NCAT Report 02-07

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ABSTRACT

Rutting has long been a problem in hot mix asphalt (HMA) pavement. Through the years, researchers have used different kinds of fundamental and simulative test methods to estimate the rutting performance of HMA.

It has been recognized that most fundamental tests are very complex while simulative tests are generally easy to perform. This paper documents a comparative study of two relatively fundamental tests, repeated shear at constant height (RSCH) and repeated load confined creep test (RLCC), and one simulative test, Asphalt Pavement Analyzer (APA) rut test. A comparison and correlation of various parameters (permanent deformation or strain, slopes and intercepts from linear or power law regressions) from these three tests results were conducted in this paper.

The analysis data showed that the two fundamental tests had significant correlation with APA rut tests. The relationship between the deformation rates and the correlation between initial deformation from the RSCH and RLCC indicate the similar deformation behavior of HMAs under RSCH and APA loading conditions.

Based upon the relationships observed in this paper and the existing guidelines for interpreting RSCH permanent shear strain and RLCC permanent strain, preliminary guidelines were recommended for evaluating rut resistance on the basis of APA rut depth. Compared with the existing APA criteria developed by Georgia DOT, the acceptable rut depth criteria generated from this paper is reasonable and applicable.

KEY WORDS: Hot mix asphalt, asphalt pavement, asphalt mixture, permanent deformation, rutting, creep test, repeated shear, Asphalt Pavement Analyzer

COMPARISON OF FUNDAMENTAL AND SIMULATIVE TEST METHODS FOR EVALUATING PERMANENT DEFORMATION OF HOT MIX ASPHAlt

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INTRODUCTION

Permanent deformation (rutting) is a prevalent form of pavement distress on the national highway system. Researchers have used different fundamental tests, empirical tests and simulative tests to evaluate the rutting potential of HMA. In fundamental tests, unconfined and confined cylindrical specimens in creep, repeated, or dynamic loading; cylindrical specimens in diametral creep or repeated loading; Superpave Shear Tester (SST) repeated shear at constant height test, shear modulus test, Quasi-Direct Shear and shear strength tests have been used. In empirical tests, Marshall and Hveem tests were used. In simulative tests, Georgia Loaded Wheel Tester, Asphalt Pavement Analyzer, Hamburg Wheel Tracking Device, LCPC Wheel Tracker, Purdue University Laboratory Wheel Tracking Device, Nottingham pavement testing facility and Model Mobile Load Simulator are being used (*1*, *2*).

Since the Superpave mixture design and analysis system was developed under the Strategic Highway Research Program (SHRP), many highway agencies in the United States have adopted the volumetric mixture design method. However, there is no current strength test to compliment the volumetric mixture design method. Industry representatives interviewed by Witczak (*3*) showed their concern that rutting was the most important distress type to be considered to supplement the Superpave volumetric mixture design procedure. For these reasons, most Superpave mix designers are considering the addition of a torture test to evaluate the rutting potential of an asphalt mixture.

It has been recognized that the fundamental tests are very complex while simulative tests are relatively easy to perform. So this paper has been prepared based upon a comparative study of two fundamental and one simulative tests.

TEST METHODS

Asphalt Pavement Analyzer

The Asphalt Pavement Analyzer, first manufactured in 1996 by Pavement Technology, Inc, is an automated, new generation of Georgia Load Wheel Tester (GLWT). The APA has been used to evaluate rutting, fatigue, and moisture resistance of HMA mixtures.

In this paper, testing with the APA was conducted according to the Georgia Department of Transportation method GDT-115, Method of Test for Determining Rutting Susceptibility Using the Load Wheel Tester (*4*). However, there was one deviation from GDT-115, instead of 50°C, tests were carried out at 64°C. This temperature corresponds to the high temperature of the standard performance grade for most project locations within the southeast. The air void content of test specimens was 6.0±0.5 percent. Hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively. Testing was carried out to 8,000 cycles and rut depths were measured continuously. Rut depths were also measured manually after 8,000 cycles.

Repeated Shear at Constant Height

In 1987, the SHRP began a five year, $50 million dollar study to address and provide solutions to the performance problems observed in HMA pavements (5). As an important procedure for Superpave volumetric mix analysis system, the Superpave repeated shear at constant height test, using the Superpave Shear Tester (SST), was used to evaluate the rutting resistance of HMA mixtures. As outlined in the AASHTO TP7-98 (6), test procedure F, the RSCH test consists of applying a repeated haversine shear stress of 68kPa (0.1 second load, 0.6 second rest) to a compacted HMA (150 mm diameter by 50 mm height) specimen while supplying necessary axial stress to maintain a constant height. The test is performed either to 5000 load cycles or until five percent permanent strain is incurred by the sample. Permanent strain is measured as the response variable at certain interval load cycles throughout the test and recorded using LVDTs and a computerized data acquisition system.

All test specimens for RSCH testing were fabricated at 3.0±0.5 percent air voids to the required dimensions and tested at 50°C. This test temperature was selected as per test protocol because it is the effective temperature for permanent deformation (T_{eff} - PD) for the southeast and is believed to be critical for inducing rutting in HMA pavements. The RSCH was performed to 5000 load cycles. The peak and valley of shear strain were recorded at periodic cycles.

Repeated Load Confined Creep Test

The repeated load confined creep test (RLCC) has been successfully used in the past by NCAT (7, 8). It is considered to be a fundamental experimental method to characterize the rutting potential of HMA, since fundamental creep principles can be applied to deformation of viscoelastic mixes. A Material Test System (MTS) was used to conduct this test. A deviator stress along with a confining stress is applied on a HMA sample for 1 hour (3600 load cycles), with 0.1 second load duration and 0.9 second rest period intervals. After the 3600 load cycles, the load is removed and the rebound measured for 15 minutes. The strain observed at the end of this period is reported as the permanent strain. The permanent strain indicates the rutting potential of the mixtures. The target air void content for mixtures tested by the confined repeated load test was 4.0±0.5 percent in accordance with earlier studies (7, 8). The test temperature was 60°C. Test loading consisted of a 138 kPa (20 psi) confining pressure and an 827 kPa (120 psi) normal pressure.

It is obvious different air voids in the compacted HMA specimens and different test temperatures were used in the proceeding three tests so as to utilize the respective test protocol and test criteria used in the past.

OBJECTIVE

The primary objective of this paper was to make comparisons of two relatively fundamental and one simulative tests for determining the permanent deformation of hot mix asphalt mixtures.

Based upon the comparison results and the existing guidelines for interpreting RSCH shear strain and RLCC permanent strain, the secondary objective of this paper was to recommend critical APA rut depths.

MIXTURES USED

Material needed for this study consisted of coarse aggregates, fine aggregates, and an asphalt binder. Two coarse aggregates, seven fine aggregates, and an asphalt binder were selected.

The following sections describe properties of the selected materials, gradations, and the Superpave volumetric mix design parameters.

Coarse Aggregates

Two coarse aggregates were used in this study. Selection criteria for these two coarse aggregates were that they should come from different mineralogical types and have different angularities and surface textures. This was done to ensure that the coarse aggregates gave a range of properties. Selected coarse aggregates were a quarried granite and a crushed siliceous gravel.

Fine Aggregates

The shape and texture of the fine aggregates are the most important factors affecting the rutting performance of HMA mixtures. Therefore, the approach taken in identifying and selecting fine aggregates for use in this study was to select aggregates of different mineralogical types and varying values of fine aggregate angularity (FAA). These aggregates were also used in NCHRP Project 9-14 (The Restricted Zone in Superpave Aggregate Gradation Specification).

The seven selected fine aggregates were numbered FA-2, FA-3, FA-4, FA-6, FA-7, FA-9 and FA-10. Their mineralogical type and FAA value (AASHTO T304) are shown below:

FA-2, No processing, natural quartz sand with some chert, from Tennessee, FAA=42.6;
FA-3, Uncrushed, natural quartz sand with some chert, from Alabama, FAA=44.1;
FA-4, Mined sandstone, cone crusher, from Alabama, FAA=49.7;
FA-6, Mined limestone, crushed by impact crusher, from Alabama, FAA=46.9;
FA-7, Mined granite, cone crusher, from Minnesota, used on MnRoad, FAA=48.9;
FA-9, Mined diabase, impact crusher, from Virginia, FAA=50.1;
FA-10, Natural sand, dredged stream deposit from Mississippi, FAA=38.6.

It is obvious the fine aggregates ranged from very rounded (FAA=38.6) to very angular (FAA=50.1)

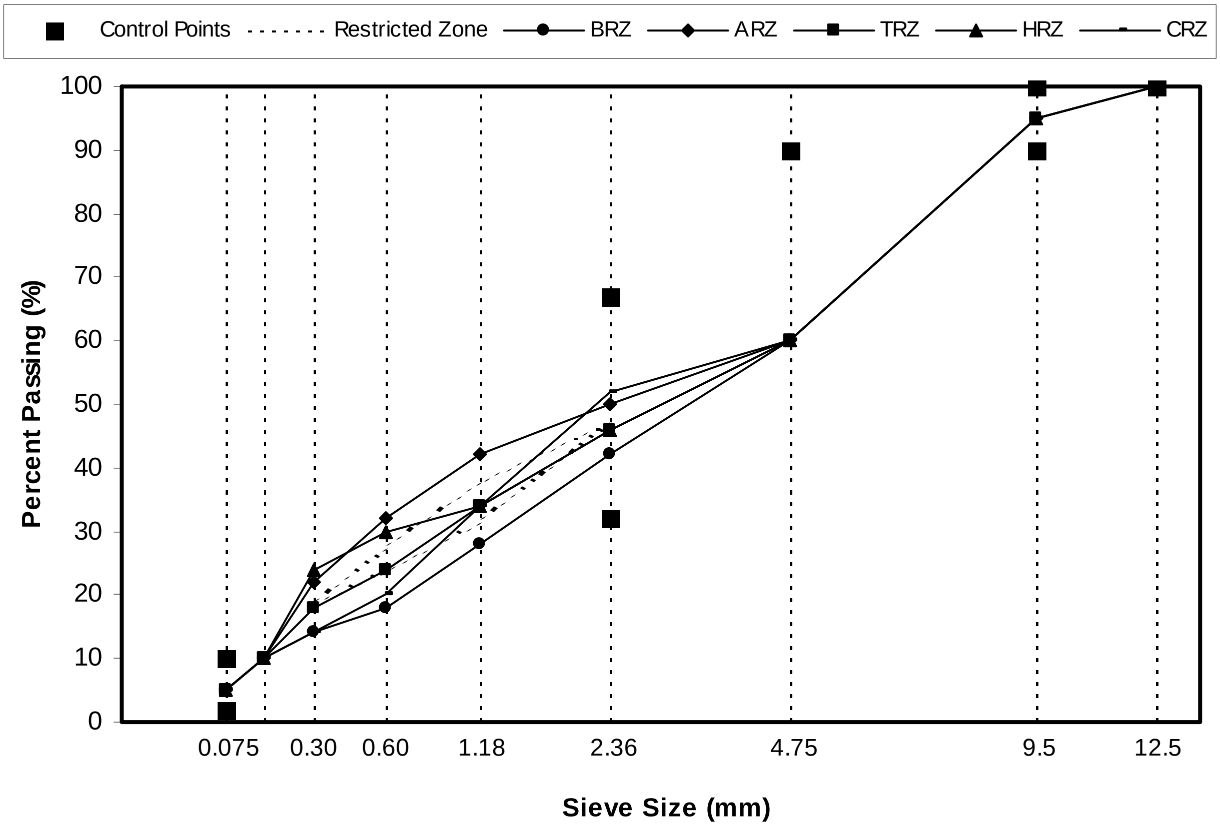

Figure 1. BRZ, ARZ, TRZ, HRZ, and CRZ Gradations NMAS = 9.5 mm

Asphalt Binder

The asphalt binder selected for this study was a Superpave performance-based PG 64-22, which is one of the most commonly used grades in the United States. This binder was unmodified, and is one of the NCAT lab stock asphalt binders and has been used on numerous research projects with success.

Gradations

As shown in Figure 1, five 9.5 mm NMAS gradations follow the same trend from the 12.5 mm sieve down to the 4.75 mm sieve. From the 4.75 mm sieve, the BRZ (below the restricted zone) gradation passes below the restricted zone and above the lower control points. The ARZ (above the restricted zone) gradations pass above the restricted zone and below the upper control points. From the 4.75 mm sieve, the TRZ (through the restricted zone) gradation passes almost directly along the maximum density line. The HRZ (humped through the restricted zone) gradation follows a similar gradation as the TRZ gradation down to the 1.18 mm sieve where it humps on the 0.6 and 0.3 mm sieves and represents gradations generally containing a large percentage of natural, wind blown sands. From the 4.75 mm sieve, the CRZ gradation begins above the restricted zone on the 2.36 mm sieve but then crosses through the restricted zone between the 0.6

and 0.3 mm sieves. The CRZ (cross-over the restricted zone) gradation represents gradations which are not continuously graded between 2.36 mm and 0.60 mm sizes and have generally exhibited low mix stability. All five of the gradations then meet at the 0.15 mm sieve and follow the same trend down to the 0.075 mm sieve. All the gradations used the same passing 0.075 mm sieve (No.200)-P200 material to eliminate P200 as a variable.

Superpave Mix Design Parameters

Table 1 shows a summary of mix designs for the mixes. The compactive efforts used in the mixes with N-design = 75, 100, 125 were for 0.3-3 million ESALs, 3-30 million ESALs, and ≥30 million ESALs, respectively. Optimum asphalt content for all mixes was defined as the asphalt content providing 4.0 percent air voids.

TEST RESULTS AND ANALYSIS

Asphalt Pavement Analyzer Test Results

This section presents the performance of the various mixtures in the Asphalt Pavement Analyzer. Forty-one mixtures were tested under the previously described procedure using the APA. In addition to measuring final rut depths manually, rut depths for 17 mixes were recorded automatically at every load cycle. Typical data (Figure 2) shows that specimens deform rapidly at beginning of the test. The amount of permanent deformation per cycle decreases and becomes linear after a certain number of load cycles. During the linear region, the development of the rut depth as a function of the wheel load counts can be described, as $RD = k_0 n + b_0$

Where,

RD= Rut depth (mm);
n = wheel load counts (loading cycles);
k_0, b_0 = regression coefficients.

Table 1. Summary of Mix Design

Mixture I.D. Fine Agg.	Gradation/Coarse Agg.	N_{design}	VMA %	VFA %	G_{mm} @ N_{ini} %	Opt. Asphalt Content %
FA-2	TRZ Granite	75	16.3	75.5	90.4	5.7
FA-3	BRZ Granite	75	15.9	74.8	89.8	5.4
FA-3	CRZ Granite	75	15.9	74.8	90.3	5.6
FA-4	TRZ Granite	75	16.3	75.5	87.5	5.7
FA-6	BRZ Granite	75	15.9	74.8	86.4	5.8
FA-6	CRZ Granite	75	16.0	75.0	86.5	5.9
FA-7	TRZ Granite	75	16.8	76.2	88.7	6.0
FA-10	HRZ Granite	75	13.8*	71.0	90.6*	4.5
FA-4	TRZ Granite	125	16.5	75.8	88.4	5.8
FA-4	BRZ Granite	125	16.7	76.0	86.2	5.9
FA-4	CRZ Granite	125	16.9	76.3*	87.8	6.1
FA-7	TRZ Granite	125	15.7	74.5	88.8	5.5
FA-7	BRZ Granite	125	16.53	75.8	87.9	5.8
FA-7	CRZ Granite	125	16.8	76.2*	88.2	6.0
FA-9	TRZ Granite	125	15.6	74.4	88.9	5.5
FA-9	BRZ Granite	125	16.6	75.9	86.4	5.8
FA-10	HRZ Granite	125	12.6*	68.3*	89.5*	3.6
FA-10	HRZ Granite	100	13.1*	69.5*	91.5*	4.2
FA-10	HRZ Gravel	100	12.8*	68.8*	91.4*	4.0
FA-6	BRZ Granite	100	14.1*	71.6*	85.4	5.3
FA-6	ARZ Granite	100	14.2*	71.8*	87.8	5.3
FA-6	TRZ Granite	100	13.4*	70.1*	86.7	5.0
FA-6	CRZ Granite	100	14.8*	73.0	87.4	5.7
FA-7	BRZ Granite	100	16.8	76.2*	86.9	6.0
FA-7	TRZ Granite	100	16.1	75.2	88.3	5.7
FA-7	BRZ Gravel	100	15.1	73.5	87.6	5.4
FA-7	CRZ Gravel	100	15.7	74.5	88.3	5.6
FA-4	BRZ Granite	100	16.9	76.3*	85.8	6.0
FA-4	ARZ Granite	100	16.8	76.2*	88.7	6.1
FA-4	TRZ Granite	100	16.4	75.6	88.6	5.8
FA-4	CRZ Granite	100	17.0	76.5*	87.9	6.2
FA-4	BRZ Gravel	100	15.8	74.7	87.0	5.6
FA-4	ARZ Gravel	100	16.2	75.3	89.0	5.7
FA-4	TRZ Gravel	100	15.2	73.7	88.4	5.3
FA-4	CRZ Gravel	100	15.9	74.8	86.8	5.6
FA-9	ARZ Granite	100	16.6	75.9	88.6	5.7
FA-9	TRZ Granite	100	16.2	75.3	87.2	5.6
FA-9	BRZ Gravel	100	16.7	76.0	88.4	6.0
FA-9	ARZ Gravel	100	15.7	74.5	87.8	5.5
FA-9	TRZ Gravel	100	15.3	73.8	87.8	5.3
FA-9	CRZ Gravel	100	16.2	75.3	86.8	5.7

* Properties did not meet Superpave volumetric requirement

The APA rut test results for all 41 mixtures are presented in Table 2.

Table 2. APA, RSCH and RLCC Test Results

Mixture I.D.		N_{des}	APA Rut (mm)	Slope $k_0\times10^{-4}$	intercept b_0	RSCH Strain (%)	y=kx+b $k_1\times10^{-6}$	$b_1\times10^{-2}$	y=ax^b $a_2\times10^{-3}$	b_2	RLCC Strain (%)
FA-2	TRZ Granite	75	15.15	3.80	9.24	6.47	8.03	2.69	2.72	0.37	17.90
FA-3	BRZ Granite	75	18.57	4.63	9.70	3.92	4.16	1.89	1.93	0.35	**
FA-3	CRZ Granite	75	17.39	4.05	10.19	8.01	11.69	2.36	2.54	0.39	**
FA-4	TRZ Granite	75	8.45	2.42	3.94	1.18	0.51	0.93	1.05	0.30	11.13
FA-6	BRZ Granite	75	7.33	2.65	4.39	2.89	1.18	2.26	3.66	0.25	7.35
FA-6	CRZ Granite	75	7.25	2.66	-	2.54	1.10	2.00	2.71	0.28	6.63
FA-7	TRZ Granite	75	10.25	3.92	5.28	2.71	1.69	1.43	1.93	0.32	8.81
FA-10	HRZ Granite	75	16.01	4.31	8.63	5.41	6.11	2.30	2.34	0.36	37.04
FA-4	TRZ Granite	125	8.13	2.44	4.12	1.64	0.83	1.24	1.32	0.31	7.70
FA-4	BRZ Granite	125	8.31	2.38	4.41	1.71	0.81	1.31	1.63	0.29	7.07
FA-4	CRZ Granite	125	8.95	3.10	4.05	1.97	0.88	1.54	1.93	0.28	10.75
FA-7	TRZ Granite	125	8.15	2.96	3.97	1.41	0.70	1.06	1.48	0.30	6.36
FA-7	BRZ Granite	125	8.65	2.74	4.28	1.82	0.79	1.43	2.08	0.27	6.43
FA-7	CRZ Granite	125	9.64	3.52	3.16	1.61	0.62	1.31	2.03	0.25	10.37
FA-9	TRZ Granite	125	9.08	3.05	4.29	1.58	0.62	1.29	2.02	0.25	4.60
FA-9	BRZ Granite	125	8.32	3.11	4.03	1.71	0.82	1.33	1.80	0.28	3.27
FA-10	HRZ Granite	125	10.51	2.74	5.75	2.64	1.39	1.97	1.76	0.33	24.80
FA-10	HRZ Granite	100	5.54	-	-	1.16	*	*	*	*	22.20
FA-10	HRZ Gravel	100	10.94	-	-	1.25	*	*	*	*	25.11
FA-6	BRZ Granite	100	4.82	-	-	1.11	*	*	*	*	3.19
FA-6	ARZ Granite	100	4.55	-	-	1.13	*	*	*	*	1.40
FA-6	TRZ Granite	100	4.31	-	-	0.94	*	*	*	*	1.80
FA-6	CRZ Granite	100	5.54	-	-	1.30	*	*	*	*	2.88
FA-7	BRZ Granite	100	4.62	-	-	1.59	*	*	*	*	3.75
FA-7	TRZ Granite	100	4.97	-	-	0.96	*	*	*	*	3.82
FA-7	BRZ Gravel	100	7.64	-	-	1.20	*	*	*	*	11.17
FA-7	CRZ Gravel	100	7.76	-	-	1.44	*	*	*	*	12.62
FA-4	BRZ Granite	100	7.84	-	-	1.33	*	*	*	*	8.79
FA-4	ARZ Granite	100	7.28	-	-	1.30	*	*	*	*	5.57
FA-4	TRZ Granite	100	7.06	-	-	1.36	*	*	*	*	3.93
FA-4	CRZ Granite	100	7.53	-	-	1.57	*	*	*	*	7.07
FA-4	BRZ Gravel	100	8.77	-	-	1.30	*	*	*	*	12.08
FA-4	ARZ Gravel	100	7.83	-	-	1.25	*	*	*	*	11.97
FA-4	TRZ Gravel	100	6.46	-	-	1.25	*	*	*	*	5.44
FA-4	CRZ Gravel	100	7.86	-	-	1.88	*	*	*	*	8.40
FA-9	ARZ Granite	100	5.12	-	-	0.92	*	*	*	*	0.83
FA-9	TRZ Granite	100	4.64	-	-	0.85	*	*	*	*	4.70
FA-9	BRZ Gravel	100	7.10	-	-	2.09	*	*	*	*	6.36
FA-9	ARZ Gravel	100	5.37	-	-	1.94	*	*	*	*	2.62
FA-9	TRZ Gravel	100	5.76	-	-	1.40	*	*	*	*	13.70
FA-9	CRZ Gravel	100	5.49	-	-	1.12	*	*	*	*	7.29

** Test specimens failed prior to 3,600 load repetitions.
- Rut depths were not recorded at each cycle.
* Data were not listed since there were no comparative data from continuous APA rut depths.

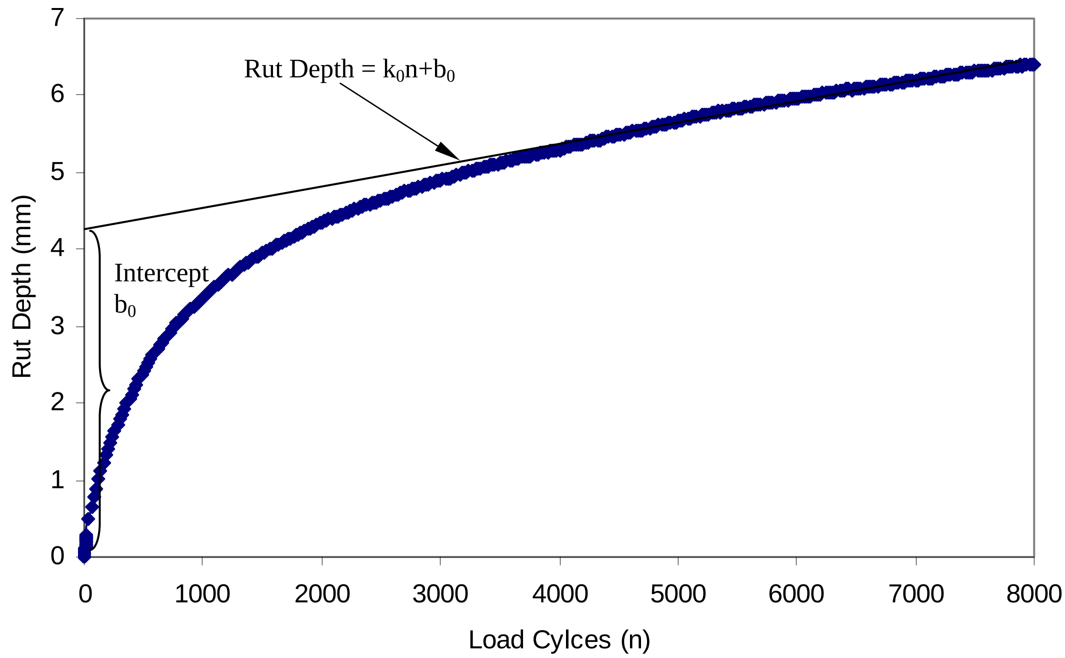

Figure 2. Typical APA Rut Depth versus Load Cycles

Table 3. Correlation Matrix among APA, RSCH and RLCC Parameters

Number R-Value P-value		APA			RSCH					RLCC
		Rut	*Slope k_0*	*Intercept b_0*	*Strain*	*y=kx+b k_1*	*y=kx+b b_1*	*y=ax^b a_2*	*y=ax^b b_2*	*Strain*
APA	*Rut* n=41	1								
	Slope k_0	0.877	1							
	n=17	0.000								
	Intercept b_0	0.964	0.776	1						
	n=16	0.000	0.000							
RSCH	*Strain*	0.827	0.680	0.919	1					
	n=41	0.000	0.003	0.000						
	y=kx+b k_1	0.848	0.541	0.487	0.983	1				
	n=17	0.000	0.025	0.056	0.000					
	y=kx+b b_1	0.618	0.488	0.789	0.848	0.745	1			
	n=17	0.008	0.047	0.000	0.000	0.000				
	y=ax^b a_2	0.183	0.231	0.363	0.507	0.382	0.779	1		
	n=17	0.482	0.373	0.166	0.038	0.131	0.000			
	y=ax^b b_2	0.851	0.645	0.897	0.837	0.858	0.585	0.020	1	
	n=17	0.000	0.005	0.000	0.000	0.000	0.000	0.939		
RLCC	*Strain*	0.725	0.553	0.760	0.541**	0.677	0.572	0.104	0.757	1
	n=39	0.000	0.033	0.002	0.000	0.006	0.026	0.713	0.001	

n = number of observations

The descriptions of variables shown in the table for APA rut tests are:

1. APA Rut - APA rut depth measured manually at 8,000 load cycles;
2. k_0 - regression coefficient from the linear regression, representing the slope of the rut deformation curve (automatic measurements);
3. b_0 - coefficient from the linear regression, representing the intercept of the rut depth deformation curve (automatic measurements).

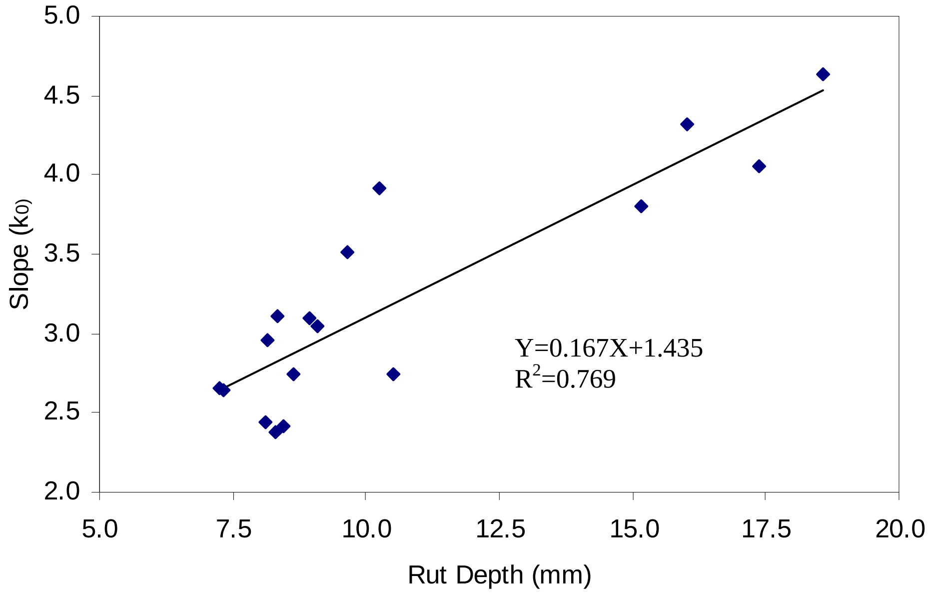

Figure 3. APA Rut Depth versus Slope k_0

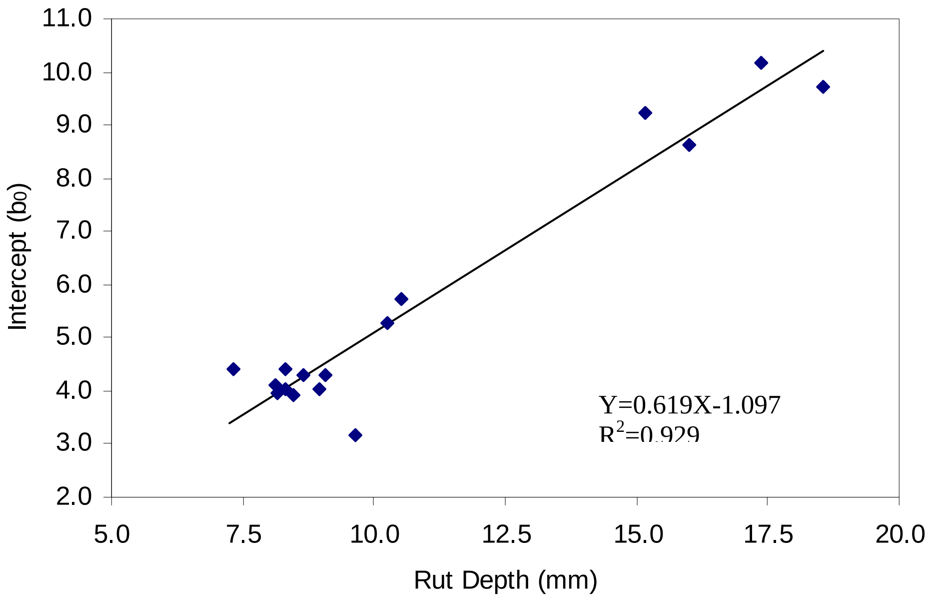

Figure 4. APA Rut Depth versus Intercept b_0

A correlation analysis was conducted to evaluate the relationships between total rut depth (manual), slope of rut depth versus cycles within the linear region (k_0), and the intercept of the rut depth deformation curve (b_0). Results of this analysis are presented in Table 3. Top and bottom numbers presented within each cell of Table 3 are the correlation coefficient (R) and the probability that the correlation does not exist (P). Probability values below 0.05 indicate a significant correlation at a level of significance of 95 percent.

As shown in Table 3, a strong correlation was found between the three properties (P values less than 0.05). Referring to Figure 2, these strong correlations were as expected. As indicated previously, 17 of the 41 mixes were recorded for rut depths at each load cycle. Hence, the initial deformation and the rate of deformation could be recovered from the original data file. As illustrated in Figure 3 and 4, the final rut depth is dependant on both the amount of initial deformation (strain) and the rate of deformation (strain) during the linear range of the deformation curve.

Repeated Shear at Constant Height

As stated previously, the Repeated Shear at Constant Height test was used to measure the resistance of HMA mixtures to permanent deformation. This section presents the performance of the various mixtures in the RSCH tests. Forty-one mixtures were tested. For each mixture, three to four replicates were tested and the average plastic strain was calculated at the completion of the 5000 shear load cycles. Figure 5 presents a percent typical plastic shear strain as a function of load. As shown in the figure, the permanent shear strain accumulates to a maximum at 5000 cycles (end of the test).

The curve indicates how the amount of accumulated permanent shear deformation increases with increasing load repetitions. The specimen deforms quite rapidly during the first several hundred loading cycles. The rate of unrecoverable deformation per cycle decreases and becomes linear for many cycles in the secondary region. At some number of loading cycles, the deformation begins to accelerate, leading towards failure in the tertiary portion of the curve. During the linear region, the development of the shear strain as a function of the shear load cycles can be described linearly (Figure 5), $\gamma_p = k_1 n + b_1$,

Where,

γ_p= permanent shear strain;
n = loading cycles at steady period;
k_1, b_1 = regression coefficients.

The development of the permanent shear strain as a function of loading also can be represented by the power law regression (9), yielding an equation of the form: $\gamma_p = a_2 n^{b_2}$.

Where,

γ_p = permanent shear strain;
n = loading cycles;
a_2, b_2 = regression coefficients.

Thus, the plastic strain versus the number of loading repetitions plotted on a log-log scale is linear, as shown in Figure 6.

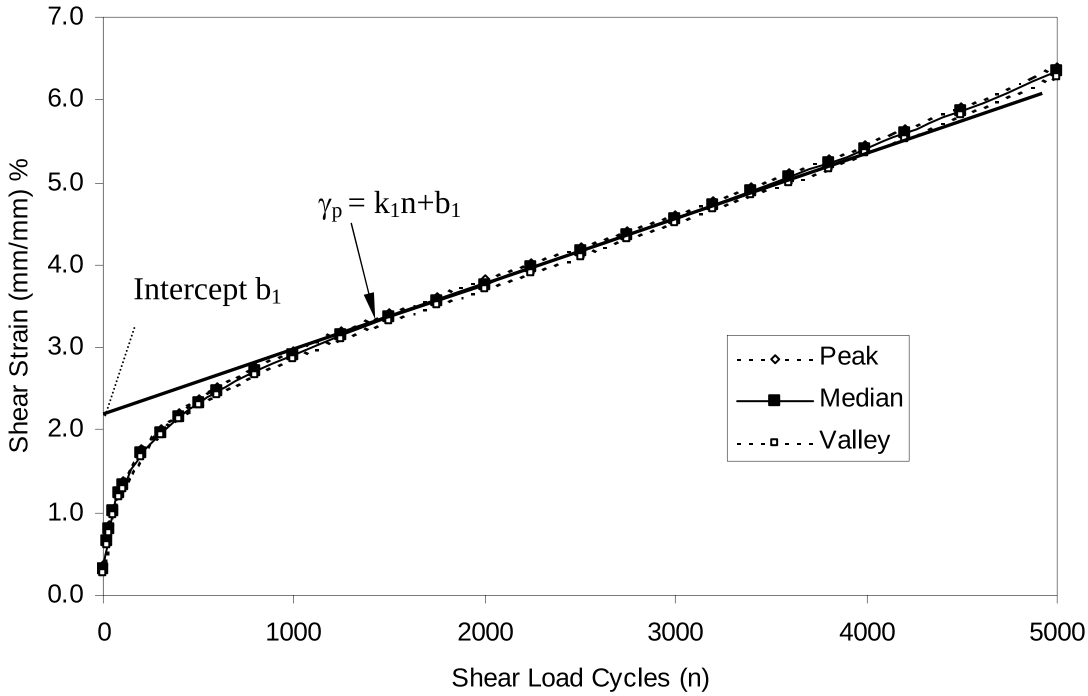

Figure 5. Typical RSCH Shear Strain versus Load Cycles

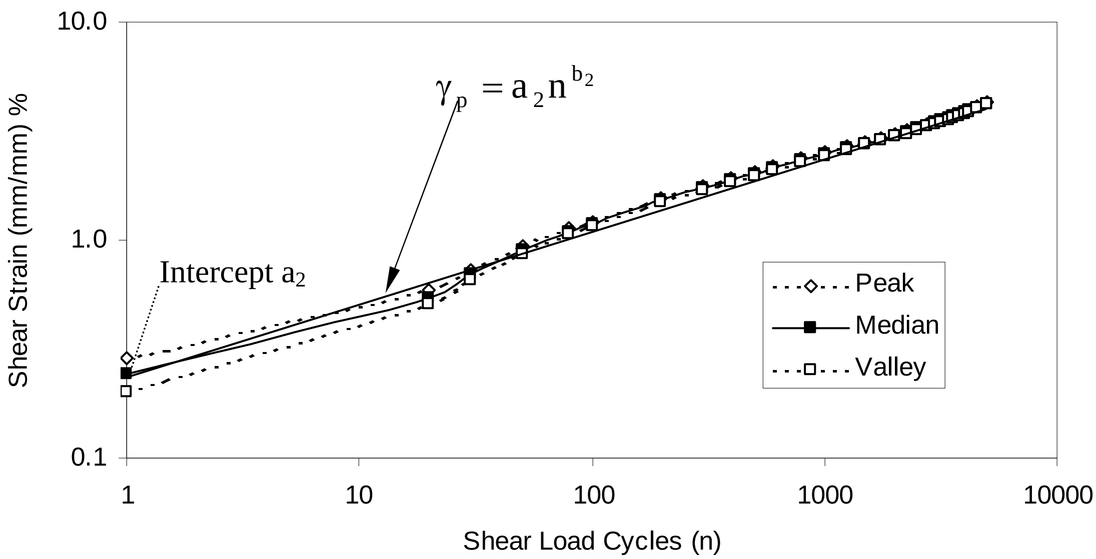

Figure 6. Typical Log RSCH Shear Strain versus Log Load Cycles

For comparison purpose, analysis on the deformation curve was conducted on the same 17 mixes with the analysis on the APA tests. A correlation matrix was developed among the five RSCH test parameters and is shown in Table 3. The correlation coefficients (R values) are the top numbers in each cell. The bottom numbers in each cell are the statistical significance levels (P values) corresponding to the correlation coefficients.

A similar correlation analysis as the APA data was conducted to evaluate the relationships between plastic shear strain form the RSCH and the regression coefficients described above. Table 3 also presents the results of this analysis. Based upon the correlation, it appears that the plastic shear strain is better defined by the linear relationship (k_1 and b_1) than the power law regression (a_2 and b_2). Interestingly, Figure 2 and Figure 5 indicate that the APA and RSCH data have similar deformation (strain) curves. Also, the linear regression coefficients are best correlated with the final deformation (strain).

Repeated Load Confined Creep Test (RLCC)

The repeated load confined creep test is a controlled-stress test that applies a constant axial load and a constant confining pressure. The haversine axial loading and unloading are applied at a frequency of 1 Hz for 1 hour. The permanent strain was reported after 15 minutes recovery period. Triplicates specimens were tested for the average permanent strain. Forty-one mixtures were tested under the previously described procedure. Table 2 (last column) shows the percentage of permanent strain for the different mixtures.

Relationship Between RSCH and RLCC and APA

Table 3 also presents results of a correlation analysis conducted on all variables for the APA, RSCH, and RLCC tests. Results indicate that the APA, RSCH, and RLCC data are well correlated. Correlation coefficients (R) are above 0.73 and P-values are all less than 0.001, which suggest significant relationships. It is interesting to note that significant relationships were found between the APA regression coefficients (k_0, b_0) and the RSCH regression coefficients (k_1, b_1).

Figure 7 illustrates the following relationships: APA rut depths versus RSCH shear strain and APA rut depths versus RLCC permanent strain. The R^2 values shown in Figure 7 were the square of the R-values on top of the cells in Table 3. For both relationships, the slope of the regression line is positive which indicates that increases in APA rut depth result in increases in strain (plastic or permanent). These results indicate that the two fundamental and one simulative tests are related. This accomplishes the primary objective of this study.

The secondary objective of this study was to utilize existing critical values of the two fundamental test procedures to recommend guidelines for critical rut depths in the APA. The literature has provided critical values for both the RSCH and RLCC test procedures. Bukowski and Harman (*10*) have suggested that plastic shear strains within the RSCH test of 2-3 percent are acceptable. Mixes with plastic shear strains above 3 percent are considered poor performing mixes while mixes with strains below 2 percent are mixes considered very rut resistant. Gabrielson (*7*) has indicated that permanent strain values within the RLCC test of 10-13 percent are acceptable.

These critical values for both tests have been superimposed onto Figure 7. Based upon the relationship between RSCH and APA results, a critical range for APA rut depth would be approximately 8.2 to 11.0 mm. For the RLCC critical values, the range of critical APA rut depth would be approximately 8.0 to 9.5 mm. Interestingly, there is an overlap in critical APA rut depth from the two fundamental tests of 8.2 to 9.5 mm. Therefore, a conservative value of 8.2 mm can be recommended for APA when tested at high temperature of the standard PG grade for a location.

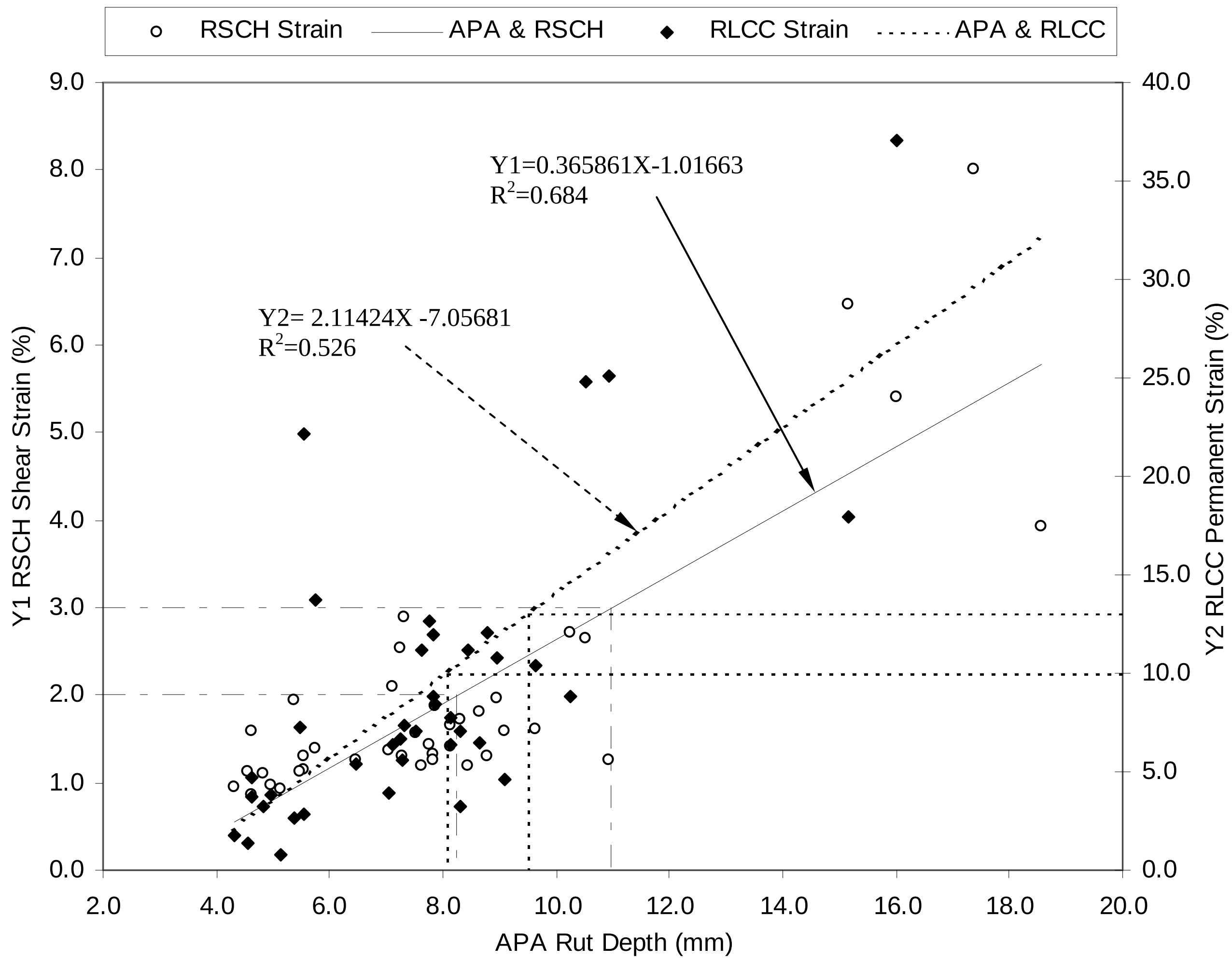

Figure 7. Correlations between APA and RSCH, RLCC

Based upon the established criteria for APA rut depths in Georgia and other states, this range in rut depths seems high. Georgia and others have long specified a maximum rut depth of 5 mm (*11*). However, the test temperature associated with this critical rut depth was 50°C. Recall that for this study a test temperature of 64°C was utilized. In 1997, Shami et. al. (*11*) presented a temperature-effect model to predict APA rut depth based upon testing conducted at a given test temperature and given number of cycles. Equation 1 presents the model:

$$\left[\frac{R}{R_0}\right] = \left[\frac{T}{T_0}\right]^{2.625} \left[\frac{N}{N_0}\right]^{0.276} \qquad \text{(Eq. 1)}$$

Where:

R = predicted rut depth;
R_0 = reference rut depth obtained at the reference test conditions T_0 and N_0;
T, N = temperature and number of load cycles the rut depth is sought;
T_0, N_0 = reference temperature and load cycles at the R_0.

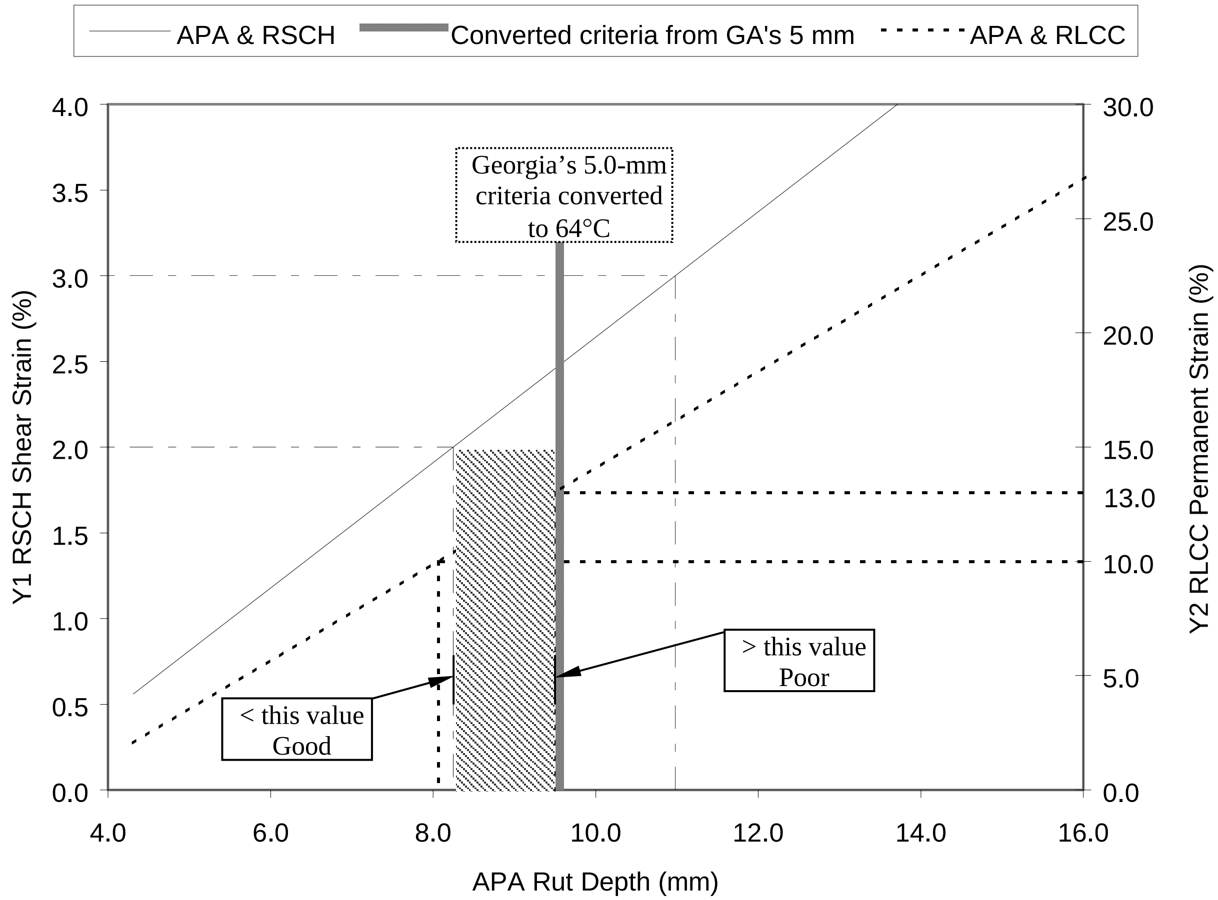

Figure 8. Recommended Criteria Compared with Georgia's Criterion

Table 4. Guideline for Evaluating Rut Resistance Using APA Rut Depth

RSCH=APA×0.365861-1.01663 R^2=0.684	RSCH Plastic Shear Strain (%)	Corresponding APA rut depth	APA Rut Depth Guidelines
	<2.0-Good >3.0-Poor	<8.245-Good >10.979-Poor	**<8.2-Good >9.5-Poor**
RLCC=APA×2.11424-7.05424 R^2=0.526	RLCC Permanent Strain (%)	Corresponding APA Rut Depth	
	<10.0-Good >13.0-Poor	<8.068-Good >9.486-Poor	
Georgia's Criterion and Temperature-effect Model: $[R/R_0] = [T/T_0]^{2.625}[N/N_0]^{0.276}$	APA @ 50°C 5.0 mm	APA @ 64°C 9.559 mm	**>9.6-Poor**

This temperature-effect model was used to convert Georgia's critical rut depth of 5-mm (R_0) at a temperature of 50°C (T_0) after 8,000 cycles (N_0) to a critical rut depth (R) at a test temperature of 64°C (T) after 8,000 cycles (N). Results of this model yield a critical rut depth of 9.56-mm for testing at 64°C. As shown in Figure 8 and Table 4, this value matches very well with the upper limit of the critical range of APA rut depths developed based upon the two fundamental tests.

CONCLUSIONS AND RECOMMENDATIONS

From the comparison and analysis in this study, the following conclusions can be drawn:

1. The three test methods, Asphalt Pavement Analyzer rut test, SST Repeated Shear at Constant Height, and Repeated Load Confined Creep test used in this study to evaluate permanent deformation have good correlations with each other.

2. The rut depth correlates well with the initial deformation. Mix has a higher deformation corresponds to a higher rut depth.

3. The initial shear deformation and the deformation in RSCH test for various mixes are different and they are correlated with the plastic shear strain in RSCH test. Mixes with higher initial shear strain and higher deformation rate have higher permanent shear strain.

4. The good correlation between slopes from RSCH and APA as well as the significant correlation between respective intercepts show the similar behavior for HMA mixtures under RSCH and APA test loading conditions.

5. Based upon the relationships developed between the APA and RSCH, the APA and RLCC, and critical values of the RSCH and RLCC, a range of critical rut depths in the APA was formulated. This range was verified with a temperature-effect model using Georgia's critical rut depth of 5-mm at 50°C. A critical rut depth of 8.2 mm for APA using the test methodology

described herein has been recommended at a test temperature corresponding to the high temperature of PG grading system determined for the project location.

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