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ABSTRACT

Rutting is a common problem in hot mix asphalt pavements, particularly in hot climates and at intersections. The Asphalt Pavement Analyzer (APA) is a laboratory accelerated loading equipment that can be used to evaluate rutting potential of HMA. This study was carried out to evaluate the potential of APA to predict rutting. Specifically, the objectives were to find the sensitivity of the equipment to changes in aggregate type and gradation, performance grade (PG) of asphalt binder, and evaluate the equipment by comparing the test results with the test results from Superpave shear tester (SST). Mixes from poor, fair and good performing pavements were also tested with the APA to develop a rut depth criteria for evaluation of mixes.

Binder and surface course mixes were made with granite, limestone and gravel aggregates, with gradations above the maximum density line, gradations through the Superpave restricted zone in close proximity of the maximum density line, and gradations below the maximum density line.

Results from tests with different aggregates, gradations, and binder types show that the APA is sensitive to these factors and, therefore, has a potential to predict relative rutting of hot mix asphalt mixtures. The APA had a fair correlation with the repeated shear constant height test conducted with the Superpave shear tester.

KEYWORDS: asphalt pavement analyzer, APA, loaded wheel tester, rutting, hot mix asphalt, restricted zone, Superpave shear tester

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EVALUATION OF ASPHALT PAVEMENT ANALYZERS FOR HMA MIX DESIGN

BACKGROUND

Many state departments of transportation are switching over to the Superpave volumetric mix design system. However, this mix design system is based entirely on mix volumetric properties and has no stability or rut test to verify or proof test designed mixes. The Asphalt Pavement Analyzer (APA) has shown some promise as a rut testing equipment (1-8). The APA is a modified version of the Georgia loaded wheel tester developed by the Georgia Department of Transportation. Rutting of asphalt mixes is assessed by placing rectangular or cylindrical samples under repetitive wheel loads and measuring the amount of permanent deformation under the wheel path. The load is applied by a wheel (going back and forth) to a pneumatic hose which rests on top of the test specimen. The rut depth is measured after the desired number of cycles (usually 8000) of load application. There is a need to evaluate the APA by testing mixes with different aggregate gradations and asphalt binders. Also, to use the APA as a routine proof test, there is a need to develop a pass/fail criteria for testing hot mix asphalt (HMA).

OBJECTIVE

The objectives of this project are to evaluate the Asphalt Pavement Analyzer (APA) as a tool of evaluating rut potential of HMA with different aggregate gradations and asphalt binders, and if possible, develop a rut depth criteria for acceptance or rejection of mixes.

THEORY AND SCOPE OF WORK

More than ninety percent of hot mix asphalt (HMA) consists of aggregates. The stability of HMA largely depends on aggregate properties. Gradation of aggregates is the single most important property that determines the stability of a mix. Mixes containing different aggregate gradations are likely to have different stability and different rutting potential. Hence, any laboratory rut tester should be evaluated on the basis of its ability to characterize mixes with different aggregate gradations. The Superpave system has specified a restricted zone through which aggregate gradations are recommended not to pass to avoid stability problems. Mixes with gradations above the restricted zone are known as fine mixes, and those passing below the restricted zone are known as coarse mixes. It is believed that mixes with gradations passing above, through and below restricted zones would differ significantly in their rutting potential. To obtain relatively stable mixes, Superpave recommends the use of below restricted zone gradations for pavements with high traffic volumes. Historically, most of the states have used gradations above the restricted zone (fine mixes). The difference in rutting potential of mixes with gradations passing above, through and below the zone can be utilized to evaluate the APA. It is hypothesized that if the APA is sensitive to mix strength properties, it should be able to differentiate the rutting potential of mixes with different gradations. Hence, it was decided to test mixes with gradations passing above, through and below the restricted zone with the APA. The gradations are shown in Table 1. The gradations are similar except near the restricted zone. This was done to observe the effect of restricted zone on mix properties. Henceforth, the gradations above, through, and below the restricted zone are referred to as ARZ, TRZ, and BRZ, respectively.

Table 1. Gradation of Aggregates

Course	**Percent Passing**			
	Sieve Size (mm)	**ARZ**	**TRZ**	**BRZ**
Wearing	19.0	100	100	100
	12.5	95	95	95
	9.5	86	86	86
	4.75	61	61	61
	2.36	45	39	33
	1.18	35	29	23
	0.6	26	21	16
	0.3	19	16	13
	0.15	11	10	9
	0.075	4.0	4.0	4.0
Binder				
	25.0	100	100	100
	19.0	95	95	95
	12.5	80	80	80
	9.5	68	68	68
	4.75	45	45	45
	2.36	41	35	29
	1.18	31	25	19
	0.6	24	19	14
	0.3	17	14	11
	0.15	11	10	9
	0.075	4.0	4.0	4.0

Many studies have shown that there is an interaction of the effect of gradation and aggregate shape and texture on rutting potential of HMA. Mixes containing different aggregates, but with same gradation can show significantly different rutting potential. In order to test the effect of aggregate type, it was decided to test mixes with three types of aggregates: granite, limestone, and gravel. The properties of the aggregates are shown in Table 2. All three aggregates are crushed aggregate. However, the percentage of crushed faces in gravel is lower than the percentage of crushed faces in granite and limestone (the latter two being 100 percent).

Table 2. Properties of Aggregates

Property	Granite	Limestone	Gravel
Bulk Specific Gravity of Coarse Aggregate	2.688	2.727	2.611
Bulk Specific Gravity of Fine Aggregate	2.712	2.639	2.623
Fractured Face (%)			
2 Face	100	100	90.3
1 Face	100	100	95.7
NAA Voids (%)	49.3	45.8	46.0

Apart from gradation and type of aggregate the top size of aggregate is also believed to have significant effect on rutting potential. Experience shows that stiff binder course with bigger aggregates have less rutting potential compared to relatively more flexible wearing courses with finer aggregates and higher binder content. Hence, any pass/fail criteria for testing mixes with the APA must be developed separately for wearing and binder courses. It was planned to test both wearing and binder courses, with maximum nominal size of 12.5 mm and 19.5 mm, respectively, with the APA. Both binder and wearing course gradations are shown in Table 1. Similar to the gradation of the wearing course, the gradation of the binder course differ only near the restricted zone.

All of the test samples were prepared at 4 percent air voids with the Superpave gyratory compactor (SGC). All of the mix designs were conducted by compacting HMA samples to N_{design}. The

N_{design} value was selected as 76, corresponding to a design traffic level of 0.3-1 million ESALS. This was done to avoid discrepancies in optimum asphalt content due to variation in correction factors. Mixes were subsequently compacted to N_{max}, using optimum asphalt content, to check density at N_{max}. Since the rate of densification of HMA during sample preparation, as indicated by slope of gyration versus density plot, may possibly indicate the rutting potential of HMA, it was decided to correlate slope of gyration plot with rut depths from APA tests.

The Superpave system has introduced the use of Performance Graded (PG) asphalt binders. The grade of asphalt binder should correspond to the expected high and low temperatures of the location of the pavement. For example, a PG 64-22 asphalt binder should be used where the expected maximum high and low pavement temperatures are 64EC and -22EC, respectively. The asphalt binders are required to exhibit specific minimum and maximum values when tested for different properties at a particular temperature, to be permitted for use at that particular temperature. For example, to be used with sufficient reliability at a location where the maximum high pavement temperature is 58EC, the asphalt binder, when tested at 58EC, must exhibit a dynamic shear rheometer stiffness of at least 1.0 kPa. Because of the influence of binder stiffness, mixes with same aggregate gradation but different asphalt binders should exhibit different rutting potential at the same temperature. However, mixes with same aggregate but two different binders (of grade PG x-z and PG y-z) should exhibit similar rutting potential when tested at xEC and yEC (PG x-z tested at xEC, PG y-z tested at yEC), respectively. To evaluate the effect of binder on rutting potential of mixes, it was decided to test mixes with PG 64-22 and PG 58-22 asphalt binder at 64EC and 58EC with the APA. Results from low and high temperature binder characterization tests for the two asphalt binders are shown in Table 3.

Table 3. Asphalt Binder Properties

Test	PG 58-22		PG 64-22	
	Test Temperature	Value	Test Temperature	Value
G*/sin* (original)	58EC	1.24 kpa	64EC	1.76 kPa
G*/sin* (RTFO)	58EC	2.91 kPa	64EC	3.24 kPa
G*sin* (RTFO-PAV)	19EC	2195 kPa	22EC	4567 kPa
Stiffness, S (RTFO-PAV)	-12EC	118 MPa	-12EC	255 MPa
Slope, m (RTFO-PAV)	-12EC	0.43	-12EC	0.32

The Superpave mix design and analysis system recommends the use of Superpave Shear Tester (SST) to determine the rutting potential of HMA. The SST is believed to be a very sensitive, sophisticated material characterization equipment with the capability of identifying the fundamental properties of HMA. To compare the results of APA with the results from the SST, it was decided to test some selected mixes with the SST as well. Two SST tests were selected for their usefulness and simplicity: the repeated shear at constant height (RSCH) and repeated shear at constant stress ratio (RSCSR). The RSCH can give an estimate of rut depth, whereas the RSCSR is capable of identifying mixes susceptible to rutting at low air voids.

Any laboratory rut tester, however sensitive it might be, is bound to have scale effects on test results. Because of the difference in layer thickness, underlying support, confining pressure, and stress distribution, among other things, the results of rut tests in a laboratory rut tester will be different from actual rut depths in pavement. However, to recommend a specific rut depth for acceptance/rejection of HMA, there is a need to correlate the results from the APA test and actual rut depths in pavements. Mixes were obtained by the Alabama Department of Transportation (ALDOT) from pavements with major, intermediate and minor rutting. It was decided to test these mixes with the APA, and correlate the results with actual rut depths. In this way, laboratory rut depths corresponding to major, intermediate and minor rutting can be used as basis for specification of acceptance/rejection criteria.

TEST PLAN

To test mixes with different aggregates, gradation, nominal maximum size aggregates and binder, mixes were prepared with granite, limestone, gravel, with gradation above, through and below the restricted zone, for typical ALDOT wearing and binder courses, and with PG 64-22 and PG 58-22 asphalt binders. Table 4 shows the mix test matrix. In the first step, dry rut tests were conducted on different mixes. Mixes with PG 64-22 and PG 58-22 asphalt binders were tested at 64EC and 58EC, respectively. Mixes with high and low rut depths, as obtained from dry rut tests, were tested with the SST under repeated shear as constant height and repeated shear at constant stress ratio conditions. The mixes exhibiting high rutting potentials in dry rut tests were tested under water, and also tested with the AASHTO T283 (Modified Lottman) procedure. Tests were also conducted under dry conditions with mixes obtained from high, intermediate and low rutting pavements. All APA tests were conducted with a wheel load of 445 N and a hose pressure of 690 kPa.

The data was analyzed to answer the following specific questions:

1. a. Is the APA sensitive to aggregate gradation?

   b. If yes, how are the gradations characterized according to their rutting potential?

2. How do the rut depths from wearing and binder courses compare? Does the APA show less rut depths for binder courses, as expected?

Table 4. Mix Test Matrix

	AGGREGATE																	
	Rounded Gravel						Granite						Limestone					
	Wearing Course			Binder Course			Wearing Course			Binder Course			Wearing Course			Binder Course		
	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ
Cylinder for APA @ 4% VTM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Totals	(6)	(6)	(6)	(6)	(6)		(6)	(6)	(6)	(6)	(6)	(6)	(6)	(6)	(6)	(6)	(6)	(6)
Cylinder for RS @ CSR 3% VTM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Totals	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)
Cylinder for RS @ CH 6% VTM	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Totals	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)

3. What is the effect of asphalt binder on rutting potential? Does the APA show similar rut depths for mixes with different binders tested at their corresponding (PG grade) high temperatures?
4. Is there any correlation between APA rut depth and gyratory compaction slopes of different mixes? Are mixes meeting $N_{initial}$ and N_{max} criteria likely to show less rutting potential compared to mixes which do not meet these criteria?
5. Is there any correlation between rut depth and binder film thickness?

6. How do the results from tests with APA compare with the results from tests with SST?

Additional work included testing three sections on I-85 (south of Georgia/Alabama border) which were showing good, fair and poor performance in terms of rutting, were identified. Cores were obtained from each of these sections from the travel lane, about 300 mm away from the pavement edge. Mixes A, B, and C are characterized as good (no rutting), fair (6 mm rutting), and poor (12.5 mm rutting or more), respectively. In the laboratory, the wearing courses were sawed off from the cores, and the bulk specific gravities were determined. The cores were then heated and part of the mixes were used for determining the theoretical maximum density, and asphalt content. Ten gyratory samples were then compacted with each type of mix, at 4 % air voids. The samples were then tested with the APA for determining the rutting potential.

TEST RESULTS AND ANALYSIS

Data from testing with the APA were analyzed as discussed in the following sections.

Differences Between Rut Depths of Mixes with Gradations Passing Above, Through and Below Restricted Zone

Statistical analyses were conducted to determine if difference between rut depths of mixes with gradations passing above (ARZ), through (TRZ), and below (BRZ) the restricted zone are significant. Specifically, an analysis of variance (ANOVA) ("=0.05) and Duncan's multiple range test (mean separation technique) were conducted with the data. Table 5 shows the mean and standard deviation of rut depths from different mixes. Analysis of whole data set indicates significant effect of aggregate type,

Table 5. Rut Depths for Mixes with Different Gradations

Asphalt	Course	Aggregate	Gradation	Mean Rut Depth (mm)	Standard Deviation, Rut Depth (mm)	Ranking (A has more rutting than B); Significance level = 5 %
PG 64-22	Wearing	Granite	ARZ	4.48	0.737	AB
			TRZ	4.30	0.825	B
			BRZ	5.35	0.561	A
		Limestone	ARZ	3.77	0.608	B
			TRZ	3.90	0.452	B
			BRZ	6.23	1.036	A
		Gravel	ARZ	6.46	0.656	A
			TRZ	5.77	0.342	AB
			BRZ	5.64	0.776	B
	Binder	Granite	ARZ	3.48	1.205	A
			TRZ	1.62	0.348	B
			BRZ	3.43	0.567	A
		Limestone	ARZ	4.07	0.294	B
			TRZ	3.98	0.287	B
			BRZ	5.62	1.531	A
		Gravel	ARZ	5.19	1.034	A
			TRZ	4.35	0.678	A
			BRZ	4.53	0.492	A
PG 58-22	Wearing	Granite	ARZ	6.59	1.191	A
			TRZ	3.81	0.442	B
			BRZ	6.01	0.622	A
		Limestone	ARZ	4.53	0.737	B
			TRZ	5.47	1.148	B
			BRZ	7.16	0.949	A
		Gravel	ARZ	7.95	0.539	A
			TRZ	6.036	0.477	B
			BRZ	5.24	0.708	C
	Binder	Granite	ARZ	3.4	0.446	A
			TRZ	2.8	0.283	A
			BRZ	2.85	0.707	A
		Limestone	ARZ	4	0.186	B
			TRZ	5.04	0.581	B
			BRZ	9.49	2.021	A
		Gravel	ARZ	6.41	1.005	A
			TRZ	5.23	0.621	B
			BRZ	4.65	0.375	B

Table 6. Analysis of Variance for Rut Depths of Mixes with Different Gradations, Binder, and Courses

Source	DF	Mean Square	F Value	Pr>F
Aggregate	2	51.59	45.64	0.0001
Asphalt	1	34.96	30.94	0.0001
Gradation	2	24.35	21.54	0.0001
Course	1	57.56	50.92	0.0001
Aggregate*Gradation	4	33.79	29.90	0.0001

asphalt binder type, gradation, course type, and an interaction of aggregate and gradation (Table 6).

Considering all data, mixes with gravel and limestone aggregates generally show higher rutting than granite and mixes with asphalt PG 58-22 showed more rutting compared to asphalt PG 64-22. Also, for granite and limestone, mixes with gradation below restricted zone generally showed highest amount of rutting, whereas through restricted zone generally showed lowest rut depth, and above restricted zone generally showed intermediate rutting. For gravel, in most cases the mixes with below restricted zone gradation show the least amount of rutting, whereas mixes with above restricted zone gradation show highest amount of rutting; mixes with gradations through the restricted zone show either higher or similar rutting as mixes with gradation below the restricted zone.

Analysis of individual groups of data showed that:

1. The effect of gradation on granite and limestone wearing and binder courses with PG 64-22 asphalt is significant, with below restricted zone gradation showing higher rutting compared to above and through restricted zone. The effect is similar and significant for granite PG 58-22 wearing courses but not significant for granite binder course.
2. The effect of gradation is not significant for rutting of gravel wearing and binder course

mixes with PG 64-22. The above and through restricted zone mixes showed slightly higher rutting compared to below zone mixes.

However, the data for PG 58-22 wearing and binder course mixes showed significant effect of gradation, and the ARZ, TRZ and BRZ gradation showed lowest, intermediate, and highest amount of rutting, respectively.

The test data and statistical analysis, therefore, show that the APA is sensitive to mix gradation.

Comparison of Rut Depths of Mixes with PG 64-22 and PG 58-22 Binder

Paired t tests were conducted to compare rut depths of mixes with PG 64-22 (tested at 64EC) and PG 58-22 (tested at 58EC) asphalt binder. Table 7 shows a table of average rut depths for each mix; mix with PG 64-22 binder paired against same mix with PG 58-22 binder. Since there were three aggregates, three gradations, and two courses, there are 18 pairs of data.

Results of paired t tests (Table 8) show that at a significant level of 5%, there is a significant difference between rut depths of mixes with PG 64-22 and PG 58-22 asphalt binder. Rut depths of mixes with PG 58-22 asphalt binder (tested at 58^{o}C) are higher than mixes with PG 64-22 asphalt binder (tested at 64^{o}C). Paired t tests were also done with mixes of wearing and binder courses separately and mixes containing different aggregates. One of the possible reasons for greater rut depths for mixes with PG 58-22 asphalt is relatively lower G*/sin* value of PG 58-22 asphalt binder compared to the G*/sin* value for PG 64-22 asphalt. The dynamic shear rheometer (DSR) stiffness (RTFOT condition) for the PG 58-22 binder at 58^{o}C is 2.9 kPa, whereas the DSR stiffness for the PG 64-22 binder at 64^{o}C is 3.2 kPa (Table 3). The test data and the statistical analysis, therefore, indicates

Table 7. Rut Data for Mixes with PG 64-22 and PG 58-22 Asphalt Binder

Mix*	PG 64-22	PG 58-22
WARZGRN	4.48	6.59
WTRZGRN	4.31	3.81
WBRZGRN	5.35	6.02
WARZLMS	3.77	4.53
WTRZLMS	3.91	5.47
WBRZLMS	6.24	7.16
WARZGRV	6.46	7.95
WTRZGRV	5.77	6.03
WBRZGRV	5.64	5.24
BARZGRN	3.48	3.40
BTRZGRN	1.62	2.80
BBRZGRN	3.43	2.85
BARZLMS	4.07	4.00
BTRZLMS	3.98	5.04
BBRZLMS	5.62	9.49
BARZGRV	5.19	6.41
BTRZGRV	4.35	5.23
BBRZGRV	4.53	4.65

Note: * First letter indicates course: W- Wearing, B - Binder
Next three letters indicate gradation: ARZ - Above Restricted Zone
TRZ - Through Restricted Zone
BRZ - Below Restricted Zone
Last three letters indicate aggregate: GRN = Granite, LMS - Limestone, GRV - Gravel

Table 8. Results of t Tests for Comparing Mixes with PG 64-22 and PG 58-22 Binders

Comparison		Mean*	Standard Error	T	Probability>T
Considering all mixes		-0.804	0.255	-3.149	0.0059
Considering wearing courses	All	-0.763	0.294	-2.599	0.0317
	Granite	-0.760	0.755	-1.007	0.420
	Limestone	-1.080	0.244	-4.419	0.048
	Gravel	-0.450	0.554	-0.812	0.502
Considering binder courses only		-0.844	0.436	-1.936	0.089

Note: * = (rut depth of mixes with PG 64-22 asphalt binder - rut depth of mixes with PG 58-22) that the APA is sensitive to binder type.

Correlation of Rut Depths with Density at $N_{initial}$ and N_{max}

$N_{initial}$ and N_{max} criteria have been specified by Superpave in order to avoid tender mixes and mixes prone to rutting, respectively. The data was analyzed to determine if rut depths are lower (or lowest) when the mix met density #89% of TMD (theoretical maximum density) criteria at $N_{initial}$ and density #98% of TMD criteria at N_{max}. An analysis of variance was conducted to observe any significant effect of difference between density at N_{intial} and 89 (x = 89 - density at N_{intial}), and difference between density at N_{max} and 98 (y = 98 - density at N_{max}), on rutting. The calculated x and y values are shown in Table 9. The analysis indicated no significant effect of x and y on rut depths (Table 10).

All of the y values were positive numbers, which indicates that none of the mixes had density higher than 98% Gmm at N_{max}. The wearing course with granite has two mixes with negative x values (density at $N_{initial}$ higher than 89%). The rut depth versus x and y values show no apparent correlation between x, y, and rut depth. However, observation of wearing course of gravel does suggest some effect of x on rut depth. This data was pooled with the binder course gravel data to run a regression between rut depth and x and y (Table 11). However, no significant model was observed.

In most cases, except for binder limestone it does seem that compared to the rut depth for a density less than 89% of TMD at $N_{initial}$, the rut depths tend to be higher for those cases in which the density is higher than 89% of TMD (Table 12). However, the data does not suggest that a mix will have the lowest rut depth when it meets the $N_{initial}$ criteria, compared to mixes which do not meet $N_{initial}$ criteria.

Table 9. Calculated x and y Values

Asphalt	Mix*	Density at $N_{initial}$	Density at N_{max}	Rut Depth	x (x = 89-density at $N_{initial}$)	y (y = 98-density at $N_{maximum}$)
PG64-22	WARZGRN	89.72	97.14	4.48	-0.72	0.86
	WTRZGRN	89.05	97.32	4.31	-0.05	0.68
	WBRZGRN	87.34	97.59	5.35	1.66	0.41
	WARZLMS	88.58	97.34	3.77	0.42	0.66
	WTRZLMS	87.13	97.71	3.91	1.87	0.29
	WBRZLMS	85.95	97.86	6.24	3.05	0.14
	WARZGRV	89.98	97.22	6.46	-0.98	0.78
	WTRZGRV	89.37	97.36	5.77	-0.37	0.64
	WBRZGRV	88.83	97.45	5.64	0.17	0.55
	BARZGRN	89.95	97.17	3.48	-0.95	0.83
	BTRZGRN	89.00	97.19	4.62	0	0.81
	BBRZGRN	87.46	97.45	3.43	1.54	0.55
	BARZLMS	88.42	97.42	4.07	0.58	0.58
	BTRZLMS	90.60	97.08	3.98	-1.60	0.92
	BBRZLMS	85.81	97.83	5.62	3.19	0.17
	BARZGRV	90.16	96.91	5.19	-1.16	1.09
	BTRZGRV	89.46	97.21	4.35	-0.46	0.79
	BBRZGRV	87.72	97.46	4.53	1.28	0.54
PG58-22	WARZGRN	89.72	97.14	6.59	-0.72	0.86
	WTRZGRN	89.05	97.32	3.81	-0.05	0.68
	WBRZGRN	87.34	97.59	6.02	1.66	0.41
	WARZLMS	88.58	97.34	4.53	0.42	0.66
	WTRZLMS	87.13	97.71	5.47	1.87	0.29
	WBRZLMS	85.95	97.86	7.16	3.05	0.14
	WARZGRV	89.98	97.22	7.95	-0.98	0.78
	WTRZGRV	89.37	97.36	6.03	-0.37	0.64
	WBRZGRV	88.83	97.45	5.24	0.17	0.55
	BARZGRN	89.95	97.17	3.40	-0.95	0.83
	BTRZGRN	89.00	97.19	2.80	0.00	0.81
	BBRZGRN	87.46	97.45	2.85	1.54	0.55
	BARZLMS	88.42	97.42	4.00	0.58	0.58
	BTRZLMS	90.60	97.08	5.04	-1.60	0.92
	BBRZLMS	85.81	97.83	9.49	3.19	0.17
	BARZGRV	90.16	96.91	6.41	-1.16	1.09
	BTRZGRV	89.46	97.21	5.23	-0.46	0.79
	BBRZGRV	87.72	97.46	4.65	1.28	0.54

Note: * First letter indicates course: W- Wearing, B - Binder. Next three letters indicate gradation: ARZ - Above Restricted Zone; TRZ - Through Restricted Zone; BRZ - Below Restricted Zone. Last three letters indicate aggregate: GRN = Granite, LMS - Limestone, GRV - Gravel

Table 10. Analysis of Variance for Rut Depths Versus x and y

	Source	DF	Mean Square	F Value	Probability>F
PG 64-22 Asphalt	Model	2	2.58	2.055	0.163
	Error	15	1.257		
	C Total	17			
PG 58-22 Asphalt	Source	2	3.227	1.045	0.376
	Model	15	3.088		
	Error	17			

Note: x = (89 - Density at $N_{initial}$)
y = (98 - Density at $N_{maximum}$)

Table 11. Analysis of Variance for Rut Depths and x and y for Gravel Mixes

	Source	DF	Mean Square	F Value	Probability>F
PG 64-22 Asphalt	Model	2	0.935	2.132	0.265
	Error	3	0.439		
	C Total	5			

Note: x = (89 - Density at $N_{initial}$)
y = (98 - Density at $N_{maximum}$)
Model: Response = True Mean + Effect of x + Effect of y + Effect of Experimental Unit

Table 12. Rut Depth and x Values

Mix*	x	Rut Depth (mm)
WTRZGRN	-0.05	0.68
WARZGRN	-0.72	0.86
WARZGRV	0.17	5.64
WTRZGRV	-0.37	5.77
WBRZGRV	-0.98	6.46
BTRZGRN	0.00	1.62
BARZGRN	-0.95	3.48
BTRZGRV	-0.46	4.35
BARZGRV	-1.16	5.19

Note: x = (89 - Density at $N_{initial}$).
*First letter indicates course: W- Wearing, B - Binder. Next three letters indicate gradation: ARZ - Above Restricted Zone; TRZ - Through Restricted Zone; BRZ - Below Restricted Zone. Last three letters indicate aggregate: GRN = Granite, LMS - Limestone, GRV - Gravel

One observation is that in those cases in which the mixes which meet the $N_{initial}$ criteria but have maximum rut depth (for a particular aggregate), the difference between the density at N_{max} and 98% (y) is observed to by very small. The exceptions are Wearing-Gravel-BRZ, Binder-Granite-BRZ and Binder-Gravel-BRZ (Table 13). However, in the case of the exceptions, the difference between the density at N_{max} and 98% of TMD are higher. The data indicates that if the density is within 0.1 - 0.2% of 98% of Gmm at N_{max}, one might expect relatively higher amount of rutting.

Table 13. Rut Depths and y Values

Mix	Meets N_{intial} Criteria?	Rut Depth	y
WBRZ GRN	yes (only one)	6.02 (2nd highest)	0.14 (lowest of all three)
WBRZ LMS	yes (all meet)	7.16 (highest)	0.14 (lowest)
exception: WBRZ GRV	yes (only one)	5.24 (lowest)	0.55 (lowest)
exception: BBRZ GRN	yes (2 meet)	2.85 (2nd highest)	0.55 (lowest)
BBRZ LMS	yes (2 meet)	9.49 (highest)	0.17 (lowest)
exception: BBRZ GRV	yes (only one)	4.65 (lowest)	0.54 (lowest)

Note: y = (98 - Density at $N_{maximum}$)

Effect of Asphalt Binder Film Thickness on Rutting

Regression analyses were done to observe any possible relation between film thickness and rutting. In the first step, only wearing courses of granite and limestone (for PG 64-22 and PG 58-22) were considered. The gravel mixes were not included since observation of the data (Table 14) showed that while granite and limestone mixes tend to have more rutting with an increase in film thickness, for gravel the rutting decreased with an increase in film thickness.

The best relation was obtained between square of film thickness and rut depth is

rut depth = 2.53 + 0.035 (film thickness)^2.

Hence, for a rut depth of 7 mm, one would expect a film thickness of 11.9 . 12 µm.

Prob > F of model = 0.0084

Prob > *t* for intercept = 0.0125

for (film thickness)^2 = 0.0084

R^2 = 0.52

Table 14. Film Thickness and Rut Depths for Different Mixes (with PG 64-22 Asphalt Binder)

Course	Aggregate	Gradation	Film Thickness (micron)	Rut Depth (mm)
Wearing	Granite	ARZ	8.70	4.48
		TRZ	9.36	4.31
		BRZ	10.58	5.35
	Limestone	ARZ	6.96	3.77
		TRZ	8.09	3.91
		BRZ	11.01	6.24
	Gravel	ARZ	7.83	6.46
		TRZ	8.47	5.77
		BRZ	10.14	5.64
Binder	Granite	ARZ	9.74	3.48
		TRZ	10.41	1.62
		BRZ	12.92	3.43
	Limestone	ARZ	8.80	5.47
		TRZ	10.41	3.98
		BRZ	15.18	5.62
	Gravel	ARZ	9.27	8.04
		TRZ	10.14	4.35
		BRZ	12.6	4.53

For binder courses with granite and limestone, the best relation was found to be:

Rut depth = 37.05 - 6.137 (film thickness) + 0.2754 (film thickness)^2

Prob > F of model = 0.0108

Prob > *t* of intercept = 0.0321

of film thickness = 0.0363

of (film thickness)^2 = 0.0256

R^2 = 0.63

While the validity of this somewhat complex regression equation is debatable, it does indicate that for binder courses rutting may actually decrease with an increase in film thickness. However, the applicability of film thickness concept to courses other than the wearing course is questionable.

In case of wearing gravel courses, the best relation was obtained as

Rut depth = 19.39 - 14.017 $\log_{10}$ film thickness

Prob > F = 0.0832 (not significant at " = 5%)

Prob > *t* = 0.0281

of intercept

of $\log_{10}$ film thickness = 0.0832

R^2 = 0.63

This indicates that rut depth decreases with an increase in film thickness.

For binder course for gravel, no significant model was found between rut depth and film thickness.

The difference in the effect of film thickness on rut depth for granite and limestone, and gravel indicates a difference in the way the aggregates and asphalt binder are packed together in a mix. One explanation is that in the case of relatively rounded and smooth textured gravel particles, increased film thickness helps in lubrication of particles during compaction, brings them closer (low VMA) and thus helps in making a tightly interlocked structure. On the other hand, in the case of relatively angular and rough textured granite and limestone presence of too much asphalt film tend to move the particles apart and break the tightly interlocked aggregate structure.

Since the fine materials, particularly material passing 0.15 mm and 0.075 mm sieve may actually be embedded in asphalt matrix and not provide surface area for coating, film thickness was also calculated by neglecting the surface area of material passing 0.15 mm and 0.075 mm sieves. However, no improvement in the model between film thickness and rut depth was obtained. In the next step film thickness was calculated by neglecting material passing 0.075 mm sieve only, but considering material passing 0.15 mm sieve. Again, no significant improvement was obtained.

Comparison of Rut Development Slope with Gyratory Slope

Each plot of passes versus rutting resulting from tests with APA consists of three lines with different slopes, between 0-1000, 1000-4000, 4000-8000 passes. The nature of the rut development curve is very similar to the nature of the gyratory compaction curve. The rut development plot gradually appears to level off (and have a lower slope) just like the gyratory compaction plot, in which the density appears to level off beyond N_{design}. Hence, it was decided to examine slope of each part of the plot and try to correlate with slope of gyratory plot.

Since the slope of gyratory plot is from log of gyration versus density, it was decided to use the log of pass versus rutting plot for determining the slope of rut development plot. Also, to consider initial zero rutting, the initial pass number was changed from zero to 10.

Hence, three slopes were determined for each rut development plot; slopes between 0-1000, 1000-4000, and 4000-8000. Each of these slopes were correlated with gyratory compaction slope (Table 15).

Table 15. Gyratory Compaction Slope and Rut Depth for Different Mixes (With PG 64-22 Asphalt Binder)

Course	Aggregate	Gradation	Gyratory Compaction Slope (between $N_{initial}$ and N_{design})	Rut Development Slope					
				Log			Normal		
				0-1000	1000-4000	4000-8000	0-1000	1000-4000	4000-8000
Wearing	Granite	ARZ	6.066	1.014	3.074	2.015	2.028	0.617	0.152
		TRZ	6.761	1.382	1.845	1.428	2.764	0.370	0.108
		BRZ	8.389	1.725	2.400	1.503	3.451	0.482	0.113
	Limestone	ARZ	7.16	0.964	1.954	2.198	1.928	0.392	0.165
		TRZ	8.653	0.936	1.412	3.931	1.872	0.283	0.296
		BRZ	9.737	1.860	2.519	3.316	3.720	0.506	0.250
	Gravel	ARZ	5.918	2.160	2.526	2.068	4.319	0.507	0.156
		TRZ	6.531	1.779	2.317	2.710	3.558	0.465	0.204
		BRZ	7.055	1.705	1.924	3.491	3.431	0.386	0.263
Binder	Granite	ARZ	5.907	0.825	1.89	2.290	1.650	0.379	0.173
		TRZ	6.701	0.485	0.615	0.914	0.970	0.123	0.069
		BRZ	8.175	0.923	1.362	2.552	1.845	0.273	0.192
	Limestone	ARZ	7.355	0.973	2.383	6.943	1.945	0.478	0.173
		TRZ	5.299	0.793	2.356	3.233	1.585	0.473	0.243
		BRZ	9.83	1.738	2.223	2.669	3.475	0.446	0.201
	Gravel	ARZ	5.518	1.634	2.234	1.905	3.268	0.448	0.143
		TRZ	6.332	1.183	2.029	2.525	2.367	0.407	0.190
		BRZ	7.963	1.205	2.323	2.392	2.410	0.466	0.180

Both log and normal slopes did not show any correlation with gyratory compaction slope (between N_{design} and $N_{initial}$) (Table 16).

Table 16. Regression Equations for Rut Development Slope Versus Gyratory Compaction Slope for Different Mixes (With PG 64-22 Asphalt Binder)

Rut Development Slope		Course	Model[a]	R^2
Log	0-1000	Wearing	y = -0.0063x + 1.55	0.0003
	1000-4000		y = -0.1057x + 2.99	0.08
	4000-8000		y = 0.3185x + 0.1725	0.21
Normal	0-1000		y = -0.0125x + 3.1001	0.0003
	1000-4000		y = -0.0212x + 0.6016	0.08
	4000-8000		y = 0.024x + 0.013	0.21
Log	0-1000	Binder	y = 0.105x + 0.3481	0.15
	1000-4000		y = -0.0061x + 1.9775	0.0002
	4000-8000		y = -0.6841x + 8.6716	0.09
Normal	0-1000		y = 0.21x + 0.6962	0.15
	1000-4000		y = -0.0012x + 0.3969	0.0002
	4000-8000		y = 0.003x + 0.1524	0.009

[a] "x" is slope of gyratory compaction curve

Voids in Mineral Aggregates (VMA) versus Rut Depth

Rut depth data and VMA data of the different mixes are shown in Figure 1. In general, for granite and limestone, there is an increase in rut depth with an increase in VMA. In case of gravel, the trend is reverse - there is a decrease in rut depth with an increase in VMA. At this time the difference in behavior cannot be explained.

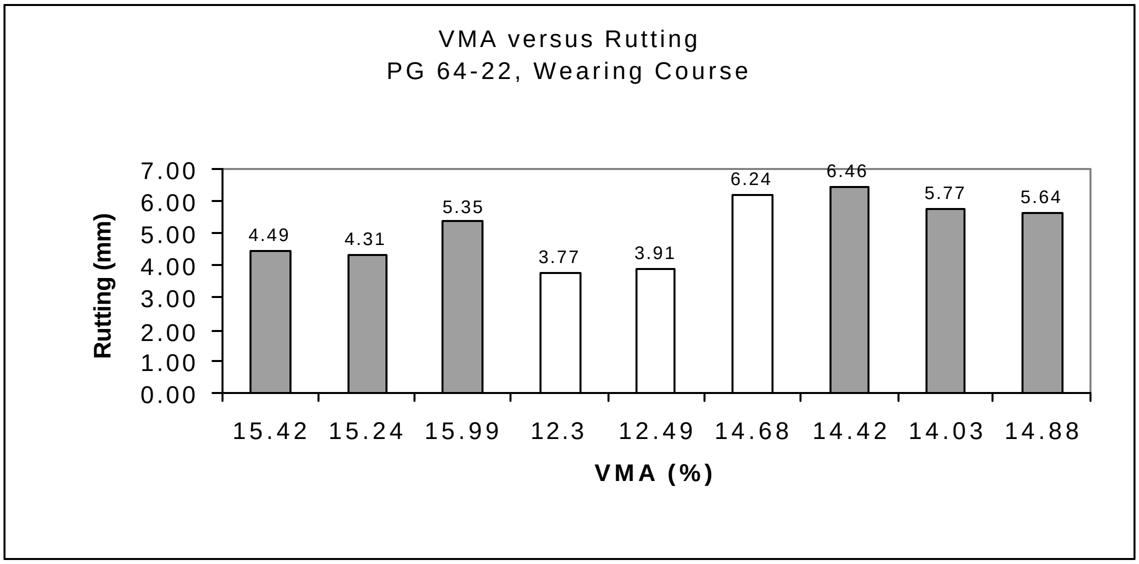

Figure 1. Plot of VMA versus Rutting for PG 64-22, Wearing Course Mixes

Table 17. RSCH Peak Shear Strain for Different Mixes

Course	Aggregate	Gradation	Strain		Average Strain
			Sample 1	Sample 2	
Wearing	Granite	ARZ	0.02676	0.01795	0.022355
		TRZ	0.01892	0.0251	0.02201
		BRZ	0.02294	0.02614	0.02454
	Limestone	ARZ	0.03824	0.03437	0.036305
		TRZ	0.00954	0.0291	0.01932
		BRZ	0.0511	--	0.0511
	Gravel	ARZ	0.07194	--	0.07194
		TRZ	0.04932	0.05166	0.05049
		BRZ	0.05049	0.08057	0.06553
Binder	Granite	ARZ	0.0064	0.02084	0.01362
		TRZ	0.01269	0.02632	0.019505
		BRZ	0.0144	0.02322	0.01881
	Limestone	ARZ	0.0405	0.02379	0.032145
		TRZ	0.03399	0.0445	0.039245
		BRZ	0.04854	0.07685	0.062695
	Gravel	ARZ	0.07154	0.06071	0.066125
		TRZ	0.03779	--	0.03779
		BRZ	0.03634	0.07214	0.05424

Comparison of results from tests with Superpave Shear Tester (SST) and APA

Table 17 shows the results of tests with RSCH. The average peak strain values show that according to the SST test, for wearing course, the TRZ mixes show the lowest rutting potential. Figure 2 shows a comparison of results from RSCH and APA test. The data shows a fair correlation (R^2= 0.62), which indicates that the RSCH and the APA rut tests have characterized the mixes in the same way. The binder course data (Figure 3) shows a slightly better correlation (R^2 = 0.69).

Table 18 shows the results from tests with RSCSR. The peak shear strain values indicate that TRZ mixes are not always the ones with the minimum rutting potential - in fact, in the case of granite wearing course TRZ mix shows the highest peak strain. Figures 4 and 5 show comparison of result from RSCSR amd APA test, for wearing and binder courses, respectively. Both correlations are relatively poor (R^2 = 0.55, 0.44, respectively) compared to RSCH, indicating that the RSCSR test does not compare well with the APA test.

Comparison of In-Place Rutting and Results From Tests With APA

The properties of the in-place mixes from I-85 are shown in Table 19. Table 20 shows the rut depths, as obtained from the tests with the APA, and the in-place rut depths for each mix. The good performing mix (A) shows the least amount of rutting from tests with APA. However, the poor performing mix (C) shows slightly less APA rutting compared to the fair (B) performing mix. This discrepancy may have resulted due to the following reasons: (a) although all three HMA sections are on the same interstate I-85, they were placed in different years and, therefore, have aged to different degrees; (b) the sections have been subjected to different amounts of ESALs; and (c) some rutting may

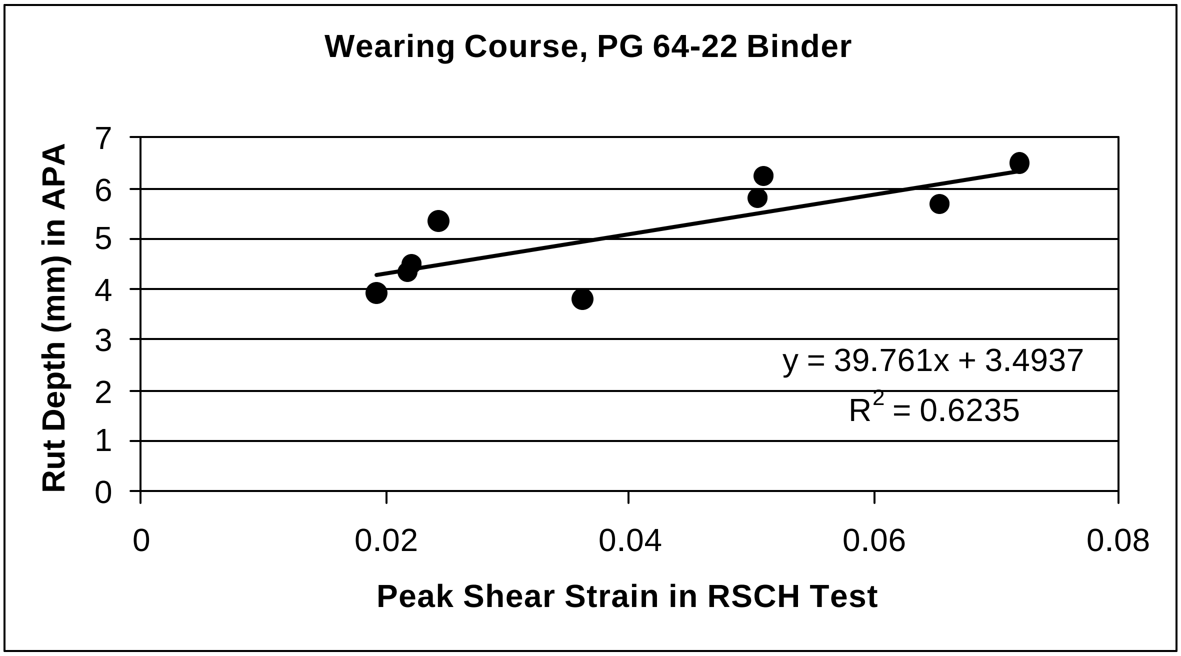

Figure 2. Plot of Peak Shear Strain in RSCH Test versus Rut Depth in APA for Wearing Course with PG 64-22 Binder

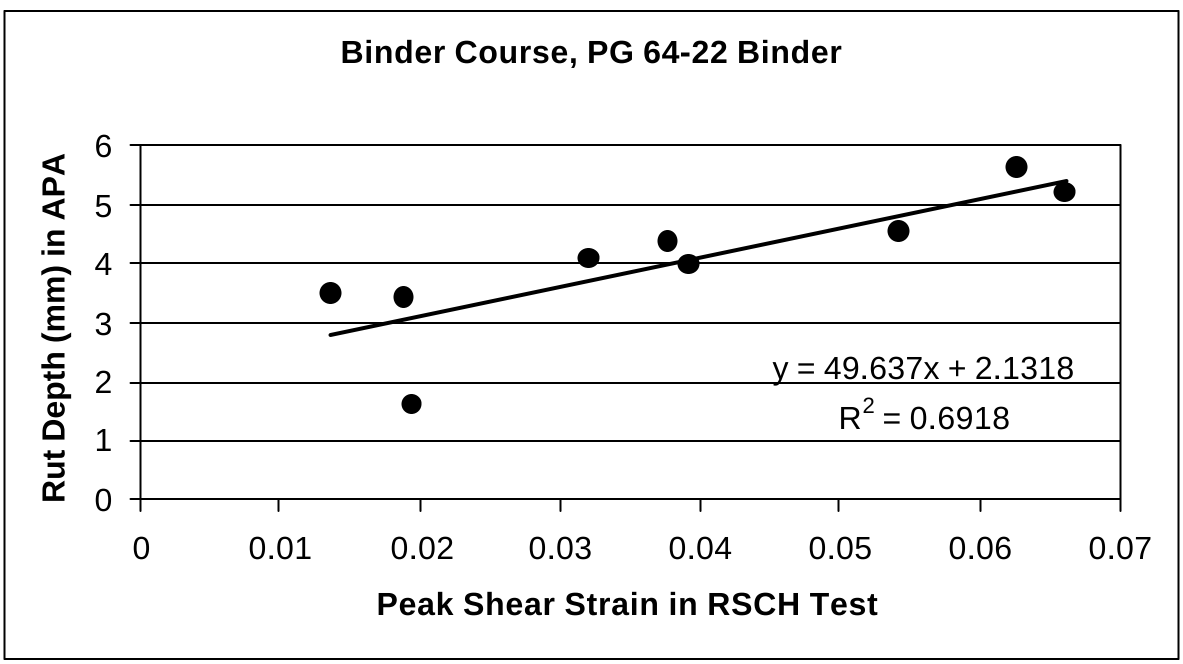

Figure 3. Plot of Peak Shear Strain in RSCH Test versus Rut Depth in APA for Binder Course with PG 64-22 Binder

Table 18. RSCSR Peak Shear Strain for Different Mixes

Course	Aggregate	Gradation	Strain		Average Strain
			Sample 1	Sample 2	
Wearing	Granite	ARZ	0.0288	0.03814	0.03347
		TRZ	0.03417	--	0.03417
		BRZ	0.02183	0.03188	0.026855
	Limestone	ARZ	0.02504	0.0429	0.03397
		TRZ	0.0309	0.05407	0.042485
		BRZ	0.04453	0.07859	0.06156
	Gravel	ARZ	--	0.08948	0.08948
		TRZ	0.03893	0.08232	0.060625
		BRZ	--	0.08457	0.08457
Binder	Granite	ARZ	0.01531	0.02651	0.02091
		TRZ	0.01966	0.02218	0.02092
		BRZ	0.0168	0.01761	0.017205
	Limestone	ARZ	0.02908	0.04326	0.03617
		TRZ	0.02537	0.04491	0.03514
		BRZ	0.04772	0.07686	0.06229
	Gravel	ARZ	0.03323	0.03655	0.03489
		TRZ	0.02024	0.01649	0.018365
		BRZ	0.03062	0.07929	0.054955

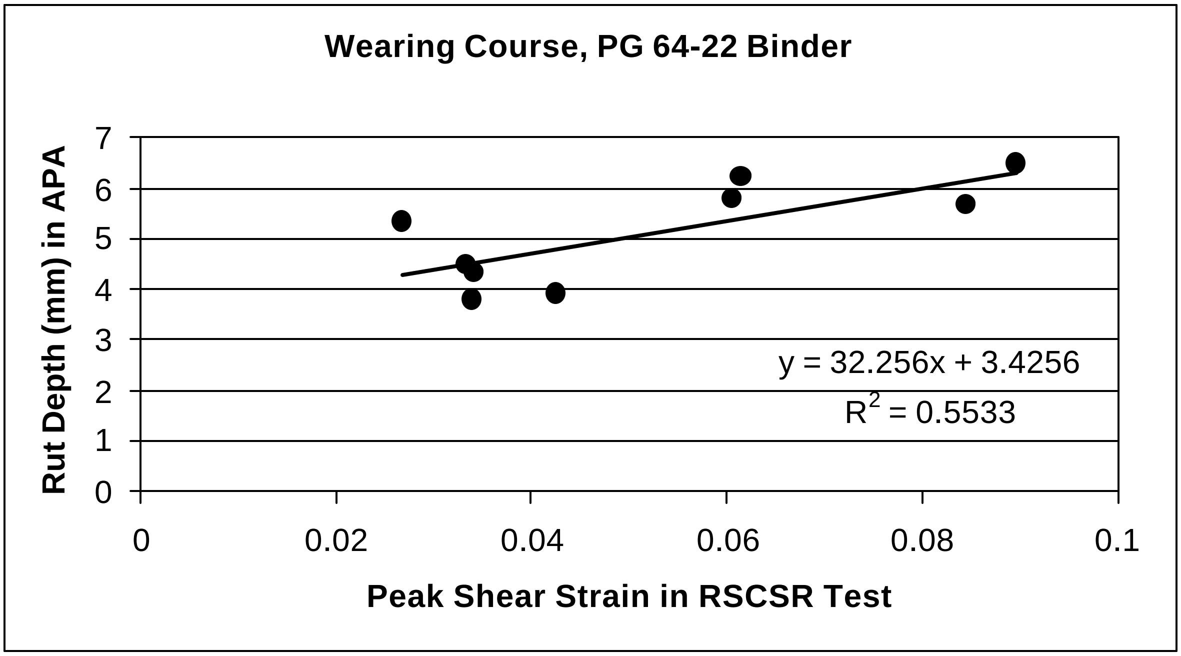

Figure 4. Plot of Peak Shear Strain in RSCSR Test versus Rut Depth in APA for Wearing Course with PG 64-22 Binder

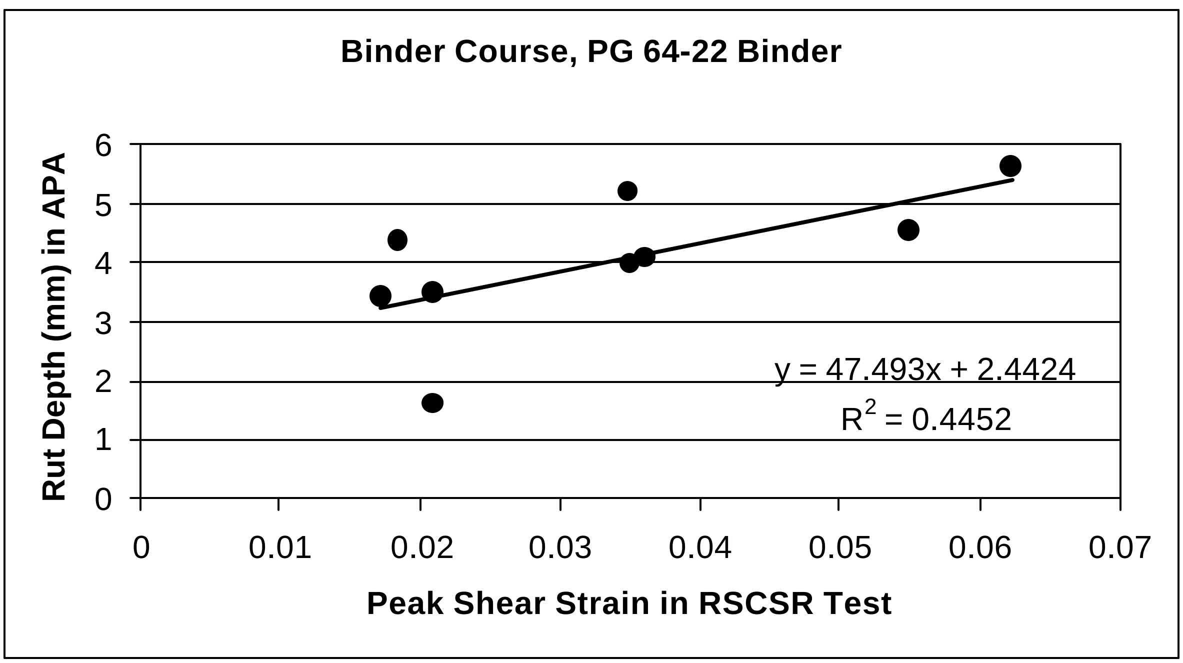

Figure 5. Plot of Peak Shear Strain in RSCSR Test versus Rut Depth in APA for Binder Course with PG 64-22 Binder

Table 19. Properties of Mixes A, B, and C (In-Place)

Property	Mix		
	A (Good)	B (Fair)	C (Poor)
Voids in Total Mix (%)	5.61	4.38	3.08
Asphalt Content	5	5.6	6
TMD	2.493	2.452	2.454
Gradation			
% Passing			
25 mm		100	
19.5 mm	100	98.6	100
12.5 mm	85.9	87.5	86.3
9.5 mm	75.2	77.9	75.8
4.75 mm	60.5	63.4	61.3
2.36 mm	44.1	52.6	49.7
1.18 mm	33.5	44.7	41.9
0.600 mm	23.3	29.9	28.4
0.300 mm	13.9	15.3	15.3
0.150 mm	7.9	7.9	8.4
0.075 mm	4.6	4.8	5.2

Table 20. In-Place Rutting and Results from Tests with APA

Mix	Rutting with APA (mm)							
	Samples							
	1	2	3	4	5	6	Average	In-Place Rutting (mm)
A	1.66	0.87	1.42	1.28	1.54	1.19	1.33	0.00
B	6.23	5.45	6.43	6.00	5.86	4.75	5.79	6.00
C	4.09	4.51	6.7	4.95	3.44	3.34	4.50	12.5

have been contributed by the underlying HMA courses which were not tested by the APT.

There is insufficient data in this study to establish a rut depth criteria. However, based on the borderline performance of Sections B and C and specifications used by some DOTs, a tentative criteria of 4.5 - 5.0 mm rut depth after 8,000 cycles appears reasonable. However, more field sections should be tested to confirm this criteria.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The asphalt pavement analyzer (APA) is sensitive to aggregate gradation based on statistical significance of differences in rut depths. In case of granite and limestone mixes the gradation below the restricted zone showed highest amount of rutting whereas the gradation through the restricted zone generally showed lowest rut depth. However, in case of gravel mixes, the gradation below the restricted zone showed the least amount of rutting whereas the gradation above the zone showed highest amount of rutting.
2. The APA was also found to be sensitive to the asphalt binder PG grade based on statistical significance of differences in rut depths. The rut depths of mixes with PG 58-22 asphalt binder (tested at 58EC) were higher than those of mixes with PG 64-22 asphalt binder (tested at 64EC). This resulted from relatively lower G*/sin* value of PG 58-22 compared to G*/sin* of PG 64-22.
3. Mixes meeting $N_{initial}$ and N_{max} criteria did not necessarily show less rutting potential than mixes which did not meet these criteria.

4. No correlation could be established between APA rut depths and the gyratory compaction slopes (between $N_{initial}$ and N_{design}) of all mixes.
5. In case of granite and limestone wearing course mixes, the APA rut depth increased with an increase in asphalt film thickness. However, an opposite effect was observed in case of gravel wearing course mixes, and binder course mixes containing granite and limestone.
6. The APA had a fair correlation (R^2=0.62) with the repeated shear constant height (RSCH) test conducted with the Superpave shear tester. Both tests characterized the mixes in the same way.
7. It appears from this study that the APA has a potential to predict the relative rutting potential of hot mix asphalt mixes.
8. Based on very limited data, it appears that the APA rut depth after 8000 passes should be less than 4.5 - 5.0 mm to minimize rutting in the field. However, more field test sections need to be evaluated to establish this criteria.

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