results of the test are summarized in Table 3. Rankings are from best to worst. It should be noted that no fatigue cracking was recorded on the MB4-G, MB15-G and the MAC15-G sections. A small area of cracking attributed to shear failure of underlying layers was observed at one end of the 45 mm MB4-G section. Ranking of the MB mixes is therefore based on the number of repetitions actually applied and not on cracking performance (Jones, et al, 2007a).

A summary of the findings from each HVS test is provided below.

90 mm AR4000-D (Control)

A total of 1,410,000 million repetitions were applied during this HVS test. Findings and observations based on the data collected include:

- Cracking was first observed after approximately 510,000 repetitions. On completion of testing, the surface crack density was 9.1 m/m², with cracking occurring predominantly on one half of the section (Figure 6). The surface crack density reached 2.5 m/m², the failure criterion set for the experiment, after about 900,000 load repetitions, but trafficking was continued to determine whether cracking would eventually spread to the remainder of the test section. Cracking on the overlay was predominantly transverse up until the 100 kN (22,500 lb) load change. Thereafter, an alligator cracking pattern was observed, similar to that on the underlying layer. The crack patterns of the two layers did not match exactly, however, the areas of most severe cracking corresponded.
- The average maximum rut depth and average maximum deformation across the entire test section at the end of the test was 15.9 mm and 8.8 mm respectively. The average maximum rut was higher than the failure criterion of 12.5 mm set for the experiment, reached after approximately 1.2 million repetitions. As indicated above, testing was continued to determine whether cracking would eventually spread to the remainder of the test section. The maximum rut depth measured on the section was 30 mm. The rate of rutting was relatively slow

during the early part of the experiment, but increased significantly after the 100 kN load change, despite the pavement temperature being reduced to 15°C. The final surface rutting pattern of the overlay generally corresponds with the fatigue cracking pattern, and the deepest part of the rut occurred on that half of the section with the highest density of cracking in the underlying DGAC layer.

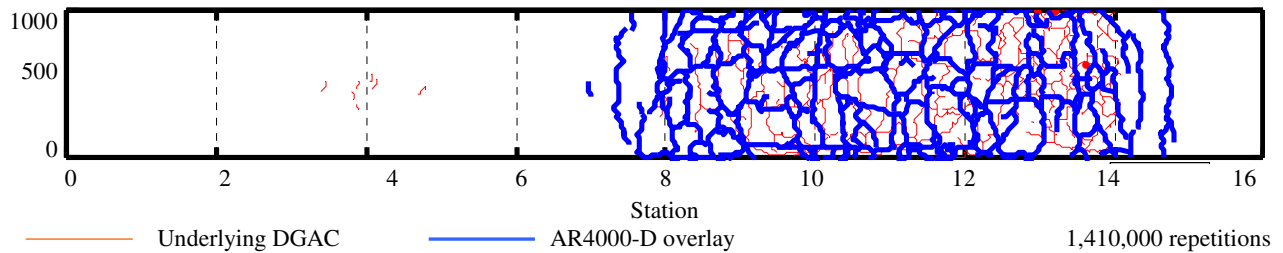


FIGURE 6: Cracking pattern comparison between underlying layer and AR4000-D overlay.

- The two failure criteria set for the experiment were reached within approximately 300,000 load repetitions of each other.
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between four and eleven times along the length of the section, indicating significant damage in the pavement structure in terms of loss of stiffness. The ratio of final-to-initial deflections was inconsistent across the section, with significantly higher values in the area overlying the most severely cracked area.
- No in-depth elastic deflection or permanent deformation data were collected in this experiment due to problems with the MDDs. Malfunction was attributed to the loss of anchorage of the modules resulting from very wet conditions in the lower layers of the pavement and subgrade. Subsequent forensic investigations indicate that most of the permanent deformation occurred in the asphalt-bound surfacing layers (overlay and underlying DGAC) with approximately twice as much damage occurring in the area of most severe cracking in the underlying DGAC layer.
- Parts of the test were carried out during relatively high rainfall. This resulted in ponding of water adjacent to the section. Some pumping of fines through the cracks was noted in the final days of testing.

45 mm RAC-G (Control)

A total of 2,024,793 repetitions were applied during this HVS test. Findings and observations based on the data collected include:

- Cracking was first observed after approximately 1.5 million repetitions. On completion of testing, the surface crack density was 3.6 m/m², considerably lower than the 5.4 m/m² recorded after 377,556 repetitions on the underlying layer during Phase 1 HVS trafficking. The surface crack density reached 2.5 m/m², the failure criterion set for the experiment, after about 1.9 million load repetitions. Cracking on the overlay was predominantly transverse, as was that on the underlying layer. The crack patterns of the two layers did not match exactly; however, the areas of most severe cracking corresponded (Figure 7).
- The average maximum rut depth across the entire test section at the end of the test was 18.2 mm, which was higher than the failure criterion of 12.5 mm set for the experiment, reached after approximately 1.8 million repetitions. The maximum rut depth measured on the section was 26.3 mm. The rate of rutting was relatively slow during the early part of the experiment; but increased significantly after the 100 kN load change, despite the pavement temperature being reduced to 15°C.

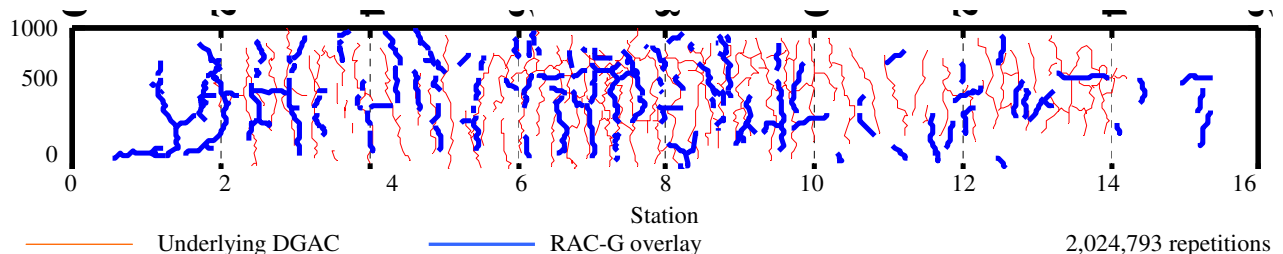


FIGURE 7: Cracking pattern comparison between underlying layer and RAC-G overlay.

- Both of the failure criteria set for the experiment were reached within 100,000 load repetitions of each other.
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between 3.4 and 5.5 times along the length of the section. The ratios for in-depth deflections show that damage had increased significantly at all depths in the pavement structure by the end of trafficking. The limited data available shows that loss of stiffness in the section was highest in the area of most severe cracking in the underlying layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicate that most of the permanent deformation occurred in the asphalt-bound surfacing layers (overlay and underlying DGAC) with approximately twice as much damage occurring in the area of most severe cracking in the underlying DGAC layer. Permanent deformation was also recorded in the upper part of the aggregate base in this area. Negligible deformation was recorded in the subgrade. These findings were confirmed in the forensic investigation.

45 mm MB4-G

A total of 2,086,004 repetitions were applied during this HVS test. Findings and observations based on the data collected include:

- Cracking was observed at one end of the section where significant deformation (rutting and shoving) had occurred. It was first recorded after 1.5 million repetitions and no further cracking was noted after about 1.6 million repetitions. On completion of testing, the crack density was 1.55 m/m², considerably lower than the failure criterion of 2.5 m/m² set for the experiment. The cracks were predominantly longitudinal and cracking patterns did not correspond with those in the underlying DGAC layer. Apart from the cracks associated with deformation at the end of the section, the MB4-G overlay appeared to successfully prevent any cracking in the underlying layer from reflecting through to the surface, despite final-to-initial deflections indicating that considerable damage had occurred in the asphalt layers.
- The average maximum rut depth across the entire test section at the end of the test was 37.2 mm, which exceeded the Caltrans (and experiment) failure criterion of 12.5 mm reached after approximately 820,000 repetitions. At this point, no cracking was observed and the test was therefore continued to gain a better understanding of the MB4-G overlay performance. The maximum rut depth measured on the section at the end of the test was 106 mm. Despite conducting HVS testing at relatively low pavement temperatures (20°C) for the first one million repetitions and 15 C for the remainder of the test, the MB4-G overlay appeared susceptible to rutting from early in the experiment.
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between 2.1 and 2.9 times along the length of the section. The ratios for in-depth deflections show that damage had increased significantly at all depths in the pavement structure by the end of trafficking. Loss of stiffness was highest in the area of most severe cracking in the underlying DGAC layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicate that most of the permanent deformation (between 68 and 86 percent along the length of the section) occurred in the asphalt-bound surfacing layers (overlay and underlying DGAC) with the remainder in the aggregate base layer. Some deformation occurred in the subgrade below the point of greatest maximum rut. Contribution to total permanent deformation at this point was 68, 26, and 6 percent for the surfacing, aggregate base, and subgrade respectively. These findings were confirmed in the forensic investigation.

90 mm MB4-G

A total of 1,981,365 repetitions were applied. Findings and observations based on the data collected during this HVS study include:

- No reflective cracking from the underlying severely cracked DGAC layer was observed on the MB4-G overlay after almost two million HVS repetitions. The MB4-G overlay thus appeared to successfully prevent any cracking in the underlying layer from reflecting through to the surface, despite final-to-initial deflections indicating that considerable damage had occurred in the asphalt layers under loading.
- The average maximum rut depth across the entire test section at the end of the test was 12.7 mm, equivalent to the Caltrans (and experiment) failure criteria. The maximum rut depth measured on the section was 19.0 mm, with a maximum rut depth of 12.5 mm reached after about 1.17 million repetitions.
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between 1.9 and 3.0 times along the length of the section. The ratios for in-depth deflections show that damage increased at all

depths in the pavement structure (between 1.9 and 2.2 times) by the end of trafficking. Loss of stiffness was highest in the area of most severe cracking in the underlying DGAC layer.

- Analysis of surface profile and in-depth permanent deformation measurements indicates that most of the permanent deformation (between 67 and 88 percent) occurred in the asphalt-bound surfacing layers (overlay and underlying DGAC) with marginal deformation in the base layer and negligible deformation in the subgrade. These findings were confirmed in the forensic investigation.

45 mm MB15-G

The failure criteria set for the experiment had not been reached after 2.5 million repetitions. Given time and fund limitations, Caltrans and the UCPRC agreed to halt the experiment at this point. Findings and observations based on the data collected during this HVS study include:

- The MB15-G overlay appeared to successfully prevent any cracking in the underlying layer from reflecting through to the surface, despite final-to-initial deflections indicating that damage had occurred in the asphalt layers under loading.
- The average maximum rut depth across the entire test section at the end of the test was just 4.6 mm, considerably lower than the Caltrans (and experiment) failure criterion of 12.5 mm. The maximum rut depth measured on the section was 7.7 mm. The MB15-G overlay thus did not appear susceptible to rutting in the temperature range at which the test was conducted (20°C for the first one million repetitions and 15°C thereafter).
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between 1.4 and 1.9 times along the length of the section. The ratios for in-depth deflections show that damage increased at all depths in the pavement structure by the end of trafficking. Loss of stiffness was highest in the area of most severe cracking in the underlying DGAC layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicated that most of the permanent deformation (approximately 55 percent) occurred in the asphalt-bound surfacing layers (overlay and underlying DGAC) with the remainder mostly in the aggregate base layer. These findings were confirmed in the forensic investigation. After the first one million repetitions had been applied, the permanent deformation in the surfacing layers was higher (approximately 70 percent).

45 mm MAC15-G

The failure criteria set for the experiment had not been reached after 2.5 million repetitions. Given time and fund limitations, Caltrans and the UCPRC agreed to halt the experiment at this point. Findings and observations based on the data collected during this HVS study include:

- The MAC15-G overlay appeared to successfully prevent any cracking in the underlying layer from reflecting through to the surface, despite final-to-initial deflections indicating that damage had occurred in the asphalt layers under loading.
- The average deformation and average maximum rut depth across the entire test section at the end of the test was just 1.7 mm and 4.6 mm respectively, with average maximum rut considerably lower than the Caltrans (and experiment) failure criterion of 12.5 mm. The maximum rut depth measured on the section was 8.2 mm. The MAC15-G overlay thus did not appear susceptible to rutting in the temperature range at which the test was conducted.
- Ratios of final-to-initial elastic surface deflections under a 60 kN wheel load increased by between 3.7 and 4.0 times along the length of the section. The ratios for in-depth deflections show that damage increased at all depths in the pavement structure by the end of trafficking. Loss of stiffness was highest in the area of most severe cracking in the underlying DGAC layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicates that most of the permanent deformation (between 55 and 60 percent) occurred in the asphalt-bound surfacing layers (overlay and cracked DGAC) with the remainder mostly in the aggregate base layer. These findings were confirmed in the forensic investigation. After the first one million repetitions had been applied, the permanent deformation in the surfacing layers was higher (between 80 and 90 percent).

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 permanent deformation measured in the rutting study occurred in the underlying DGAC layer (Figure 8). 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 (Figure 9). There was no observed cracking on the surface of the MB sections. 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-ementation of the recycled construction waste that occurred after construction. The strongest part of the base was typically between 100 mm and 250 mm below the asphalt concrete (Jones et al, 2007b).

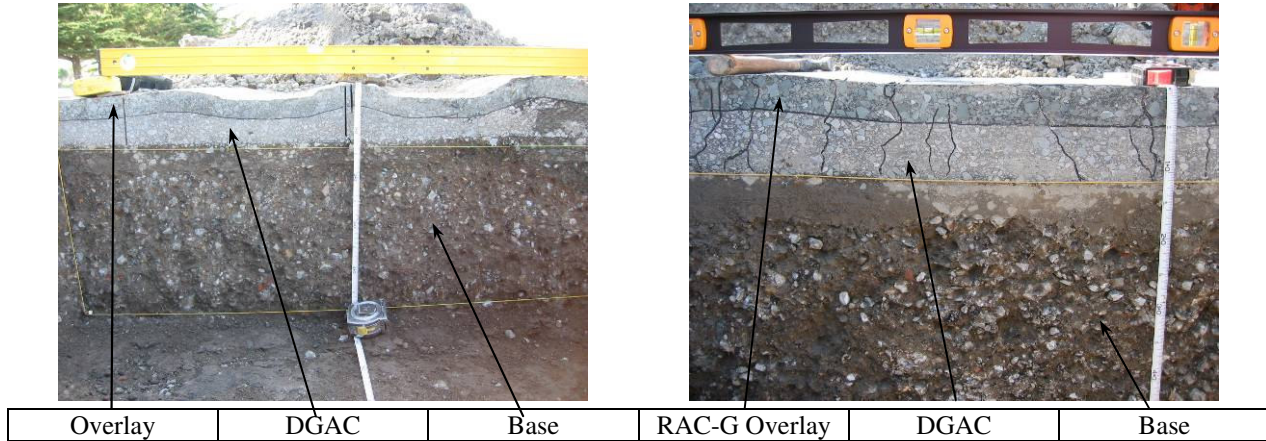


FIGURE 8: Rutting section forensic.

FIGURE 9: Fatigue section forensic (cracks are highlighted with marker pen).

PHASE 2: LABORATORY STUDY

Laboratory fatigue and shear studies were conducted in parallel with Phase 2 HVS testing.

Laboratory Fatigue

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. The experiment design was formulated to quantify the effects of mix temperatures, air-void content, aging, mixing and compaction conditions, aggregate gradation, and time of loading (load frequency). To test a full factorial considering all the variables, a total of 1,440 tests would have been required. Because of time and fund constraints, a partial factorial experiment was completed with 172 tests. Rolling wheel compaction was used to prepare slab specimens of the various mixes, from which beams were cut for flexural fatigue testing and stiffness (frequency sweep) determinations following the AASHTO 321 procedure (four point bending). Beam fatigue tests were all conducted at 10 Hz and temperatures of 10°C, 20°C and 30°C. Stiffness measurements were conducted over the range of 15 Hz to 0.01 Hz and at temperatures of 10°C, 20°C, and 30°C to define the effect of time-of-loading and temperature on this mix characteristic. Results are described below (Tsai, et al, 2006).

Summary of Binder Tests

- Based on Bending Beam Rheometer (BBR) test results conducted by FHWA, the ranking of propensity to low temperature thermal cracking is listed below, from best to worst. The RAC binder was not tested.
 1. MB4→2. MB15→3. MAC15→4. AR4000.
- The order of thermal cracking potential was closely matched with the order of initial stiffness in the fatigue beam tests and flexural frequency sweep results; hence a mix with a higher initial stiffness might have a higher thermal cracking potential.
- The Dynamic Shear Rheometer (DSR) test results indicated that:
 - According to the Superpave specification, the ranking of fatigue resistance capacity, from best to worst, was in the order listed below, which is the same ranking obtained for initial stiffness during laboratory mix fatigue tests.
 1. MB4→2. MB15→3. MAC15→4. AR4000
 - MB4 and MB15 binders had better rutting resistance capacities than AR4000 binder.

Construction and Environment Effects

- The binder type had an overall effect on all the response variables including initial phase angle, initial stiffness, and fatigue life. As expected, the temperature effect on all three response variables was immediately apparent. The other effects assessed at 20°C (for comparison with HVS testing) revealed that:
 - Air-void content had a significant effect for some parts of the experiment, such as the FMLC mixes at 20°C, but the effect was not significant for many of the mixes and test conditions for all of the response variables (stiffness, fatigue life and shear resistance).
 - The effect of long-term oven aging at 85°C for 6 days (SHRP I procedure) was only significant for initial phase angle and stiffness but not for fatigue life.

Ranking of Initial Stiffness and Fatigue Performance

- The ranking of predicted initial stiffness (most to least stiff) and fatigue life (longest to shortest) under various specimen preparation and testing conditions, and specifically for the controlled strain mode of loading used in this experiment, was normally in the order listed below. For initial stiffness, no apparent differences exist between MB15-G and MB4-G mixes, while for fatigue life, no apparent differences exist between MAC15-G and MB15-G mixes. As expected, the two orders are reverse mirror images of each other.

Initial stiffness	Fatigue Life
1 AR-4000-D	1 MB4-G
2 RAC-G	2 MAC15-G
3 MAC15-G	3 MB15-G
4 MB15-G	4 RAC-G
5 MB4-G	5 AR-4000-D

- Fatigue test results indicate that initial stiffness and fatigue life are moderately negative-correlated ($\rho = -0.604$), confirming a general observation that lower stiffnesses equate to higher fatigue life at a given tensile strain under controlled-strain testing when ranking fatigue life performance against initial stiffness or vice versa. When using this observation, consideration must also be given to rutting, as mixes with low stiffness are generally susceptible to this distress. It must be emphasized that cracking performance can only be assessed from simulation considering overlay thickness, stiffness, laboratory fatigue life, climate and traffic, and not directly from these laboratory fatigue life test rankings.
- Preliminary analysis of stiffness versus strain repetition curves using three-stage Weibull analysis indicated differences in crack initiation and propagation. The AR4000-D mix had different behavior from that of the RAC-G mix, while the RAC-G mix performed differently than the MB4-G, MB15-G, and MAC15-G mixes. The results indicate that damage slows during the propagation phase of the latter four mixes, while it accelerates for the AR4000-D mix (Figure 10).

Dense-Graded versus Gap-Graded Mixes

- The optimum binder contents used in the mix designs for the MAC15, MB15, and MB4 dense-graded mixes (6.0, 6.0, and 6.3 percent respectively) were lower than the optimum binder contents used in the mix designs of the gap-graded mixes (7.4, 7.1, and 7.2 percent respectively). Limited fatigue testing of modified binders in dense-graded mixes led to the following observations:
 - The initial stiffnesses of the dense-graded mixes were generally greater than those of the corresponding gap-graded mixes but less than those of the AR4000-D and RAC-G mixes. The beam fatigue life at a given tensile strain of the dense-graded mixes was generally less than those of the corresponding gap-graded mixes, but greater than those of the AR4000-D and RAC-G mixes.
 - The mix ranking of the E* master curves, from most to least stiff, for laboratory mixed, laboratory compacted specimens at 6 percent air-voids was:
 1. AR4000-D→2. MAC15-D→3. RAC-G→4. MB15-D→5. MB4-D→6. MAC15-G→
 7. MB15-G→8. MB4-G
 - The mix ranking (longest to shortest) for the same conditions for beam fatigue life at 400 microstrain shows exactly the reverse trend from the above except that MAC15-D and RAC-G change places:
 1. MAC15-G→2. MB4-G→3. MB15-G→4. MB4-D→5. MB15-D→6. MAC15-D→
 7. RAC-G→8. AR4000-D

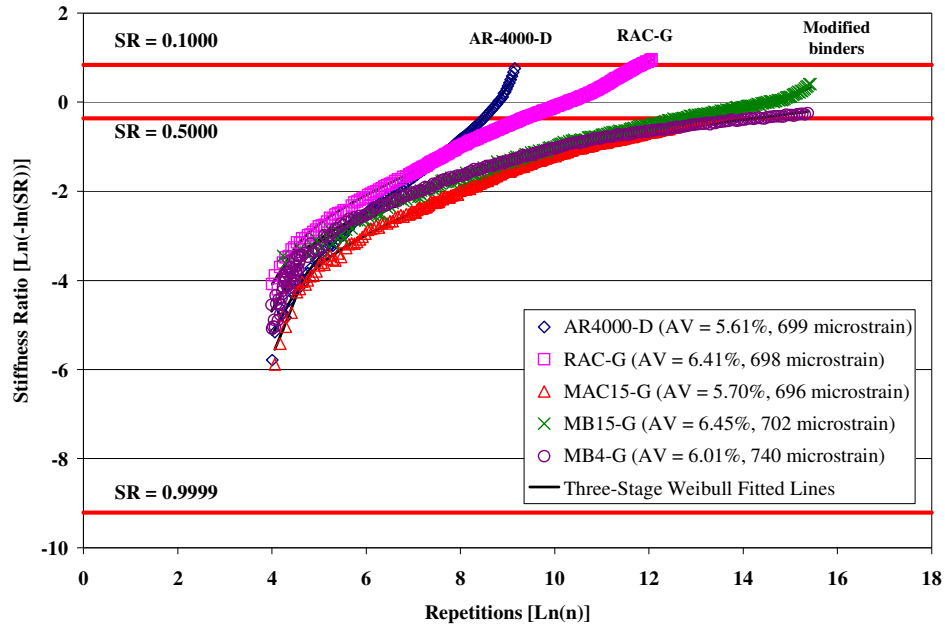


FIGURE 10: Typical Weibull curves for Reflection Cracking Study mixes

Complex Modulus (E^*) Master Curves of Mixes

- Complex modulus master curves from flexural frequency sweep tests showed mix stiffnesses for a wide range of temperature and time of loading conditions. Initial stiffnesses determined from beam fatigue tests were only for 10 Hz and the temperature at which the fatigue test was performed. Nevertheless, the mix ranking of E^* master curves under various combinations of material properties and testing conditions was generally in the order listed below (most to least stiff), and was comparable to the overall general ranking of beam fatigue performance in the controlled-strain testing (longest to shortest life). The MB4 and MB15 mixes showed no significant difference.

Initial stiffness	Fatigue Life
1 AR-4000-D	1 MB4-G
2 RAC-G	2 MB15-G
3 MAC15-G	3 MAC15-G
4 MB15-G	4 RAC-G
5 MB4-G	5 AR-4000-D

- The ranking of E^* master curves (most to least stiff) for dense-graded mixes considering the effect of gradation is in the order below, with no significant difference between the MB4 and MB15 mixes:
 - MAC15-D→2. MB4-D→3. MB15-D

Laboratory Shear

In the shear study, stiffnesses and permanent deformation at high temperatures were used to evaluate rutting resistance. Tests were carried out on field-mixed/field-compacted (FMFC), field-mixed/laboratory-compacted (FMLC - rolling wheel compaction), and laboratory-mixed/laboratory-compacted (LMLC - rolling wheel compaction) specimens.

Laboratory results were statistically analyzed to identify the significant variables affecting stiffness, fatigue and permanent shear deformation performance (Guada et al, 2006). 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^*). Detailed results are not provided in this paper. The ranking of performance, from best to worst, based on an average of the results from all tests results (Permanent Shear Strain at 5,000 cycles and Cycles to 5 percent Permanent Shear Strain) is as follows:

- AR4000-D→2. MAC15-G→3. RAC-G→4. MB4-G→5. MB15

Use of the MAC15, MB4 and MB15 binders with dense gradations increased shear test performance and stiffness in the laboratory tests compared to gap-graded mixes with the same binders.

Simulation

Simulation models developed for Caltrans by the UCPRC were used to extrapolate HVS results to identical test and in-service pavement conditions to obtain a more realistic indication of expected performance and to eliminate the effects of variation in the test track, specifically those related to stiffness in the aggregate base. Two approaches were used:

- A recursive mechanistic-empirical design model for rutting and reflection cracking included in the CalME (California Mechanistic Empirical Design) software (Ullidtz et al, 2006). This was used with laboratory shear, fatigue and frequency sweep tests results to simulate rutting and fatigue cracking performance on the HVS sections and then in three California climate regions (Desert, Valley, South Coast) at various traffic levels, with two truck traffic speeds (10 km/h 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 sections 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.

Detailed analysis and results are not discussed in this paper.

CONCLUSIONS

A comprehensive laboratory and accelerated pavement testing experiment comparing gap-graded, terminal blend modified binder mixes with gap-graded rubberized asphalt concrete and conventional dense-graded asphalt concrete (using an equivalent PG64-16 binder) has recently been completed in California. The results indicate that gap-graded mixes with MB4, MB4 with 15 percent recycled rubber, and MAC15TR with 15 percent recycled rubber binders will provide superior performance in terms of reflection cracking compared to the same half thickness of RAC-G and full thickness of DGAC, 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.

The following interim recommendations were made with regard to implementation, based on the findings of this task of the study and initial 2nd level analysis. More detailed recommendations will be made on completion of the second-level analysis and simulations.

- MB4, MB4 with 15 percent rubber, and MAC15TR binders can be used in appropriately designed half-thickness overlay mixes for reflection 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 they should not be used in locations with these conditions until proven in pilot projects on in-service highways.
- Simulation models calibrated with the HVS results should be used to assess the performance of other mixes or changes in binder specifications and to validate future mix and thickness design changes.
- 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.

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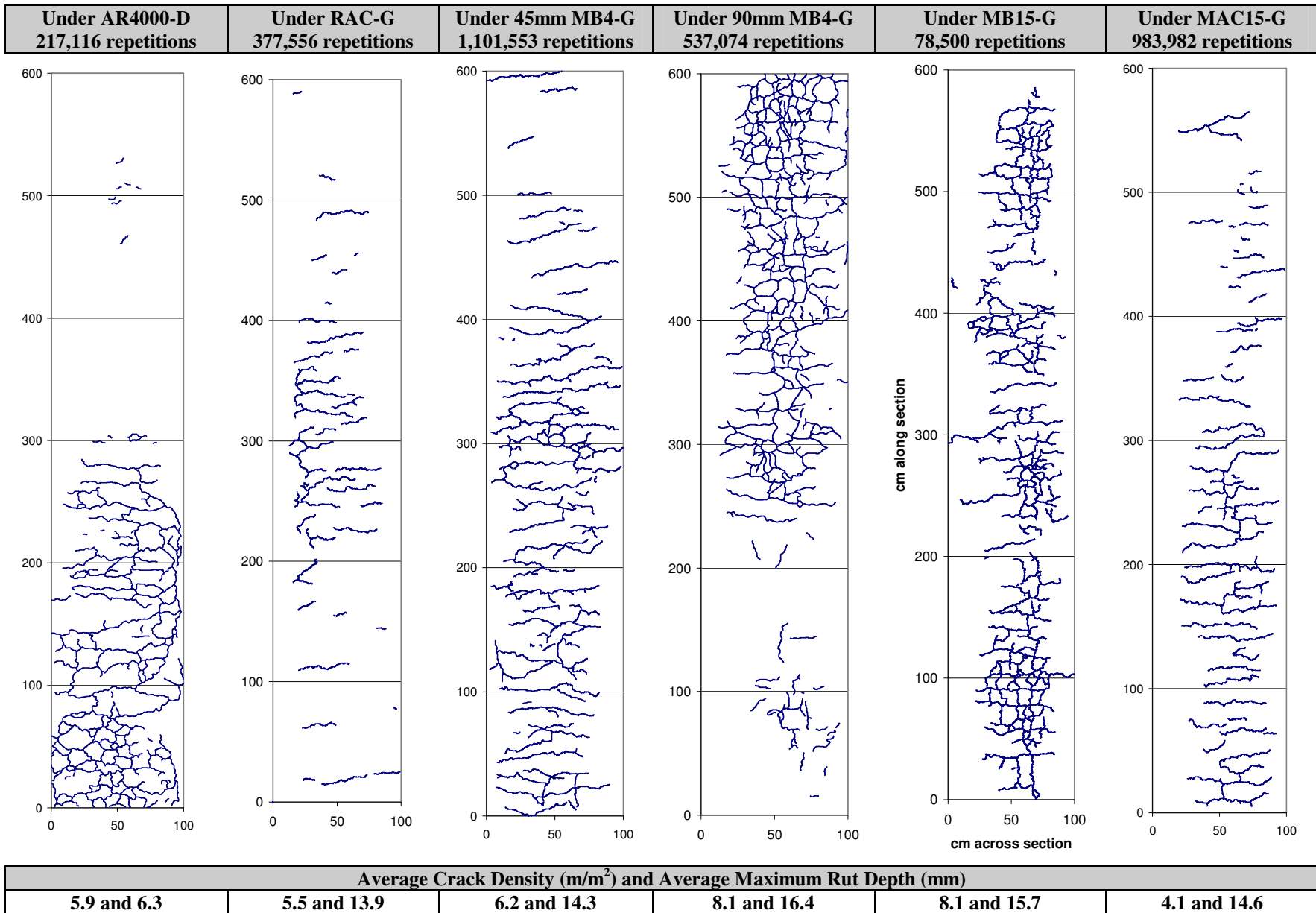


Figure 2: Cracking patterns and rut depths on completion of Phase 1 HVS trafficking.

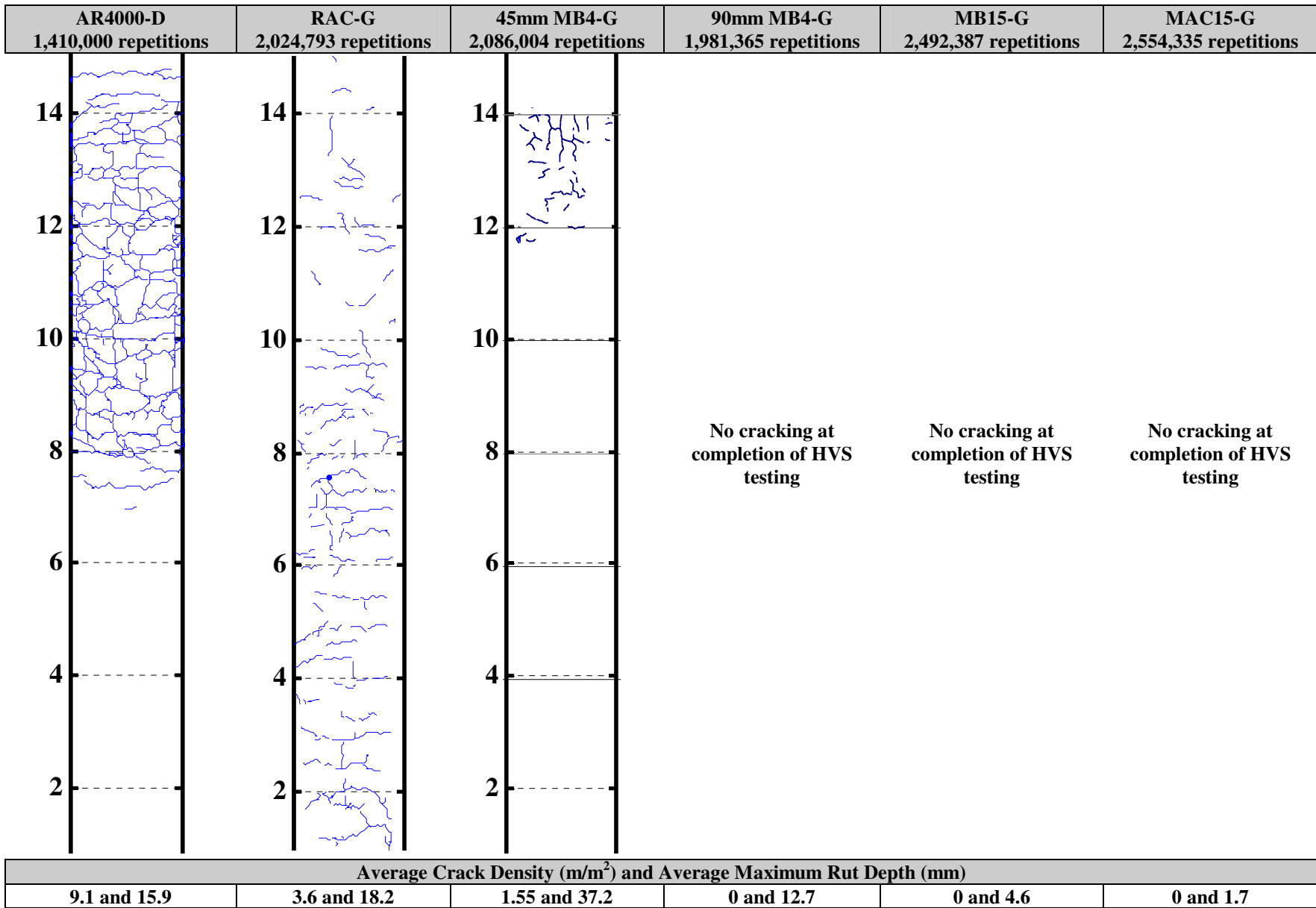


Figure 3: Cracking patterns and rut depths on completion of Phase 2 HVS testing.