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Advanced Characterization Testing of the Port Authority of NY/NJ's Hot Mix Asphalt Materials

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16. Abstract

The PANYNJ is moving towards performance-based evaluations of hot mix asphalt (HMA) to verify the cost new and innovative HMA mixes for use on the George Washington Bridge and on airports, such as Newark Liberty International. HMA mixes for the George Washington Bridge were evaluated using repeated load testing, the Asphalt Pavement Analyzer, Flexural Beam Fatigue, and Dynamic Modulus. The various mixes evaluated consisted of Epoxy-based HMA, asphalt-rubber HMA, Rosphalt (which is an asphalt rubber based mix), and a PG76-22 asphalt binder with fibers. Laboratory testing concluded that the Epoxy-based HMA provided excellent rutting and fatigue properties, however, the mix has a tendency "set-up" and cure at sometimes unpredictable times, thereby, not lending itself to traditional paving delays that occur. The Rosphalt mix performed almost as well as the Epoxy-based HMA, but without the "set-up" issues. All "innovative" HMA mixes tested outperformed the current in-place I-5 PG76-22 in both rutting and fatigue testing. Work conducted on the interface bond testing of HMA cores taken from Newark Liberty International Airport showed clearly showed that HMA with a granite-gneiss aggregate had lower repetitions to debonding than HMA with Trap Rock aggregates. The laboratory results were validated by field observations of debonding in areas where granite-gneiss aggregates were used. Testing was conducted used a bi-axial repeated load test to simulate the axial and shear stresses developed during airplane trafficking. Asphalt Pavement Analyzer (APA) testing of different a FAA #3 surface course mix with various PG-graded asphalt binders showed that, as expected, asphalt binders with higher PG grades are less susceptible to rutting. The results indicated that the fuel resistance asphalt binder, high PG graded at 94°C, accumulated half of the total APA rutting as the PG64-22.

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TABLE OF CONTENTS

ABSTRACT

The PANYNJ is moving towards performance-based evaluations of hot mix asphalt (HMA) to verify the cost new and innovative HMA mixes for use on the George Washington Bridge and on airports, such as Newark Liberty International. HMA mixes for the George Washington Bridge were evaluated using repeated load testing, the Asphalt Pavement Analyzer, Flexural Beam Fatigue, and Dynamic Modulus. The various mixes evaluated consisted of Epoxy-based HMA, asphalt-rubber HMA, Rosphalt (which is an asphalt rubber based mix), and a PG76-22 asphalt binder with fibers. Laboratory testing concluded that the Epoxy-based HMA provided excellent rutting and fatigue properties, however, the mix has a tendency “set-up” and cure at sometimes unpredictable times, thereby, not lending itself to traditional paving delays that occur. The Rosphalt mix performed almost as well as the Epoxy-based HMA, but without the “set-up” issues. All “innovative” HMA mixes tested outperformed the current in-place I-5 PG76-22 in both rutting and fatigue testing. Work conducted on the interface bond testing of HMA cores taken from Newark Liberty International Airport showed clearly showed that HMA with a granite-gneiss aggregate had lower repetitions to debonding than HMA with Trap Rock aggregates. The laboratory results were validated by field observations of debonding in areas where granite-gneiss aggregates were used. Testing was conducted used a bi-axial repeated load test to simulate the axial and shear stresses developed during airplane trafficking. Asphalt Pavement Analyzer (APA) testing of different a FAA #3 surface course mix with various PG-graded asphalt binders showed that, as expected, asphalt binders with higher PG grades are less susceptible to rutting. The results indicated that the fuel resistance asphalt binder, high PG graded at 94^{o}C, accumulated half of the total APA rutting as the PG64-22.

1.0 PANYNJ HMA FOR THE GEORGE WASHINGTON BRIDGE

The scope of work encompasses the advanced characterization of the Port Authority of NY/NJ’s hot mix asphalt materials. The advanced characterization is comprised of using the Repeated Load Simple Performance Test (SPT), as described by NCHRP 465, and the Flexural Beam Fatigue device. The SPT was used to evaluate the rutting potential of HMA, while the Flexural Beam Fatigue was used to evaluate the fatigue properties of the HMA materials.

1.1 PANYNJ SMA and I-4A

The HMA material testing occurred in two phases. The first phase (Phase I) was an evaluation of an SMA and an I-4A mix. The samples were compacted and cored by the Materials Engineering Division of the Port Authority of NY/NJ (PANYNJ). The evaluation was solely based on the Repeated Load Simple Performance Test (SPT), as described by NCHRP 465. In this test, the permanent deformation properties of the HMA samples were measured by applying a 20 psi cyclic stress on a cylindrical sample that had been heated to 140^{o}F. Work conducted under NCHRP 465 had recommended 130^{o}F; however, officials from the PANYNJ specified a test temperature of 140^{o}F.

The second phase (Phase II) of the evaluation utilized both permanent deformation testing (Repeated Load SPT) and flexural fatigue testing. The HMA material tested in the second phase was an I-5 mix that contained a PG76-22 asphalt binder and polyester fibers. Virgin materials were delivered to the Rutgers Asphalt/Pavement Laboratory (RAPL) for mixing and compaction. However, two different asphalt binder contents were used; 5.9% and 6.3%. The asphalt binder contents were specified for the identical aggregate gradation, although to be compacted to different final air voids. The I-5 samples that contained 5.9% AC were to be compacted to 6.0% (± 0.5%) air voids, while the I-5 samples that contained 6.3% AC were to be compacted to 5.0% (± 0.5%) air voids. For the Repeated Load SPT testing, the permanent deformation properties of the HMA samples were measured by applying a 20 psi cyclic stress on a cylindrical sample that had been heated to 140^{o}F. The testing specifications followed those outlined in NCHRP 465. For the flexural fatigue testing, a Flexural Beam Fatigue device, described by AASHTO 321, was used to evaluate the fatigue properties of the two mixes. The fatigue testing was conducted under a constant-strain test mode at a test temperature of 15^{o}C (59^{o}F). A haversine waveform was applied at a rate of 2 Hz (2 loads per second).

More details of the Repeated Load SPT and Flexural Beam Fatigue testing are included in the Appendix.

1.1.1 Repeated Load Testing of SMA and I-4A

After the specimens were fabricated, three LVDT (linear variable differential transformers) were glued to the sides of the HMA specimen at 120 degrees apart with a final gage length of 100 mm. The samples were then heated to 140^{o}F. A dummy sample, instrumented with internal and skin thermocouples, was used to ensure the test sample reaches the required test temperature. Once temperature was achieved, the samples were cyclically loaded using a haversine waveform. A deviatoric cyclic stress of 20 psi was applied for a duration of 0.1 seconds and then followed by a 0.9 second rest period.

The Flow Number is determined by plotting the rate of change of axial strain versus the number of loading cycles. The number of loading cycles pertaining to the part of the curve where the slope is zero is designated as the Flow Number. Preliminary specifications from NCHRP 465 (Witczak et al., 2002) are located in Appendix A.

Three samples of an SMA and a Port Authority I-4A HMA mix were tested under repeated load testing conditions to compare the permanent deformation properties. The samples were loaded with a 20 psi deviatoric stress at a temperature of 140^{o}F. Three properties were evaluated from the testing:

1. Flow Number (F_N) – The larger the flow number, the more resistant the HMA mix is to permanent deformation;

2. Slope of the Linear Portion of the Permanent Strain vs Cycles Plot (b) – The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates; and
3. Accumulated Permanent Deformation at 1,000 Loading Cycles (ε_P (%) @ N = 1,000) – The larger the e_P (%) @ 1,000 cycles, the greater the potential for rutting in the field.

These three parameters were shown to provide the best correlation to measured field rutting (NCHRP 465) when conducting the repeated load permanent deformation test. The correlation results determined in NCHRP 465 are shown in Table 1.1.

The table clearly shows that at the test temperature of 130^{o}F, the R^2 values for the 3 parameters when compared to measured field rutting were all greater than 0.86. This should also correspond to the requested test temperature of 140^{o}F used in this study.

The final results are shown in Table 1.2. A statistical analysis was conducted using a Student's t-Test analysis (two samples assuming equal or unequal variances) to compare the derived parameters of the two mixes. Prior to using the t-Test, the F-Test was used to determine if the variances were equal or unequal. The results of the F-Test were used to select the appropriate condition of the t-Test (equal or unequal variances). The analysis was utilized to determine if the samples were statistically equal or statistically not equal among the common test results and parameters. A 95 % confidence interval was chosen for the analysis.

Table 1.1 – Results of Test Parameter Correlation to Field Rutting (NCHRP 465)

Unconfined Repeated Load	Model	100^{o}F				130^{o}F			
		R^2	Se/Sy	Rational	Rating	R^2	Se/Sy	Rational	Rating
Flow Number (F_N)	Power	0.96	0.229	Yes	Excellent	0.90	0.359	Yes	Good
Slope (b)	Linear	0.59	0.743	Yes	Fair	0.87	0.393	Yes	Good
Permanent Strain	Linear	0.95	0.256	Yes	Excellent	0.86	0.410	Yes	Good
Resilient Strain	Linear	0.90	0.362	Yes	Excellent	0.66	0.652	Yes	Fair
Resilient Modulus at Flow	Linear					0.72	0.548	Yes	Good
$\varepsilon_p/\varepsilon_r$ Ratio	Linear	0.83	0.472	Yes	Good	0.59	0.676	Yes	Fair
Mu (μ)	Linear	0.79	0.530	-	Good	0.25	0.881	-	Poor
Intercept (a)	Linear	0.30	0.964	Yes	Poor	0.13	1.055	Yes	Very Poor

Table 1.2 – Summary of Test Results from the Repeated Load Permanent Deformation Test for SMA and I-4A

Test Property →		**Flow Number (F_N)**	**Slope (b)**	**ε_P (%) @ N = 1,000**
SMA	# 3	978	0.324	1.843
	# 6	1,050	0.324	1.654
	# 7	1,092	0.335	1.882
	Average =	***1,040***	***0.327***	***1.793***
I-4A	# 1	790	0.223	0.862
	# 3	900	0.279	1.044
	# 4	1,524	0.269	0.605
	Average =	***1,071***	***0.257***	***0.837***

The statistical analysis comparisons indicate that:

- The flow number (F_N) of the SMA and I-4A mix are not significantly different at a 95% confidence level, although a direct comparison of the mean shows that the I-4A performed slightly better.
- The slopes of the permanent strain curve (b) were significantly different at a 95% confidence level. The results show that the SMA mix had a larger slope, which would indicate that this mix would have a greater potential for permanent deformation in the field.
- The permanent deformation determined at the 1,000th loading cycle was found to be significantly different at a 95% confidence level. The results show that the SMA mix accrued more than twice the amount of permanent deformation than the I-4A mix at the 1,000th loading cycle. Therefore, based on the work conducted within the NCHRP 465 project, the SMA mix would have a greater potential to develop permanent deformation than the I-4A mix.

Plots of the tests are shown as Figures 1.1 and 1.2.

1.1.2 Discussion of Results for SMA and I-4A Mixes

Based on the comparison of the Flow Number, (F_N), the Permanent Deformation Slope (b), and the Permanent Deformation (ε_P) measured at the 1,000th cycle from the Repeated Load Permanent Deformation test, the I-4A mix is more resistant to permanent deformation than the SMA. Although the Flow Number results were shown to be statistically equal, both the Slope (b) and the Permanent Deformation (ε_P) at the 1,000th loading cycle indicate that the I-4A mix will accumulate less permanent deformation than the SMA mix.

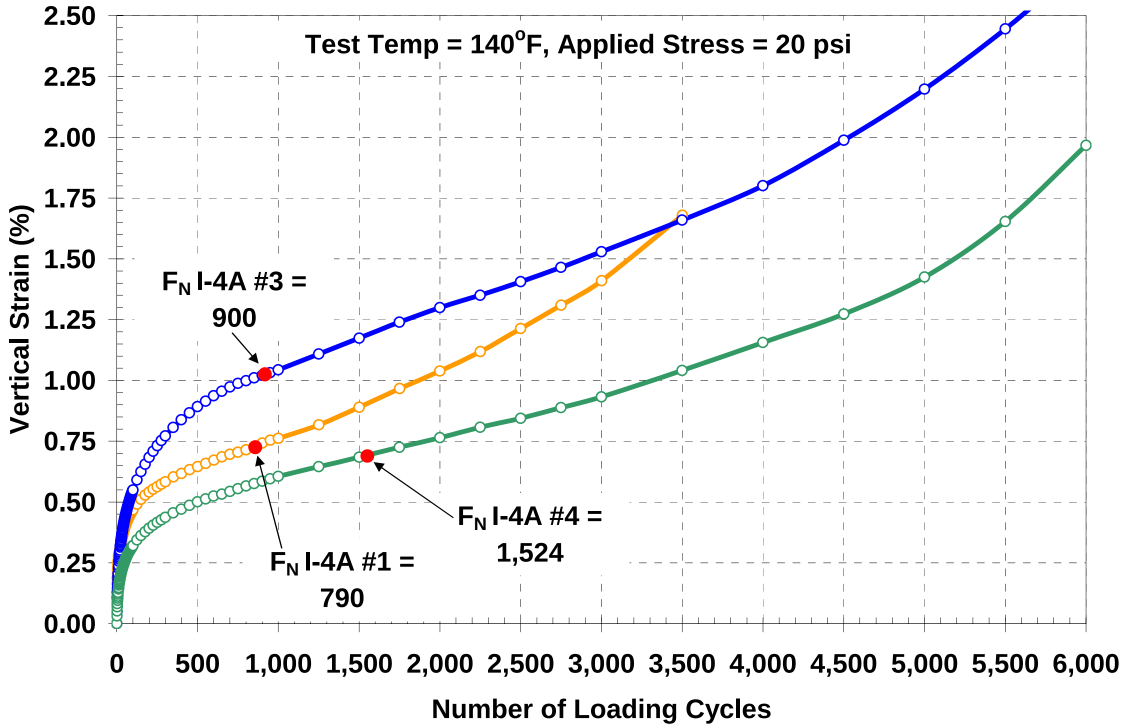


Figure 1.1 – Repeated Load Permanent Deformation Test Results for the Port Authority I-4A HMA Mix

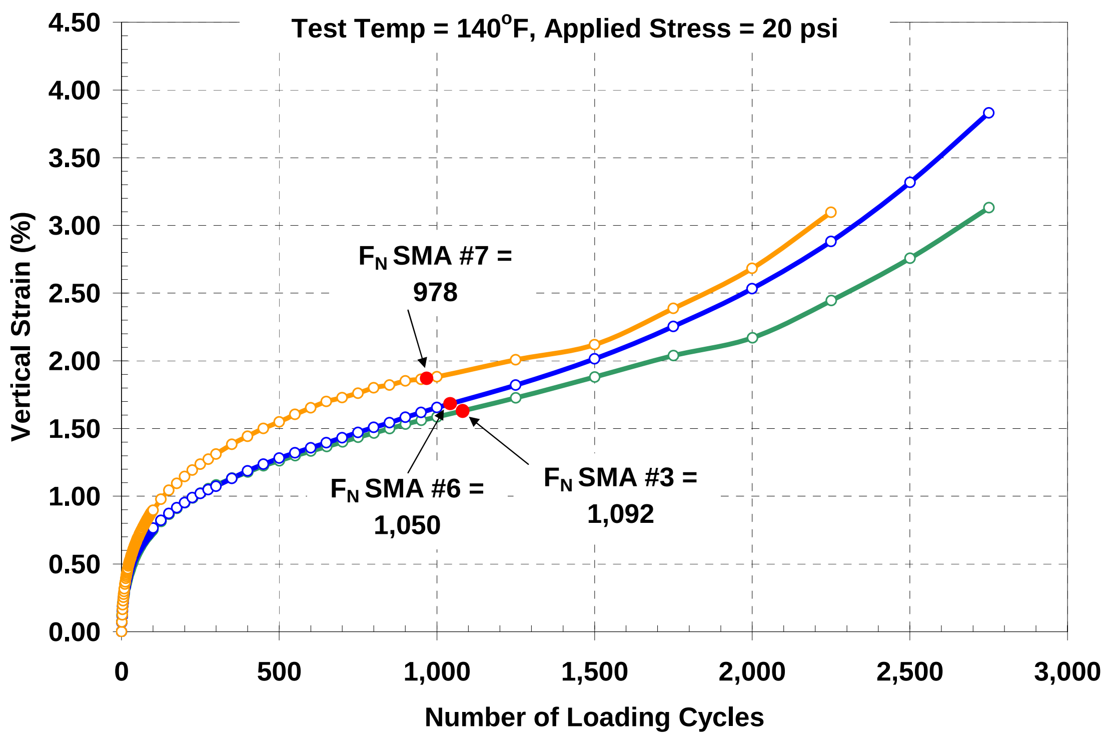


Figure 1.2 – Repeated Load Permanent Deformation Test Results for Port Authority SMA Mix

1.2 Evaluation of Baseline Mix for George Washington Bridge

1.2.1 Repeated Load SPT Testing

Three samples each of the 5.9% AC and 6.3% AC I-5 mix were tested using the Repeated Load Permanent Deformation test. The same permanent deformation properties used for evaluation in Phase I were also utilized in Phase II. For review, the properties were:

1. Flow Number (F_N) – The larger the flow number, the more resistant the HMA mix is to permanent deformation;
2. Slope of the Linear Portion of the Permanent Strain vs Cycles Plot (b) – The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates; and
3. Accumulated Permanent Deformation at 1,000 Loading Cycles (ε_P (%) @ N = 1,000) – The larger the e_P (%) @ 1,000 cycles, the greater the potential for rutting in the field.

A summary of the permanent deformation parameters are shown in Table 1.3. A statistical analysis was conducted using a Student's t-Test analysis (two samples assuming equal or unequal variances) to compare the derived parameters of the two mixes. Prior to using the t-Test, the F-Test was used to determine if the variances were equal or unequal. The results of the F-Test were used to select the appropriate condition of the t-Test (equal or unequal variances). The analysis was utilized to determine if the samples were statistically equal or statistically not equal among the common test results and parameters. A 95 % confidence interval was chosen for the analysis.

Table 1.3 - Summary of Test Results from the Repeated Load Permanent Deformation Test for I-5 Mix

Test Property →		**Air Voids (%)**	**Flow Number (F_N)**	**Slope (b)**	**ε_P (%) @ N = 1,000**
5.9% AC	A	5.6	1,410	0.212	0.699
	C	5.8	1,961	0.192	0.629
	E	5.8	1,243	0.209	0.761
	Average =	***5.73***	***1,538***	***0.204***	***0.696***
6.3% AC	B	4.7	1,460	0.246	0.78
	C	5.3	1,703	0.232	0.819
	D	5.1	1,414	0.222	0.762
	Average =	***5.03***	***1,526***	***0.233***	***0.787***

The statistical analysis comparisons indicate that:

- The flow number (F_N) of the 5.9% AC mix and 6.3% AC mix are not significantly different at a 95% confidence level, although a direct comparison of the mean shows that the 5.9% AC mix performed slightly better.
- The slopes of the permanent strain curve (b) were significantly different at a 95% confidence level. The results show that the 6.3% AC mix had a slightly larger slope, which would indicate that this mix would have a greater potential for

permanent deformation in the field, as well as accumulate permanent deformation slightly faster.

- The permanent deformation determined at the 1,000th loading cycle was found to be significantly different at a 95% confidence level. The results show that the 6.3% AC mix developed more permanent deformation than the 5.9% AC mix in the first 1,000 loading cycles. Therefore, based on the work conducted within the NCHRP 465 project, the 6.3% AC mix would have a greater potential for rutting than the 5.9% AC mix.

Plots of the Repeated Load Permanent Deformation testing are shown as Figures 1.3 and 1.4.

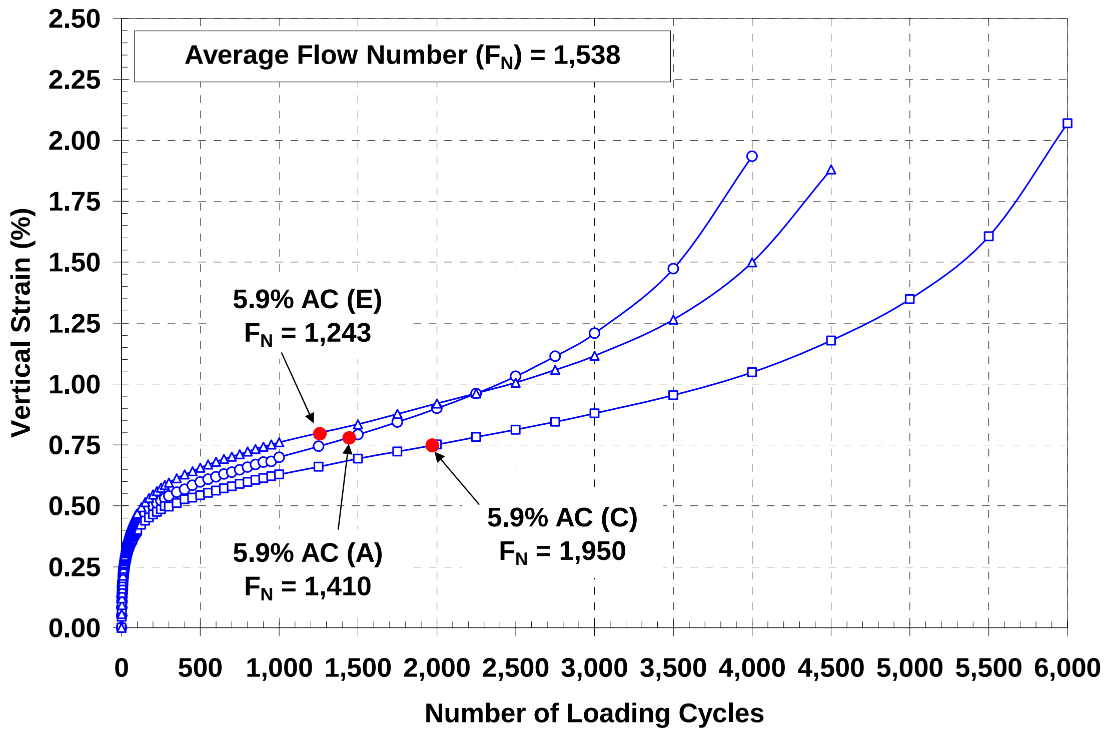


Figure 1.3 – Repeated Load Permanent Deformation Test Results for I-5 with 5.9% AC

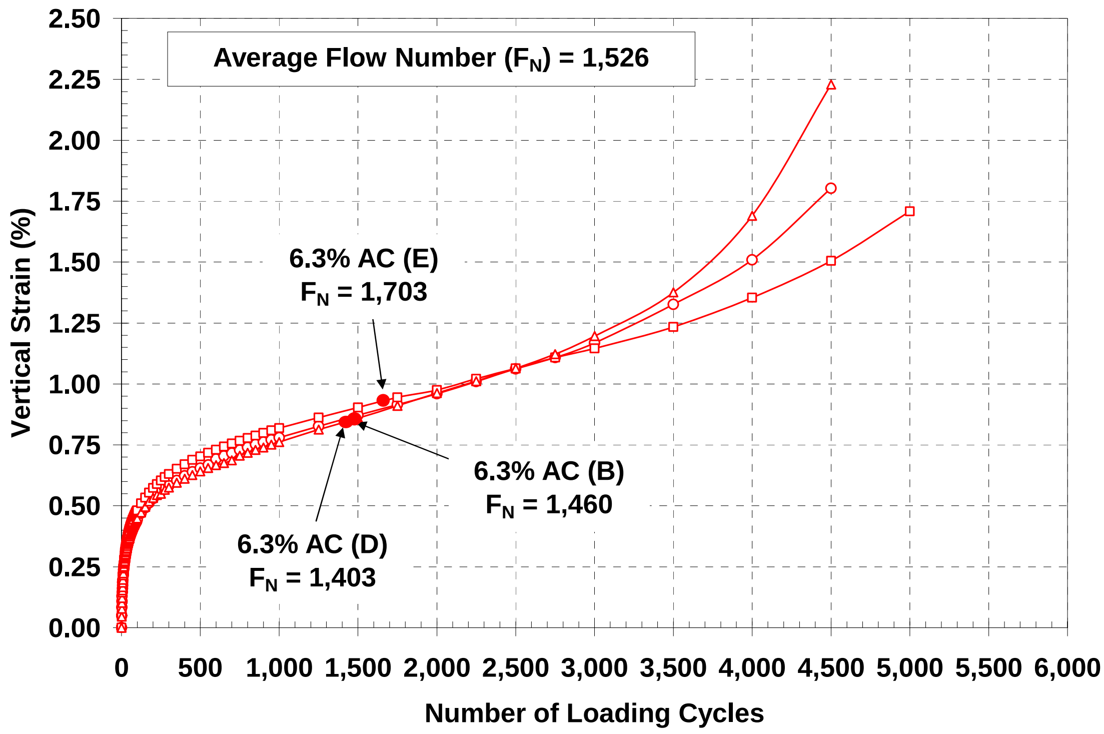


Figure 1.4 – Repeated Load Permanent Deformation Test Results for I-5 with 6.3% AC

1.2.2 Flexural Fatigue Test Results

All samples were tested at a test temperature of 15^{o}C. The test specimens were tested until 1,000,000 loading cycles, or until the specimen's flexural strength reached a pre-determined minimum value. Samples that were tested out until 1,000,000 cycles lasted 5.7 days due to the slower loading frequency (2 Hz or 2 loads per second). This was achieved at both the 200 and 400 μstrain levels for the 5.9% AC and 6.3% AC samples. The limit of load cycles was chosen due to time constraints associated with the testing. Each mix, 5.9% AC and 6.3% AC, had samples tested at 200, 400, 600, 750, and 900 μ-strains.

Throughout the test, the flexural stiffness of the samples were calculated and recorded. The stiffness of the beams was plotted against the load cycles and the resulting data was fitted to an exponential function as follows (AASHTO T321):

$$S = S_O e^{bN} \qquad (11.)$$

where,

S = flexural stiffness after the n load cycles;

S_O= initial flexural stiffness;

e = natural algorithm to the base e
b = constant from regression analysis
N = number of load cycles

Equation (1.1) was then modified to determine the number of loading cycles to achieve 50% of the initial flexural stiffness. This was conducted for the five different applied strain levels to provide a regression equation in the form of Equation (1.2).

$$N_f = k_1 \varepsilon_t^{k_2} \tag{1.2}$$

where,

N_f = number of loading repetitions until fatigue failure (50% of the initial stiffness)
k_1, k_2 = regression coefficients depending on material type and test conditions
ε_t = tensile strain

Tables 1.4 and 1.5 show the calculated values determined from equations (1.1) and (1.2). The number of cycles until fatigue failure ($N_{f,\ 50\%}$) for the 5.9% AC and 6.3% AC samples are shown in Figure 1.5. The results indicate that at the lower applied strain levels, the fatigue life of the samples was approximately equal, although the 6.3% AC samples showed slightly better fatigue resistance. This is rational and follows the theory of "Fatigue Endurance Limit". "Fatigue Endurance Limit" states that at a small enough applied tensile strain, the material will have an infinite fatigue life (Monismith et al., 1970; Carpenter et al., 2003). However, as the applied tensile strain increases, the fatigue performance starts to differentiate between one another. The figure clearly shows that the samples with 6.3% AC have a greater fatigue life than the 5.9% AC samples when the tensile strains increase.

Table 1.4 – Flexural Beam Fatigue Results for I-5, 5.9% AC Samples

I-5, 5.9% AC				
Tensile Strain (μ–strain)	**Air Voids (%)**	**Cycles to Failure, $N_{f,\ 50\%}$**	**Initial Stiffness, S_O (MPa)**	**Slope, b**
200	5.9	5,465,599	5635.2	-1.27E-07
400	5.6	1,406,150	4481.1	-4.93E-07
600	5.6	53,279	4596.6	-1.30E-05
750	5.9	23,796	3882.5	-2.91E-05
900	5.8	11,558	3568.5	-6.00E-05

Table 1.5 – Flexural Beam Fatigue Results for I-5, 6.3% AC Samples

I-5, 6.3% AC				
Tensile Strain (μ–strain)	Air Voids (%)	Cycles to Failure, $N_{f,\ 50\%}$	Initial Stiffness, S_O (MPa)	Slope, b
200	5.2	6,123,983	4483.3	-1.13E-07
400	5.1	1,216,219	4236.5	-5.70E-07
600	5.2	91,072	3864.3	-7.61E-06
750	4.8	71,329	3432.6	-9.72E-06
900	5.1	17,712	2803.7	-3.91E-05

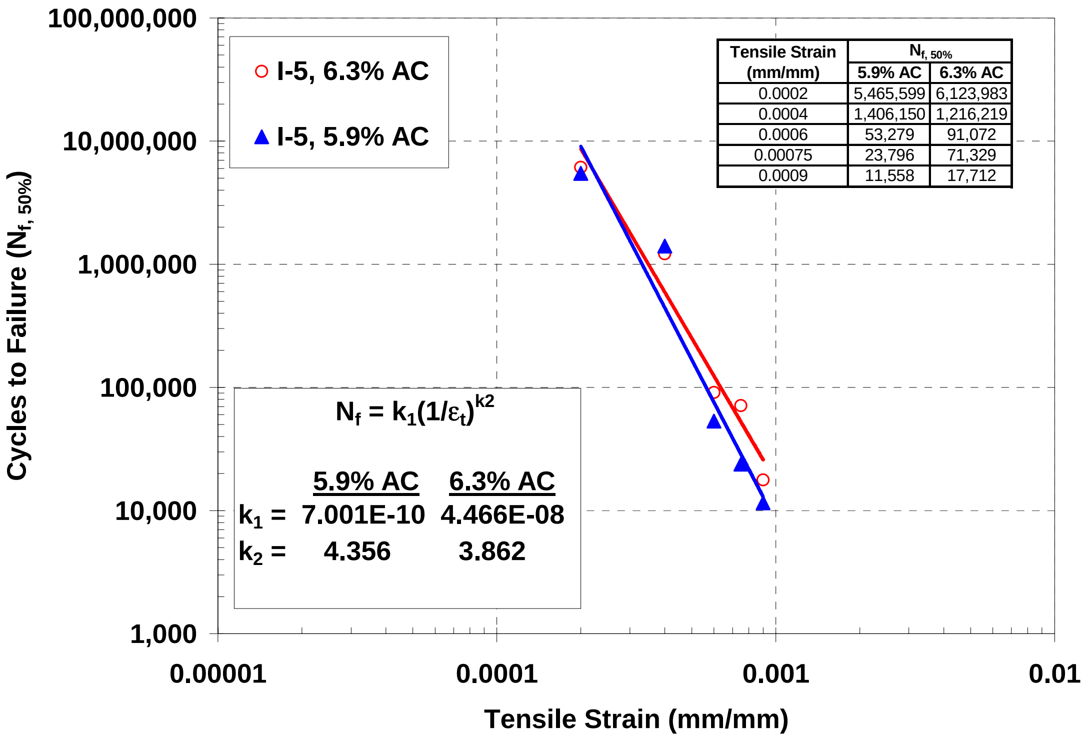


Figure 1.5 – Fatigue Properties of I-5 Samples with 5.9% and 6.3% AC

1.2.3 Discussion of Results – Baseline Mixes for George Washington Bridge

The permanent deformation and fatigue resistance properties of an I-5 HMA mix, with two different asphalt binder contents and compacted air void levels, were determined using advanced material characterization testing procedures. The permanent deformation properties were evaluated using the Repeated Load Permanent Deformation test procedure as described by NCHRP 465. The flexural fatigue properties were evaluated using the Flexural Beam Fatigue device and test procedure described in AASHTO T321.

Based on the performance testing, the following conclusions were drawn:

- From the flow number (F_N), permanent deformation slope (b), and the accumulated permanent strain at the 1,000th loading cycle (ε_P) properties determined from the permanent deformation testing, the I-5 mix containing 5.9% asphalt binder had slightly better rutting resistance properties than the I-5 mix containing 6.3% asphalt binder.

- The flexural beam fatigue tests showed that the two mixes had approximately equal fatigue resistance at lower applied strains, with the 6.3% AC samples having slightly better fatigue resistance. This follows the "Fatigue Endurance Limit" theory which states that at a particularly low tensile strain, the HMA samples will have an infinite fatigue life. However, as the applied tensile strain increased, the 6.3% AC samples showed to have better flexural fatigue properties. This is clearly illustrated in Figure 1.5, which shows the trendline of 6.3% AC samples moving further away from the 5.9% AC samples as the applied tensile strain increased.

2.0 EVALUATION OF EPOXY ASPHALT FOR GEORGE WASHINGTON BRIDGE

Virgin materials were delivered to the Rutgers Asphalt/Pavement Laboratory (RAPL) for mixing and compaction of the epoxy HMA. The epoxy binder is a 2-part binder system, with each part needing to be heated to a different temperature. For accurate heating of the epoxy mix, 1-gallon can heaters were used with a calibrated thermocouple controller that is accurate to 0.1^{o}F (Figure 2.1). All heating, mixing, and compaction temperatures, as well as the HMA mixture design, were supplied by the PANYNJ, and also later verified by the epoxy binder manufacturer.

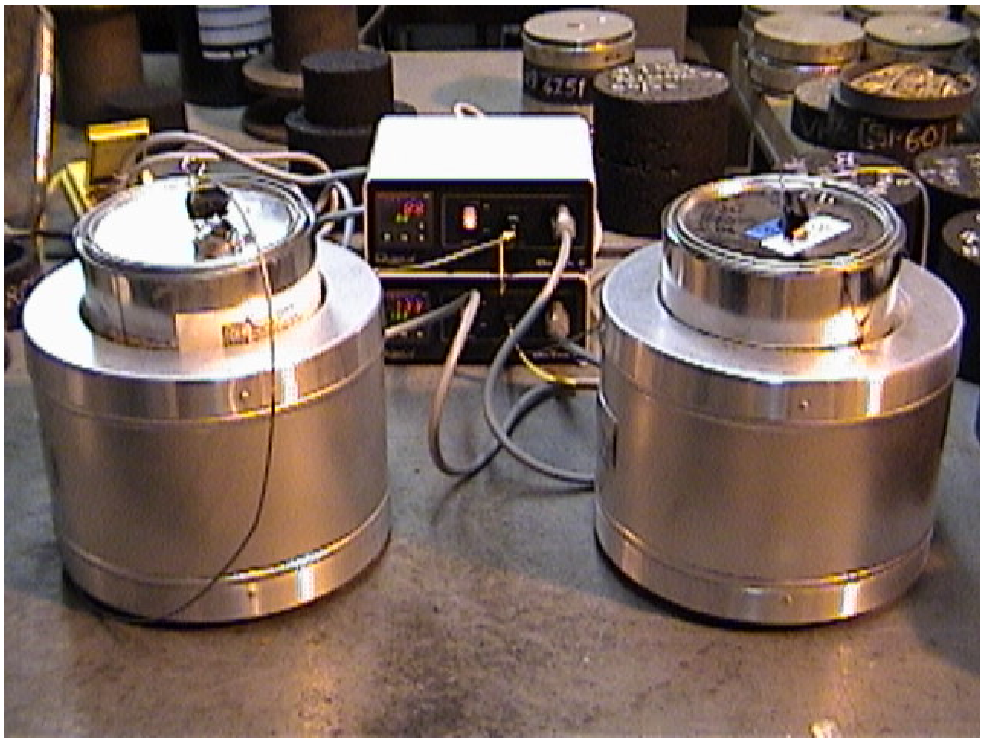


Figure 2.1 – Gallon Can Heaters Used for Blending and Mixing the Epoxy Asphalt Binder

All epoxy HMA samples were compacted to have a final air void content of 2.0% (± 0.5%) air voids.

For the Repeated Load SPT testing, the permanent deformation properties of the HMA samples were measured by applying a 20 psi cyclic stress on a cylindrical sample that had been heated to 140^{o}F. The testing specifications followed those outlined in NCHRP 465. For the flexural fatigue testing, a Flexural Beam Fatigue device, described by AASHTO 321, was used to evaluate the fatigue properties of the two mixes. The fatigue testing was conducted under a constant-strain test mode at a test temperature of 15^{o}C (59^{o}F). A haversine waveform was applied at a rate of 2 Hz (2 loads per second).

2.1 Epoxy HMA Test Results – Repeated Load

After the specimens were fabricated, three LVDT (linear variable differential transformers) were glued to the sides of the HMA specimen at 120 degrees apart with a final gage length of 100 mm. The samples were then heated to 140^{o}F. A dummy sample, instrumented with internal and skin thermocouples, was used to ensure the test sample reaches the required test temperature. Once temperature was achieved, the samples were cyclically loaded using a haversine waveform. A deviatoric cyclic stress of 20 psi was applied for a duration of 0.1 seconds and then followed by a 0.9 second rest period.

The Flow Number is determined by plotting the rate of change of axial strain versus the number of loading cycles. The number of loading cycles pertaining to the part of the curve where the slope is zero is designated as the Flow Number.

Three samples of the epoxy asphalt mix were tested under repeated load testing conditions to determine the permanent deformation properties. The samples were loaded with a 20 psi deviatoric stress at a temperature of 140^{o}F. Three properties were evaluated from the testing:

4. Flow Number (F_N) – The larger the flow number, the more resistant the HMA mix is to permanent deformation;
5. Slope of the Linear Portion of the Permanent Strain vs Cycles Plot (b) – The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates; and
6. Accumulated Permanent Deformation at 1,000 Loading Cycles (ε_P (%) @ N = 1,000) – The larger the e_P (%) @ 1,000 cycles, the greater the potential for rutting in the field.

These three parameters were shown to provide the best correlation to measured field rutting (NCHRP 465) when conducting the repeated load permanent deformation test. The correlation results determined in NCHRP 465 are shown in Table 2.1. The table clearly shows that at the test temperature of 130^{o}F, the R^2 values for the 3 parameters when compared to measured field rutting were all greater than 0.86. This should also correspond to the requested test temperature of 140^{o}F used in this study.

The final repeated load results of the Epoxy Asphalt are shown in Table 2.2, along with the test results from the two previous HMA mixes. A statistical analysis was conducted using a Student's t-Test analysis (two samples assuming equal or unequal variances) to compare the derived parameters of the Epoxy Asphalt to the other 2 mixes. Prior to using the t-Test, the F-Test was used to determine if the variances were equal or unequal. The results of the F-Test were used to select the appropriate condition of the t-Test (equal or unequal variances). The analysis was utilized to determine if the samples were statistically equal or statistically not equal among the common test results and parameters. A 95 % confidence interval was chosen for the analysis.

Table 2.1 – Results of Test Parameter Correlation to Field Rutting (NCHRP 465)

Unconfined Repeated Load	Model	100°F				130°F			
		R^2	Se/Sy	Rational	Rating	R^2	Se/Sy	Rational	Rating
Flow Number (F_N)	Power	0.96	0.229	Yes	Excellent	0.90	0.359	Yes	Good
Slope (*b*)	Linear	0.59	0.743	Yes	Fair	0.87	0.393	Yes	Good
Permanent Strain	Linear	0.95	0.256	Yes	Excellent	0.86	0.410	Yes	Good
Resilient Strain	Linear	0.90	0.362	Yes	Excellent	0.66	0.652	Yes	Fair
Resilient Modulus at Flow	Linear					0.72	0.548	Yes	Good
$\varepsilon_p/\varepsilon_r$ Ratio	Linear	0.83	0.472	Yes	Good	0.59	0.676	Yes	Fair
Mu (μ)	Linear	0.79	0.530	-	Good	0.25	0.881	-	Poor
Intercept (*a*)	Linear	0.30	0.964	Yes	Poor	0.13	1.055	Yes	Very Poor

Table 2.2 – Summary of Test Results from the Repeated Load Permanent Deformation Test

Test Property →		**Air Voids (%)**	**Flow Number (F_N)**	**Slope (b)**	**ε_P (%) @ N = 1,000**
5.9% AC PG76-22	A	5.6	1,410	0.212	0.699
	C	5.8	1,961	0.192	0.629
	E	5.8	1,243	0.209	0.761
	Average =	***5.73***	***1,538***	***0.204***	***0.696***
6.3% AC PG76-22	B	4.7	1,460	0.246	0.78
	C	5.3	1,703	0.232	0.819
	D	5.1	1,414	0.222	0.762
	Average =	***5.03***	***1,526***	***0.233***	***0.787***
Epoxy Asphalt	# 2	1.3	> 20,000	0.059	0.034
	# 7	1.8	> 20,000	0.054	0.02
	# 8	1.9	> 20,000	0.032	0.015
	Average =	***1.67***	***> 20,000***	***0.048***	***0.023***

The statistical analysis comparisons indicate that:

- The flow number (F_N) of the Epoxy Asphalt and the two previous PG76-22 mixes are significantly different at a 95% confidence level, with the ***Epoxy Asphalt never obtaining a Flow Number after 20,000 loading cycles (the samples never failed – assumed F_N = 20,000 for statistical analysis)***. Results from NCHRP 465 indicated that the larger the Flow Number, the more rut resistant the HMA.
- The slope of the permanent strain curve, b, from the Epoxy Asphalt samples was significantly different at a 95% confidence level. The results show that the ***Epoxy Asphalt had a permanent deformation rate (slope) almost 4 times lower*** than the previous PG76-22 mixes. Results from NCHRP 465 indicated that the smaller the slope (b) parameter, the more rut resistant the HMA.

- The permanent deformation determined at the 1,000th loading cycle from the Epoxy Asphalt samples was found to be significantly different at a 95% confidence level when compared to the previously tested PG76-22 samples. The results show that the ***Epoxy Asphalt accumulated approximately 30 times less permanent axial strain*** when compared to the previous two PG76-22 mixes. Results from NCHRP 465 indicated that the smaller the permanent deformation at the 1,000th loading cycle, the more rut resistant the HMA.

Plots of the repeated load tests for the Epoxy Asphalt mix are shown as Figure 2.2. Figure 2.3 shows the repeated load results of the Epoxy Asphalt compared to one of the previous PG76-22 mixes. Both PG76-22 mixes performed almost identically under the repeated loading in the previous study. Figure 2.3 illustrates the drastic difference between the Epoxy Asphalt and the PG76-22 I-5 when tested using the repeated load test at 140^{o}F and an applied deviatoric stress of 20 psi.

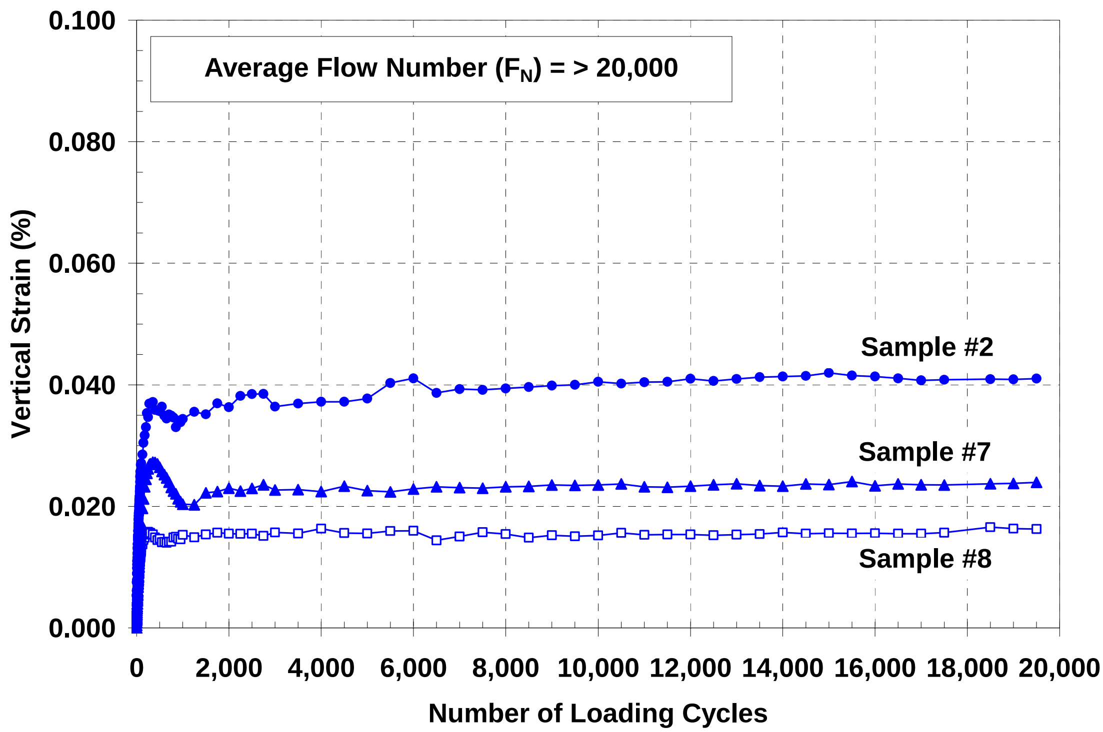


Figure 2.2 – Repeated Load Permanent Deformation Test Results for the Port Authority Epoxy HMA Mix

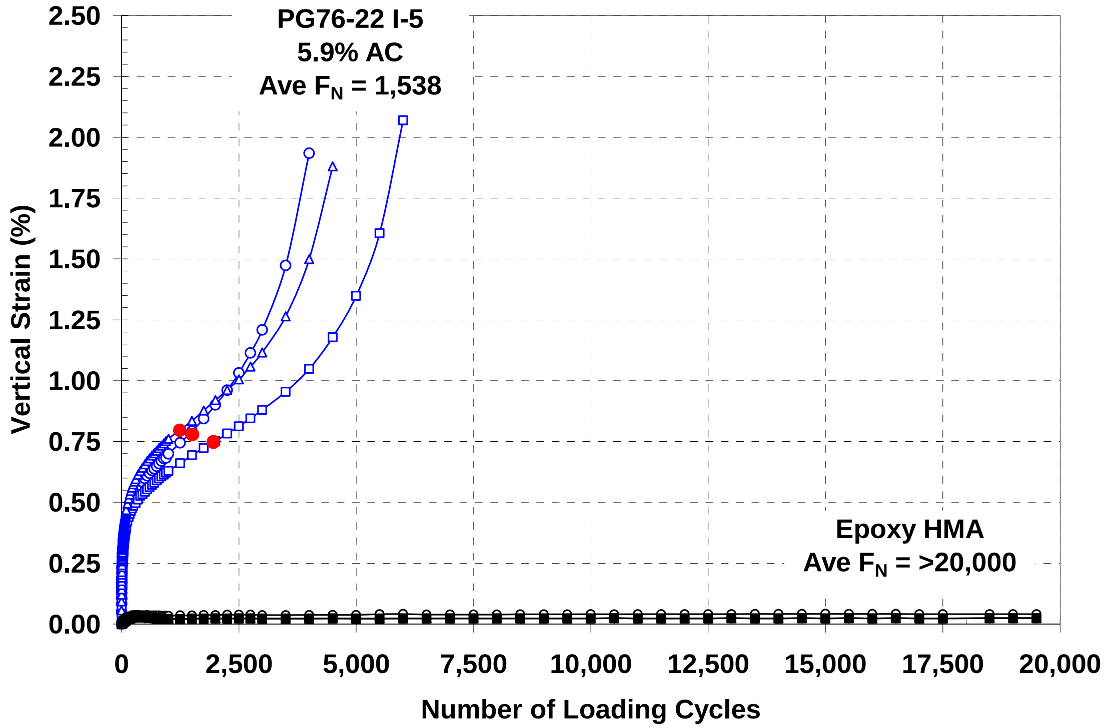


Figure 2.3 – Comparison of Repeated Load Permanent Deformation Test Results for the PANYNJ Epoxy HMA and PG76-22 I-5 Mix (5.9% AC)

2.2 Epoxy HMA Test Results – Flexural Beam Fatigue

All samples were tested at a test temperature of 15°C. The test specimens were tested until a minimum of 3,000,000 loading cycles, or until the specimen's flexural strength reached 50% of its initial flexural stiffness. Samples that were tested out until 3,000,000 cycles lasted at least 17 days due to the slower loading frequency (2 Hz or 2 loads per second). This was achieved at the 200, 400, and 900 μstrain levels (600 and 750 μ-strains have not been completed to date). The limit of load cycles was chosen due to time constraints associated with the testing. The Epoxy HMA samples were to be tested at 200, 400, 600, 750, and 900 μ-strains.

Throughout the test, the flexural stiffness of the samples were calculated and recorded. The stiffness of the beams was plotted against the load cycles and the resulting data was fitted to an exponential function as follows (AASHTO T321):

$$S = S_O e^{bN} \qquad (2.1)$$

where,

S = flexural stiffness after the n load cycles;
S_O= initial flexural stiffness;
e = natural algorithm to the base e
b = constant from regression analysis

N = number of load cycles

Equation (2.1) was then modified to determine the number of loading cycles to achieve 50% of the initial flexural stiffness. This was conducted for the five different applied strain levels to provide a regression equation in the form of Equation (2.2).

$$N_f = k_1 \varepsilon_t^{k_2} \qquad (2.2)$$

where,

N_f = number of loading repetitions until fatigue failure (50% of the initial stiffness)

k_1, k_2 = regression coefficients depending on material type and test conditions

ε_t = tensile strain

Table 2.3 shows the fatigue results for Epoxy Asphalt samples tested. Table 2.4, which contains the fatigue results from the previously tested PG76-22 I-5 mix, is also shown for comparative purposes. The fatigue lives of the Epoxy Asphalt samples, for the different tensile strain levels, are far greater than those achieved by the PG76-22 I-5 samples. Figure 2.4 shows the fatigue life (N_f) – Tensile Strain (ε_t) relationship. Obviously, the higher the regression curve, the more fatigue-type loading the material can withstand before failing due to fatigue cracking.

Table 2.3 – Flexural Beam Fatigue Results for Epoxy Asphalt Samples

Epoxy Asphalt				
Tensile Strain (μ–strain)	**Air Voids (%)**	**Cycles to Failure, $N_{f, 50\%}$**	**Initial Stiffness, S_O (MPa)**	**Slope, b**
200	1.3	225,194,016	10,571.10	-3.08E-09
400	1.8	159,818,123	10,261	-4.34E-09
600	1.6	90,359,429	9,094.20	-7.67E-09
750	1.8	12,440,498	8,742.90	-5.57E-08
900	1.4	16,626,222	7,917.20	-4.17E-08

Table 2.4 – Flexural Beam Fatigue Results for I-5, 6.3% AC Samples

I-5, 6.3% AC				
Tensile Strain (μ–strain)	**Air Voids (%)**	**Cycles to Failure, $N_{f, 50\%}$**	**Initial Stiffness, S_O (MPa)**	**Slope, b**
200	5.2	6,123,983	4483.3	-1.13E-07
400	5.1	1,216,219	4236.5	-5.70E-07
600	5.2	91,072	3864.3	-7.61E-06
750	4.8	71,329	3432.6	-9.72E-06
900	5.1	17,712	2803.7	-3.91E-05

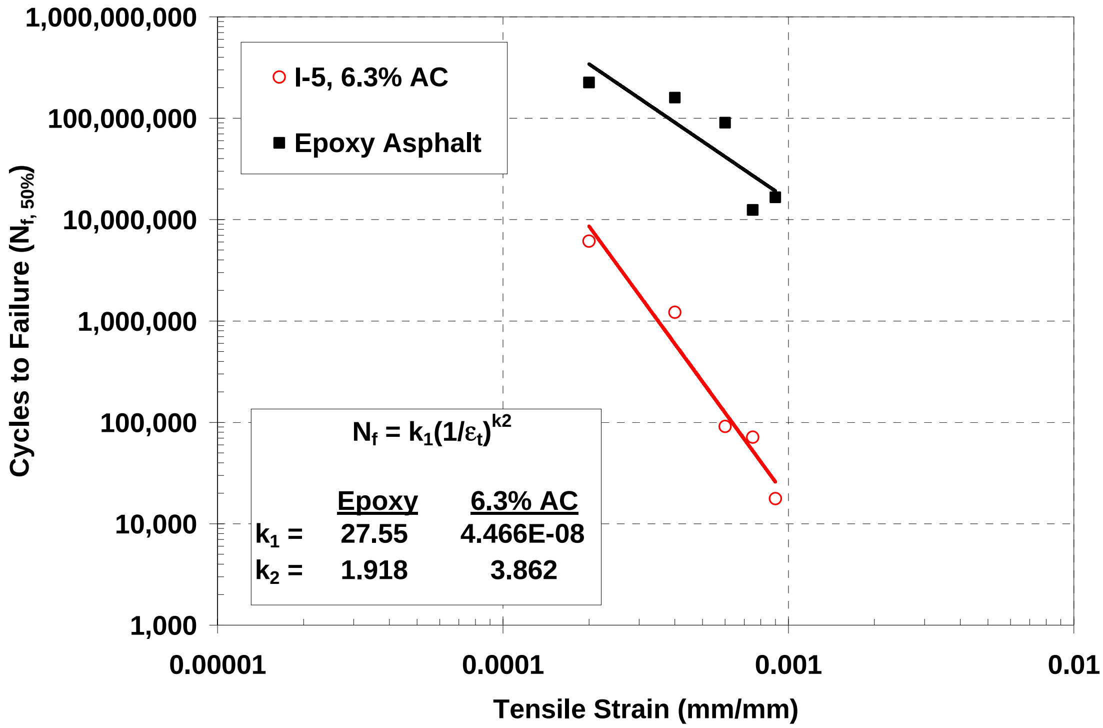


Figure 2.4 – Fatigue Properties of Epoxy Asphalt and PG76-22 I-5 Samples (6.3% AC)

It should be noted that the fatigue lives of the 200 and 400 micro-strain Epoxy Asphalt samples were highly dependent on the Power Law regression used (meaning that they could be a little more or less). This is mainly due to the extremely high fatigue lives (> 100,000,000 cycles) and the relatively short testing times (only up to 3.5 million cycles or 3 weeks).

2.3 Discussion of Results – Epoxy HMA for George Washington Bridge

The permanent deformation and fatigue resistance properties of an Epoxy Asphalt mix were determined using advanced material characterization testing procedures. The permanent deformation properties were evaluated using the Repeated Load Permanent Deformation test procedure as described by NCHRP 465. The flexural fatigue properties were evaluated using the Flexural Beam Fatigue device and test procedure described in AASHTO T321. For comparative purposes, a previously tested PG76-22 I-5 mix was also shown.

Based on the performance testing, the following conclusions were drawn:

- From the flow number (F_N), permanent deformation slope (b), and the accumulated permanent strain at the 1,000th loading cycle (ε_P) properties determined from the permanent deformation testing, the Epoxy Asphalt mix was found to be more rut resistant than the PG76-22 I-5 mix.

- The flexural beam fatigue tests showed that the Epoxy Asphalt mix has excellent fatigue properties, especially when compared to the PG76-22 I-5 mix. The direct comparison of the fatigue life at each tensile strain shows the ***Epoxy Asphalt has a fatigue life of 2 to 3 orders of magnitude greater than the PG76-22 I-5 mix***. When directly comparing the 900 micro-strain test results, which researchers have indicated closely simulates the actual movement in steel orthotropic bridge decks (Medani et al, 2004), the Epoxy Asphalt has a fatigue life of 3 orders of magnitude greater than the PG76-22 I-5 mix (Figure 2.5).

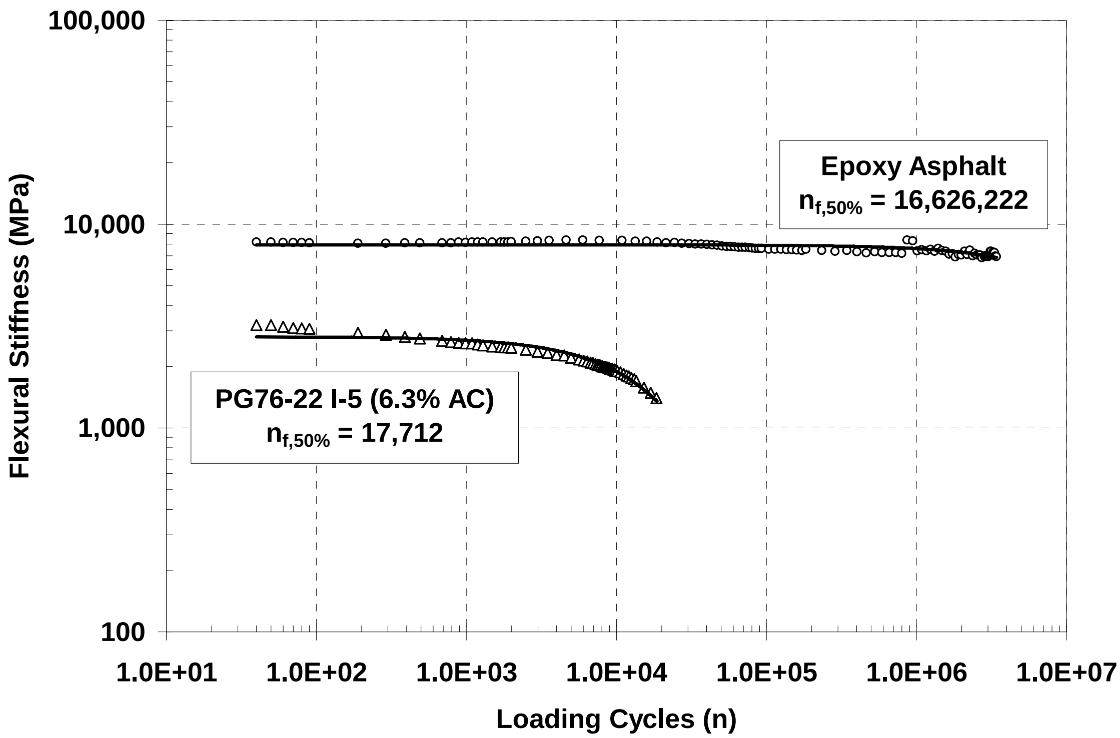


Figure 2.5 – Fatigue Life of Epoxy Asphalt and PG76-22 I-5 (6.3% AC) at 900 Micro-strains

3.0 ROSPHALT 50 – PERFORMANCE EVALUATION FOR THE GEORGE WASHINGTON BRIDGE

The Rosphalt 50 hot mix asphalt (R-50) was evaluated for both permanent deformation and flexural fatigue properties. The PANYNJ provided two different mix designs proposed for use with the Rosphalt material. The first design was conducted to a design air void level of 1%, while the second design was conducted to a design air void level of 3%. The PANYNJ requested testing conducted at the design air void level and 2.0% above design air void level for the flexural fatigue tests. Permanent deformation testing was only conducted on the 1% design air void level mix.

For the flexural fatigue testing, a Flexural Beam Fatigue device described by AASHTO 321, was used to evaluate the fatigue properties of the R-50 designed and compacted in four different manners; 1) R-50 designed at 1% air voids and tested at 1% air voids, 2) R-50 designed at 1% air voids and tested at 3% air voids, 3) R-50 designed at 3% air voids and tested at 3% air voids, and 4) R-50 designed at 3% air voids and tested at 5% air voids. The fatigue testing was conducted under a constant-strain test mode at a test temperature of 15°C (59°F). A haversine waveform was applied at a rate of 2 Hz (2 loads per second) and a magnitude of 900 micro-strains. The loading type described was supposed to simulate the typical loading and bending action on the orthotropic steel decks on the George Washington Bridge.

For the Repeated Load Permanent Deformation testing, the permanent deformation properties of the HMA samples were measured by applying a 20 psi cyclic stress on a cylindrical sample that had been heated to 140°F. The testing specifications followed those outlined in NCHRP 465. Permanent deformation testing was only conducted on the R-50 designed at 1% air voids and tested at 1% air voids and also the R-50 designed at 1% air voids and tested at 3% air voids, as requested by the PANYNJ.

3.1 Flexural Fatigue Test Results

All samples were tested at a test temperature of 15°C. The test specimens were tested until approximately 3,000,000 loading cycles, or until the specimen's flexural strength reached a pre-determined minimum value. Samples that were tested out until 3,000,000 cycles lasted 17 days due to the slower loading frequency (2 Hz or 2 loads per second). Testing was only conducted at 900 μ-strains due to the extremely, high fatigue resistance of the Rosphalt 50 material.

Throughout the test, the flexural stiffness of the samples was calculated and recorded. The stiffness of the beams was plotted against the load cycles and the resulting data was fitted to an exponential function as follows (AASHTO T321):

$$S = S_O e^{bN} \tag{3.1}$$

where,

S = flexural stiffness after the n load cycles;

S_O= initial flexural stiffness;
e = natural algorithm to the base e
b = constant from regression analysis
N = number of load cycles

Equation (3.1) was then modified to determine the number of loading cycles to achieve 50% of the initial flexural stiffness

The test results for the four different Rosphalt 50 HMA mixes are shown in Figure 3.1 and Table 3.1. The flexural beam fatigue results show that as long as the compacted air voids are less than 3% air voids, the R-50 material will provide excellent fatigue resistance.

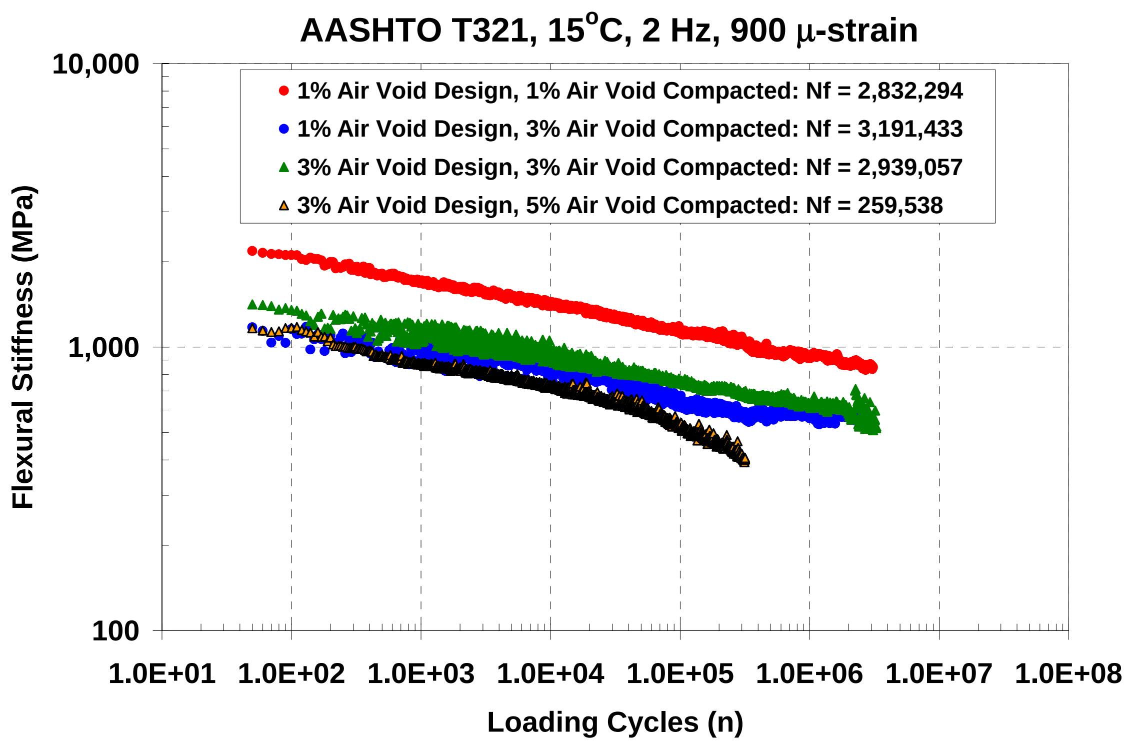


Figure 3.1 – Flexural Beam Fatigue Test Results for the Rosphalt 50 Material

Table 3.1 – Flexural Beam Fatigue Test Results for Rosphalt 50 Material

Sample Type	Air Voids (%)	Initial Stiffness, S_O (MPa)	Exp. Constant, b	Fatigue Life, $N_{f,\ 50\%}$ (cycles)
1% Air Void Design, 1% Air Void Compacted	1.4	1,347,7	-2.45E-07	2,832,294
1% Air Void Design, 3% Air Void Compacted	2.7	782.9	-2.17E-07	3,191,433
3% Air Void Design, 3% Air Void Compacted	3.1	891.4	-2.36E-07	2,939,057
3% Air Void Design, 5% Air Void Compacted	4.5	766.6	-2.67E-06	259,538

3.2 Repeated Load Permanent Deformation Test Results

Three samples each of the 1% design/tested at 1% air voids and 1% design/tested at 3% air voids were tested using the Repeated Load Permanent Deformation test. The permanent deformation properties used for evaluation/comparison, and outlined in NCHRP Report 465, were:

1. Flow Number (F_N) – The larger the flow number, the more resistant the HMA mix is to permanent deformation;
2. Slope of the Linear Portion of the Permanent Strain vs Cycles Plot (b) – The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates; and
3. Accumulated Permanent Deformation at 1,000 Loading Cycles (ε_P (%) @ N = 1,000) – The larger the e_P (%) @ 1,000 cycles, the greater the potential for rutting in the field.

These three parameters were shown to provide the best correlation to measured field rutting (NCHRP 465) when conducting the repeated load permanent deformation test. The correlation results determined in NCHRP 465 are shown in Table 3.2.

The table clearly shows that at the test temperature of 130°F, the R^2 values for the 3 parameters when compared to measured field rutting were all greater than 0.86. This should also correspond to the requested test temperature of 140°F used in this study.

Table 3.2 – Results of Test Parameter Correlation to Field Rutting (NCHRP 465)

Unconfined Repeated Load	Model	100°F				130°F			
		R^2	Se/Sy	Rational	Rating	R^2	Se/Sy	Rational	Rating
Flow Number (F_N)	Power	0.96	0.229	Yes	Excellent	0.90	0.359	Yes	Good
Slope (b)	Linear	0.59	0.743	Yes	Fair	0.87	0.393	Yes	Good
Permanent Strain	Linear	0.95	0.256	Yes	Excellent	0.86	0.410	Yes	Good
Resilient Strain	Linear	0.90	0.362	Yes	Excellent	0.66	0.652	Yes	Fair
Resilient Modulus at Flow	Linear					0.72	0.548	Yes	Good
$\varepsilon_p/\varepsilon_r$ Ratio	Linear	0.83	0.472	Yes	Good	0.59	0.676	Yes	Fair
Mu (μ)	Linear	0.79	0.530	-	Good	0.25	0.881	-	Poor
Intercept (a)	Linear	0.30	0.964	Yes	Poor	0.13	1.055	Yes	Very Poor

A summary of the permanent deformation parameters are shown in Table 3 and the permanent deformation plots are shown in Figure 3.2 and Figure 3.3. Samples #1 and #2 were not used in the calculation of the average values. During the sample preparation process, coring in particular, both Sample #1 and #2 witnessed extreme bleeding of the asphalt binder and almost seized the core barrel during coring. It is believed that during this coring process, as well as the extraction process of the samples from inside the core barrel, Sample #1 and Sample #2 may have been damaged. This is in agreement with the permanent deformation results shown in Table 3.3, Figures 3.2 and 3.3. A resolution to the excessive bleeding and seizing problem was quickly found by freezing the samples overnight prior coring.

Table 3.3 - Summary of Test Results from the Repeated Load Permanent Deformation Test for Rosphalt HMA

Sample Type	Sample ID	Air Voids (%)	Flow Number (FN)	Permanent Strain (%)		Slope (b)
				@ 1,000 Cycles	@ 10,000 Cycles	
1% Air Void Design, 1% Air Void Compacted	#1	1.2	> 20,000	0.958	1.484	0.184
	#3	0.5	> 20,000	0.268	0.372	0.143
	#6	0.7	> 20,000	0.234	0.325	0.14
	Average	***0.6***	***> 20,000***	***0.251***	***0.349***	***0.142***
1% Air Void Design, 3% Air Void Compacted	#2	2.9	6,500	0.725	2.267	0.302
	#4	2.7	> 20,000	0.315	0.474	0.18
	#8	2.5	> 20,000	0.205	0.272	0.122
	Average	***2.6***	***> 20,000***	***0.260***	***0.373***	***0.151***

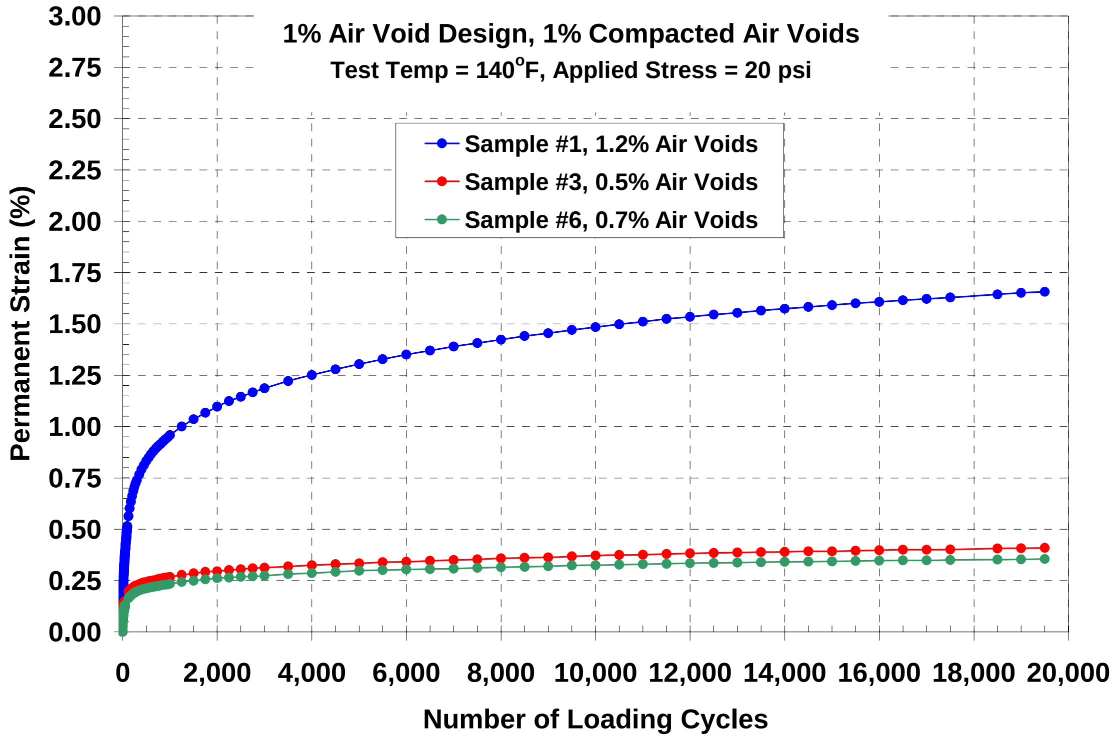


Figure 3.2 – Permanent Deformation Plots of 1% Air Void Design and 1% Air Void Compacted

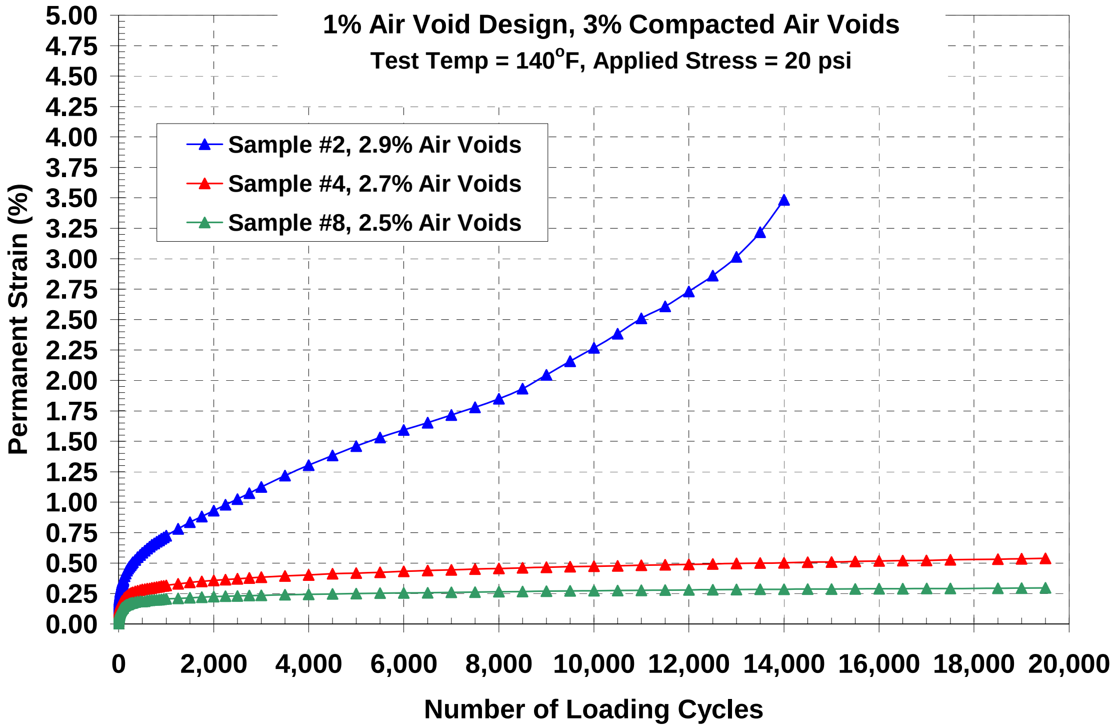


Figure 3.3 – Permanent Deformation Plots of 1% Air Void Design and 3% Air Void Compacted

The results of the permanent deformation testing indicated that:

- The flow number (F_N) of the 1% Air Void Compacted mix and 3% Air Void Compacted mix were shown to both be >20,000 loading cycles. It should be noted that the testing procedure used in the study was held to a maximum of 20,000 loading cycles.
- The slope of the permanent strain curve (b) for the 1% Air Void Compacted mix was found to be slightly less than that of the 3% Air Void Compacted mix. This would indicate that the 1% Air Void Compacted mix would accumulate permanent deformation at a lesser rate when compared to the 3% Air Void Compacted mix.
- The permanent deformation measured at the 1,000th loading cycle for the 1% Air Void Compacted mix was slightly lower than the 3% Air Void Compacted mix. This would indicate that the 1% Air Void Compacted mix would accumulate a lesser amount of permanent strain than the 3% Air Void Compacted mix.

3.3 Asphalt Pavement Analyzer Test Results

Although not part of the testing plan, the Asphalt Pavement Analyzer (APA) was also used to determine the rutting potential of the Rosphalt HMA. The APA is a loaded wheel testing unit that tests the rutting potential of HMA by running a loaded wheel over a pressurized hose which lies directly on the HMA samples. The testing was conducted using a 100 psi pressurized hose with a 100 lb wheel load being applied to the hose. All testing was conducted at 147°F (64°C).

To compare the test results, the APA rutting at 8,000 loading cycles is typically used by industry for comparative purposes. All Rosphalt 50 samples tested were compacted to the same target air voids as the Repeated Load Permanent Deformation tests. The APA tests results are shown in Figure 3.4. The results indicate that the 1% Air Void Design, 1% Air Void Compacted samples is slightly less susceptible to rutting than the 1% Air Void Design, 3% Air Void Compacted samples.

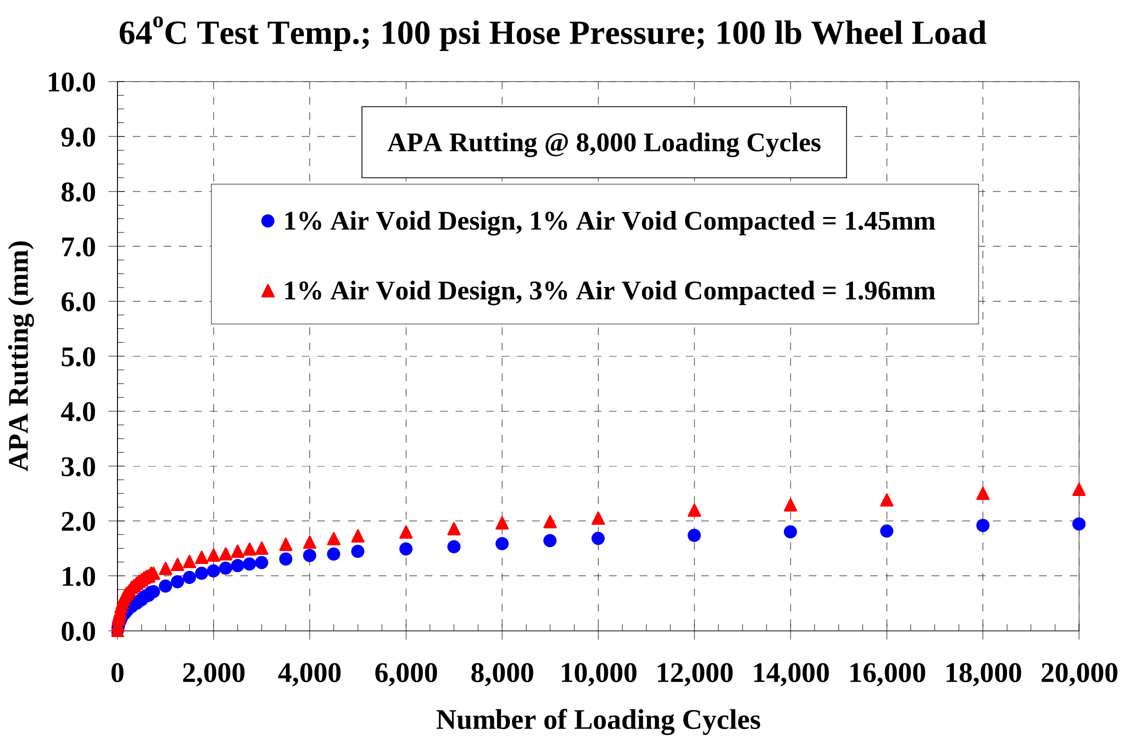


Figure 3.4 – Asphalt Pavement Analyzer Test Results for Rosphalt 50 Samples

3.4 Discussion of Results – Rosphalt 50 for the George Washington Bridge

The permanent deformation and fatigue resistance properties of the Rosphalt 50 materials were determined using advanced material characterization testing procedures. The permanent deformation properties were evaluated using the Repeated Load Permanent Deformation test procedure as described by NCHRP 465, as well as the Asphalt Pavement Analyzer. The flexural fatigue properties were evaluated using the Flexural Beam Fatigue device and test procedure described in AASHTO T321.

Based on the performance testing, the following conclusions were drawn:

- The Flexural Beam Fatigue test results showed that the Rosphalt 50 material should provide excellent fatigue resistance when the compacted air voids are less than 3% for the mixes evaluated in this study. The one sample, 3% Air Void Design, 5% Air Void Compacted, had the lowest fatigue life of 259,538 cycles, while the other three samples had a **fatigue life one order of magnitude greater.**

- The Repeated Load Permanent Deformation testing showed that 1% Air Void Design, 1% Air Void Compacted had a slightly better rutting resistance than the 1% Air Void Design, 3% Air Void Compacted samples. The same conclusion was drawn from the Asphalt Pavement Analyzer testing.
- A summary of all the samples that have been tested to date regarding the rehabilitation of the George Washington Bridge is provided.

3.5 Summary of Test Results for All Materials Evaluated for the George Washington Bridge

Table 3.4 – Summary of Flexural Beam Fatigue Tests Conducted at 900 μ-strains

Sample Type	Air Voids (%)	Initial Stiffness, S_O (MPa)	Exp. Constant, b	Fatigue Life, $N_{f, 50\%}$ (cycles)
R-50 1% Air Void Design, 1% Air Void Compacted	1.4	1,347,7	-2.45E-07	2,832,294
R-50 1% Air Void Design, 3% Air Void Compacted	2.7	782.9	-2.17E-07	3,191,433
R-50 3% Air Void Design, 3% Air Void Compacted	3.1	891.4	-2.36E-07	2,939,057
R-50 3% Air Void Design, 5% Air Void Compacted	4.5	766.6	-2.67E-06	259,538
Epoxy HMA	1.4	7,917.20	-4.17E-08	16,626,222
I-5, PG76-22, 5.9% AC	5.8	3,568.50	-6.00E-05	11,558
I-5, PG76-22, 6.3% AC	5.1	2,803.70	-3.91E-05	17,712

Table 3.5 – Summary of Repeated Load Permanent Deformation Tests

Sample Type	Sample ID	Air Voids (%)	Flow Number (FN)	Permanent Strain (%)		Slope (b)
				@ 1,000 Cycles	@ 10,000 Cycles	
R-50 1% Air Void Design, 1% Air Void Compacted	#3	0.5	> 20,000	0.268	0.372	0.143
	#6	0.7	> 20,000	0.234	0.325	0.14
	Average	***0.6***	***> 20,000***	***0.251***	***0.349***	***0.142***
R-50 1% Air Void Design, 3% Air Void Compacted	#4	2.7	> 20,000	0.315	0.474	0.18
	#8	2.5	> 20,000	0.205	0.272	0.122
	Average	***2.6***	***> 20,000***	***0.260***	***0.373***	***0.151***
Epoxy HMA	# 2	1.3	> 20,000	0.034	0.041	0.059
	# 7	1.8	> 20,000	0.02	0.024	0.054
	# 8	1.9	> 20,000	0.015	0.015	0.032
	Average	***1.85***	***> 20,000***	***0.018***	***0.020***	***0.043***
I-5, PG76-22, 5.9% AC	A	5.6	1,410	0.699	> 2.0	0.212
	C	5.8	1,961	0.629	> 2.0	0.192
	E	5.8	1,243	0.761	> 2.0	0.209
	Average	***5.8***	***1,538***	***0.695***	***> 2.0***	***0.200***
I-5, PG76-22, 6.3% AC	B	4.7	1,460	0.78	> 2.0	0.246
	C	5.3	1,703	0.819	> 2.0	0.232
	D	5.1	1,414	0.762	> 2.0	0.222
	Average	***5.2***	***1,526***	***0.791***	***> 2.0***	***0.227***

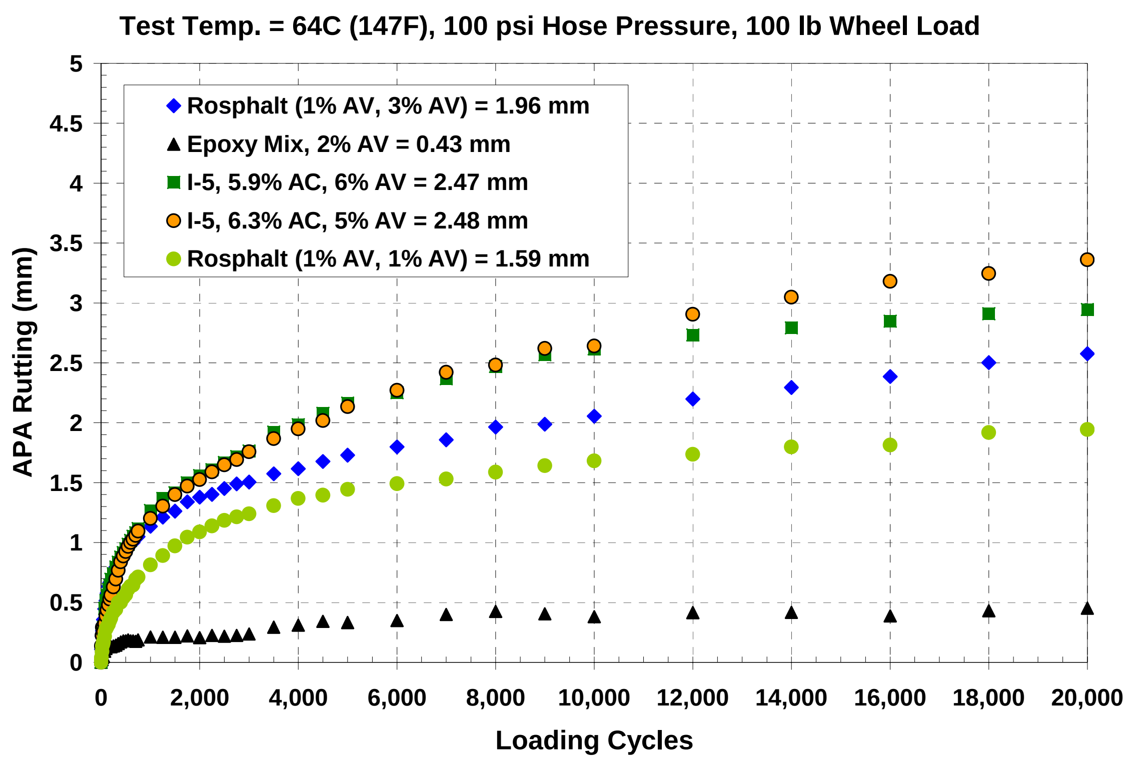


Figure 3.5 – Asphalt Pavement Analyzer Test Results

4.0 EVALUATION OF HMA INTERFACE BONDING

The scope of work encompassed testing the bond strength between successive HMA lifts that were placed on a runway at Newark Liberty International Airport. Visual surveys indicated that sections of the runway that contained a Granite/Gneiss had significant debonding (Figures 4.1 and 4.2). The debonding at the HMA lift interface caused the top section of the runway to "slide" in the same direction where excessive breaking and turning of the aircrafts occurred.

The Superpave Shear Tester (SST) was used to simulate typical loading conditions found in the field (Figure 4.3). This consisted of applying a shear and axial stress on the specimen at the same time, called biaxial loading. The biaxial loading condition models the applied stress due to a moving, yet breaking, wheel load over the asphalt section. The axial and shear stresses were applied in a cyclic manner at a rate of 2 Hz (0.5 second load duration) with a 1 second rest period at a test temperature of 100^{o}F.

Results of the testing indicated that the Granitic Gneiss samples, on average, debonded after 3,384 cycles, while the Trap Rock samples showed no evidence of debonding within the 10,000 loading cycle period. This trend corresponds to the field observations of the Granite/Gneiss section debonding on the runway.

4.1 Laboratory Evaluation of HMA Interface Bond Strength

Runway cores taken from Newark Liberty International Airport were delivered to the Rutgers Asphalt Pavement Laboratory (RAPL) for sample preparation and testing. Sample preparation encompassed trimming the cores samples to a final specimen height of 2 inches. This allowed for 1 inch of asphalt to be above and below the lift interface. The specimens were first tested for their respective bulk specific gravity (AASHTO T166) and the remaining HMA from the cores were used to determine the maximum specific gravity (AASHTO T209). The results of the specimens are shown in Table 4.1.

Table 4.1 – Bulk and Maximum Specific Gravity Properties of the Specimens

Sample #	Bulk Specific Gravity (g/cm^3)	Maximum Specific Gravity (g/cm^3)	Air Voids (%)
Trap Rock #3	2.471	2.571 *	3.9
Trap Rock #4	2.472	2.571 *	3.8
Trap Rock #5	2.459	2.571 *	4.3
		Trap Rock Average =	**4.0**
Granite/Gneiss #1	2.456	2.551 *	3.7
Granite/Gneiss #4	2.472	2.551 *	3.1
Granite/Gneiss #5	2.463	2.551 *	3.5
		Granite/Gneiss Average =	**3.4**

Figure 4.1 – Slipping at Newark Airport – Middle of Paving Lane

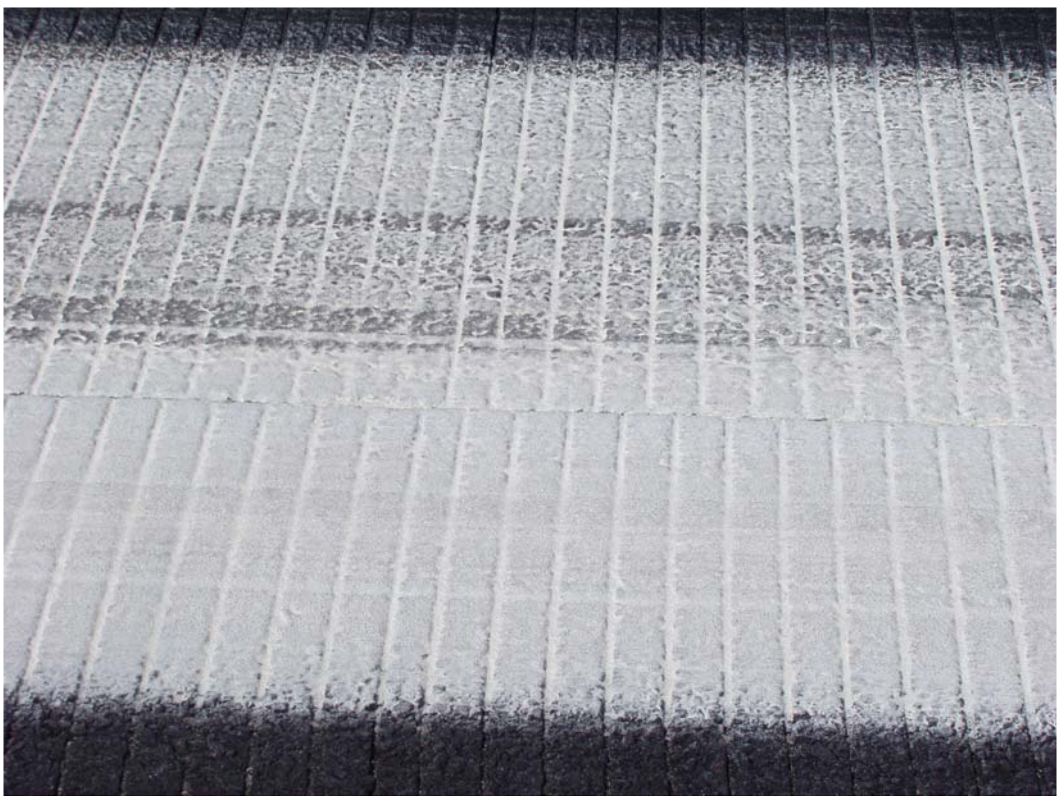


Figure 4.2 – Slipping at New Airport – Longitudinal Joint

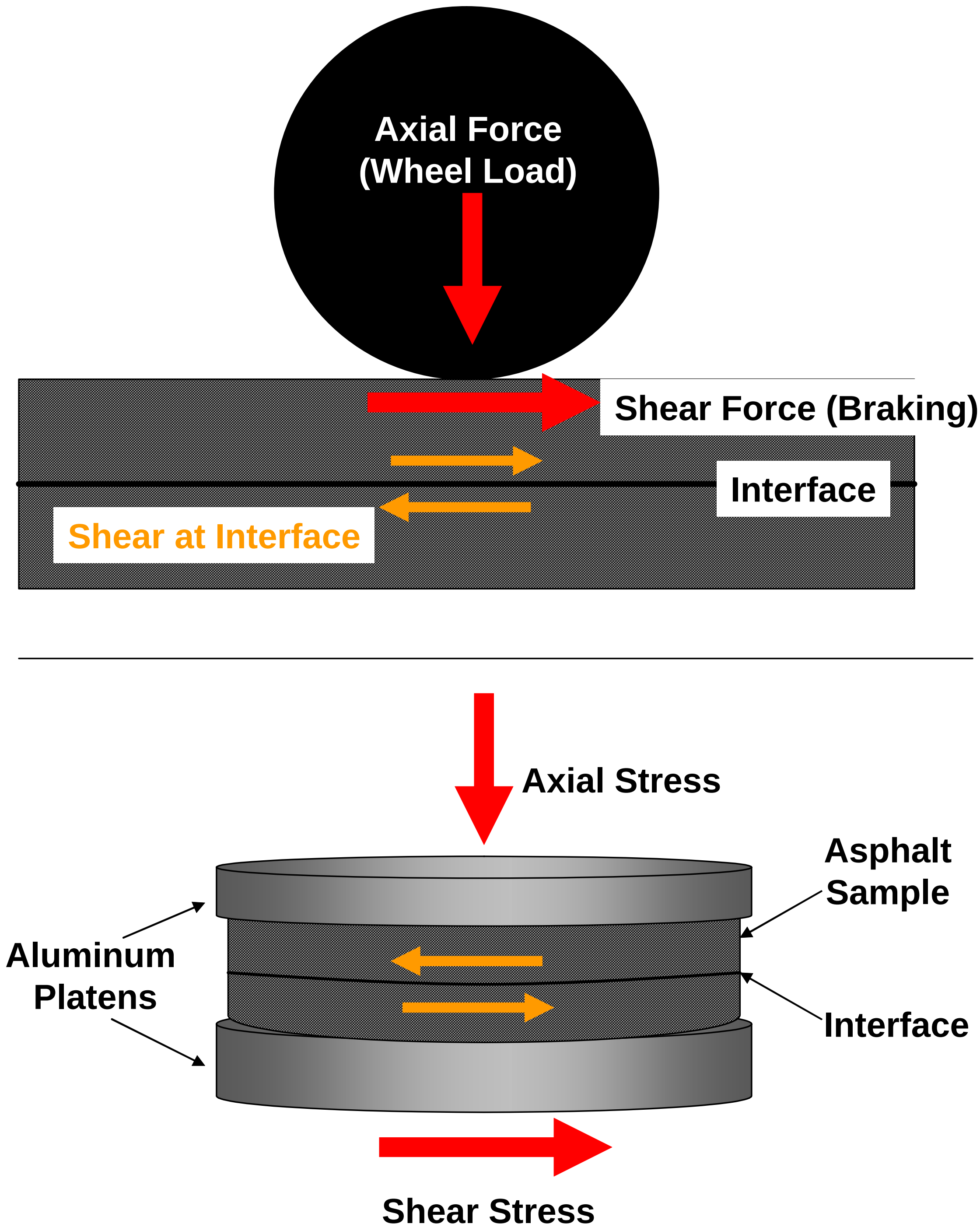


Figure 4.3 – Comparison of Field Stress and Laboratory Applied Stress Conditions

Before testing, each specimen was placed in the environmental chamber of the SST for a minimum of 4 hours at a test temperature 100°F. After the 4 hour conditioning time, the samples were clamped in the SST unit for bond strength testing (Figure 4.4).

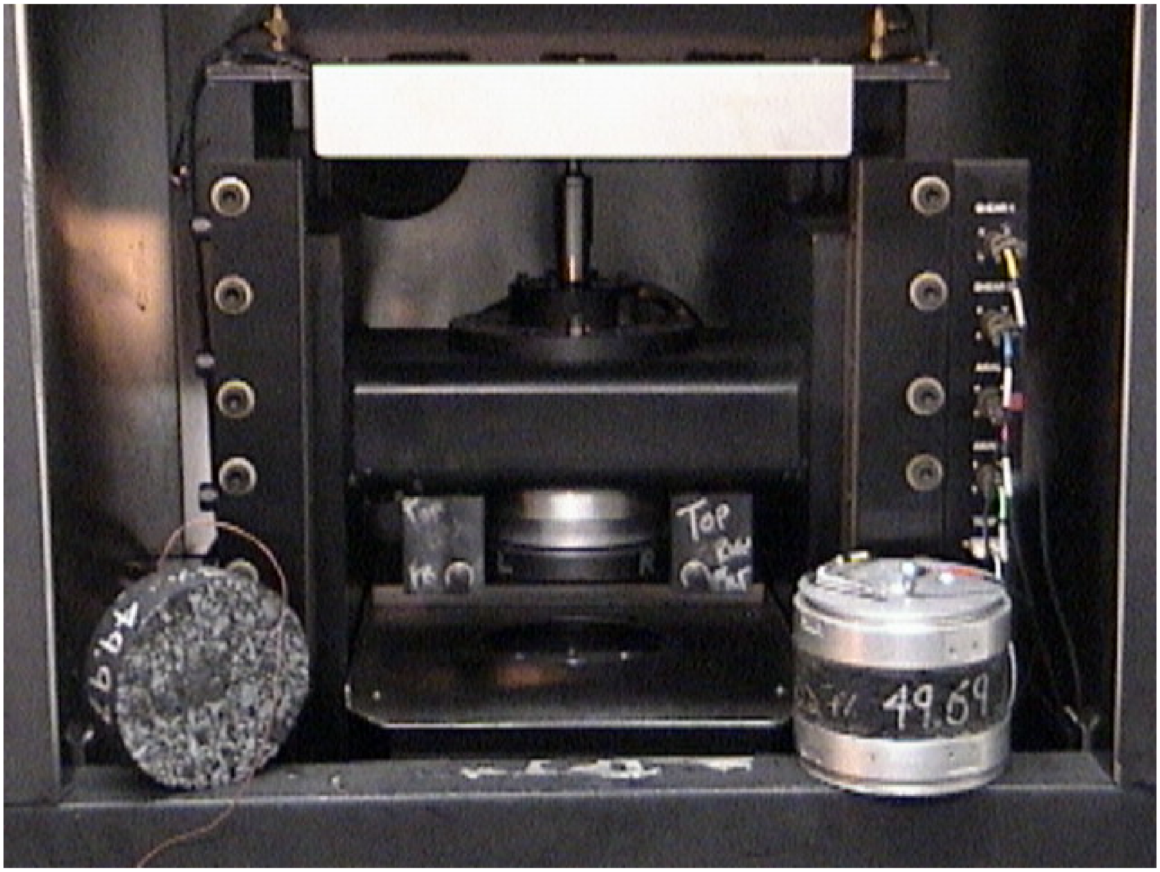


Figure 4.4 – Superpave Shear Tester (SST)

The test specimens were instrumented with 2 Linear Variable Differential Transducers (LVDT's) to measure the change in height (axial strain) and change in horizontal distance (shear strain). The shear strain measured in the SST device would model the horizontal movement of the HMA layer, while the axial strain would model the vertical separation of the two layers.

The test procedure used for the testing consisted of the following:

- Test temperature = 100°F
- Loading Frequency = 2 Hz (or the load pulse was applied in 0.5 seconds)
- Rest Period = 1 second (the time in-between each applied load)
- Applied Shear Stress = 15 psi
- Applied Axial Stress = 18.75 psi
- Applied Stress Ratio (Axial : Shear) = 1.25
- Number of Loading Cycles = 10,000

The test results for the Granite/Gneiss aggregate samples are shown in Figures 4.5 through 4.7. There are two distinct changes in the performance of the Granite/Gneiss samples that indicate the interface bond had been broken.

1. Sudden Change in the Slope of the Permanent Shear Strain Curve – As the sample is being loaded in the shear direction, permanent shear strain starts to develop. This is typical for most HMA samples due to this shear-type of loading and it simulates permanent deformation (rutting). However, what is not typical of the "Shear Strain" curve, shown as the Black line in the figures, is that there is a sudden jump at a particular point in the loading. This sudden "jump" signifies the start of where the rate of permanent shear strain becomes greater (i.e. – the rate at which the sample deforms in the horizontal direction increases). This point at which the sudden increase occurs is where the bond at the interface has been broken and results in a faster accumulation of shear strain due to the weakened plain.

2. Sudden Change in the Slope of the Axial Strain Curve – As the bond at the interface of the sample begins to break, there is a sudden increase in the axial strain (increase in sample height) due to the aggregates from each layer starting to move over one another. The axial strain curve, once the break has occurred, also continues to increase (distance between HMA lifts continues to move apart from one another).

Based on the above two criteria for the indication of the interface bond break, a comparison of the three Granite/Gneiss samples shows that the interface bond broke between 2,800 and 4,450 cycles, with an average of 3,384 loading cycles until the interface bond breaks.

When evaluating the same performance curves for the Trap Rock aggregate samples (Figures 4.8 through 4.10), there was no indication that a bond had been broken. In fact, the Trap Rock samples perform in an identical manner to HMA samples that do not have a bonded interface. This indicates a strong interface bond where the two HMA lifts perform in a manner that would represent one single layer in the field.

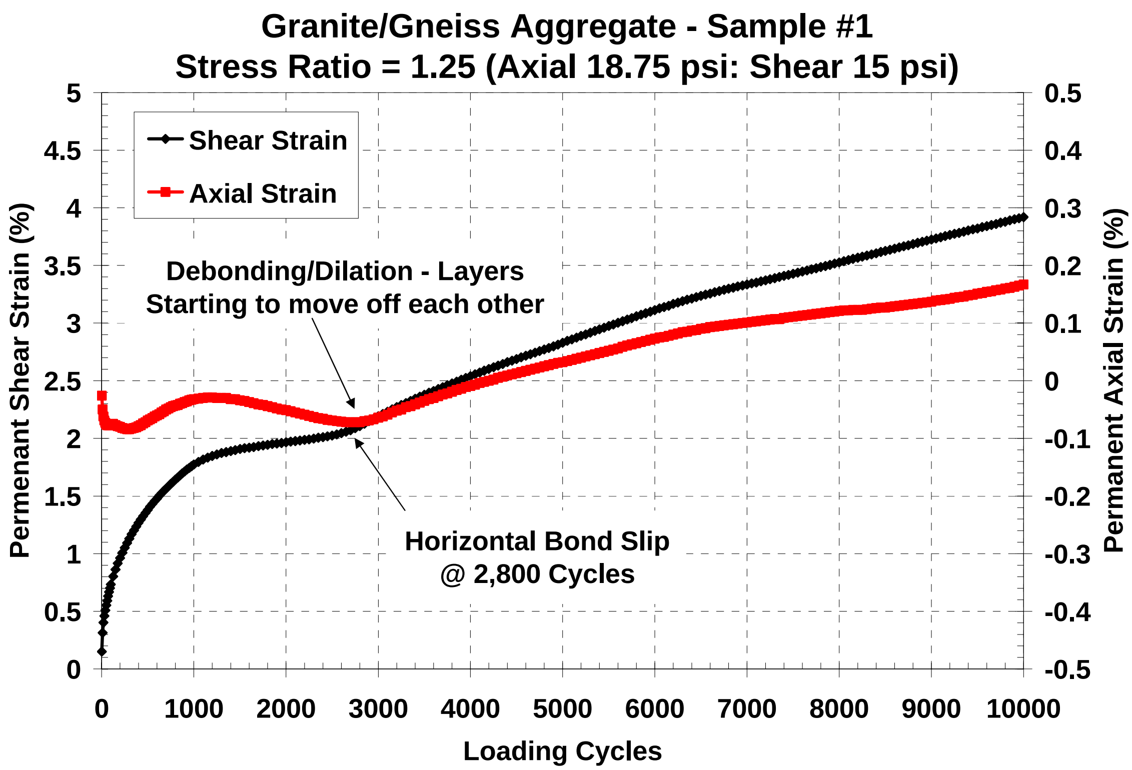


Figure 4.5 – Granite/Gneiss Core #1

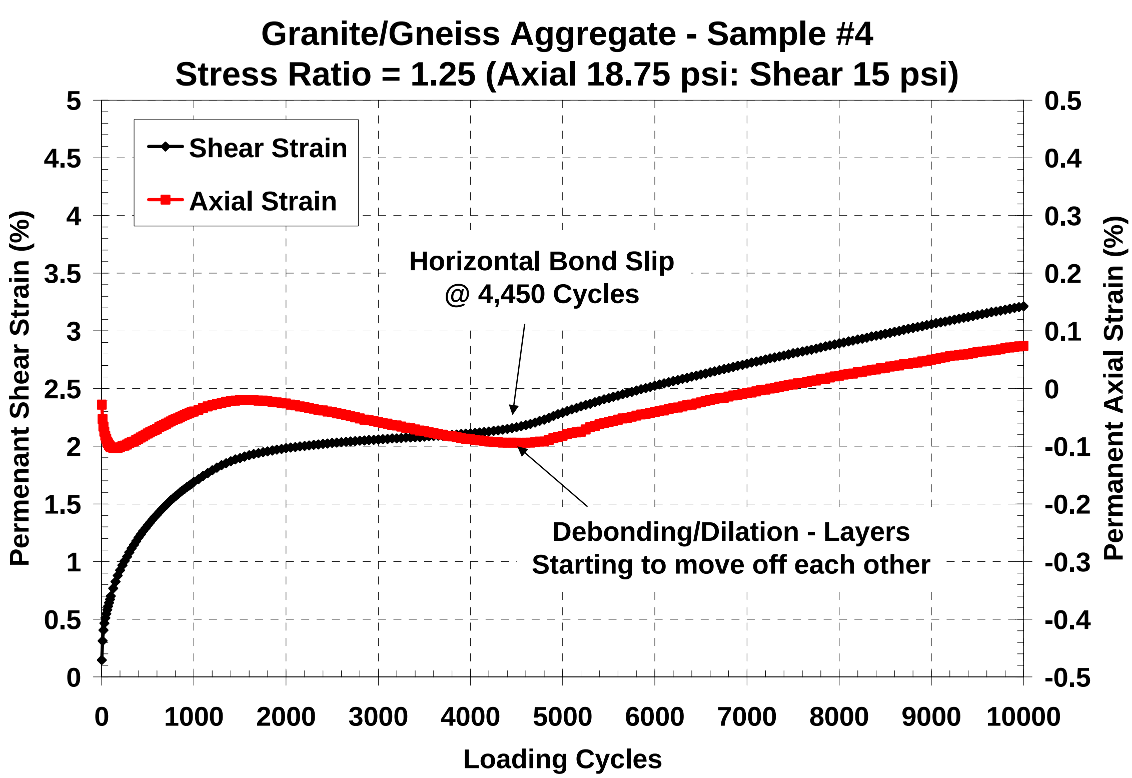


Figure 4.6 – Granite/Gneiss Core #4

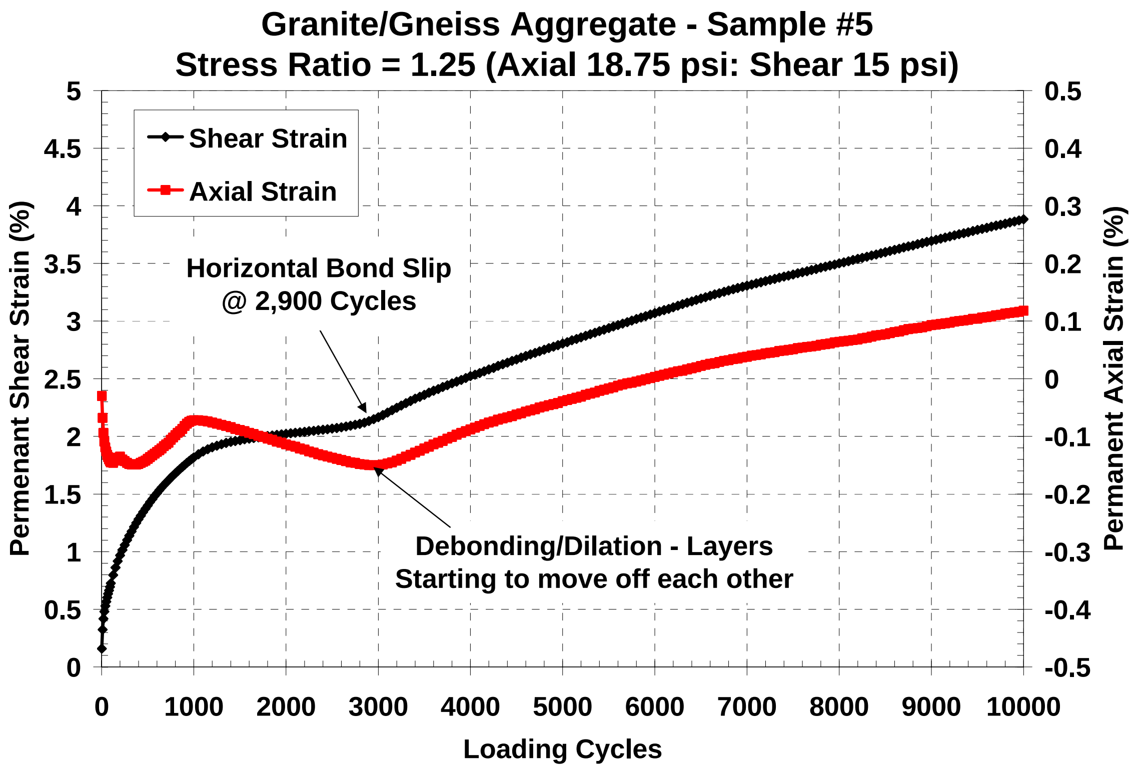


Figure 4.7 – Granite/Gneiss Core #5

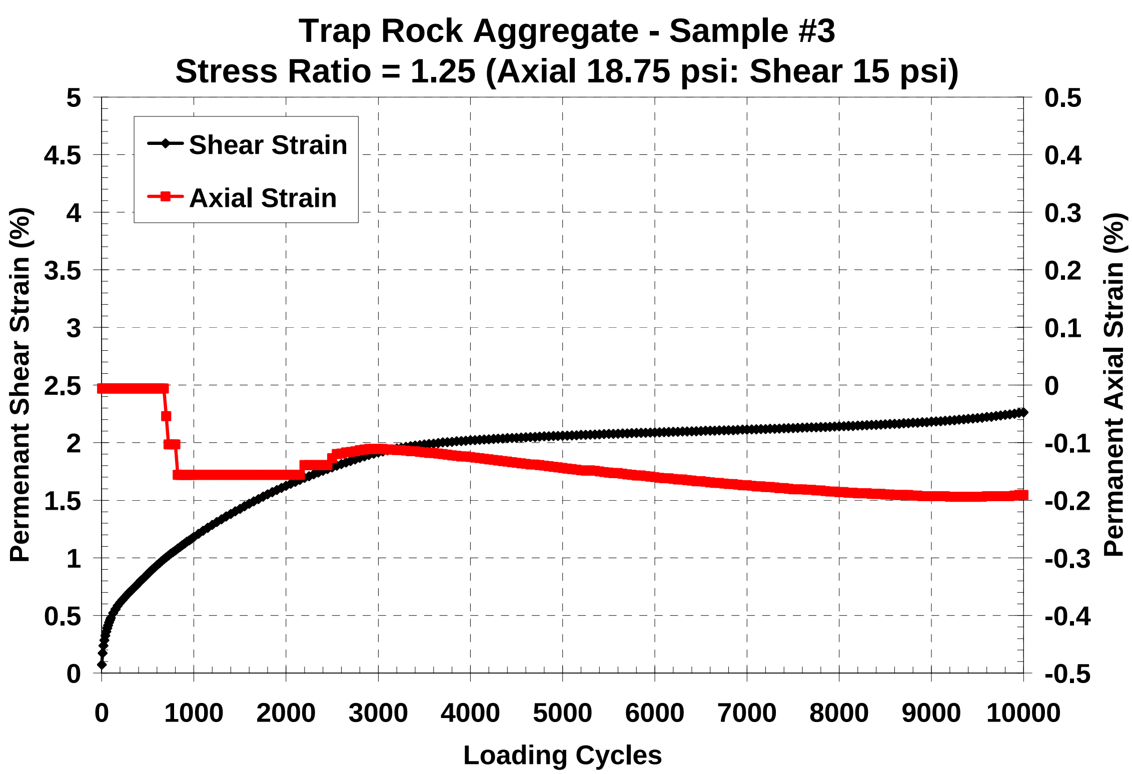


Figure 4.8 – Trap Rock Core #3

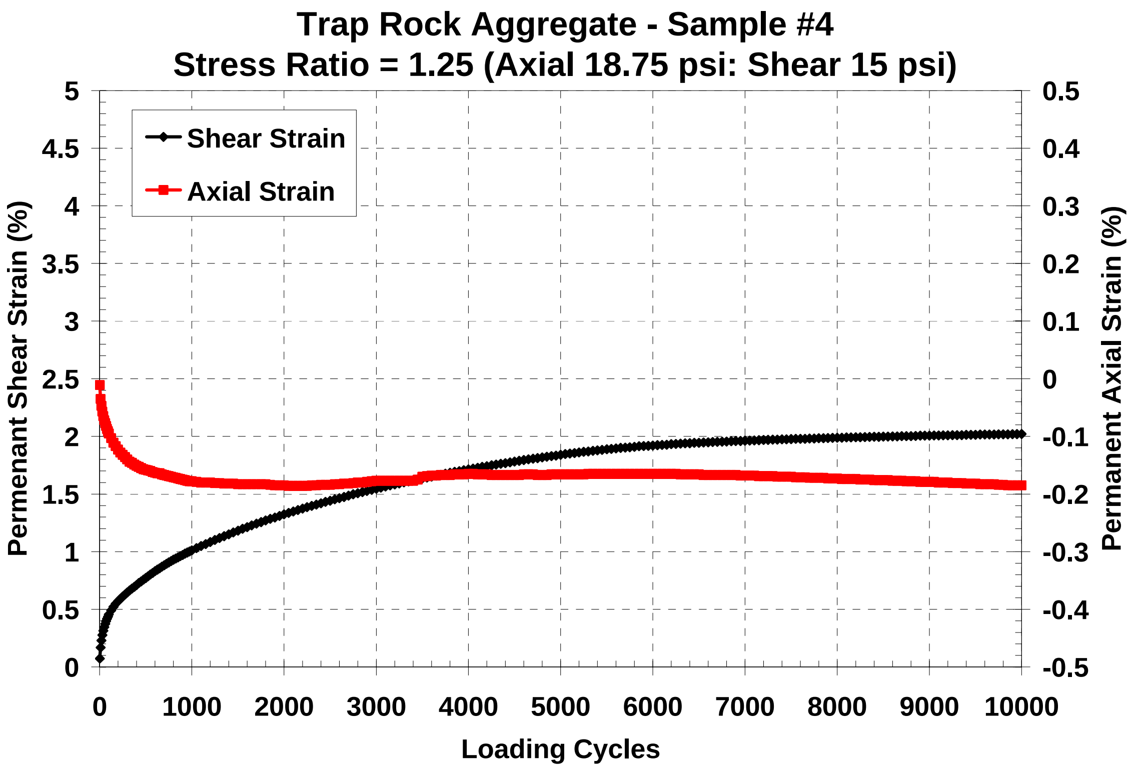


Figure 4.9 – Trap Rock Core #4

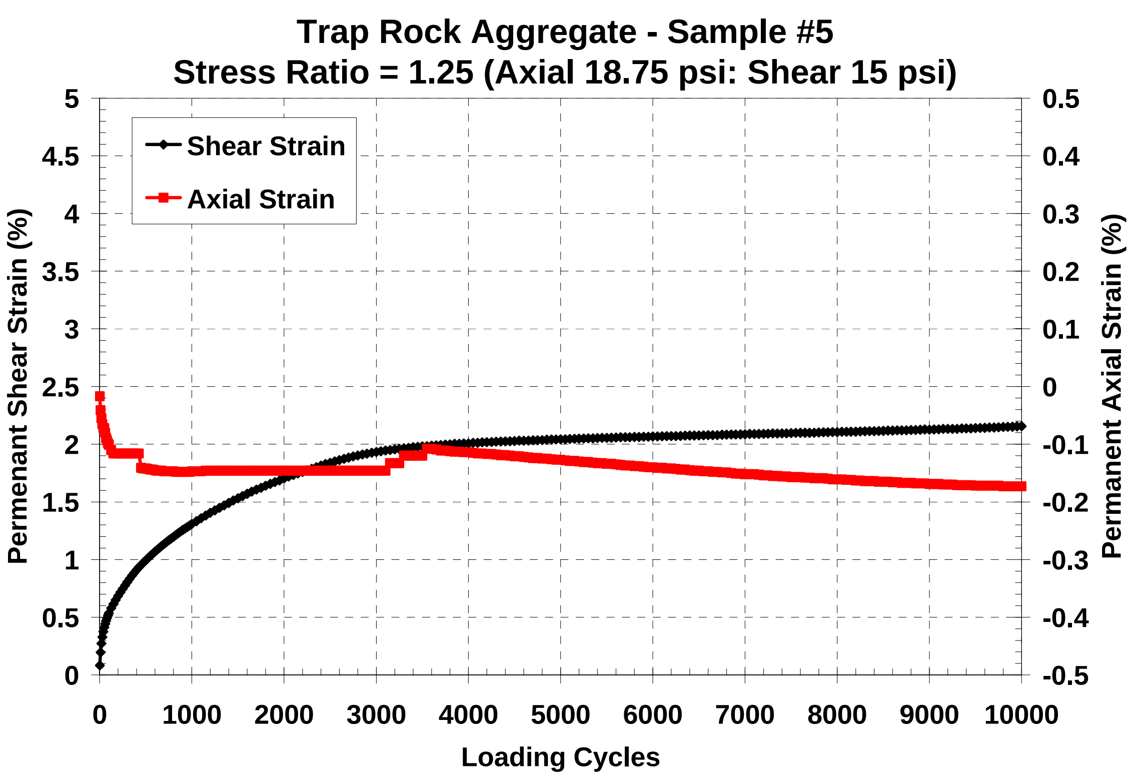


Figure 4.10 – Trap Rock Core #5

5.0 INFLUENCE OF HIGH PG GRADE ON RUTTING POTENTIAL

The scope of work encompassed evaluating the affect of different performance-graded asphalt binders on the rutting performance of a FAA #3 Surface Course Mix tested under repeated load conditions (permanent deformation testing). A FAA #3 mix design was developed at the Rutgers Asphalt Pavement Laboratory (RAPL) using aggregates supplied by Tilcon's Mt. Hope facility. Four different performance-graded asphalt binders where used in the study; 1) CITGO Fuel Resistant Binder (graded as a 94-22), 2) PG82-22, 3) PG76-22, and 4) PG64-22. All asphalt binders were supplied by CITGO Asphalt's Paulsboro, NJ facility.

5.1 Materials Used and Marshall Mix Design

The aggregate gradation chosen was based on a preliminary mix design currently on the books at the Mt. Hope facility, and was approved by Port Authority of New York/New Jersey (PANYNJ) personnel. The gradation band was specified by the PANYNJ and is noted as Top Course Mix #3 in Section 02561, Asphalt Paving Concrete (FAA). The final gradation used in the study is shown in Figure 5.1.

The materials supplied by the Tilcon Mt. Hope facility were used for a 75 Blow Marshall design. A design air void requirement of 4.0% was used. The 75 Blow Marshall mix design volumetrics are shown in Figure 5.2 for review. The optimum asphalt content selected for use in the study was 6.1%. The optimum asphalt content was determined using the PG76-22 asphalt binder and assumed to be the same for the remaining asphalt binders used in the study. Stability and Flow measurements were not conducted.

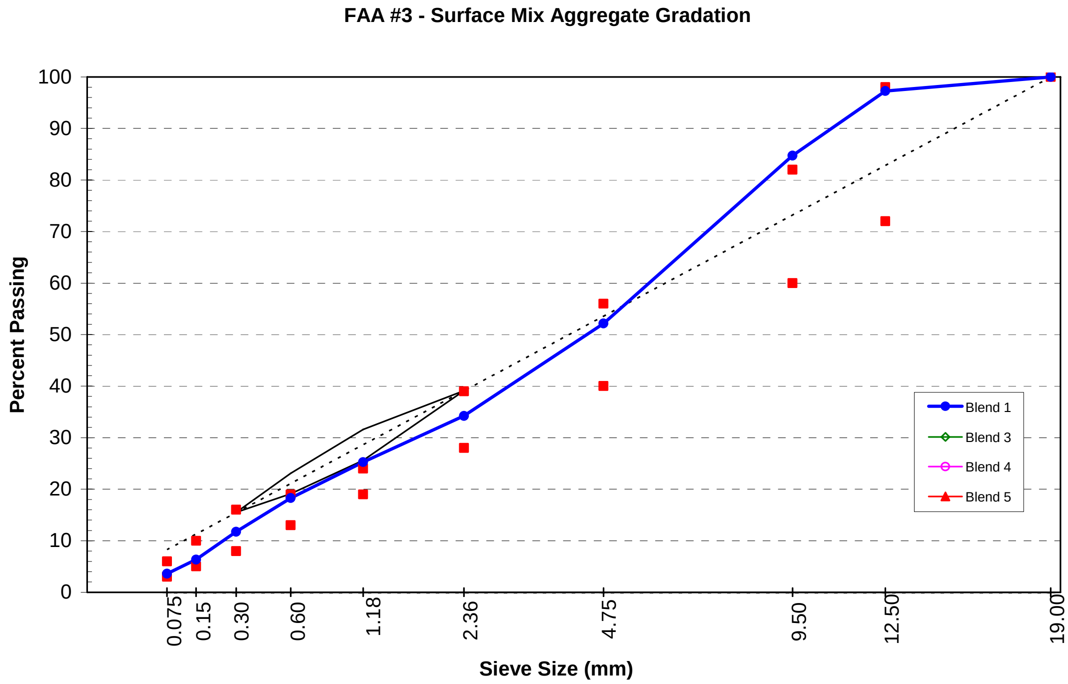


Figure 5.1 – Aggregate Gradation of FAA #3 Surface Course Mix Used in Study (Mt. Hope Aggregates)

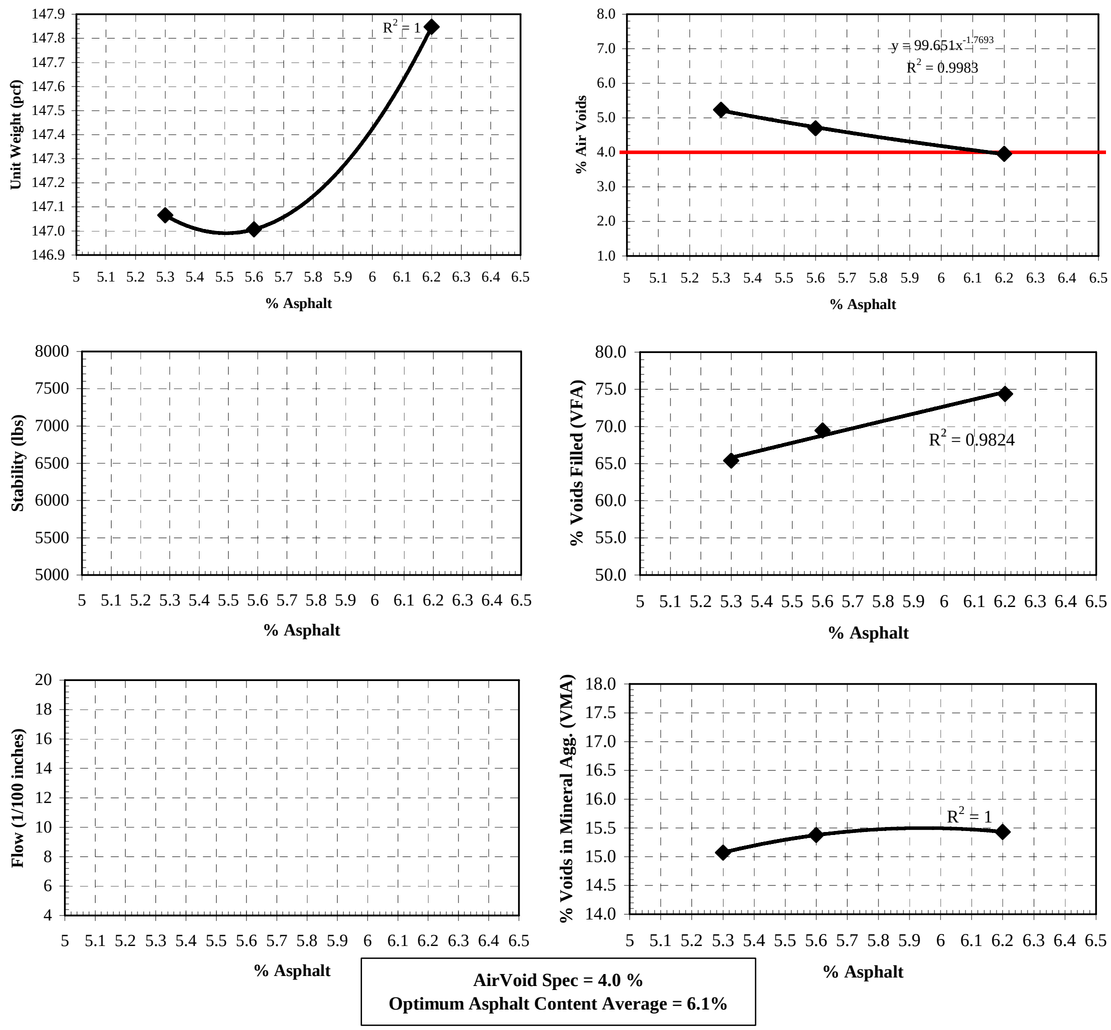


Figure 5.2 – 75 Blow Marshall Design Results for FAA #3 Surface Course Mix

5.2 Permanent Deformation Testing

To evaluate the permanent deformation potential of the different mixes, repeated load testing was conducted using the Simple Performance Test (SPT) set-up. The SPT test set-up requires a sample be compacted using the gyratory compactor to 7 inches in height and 6 inches in diameter. After compaction, a final sample is cored out from the inside of gyratory sample and then trimmed using a masonry saw (Figure 5.3). Once the sample is trimmed, it is checked to verify the dimensions meet the tolerance as specified in AASHTO TP63.

After the specimens were fabricated, three LVDT (linear variable differential transformers) were glued to the sides of the HMA specimen at 120 degrees apart with a final gage length of 100 mm (Figure 4). The samples were then heated to 140^{o}F. A dummy sample, instrumented with internal and skin thermocouples, was used to ensure the test sample obtained the required test temperature. Once temperature was achieved, the samples were cyclically loaded using a haversine waveform. A deviatoric cyclic stress of 25 psi was applied for a duration of 0.1 seconds and then followed by a 0.9 second rest period.

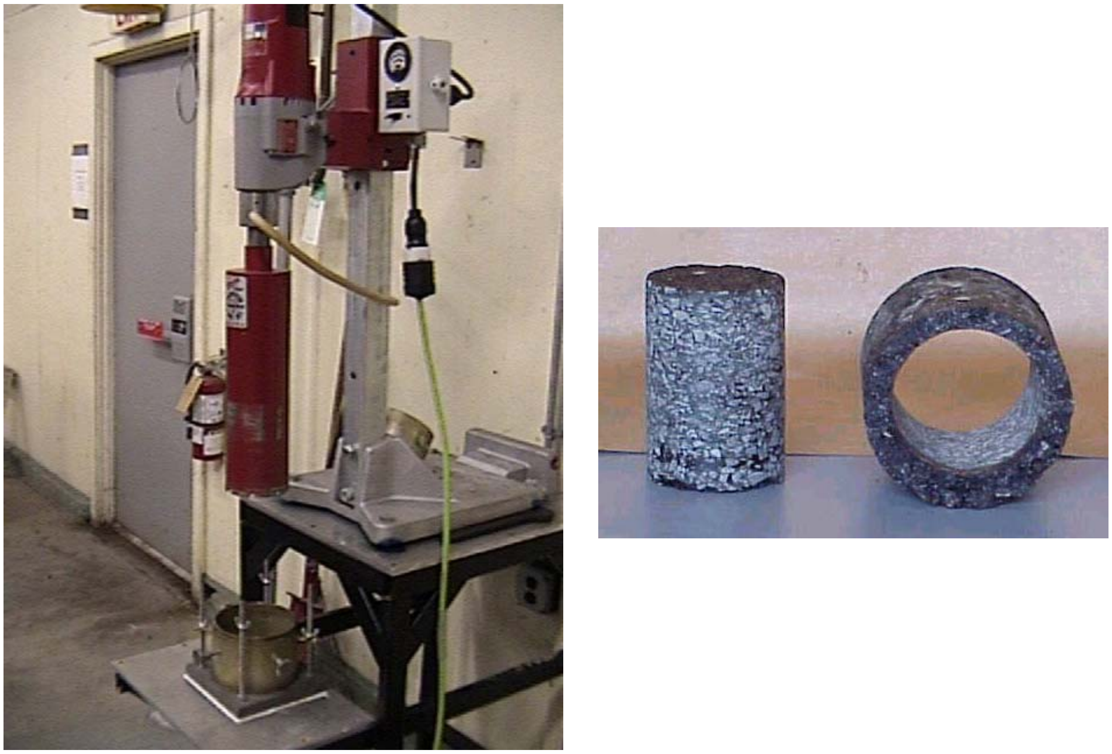


Figure 5.3 – Sample Preparation for Repeated Load Using the SPT Set-up

Figure 5.4 – Instrumented Simple Performance Test Specimen

Three test properties are determined and compared from the repeated load testing:

7. Flow Number (F_N) – The Flow Number is determined by plotting the rate of change of axial strain versus the number of loading cycles (Figure 5.5). The number of loading cycles pertaining to the part of the curve where the slope is zero is designated as the Flow Number. The larger the flow number, the more resistant the HMA mix is to permanent deformation;
8. Slope of the Linear Portion of the Permanent Strain vs Cycles Plot (b) – The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates (Figure 5.6); and
9. Accumulated Permanent Deformation at 1,000 Loading Cycles (ε_P (%) @ N = 1,000) – The larger the ε_P (%) @ 1,000 cycles, the greater the potential for rutting in the field.

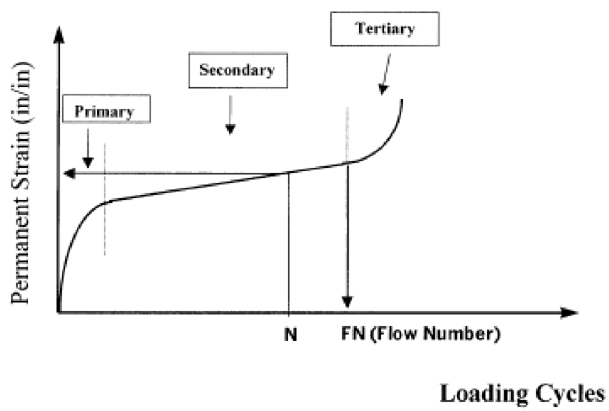


Figure 5.5 – Example of Flow Number During Repeated Load Test

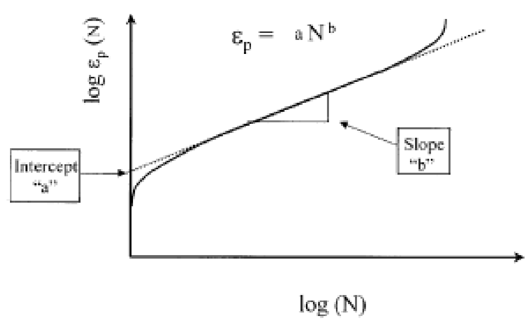


Figure 5.6 – Example of Slope, b, During the Repeated Load Test

These three parameters were shown to provide the best correlation to measured field rutting (NCHRP 465) when conducting the repeated load permanent deformation test. The correlation results determined in NCHRP 465 are shown in Table 5.1.

Table 5.1 – Results of Test Parameter Correlation to Field Rutting (NCHRP 465)

Unconfined Repeated Load	Model	100°F				130°F			
		R^2	Se/Sy	Rational	Rating	R^2	Se/Sy	Rational	Rating
Flow Number (F_N)	Power	0.96	0.229	Yes	Excellent	0.90	0.359	Yes	Good
Slope (b)	Linear	0.59	0.743	Yes	Fair	0.87	0.393	Yes	Good
Permanent Strain	Linear	0.95	0.256	Yes	Excellent	0.86	0.410	Yes	Good
Resilient Strain	Linear	0.90	0.362	Yes	Excellent	0.66	0.652	Yes	Fair
Resilient Modulus at Flow	Linear					0.72	0.548	Yes	Good
$\varepsilon_p/\varepsilon_r$ Ratio	Linear	0.83	0.472	Yes	Good	0.59	0.676	Yes	Fair
Mu (μ)	Linear	0.79	0.530	-	Good	0.25	0.881	-	Poor
Intercept (a)	Linear	0.30	0.964	Yes	Poor	0.13	1.055	Yes	Very Poor

The table clearly shows that at the test temperature of 130°F, the R^2 values for the 3 parameters when compared to measured field rutting were all greater than 0.86. This should also correspond to the requested test temperature of 140°F used in this study.

The SPT repeated loaded permanent deformation test results are shown in Table 5.2 and Figures 5.7, 5.8, 5.9, and 5.10. A direct comparison of each of the test parameters is shown in Figures 5.11, 5.12 and 5.13. The test results clearly show that as the high-temperature performance grade of the asphalt binder increases, the resistance to permanent deformation increases. Therefore, the best performing asphalt binder was the CITGO FR binder (PG94-22), and the poorest performing asphalt binder was the PG64-22.

Table 5.2 – Summary of Test Results from the Repeated Load Permanent Deformation Test for Laboratory Produced Mixes with Varying Asphalt Binder Grades

SPT Repeated Load Test Results (140°F, 25 psi Applied Stress)							
Research Phase	**Mix Type**	**Sample ID**	**Air Voids (%)**	**Flow Number, F_N (cycles)**	**Slope, b**	**ε_P @ 1,000 (%)**	**ε_P @ 10,000 (%)**
FAA #3 Surface Course Mix with Varying Asphalt Binder Grades	FAA#3 Surface Mix, 75 Blow, 6.1% AC, FR Binder, 4% AV Design	#1	5.70	>20,000	0.162	0.397	0.580
		#3	5.30	>20,000	0.135	0.301	0.413
		#5	5.40	>20,000	0.155	0.299	0.435
		Average	***5.35***	***20,000***	***0.151***	***0.332***	***0.476***
	FAA#3 Surface Mix, 75 Blow, 6.1% AC, PG82-22 Binder, 4% AV Design	#6	6.00	2,894	0.234	0.725	3.495
		#7	5.40	> 20,000	0.229	0.413	0.776
		#8	5.70	4,041	0.279	0.735	2.046
		Average	***5.70***	***8,978***	***0.247***	***0.624***	***2.106***
	FAA#3 Surface Mix, 75 Blow, 6.1% AC, PG76-22 Binder, 4% AV Design	#1	5.40	1,206	0.301	1.081	---
		#2	5.70	604	0.318	1.087	---
		#3	5.50	858	0.328	1.203	---
		Average	***5.53***	***889***	***0.316***	***1.124***	***> 3.0***
	FAA#3 Surface Mix, 75 Blow, 6.1% AC, PG64-22 Binder, 4% AV Design	#1	5.60	215	0.503	---	---
		#2	5.30	120	0.575	---	---
		#3	5.40	267	0.410	---	---
		Average	***5.43***	***201***	***0.496***	***> 3.0***	***> 3.0***

* - For averaging purposes, a Flow Number of >20,000 was assumed as 20,000

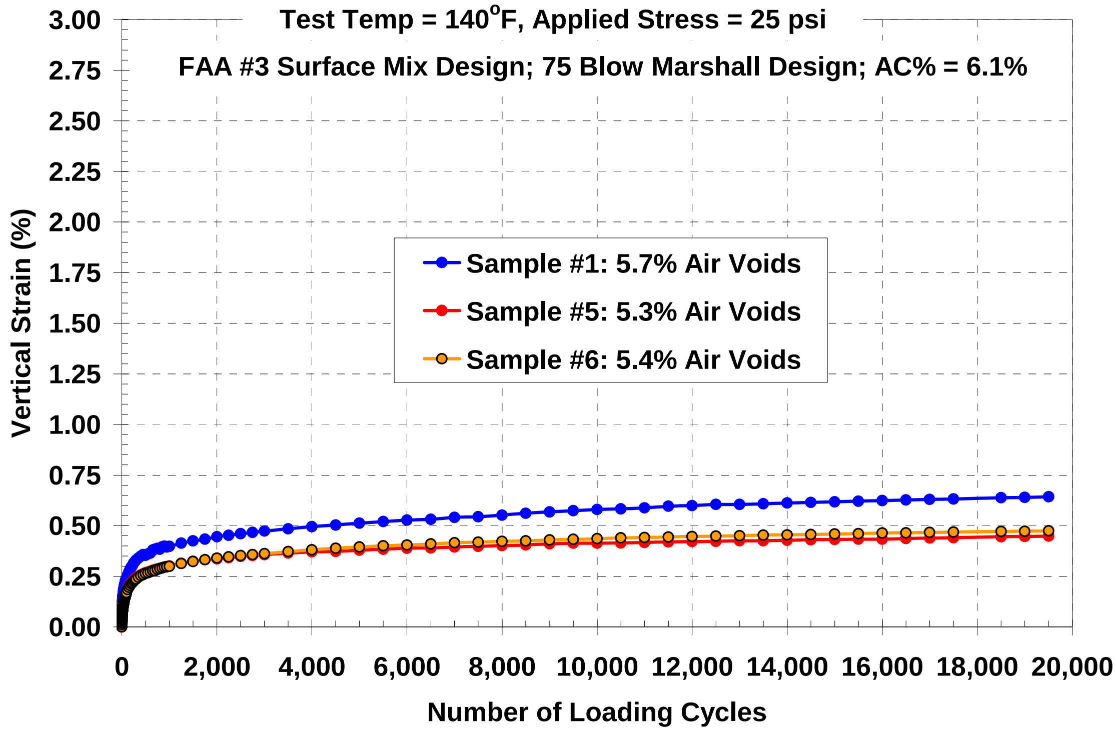


Figure 5.7 – FAA #3 Surface Course Mix with CITGO Fuel Resistant Asphalt Binder

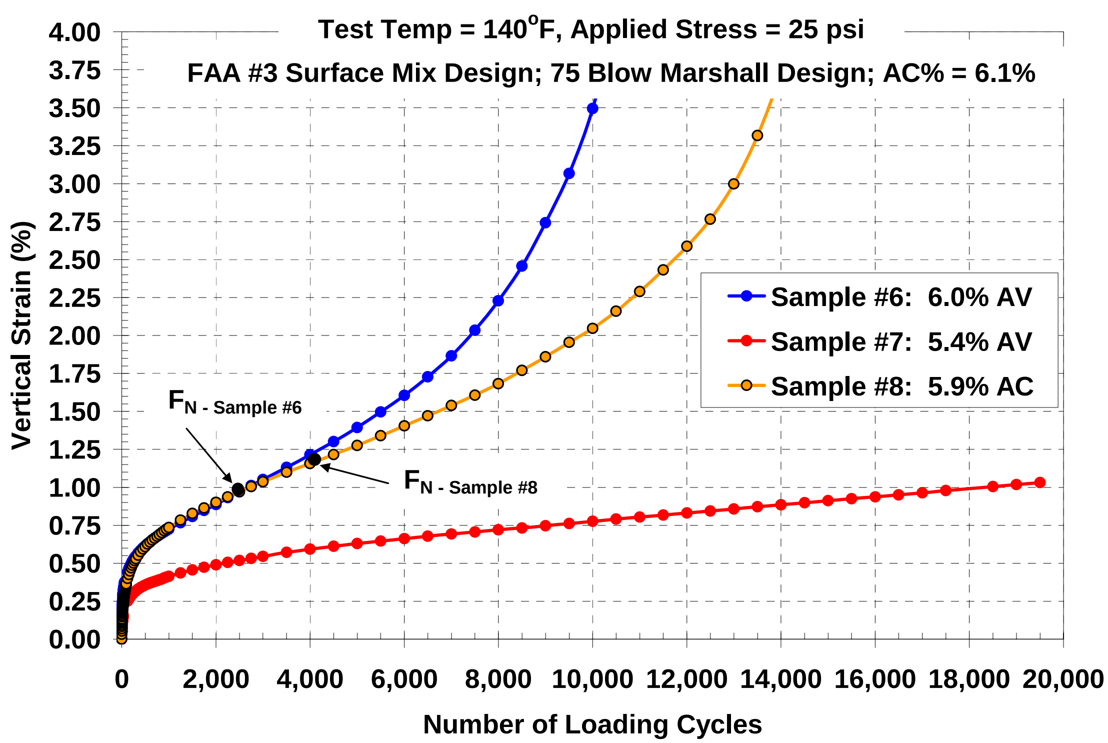


Figure 5.8 – FAA #3 Surface Course Mix with PG82-22 Asphalt Binder (CITGO Asphalt)

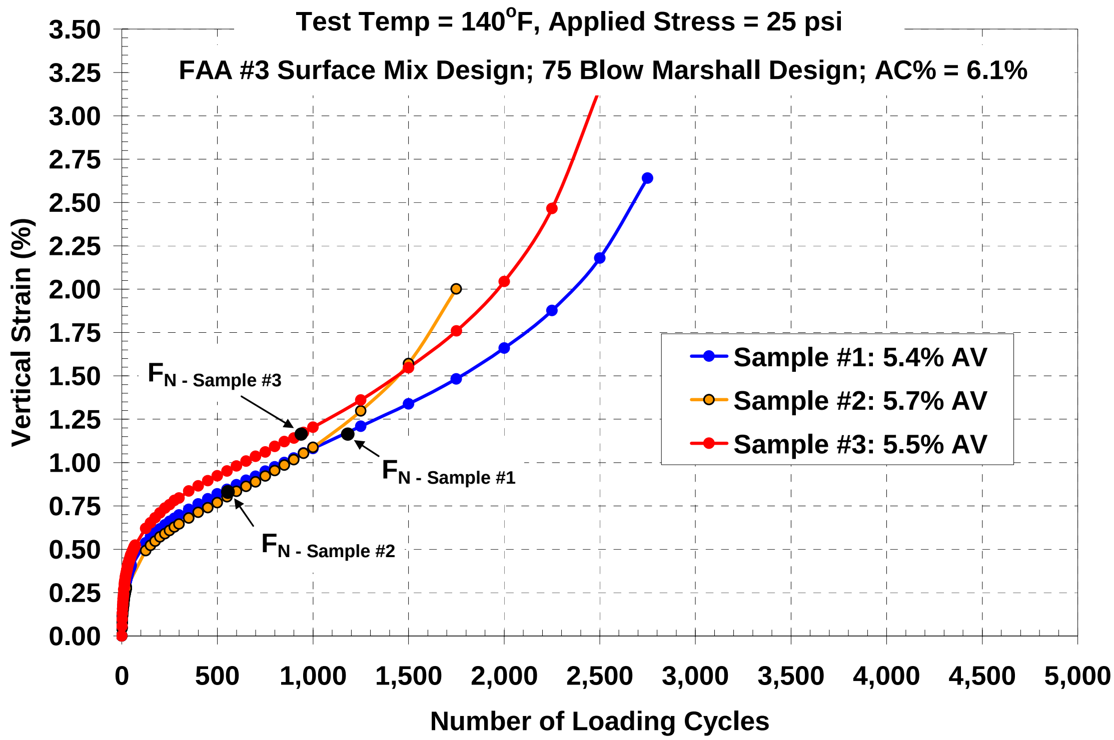


Figure 5.9 – FAA #3 Surface Course Mix with PG76-22 Asphalt Binder (CITGO Asphalt)

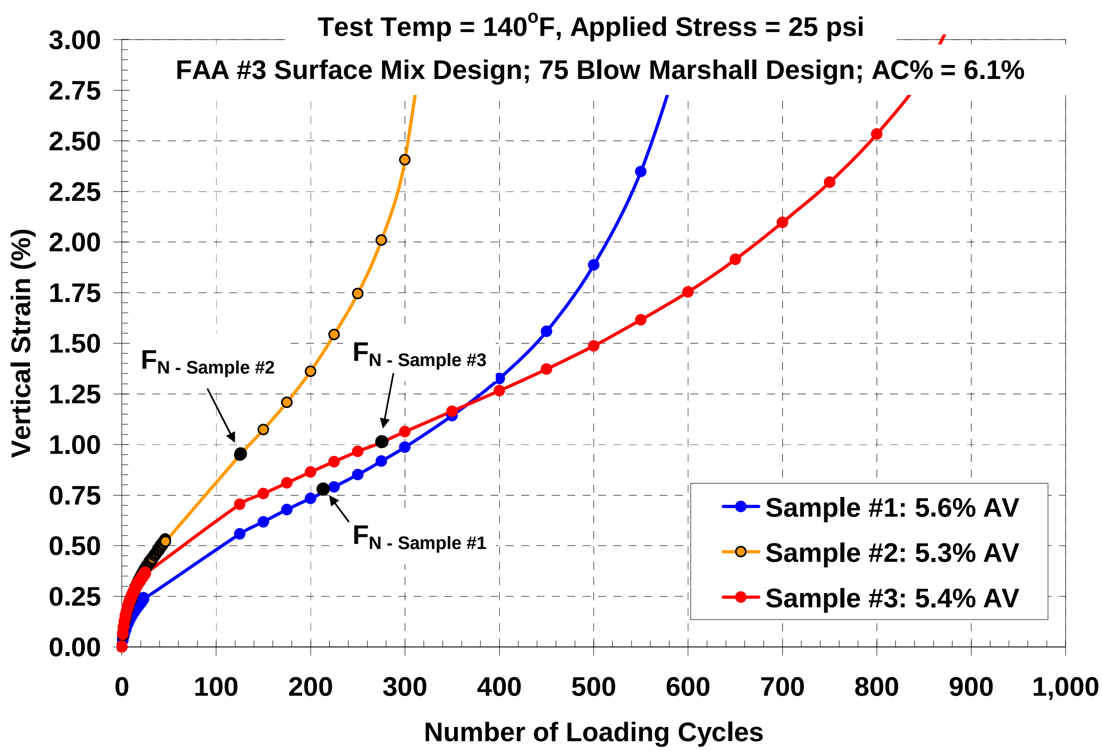


Figure 5.10 – FAA #3 Surface Course Mix with PG64-22 Asphalt Binder (CITGO Asphalt)

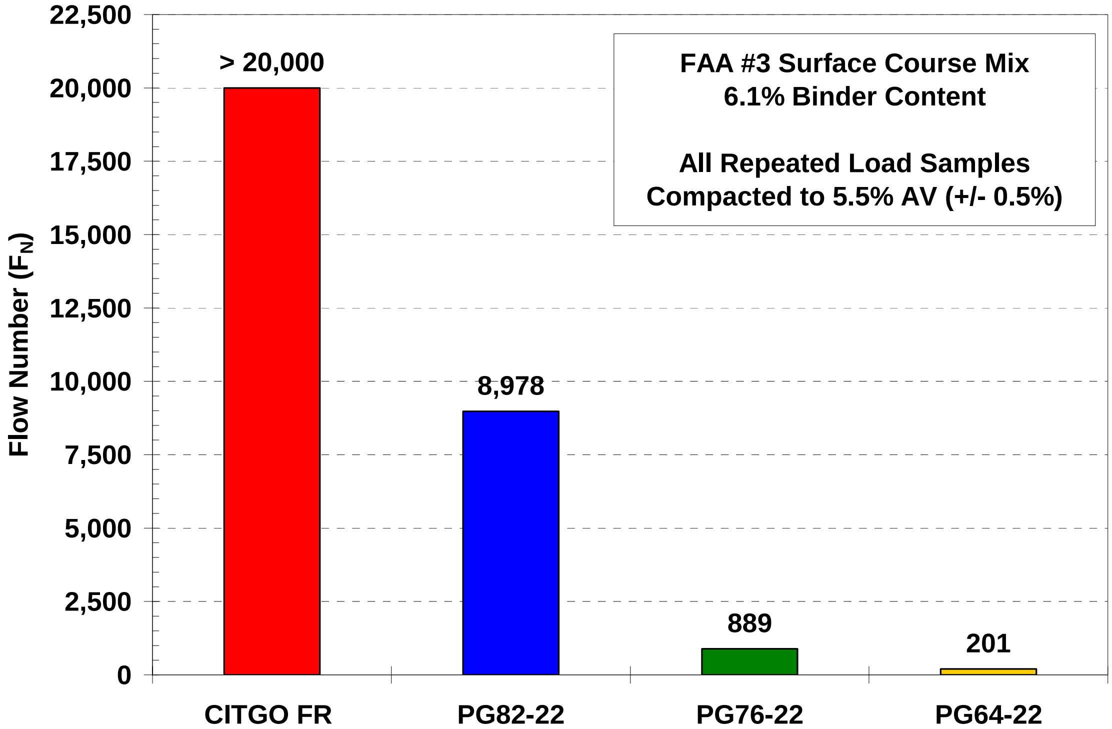


Figure 5.11 – Summary of Flow Number Results from Repeated Load Permanent Deformation Testing (Higher F_N, Lower Rutting Potential)

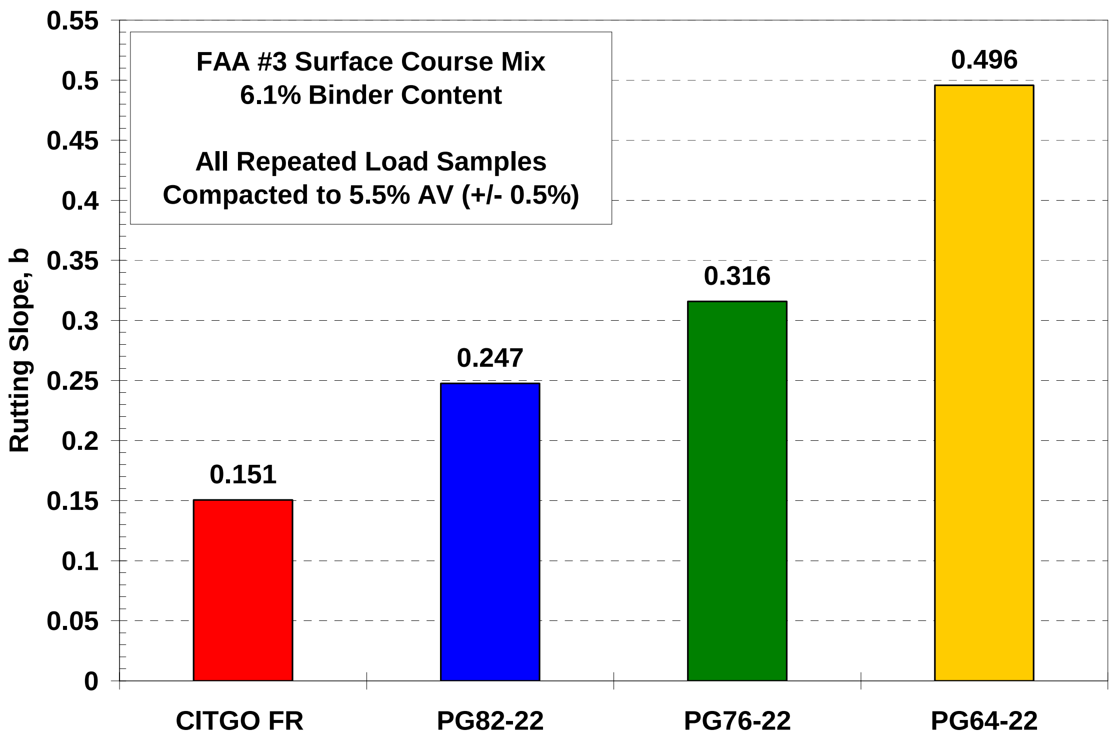


Figure 5.12 – Summary of Rutting Slope, b, Results from Repeated Load Permanent Deformation Testing (Higher b, Higher Rutting Potential)

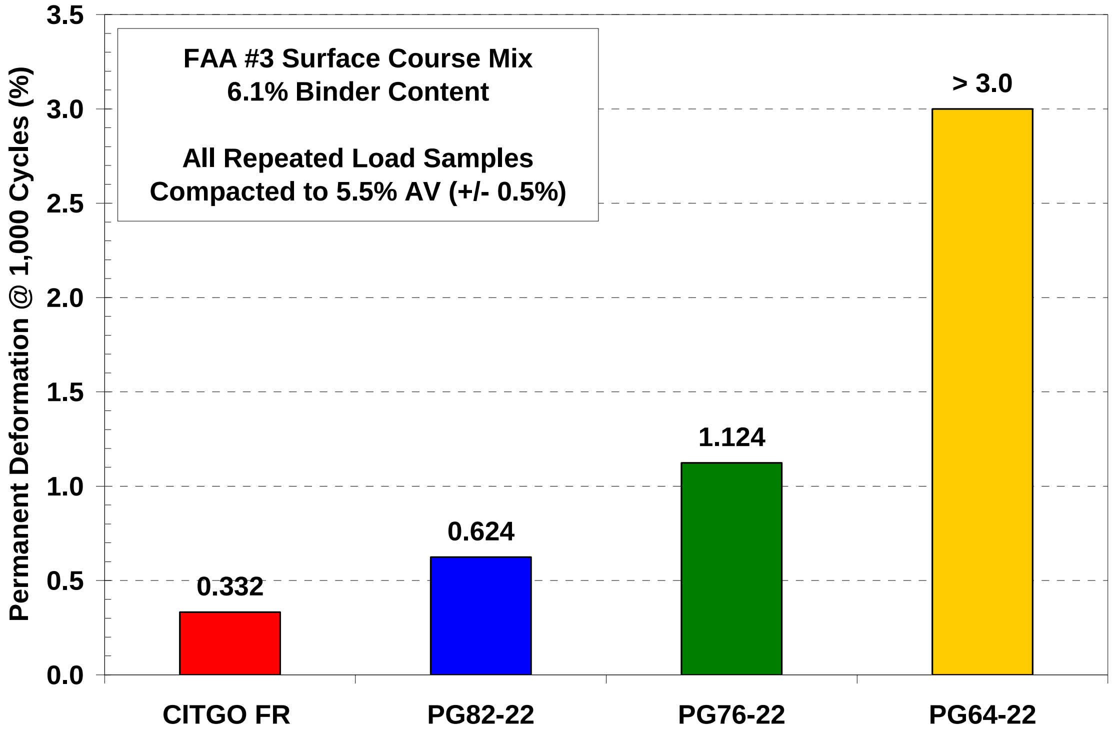


Figure 5.13 - Summary of Permanent Deformation @ 1,000 Loading Cycles from Repeated Load Permanent Deformation Testing (Higher Permanent Deformation, Higher Rutting Potential)

RELATED REFERENCES

Carpenter, S., Ghuzlan, K., and Shen, S., 2003, “A Fatigue Endurance Limit for Highway and Airport Pavements”, Presented at the Annual Meeting of the Transportation Research Board, January, 2003.

Monismith, C.L., Epps, J.A., Kasianchuk, D.A., and McLean, D.B., 1970, “Asphalt Mixture Behavior in Repeated Flexure”, Report No. TE 70-5, Insititute of Transportation and Traffic Engineering, University of California, Berkeley.

Monismith, C.L., N. Ogawa, and C. Freeme, 1975, “Permanent Deformation of Subgrade Soils Due to Repeated Loadings”, *Transportation Research Record 537*, Transportation Research Board, National Research Council, Washington D.C.

Witczak, M.W., K.E. Kaloush, T. Pellinen, M. El-Basyouny, and H. Von Quintus, 2002, *Simple Performance Test for Superpave Mix Design, NCHRP Report 465*.

APPENDIX A – SIMPLE PERFORMANCE TEST (REPEATED LOAD) SPECIFICATIONS

TEST METHOD FOR REPEATED LOAD TESTING OF ASPHALT CONCRETE MIXTURES IN UNIAXIAL COMPRESSION

1. Scope

1.1 This test method covers procedures for the preparation, testing and measurement of permanent deformation of cylindrical asphalt concrete specimens in a triaxial state of compressive loading.

1.2 The procedure uses a loading cycle of 1.0 second in duration, and consisting of applying 0.1-second haversine load followed by 0.9-second rest period. Permanent axial and/or radial strains are recorded through out the test.

1.3 The test is conducted at a single effective temperature T_{eff} and design stress levels.

1.4 This standard is applicable to laboratory prepared specimens 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.5 *This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 AASHTO Standards

TP4	Method for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor
PP2	Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)
T67	Standard Practices for Load Verification of Testing Machines (cross-listed with ASTM E4)
T269	Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

3. Definitions

3.1 *Permanent Deformation*—is a manifestation of two different mechanisms and is a combination of densification (volume change) and repetitive shear deformation (plastic flow with no volume change).

3.2 *Flow Number*—is defined as the number of load repetitions at which shear deformation, under constant volume, starts.

3.3 *Effective Temperature* T_{eff}—Is a single test temperature at which an amount of permanent deformation would occur equivalent to that measured by considering each season separately throughout the year.

4. Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a haversine axial load. The load is applied for duration of 0.1-second with a rest period of 0.9-second. The rest period has a load equivalent to the seating load. The test can be performed either without confinement, or a confining pressure is applied to better simulate in situ stress conditions. Cumulative permanent axial and radial strains are recorded throughout the test. In addition, the number of repetitions at which shear deformation, under constant volume, starts is defined as the Flow Number.

5. Significance and Use

5.1 Current Superpave volumetric mix design procedure lacks a fundamental design criterion to evaluate fundamental engineering properties of the asphalt mixture that directly affect performance. In this test, the selection of the design binder content and aggregate structure is fundamentally enhanced by the evaluation of the mix resistance to shear flow (Flow Number of Repetitions).

5.2 This fundamental engineering property can be used as a performance criteria indicator for permanent deformation resistance of the asphalt concrete mixture, or can be simply used to compare the shear resistance properties of various bituminous paving mixtures.

6. Apparatus

6.1 Load Test System—A load test system consisting of a testing machine, environmental chamber, measuring system, and specimen end fixtures.

6.1.1 *Testing Machine*—The testing machine should be capable of applying haversine loads up to 25 kN (5,600 1bs). An electro-hydraulic machine is recommended but not necessarily required. The loading device should be calibrated as outlined in the "Equipment Calibration" Section of the testing manual.

6.1.2 *Confining Pressure Device*—A system capable of maintaining a constant confining pressure, up to 207 kPa (30 psi), such as an air pressure intensifier or a hydraulic pump. The device shall be equipped with a pressure relief valve and a system to pressurize and depressurize the cell with gas or fluid. The device should also have a high temperature control subsystem for testing up to 60°C (140°F) within an accuracy of ±0.5°C (1°F) at constant pressure.

Note 1—It has been found that feedback control of a servovalve to control the pressure is the preferred method of control. However, manual valves or proportional valves may be adequate for some applications. The axisymmetric triaxial cells of AASHTO T292 or T294 may be used for this purpose. Other types of triaxial cells may be permitted. In all cases, see-through cells are not recommended for use with gas confining media. Sight glass ports or reduced area windows are recommended with gas media for safety reasons. It is not required that the specimen be visible through the cell wall if specimen centering and proper instrumentation operation can be verified without a see-through pressure vessel. Certain simulations of pavement loads and extended material characterization desired for local conditions may suggest using confining pressures greater than 207 kPa. For pressures higher than 690 kPa (100 psi), fluid cells are recommended.

6.1.3 *Environmental Chamber*—A chamber for controlling the test specimen at the desired temperature is required. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 25 to 60°C (77 to 140°F) to an accuracy of ±0.5°C (1°F). The chamber shall be large enough to accommodate the test specimen and a dummy specimen with temperature sensor mounted at the center for temperature verification.

Note 2—If the chamber does not have sufficient room for a dummy specimen, it is permissible to have a second chamber controlling the temperature of the dummy. The separate dummy chamber must be operated similar to the operation of the main test specimen chamber so that the dummy will accurately register the time required to obtain temperature equilibrium on the test specimen.

6.1.4 *Measurement System*—The system shall include a data acquisition system comprising analog to digital conversion and/or digital input for storage and analysis on a computer. The system shall be capable of measuring and recording the time history of the applied load, axial and radial deformations for the time duration required by this test method. The system shall be capable of measuring the load and resulting deformations with a resolution of 0.5 percent.

6.1.4.1 *Load*—The load shall be measured with an electronic load cell having adequate capacity for the anticipated load requirements. The load cell shall be calibrated in accordance with AASHTO T67. The load measuring transducer shall have accuracy equal to or better than 0.25 percent of full scale.

Note 3—A 25 kN (5600 lbf) load cell has been found to be the approximate maximum capacity limit for this test method because of range versus resolution factors. It is recommended that if the selected load cell capacity is 25 kN or greater, the system should be equipped with either manual or automatic amplification selection capability so that it can be used to enhance control of the system at lower anticipated loads.

6.1.4.2 *Axial and Radial Deformations*—Axial and/or radial deformations shall be measured with displacement transducers referenced to gauge points contacting the specimen as shown in Figure 1. The axial deformations shall be measured at a minimum of two locations 180° apart (in plan view); radial deformations shall be measured at a minimum of four locations aligned, in planform, on diametral, perpendicular lines which intersect at the center of the specimen.

Note 4—Analog transducers such as linear variable differential transformers (LVDTs) having a range of ±0.5 mm (0.02 in) and inherent nonlinearity equal to or better than ±0.025 percent of full scale have been found adequate for this purpose. Software or firmware linearization techniques may be used to improve the inherent nonlinearity. Amplification and signal conditioning techniques may be used with the ±0.5 mm range LVDTs to obtain resolutions down to 0.001mm (0.00004 in) or better for small strain test conditions. These techniques may be manual or automatic. In general, increasing the resolution by manual signal amplification will result in reduction of the overall range of the instrument by the same factor.

6.1.5 *Loading Platens*—Platens, with a diameter equal to or greater than that of the test specimen are required above and below the specimen to transfer the load from the testing machine to the specimen. Generally, these platens should be made of hardened or plated steel, or anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used.

6.1.6 *Flexible Membrane*—For the confined tests, the specimen should be enclosed in an impermeable flexible membrane. The membrane should be sufficiently long to extend well onto the platens and when slightly stretched be of the same diameter as the specimen. Typical membrane wall thickness ranges between 0.012 and 0.0625 inches (0.305–1.588 mm).

6.1.7 *End Treatment*—Friction reducing end treatments shall be placed between the specimen ends and the loading platens.

Note 5—End treatments consisting of two 0.5 mm (0.02 in) thick latex sheets separated with silicone grease have been found to be suitable friction reducing end treatments.

6.2 *Gyratory Compactor*—A gyratory compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO TP4 shall be used. Field cores shall meet the requirements of paragraphs 7.4 through 7.6 of this test method and any reports on cores so tested will contain a detailed description of the location of any lift boundaries within the height of the specimen (e.g. lift order, thickness and material homogeneity).

6.3 *Saw*—A machine for sawing test specimen ends to the appropriate length is required. The saw machine shall be capable of cutting specimens to the prescribed dimensions without excessive heating or shock.

Note 6—A diamond masonry saw greatly facilitates the preparation of test specimens with smooth, parallel ends. Both single- or double-bladed diamond saws should have feed mechanisms and speed controls of sufficient precision to ensure compliance with paragraphs 7.5 and 7.6 of this method. Adequate blade stiffness is also important to control flexing of the blade during thin cuts.

6.4 *Core Drill*—A coring machine with cooling system and a diamond bit for cutting nominal 100 mm (4 in) diameter test specimens.

Note 7—A coring machine with adjustable vertical feed and rotational speed is recommended. The variable feeds and speeds may be controlled by various methods. A vertical feed rate of approximately 0.05 mm/rev (0.002 in/rev) and a rotational speed of approximately 455 RPM has been found to be satisfactory for several of the Superpave mixtures.

7. Test Specimens

7.1 *Size*—Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens cored from gyratory compacted mixtures.

7.2 *Aging*—Mixtures shall be aged in accordance with the short-term oven aging procedure in AASHTO PP2.

7.3 *Gyratory Specimens*—Prepare 165 mm (6.5 in) high specimens to the required air void content in accordance with AASHTO TP-4.

7.4 *Coring*—Core the nominal 100 mm (4 in) diameter test specimens from the center of the gyratory specimens. Both the core drill and the gyratory specimen should be adequately supported to ensure that the resulting test specimen is cylindrical with sides that are smooth, parallel, and free from steps, ridges, and grooves.

7.5 *Diameter*—Measure the diameter of the test specimen at the mid-height and third points along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm (0.05 in). Calculate the average and the standard deviation of the six measurements. If the standard deviation is greater than 2.5 mm (0.01 in) discard the specimen. For acceptable specimens, the average diameter, reported to the nearest 1 mm, shall be used in the stress calculations.

7.6 *End Preparation*—The ends of all test specimens shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the specimen by sawing with a single- or double-bladed saw. To ensure that the sawed samples have parallel ends, the prepared specimen ends shall meet the tolerances described below. Reject test specimens not meeting these tolerances.

7.6.1 The specimen ends shall have a cut surface waviness height within a tolerance of ±0.05 mm across any diameter. This requirement shall be checked in a minimum of three positions at approximately 120° intervals using a straight edge and feeler gauges approximately 8–12.5 mm (0.315–0.5 in) wide or an optical comparator.

7.6.2 The specimen end shall not depart from perpendicular to the axis of the specimen by more than 0.5 degrees (i.e. 0.87 mm or 0.03 in across the diameter of a 100 mm diameter specimen). This requirement shall be checked on each specimen using a machinists square and feeler gauges.

7.7 *Air Void Content*—Determine the air void content of the final test specimen in accordance with AASHTO T269. Reject specimens with air voids that differ by more than 0.5 percent from the target air voids.

7.8 *Replicates*—The number of test specimens required depends on the number of axial and/or radial strain measurements made per specimen and the desired accuracy of the average flow time values. Table 1 summarizes the LVDTs and replicate number of specimens needed to obtain a desired accuracy limit.

7.9 *Sample Storage*—Wrap completed specimens in polyethylene and store in an environmentally protected storage area at temperatures between 5 and 25°C (40 and 75°F).

Note 8—To eliminate effects of aging on test results, it is recommended that specimens be stored no more than two weeks prior to testing.

8. Test Specimen Instrumentation

8.1 Attach mounting studs for the axial LVDTs to the sides of the specimen with epoxy cement. Figure 2 presents details of the mounting studs and LVDT mounting hardware.

Note 9—Quick setting epoxy such as Duro Master Mend Extra Strength Quick Set QM-50 has been found satisfactory for attaching studs. Under certain conditions when using the triaxial cell with confining pressure, the mounting studs may not require gluing to the specimen. While the surface contact area of the mounting studs is normally minimized consistent with transducer support requirements, it is generally recommended that the area of the studs be sufficiently large to bridge any open void structure features evident on the cut face of the specimen. The minimum diameter mounting stud consistent with support requirements is normally set at 8 mm (0.315 in), maximum diameters have not been established. A circular stud contact surface shape is not required, rectangular or other shapes are acceptable.

8.2 The gauge length for measuring axial deformations shall be 100 mm ±1 mm. Suitable alignment and spacing fixture shall be used to facilitate mounting of the axial deformation measuring hardware. The gauge length is normally measured between the stud centers.

9. Procedure

9.1 The recommended test protocol for the Simple Performance Test for use in the Superpave volumetric mix design consists of testing the asphalt mix at one effective pavement temperature T_{eff} and one design stress level selected by the design engineer. The effective pavement temperature T_{eff} covers approximately the temperature range of 25 to 60°C (77 to 140°F). The design stress level covers the range between 69 and 207 kPa (10–30 psi) for the unconfined tests, and 483 to 966 kPa for the confined tests. Typical confinement levels range between 35 and 207 kPa (5–30 psi).

9.2 Place the test specimen in the environmental chamber and allow it to equilibrate to the specified testing temperature. For the confined tests in a standard geotechnical cell, glue the gauge points to the specimen surface as necessary, fit the flexible membrane over the specimen and mount the axial hardware fixtures to the gauge points through the membrane. Place the test specimen with the flexible membrane on in the environmental chamber. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table 2 provides a summary of the minimum required temperature equilibrium times for samples starting from room temperature (i.e. 25°C).

Unconfined Tests

9.3 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, and mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.4 Place the upper friction reducing end treatment and platen on top of the specimen. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.5 Apply a contact load equal to 5 percent of the total load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., check for proper direction sensing for all LVDTs).

9.6 Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation. Adjust and balance the electronic measuring system as necessary.

9.7 Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

9.8 After the time required for the sample to reach the testing temperature, apply the haversine load, which yields the desired stress on the specimen. The maximum applied load (Pmax) is the maximum total load applied to the sample, including the contact and cyclic load: Pmax = Pcontact + Pcyclic.

9.9 The contact load (Pcontact) is the vertical load placed on the specimen to maintain a positive contact between loading strip and the specimen: Pcontact = 0.05 × Pmax.

9.10 The cyclic load (Pcyclic) is the load applied to the test specimen which is used to calculate the permanent deformation parameters: Pcyclic = Pmax – Pcontact.

9.11 Apply the haversine loading (Pcyclic) and continue until 10,000 cycles (2.8 hours) or until the specimen fails and results in excessive tertiary deformation to the specimen, whichever comes first. The total number of cycles or the testing time will depend on the temperature and the stress levels applied.

9.12 During the load applications, record the load applied, the axial and radial deflection measured from all LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, it is recommended to use the data acquisition of the cycles shown in Table 3.

Confined Tests

9.13 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, place the top platen and extend the flexible membrane over the top and bottom platens. Attach the O-rings to seal the specimen on top and bottom platens from the confining air/fluid. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.14 Mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.15 Connect the appropriate hose through the upper or lower platen (or take other appropriate steps) to keep the specimen's internal void structure under atmospheric pressure while pressure greater than atmospheric is applied to the outside of the membrane during testing.

9.16 Assemble the triaxial cell over the specimen, ensure proper seal with the base and connect the fluid (or gas) pressure lines.

9.17 Apply a contact load equal to 5 percent of the load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., both decrease accordingly). Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation.

9.18 Record the initial LVDT readings and slowly increase the lateral pressure to the desired test level (e.g. 2 psi /sec). Adjust and balance the electronic measuring system as necessary. Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

9.19 After the time required for the sample to reach the testing temperature, apply the haversine load, which yields the desired stress on the specimen. Continue until 10,000 cycles (2.8 hours) or until the specimen fails and results in excessive tertiary deformation to the specimen, whichever comes first. The total number of cycles or the testing time will depend on the temperature and the stress levels applied.

9.20 During the load applications, record the load applied, confining pressure, the axial and radial deflection measured from all LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, it is recommended to use the data acquisition of the cycles shown in Table 3.

10. Calculations

10.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain (ε_{Ta}), in/in, by dividing by the gauge length, L [100mm (4-inches)]. Typical total axial strain versus time is shown in Figure 3.

10.2 Compute the cumulative axial permanent strain.

10.3 Plot the cumulative axial permanent strain versus number of loading cycles in log space. Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (see Figure 4).

10.4 The flow number of repetitions is viewed as the lowest point in the curve of rate of change in axial strain versus number of loading cycles (see Figure 5). The rate of change of axial strain versus number of loading cycles should be plotted and the flow number (F_N) is estimated where a minimum or zero slope is observed.

11. Report

11.1 Report all specimen information including mix identification, storage conditions, dates of manufacturing and testing, specimen diameter and length, volumetric properties, stress levels used, confining pressure, axial permanent deformation parameters (a, b) and flow number of repetitions.

TABLE 1 Recommended number of specimens

LVDTs per Specimen (Total for either vertical or horizontal, not combined total)	Number of Specimens	Estimated Standard Error of the Mean, % Per Mixture's Nominal Aggregate Size		
		12.5mm	19mm	37.5mm
2	2	7.6	9.5	18.8
2	3	6.2	7.7	15.3
3	2	6.7	8.9	17.4
3	3	5.5	7.3	14.2
4	2	6.2	8.6	16.6
4	3	5.0	7.0	13.6

TABLE 2 Recommended equilibrium times

Specimen Test Temperature, ^{o}C (^{o}F)	Time, hrs
25 (77)	0.5
30 (86)	1.0
37.8 (100)	1.5
>54.4 (130)	2.0

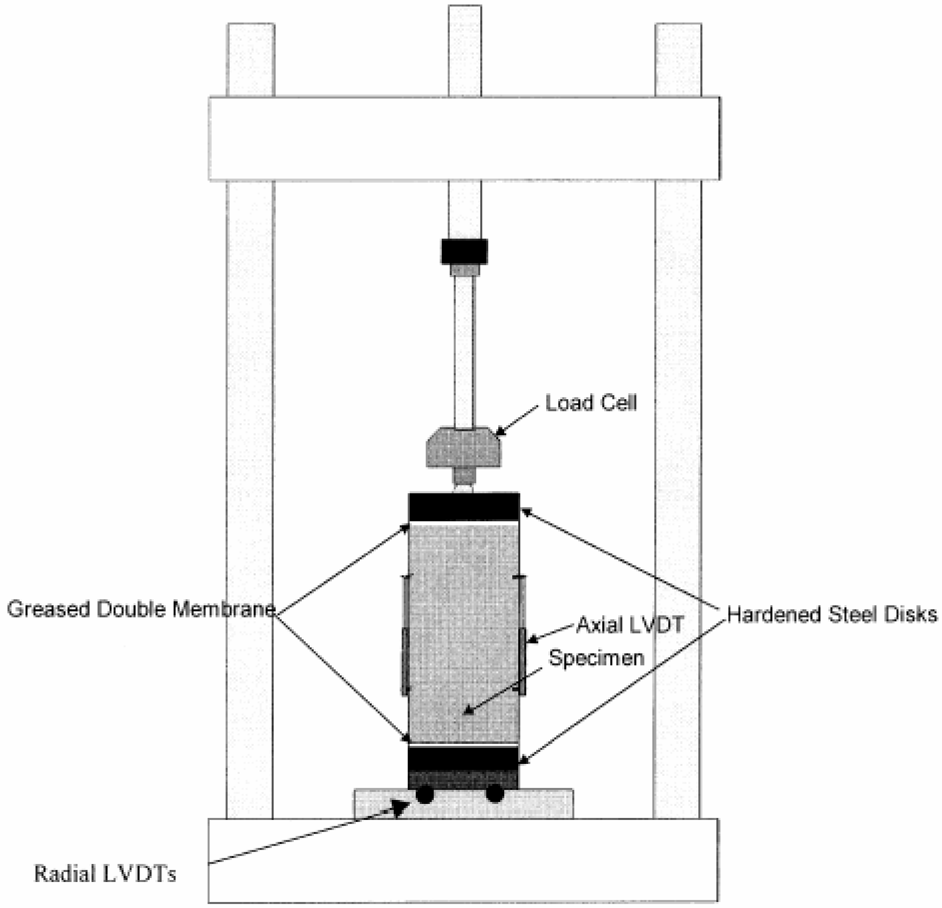


Figure 1. Schematic of repeated load permanent deformation test.

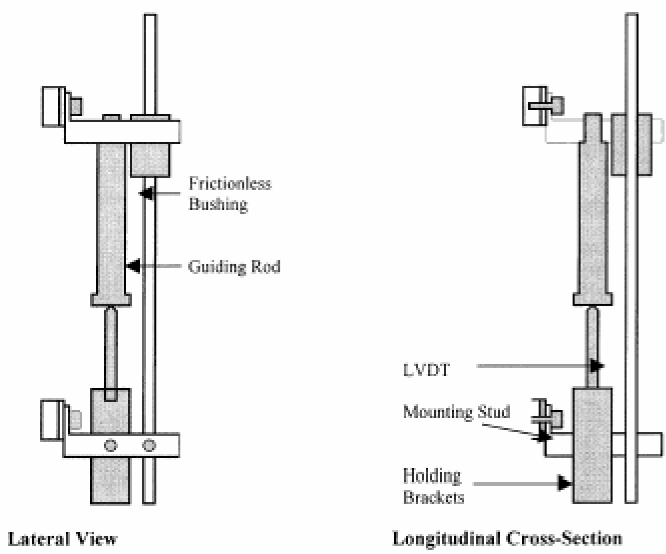
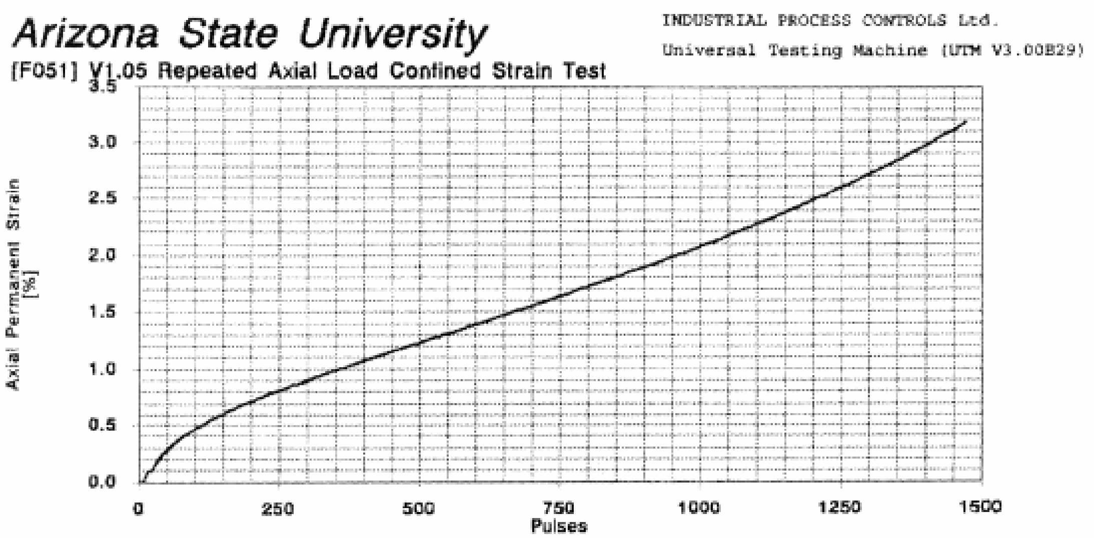


Figure 2. Axial LVDTs instrumentation.

TABLE 3 Suggested data collection for the repeated load permanent deformation test

Data collected During Cycles	Data collected During Cycles	Data collected During Cycles
1 through 100	700	4,500
130	750	5,000
170	800	5,500
200	850	6,000
230	900	6,500
270	950	7,000
300	1,000	7,500
350	1,300	8,000
400	1,700	8,500
450	2,000	9,000
500	2,300	9,500
550	2,700	10,000
600	3,000	
650	4,000	

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final reading of measured parameters:
        loading pulse count       1476
        deviator stress (kPa)   134.44
         seating stress (kPa)   17.096
    axial permanent strain (%)  3.2537
    axial resilient strain (%)  0.0234
     axial resil modulus (MPa)  574.13
   radial permanent strain (%)  3.9636
   radial resilient strain (%)  0.0134
       resilient Poisson ratio  0.5755
        actuator perm strain (%)  3.182
       actuator resil strain (%) 0.0693
  actuator resil modulus (MPa)  193.87
  min ax'l strn slope (um/m/p)   16.08
   min axial slope pulse count     626
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Figure 3. Cumulative permanent strain vs. loading cycles from a repeated load permanent deformation test.

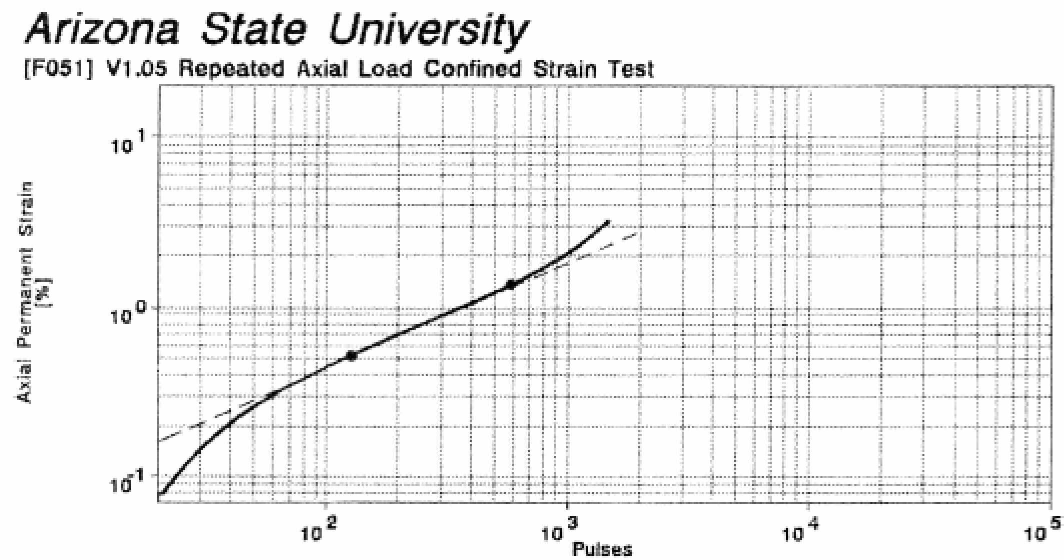

Figure 4. Regression constants "a" and "b" from log permanent strain—log number of loading cycles plot.

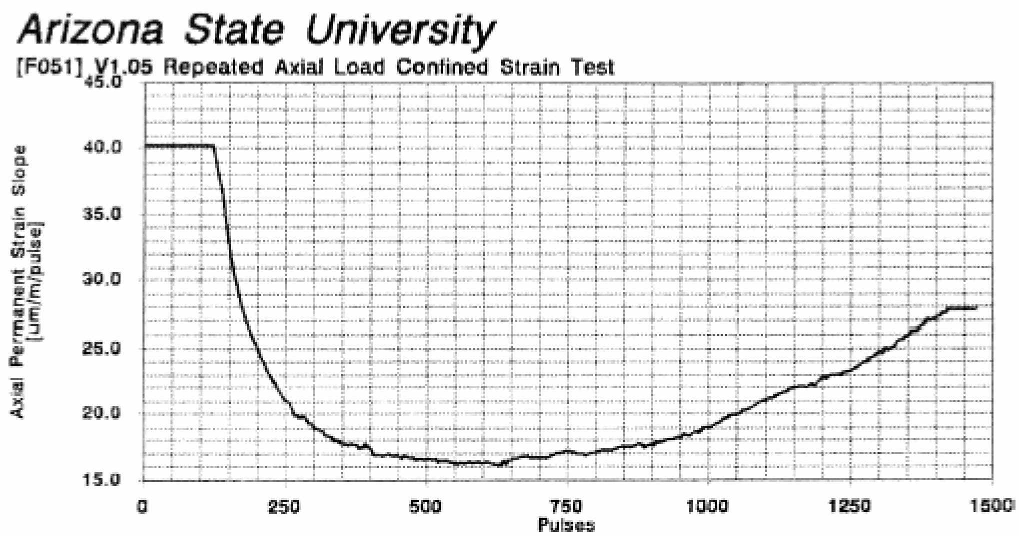

Figure 5. Typical plot of the rate of change in permanent strain vs. loading cycles.

APPENDIX B – TESTING SPECIFICATION FOR FLEXURAL BEAM FATIGUE TEST

Standard Method of Test for

Determining the Fatigue Life of Compacted Bituminous Mixtures Subjected to Repeated Flexural Bending

SHRP Designation: M-009[1]

1. SCOPE

1.1 This method determines the fatigue life and fatigue energy of a bituminous mixture beam specimen subjected to repeated flexural bending until failure. The failure point is defined as the load cycle at which the specimen exhibits a 50% reduction in stiffness relative to the initial stiffness.

1.2 The values stated in SI units are to be regarded as the standard.

1.3 *This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. APPARATUS

2.1 *Test System*—The test system shall be capable of providing repeated sinusoidal loading at a frequency of between 5 and 10 Hz. The specimen shall be subjected to 4-point bending with free rotation and horizontal translation at all load and reaction points. Figure 1 illustrates the loading conditions. The specimen shall be forced back to its original position (i.e., zero deflection) at the end of each load pulse. The test system or surrounding environment shall maintain the specimen at 20°C during testing.

The test system shall be a closed-loop, computer-controlled system that, during each load cycle, measures the deflection of the beam specimen, computes the strain in the specimen, and adjusts the load such that the specimen experiences a constant level of strain on each load cycle. The test system should record load cycles, the applied load and beam deflection, and compute the maximum tensile stress, maximum tensile strain, phase angle, stiffness, dissipated energy, and cumulative dissipated energy at load cycle intervals specified by the user.

As a minimum, the test system should meet the following requirements:

<u>Load Measurement and Control</u>

Range: $\pm$ 4.5 kN
Resolution: 0.002 kN
Accuracy: $\pm$0.004 kN

<u>Displacement Measurement and Control</u>

Range: $\pm$ 5.0 mm
Resolution: 0.00254 mm
Accuracy: $\pm$ 0.005 mm

<u>Frequency Measurement and Control</u>

Range:	5 to 10 Hz
Resolution:	0.005 Hz
Accuracy:	0.01 Hz

<u>Temperature Measurement and Control</u>

Resolution:	0.25°C
Accuracy:	$\pm$ 0.5°C

2.2 *Miscellaneous Apparatus:*

- epoxy for attaching nut to specimen
- screw, nut, block assembly for referencing LVDT to neutral axis of specimen
- jig for setting proper clamp spacing

3. TEST SPECIMENS

3.1 *Compacted Bituminous Concrete Specimens*—Specimens shall be sawn on all sides with a diamond blade from a slab or beam of bituminous mixture prepared by kneading compaction or rolling wheel compaction. Specimens shall be 381 $\pm$ 6.35 mm in length, 50.8 $\pm$ 6.35 mm in height and 63.5 $\pm$ 6.35 mm in width.

3.2 *Measurement of Specimen Size*—Measure the height and width of the specimen at three different points along the middle 90 mm of the specimen length. Report measurements to the nearest 0.025 mm. Average the three measurements for each dimension and report the averages to the nearest 0.25 mm.

3.3 *Epoxy Nut to Neutral Axis of Specimen*—Figure 2 illustrates a nut epoxied to the neutral axis of the specimen. Locate the center of a specimen side. Apply epoxy in a circle around this center point and place the nut on the epoxy such that the center of the nut is over the center point. Avoid applying epoxy such that it fills the center of the nut. Allow the epoxy to harden before moving the specimen.

4. TEST PROCEDURE

4.1 *Stabilize Specimen to Test Temperature*—If the ambient temperature is not 20°C, place the specimen in an environment which is at 20 ± 1°C for 2 hours to ensure the specimen is at the test temperature prior to beginning the test.

4.2 *Specimen Setup*—Refer to figures 3 and 4.

The clamps should be open to allow the specimen to be slid into position. The jig is used to ensure proper horizontal spacing of the clamps: 119 mm center-to-center. Once the specimen and clamps are in the proper positions, close the outside clamps by applying sufficient pressure to hold the specimen in place. Next, close the inside clamps by applying sufficient pressure to hold the specimen in place.

Figure 4 illustrates the connection of the screw/nut/block assembly and the LVDT such that beam deflections at the neutral axis will be measured. Attach the LVDT block to the specimen by screwing the screw into the nut epoxied to the specimen. The LVDT probe should rest on top of the block and the LVDT should be positioned and secured within its clamp so its reading is as close to zero as possible.

4.3 *Test Parameter Selection*—The operator selects the following test parameters and enters them into the automated test program: deflection level, loading frequency and load cycle intervals at which test results are recorded and computed by the computer. The deflection level depends on the strain level desired. The loading frequency should be between 5 and 10 Hz. The selection of load cycle intervals at which test results are computed and recorded is limited by the amount of memory available for storing data.

4.4 *Estimation of Initial Stiffness*—Apply 50 load cycles at a constant strain of 100–300 micro-in/in. Determine the specimen stiffness at the 50th load cycle. This stiffness is an estimate of the initial stiffness which will be used as a reference for determining specimen failure.

4.5 *Selection of Strain Level*—The selected deflection level should correspond to a strain level such that the specimen will undergo a minimum of 10,000 load cycles before its stiffness is reduced to 50% or less of the initial stiffness. A stiffness reduction of 50% or more represents specimen failure. A minimum of 10,000 load cycles ensures the specimen does not decrease in stiffness too rapidly.

4.6 *Testing*—After selecting the appropriate test parameters, begin the test. Monitor and record (*if not automated*) the test results at the selected load cycle intervals to ensure the system is operating properly. When the specimen has experienced greater than 50% reduction in stiffness, stop the test.

5. CALCULATIONS

5.1 The following calculations shall be performed at the operator-specified load cycle intervals:

5.1.1 *Maximum Tensile Stress (kN)*

$$\sigma_t = \frac{300aP}{wh^2} \tag{1}$$

where

a	$= L/3$
L	= the beam span, typically 356 mm
P	= the load in kilonewtons
w	= the beam width in millimeters
h	= the beam height in millimeters

5.1.2 *Maximum Tensile Strain (mm/mm)*

$$\epsilon_t = (12\delta h)/(3L^2 - 4a^2) \tag{2}$$

where

δ	= maximum deflection at center of beam, in mm
L	= length of beam between outside clamps, 356 mm

5.1.3 *Flexural Stiffness (kPa)*

$$S = \sigma_t/\epsilon_t \tag{3}$$

5.1.4 *Phase Angle (deg)*

$$\phi = 360fs \tag{4}$$

where

f	= load frequency, in Hz
s	= time lag between P_{max} and δ_{max}, in seconds

5.1.5 *Dissipated Energy (kPa) per cycle*

$$\mathrm{D} = \pi\sigma_t\epsilon_t\sin(\phi) \tag{5}$$

5.1.6 *Cumulative Dissipated Energy (kPa)*

$$\sum_{i=1}^{i=n} D_i \tag{6}$$

where

D_i = D for the i^{th} load cycle

NOTE 1.—If data acquisition is automated, dissipated energy (D) cannot be calculated for *every* load cycle, due to memory limitations of the computer system. Therefore, dissipated energy must be plotted against load cycles for the particular load cycles at which data was collected (i.e., the load cycles selected by the operator) up to the load cycle of interest. The area under the curve represents the cumulative dissipated energy. See figure 5 for a typical dissipated energy versus load cycle plot.

5.1.7 *Initial Stiffness (kPa)*—The initial stiffness is determined by plotting stiffness (S) against load cycles (N) and best-fitting the data to an exponential function of the form

$$S = Ae^{bN} \tag{7}$$

where

e = natural logarithm to the base e
A = constant
b = constant

Figure 6 presents a typical plot of stiffness versus load cycles. The constant A represents the initial stiffness.

5.1.8 *Cycles to Failure*—Failure is defined as the point at which the specimen stiffness is reduced to 50% of the initial stiffness. The load cycle at which failure occurs is computed by solving for N from equation 7, or simply

$$N_{f,50} = [\ln(S_{f,50}/A)]/b \tag{8}$$

where

$S_{f,50}$ = stiffness, 50% of initial stiffness, in kPa
$S_{f,50}/A$ = 0.5, by definition

5.1.9 *Cumulative Dissipated Energy to Failure (kPa)*

$$\sum_{i=1}^{i=N_{f,50}} D_i \tag{9}$$

NOTE 2.—It is not necessary to measure the dissipated energy for *every* load cycle; the computer program used to control the fatigue test will systematically determine the dissipated energy at specified load cycles during the test. The total dissipated energy to failure will be summarized as part of the computer output.

6. REPORT

6.1 The test report shall include the following information:

6.1.1 *Bituminous Mixture Description*—bitumen type, bitumen content, aggregate gradation, and air void percentage.

6.1.2 *Specimen Length*—millimeters, to four significant figures

6.1.3 *Specimen Height*—millimeters, average as per section 3.2, to three significant figures

6.1.4 *Specimen Width*—millimeters, average as per section 3.2, to three significant figures

6.1.5 *Test Temperature*—average during test, to the nearest 1.0°C

6.1.6 *Test Results*—table listing the following results (to three significant figures) for each load cycle interval selected by the operator:

Load Cycle	Applied Load	Beam Deflection	Tensile Stress	Tensile Strain	Flexural Stiffness	Phase Angle	Cumulative Dissipated Energy	Dissipated Energy
	kN	mm	kPa	mm/mm	kPa	deg	kPa	kPa

6.1.7 *Plot of Stiffness versus Load Cycles*—refer to figure 6 for typical plot

6.1.8 *Initial Flexural Stiffness*—kPa, to three significant figures

6.1.9 *Cycles to Failure*

6.1.10 *Cumulative Dissipated Energy to Failure*—kPa, to three significant figures

6.1.11 *Plot of Dissipated Energy versus Load Cycles*—refer to figure 5 for typical plot

7. PRECISION

7.1 A precision statement has not yet been developed for this test method.

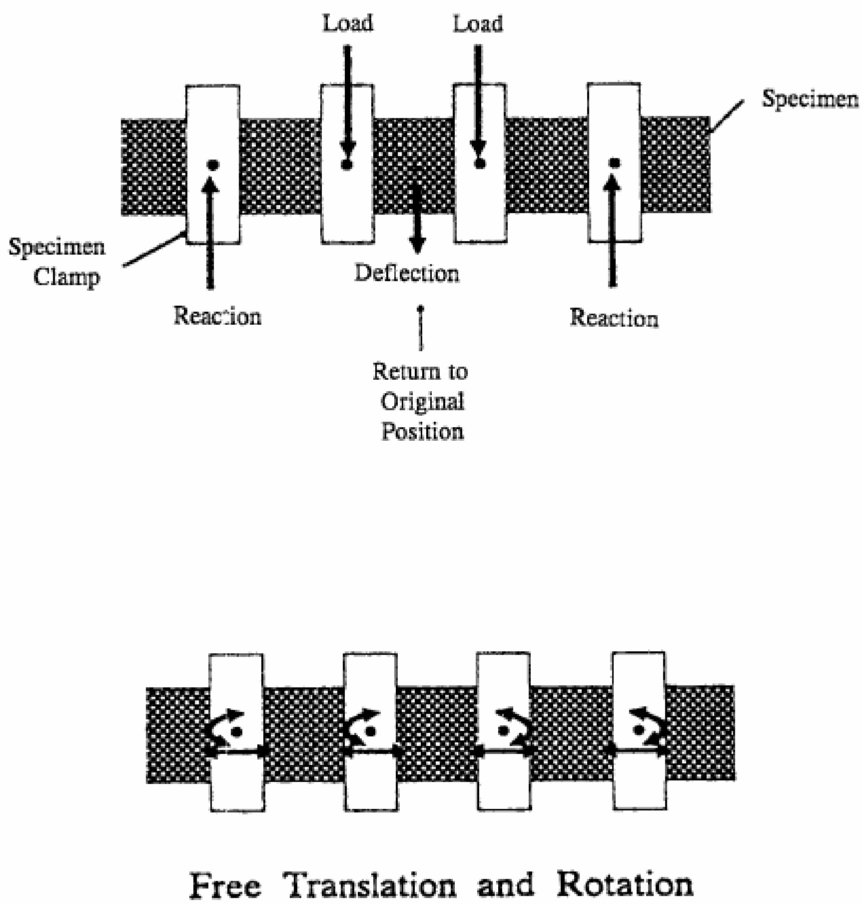

Figure 1. Load and Freedom Characteristics of Fatigue Test Apparatus

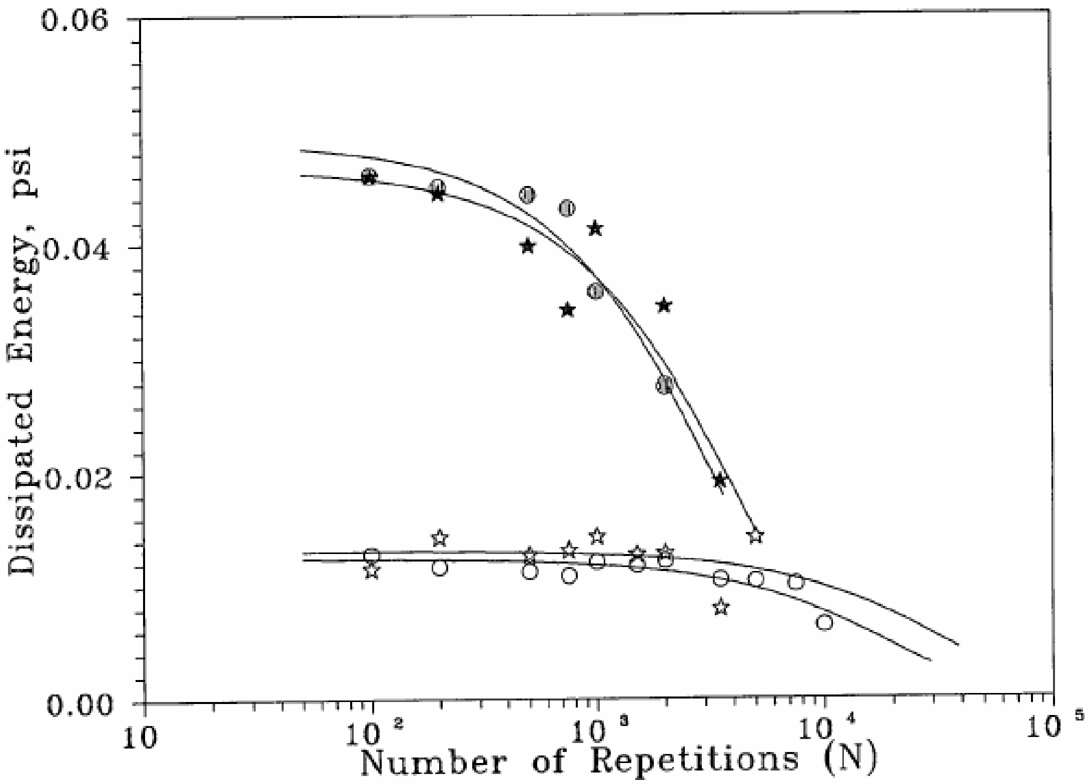

Figure 5. Dissipated Energy versus Load Cycles (Repetitions)

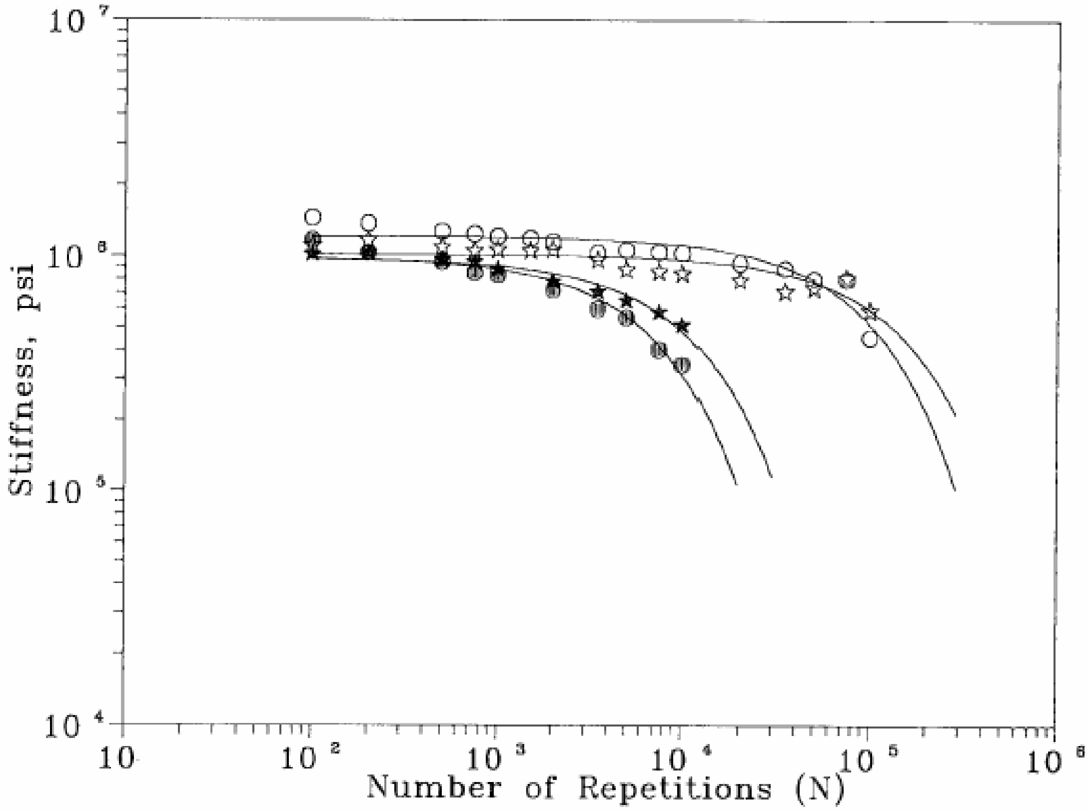

Figure 6. Stiffness versus Load Cycles (Repetitions)