

Louisiana Experience with Crumb-Rubber Modified Hot-Mix Asphalt Pavement

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ABSTRACT

This paper presents a comparative study of both laboratory and field performance of several applications of crumb-rubber modified (CRM) hot-mix asphalt in Louisiana. Eight CRM asphalt pavement sections were constructed using eight different CRM processes or applications. These eight CRM sections were built at five state highway projects. A control section with conventional asphalt mixture was constructed at each project to compare the performance of pavement sections built with CRM asphalt mixtures.

To evaluate the mixture characteristics of the CRM and conventional mixes, laboratory tests of Marshall stability and flow, indirect tensile strength (ITS) and strain, and indirect tensile resilient modulus (M_R) were conducted on field compacted Marshall specimens.

Comparisons of the field performances of the pavements were achieved through roadway core air void analysis, rut-depth measurement, international roughness index (IRI), pavement structure numbers measured through the DYNAFLECT system, and visual inspections of cracks.

The result of this study indicated that the conventional mixtures exhibited higher laboratory strength characteristics than the CRM mixtures. The pavement sections constructed with CRM asphalt mixtures showed overall better performance indices (rut depth, fatigue cracks, and IRI numbers) than the corresponding control sections after five to seven years of traffic.

KEYWORDS: crumb-rubber, CRM, asphalt mixture, pavement performance, mix characterization

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INTRODUCTION

The use of crumb-rubber modifier (CRM) in hot-mix asphalt mixtures can be traced back to the 1840s when natural rubber was introduced into bitumen to increase its engineering performance (1). Since the 1960s, researchers and engineers have used shredded automobile tires in hot-mix asphalt (HMA) mixtures for pavements. It was not until the late 1980s that the use of recycled tire crumb rubber in HMA mixtures became popular. In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) specified that all asphalt pavement project funded by federal agencies must use certain percentages of scrap tires (2, 3). Although this mandate was later suspended from the ISTEA legislation, it has greatly encouraged the research and application of CRM asphalt in HMA pavement.

The processes of applying crumb-rubber in asphalt mixtures can be divided into two broad categories: a dry process and a wet process. In the dry process, crumb rubber is added to the aggregate before the asphalt binder is charged into the mixture. In the wet process, asphalt cement is pre-blended with the rubber at high temperature (177 – 210 °C) and specific blending conditions. Crumb rubber particles in the dry process are normally coarser than those in the wet process and are considered as part of the aggregate gradations (called “rubber-filler”) whereas, in wet process, fine crumb rubber powders fully react with asphalt binders (called “asphalt-rubber”) and improve the binder properties. Common dry process methods include the PlusRide™, chunk rubber, and generic dry. Common wet process methods include the Arizona (ISI), McDonald, Ecoflex, and Rouse continuous blending method (1).

The Federal Highway Administration (FHWA) and many state agencies have conducted numerous field studies for the feasibility of using recycled rubber tire products in HMA pavements. The National Cooperative Highway Research Programs (NCHRP) “Synthesis of Highway Practice 198 – Uses of Recycled Rubber Tires in Highways” provides comprehensive review of the use of recycled rubber tires in highways based on a review of nearly 500 references and on information recorded from state highway agencies’ responses to a 1991 survey of current practices (4). Florida DOT began constructing demonstration projects of asphalt pavement with CRM wet processes in 1989 and has reported satisfactory pavement performance (5). They concluded that the addition of CRM would increase the asphalt film thickness, binder resiliency, viscosity, and shear strength. Virginia DOT constructed pavements containing CRM asphalt mixtures produced by two wet processes, McDonald and Rouse and compared the pavement performance to that of conventional asphalt mixtures. Maupin (6) reported that the mixes containing asphalt rubber performed at least as well as conventional mixes. In Virginia mixes, the inclusion of asphalt rubber in HMA pavements increases construction cost by 50 to 100 percent as compared to the cost of conventional mixes (6). Troy et al (7) conducted a research on CRM pavements in the State of Nevada. In their study, they evaluated a CRM binder using the Superpave binder testing protocols and conducted the mix design using the Hveem procedure. They concluded that the conventional sample geometry in Superpave binder test protocols cannot be used to test the CRM binders and that the Hveem compaction is inadequate for mixtures containing CRM binders.

The Louisiana Department of Transportation and Development (LADOTD) started a research project to evaluate different procedures of CRM applications in 1994 in which the long-term pavement performance of the CRM asphalt pavements was compared to that of the control sections built with conventional asphalt mixtures (8). This paper reports the main findings from the study.

OBJECTIVE

The objective of this study was to evaluate the mixture characteristics and field performance of asphalt pavements constructed with eight different CRM applications as opposed to the control sections built with conventional HMA mixtures.

SCOPE

The scope of the study included the evaluation of eight CRM applications as follows:

- Arizona wet process incorporated into a gap-graded mixture;
- Arizona wet process incorporated into a stress absorbing membrane interlayer (SAMI);
- Arizona wet process incorporated into an open-graded friction course (OGFC);
- PlusRide™ dry process utilizing a gap-graded aggregate structure;
- Rouse powdered rubber wet process incorporated into a typical dense-graded mixture;
- A terminal-blended material formulated by Neste Wright in a dense-graded mixture;
- Rouse dry-powdered rubber process blended into a dense-graded aggregate structure;
- Generic dry process incorporated into a gap-graded mixture.

Conventional and CRM asphalt mixtures were evaluated through laboratory engineering performance tests such as indirect tensile strength (ITS) and indirect tensile resilient modulus (M_R) tests. In addition, Marshall Stability and Flow tests were conducted during the mixture design.

Comparisons of pavement field performance were achieved through the pavement structural non-destructive test of DYNAFLECT and long-term pavement performance measurement, such as roadway core density, International Roughness Index (IRI), rutting and fatigue cracking.

EXPERIMENT DESIGN

Six CRM products, including dry and wet processes, were incorporated into eight pavement sections. These eight CRM asphalt pavement sections were built on five different projects throughout the state as shown in Figure 1. Each route had a control section where conventional HMA mixtures were constructed and one or two CRM asphalt pavement sections (Figure 2). Table 1 presents a summary of the experimental

design of eight test sections as categorized by the CRM procedures. A detailed description of the CRM asphalt pavement in the five field projects is as follows:

- In US61, the comparison was made between the gap-graded conventional wearing course mixture and two alternative applications of Arizona Wet processed CRM mixtures. The two alternative CRM sections were:
 - Gap-graded wearing course mixture blended with Arizona Wet Process;
 - Gap-graded wearing course mixture blended with Arizona Wet process placed on the top of stress-absorbing membrane interlayer (SAMI).
- In LA15, the control section consisted of dense-graded conventional wearing and binder mixtures. The control section was compared with:
 - CRM mixtures with 10% Rouse Wet Process on the wearing and binder mixtures that had similar gradations as the control mixtures;
 - Gap-graded CRM wearing mixtures with 17% Arizona Wet Process on the top of the same conventional binder mixture as the control section.
- In US84, the comparison was made between the conventional dense-graded mixtures (control section) and the CRM mixtures with the similar gradations and processed with 5% Neste Wright Wet Process.
- In US167, the control section consisted of conventional dense-graded wearing and binder mixtures. The control section was compared with:
 - Gap-graded CRM wearing mixture processed with Generic Dry Process on the top of the same conventional binder mixture;
 - CRM wearing and binder mixtures processed with Rouse Dry and had the similar gradation to the mixtures in the control section.
- In LA1040, the comparison was made between the control section that had conventional dense-graded wearing and binder mixtures and the CRM section that replaced the conventional wearing course mixture with the gap-graded CRM mixture processed with PlusRide™ Dry.

Comparisons of mixture performance characteristics were achieved through laboratory performance tests among all the mixtures in this study; whereas the comparisons of field performance were achieved through the field measurement between the control section and the CRM test section(s) within each individual project.

MATERIAL PROPERTIES AND MIXTURE DESIGN

Asphalt Cement

Two types of original asphalt cement, a conventional viscosity graded AC30 and an SB polymer modified asphalt cement PAC 40HG, were used to produce conventional asphalt mixtures. Three types of CRM powder were blended into the conventional AC30 asphalt cement at different percentages to form six different asphalt rubber (wet) applications. Table 2 presents the properties of conventional asphalt cement and the CRM asphalt rubber.

Aggregate

Three types of aggregates including limestone, sandstone and crushed gravel were used to make the HMA mixtures in this study. These aggregates are commonly used in highway construction in Louisiana. They all met the Louisiana contract specifications (9) for these projects.

CRM Product

Four types of CRM were considered: a 16-mesh CRM made by the International Surfacing Inc. (ISI), a Rouse-80 powder, a Neste Wright powder for terminal blending, and a PlusRide™ shredded rubber. Table 3 presents the gradations of these CRM products and their applications in this research.

Mixture Design

The Marshall design procedure was used to determine the optimum asphalt content of the asphalt mixtures. The design criteria were set by the “Louisiana Standard Specifications for Roads and Bridges” in addition to the special provisions set for these projects (9). Table 4 presents the gradations and the mix design properties from the CRM asphalt wearing course mixtures and the corresponding control mixtures.

Except for the LA1040, all projects had at least one CRM test section that had the gradation and other volumetric properties similar to the control section. In the CRM test section of LA1040 and in one test section of LA15, gap-graded CRM asphalt mixtures were compared with conventional dense-graded mixtures.

The amount of crumb-rubber modifiers added to the mixtures was expressed in the percentage of the total weight of the asphalt cement for wet processes, and in the total weight of mixtures for dry processes. For example, one mega-gram of HMA mixture with 4.5% asphalt content and with 10% Rouse wet process CRM has a total amount of Rouse CRM powder of 4.5 kg whereas, one mega-gram of HMA mixture in the CRM section with 2% Rouse dry process has 20 kg of CRM.

It is shown in Table 4 that the asphalt contents for CRM asphalt mixtures in mix designs were generally higher than similar mixes without crumb-rubber modifier.

LABORATORY MIXTURE CHARACTERIZATION

Mixtures in this study were characterized in the laboratory through comparisons of Marshall stability and flow, indirect tensile strength (ITS), and indirect tensile resilient modulus (M_R) tests.

Marshall Test

The Marshall test was performed during the mix design according to the AASHTO T245-97. This test is performed at a deformation rate of 51 mm/min (2 inch/min) and a temperature of 60 °C (140 °F). The properties obtained from this test are the Marshall stability and flow. The Marshall stability of an asphalt mixture is the maximum load the material can carry when tested in the Marshall apparatus. The Marshall flow is the deformation of the specimen when the load starts to decrease. Stability is reported in Newtons (mostly in pounds) and flow is reported in 0.25 mm (0.01 inch.) of deformation. Three specimens were tested and an average is reported and used in the analysis.

Indirect Tensile Strength (ITS) Test

The indirect tensile strength (ITS) and strain test is conducted at 25 °C according to AASHTO T245. Test specimen is loaded to failure at a 50.8 mm/min (2 inch/min) deformation rate. The load and deformation were continuously recorded and indirect tensile strength and strain were computed as follows:

$$ITS = \frac{2 \cdot P_{ult}}{\pi \cdot t \cdot D} \quad (1)$$

$$\varepsilon_T = 0.0205 \cdot H_T \quad (2)$$

where:

ITS – Indirect tensile strength, kPa

P_{ult} – Peak load, N

T – Thickness of the sample, mm

D – Diameter of the specimen, mm

ε – Horizontal tensile strain at failure, mm/mm, and

H_T – Horizontal deformation at peak load, mm.

Indirect Tensile Resilient Modulus (M_R) Test

The indirect tensile resilient modulus test is conducted at temperatures of 4, 25, and 40 °C according to the modified ASTM D4123 (10). It is a repeated load indirect tension test for determining the resilient modulus of the asphalt mixtures. The recoverable vertical deformation, δV , and horizontal deformation, δH were used to calculate the indirect tensile resilient modulus, M_R and Poisson's ratio in Equations 3 and 4.

$$M_R = \frac{P \cdot (\mu + 0.27)}{t \cdot \delta H} \quad (3)$$

$$\mu = 3.59 \cdot \frac{\delta H}{\delta V} - 0.27 \quad (4)$$

where:

M_R – Resilient Modulus, MPa

P – Applied vertical load, N

t – Sample thickness, mm

μ – Poisson's ratio

δH – Horizontal deformation, mm, and

δV – Vertical deformation.

FIELD PERFORMANCE OF PAVEMENTS

Pavement densifications were monitored through the coring of pavements. In addition, visual observation of cracks, International Roughness Index (IRI), rut depth, and DYNAFLECT tests were performed on the pavement sections in this study.

IRI

The international roughness index (IRI) is a standard roughness measurement related to those obtained by road meters installed on vehicles or trailers. During this study, a laser beam profiler was used to measure the pavement profile. The IRI is a mathematical model applied to a measured profile. The model simulates a quarter-car system (QCS), traveling at a constant speed of 80 km/hr. The IRI is computed as the cumulative movement of the suspension of the QCS divided by the traveled distance. The calculation of IRI can be found in reference (11).

Field Rut Depth Measurement

Field rut depth measurement was performed five to seven years after the pavements were constructed. A vehicle-mounted laser beam profiler was used to measure the roadway profiles. The reported value of rut depth for each test section was an average rut depth of both wheel paths in both traffic directions.

DYNAFLECT

The Dynamic Deflection Determination System (DYNAFLECT) is a trailer mounted device which induces a dynamic load on the pavement and measures the resulting slab deflections by using five geophones spaced under the trailer at approximately 300 mm (1 foot) intervals from the application of the load. The pavement is subjected to 4.45 kN (1000 lbf) of dynamic load at a frequency of 8 Hz. The load is produced by a counter rotation of two unbalanced flywheels. The generated cyclic force is transmitted vertically to the pavement through two steel wheels spaced 508 mm (20 inches) from center-to-center. The dynamic force during each rotation of the flywheels varies from 4.9 to 9.3 kN (1100 to 2100 lbf).

Figure 3 presents the deflection basin, which the DYNAFLECT generates. The DYNAFLECT actually measures only half of the deflection bowl. The other half is assumed to be a mirror image of the measured portion. In Figure 8, the measurement W1 is the maximum depth of the deflection bowl and occurs near the force wheels. The terms W2, W3, W4 and W5 are the deflections measured by geophones 2 through 5, respectively.

The maximum (first sensor) deflection, W1, provides an indication of the relative strength of the total road section. The Surface Curvature Index, SCI (W1-W2), provides

and indication of the relative strength of the upper (pavement) layers of the road section. The Base Curvature Index, BCI (W4-W5), and the fifth sensor value, W5, provide a measure of the relative strength of the foundation. For all four parameters, W1, SCI, BCI, and W5 lower values indicate greater strength. The overall structural number (SN) is determined from a nomograph, utilizing the afore-mentioned measured values.

DISCUSSION OF RESULTS

Laboratory Characteristics of Mixtures

Only the wearing course mixtures were evaluated in this paper. An average of three specimen results was reported. The air voids for the laboratory test specimens were $4\pm 1\%$.

Figure 4 presents the results of Marshall tests. It shows that the conventional mixtures had higher or equal values of Marshall stability than the crumb-rubber modified asphalt mixtures. Gap-graded CRM mixtures had lower Marshall stabilities than dense-graded CRM mixtures. The gap-graded CRM mixtures had higher numbers of Marshall flow than the corresponding control mixes, whereas, the dense-graded CRM mixtures had similar Marshall flows to the conventional control mixes.

Figure 5 presents the results of the indirect tensile strength (ITS) test for the wearing course mixtures. The ITS results for US167 were not available. The conventional mixtures in the control sections exhibited higher indirect tensile strength values than the crumb-rubber modified wearing course mixes. Except for LA1040, the CRM asphalt wearing course mixtures had higher strains than the conventional wearing course mixes. Higher strain indicates the mixes to be more ductile under tension. This characteristic is desired for mixtures to resist fatigue cracks.

Figure 6 presents the results of the indirect tensile resilient modulus (M_R) of the wearing course mixtures for the test sections. The M_R results for US167 were not available. A statistical analysis using ANOVA procedure indicated that the conventional wearing course mixtures exhibited significantly higher values of M_R than the CRM asphalt mixtures at 5 and 25 °C. At 40 °C, the conventional wearing course mixture in US 84 showed significantly higher M_R than the CRM asphalt mixtures. The conventional and gap-graded CRM asphalt mixtures showed similar M_R values in US61 and LA1040 at a temperature of 40 °C.

Field Performance Tests and Observations

Figure 7 presents the results of the DYNAFLECT test. The DYNAFLECT tests were performed shortly after the pavements were constructed. Pavement sections were labeled by the types of wearing course mixtures. It appeared that the overall structural number (SN) for the US61 pavement sections were similar. The pavement sections in US61 also had the lowest SN in all the five projects. This might be due to the fact that in US61, there was no binder course, and the wearing course mixtures were constructed directly

above the existing old pavements (as shown in Figure 2). For pavements with dense-graded mixtures, the CRM wet-processed pavements (LA15 and US84) exhibited higher SN values than the control pavement sections. CRM dry-processed pavement (US167 and LA1040) had lower SN values than the control sections. Except for the open-graded friction course (OGFC) with Arizona wet CRM (US61) and the gap-graded mix with PlusRide™ dry CRM, pavement sections constructed with CRM asphalt mixtures exhibited higher modulus values than the control sections.

The IRI, rut depth, roadway core air voids, and crack observations were taken after the pavements had been in service for five to seven years. Because the traffic data for each project was different, it would be difficult to compare the pavement performance between two projects. Therefore, comparisons were only made for pavement sections within the same project.

Figure 8 presents the results of IRI as calculated from the measured pavement profiles. The pavement profiles were measured after five to seven years of pavement service. A lower IRI number indicates smoother and a better ride pavement. Newly constructed asphalt pavements normally have IRI values between 40 to 60. An IRI value below 100 is considered as a decent ride whereas, a value above 150 indicates poor ride. From Figure 8, it showed that the control section in US61 had an IRI value close to poor rating. In LA1040, pavement sections constructed with crumb-rubber modified asphalt mixtures exhibited slightly higher IRI than the control section, whereas CRM sections in LA15, US84 and US167 exhibited similar or lower IRI numbers than the control sections.

Figure 9 presents the average rut depth as calculated from the measured pavement profiles after five to seven years of pavement service. All mixes had less than 6-mm of rutting after seven years of traffic. Except US61, pavement sections constructed with CRM asphalt mixtures exhibited similar or significantly lower rut depth than the control sections. In US61, the pavement section with the gap-graded CRM (17% Arizona wet) mixture exhibited higher rut depth than the control section whereas the section built with open-graded CRM (17% Arizona wet) mixture showed similar rut depth to the control section.

Figure 10 presents the roadway core air voids after six years of pavement service. The bar chart shows the range of air voids within one standard deviation below and above the average air voids from roadway cores. It appeared that except for LA15, the roadway core air voids in the rest of the four projects overlaps with the conventional mixtures within one standard deviation. In LA15, the gap-graded CRM wearing course mix had a significantly lower air voids than the conventional mixtures.

Table 5 presents a summary of the visual observation of crack development for the test sections in this study. It appeared that the pavement sections with CRM asphalt mixtures exhibited less cracking than the control sections.

COST OF APPLYING CRM

The addition of CRM in asphalt mixtures generally significantly increases the cost of HMA construction. Table 6 lists the unit cost of the HMA concrete for the eight CRM sections in this paper. For LA15 dense mix with 10% Rouse wet CRM, the construction cost was similar to the control section with conventional mixtures. For the rest of the CRM sections in this study, the unit costs of CRM asphalt mixtures varied from 118% to 360% to those of the conventional mixtures.

SUMMARY AND CONCLUSIONS

Research has been conducted on the evaluation of crumb-rubber modified asphalt pavements in Louisiana. Eight CRM asphalt pavement sections were constructed using eight different CRM processes or applications. Test sections have been compared to more typical control sections constructed through out Louisiana. Laboratory mixture characterization and field performance testing and observation were conducted to evaluate the performance of CRM asphalt pavements. The following observations were drawn based on the analysis of the results:

- CRM wearing course mixtures in this study generally exhibited the overall lower strength characteristics than the conventional mixtures in the laboratory tests;
- Gap-graded CRM mixtures had lower Marshall stabilities than dense-graded CRM mixtures;
- Gap-graded CRM mixtures had higher Marshall flows than the control conventional gap- and dense-graded mixtures, whereas the dense-graded CRM mixture had Marshall flows similar to the corresponding control dense-graded mixtures;
- The CRM mixtures generally lower ITS and M_R than the control mixtures;
- Pavement sections built with dense-graded, wet-processed CRM asphalt mixtures generally showed higher initial structural capacities (DYNAFLECT structural number) than the control sections;
- CRM dry-processed pavement with gap-graded mixtures had lower initial structural capacities (DYNAFLECT structural number) than the control sections with dense-graded conventional mixtures;
- After five to seven years of service, the CRM pavement sections exhibited similar or lower IRI;
- The CRM pavement sections in this study generally exhibited similar or lower rut depth than the control sections after five to seven years in service;
- The CRM pavements in this study generally exhibited similar or less fatigue cracks than the control sections;
- Generally, the use of CRM in asphalt pavement significantly increased the construction cost of HMA mixtures.

ACKNOWLEDGEMENT

The research work reported in this paper was sponsored by the Louisiana Department of Transportation and Development (LaDOTD) through the Louisiana Transportation

Research Center (LTRC). The authors would like to express thanks to all who have provided valuable help in this study.

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CRUMB RUBBER PROJECTS

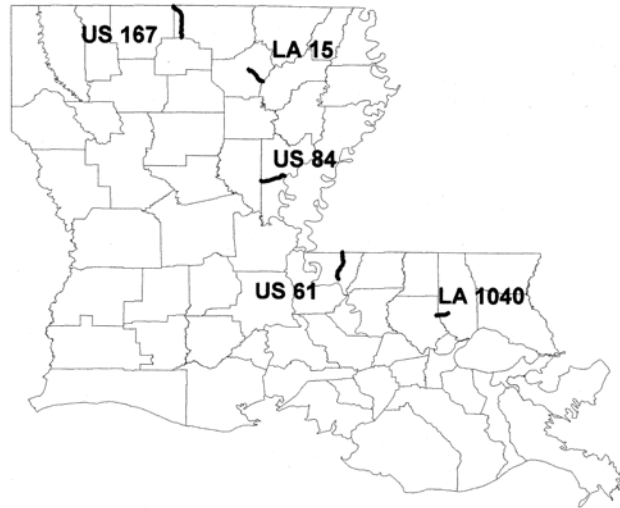


Figure 1. Locations of Crumb-Rubber Modified Asphalt Pavement

Route	CRM Section 1	CRM Section 2	Control Section
US 61	<hr/> 1.0" OGFC, 17% Arizona Wet <hr/> SAMI <hr/> Existing roadway <hr/>	<hr/> 1.5" Gap-graded WC, Arizona Wet <hr/> Existing roadway <hr/>	<hr/> 1.5" Gap-graded WC, PAC 40HG <hr/> Existing roadway <hr/>
LA 15	<hr/> 1.5" Dense-graded WC, 10% Rouse Wet <hr/> 2.0" Dense-graded BC, 10% Rouse Wet <hr/>	<hr/> 1.5" Gap-graded WC, 17% Arizona Wet <hr/> 2.0" Dense-graded BC, PAC 40HG <hr/>	<hr/> 1.5" Dense-graded WC, PAC 40HG <hr/> 2.0" Dense-graded BC, PAC 40HG <hr/>
US 84	<hr/> 1.5" Dense-graded WC, 5% Neste Wright Wet <hr/> 2.0" Dense-graded BC, 5% Neste Wright Wet <hr/>		<hr/> 1.5" Dense-graded WC, AC 30 <hr/> 2.0" Dense-graded BC, AC 30 <hr/>
US 167	<hr/> 1.5" Gap-graded WC, Generic Dry <hr/> 2.0" Conv. Dense-graded BC, AC 30 <hr/>	<hr/> 1.5" Dense-graded WC, Rouse Dry <hr/> 2.0" Dense-graded BC, Rouse Dry <hr/>	<hr/> 1.5" Conv. Dense-graded WC, PAC 40HG <hr/> 2.0" Conv. Dense-graded BC, AC 30 <hr/>
LA 1040	<hr/> 1.5" Gap-graded WC, PlusRide™ Dry <hr/> 2.0" Conv. Dense-graded BC, AC 30 <hr/>		<hr/> 1.5" Conv. Dense-graded WC, AC 30 <hr/> 2.0" Conv. Dense-graded BC, AC 30 <hr/>

Figure 2. CRM Test Sections

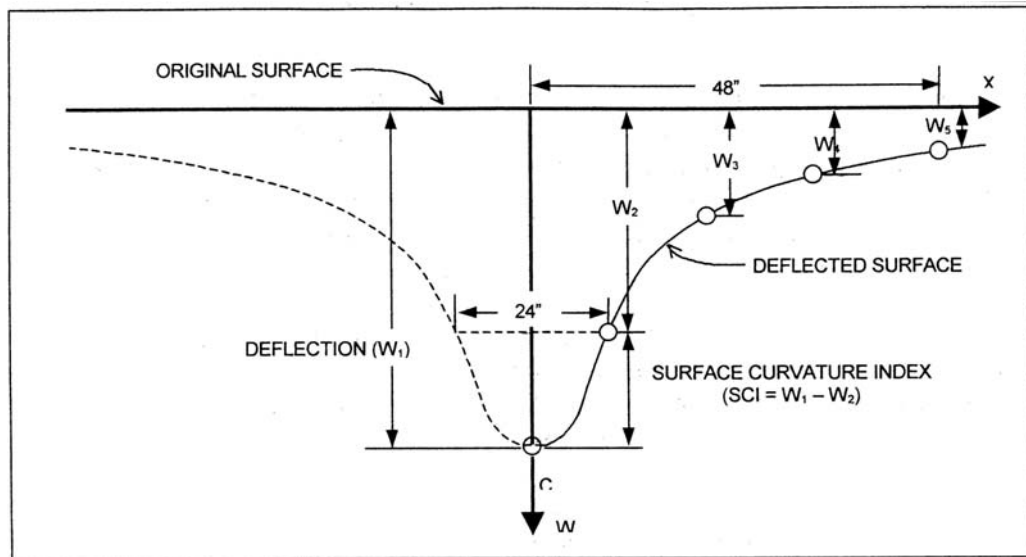


Figure 3. Typical DYNAFLECT Deflect Bowl

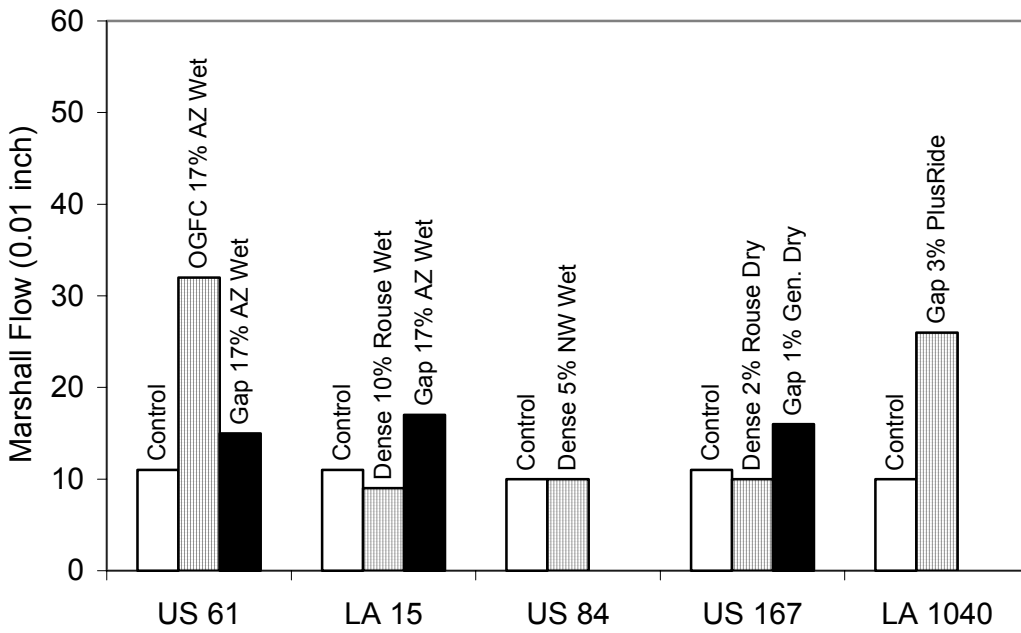
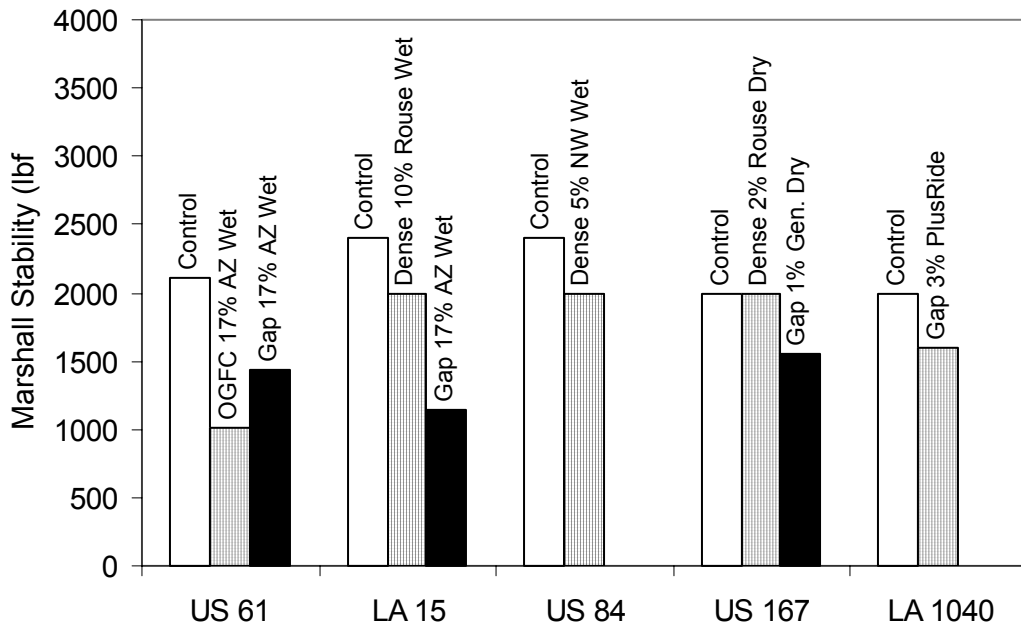


Figure 4. Marshall Test Results

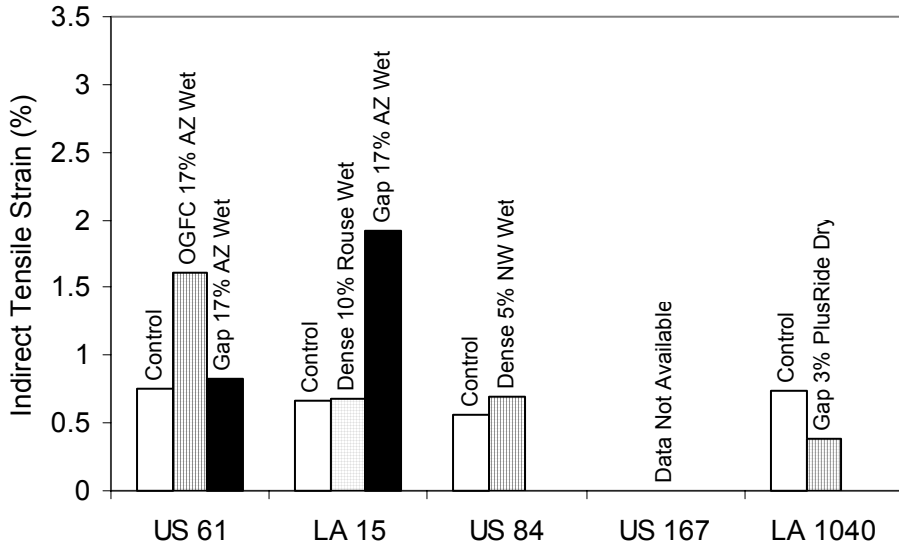
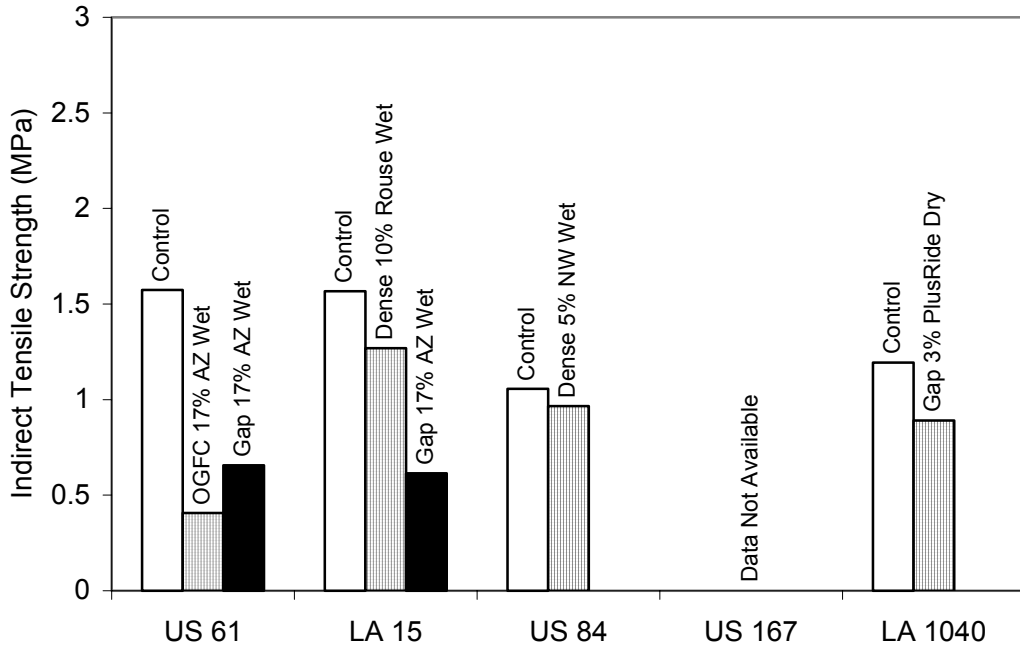


Figure 5. Indirect Tensile Test Results

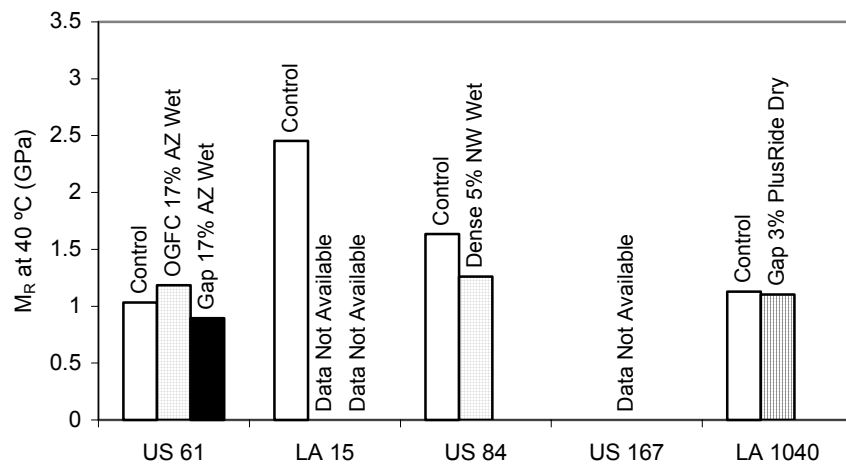
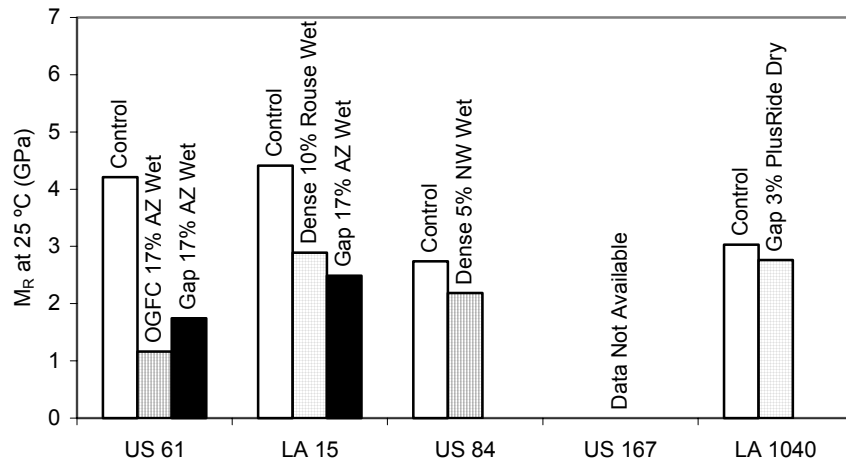
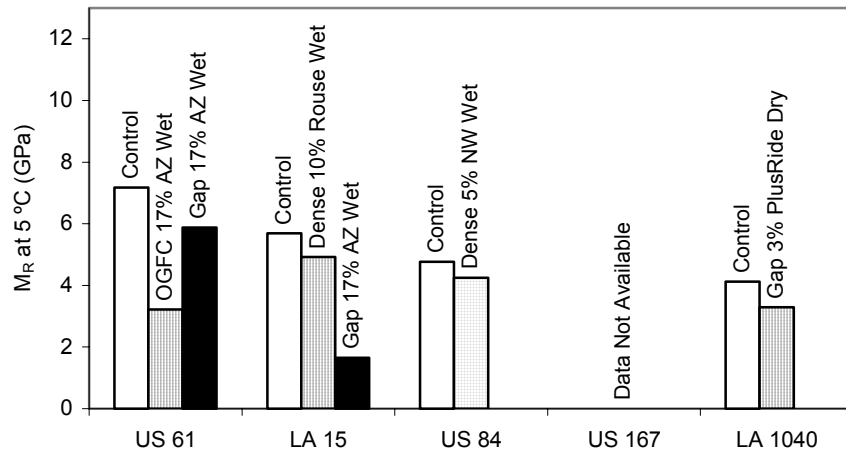


Figure 6. Indirect Tensile Resilient Modulus (M_R) Test Results

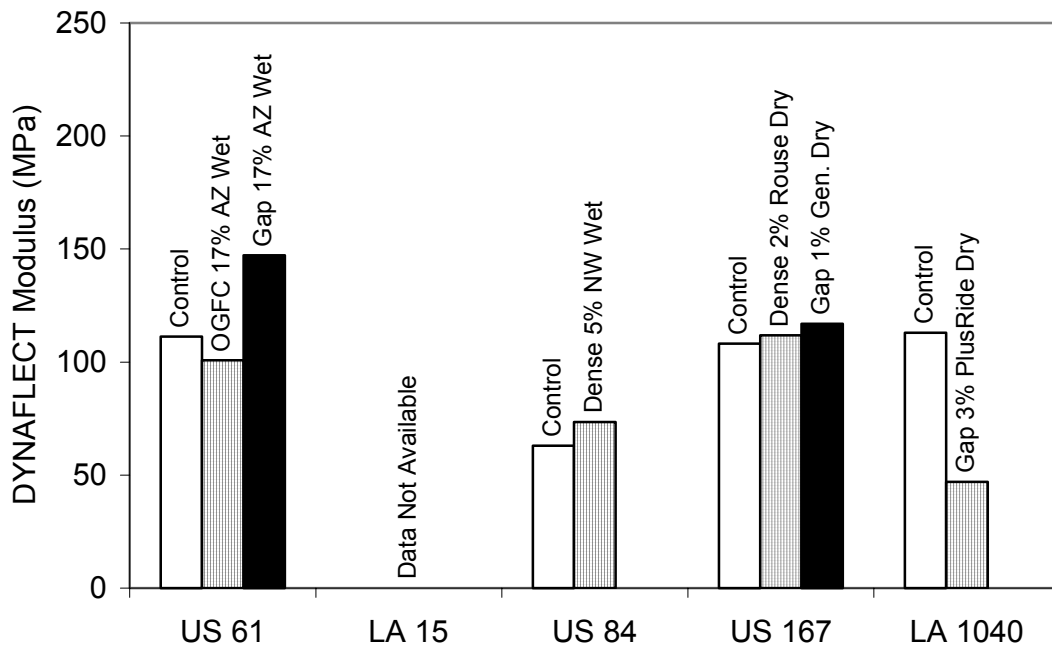
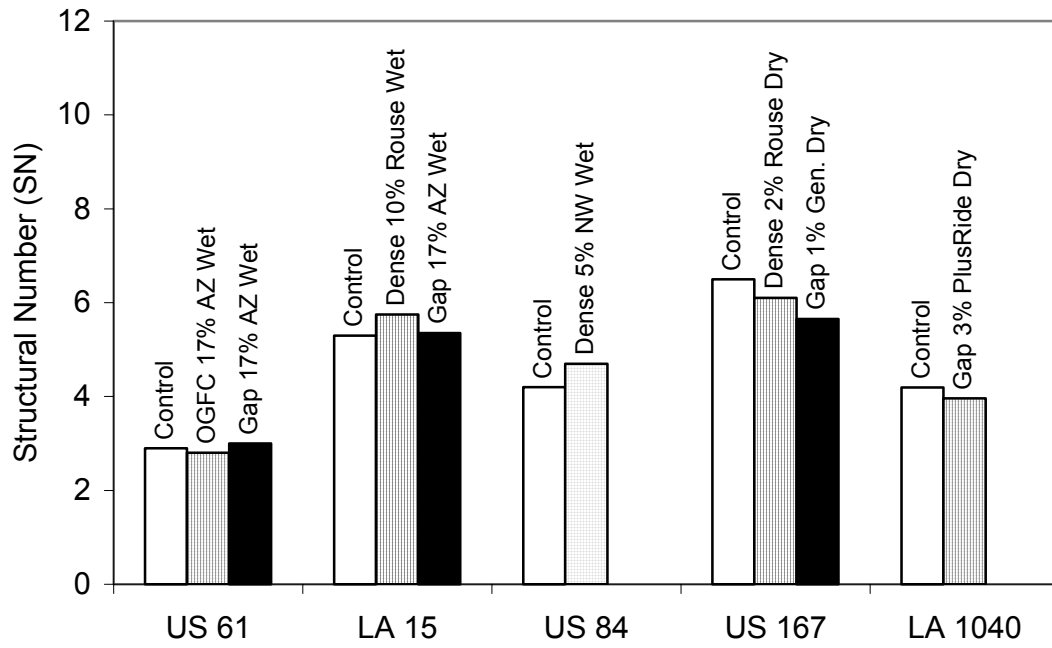


Figure 7. DYNAFLECT Test Results on Newly Constructed Pavements

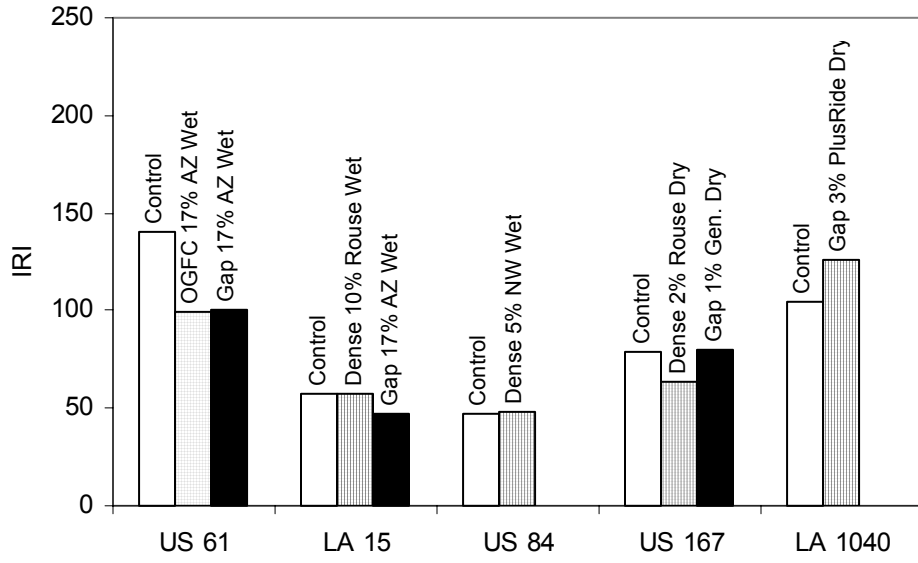


Figure 8. International Roughness Index (IRI)

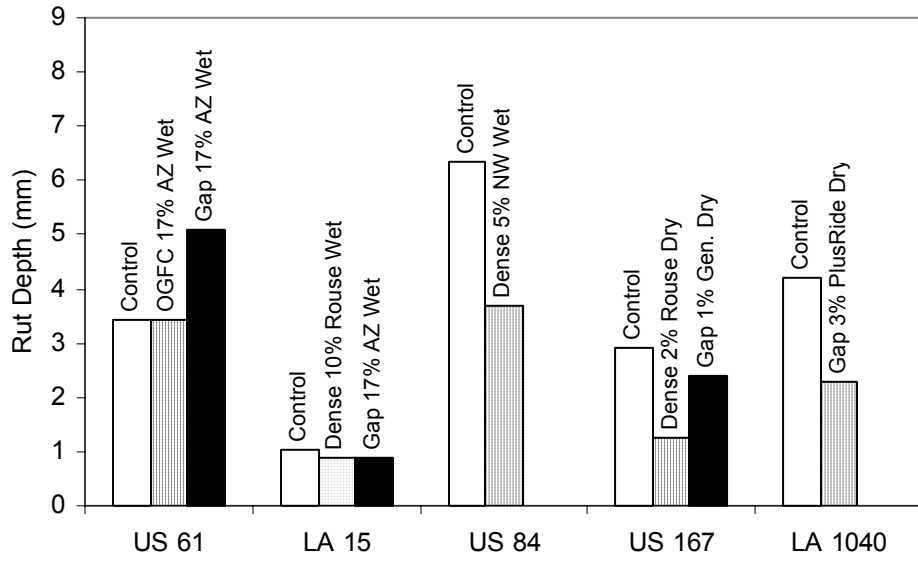


Figure 9. Average Rut Depth of Pavement Sections

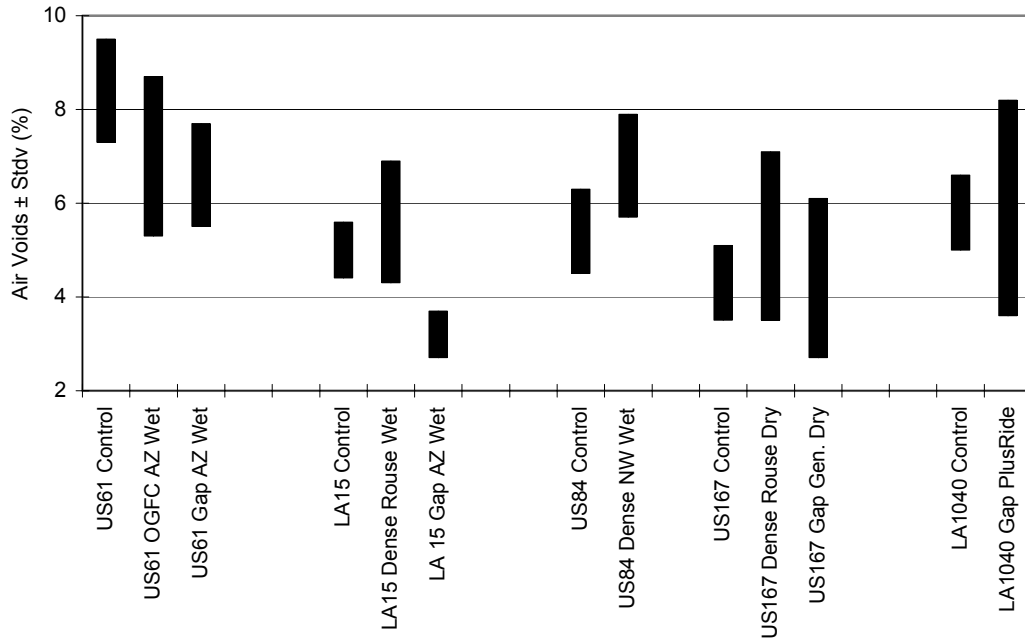


Figure 10. Roadway Core Air Voids (after 5 – 7 years of service)

Table 1. Experimental Design of CRM-HMA Pavements

Process	Products	Applications	Route	Mix Function	Control Section Mixes
Wet	ISI (Arizona) Wet	SAMI	US 61	Interlayer	N/A
		OGFC	US 61	WC	Gap-graded with PAC 40HG
		Gap-graded	US 61	WC	Gap-graded with PAC 40HG
	LA 15		WC	Type 8 with PAC 40HG	
	Rouse Wet	Dense-graded	LA 15	WC, BC	Type 8 with PAC 40HG
	Neste Wright	Dense-graded	US 84	WC, BC	Type 8 with AC 30
Dry	Generic Dry	Gap-graded	US 167	WC	Type 8 with PAC 40HG
	Rouse Dry	Dense-graded	US 167	WC, BC	Type 8 with PAC 40HG
	Plusride™ Dry	Gap-graded	LA 1040	WC	Type 8 with AC 30

Note: WC – wearing course; BC – binder course; SAMI – Stress Absorbing Membrane Interlayer; ISI – International Surfacing Inc.; OGFC – Open-graded Friction Course

Table 2. Conventional Asphalt Cement and Asphalt-Rubber Cement Properties

Description	AC 30	AC 30 + 17% ISI	AC 30 + 10% Rouse	AC 30 + 5% NW	PAC 40HG	AASHTO Method
Original Binder						
Rotational Viscosity: Brookfield, Pa·s 135 °C	0.463	5.475	3.10	1.112	1.05	TP48
Dynamic Shear Rheometer, DSR, $G^*/\sin\delta$, kPa						
64 °C	1.7274		3.1	2.9		TP5
70 °C	0.8405		2.4	1.6	1.9	TP5
76 °C		3.3	0.9	0.88	1.0	TP5
82 °C		2.8				
RTFO (TFO for Asphalt Rubber)						
% Loss		0.34	0.1	0.011	0.187	TP240
64 °C			6.6	4.4		TP5
70 °C	2.2942	6.7	3.2	2.2	3.2	TP5
76 °C		4.8	1.7	1.3	1.9	TP5
82 °C		3.8				
PAV						
DSR, $G^*\cdot\sin\delta$, kPa, @10 rad/s, (25 °C)	3628	3564	2123	1353	3175	TP5
BBR Creep Stiffness, S, Mpa	238				99	TP5
BBR Creep Slope, m value	0.310				0.452	TP5

Table 3. CRM Powder (Chunk) Gradations and Applications

Products		ISI	Rouse	Generic	Neste Wright	PlusRide™
Applications		Arizona Wet on Gap-graded (US 61 WC, LA 15 WC)	Rouse Wet on Dense-graded (LA 15 WC, BC)	Generic Dry on Gap-graded (US 167)	Neste Wright Wet on Dense-graded (US 84 WC, BC)	PlusRide™ Dry on Gap-graded (LA 1040 WC)
		Arizona Wet on SAMI (US 61)	Rouse Dry on Dense-graded (US 167)			
		Arizona Wet on OGFC (US 61)				
Percent Passing (%)	¼"					100
	#4					80
	#8	100				
	#10	97		100		41
	#16	50		85		
	#20				100	23
	#30	10		43		
	#40		100		80	
	#50	5	99	10		
	#80		94			
	#100		83			
#200			3			

Table 4. Gradations and Mix Design Properties

Route	Gradation Chart	Property	Mixtures		
US 61	<p>Legend: Control (diamond), OGFC (square), Gap-graded (ISI) (triangle)</p>		Control Mix	OGFC17% AZ wet	Gap 17% AZ wet
		AC %	6.3	9.0	8.4
		G _{mm}	2.368	2.302	2.312
		Air void	3.0	9.3	3.5
		VMA	17.0	26.5	18.1
		VFA	82.0	64.9	81.0
		Stability	2115	1010	1436
		Flow	11	32	15
LA 15	<p>Legend: Control (diamond), Dense (Rouse) (square), Gap (ISI) (triangle)</p>		Control Mix	Dense 10% Rouse wet	Gap 17% AZ wet
		AC %	4.4	4.5	7.8
		G _{mm}	2.481	2.480	2.356
		Air void	3.5	3.6	3.3
		VMA	13.0	13.3	19.6
		VFA	73.0	73.0	83.0
		Stability	2400	2000	1140
		Flow	11	9	17
US 84	<p>Legend: Control (diamond), Dense (Neste Wright) (square)</p>		Control Mix	Dense 5%Neste Wright wet	
		AC %	4.2	5.4	
		G _{mm}	2.477	2.420	
		Air void	3.4	4.2	
		VMA	12.4	16.4	
		VFA	73.0	74.0	
		Stability	2400	2000	
Flow	10	10			
US 167	<p>Legend: Control (diamond), Dense (Rouse dry) (square), Gap (Generic Dry) (triangle)</p>		Control Mix	Dense 2% Rouse Dry	Gap 1% Gen. Dry
		AC %	4.3	4.4	6.0
		G _{mm}	2.512	2.474	2.353
		Air void	3.7	3.9	3.0
		VMA	13.8	14.0	18.4
		VFA	73.0	73.0	83.7
		Stability	2000	2000	1550
Flow	11	10	16		
LA 1040	<p>Legend: Control (diamond), Gap (PlusRide) (square)</p>		Control Mix	Gap 3% PlusRide™ Dry	
		AC %	5.5	8.2	
		G _{mm}	2.416	2.243	
		Air void	4.1	3.0	
		VMA	15.7	19.1	
		VFA	74.0	84.0	
		Stability	2000	1600	
Flow	10	26			

Note: %CRM referred to the weight of the asphalt cement in wet processes;
 %CRM referred to the total weight of the mixture in dry processes.

Table 5. Visual Observation of Pavement Cracks after Six to Seven Years

Route	Sections	Distress	
		Block, Transverse, or Shrinkage Cracks	Wheel Path Cracking
US 61	Control	1/8-1" Wide < 20% Length	Low < 20% Wheel Path
	OGFC 17% AZ Wet	< 1/8" Wide 20-50% Length	Not Visible
	Gap 17% AZ Wet	< 1/8" Wide < 20% Length	Low < 20% Wheel Path
LA 15	Control	< 1/8" Wide < 20% Length (Slightly worse than Gap but not as bad as Dense)	Not Visible
	Dense 10% Rouse wet	< 1/8" Wide < 20% Length (Slightly worse than Control)	Low < 20% Wheel Path (Hardly noticeable)
	Gap 17% AZ Wet	Not Visible	Not Visible
US 84	Control	Not Visible	Low < 20% Wheel Path (Hardly noticeable)
	Dense 5% Neste Wright	< 1/8" Wide < 20% Length (Hardly noticeable)	Low 20-50% Wheel Path (Slightly more severe than the Control)
US 167	Control	< 1/8" Wide < 20% Length (Hardly noticeable)	Not Visible
	Dense 2% Rouse Dry	< 1/8" Wide < 20% Length (Slightly worse than Control but not as bad as Gap)	Low < 20% Wheel Path (Hardly noticeable)
	Gap 1% Generic Dry	1/8-1" Wide < 20% Length (More noticeable)	Not Visible
LA 1040	Control	1/8-1" Wide > 50% Length (Continuous throughout the length of the pavement)	Moderate > 50% Wheel Path (Continuous throughout the length of the pavement)
	Gap 3% PlusRide™ Dry	1/8-1" Wide > 50% Length (Continuous throughout the length of the pavement, but not as bad as the Control)	Not Visible

Note: %CRM referred to the weight of the asphalt cement in wet processes;

%CRM referred to the total weight of the mixture in dry processes.

*Description of severity levels for wheel path cracking as defined as follows:

Low-An area of cracks with no or only a few connecting cracks; cracks are not spalled or sealed; pumping is not evident.

Moderate-An area of interconnected cracks forming a complete pattern; cracks may be sealed; pumping is not evident.

High-An area of moderately or severely spalled interconnected cracks forming a complete pattern; pieces may move when subjected to traffic; cracks may be sealed; pumping may be evident.

Table 6. Construction Costs of CRM HMA Concrete

Route	Section	Process Description	Miles of CRM Paving	Tons of CRM	Unit Cost (\$/ton mix)	CRM Cost vs. Control (%)
US 61	OGFC 17% AZ Wet	Wet process, batch blending at plant, 17% OGFC, 23% SAMI	1.0	36.5	123	360
	Gap 17% AZ Wet	Wet process, batch blending at plant, 17%	4.5	129	69	176
LA 15	Dense 10% Rouse Wet	Wet process, batch or continuous at 10%	2.0	27	34	100
	Gap 17% AZ Wet	Wet process, batch blending at plant, 17%	2.0	31.5	68	200
US 84	Dense 5% Neste Wright Wet	Terminal blending, 5%	2.0	15	40	118
US 167	Dense 2% Rouse Dry	Dry process, 1% by weight, 80 mesh	2.0	54	40	118
	Gap 1% Generic Dry	Dry process, 2% by weight, 65% retained on #30 sieve	2.0	46	47	138
LA 1040	Gap 3% PlusRide™	Patented dry process, 3% by weight	4.5	177	70	206
Total			20	516		