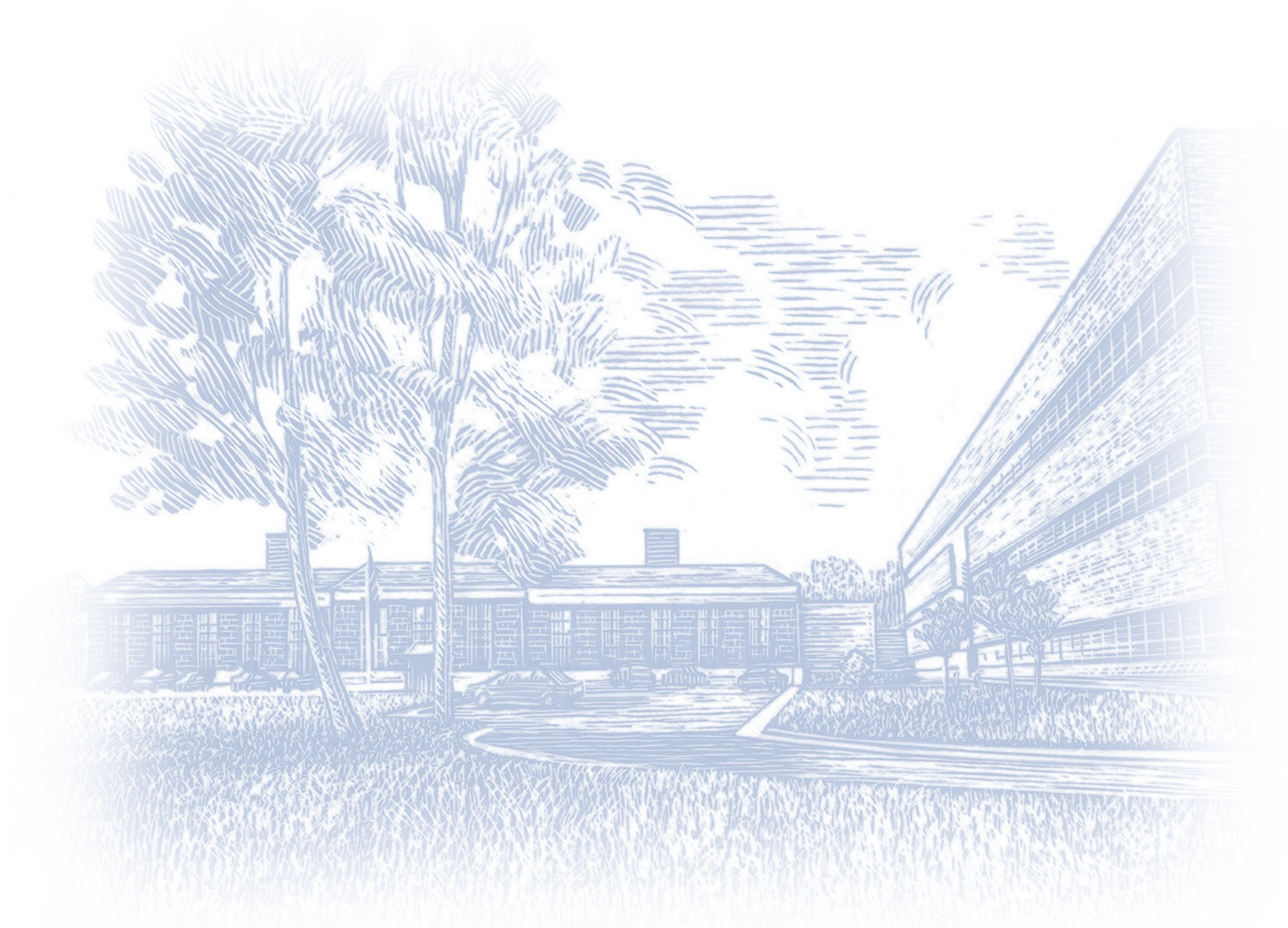
Performance of Coarse-Graded Mixes At Westrack- Premature Rutting

Publication No.: FHWA-RD-99-134 **June 1998**



U.S. Department of Transportation
Federal Highway Administration

Federal Highway Administration
Turner-Fairbank Highway Research Center
6300 Georgetown Pike, McLean, VA 22101

The original format of this document was an active HTML page(s). The Federal Highway Administration converted the HTML page(s) into an Adobe® Acrobat® PDF file to preserve and support reuse of the information it contained.

The intellectual content of this PDF is an authentic capture of the original HTML file. Hyperlinks and other functions of the HTML webpage may have been lost, and this version of the content may not fully work with screen reading software.

Foreword

WesTrack is the Federal Highway Administration's (FHWA) test facility in Nevada for developing performance-related specifications for hot-mix asphalt pavement construction. It is also providing some of the earliest data on the performance of Superpave asphalt mixture designs under high rates of heavy truck loading. When Superpave-designed test sections placed at the track in June 1997 had very rapid rutting failures, the highway community was concerned that the mixture design and construction procedures might be missing important, but unknown, constraints. A forensic team composed of academicians, asphalt industry representatives, and State highway agency engineers was assembled to study the early failures and, if appropriate, to make recommendations for revising the Superpave procedures; this is their report. The contents of the report are the views of the forensic team itself, and do not necessarily reflect the views of the U.S. Department of Transportation or the WesTrack research team. Readers should also note that the main body of the report is the consensus of the full forensic team; several members of the team believe that the structural design of the pavement may have significantly contributed to the failures, and their minority report is included as a separate appendix. Lastly, the minority report is followed by an FHWA response to a number of the team's recommendations.

The forensic team has also prepared a second publication, Superpave Mixture Design Guide. This publication, which will be available from FHWA later in 1999, will be a useful tool for the designers and constructors of Superpave pavements.

T. Paul Teng, P.E.
Director
Office of Infrastructure
Research and Development

Table of Contents

List of Tables

List of Figures

Introduction

As it neared the end of its planned loading in June 1998, WesTrack--the Federal Highway Administration's (FHWA) hot-mix asphalt (HMA) performance-related specification (PRS) test facility in Nevada--had been trafficked for more than 2 years. During that time, more than 4.5 million 80-kN (18,000-lb) equivalent single-axle loads (ESALs) were applied to the track. The loading was accomplished with tractor-triple-trailer combinations and 89-kN (20,000-lb) axle loads. Loading of 4.5 million ESALs in 2 years is a very high rate, comparable to the application of 45 million ESALs in a typical highway design period of 20 years.

WesTrack was established primarily to develop performance-related specifications based on construction variables. The original 26 test sections placed in late 1995 included two mix designs, one with a gradation above (fine-graded) and the other below (coarse-graded) the Superpave restricted zone. All of these mixes were 19-mm nominal maximum size, with an unmodified performance grade (PG) 64-22 binder. The original mixes were placed with several variations. For each gradation, three different binder contents were used: (1) optimum (medium), (2) optimum + 0.7 percent (high), and (3) optimum - 0.7 percent (low). In addition, each mix was compacted on the track to three different air void contents: 4, 8, and 12 percent (high, medium, and low density, respectively). The coarse-graded mixes showed the most severe distresses and hence made up most of the sections that were replaced. The "fine plus" mixes in the experiment duplicated the fine-graded design; however, approximately 2 percent more "baghouse" fines (fine aggregate dust recovered from the plant exhaust by emission-control equipment) were metered back into the mix during production. The mixture design procedure was not repeated for the "fine plus" gradation, i.e., the "fine plus" mixtures used the same optimum binder content as had already been established for the fine-graded mixtures. Table 1 (tables follow at end of this section) shows the experiment matrix for the original 26 test sections constructed in fall 1995 and for replacement sections constructed in June 1997. Figure 1 (figures follow at the end of this section) shows the layout of the initial and replacement sections on the track itself.

It was not considered realistic to produce mixes with high binder content and high roadway air voids, nor to produce mixes with low binder content and low roadway air voids; thus, these combinations were not included in the study. Also, as the table shows, the medium binder content and medium roadway air void content was duplicated in two sections for each gradation, while all other combinations were placed in just one test section for each gradation.

Some of the original mixtures were expected to fail from fatigue, while others were expected to fail by rutting. It was no surprise that some of the mixtures failed early, but the order in which they failed was unexpected in many cases, and the rate at which some of the sections failed was also a surprise. By spring 1997, the application of more than 2.7 million ESALs resulted in rutting in almost every test section and fatigue cracking in many of the test sections. Several sections had rutted more than 25 mm and severe fatigue cracking had occurred in others. As a result, 10 sections (Sections 5-9, 13, 21, and 24-26) had to be removed and replaced during May and June 1997.

A new mix design was developed for eight of the replacement sections. This mix design duplicated the coarse-graded mix experiment in the original construction, but changed to a more angular aggregate. A quarried andesite replaced the crushed gravel used in the original construction. The change in aggregate resulted in changes in the volumetric properties from those obtained with the original coarse-graded mixes. The other two replacement sections (Sections 43 and 51) utilized conventional Nevada Department of Transportation (DOT) mixtures containing polymer-modified binders.

The replacement sections were placed in June 1997 and loading began in mid-July. Most of the new sections exhibited significant deformation in the first 5 days of trafficking. As a result of this early rutting and a concern that Superpave mixture design or construction procedures might be missing a critical step or steps, FHWA assembled a team of academicians, asphalt industry representatives, and State highway agency engineers to investigate the performance at WesTrack. The team members--Ray Brown, Erv

Dukatz, Gerry Huber, Larry Michael, Jim Scherocman, and Ron Sines--were charged with determining the likely causes of the early rutting in the various coarse-graded mixtures, and recommending steps that could be taken to avoid rutting in coarse-graded mixtures. Two representatives from FHWA, John D'Angelo and Chris Williams, were added to the team as liaisons to provide laboratory support and other assistance as needed.

Investigation

By the end of August 1997, and before any significant amount of laboratory testing of the track materials could be completed, the team prepared a preliminary report of its findings. The laboratory testing has now been completed and the applicable portions are included in this report, along with the team's final findings and recommendations.

A test program was developed to evaluate the properties of the in-place mixtures. This plan involved determining gradations, densities, binder contents, and volumetrics of the mixtures, and comparing this data to initial production test results. Roadway samples were taken both in and between the wheelpaths in August and September 1997. Roadway samples of the various mixtures were also prepared for evaluation in several currently available performance testers to determine if test results from these devices correlated well with actual track performance. The devices included four rut testers (French, Hamburg, Asphalt Pavement Analyzer, and PurWheel) and the Superpave shear tester (SST). Tests with the latter device included simple shear at constant height, frequency sweep at constant height, and repeated shear at constant height.

Because the HMA placed in the track curves had performed particularly well during the 3.3 million ESAL applications, the team asked that roadway samples of this material be included in the test program for comparison purposes. All performance testing was conducted on samples removed from the 10 replacement sections and the entrance to one curve. The 11 sections that were tested can be summarized as follows: Eight sections (35-39 and 54-56) involved a Lockwood (Nevada) aggregate (a crushed andesite) in a mixture that met the requirements for a coarse-graded Superpave gradation. Another two sections evaluated were Nevada DOT mixes that contained a significantly different aggregate gradation and an AC-20P styrene-butadiene-styrene-modified (SBS) binder that graded to be a PG 64-22. (The AC-20P designation signifies that a lower grade AC binder was blended with a polymer to achieve the AC-20 grade.) One of the Nevada DOT mixtures (Section 43) contained Lockwood andesite aggregate and the other (Section 51) contained Dayton gravel (the crushed river gravel used in the original 26 WesTrack sections). The Nevada mixes were designed using Hveem mixture design criteria. The eleventh section evaluated was one of the curves from the original track construction; it was a coarse-graded Superpave mix containing Dayton aggregate.

The aggregate gradations for the 11 sections are shown in tables 2 and 3. As shown in figure 2, the design gradations for Sections 35-39 and 54-56 and the curve met all of the requirements for coarse-graded Superpave mixtures recommended in American Association of State Highway and Transportation Officials (AASHTO) provisional specification MP2-97. Figure 3 shows that the design gradations for Sections 43 and 51 did not meet the requirements for coarse-graded Superpave mixtures (both gradations pass through the restricted zone), but were typical of Nevada DOT mixes used prior to Superpave. Generally, the tables show the gradation results from the samples taken behind the paver--and the results from truck and wheelpath core samples--are within typical construction variabilities and tolerances. However, the gradation of the cores, especially the percent passing the 0.075-mm sieve, was finer than truck or behind-the-paver gradations. The cores were typically 1.5 to 2.5 percent higher in fines than the samples taken from the truck or behind the paver. Other than possible traffic degradation, no explanation could be developed for the increased dust in the cores.

The binder test results from the various test sections are provided in table 4. Since the binder for Sections 35-39 and 54-56 was all from the same tank, only one set of binder classification tests was conducted. The binder graded to be a PG 64-22. The test results for the binder recovered from cores were similar to the tank results, except for the binder from the curves. The latter binder was originally a PG 64-22 (based on data developed by the WesTrack researchers); by late 1997, after 2 years in place, binder recovered from the curves tested to be a PG 76-16 material. A sample of this extracted binder from the curves was also analyzed to determine if it had been polymer-modified. Sequential examination of the binder by size exclusion chromatography, modulated differential scanning calorimetry, and nuclear magnetic resonance did not indicate the presence of styrene-butadiene-rubber (SBR) or SBS modifiers in the asphalt. The team concluded that the binder test results did not show any obvious cause for the rutting problem.

The binder content and volumetric test results are shown in table 5. The reason for the variations in the data from the different sampling locations (truck, behind paver, and pavement cores) could not be determined. For the purposes of this report, the forensics team decided to base conclusions and recommendations on the core test results, specifically those from Sections 35, 38, 39, 43, 51, and 54, and from the curve. Sections 35, 38, 39, and 54 were sections that were supposed to have been placed at either design or low binder content and either optimum or low roadway air voids. Sections 43 and 51 were the Nevada DOT mixes that were evaluated for comparison purposes. The cores from the remaining replacement sections were not tested because the design binder content was high or in-place air voids were high and they were expected to be the worst performers among the replacement sections; a comparison of their performance with the other sections indicated that this was correct.

The forensic team selected the core data as the basis for its recommendations for several reasons. The behind-the-paver data was not consistent with practical knowledge, that is, for varying binder contents and voids in the mineral aggregates (VMAs), all gyratory air voids were close to 4 percent. The truck data indicated no low binder contents for any mix, and no truck data was available for the curve section or the Nevada DOT sections.

Based on the behind-the-paver volumetrics, all of the sections, except Nevada DOT Sections 43 and 51 (which were not tested), were reasonably close to meeting requirements for Superpave mixes. This was unexpected since several of the sections were intended to deviate from the optimum mix design target. Section 39 appeared to be slightly high in voids and Section 54 appeared to be slightly low in voids. However, both of these sections had the optimum amount of binder added (5.7 percent). Sections 37 and 55 were expected to have lower voids and Sections 38 and 56 were expected to have higher voids, but the volumetric data did not show that. The VMA established previously from behind-the-paver data for the coarse-graded Superpave mixes ranged from 13.0 to 16.2. The range of VMA was high; however, based on this data, all of the sections met the minimum requirements. From this data, the Superpave system appears to allow mixes with high VMA and high binder contents for certain aggregate types, which may cause mixes to be rut-susceptible.

FROM THIS DATA, THE SUPERPAVE SYSTEM APPEARS TO ALLOW MIXES WITH HIGH VMA AND HIGH BINDER CONTENTS FOR CERTAIN AGGREGATE TYPES, WHICH MAY CAUSE MIXES TO BE RUT-SUSCEPTIBLE.

The Nevada DOT mixes, Sections 43 and 51, were Hveem-design mixes with an AC-20P modified binder; samples of these mixes were also compacted in the Superpave Gyratory Compactor and the properties of the mixes are shown in table 5. The mixture for Section 43 appeared to deviate significantly from the Superpave volumetric requirements. The mix design data for this section showed 1.7 percent air voids and the in-place cores were measured to have 1.6 percent air voids. Based on the volumetrics, this section would have been expected to rut; however, in-place results (table 6) showed this mix to have less rutting than any replacement section except 51. Section 51 had 4.2 percent air voids at design, with in-place air voids of 6.8 percent. This section had minimal downward rutting (3.6 mm). Visually, the rutting performance of these Nevada DOT mixes was similar to that of the curves (data for the latter is not shown in tables, but is estimated typically to be about 2 mm). Table 6 shows the rutting performance of the 10 sections in the field, as well as the performance of roadway samples from those sections in the various performance-testing devices. Figure 4 shows the distinction between total and downward rut-depth measurements.

Dust-to-binder ratio is an important factor in the performance of a mix. Based on core data, the mix in the curves that performed well had a dust-to-binder ratio of 1.5. Work with Stone Matrix Asphalt (SMA) has shown that a stiff mastic (binder and dust) is needed for coarse-graded, high-VMA mixtures. The same is probably true for Superpave mixes that are on the coarse side of the restricted zone. The mastic can be stiffened by increasing the amount of filler and/or by increasing the stiffness of the binder. This has been shown to be effective for SMA and should be effective for Superpave as well.

The WesTrack data shows that the two worst performers (Sections 56 and 36) were the two sections with the highest initial in-place air voids. Compaction is very important in minimizing rutting in asphalt pavements. Where air voids in the pavement exceed 8 percent, it is difficult to generate internal friction. Good compaction is one way to increase lateral support. Inadequate compaction will very likely result in an unstable mixture. This ap- pears to be more of a problem with coarse-graded mixes than with fine-graded mixes.

The data in tables 2, 3, 5, and 6 show that controlling aggregate properties, binder content, and volumetrics using the current Superpave criteria is not always sufficient to ensure satisfactory performance for high-volume traffic. Some type of laboratory performance test, coupled with a proper sample preparation method, is the apparent key to ensuring good performance in the field.

Some forensic team members believe that reduced structural thickness may have played a significant role in the performance of the test sections. Appendix A is a statement of their opinion.

Performance Tests

Table 6 presents the actual performance and the predicted performance using the four rut testers and the Superpave simple shear tester (SST); table 7 shows the variations in test conditions and device configurations among the four rut testers. The tests were conducted on actual replacement pavement samples removed from the field after 582,000 ESALs and curve pavement samples after 3.3 million ESALs. The samples were taken from untrafficked areas between the wheelpaths. The data is plotted graphically in figures 5 through 11. (Note: In figures 6 and 9, some of the samples failed before the total number of passes or cycles specified in the test had been completed. Although it may unfavorably bias the correlation calculations, extrapolated test results are reported for those samples and are used in the calculations.) The data shows that four rut testers and one of the SST protocols, repeated shear at constant height (RSCH), correlate reasonably well with the rutting on the track. As the figures show, the French device had a correlation coefficient (R^2) of 0.69, the Hamburg tester had an R^2 of 0.76, the Asphalt Pavement Analyzer had an R^2 of 0.80, the PurWheel had an R^2 of 0.80 (with one outlier removed), the SST RSCH had an R^2 of 0.55, the SST simple shear at constant height (SSCH) had an R^2 of 0.26 (with one outlier removed), and the SST frequency sweep at constant height (FSCH) at 10 Hz had an R^2 of 0.40. Moreover, the slope of the line for the frequency sweep data was in the opposite direction from what it should have been, i.e., the frequency sweep results should decrease as rut depth increases. This limited set of results appears to show that use of the rut testers or the SST RSCH may indicate that a satisfactory mix has been designed and produced.

Based on previous experience, the forensic team members suggest that SST RSCH and the rut testers provide the most useful data when experience with similar material (aggregates and asphalts) is available. Properly calibrated rut testers have been used by some agencies as effective proof testers. However, they should not be used to predict actual pavement performance because of differences in the in-service temperature and loading conditions. The devices use empirical evaluation of some measured response to a loaded wheel as an indicator of performance. Local criteria from one region are not applicable to another. Each potential user agency needs to develop its own evaluation of wheel-test results using local conditions.

Conclusions

* The No. 1 cause of rutting at WesTrack was a relatively high design binder content. Over-asphalting during construction compounded the problem.

* Much of the rutting appeared to be related to high binder contents due to high VMA values, in conjunction with relatively low mastic stiffnesses.

* From the data presented, only one replacement section as constructed met all of the aggregate, binder, and volumetric requirements for Superpave. However, it did not perform adequately.

* Of the 11 mixes placed at WesTrack and evaluated in this report, the mixture placed at the entrance to the curves had the least rutting. This mixture had a low binder content, high dust-to-binder ratio, and relatively low VMA.

* The Nevada DOT mixtures performed better than the replacement coarse-graded mixtures. The Nevada mixtures had low design and in-place binder contents and relatively low design VMA.

* Material properties and mixture volumetrics may not be adequate by themselves to ensure good performance for high-volume roadways.

* Results from the four wheel-track testers and the SST RSCH, when testing roadway samples, related reasonably well to field performance and, therefore, show potential for identifying poor-performing mixtures.

* The resistance of these coarse-graded Superpave mixes to rutting is significantly affected by in-place density.

Recommendations

* The allowable range for the dust-to-binder ratio is currently set at 0.6 to 1.2 in AASHTO provisional specification MP2-97. Generally, coarse-graded mixes will require a higher dust-to-binder ratio than fine-graded mixes. For mixes below the restricted zone, the dust-to-binder ratio should be set at 0.8 to 1.6. However, the minimum VMA requirements must still be met to ensure adequate mixture durability.

* For high-volume roads, a performance test should be conducted on the mixture design established by volumetric procedures. The four rut testers and SST RSCH showed some merit in identifying unsatisfactory mixtures. Until a universally acceptable test and performance criteria can be established, agencies should rely on local experience with existing devices.

* AASHTO MP2-97 currently sets minimum VMA requirements for mixes, but does not set maximums. For coarse-graded Superpave mixtures, the VMA should be restricted to 2 percent above the minimum value. A draindown test (AASHTO T305-97) should also be run on the mix. Running the draindown test is critical if the VMA is 1.5 percent or more above the minimum value.

* All volumetric mix properties, including VMA, must be measured on plant-produced mix. These values should meet all specified design criteria.

* The N_{design} for any mix placed should be based on a 20-year design life. For example, a mix designed to receive 8 million ESALs in a 5-year period should use the N_{design} (in AASHTO provisional practice PP28-97) for a mix designed to receive 32 million ESALs in a 20-year design life. The rate of loading is critical to the performance of the mix; the Superpave criteria were all based on 20 years of traffic loading.

Table 1. Experiment layout (section numbers).

Table 1. Experiment layout (section numbers).

Design Air Voids	Fine			Fine Plus			Coarse		
	Design Asphalt Content								
	Low	Opt.	High	Low	Opt.	High	Low	Opt.	High
Low	–	4	18	–	12	9/21	–	23 (39)	25 (55)
Medium	2	1/15	14	22	11/19	13	8 (38)	5/24 (35/54)	7 (37)
High	3/16	17	–	10	20	–	26 (56)	6 (36)	–

Notes: 1. Numbers separated by slashes are replicated sections.
2. Numbers in parentheses are replacement sections.

Table 2. Aggerate gradations (design and behind paver sampes).

Table 2. Aggregate gradations (design and behind-paver samples).

	Test Section										
	35	36	37	38	39	43	51	54	55	56	curve
Design											
Sieve Size (mm)	Percent Passing										
25.0	100	100	100	100	100	100	100	100	100	100	100
19.0	99	99	99	99	99	93	100	99	99	99	100
12.5	83	83	83	83	83	–	–	83	83	83	82
9.5	70	70	70	70	70	–	–	70	70	70	65
4.75	41	41	41	41	41	53	50	41	41	41	41
2.36	26	26	26	26	26	–	–	26	26	26	28
1.18	17	17	17	17	17	24	27	17	17	17	20
0.6	12	12	12	12	12	–	–	12	12	12	15
0.3	9	9	9	9	9	–	–	9	9	9	11
0.15	7	7	7	7	7	–	–	7	7	7	8
0.075	5.8	5.8	5.8	5.8	5.8	4.6	4.8	5.8	5.8	5.8	5.1
Behind-Paver Samples											
Sieve Size (mm)	Percent Passing										
25.0	100	100	100	100	100	–	–	100	100	100	–
19.0	100	100	100	100	100	–	–	100	100	100	–
12.5	82	84	84	85	85	–	–	85	85	85	–
9.5	67	70	68	70	70	–	–	68	69	70	–
4.75	39	40	40	42	41	–	–	39	39	41	–
2.36	25	26	26	28	26	–	–	24	24	26	–
1.18	16	17	17	17	17	–	–	16	16	17	–
0.6	12	12	12	11	12	–	–	12	12	12	–
0.3	9	9	9	9	9	–	–	9	9	9	–
0.15	7	7	8	7	7	–	–	7	7	7	–
0.075	5.8	6.0	6.1	6.1	6.1	–	–	5.6	5.6	5.6	–

Notes: 1. Sections 43 and 51 were Nevada DOT mixes.
2. Section 51 and the curve had Dayton gravel, other mixes had Lockwood aggregate.
3. The University of Nevada-Reno staff performed design and behind-paver tests; FHWA performed tests for truck samples and cores.
4. Behind-paver samples were tested using the ignition oven. Truck and core samples were tested using solvent extractions.

Table 3. Aggregate gradations (truck samples and cores).

Table 3. Aggregate gradations (truck samples and cores).

	Test Section										
	35	36	37	38	39	43	51	54	55	56	curve
Truck Samples											
Sieve Size (mm)	Percent Passing										
25.0	100	–	–	100	100	–	–	100	100	100	–
19.0	99	–	–	100	100	–	–	100	–	–	–
12.5	83	–	–	83	83	–	–	83	83	83	–
9.5	70	–	–	70	70	–	–	70	70	70	–
4.75	42	–	–	48	44	–	–	44	–	–	–
2.36	26	–	–	26	26	–	–	26	26	26	–
1.18	16	–	–	20	17	–	–	17	–	–	–
0.6	12	–	–	12	12	–	–	12	12	12	–
0.3	9	–	–	9	9	–	–	9	9	9	–
0.15	7	–	–	7	7	–	–	7	7	7	–
0.075	5.2	–	–	7.1	6.0	–	–	5.9	–	–	–
Cores											
Sieve Size (mm)	Percent Passing										
25.0	100	–	–	100	100	100	100	100	–	–	100
19.0	99	–	–	99	100	99	100	100	–	–	100
12.5	87	–	–	90	87	87	91	88	–	–	90
9.5	73	–	–	78	73	83	71	74	–	–	73
4.75	43	–	–	48	45	59	44	44	–	–	42
2.36	29	–	–	33	32	39	33	31	–	–	31
1.18	19	–	–	22	21	28	25	20	–	–	23
0.6	14	–	–	17	15	22	18	15	–	–	18
0.3	11	–	–	13	12	15	13	12	–	–	14
0.15	9	–	–	11	9	10	8	10	–	–	11
0.075	7.4	–	–	8.6	7.4	6.7	5.4	7.9	–	–	8.0

Notes: 1. Sections 43 and 51 were Nevada DOT mixes.
2. Section 51 and the curve had Dayton gravel, other mixes had Lockwood aggregate.
3. The University of Nevada-Reno staff performed design and behind-paver tests; FHWA performed tests for truck samples and cores.
4. Behind-paver samples were tested using the ignition oven. Truck and core samples were tested using solvent extractions.

Table 4. Asphalt cement properties

Table 4. Asphalt cement properties.

	Test Temperature, °C	Sections 35-39/54-56	Section 43	Section 51	Curve
Tank Asphalt					
DSR					
$G^*/\sin\delta$, kPa	58	2.97	–	–	–
	64	1.35	–	–	–
	70	0.64	–	–	–
DSR (after RTFO)					
$G^*/\sin\delta$, kPa	58	7.13	–	–	–
	64	3.09	–	–	–
	70	1.42	–	–	–
DSR (after PAV)					
$G^*(\sin\delta)$, kPa	15	15,198	–	–	–
	18	10,875	–	–	–
	21	7,583	–	–	–
	24	5,179	–	–	–
BBR (after PAV)					
stiffness, MPa	-12	235	–	–	–
	-18	464	–	–	–
m-value	-12	0.32	–	–	–
	-18	0.26	–	–	–
Recovered Asphalt					
DSR					
$G^*/\sin\delta$, kPa	64	4.2	2.7	2.4	15.6
	70	2.0	1.4	1.4	6.8
DSR					
$G^*(\sin\delta)$, kPa	18	3,916	2,249	2,691	7,232
	21	2,486	1,396	1,630	5,074
	24	1,532	856	975	2,487
BBR					
stiffness, MPa	-12	118	119	131	276
	-18	270	226	270	524
m-value	-12	0.40	0.353	0.372	0.272
	-18	0.33	0.313	0.307	0.224

Notes: 1. Sections 43 and 51 were Nevada DOT mixes.
2. All tests conducted per procedures in *AASHTO Provisional Standards* and *AASHTO Materials*.
3. DSR = Dynamic Shear Rheometer, BBR = Bending Beam Rheometer, RTFO = Rolling Thin Film Oven, PAV = Pressurized Aging Vessel, G^* = Complex Shear Modulus, δ = Phase Angle.

Table 5. Asphalt content and volumetrics

Table 5. Asphalt content and volumetrics.

	Section										
	35	**36**	**37**	**38**	**39**	**43**	**51**	**54**	**55**	**56**	**curve**
Design											
Binder Content, %	5.7	5.7	6.4	5.1	5.7	5.5	5.5	5.7	6.4	5.1	5.7
VMA, %	15.0	15.0	–	–	15.0	13.0	14.2	15.0	–	–	14.2
Voids, %	4.0	4.0	–	–	4.0	1.7	4.2	4.0	–	–	4.0
G_{mm}	2.433	2.433	–	–	2.433	2.461	2.429	2.433	–	–	2.380
G_{se}	2.651	2.651	–	–	2.651	2.677	2.637	2.651	–	–	2.584
Behind-Paver Samples											
Binder Content, %	5.9	5.8	6.1	5.2	5.8	–	–	5.9	6.2	5.3	5.2
VMA, % @ N_{design}	15.8	14.8	16.2	13.9	16.1	–	–	15.1	15.9	14.2	13.0
Voids, % @ N_{design}	4.3	4.0	3.9	4.1	5.3	–	–	3.3	3.7	4.0	4.0
G_{mm}	2.429	2.447	2.417	2.459	2.441	–	–	2.424	2.419	2.452	2.401
G_{se}	2.655	2.673	2.648	2.661	2.665	–	–	2.648	2.655	2.657	2.590
Truck Samples											
Binder Content, %	6.1	–	–	5.8	6.0	–	–	6.0	–	–	–
Voids, % @ N_{design}	3.6	–	–	2.8	4.5	–	–	6.0	–	–	–
G_{mm}	2.440	–	–	2.436	2.436	–	–	2.452	–	–	–
G_{se}	2.678	–	–	2.659	2.668	–	–	2.689	–	–	–
Cores											
Binder Content, %	6.4	–	–	5.9	6.8	5.5	5.2	6.5	–	–	5.3
Initial In-Place Voids	7.4	–	–	6.6	3.8	1.6	6.8	6.9	–	–	7.2
G_{mm}	2.457	–	–	2.460	2.435	2.447	2.454	2.452	–	–	2.454
G_{se}	2.714	–	–	2.694	2.704	2.660	2.655	2.712	–	–	2.635
$P_{0.075}/P_{be}$	1.37	–	–	1.66	1.25	1.26	1.15	1.17	–	–	1.51
In-Place Air Voids After Traffic	7.1	8.6	6.8	6.5	5.0	1.4	7.4	6.1	2.0	8.8	8.2

Notes: 1. Sections 43 and 51 were Nevada DOT mixes.
2. All tests conducted as per procedures in *AASHTO Provisional Standards* and *AASHTO Materials*.
3. VMA = voids in mineral aggregate, N_{design} = number of gyrations to achieve design compaction level, G_{mm} = theoretical maximum specific gravity of mixture, G_{se} = effective specific gravity of aggregate, $P_{0.075}/P_{be}$ = dust-to-effective-binder ratio.

Table 6. Field and laboratory rutting performance test results.

Table 6. Field and laboratory rutting performance test results.

	Section										
	35	**36**	**37**	**38**	**39**	**43**	**51**	**54**	**55**	**56**	**curve**
Actual Rutting[1]											
Peak to Valley, mm	15.8	34.6	24.3	11.6	11.4	6.2	–	12.3	20.5	25.2	–
Baseline to Valley, mm	12.1	25.4	14.1	7.7	7.7	5.2	3.6	12.3	14.2	20.3	–
French Rut Test, mm	11.7	20+	12.7	9.4	7.1	7.1	8.4	11.8	8.2	18.9	–
Hamburg Rut Test, mm	21.3	69.0	20.6	12.0	13.1	7.6	1.8	18.8	13.5	30.4	–
Asphalt Pavement Analyzer, mm	7.0	20.0	8.4	8.4	5.8	3.0	2.4	7.2	7.6	9.8	3.6
PurWheel, cycles to 6.35-mm rut depth	2533	417	1167	5417	–	–	–	6250	10,125	1500	–
Shear Test											
Repeated Shear at Constant Height (RSCH), 58°C, microstrain	66.5	76.5	106.5	24.1	15.5	12.5	9.9	50.9	18.0	67.7	17.3
Simple Shear at Constant Height (SSCH), 58°C, max. axial stress, kPa	26.0	25.2	23.0	25.2	49.5	14.5	16.3	23.6	15.1	25.1	17.7
Frequency Sweep at 10 Hz, 58°C, complex shear modulus (G*), MPa	55.6	54.9	57.4	56.9	53.0	41.0	44.1	52.7	56.4	75.0	90.4

Notes: 1. After 582,000 ESALs.
2. Sections 43 and 51 were Nevada DOT mixes.

Table 7. Test condition and device configuration for laboratory rut testers.

Table 7. Test condition and device configuration for laboratory rut testers.[1]

Device	FPRT	HWTD	APA	PurWheel
Test Temperature, °C	60	50	60	60
Environmental Condition	Dry	Wet	Dry	Dry
Specimen Size, mm	500x180x100	320x260x80	300x125x75	320x260x75
Wheel Type	Pneumatic (600 kPa)	Steel	Aluminum wheel on pressurized hose (830 kPa)	Pneumatic (862 kPa)
Wheel Size	400 mm dia., 90 mm wide	204 mm dia., 47 m wide	Maximum hose dia. of 29 mm	620 mm dia., 75 mm wide
Load, N	5000	685	533	1900
Wheel Speed, m/s	1.6	Sinusoidal with a maximum of 0.33 m/s at the center of sample	0.6	0.6

[1] The Superpave simple shear tester (SST) employs a significantly different test configuration than the rut testers. SST tests were conducted at 58 °C, following AASHTO Provisional Test Method TP-7.

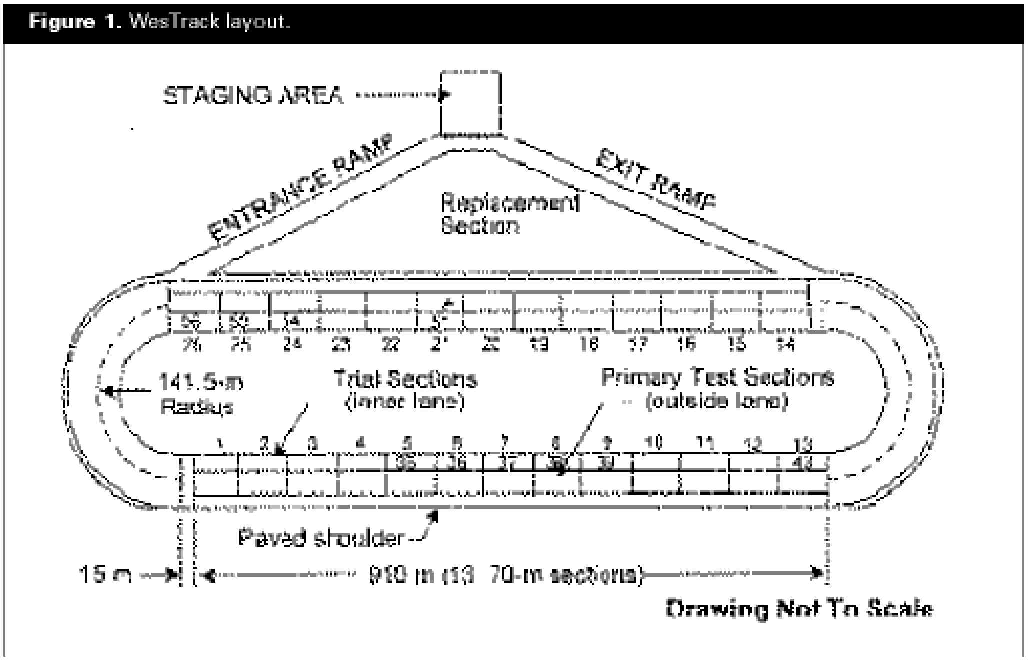


Figure 1. WesTrack layout

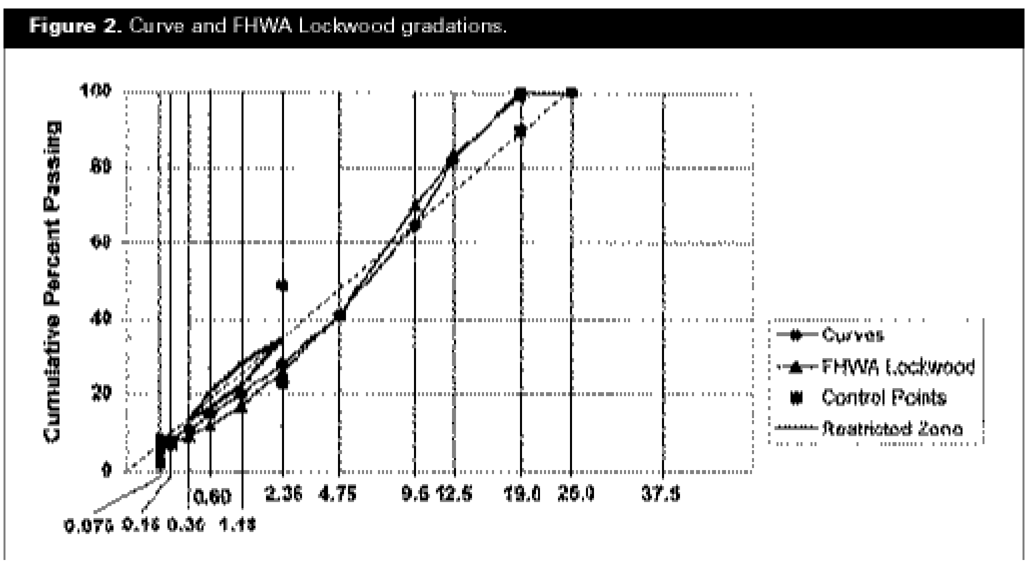


Figure 2. Curve an FHWA Lockwood gradations.

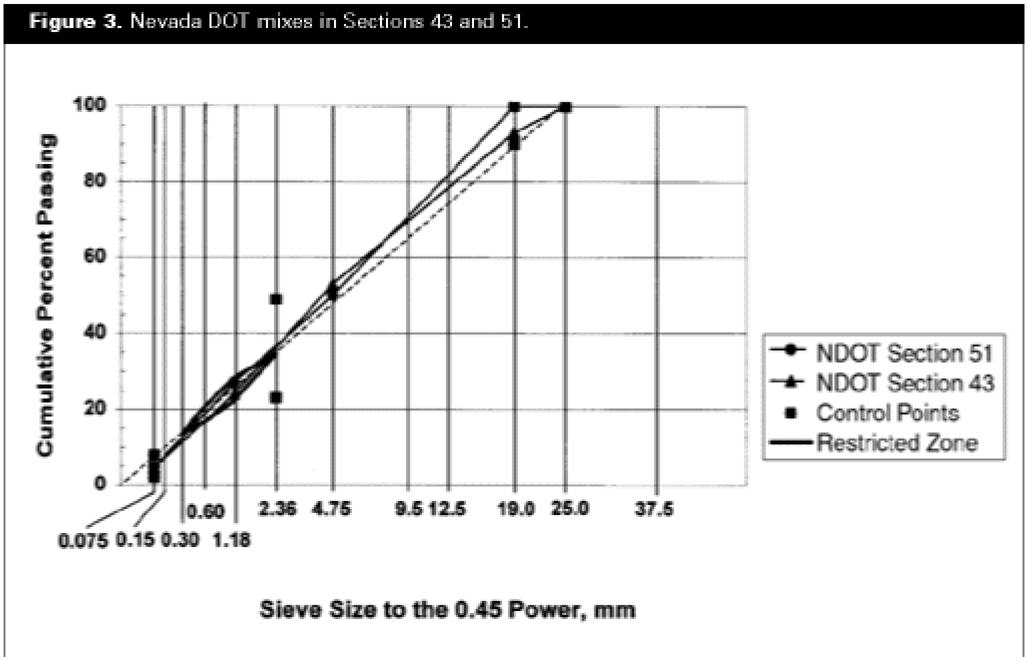


Figure 3. Nevada DOT mixes in Sections 43 and 51

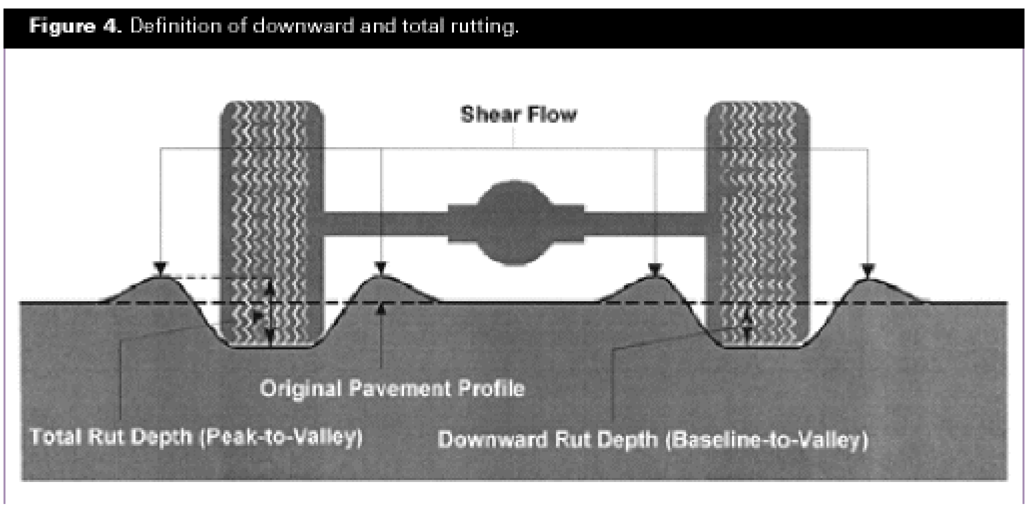


Figure 4. Definition of downward and total rutting

Figure 5. French Rutting Tester results vs. WesTrack performance.

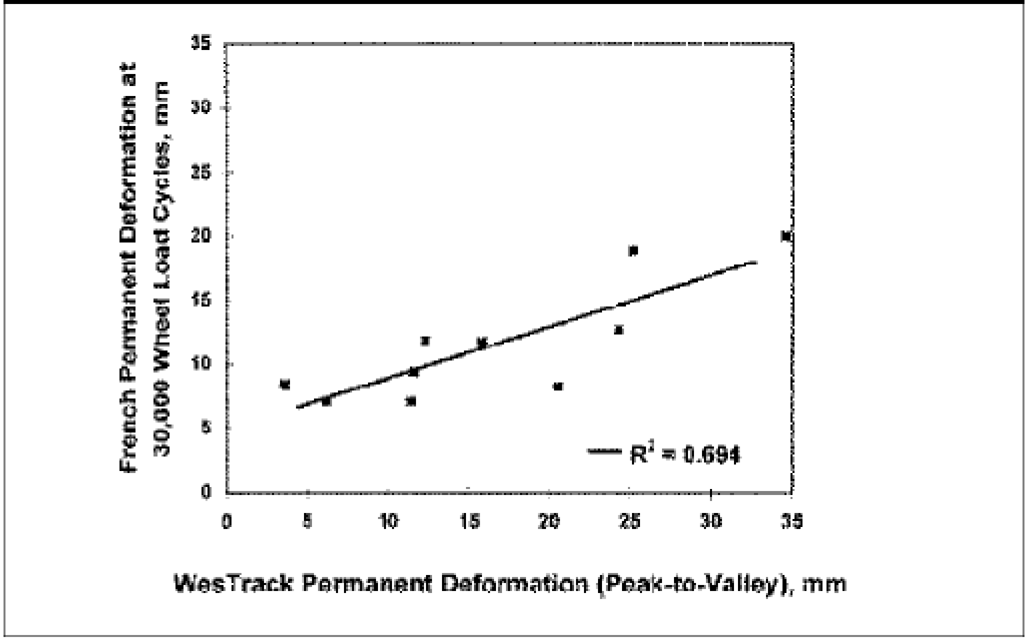


Figure 5. French Rutting Tester results vs. WeTrack performance

Figure 6. Hamburg wheel-tracking test results vs. WesTrack performance.

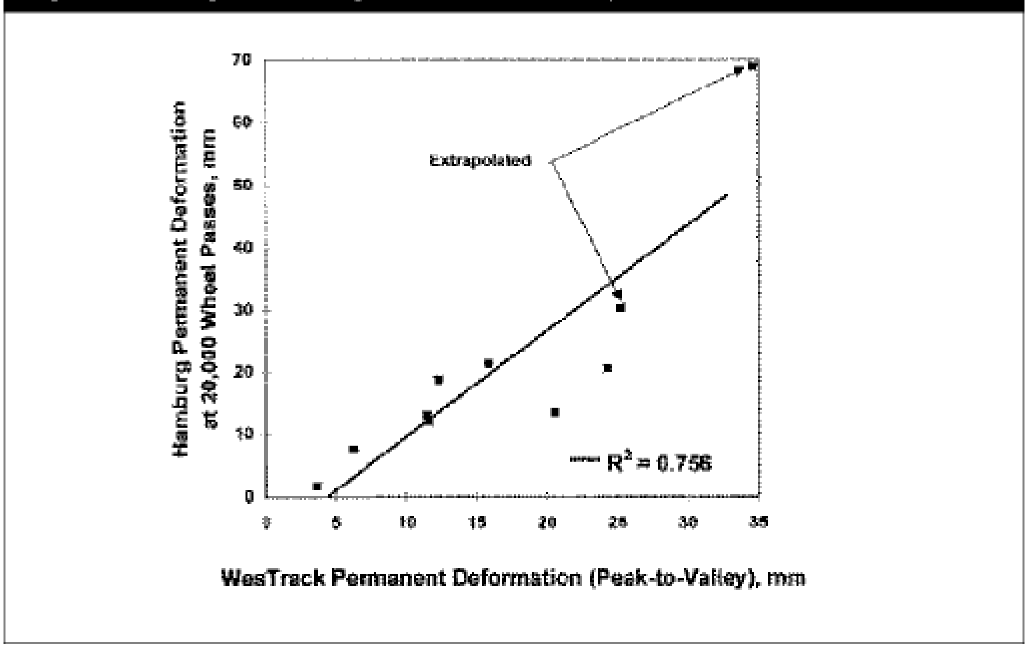


Figure 6. Hamburg wheel-tracking test results vs. WesTrack performance

Figure 7. APA results vs. WesTrack performance.

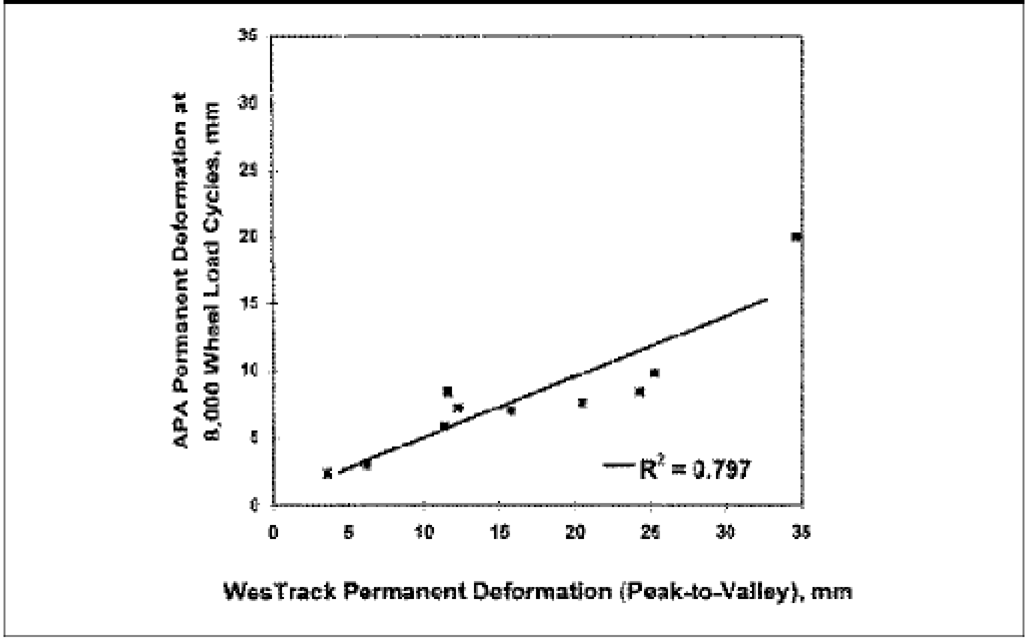


Figure 7. APA results vs. WesTrack performances

Figure 8. PurWheel test results vs. WesTrack performance.

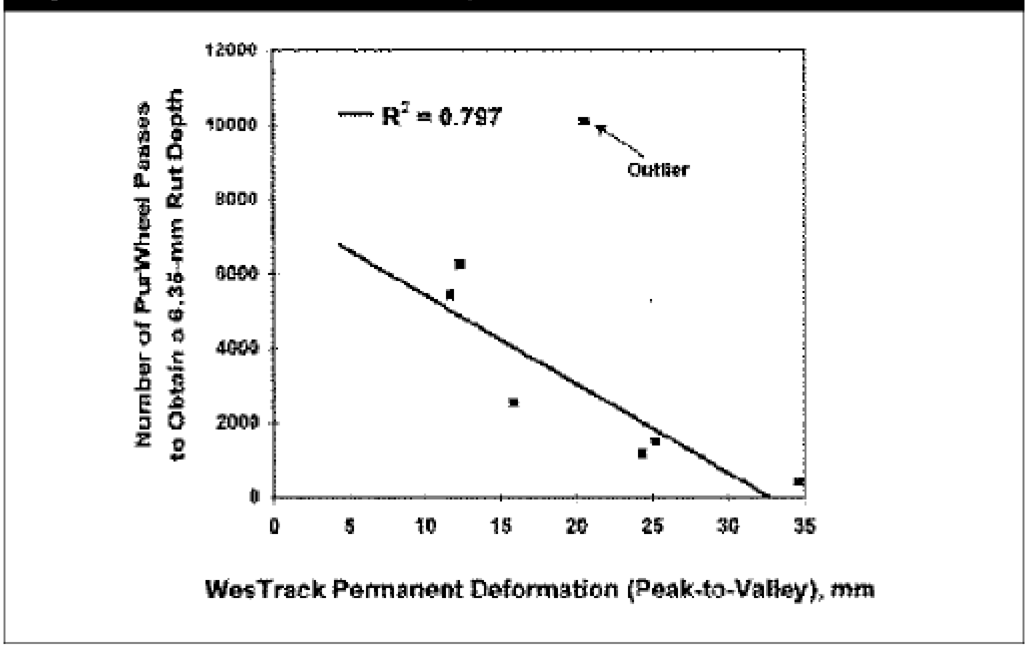


Figure 8. PurWheel test results vs. WesTrack performance

Figure 9. Repeated shear at constant height test results vs. WesTrack performance.

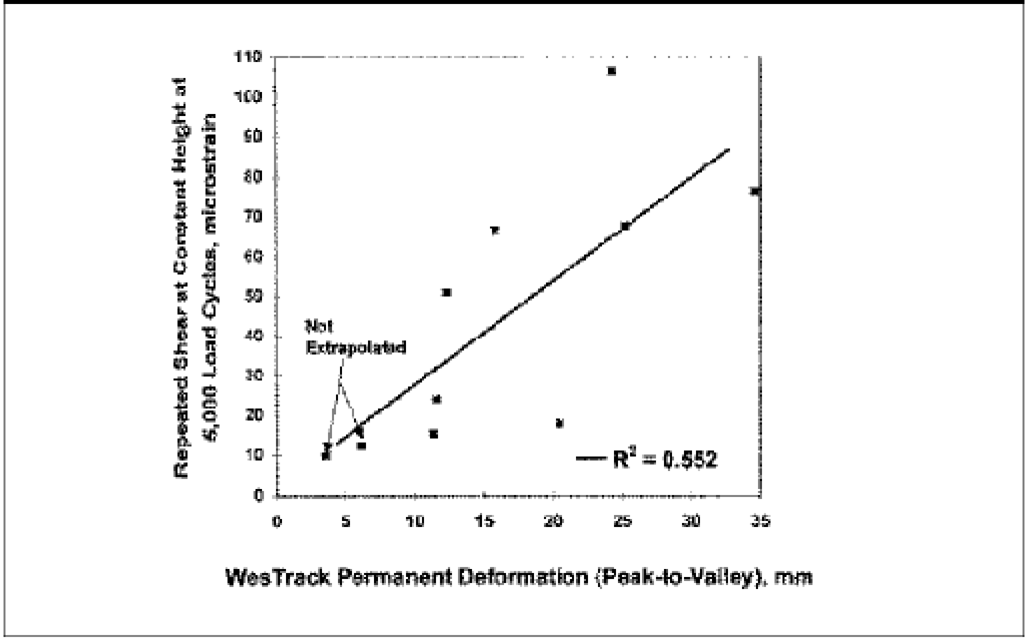


Figure 9. Repeated shear at constant height test resuls vs. WesTrack performance

Figure 10. Simple shear at constant height test results vs. WesTrack performance.

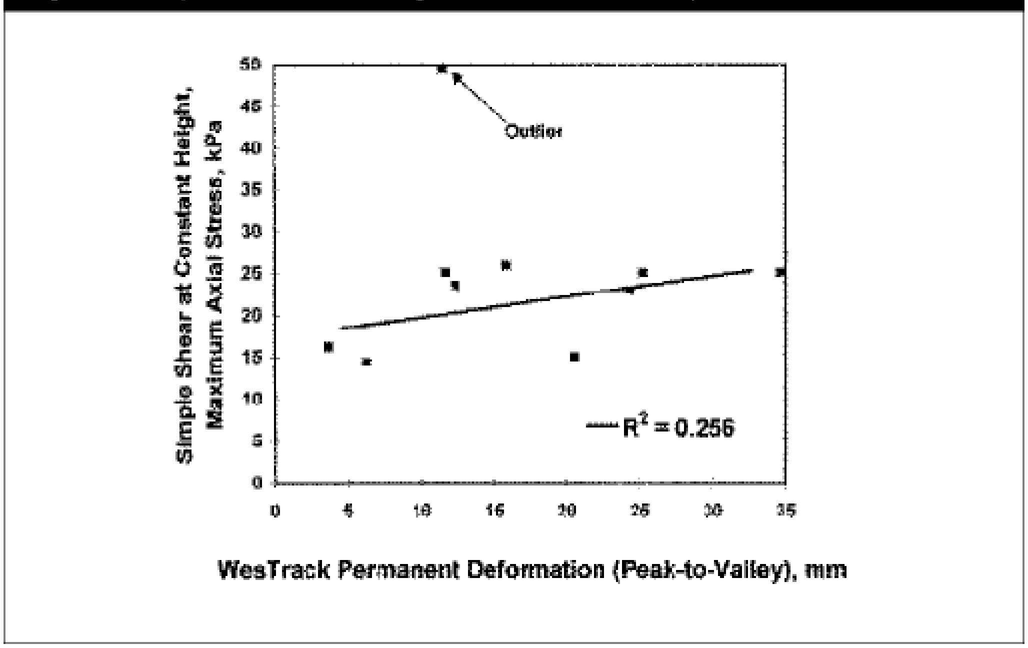


Figure 10. Simple shear at constant height test results vs. WesTrack performance

Figure 11. Frequency sweep at constant height test results vs. WesTrack performance.

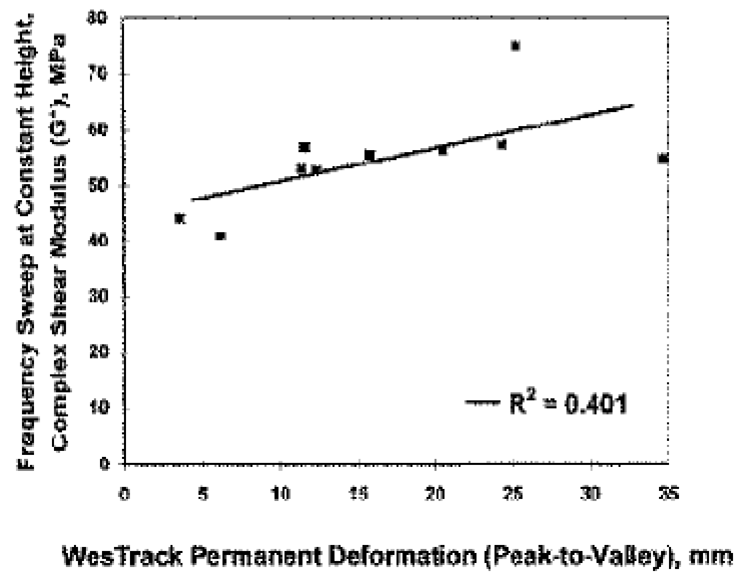


Figure 11. Frequency sweep at constant height test results vs. WesTrack performances

Appendix A

Potential Role of Structural Thickness in the WesTrack Mixture Performance

A written opinion by Gerald Huber, Jim Sckerocman, and Erv Dukatz, members of the WesTrack Forensic Team

The mixture performance at WesTrack was different than performances typically seen on other high truck traffic pavements. Several indicators of performance were different than the experience of the team members. The differences are listed as follows:

- Mixtures that showed rutting in the summer were the same mixtures that suffered fatigue cracking in the winter. Usually, mixtures that exhibit fatigue cracking do not have plastic deformation.
- The pattern of fatigue cracking developed first with transverse cracks across the wheelpath, followed by longitudinal cracks. Usually, longitudinal cracks are the first sign of fatigue, followed by transverse cracks.
- Plastic deformation in the mixture is shallow, less than 75 mm deep. Usually, plastic deformation disturbs mixture 50 to 100 mm deep.

Based on these observations, some members of the Forensic Team believe that the structural design had a significant influence on the mixture performance.

Hypothesis

Strain in the asphalt mastic influences rutting and fatigue behavior. Coarse gradation mixtures have higher strain in the mastic than fine mixtures. In a high-strain environment, coarse mixtures will not perform as well as expected.

Discussion

Some of the WesTrack Forensic Team members believe that structural thickness played a role in the unexpected performance of mixtures at WesTrack. The coarse mixtures had much poorer rutting performance than the fine mixtures, contrary to what had been expected. Both the original coarse-graded sections and, in particular, the replacement sections rutted very quickly.

The performance was unusual. The original sections did rut prematurely; surprisingly, however, they also experienced more fatigue cracking than the fine sections. Usually, mixtures that rut do not suffer fatigue cracking. Also unusual was that the fatigue cracking was different. It started as short transverse cracks across the wheelpath. Then, the cracks started to connect and a typical fatigue-cracking pattern occurred, as shown in figure A-1. The short cracks are a different manifestation of fatigue cracking than the experience of most team members. Usually, fatigue cracks start as longitudinal cracks along the edge of the wheelpath, followed by transverse cracks between them. Team members familiar with thin pavements carrying heavy traffic have seen the WesTrack pattern before on thin pavements.

The test sections at WesTrack are thinner than typical Interstate pavements carrying heavy trucks. The pavement structure is 150 mm of asphalt mixture, underlayed with 300 mm of granular base. The thickness was designed to be less than a 20-year design thickness to ensure that fatigue cracking occurred within the life of the project. The truck axle load is 89 kN (20,000 lb). The net result is a relatively thin asphalt layer operating with high deflections. Surface deflection under Falling-Weight Deflectometer testing is similar among the test sections and considerably higher than normal Interstate pavements.

With the relatively thin asphalt layer in the test sections, the granular base and underlying select subgrade control the pavement surface deflection. In other words, surface deflection in the test sections is not strongly influenced by the asphalt mixture properties. Surface deflections among the test sections are much higher than deflections on the adequate structural thickness of the curves.

Within a loaded HMA layer, the strain in the aggregate particles or in the asphalt mastic is not the same as the average strain in the layer. Aggregate particles are very hard in comparison to the asphalt mastic surrounding them. Asphalt mastic is composed of the asphalt binder and the fine aggregate which passes the 0.075-mm sieve. When the HMA layer is strained, the rocks deform very little, much less than the average strain. The asphalt mastic deforms more than the average strain. In other words, strain is concentrated in the asphalt mastic.

If strain within the asphalt mastic is large enough, aggregate particles will have the ability to reorient. If aggregate particles reorient, the skeleton collapses. Air voids decrease and rutting occurs. The amount of reorientation will depend on the amount of strain in the mastic and the mastic stiffness. If the mastic is very stiff, the aggregate will have less opportunity to reorient during a load application.

Coarse mixtures have a larger number of large aggregate particles than fine mixtures. In the coarse mixes, the concentration of strain at the points of contact is greater than in fine mixes. The absolute value of movement at the rock contact points is greater in a coarse mix than in a fine mix. For the same mastic stiffness, i.e., the same asphalt binder grade and the same amount and type of filler, the mastic in the coarse mixture will experience greater strain. The higher the strain in the mastic, the greater the chance of rutting. Therefore, in a high-strain environment, the coarse mixture will rut more than a fine mixture.

High strain in the mastic also explains the early fatigue cracking that occurred in the coarse mixtures. Fatigue cracking is directly related to the level of applied strain in the asphalt mastic.

> THE TEST SECTIONS AT WESTRACK ARE THINNER THAN TYPICAL INTERSTATE PAVEMENTS CARRYING HEAVY TRUCKS....THE THICKNESS WAS DESIGNED TO BE LESS THAN A 20-YEAR DESIGN THICKNESS TO ENSURE THAT FATIGUE CRACKING OCCURRED WITHIN THE LIFE OF THE PROJECT.

Situation At WesTrack

In the original WesTrack sections, the coarse gradation mixtures showed more rutting than the fine mixtures. Trenching in fall 1996, after 1.1 million ESALs, showed that the rutting was occurring within the asphalt mixture and not in the aggregate base as shown in figure A-2.

In a normal pavement, rutting typically disturbs mixture 50 to 100 mm below the surface. At WesTrack, the rutting disturbed mixture only in the upper lift, which is 75 mm thick. Aggregate reorientation at the surface is apparent in the upper layer as shown in figure A-3.

In figure A-3, the marks on the aggregate particles are grooves from diamond grinding that was done during construction to obtain smoothness. The grooves were originally aligned in the direction of the pencil. In sections that rutted, the aggregate particles rotated and moved.

The sections at WesTrack are responding according to the hypothesis presented here. The coarse sections in the original experiment showed more rutting than the fine sections. The replacement sections, which had a higher design asphalt content and consequently a less stiff mastic, rutted even more rapidly than the original sections.

At the entrance to the curves, traffic provides the same loading as the tangent test sections. When fully in the curve, the loading is different because of superelevation and staggering of the trailing axles; however, for approximately 15 m at the beginning of each curve, the traffic loads are unchanged from the tangent sections. At the joint between the research sections and the curve, the asphalt mixture in the curve is 150 mm thick. Approximately 4 to 5 m into the curve, there is an abrupt change and the mixture increases to 300 mm thick.

Mixture in the curves was intended to be the same coarse mixture used in the original experiment with medium (design) asphalt content and medium (92 percent of theoretical maximum specific gravity) in-place density. In actuality, the in-place asphalt content was 0.4 percent less than the design value. In the research sections, where the mixture was 150 mm thick, both "medium-medium" sections were removed because of excessive rutting. In the curves where the mixture thickness is 300 mm, the rutting is 3 mm in the entrance to one curve and 2 mm in the other. The increased structural thickness decreased the strain in the mastic. Decreased asphalt content also influenced the performance. Without excess asphalt and with reduced deflections, the aggregates were unable to reorient and rutting did not occur.

Conclusion

The structural thickness is believed to play a role in the performance of the coarse mixtures at WesTrack. Reduced asphalt content influenced rutting in the curves, but does not account for the improved performance.

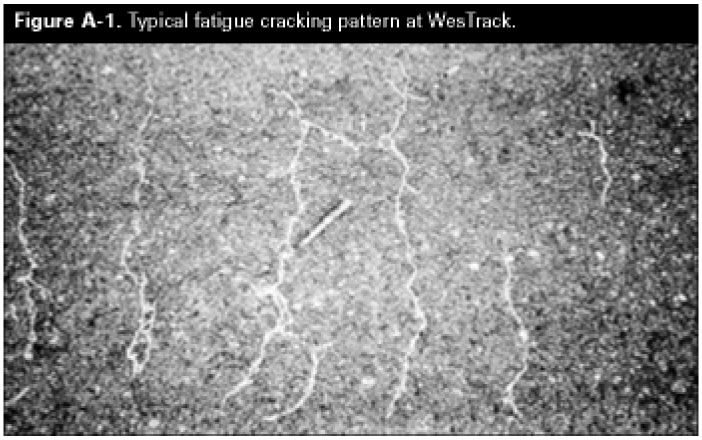


Figure A-1. Typical fatigue cracking pattern a WesTrack

Figure A-2. Forensic trench showing rutting confined to upper asphalt layer

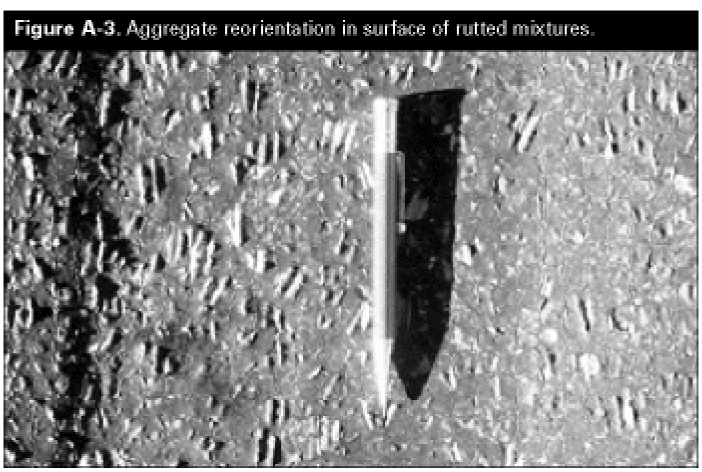


Figure A-3. Aggregate reorientation in surface of rutted mixtures.

Team Members

Ray Brown, *Director*
National Center for Asphalt Technology
211 Ramsay Hall
Auburn, AL 36849
Tel. (334) 844-6228
Fax (334) 844-6248

Erv Dukatz, V.P., *Materials & Research*
Mathy Construction Company
915 Commercial Court
P.O. Box 563
Onalaska, WI 54650
Tel. (608) 779-6392
Fax (608) 781-4694

Gerald Huber
Heritage Research Group
7901 W. Morris Street
Indianapolis, IN 46231
Tel. (317) 243-0811
Fax (317) 486-5095

Larry Michael, *Regional Engineer*
Maryland Department of Transportation
528 East Main Street
Hancock, MD 21750
Tel. (301) 678-6134
Fax (301) 678-5190

Jim Scherocman, *Consulting Engineer*
11205 Brookbridge Dr.
Cincinnati, OH 45249
Tel. (513) 489-3338

Ron Sines
New York State Dept. of Transportation
1220 Washington Avenue
Albany, NY 12232
Tel. (518) 457-4 582
Fax (518) 457-8171

Liaison Members:

John D'Angelo, *Asphalt Materials Leader*
Office of Pavement Technology (HIPT)
Federal Highway Adminstration
Room 3118, Nassif Building
400 Seventh St., S.W.
Washington, DC 20590
Tel. (202) 366-0121
Fax (202) 366-7909

Chris Williams, *Research Highway Engineer*
Office of Infrastructure R&D (HRDI-11)
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296
Tel. (202) 493-3154
Fax (202) 493-3161

FHWA Response

First and foremost, the Federal Highway Administration would like to thank the members of the forensic team for the many hours that they voluntarily dedicated to examining the failures at WesTrack. The team worked long and hard to understand why the test sections failed so quickly and to define Superpave issues that the members believe need to be examined. These issues have been, and will continue to be, addressed by FHWA, working with State highway agency (through AASHTO) and industry representatives.

The WesTrack experiment involves a very limited set of materials and a singular mix of construction, traffic, and environmental conditions; however, the forensic team members combined track and laboratory data and performance results with their own experiences with Superpave and HMA to generate a number of recommendations. While the team's report was still being completed, FHWA moved to address the issues that the team was raising.

First, FHWA's Asphalt Mixture Expert Task Group approved the change in the dust-to-binder ratio from 0.6 to 1.2 to the new limits of 0.6 to 1.6; that proposal has been forwarded to AASHTO's Subcommittee on Materials for inclusion in the provisional mixture design standard. It should be noted that at low dust-to-binder ratio values, additional fines act as an asphalt binder extender and worsen rutting performance. At some point, that performance reaches its lowest point and additional fines then act to dry the mixture out and to improve rutting performance. The additional fines also, however, cause fatigue performance to decline. More research is needed on this complex topic so that specifications will be able to accommodate other mixtures, such as stone mastic asphalt.

The forensic team's report emphasizes the need for a performance test or tests to augment the Superpave volumetric properties. FHWA has had a contract in place to identify a set of such performance tests, and that effort is continuing, in collaboration with AASHTO, under the National Cooperative Highway Research Program. FHWA agrees that the identification and use of performance prediction tests continues to be critical, as was established in the Strategic Highway Research Program.

The forensic team also has raised concerns about VMA criteria. VMA issues will continue to be problematic in the industry until accurate methods of measuring aggregate specific gravities have been developed and standardized. FHWA is working with the National Center for Asphalt Technology to identify such a test.

Finally, the team noted that the gyratory compaction criteria for Superpave mixtures were based on research that used a design life of 20 years. When a pavement is being designed for a shorter lifetime, the team members emphasize that the extrapolated 20-year traffic totals should be used in establishing the compaction criteria. This point was recently raised in the Asphalt Mixture Expert Task Group, and a proposal has been forwarded to AASHTO's Subcommittee on Materials for clarifications in the provisional standards.

In summary, FHWA believes the WesTrack project and the forensic team have served the States and the industry well by identifying some deficiencies in the Superpave system and by proposing improvements. We expect that the WesTrack research will continue to serve users and producers of HMA well with the completion of performance-related specifications.