DOT/FAA/TC-18/26

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Laboratory Performance Testing of Warm-Mix Asphalt Mixtures for Airport Pavements

July 2018

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/TC-18/26	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LABORATORY PERFORMANCE TESTING OF WARM-MIX ASPHALT MIXTURES FOR AIRPORT PAVEMENTS		5. Report Date July 2018
		6. Performing Organization Code
7. Author(s) Mariely Mejías-Santiago and John F. Rushing		8. Performing Organization Report No.
9. Performing Organization Name and Address U.S. Army Engineer Research and Development Center Geotechnical and Structures Laboratory 3909 Halls Ferry Road Vicksburg, MS 39180-6199		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Air Traffic Organization Operations Planning Office of Aviation Research and Development Washington, DC 20591		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code AAS-100
15. Supplementary Notes The Federal Aviation Administraion COR was Navneet Garg.		

16. Abstract

In many paving projects, warm-mix asphalt (WMA) has replaced hot-mix asphalt (HMA) as a means of reducing the environmental impacts, which include air pollution, fossil fuel depletion, and smog formation, during production of asphalt mixtures. As state Departments of Transportation (DOT) gain experience with WMA, conventional HMA may become less available for paving. Empirical evidence suggests that WMA performs well under heavy military aircraft loads and can be adopted for use in airfield pavements. However, further research is required to develop guidance for using WMA for commercial airport pavements. Additional laboratory and field performance evaluation of WMA technologies under heavy aircraft loads will provide the information needed to develop such guidance.

This report presents a laboratory rutting performance evaluation of WMA compared to HMA. The study includes evaluation of the three main categories of WMA technologies: chemical additive, organic wax, and a foaming process. A laboratory replicated WMA mixtures from two airport paving projects using the same materials and mix design procedures used for construction. The laboratory designed a third mixture using Federal Aviation Administration (FAA) local materials and mix design specifications. The repeated load test, static creep test, indirect tensile strength test, and asphalt pavement analyzer test evaluated all three mixtures for rutting. A mixture for full-scale evaluation of WMA under heavy aircraft loads at the FAA High Temperature Pavement Test Facility (is recommended based on the results.

17. Key Words Warm-mix asphalt, Hot-mix asphalt, Asphalt mixtures, Performance tests, Asphalt Pavement Analyzer, Flow number, Flow time, Indirect Tensile Strength, Airport pavement		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 51	22. Price

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LIST OF SYMBOLS AND ACRONYMS

G_{mb}	Bulk specific gravity
G_{mm}	Maximum specific gravity
G_{sa}	Apparent specific gravity
G_{sb}	Bulk specific gravity
G_{se}	Effective specific gravity
N_{design}	Design number of gyrations
P_b	Percent asphalt by total weight of mixture
P_{ba}	Absorbed asphalt, percent by weight of aggregate
P_{be}	Effective asphalt content, percent by total weight of mixture
V_a	Percent air voids in the compacted mixture

AASHTO	American Association of State Highway and Transportation Officials
Abs	Water absorptions
AC	Advisory Circular
APA	Asphalt pavement analyzer
APT	Accelerated pavement testing
BOS	Boston Logan International Airport
CBR	California bearing ratio
DOT	Department of Transportation
ERDC	Engineer Research and Development Center
ETL	Engineering technical letter
FAA	Federal Aviation Administration
FN	Flow number
FT	Flow time
HMA	Hot-mix asphalt
HTPTF	High Temperature Pavement Test Facility
IDT	Indirect tensile strength test
JMF	Job mix formula
kPa	Kilopascals
MMPT	Mean monthly pavement temperature
N	Newtons
NAPMRC	National Airport Pavement and Materials Research Center
NAPTF	National Airport Pavement Testing Facility
NCHRP	National Cooperative Highway Research Program
PG	Performance Grade
RAP	Recycled asphalt pavement
SBR	Styrene-butadiene rubber
UFGS	Unified Facilities Guide Specification
U.S.	United States
WMA	Warm-mix asphalt

EXECUTIVE SUMMARY

In many paving projects, warm-mix asphalt (WMA) has replaced hot-mix asphalt (HMA) as a means of reducing the environmental impacts, which include air pollution, fossil fuel depletion, and smog formation, during production of asphalt mixtures. As state Departments of Transportation (DOTs) gain experience with WMA, conventional HMA may become less available for paving. WMA performs well under heavy military aircraft loads according to research studies. However, further research is required to develop guidance for use of WMA for commercial airport pavements. Currently, the Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5370-10G, Item P-401 specification does not include guidance for the use of WMA for airport pavements. Laboratory and field performance evaluation of WMA technologies under heavy aircraft loads will provide the information needed to develop such guidance.

This report presents a laboratory rutting performance evaluation of WMA. The study includes evaluation of the three main categories of WMA technologies−chemical additive, organic wax, and a foaming process−when compared to an HMA control mixture. In the laboratory, WMA mixtures from two airport paving projects were replicated using the same materials and mix design procedures used for construction. A laboratory-designed third mixture used materials sampled during a test section construction at the FAA National Airport Pavement Test Facility (NAPTF) according to Item P-401 mix design specifications. The repeated load, static creep, asphalt pavement analyzer, and indirect tensile strength (IDT) tests evaluated all three mixtures for rutting. A mixture for full-scale evaluation of WMA under heavy aircraft loads at the new FAA High Temperature Pavement Test Facility is recommended based on test results.

The following are the main findings of the evaluation:

- Evaluating the laboratory rutting performance of an in-place WMA airport mixture used successfully in three runway paving projects provided a good reference point for comparing the rutting potential of other WMA mixtures.

- The Mississippi (MS) airport mixture (sourced from a runway paving project in Mississippi) was susceptible to rutting under aircraft loads compared to mixtures previously evaluated using the same performance tests. The rutting performance was slightly improved when the mixture was prepared as WMA. Although the mixture met current FAA mix design criteria, modifications to the aggregate stockpiles or binder grade would be required to meet recommended performance criteria.

- The New Jersey (NJ) laboratory mixture (sourced from a test section at the FAA National Airport Pavement Test Facility (NAPTF) in Atlantic City) met the criteria for all the performance tests conducted. Rutting was generally improved using WMA. This mixture is expected to have good rutting performance under heavy aircraft loads when produced as HMA or WMA.

- The range of IDT values observed throughout all mixtures evaluated did not provide a clear distinction between mixtures with high rutting potential and those considered to be rut resistant mixtures. This indicates that the IDT parameters and perhaps the minimum IDT criteria need to be revisited to verify and refine these criteria and to re-evaluate the use of the IDT as an indicator of rutting performance.

1. INTRODUCTION.

Warm-mix asphalt (WMA) has replaced hot-mix asphalt (HMA) in many paving projects as a means of reducing the environmental impacts associated with the production of HMA mixtures, including air pollution, fossil fuel depletion, and smog formation. State Departments of Transportation (DOT) are using WMA for roadway paving, and many are using it to replace conventional HMA. As state DOTs gain experience with WMA, conventional HMA may become less available for paving. Empirical evidence to date indicates that WMA performs well under heavy aircraft loads and can be adopted for airfield pavements use [1-4]. The United States (U.S.) Army Corps of Engineers developed the Unified Facilities Guide Specification (UFGS) 32-12-15.16 [5] and an engineering technical letter (ETL) 11-3 [6] to provide guidance for use of WMA on airfields. Additional relevant guidance includes the *Warm-Mix Asphalt: Best Practices* manual by the National Asphalt Pavement Association (NAPA), which presents the state of the practice for use of WMA [7]. Also, the National Cooperative Highway Research Program (NCHRP) Report 691 "Mix Design Practices for Warm Mix Asphalt" provides guidance on special considerations that have to be addressed in WMA mix design [8].

1.1 BACKGROUND.

WMA is the general term for technologies that allow the production and placement temperatures of asphalt mixes to be reduced. These technologies reduce the asphalt viscosity and provide complete aggregate coating at temperatures that are up to 50°C lower than typical HMA. The reduction in temperatures and the improved workability for production and placement of asphalt mixtures provide a number of benefits related to sustainable development and improved working conditions. These benefits include the

- reduction of fuel consumption,
- reduction of plant emissions,
- improvement of compaction for stiff mixes,
- ability to pave in cool ambient temperatures without sacrificing quality,
- ability to accept longer hauling distances without sacrificing workability, and
- ability to incorporate higher percentages of recycled asphalt pavement (RAP) in the mixtures.

WMA processes can be classified into three main groups: chemical additive or surfactant, organic additive or wax, and water for foaming. The use of chemical additives rely on a variety of mechanisms, such as surface-active agents to promote improved coating of the aggregate by the binder at lower temperatures. The processes that use organic additives or waxes show a decrease in binder viscosity above the wax's melting point. The asphalt foaming process relies on the water vaporization when dispersed in hot asphalt cement. Once vaporization occurs, the steam causes a binder expansion, which allows for improved aggregate coating and a corresponding reduction in the mix viscosity.

Procedures for placing and compacting WMA do not differ from those used for placing and compacting HMA except for the temperature at which these operations occur. The WMA's reduced temperature makes its placement much safer for construction personnel. WMA also allows placing multiple lifts within a short timeframe The reduced compaction temperatures of WMA allow more time to roll the mixture and obtain adequate density [6].

Performance evaluations comparing WMA to HMA were conducted extensively during the past several years. Studies indicate that WMA mixes are more susceptible to rutting and moisture damage because of reduced binder aging and an increased probability of retained moisture in the mix at reduced production temperatures [9-16]. These susceptibilities are more evident in laboratory studies where the exposure to high temperatures is more limited [17]. Data available on WMA field mixes have not shown rutting or moisture damage problems solely attributable to the WMA technologies [18 and 19]. Low-temperature cracking and fatigue damage are expected to decrease when WMA is used because binder stiffness is lower than for HMA mixes [1].

Currently, more than 30 WMA technologies are available in the U.S. So far, the implementation of these technologies has proceeded with few complications. Forty-seven states adopted permissive specifications for contractors to produce and place asphalt mix at lower temperatures using WMA technologies.

1.2 POTENTIAL ISSUES.

Currently, the Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5370-10G, Item P-401 [20] specification does not include guidance for using WMA for airport pavements. Laboratory and field performance evaluations of WMA technologies will provide the information needed to develop such guidance. Specifically, WMA has increased potential for rutting in WMA resulting from reduced aging and for binder stiffening during WMA production, which require additional investigation.

1.3 OBJECTIVE AND SCOPE.

The purpose of this project was to evaluate the laboratory rutting performance of WMA and to compare results to an HMA control mix to develop recommendations for full-scale evaluation of WMA under heavy aircraft loads. The study included evaluation of the three main categories of WMA technologies: chemical additives, organic wax, and foaming agents or processes. WMA airport mixtures were identified at two airport paving projects and one test section. Replicated in the laboratory, these mixtures used the same materials and mix design procedures used for construction. The repeated load, static creep, asphalt pavement analyzer (APA), and indirect tensile strength (IDT) tests evaluated all three mixtures for rutting. Evaluation results were the basis for recommending a mixture for full-scale evaluation of WMA under heavy aircraft loads.

2. MATERIALS.

The materials used in this research came from three sources: one test section project and two airport paving projects. The first source was from a test section at the FAA National Airport Pavement Test Facility (NAPTF) in Atlantic City, New Jersey (NJ). Materials were sampled during construction in November 2013 to reproduce the job mix formula (JMF) in the laboratory. The second source was from a runway paving project at Columbus Air Force Base, Mississippi (MS). In August 2013, materials were sampled during construction to reproduce the JMF in the laboratory. The third source was comprised of materials used at Boston Logan International Airport (BOS), Massachusetts (MA), where a WMA surface mixture containing Sasobit® and RAP was placed on three main runways. Materials were obtained from the same sources used during the last runway rehabilitation, and the JMF was reproduced in the laboratory.

The next sections provide properties of all materials tested in this study. Nine mixtures using three different aggregate blends and three different WMA additives were designed and tested. The nomenclature system used to identify each mixture is described in section 2.1.

2.1 MIXTURE NOMENCLATURE SYSTEM.

A nomenclature system was established to identify each mixture according to the material's source and the WMA additive used. The mixture identifier begins with the state postal abbreviation from which the materials were obtained, followed by a letter representing the WMA additive used in the mixture. Each mixture's materials source is identified as either NJ for New Jersey, MS for Mississippi, or MA for Massachusetts. The WMA additives are represented by either E for Evotherm® 3G, S for Sasobit, or F for foamed asphalt. The corresponding HMA mixtures are identified with an H at the end. For example, the HMA mixture from New Jersey is represented by NJ-H. Table 1 provides designations for all mixtures evaluated in this study.

Table 1. Mixture Designations

Materials Source	WMA Additive	Mix Designation
New Jersey	HMA	NJ-H
	Evotherm 3G	NJ-E
	Sasobit	NJ-S
	Foamed asphalt	NJ-F
Mississippi	HMA	MS-H
	Evotherm 3G	MS-E
	Sasobit	MS-S
	Foamed asphalt	MS-F
Massachusetts	Sasobit	MA-S

2.2 BINDER AND WARM-MIX ADDITIVES.

One asphalt binder was used to produce HMA and WMA mixtures with the MS and NJ aggregates. This binder was graded Performance Grade (PG) 64-22 and supplied from Axion Materials. Additives for producing the WMA mixtures were obtained from suppliers. These mixtures were reproduced in the laboratory as HMA and as WMA using three methods: organic additive Sasobit, chemical additive Evotherm 3G, and the asphalt foamer. The MA mixture was produced using a PG 64-28 binder, 4% (by weight of virgin binder) of styrene-butadiene rubber (SBR) modifier and 1.5% (by weight of virgin binder) of WMA organic (wax) additive Sasobit, replicating field mixtures placed at BOS. The SBR came in liquid latex form and was added during the mixing process at the same time the binder was added to the hot aggregate, as recommended by the manufacturer. This mixture was not produced as HMA since it was used only to provide a laboratory performance threshold for the other WMA mixtures, as it is already established as a well-performing, in-place WMA airport mixture.

Warm-mix dosage rates were selected based on manufacturers' recommendations by percentage of binder weight: Evotherm 3G was added at 0.5%; Sasobit, at 1.5%; and the foaming process, at 2% water. Evotherm 3G and Sasobit additives were preblended with the base binder prior to use. Each additive was mixed into the base binder with a high-shear mixer for 10 minutes. Foamed asphalt was produced by using a laboratory foaming device, which featured an automated control system that proportioned the water and asphalt binder at an operator-selected ratio. The binder temperature was set to 160°C, and the binder discharge temperature was set to 149°C.

2.3 AGGREGATES.

Aggregates for the three blends were obtained from five sources. Obtained from a quarry in Malvern, Pennsylvania (PA), the NJ mixtures' aggregates consisted of dolomite. The MS mixtures' aggregates were obtained from two sources: limestone from Tuscaloosa, Alabama, and crushed chert gravel from Hamilton, MS. The MA mixture aggregates obtained from Swampscott, MA, consisted of basalt (trap rock). RAP material came from the asphalt plant at Saugus, MA.

The aggregate properties obtained from the suppliers are listed in table 2. Washed gradations, bulk specific gravities (G_{sb}), apparent specific gravities (G_{sa}), and water absorptions (Abs) were obtained in duplicate from representative samples of each aggregate stockpile. The averages are provided in tables 3 through5 for each aggregate used in each of the three mixtures. Aggregate blends met the JMF gradation requirements for a 19.0-mm maximum aggregate size mixture according to FAA P-401 [20] and are provided in tables 3 through 5. One-percent hydrated lime was added to the MS and MA mixtures. Figure 1 shows the three aggregate gradations used and the FAA P-401 [20] specification band for airfields.

Table 2. Aggregate Properties

Aggregate Property	NJ JMF (%)	MS JMF (%)	MA JMF (%)
Coarse aggregate angularity (CAA)	100	84.5	100
Flat or elongated particles 3:1 ratio	1.0	10.5	3.1
Los Angeles (L.A.) abrasion test, % loss	29	16	15
Magnesium Sulfate Soundness, % loss	0.6	2.8	0.6
Sand equivalent	74	72	83

Table 3. Aggregate Blend Gradation for NJ Mixtures

Aggregate Type	Dolomite	Dolomite	Dolomite	Dolomite	
Aggregate Size	19.0 mm	12.5 mm	<9.5 mm	<9.5 mm	
Percent Used	9	30	10	51	
Sieve Size (mm)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	JMF
25.0	100	100	100	100	100
19.0	100	100	100	100	100
12.5	38	100	100	100	94
9.5	8	80	100	100	86
4.75	3	9	83	99	62
2.36	3	2	13	67	36
1.18	2	2	3	41	22
0.6	2	2	2	29	16
0.3	2	2	1	21	11
0.15	2	2	1	12	7
0.075	2.0	1.7	1.0	5.7	3.7
G_{sb}	2.829	2.828	2.815	2.803	2.814
G_{sa}	2.863	2.866	2.864	2.861	2.862
Abs %	0.4	0.5	0.6	0.7	0.61

Table 4. Aggregate Blend Gradation for MS Mixtures

Aggregate Type	Chert Gravel	Chert Gravel	Limestone	Limestone	Natural Sand	
Aggregate Size	19.0 mm	12.5 mm	<19.0 mm	<9.5 mm	<9.5 mm	
Percent Used	17	29	12	26	15	
Sieve Size (mm)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	JMF
25.0	100	100	100	100	100	100
19.0	100	100	100	100	100	100
12.5	91	100	70	100	100	94
9.5	78	90	37	100	100	85
4.75	47	55	9	99	97	65
2.36	25	31	3	75	87	46
1.18	14	18	2	44	79	31
0.6	9	12	2	27	62	22
0.3	7	8	2	16	9	9
0.15	5	6	2	8	1	5
0.075	3.9	4.3	1.8	4.1	0.4	4.3
G_{sb}	2.373	2.342	2.728	2.689	2.600	2.511
G_{sa}	2.621	2.652	2.766	2.747	2.653	2.680
Abs %	4.00	4.90	0.49	0.80	0.78	2.48

Table 5. Aggregate Blend Gradation for MA Mixtures

Aggregate Type	Basalt	Basalt	Basalt	Basalt	RAP[*]	
Aggregate Size	12.5 mm	4.76 mm	< 4.76 mm	< 9.5 mm	<19.0 mm	
Percent Used	11	18	30	20	20	
Sieve Size (mm)	Percent Passing (%)	Percent Passing (%)	Percent Passing (%)	Percent Passing %	Percent Passing (%)	JMF
25.0	100	100	100	100	100	100
19.0	100	100	100	100	100	100
12.5	83	100	100	100	99	97
9.5	16	97	100	100	93	84
4.75	1	32	100	98	70	67
2.36	1	3	62	67	53	42
1.18	1	2	31	41	41	25
0.6	1	2	18	29	31	17
0.3	1	2	10	21	20	11
0.15	1	1	6	12	11	7
0.075	0.9	1.3	2.3	5.7	6	4.4
G_{sb}	2.934	2.914	2.860	2.803	2.702	2.823
G_{sa}	2.959	2.960	2.933	2.861	2.773	2.884
Abs %	0.43	0.50	0.87	0.72	0.93	0.73

[*] An asphalt content of 5.5% was estimated for the RAP using the ignition oven. A correction factor of -0.5% was applied; thus, the corrected asphalt content used was 5.0%.

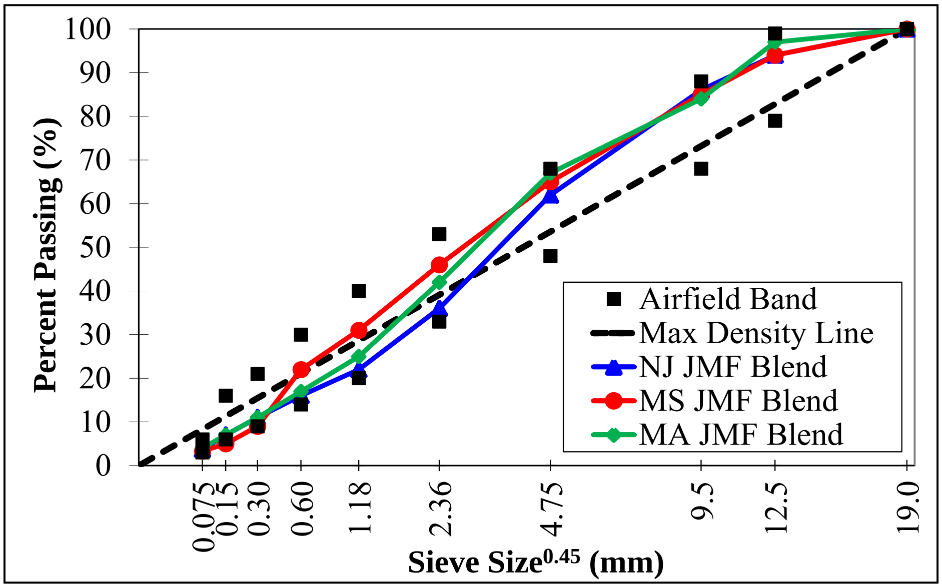

Figure 1. Gradation Curves for Aggregate Blends Used

2.4 ASPHALT MIXTURES.

Laboratory mixing and compaction temperatures for the HMA were based on data provided by the binder suppliers. HMA was mixed and compacted at 154°C and 144°C, respectively. WMA was mixed and compacted at 130°C and 116°C, respectively. The MA mixture was mixed and compacted at higher temperatures (132°C and 124°C, respectively) than the other WMA mixtures because of the latex modifier.

For mixture designs, individual batches for each mixture were prepared by weighing the target batch for each stockpile or sieve size into a shallow mixing pan. Aggregate batches were placed in an oven overnight at the target mixing temperature prior to performing mixture designs. To perform the mixture design, the asphalt binder was heated to 154°C for all HMA and WMA mixtures with the exception of the foamed asphalt mixtures and the MA mixture. For the MA mixture, the asphalt binder was heated to 160°C. Binder temperatures for foamed asphalt were previously discussed in section 2.2.

The aggregate was weighed into a mixing bowl, and binder was added to achieve the target binder content for the mixture. The sample was mixed in a bucket mixer until the aggregate was thoroughly coated with binder. The mixture was placed into a shallow pan and stored in the oven at the compaction temperature for two hours before being placed into the preheated compaction molds. A Pine Instrument Company model AFGC125X gyratory compactor was used to compact cylindrical asphalt concrete specimens with a 150-mm diameter at a 115-mm target height. Compaction was performed using a 600-kPa ram pressure and an internal 1.16° ±0.02° angle of gyration. Asphalt mixtures were compacted to 70 gyrations at a rate of 30 revolutions per minute. Seventy gyrations were recommended for N_{design} for HMA mixtures designed for high tire pressure aircraft [21]. The same material handling, mixing, and compaction procedure used for mix design was used for the laboratory test specimen preparation. Specimens differed for testing in dimension and height compaction only. Height compaction, rather than gyration level, was specified for each test in an attempt to reduce the variability in air voids content caused by the three specimen geometries produced by the respective performance tests.

The optimum binder content for each mixture was determined by compacting specimens using at least three different binder contents. Theoretical maximum specific gravity (G_{mm}) of each mixture was determined on duplicate specimens in accordance with American Association of State Highway and Transportation Officials (AASHTO) T 209 [22], and the average value was reported. Bulk specific gravity (G_{mb}) of compacted cylindrical specimens was determined in accordance with AASHTO T 166 [23]. The percentage of air voids (V_a) in the specimen was determined in accordance with AASHTO T 269 [24]. The percentage of air voids versus the percentage of binder in the mixture (P_b) was plotted to determine the percentage of binder required to compact the mixture to 3.5% air voids at the design compaction effort. The air voids content of 3.5% percent ±0.5% was selected because it is the center of the allowable design range in FAA specifications. This percentage of binder was considered the design binder content. Specimens for further testing were prepared using this design binder content. Mixture volumetric properties were determined in accordance with procedures in the Asphalt Institute MS-02 manual [25] and are listed in table 6.

Table 6. Mixture Volumetrics

Mix Identification	G_{mm}	G_{se}	G_{mb}	P_b^* (%)	P_{ba} (%)	P_{be} (%)	V_a (%)	VMA (%)	VFA (%)	D/B
NJ-H	2.625	2.858	2.536	5.0	0.56	4.47	3.4	14.4	85.0	0.83
NJ-E	2.615	2.845	2.521	5.0	0.40	4.62	3.6	14.9	81.5	0.80
NJ-S	2.620	2.852	2.536	5.0	0.48	4.54	3.2	14.4	85.0	0.81
NJ-F	2.617	2.848	2.529	5.0	0.44	4.59	3.5	14.7	83.2	0.81
MS-H	2.362	2.595	2.280	6.5	1.33	5.26	3.5	15.2	77.1	0.81
MS-E	2.360	2.593	2.269	6.5	1.29	5.30	3.9	15.6	75.3	0.80
MS-S	2.359	2.591	2.278	6.5	1.27	5.32	3.4	15.2	77.6	0.80
MS-F	2.357	2.585	2.282	6.4	1.16	5.31	3.2	15.0	78.7	0.80
MA-S	2.590	2.868	2.515	6.0	0.56	5.48	2.9	15.3	79.3	0.80
Target	---	---	---	---	---	---	3.5	min 15.0	64-78	0.8-1.2

*Assumed 100% contribution of RAP asphalt binder to the P_b

VMA = Voids in mineral aggregate
VFA = Voids filled with asphalt
D/B = Dust in the bin

3. PERFORMANCE TESTS.

Four laboratory performance tests were performed on compacted mixtures:

- Repeated load
- Static creep
- IDT
- APA

Performance tests selected for this study were among those most recommended by previous research. The following sections describe the details of the four performance tests used in this study. Performance criteria from Rushing, Little, and Garg [26] were applied to the repeated load, static creep, and APA tests. Criteria from Advanced Asphalt Technologies, LLC [27] were applied for the IDT strength test. These criteria provided a reasonable assessment of the different HMA and WMA mixtures rutting performance that could be compared to what is found in the literature.

3.1 REPEATED LOAD TEST.

The repeated load test measured permanent deformation as axial load cycles were applied to cylindrical HMA specimens. Cumulative permanent deformation was reported as a number of load cycles function. Cumulative permanent deformation historically was categorized for a wide range of materials into three zones: primary, secondary, and tertiary (figure 2). The primary zone was characterized by a decreasing rate of accumulated permanent deformation during specimen densification. In the secondary zone, permanent strain accumulated in a relatively linear fashion. The tertiary zone occurred as the specimen failed and was characterized by an increasing rate of accumulated permanent deformation.

The repeated load test was performed on cylindrical specimens, 100 mm in diameter by 150-mm high, cored from gyratory compacted mixtures. A confining stress of 276 kPa and a deviator stress of 1380 kPa were selected for testing. The load pulse consisted of a 0.1-second load followed by 0.9-second dwell time. The test temperature was selected to be the mean monthly pavement temperature (MMPT) and was defined by Witczak [28]. The MMPT was 43°C in Vicksburg, MS, the selected climate for the project. The results from three replicate specimens were averaged and reported.

The repeated load test was used to determine the flow number (FN). The FN was defined as the number of cycles corresponding to the minimal rate of change of permanent axial strain during the repeated load test. The FN for each specimen was determined by fitting a Francken model to the repeated load test data by a least sum of squares method. The Francken model (equation 1) fit the permanent strain data by using a combination of a power law and an exponential model. Four fitting coefficients were used to fit the model to experimental data (figure 3). The FN was defined as the number of cycles when the second derivative of the model (equation 2) changed from negative to positive. Rushing, Little, and Garg [26] recommend a FN greater than 200 for airfield paving mixtures.

$$\varepsilon_p = An^B + C(e^{Dn} - 1) \tag{1}$$

where:

n = number of load cycles
A, B, C, and D = fitting coefficients

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{(B-2)} + CD^2e^{Dn} \tag{2}$$

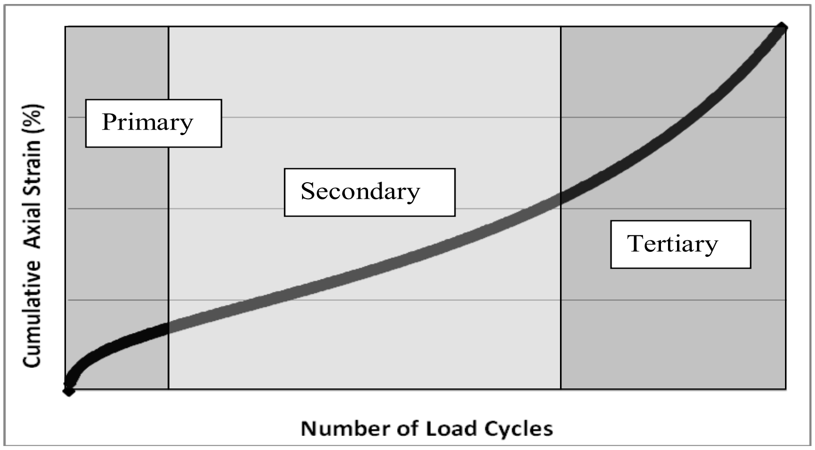

Figure 2. Typical Permanent Deformation Behavior of Asphalt Mixtures

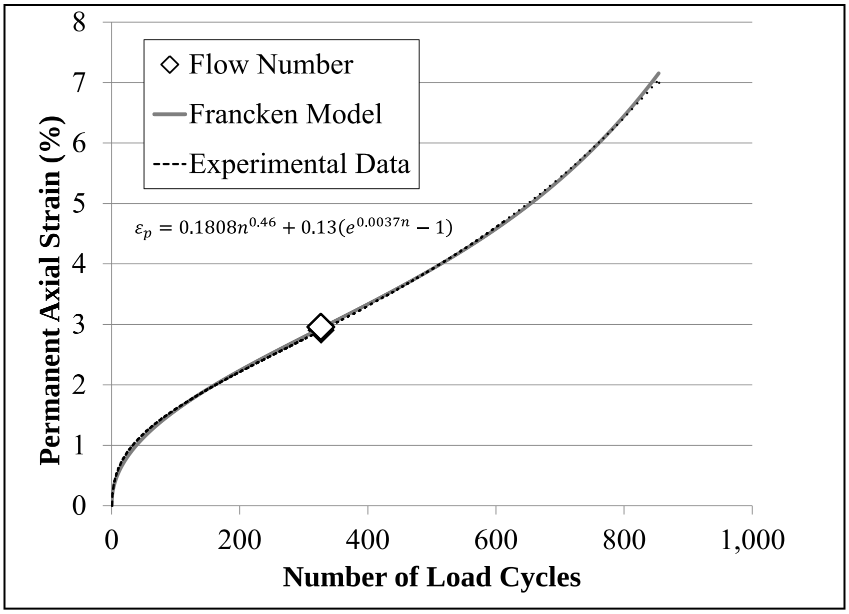

Figure 3. Determining the FN

3.2 STATIC CREEP TEST.

The static creep test measured permanent deformation as a function of time when a constant load was applied to cylindrical HMA specimens. Cumulative permanent deformation was reported as a function of time during loading. The static creep test was performed on cylindrical specimens, 100 mm in diameter by 150 mm high, cored from gyratory compacted mixtures. A confining stress of 276 kPa and a deviator stress of 1380 kPa were selected for testing. The test temperature was selected to be the MMPT and was defined by Witczak [28]. The MMPT was 43°C in Vicksburg, MS, the selected climate for the project. The results from three replicate specimens were averaged and reported.

The static creep test was used to determine the flow time (FT). The FT was defined as the time corresponding to the minimal rate of change of permanent axial strain during the static creep test. The FT for each specimen was determined by fitting the Francken model (equation 3) to repeated load test data by a least sum of squares method. Four fitting coefficients were used to fit the model to experimental data (figure 4). The FT was defined as the time when the second derivative of the model (equation 4) changed from negative to positive. Rushing, Little, and Garg [26] recommend a FT greater than 30 for airfield paving mixtures.

$$\varepsilon_p = Wt^X + Y(e^{Zt} - 1) \tag{3}$$

where:

t = time
W, X, Y, and Z = fitting coefficients

$$\frac{d^2\varepsilon_p}{dt^2} = WX(X-1)t^{(X-2)} + YZ^2e^{Zt} \qquad (4)$$

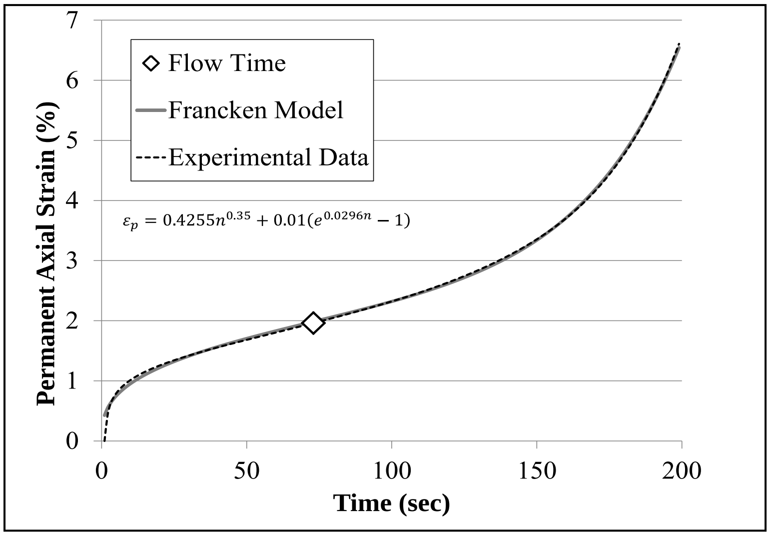

Figure 4. Determining the FT From Static Creep Data

3.3 THE IDT STRENGTH TEST.

The IDT strength test was used to measure the cohesive properties of each mixture. The test applies a compressive load to the diametral axis of a cylindrical specimen. A specimen diameter of 150 mm and height of 100 mm was used for testing. Specimens were compacted in the superpave gyratory compactor (SGC) to the target height of 100 mm using the appropriate mass of asphalt mixture to result in a target air voids content of 3.5%. Specimens were submerged in a water bath at the test temperature of 40°C for 2 hours prior to testing. The load was applied in a load frame at a rate of 50 mm/min. The peak load was recorded from a dial gage and used to calculate IDT according to equation 5. The results from three replicate specimens were averaged and reported.

$$IDT = \frac{(2000 \times P)}{(\pi \times d \times h)} \qquad (5)$$

where:

IDT = Indirect tensile strength, kilopascal (kPa)
P = Peak load at failure, Newtons (N)
d = Specimen diameter, mm
h = Specimen height, mm.

Advanced Asphalt Technologies, LLC [27] prepared recommendations for the FAA's gyratory compaction-based specification. These recommendations included requirements for IDT strength test results. The requirements are based on the binder grade used in the mixture. Since testing is performed at 40°C, higher-binder grade temperatures are expected to result in higher IDT. Two sets of requirements exist: those for normal-duty HMA designs and those for heavy-duty HMA designs. Heavy-duty HMA designs are defined as those intended for runways or taxiways with total annual departures exceeding 60,000 and handling a design aircraft with gross weight exceeding 890 kN or with tire pressure exceeding 1380 kPa. Table 7 lists the requirements for mixtures prepared with common airfield binder PGs.

Table 7. The FAA Minimum IDT Requirements

Specified Minimum High-Temperature Binder PG	Minimum Design IDT, kPa	
	Normal-Duty HMA Designs	Heavy-Duty HMA Designs
PG 52-XX	138	207
PG 58-XX	207	276
PG 64-XX	310	414
PG 67-XX	345	483
PG 70-XX	414	552
PG 76-XX	552	758
PG 82-XX	758	965

3.4 THE APA TEST.

This study used an APA designed specifically to simulate high tire pressures associated with aircraft. An APA tube or hose pressure of 1724 kPa under a wheel load of 1113 N was used for testing. The test temperature was 64°C, the high PG binder temperature. Figure 5 shows the APA test configuration and the specimens after the completed test. Cylindrical, 150-mm-diameter by 75-mm-thick asphalt concrete specimens with a target air voids content of 3.5% were prepared and tested. The air voids content was selected as the allowable range midpoint in the FAA mix design procedure. Six specimens were tested for each mix in three test positions. The APA applied cyclic loads at a rate of one cycle per second. The specimens' terminal rut depth was set at 12 mm after 8000 cycles; however, the test was terminated when the 12-mm rut depth was achieved if this occurred before 8000 cycles. Once one of the two specimens at each test position reached terminal rut depth, the test was stopped. However, since the APA reports the average rut depth for the two specimens in each test position, some average rut depths were less than 12 mm. The APA rut depth reported for each mixture tested was the overall average rut depth for the three test positions from the six cylindrical specimens. Rushing, Little, and Garg [29] recommended a criterion of a minimum 4000 cycles to achieve 10 mm of rutting for airfield mixture acceptance when tested using 1113-N wheel load and 1724-kPa hose pressure.


(a) (b)

Figure 5. The APA Test Configuration (a) and HMA Specimens After Testing in the APA (b)

4. PERFORMANCE TESTS RESULTS.

4.1 REPEATED LOAD TEST.

A summary of the average FN values for each of the mixtures tested is shown in figure 6, and the test results for all nine mixtures evaluated are presented in table 8. The specimen air voids content, the calculated FN values, and the regression coefficients are provided for each specimen tested. The raw data plots are provided in appendix A. The minimum FN required for ensuring good rutting performance, as recommended by Rushing, Little, and Garg [26], for airfield applications is shown in figure 6 as a red horizontal dashed line.

FN values for the NJ mixtures show HMA and all WMAs met the suggested performance test criteria. The same was observed for the MA-S mixture. However, none of the MS mixtures met the minimum FN requirement. In general, most WMA mixtures had FN values similar to or higher than those of HMA mixtures. Previous research has indicated that WMA can have lower rutting resistance than HMA. For example, Doyle, Rushing, and Mejías-Santiago [3] conducted repeated load tests for HMA and WMA using the same test parameters and laboratory mixing and compaction temperatures used in this study. Their data showed FN values for WMA being slightly lower than those of comparative HMA.

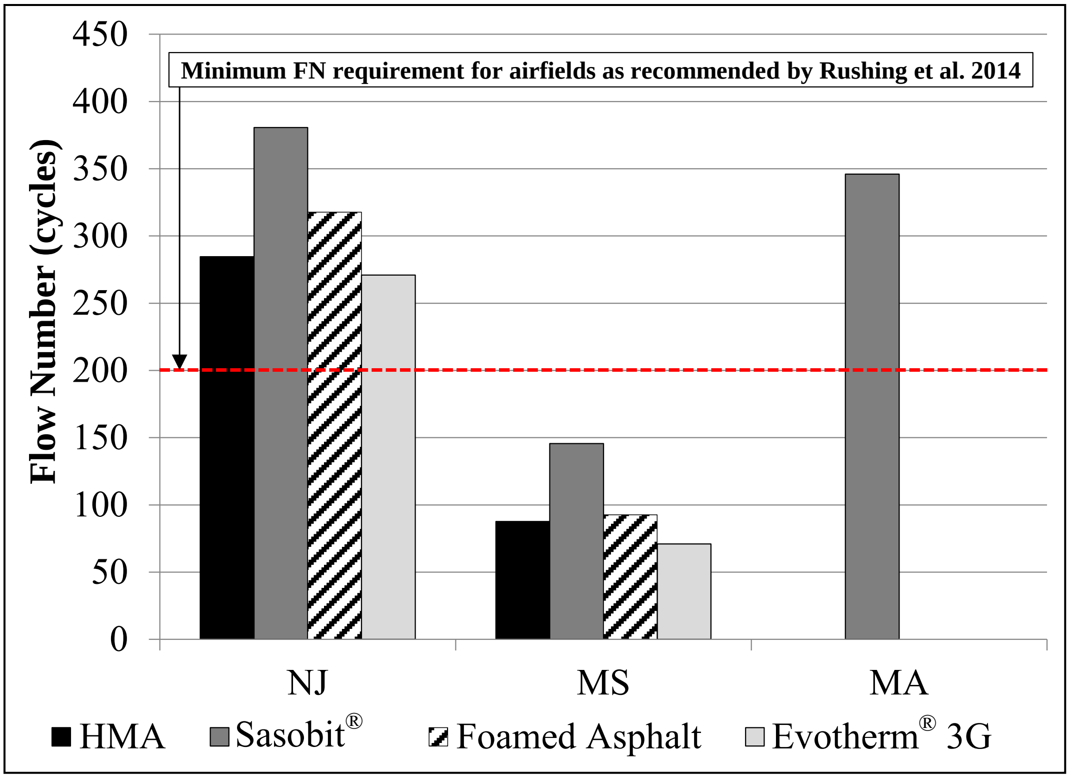

Figure 6. The FN Results

Table 8. Repeated Load Test Results

Mix	Sample	V_a	FN	Regression Coefficients			
				A	*B*	*C*	*D*
NJ-H	FN1	3.9	327	0.1808	0.4621	0.1313	0.0037
	FN2	3.6	299	0.1672	0.4643	0.1248	0.0041
	FN3	3.8	228	0.2116	0.4099	0.3936	0.0033
	Average	3.8	285	0.1865	0.4454	0.2166	0.0037
NJ-E	FN1	3.1	301	0.1199	0.4630	0.2026	0.0032
	FN2	3.0	228	0.1933	0.3918	0.3147	0.0033
	FN3	3.0	284	0.1370	0.4527	0.1964	0.0033
	Average	3.0	271	0.1501	0.4358	0.2379	0.0032
NJ-S	FN1	3.0	436	0.1852	0.3460	0.2006	0.0020
	FN2	3.0	309	0.2053	0.3346	0.4601	0.0018
	FN3	3.2	397	0.6694	0.2095	0.1717	0.0024
	Average	3.1	381	0.3533	0.2967	0.2775	0.0020
NJ-F	FN1	3.0	331	0.1430	0.4370	0.2000	0.0026
	FN2	3.1	335	0.1394	0.4536	0.1960	0.0030
	FN3	3.0	287	0.2807	0.3328	0.4973	0.0024
	Average	3.0	318	0.1877	0.4078	0.2978	0.0027

Table 8. Repeated Load Test Results (Continued)

				Regression Coefficients			
Mix	Sample	V_a	FN	*A*	*B*	*C*	*D*
MS-H	FN1	3.4	99	0.3086	0.3804	0.9867	0.0051
	FN2	3.0	80	0.2419	0.4345	0.9096	0.0064
	FN3	3.3	84	0.2375	0.4222	1.0265	0.0057
	Average	3.2	88	0.2627	0.4124	0.9743	0.0057
MS-E	FN1	3.0	73	0.3135	0.3361	0.9888	0.0060
	FN2	3.0	75	0.2475	0.4262	1.6204	0.0053
	FN3	3.0	65	0.3250	0.3473	1.1464	0.0065
	Average	3.0	71	0.2953	0.3698	1.2519	0.0059
MS-S	FN1	3.0	154	0.1955	0.3835	2.7270	0.0019
	FN2	3.2	198	0.1895	0.4347	3.0930	0.0017
	FN3	3.3	85	0.2081	0.4534	0.5955	0.0071
	Average	3.2	146	0.1977	0.4239	2.1385	0.0036
MS-F	FN1	3.0	83	0.2155	0.4256	1.8507	0.0044
	FN2	2.5	96	0.2105	0.4402	1.4425	0.0044
	FN3	2.6	99	0.2479	0.4018	1.2340	0.0045
	Average	2.7	93	0.2246	0.4225	1.5091	0.0044
MA-S	FN1	4.0	411	0.1534	0.4746	0.1874	0.0026
	FN2	3.8	312	0.2618	0.3994	0.3988	0.0027
	FN3	4.0	315	0.2317	0.4310	0.2798	0.0031
	Average	3.9	346	0.2156	0.4350	0.2887	0.0028

4.2 STATIC CREEP TEST.

An average FT values summary for each tested mixture is presented in figure 7, and the test results for all nine mixtures evaluated are presented in table 9. The specimen air voids content, the calculated FT values, and the regression coefficients are provided for each specimen tested. The raw data plots are provided in appendix B. The minimum FT recommended by Rushing, Little, and Garg [26] to ensure good rutting performance on airfield pavements is shown in the figure as a red horizontal dashed line.

FT values for the NJ mixtures show that the HMA and all WMAs easily met the minimum FT requirement. The same was observed for the MA mixture. For the MS mixtures, the HMA mixture was the only one that did not meet the FT criteria. The FN results indicated WMA mixtures showed better rutting performance than HMA mixtures by having higher FT values. In this case, the WMA specimens air void contents were generally equal to or higher than those of the HMA specimens; however, WMA still showed better rutting performance than HMA.

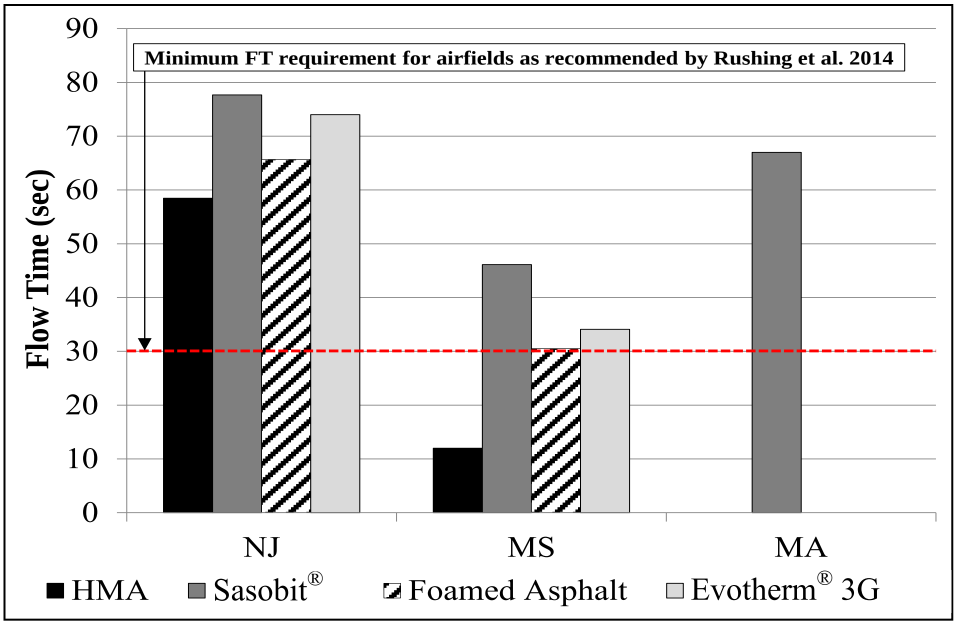

Figure 7. The FT Results

Table 9. Static Creep Test Results

Mix	Sample	V_a (%)	FT	Regression Coefficients			
				W	*X*	*Y*	*Z*
NJ-H	FT1	3.2	35	0.4984	0.2525	0.0809	0.0294
	FT2	3.0	102	0.4697	0.2201	0.9165	0.0040
	FT3	3.3	39	0.5161	0.1663	1.9930	0.0059
	Average	3.2	58	0.4947	0.2129	0.9968	0.0131
NJ-E	FT1	3.7	79	0.4000	0.2501	0.0411	0.0158
	FT2	3.4	79	0.3496	0.3495	0.0002	0.0590
	FT3	3.4	64	0.5133	0.1408	1.0055	0.0046
	Average	3.5	74	0.4210	0.2468	0.3489	0.0265
NJ-S	FT1	2.8	90	0.4809	0.1464	0.2959	0.0056
	FT2	3.0	70	0.4612	0.2005	0.1165	0.0117
	FT3	3.3	73	0.4003	0.1655	0.1269	0.0093
	Average	3.0	78	0.4475	0.1708	0.1798	0.0089
NJ-F	FT1	3.0	64	0.5504	0.1352	0.7273	0.0052
	FT2	3.0	47	0.4937	0.1632	0.1744	0.0132
	FT3	3.4	86	0.5658	0.1357	1.0283	0.0035
	Average	3.1	66	0.5366	0.1447	0.6433	0.0073
MS-H	FT1	2.9	11	0.5614	0.4580	0.0506	0.1244
	FT2	3.0	11	0.5879	0.3847	0.7022	0.0476
	FT3	2.9	13	0.7598	0.5358	0.0346	0.1406
	Average	2.9	12	0.6364	0.4595	0.2625	0.1042

Table 9. Static Creep Test Results (Continued)

Mix	Sample	V_a (%)	FT	Regression Coefficients			
				W	*X*	*Y*	*Z*
MS-E	FT1	3.0	49	0.5801	0.4099	0.9428	0.0129
	FT2	3.0	21	0.5505	0.3157	2.1778	0.0151
	FT3	4.5	32	0.5906	0.4024	0.3685	0.0256
	Average	3.5	34	0.5737	0.3760	1.1631	0.0179
MS-S	FT1	2.7	54	0.4982	0.4306	0.8467	0.0120
	FT2	3.0	32	0.5378	0.3719	1.0711	0.0159
	FT3	3.0	53	0.4146	0.4642	0.6899	0.0131
	Average	2.9	46	0.4835	0.4222	0.8692	0.0136
MS-F	FT1	3.3	19	0.5392	0.2632	3.4397	0.0121
	FT2	3.4	21	0.5748	0.2411	3.7172	0.0104
	FT3	3.4	52	0.5526	0.3877	1.2448	0.0103
	Average	3.4	30	0.5555	0.2974	2.8006	0.0110
MA-S	FT1	4.0	70	0.4803	0.3199	0.0142	0.0284
	FT2	4.0	65	0.5916	0.2299	0.2014	0.0121
	FT3	4.0	66	0.6539	0.2344	0.4100	0.0096
	Average	4.0	67	0.5753	0.2614	0.2085	0.0167

4.3 THE IDT STRENGTH TEST.

A summary of the air voids contents for all the IDT specimens is presented in table 10. The raw IDT strength test results are provided in appendix C. Average IDT results are presented in figure 8. The acceptance criteria for the IDT strength tests recommended by Advanced Asphalt Technologies, LLC [27] for normal- and heavy-duty HMA designs are shown in the figure as horizontal dashed lines (blue and red, respectively). IDT values indicated that all mixtures were at the margin of the suggested performance test criteria for normal-duty design, except for MS-H and MS-E, which had slightly lower IDT values. These results show the same trend as the FN, FT, and APA results (discussed in section 4.4), with WMA mixtures having higher IDT values than their comparative HMA. However, IDT results do not show a noticeable difference in performance between NJ, MS, and MA mixtures, as shown by the other performance tests. IDT values ranged from approximately 270-350 kPa throughout all mixtures tested, which did not provide a clear distinction between poor and good performing mixtures under heavy aircraft loads.

Table 10. The IDT Specimen Air Voids Content

Test Specimen	Air Voids (%)								
	NJ-H	NJ-E	NJ-S	NJ-F	MS-H	MS-E	MS-S	MS-F	MA-S
IDT1	3.3	3.2	3.4	3.0	3.4	3.8	3.7	3.5	3.5
IDT2	3.1	3.1	3.5	3.3	3.3	3.6	3.7	3.3	3.3
IDT3	3.2	3.2	3.4	3.3	3.2	3.5	3.6	3.5	3.3
Average	3.2	3.2	3.4	3.2	3.3	3.6	3.7	3.4	3.4

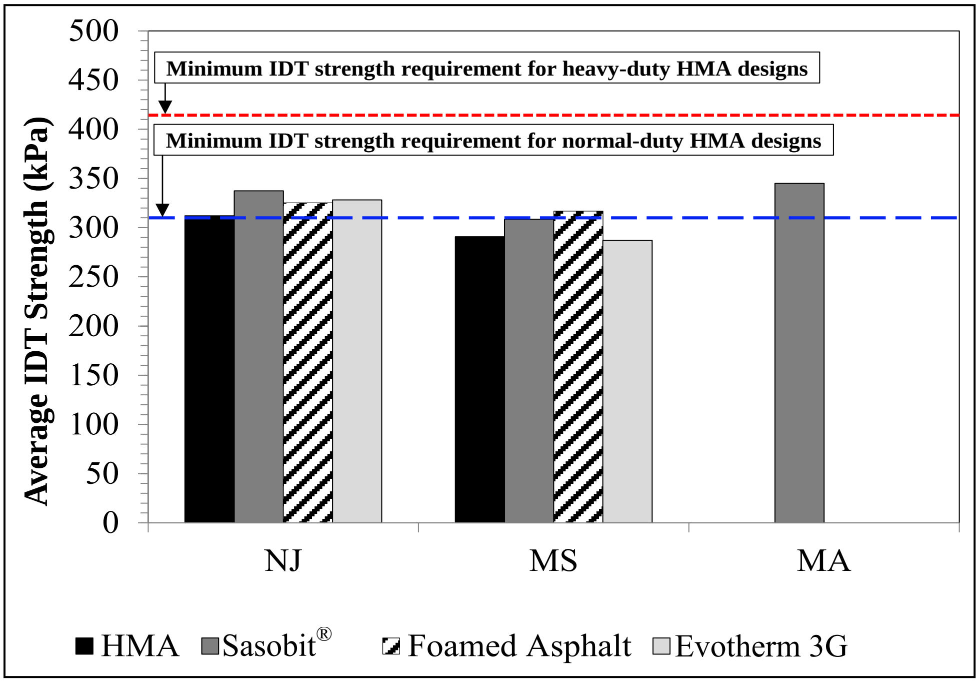

Figure 8. The IDT Strength Test Results

4.4 THE APA TEST.

A summary of the air voids content for each APA specimen is presented in table 11. The raw APA data plots are provided in appendix D. Average APA results are presented in figure 9. The threshold criterion of a minimum 4000 cycles to achieve 10 mm of rutting recommended by Rushing, Little, and Garg [29] for airfield mixture acceptance is shown in the figure as a red horizontal dashed line. APA results for NJ and MA mixtures indicated that these mixtures exceeded the threshold, however, none of the MS mixtures, including HMA, met the requirement. Differences between WMA and HMA were mixed, but data show that when HMA did not meet the criterion, its corresponding WMA did not meet it either. These APA results clearly show a noticeable higher rutting potential for the MS mixtures compared to the other mixtures tested. APA test results have previously shown the capability for identifying mixtures with high rutting potential [29].

Table 11. The APA Specimen Air Voids Content

Test Specimen	Air Voids (%)								
	NJ-H	NJ-E	NJ-S	NJ-F	MS-H	MS-E	MS-S	MS-F	MA-S
APA1	3.2	3.0	3.3	3.3	4.2	3.1	2.9	3.0	3.6
APA2	3.2	3.1	3.5	3.1	3.8	3.0	3.0	2.7	3.2
APA3	3.2	3.1	3.1	3.0	3.5	2.9	2.8	2.8	3.2
APA4	3.1	3.1	3.3	3.1	3.5	2.9	2.7	2.8	*Not available*
APA5	3.4	3.0	3.2	3.0	3.5	2.9	2.9	2.6	3.4
APA6	3.3	3.0	3.3	3.0	3.6	2.9	2.8	3.0	3.4
Average	3.2	3.1	3.3	3.1	3.7	3.0	2.9	2.8	3.4

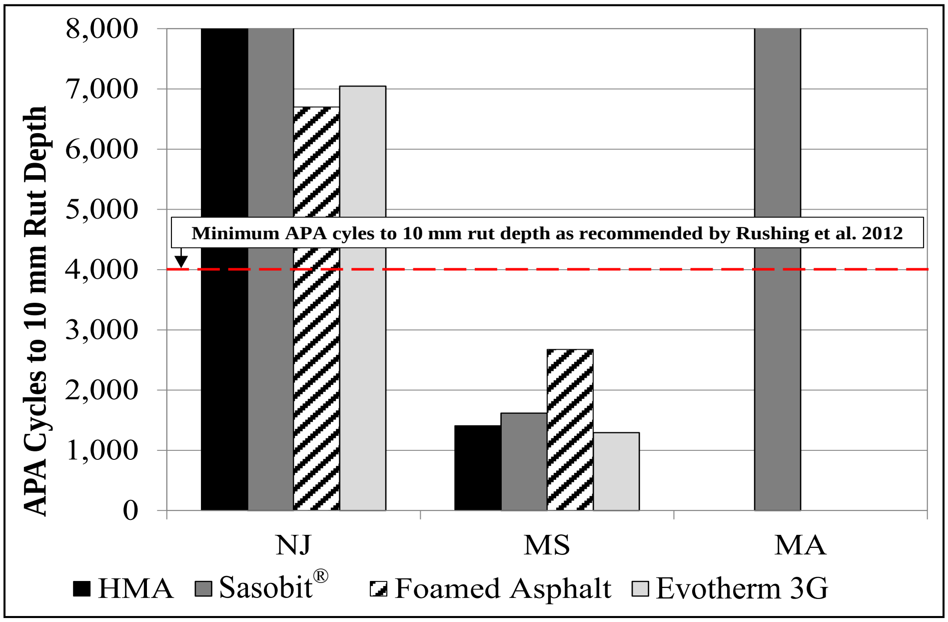

Figure 9. The APA Results for all Three Mixtures

5. PERFORMANCE TEST RESULTS DISCUSSION.

The MA-S mixture exceeded all performance test criteria. Research has shown that adding RAP to WMA can improve rutting performance, even though RAP is not currently allowed by Item P-401 for surface mixtures [20]. This mixture was placed in several heavy traffic areas at BOS. BOS is possibly the only airport where WMA was used for runway surface pavement, and performance issues have not been reported. Therefore, this mixture was evaluated to establish reference data based on a well-performing, in-place WMA airport mix for use in comparing the other WMA mixtures rutting performance.

Rutting results from three out of four performance tests indicated that the MS mixture was susceptible to rutting under aircraft loads, as the mixture did not meet any of the performance test requirements. The rutting performance changed when the mixture was produced as WMA:

most WMAs performed similarly to or better than HMA. However, rutting resistance was still under the minimum criteria and was lower than the MA-S mixture for most of the WMAs. A more rut-resistant gradation or a modified asphalt binder would improve the rutting resistance of this mixture to meet performance test criteria and perhaps match the MA-S mixture.

The NJ HMA mixture met the criteria for all the performance tests conducted. However, the rutting resistance of this mixture was lower than that of the MA-S mixture. Results from the repeated load, static creep, and IDT strength tests indicated that the rutting performance of this mixture generally improved when it was produced as WMA. In addition, the NJ HMA mixture matched or exceeded the rutting performance of the MA-S mixture when produced as WMA in most cases. APA results showed improvement only when the mixture was produced using Sasobit. However, the mixture still met the minimum APA rutting requirement when it was produced using Evotherm 3G and foamed asphalt. These results show that the NJ mixture is expected to have good rutting performance under heavy aircraft loads when produced as both HMA and WMA.

While the repeated load, static creep, and APA tests results highlighted a marked lower rutting performance for the MS mixtures as compared to the NJ and MA mixtures, the IDT strength test results did not show much difference. The range of IDT values observed across all mixtures evaluated did not provide a clear distinction between poor and good performing mixtures under heavy aircraft loads. This may indicate that the use of IDT strength test parameters and possibly the minimum IDT criteria as indicators of rutting performance requires re-evaluation. Additional data collection is required from airfields that are currently being constructed to verify and refine these criteria and re-evaluate the IDT.

6. RECOMMENDATIONS FOR FULL-SCALE ACCELERATED PAVEMENT TESTING OF WARM-MIX ASPHALT.

This section summarizes the test plan for Construction Cycle 1 of the FAA National Airport Pavement and Materials Research Center (NAPMRC) and provides the main recommendations for full-scale accelerated pavement testing (APT) to evaluate rutting performance of WMA under heavy aircraft loads. These recommendations are based on previous research on WMA conducted at the Engineer Research and Development Center, Vicksburg, MS, [1-4] and the laboratory performance test results presented in this report.

The general layout of the planned test strips for the new FAA NAPMRC Construction Cycle 1 was provided by the FAA [30] and is shown in figure 10. The FAA plan includes testing WMA and corresponding HMA on test strips that will be constructed both indoors and outdoors for comparison. Other variables of the plan include tire pressure and binder type. APT will be conducted using a heavy-vehicle simulator (HVS-A) at high pavement temperatures (approximately 60°C). The intent of the FAA-designed pavement structure was to minimize deformation in the granular layers so that failure would occur predominantly in the asphalt surface layer. The resulting pavement structure consists of 130 mm of asphalt concrete over 300 mm of base material with a modulus of 410 MPa over a 300-mm-thick subbase course with a modulus of 170 MPa over a subgrade with an assumed California bearing ratio (CBR) of 15 (modulus=155 MPa). These design layer thicknesses and granular material properties will be consistent throughout the test strips. Figure 11 shows the cross sections of the pavement structure [30].

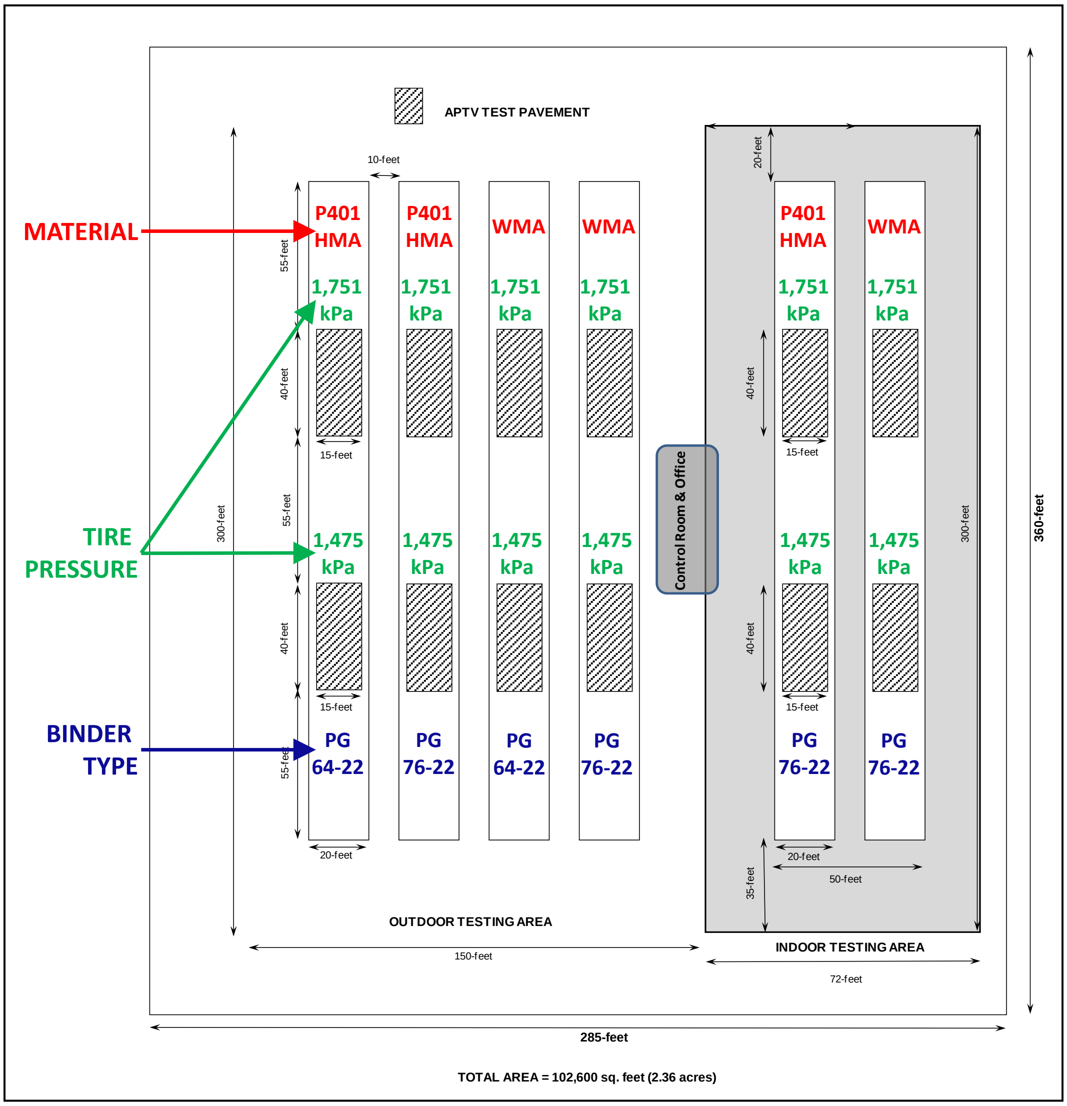

Figure 10. The FAA NAPMRC—Construction Cycle 1 Layout

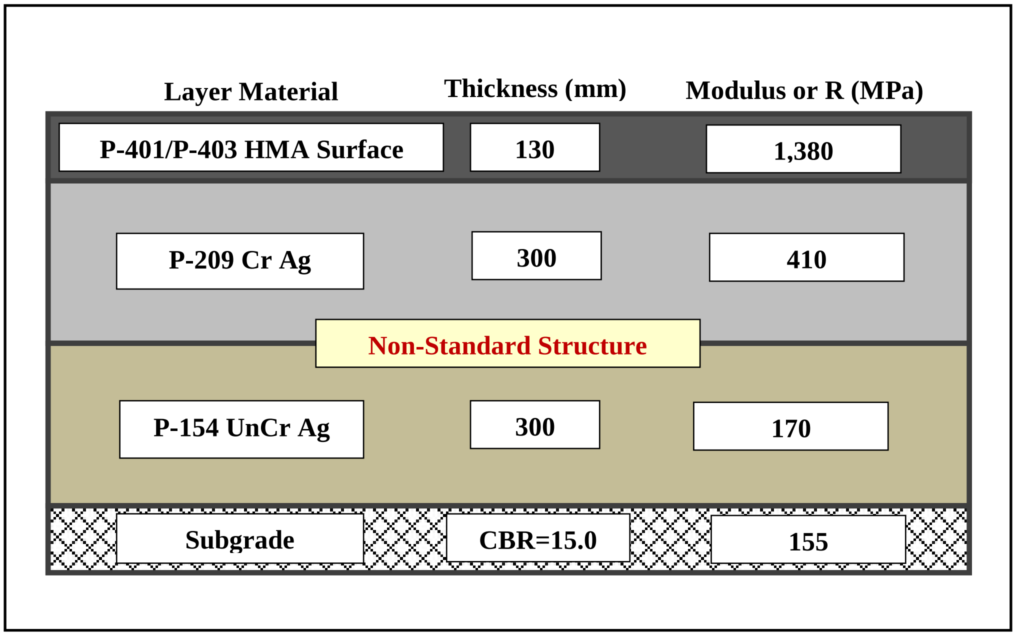

Figure 11. The FAA NAPMRC—Construction Cycle 1 Cross Sections

Based on the results presented in this report, the NJ mixture is recommended for full-scale APT evaluation of WMA at the High Temperature Pavement Test Facility (HTPTF). This mixture meets FAA P-401 [20] requirements and was produced using materials available locally in the NJ/PA area. The mixture met all the performance test requirements evaluated in this report when produced as either HMA or WMA.

The FAA HTPTF test plan for Cycle 1 includes evaluation of only one WMA technology. In practice, contractors usually propose using WMA technologies because they have experience with them. Considering this and based on the results presented in this report and those from previous research [1-4], it is recommended to use either Sasobit, Evotherm 3G, or foamed asphalt—as these are the most widely used WMA technologies in the U.S. within each WMA category. Results from previous laboratory tests show that the category of WMA technology is not generally indicative of laboratory rutting performance [1 and 3]. Results from APT conducted at the Engineer Research and Development Center (ERDC) [4] indicated that foamed asphalt may be more rut resistant than the other two WMAs under heavy aircraft loads. Sasobit and Evotherm 3G showed similar rutting performance during APT. The laboratory rutting performance results presented in this report showed Sasobit as the overall top performer, followed by Evotherm 3G and foamed asphalt having similar rankings. These observations show the difficulty in establishing a single technology for evaluation; however, it is very probable that this will be determined by the contractor's preference.

Regardless of which WMA technology is selected for testing, the mix design and production and placement procedures need to be monitored closely to assure that everything is as consistent as possible between the WMA mixture selected and its corresponding HMA mixture. If the mix design is conducted at HMA temperatures and without the WMA additive, verifications need to be conducted to measure G_{mm} and to verify that the mixture volumetrics meet the requirements when produced as WMA. Previous studies show that for aggregates with intermediate to high absorption, the asphalt absorption tends to decrease when the mixture is produced as WMA [3]. For testing purposes, it is important to keep variables such as the effective asphalt content as consistent as possible to allow for fair comparisons, especially if rutting is being evaluated. Adjustments in the asphalt content may be required in some cases when producing HMA mix designs as WMA depending on the aggregate gradation and type and sometimes depending on the WMA technology.

During production, placement and compaction, monitoring the mix temperatures, and documenting the overall temperature difference between the WMA and the HMA are critical steps. The recommended WMA mix production temperatures for the PG 64-22 and PG 76-22 binders are 130°C and 141°C, respectively. Recommended compaction temperatures for the PG 64-22 and PG 76-22 binders are 116°C and 127°C, respectively. These temperatures may vary depending on the contractor's experience with WMA technology, but the temperature difference between the HMA and the WMA should be at least 30°C.

Monitoring compaction patterns used during compaction is important because the WMA may require less compaction effort. Also, controlling and measuring the final asphalt layer thicknesses is critical in this type of test. If there are variations in the asphalt layer thickness throughout the tests items, grinding the surface down to the thinnest measurement is recommended.

7. SUMMARY AND CONCLUSIONS.

Currently, the Federal Aviation Administration (FAA) P-401 specification does not include guidance for using warm-mix asphalt (WMA) for airport pavements. Laboratory and field performance evaluation of WMA technologies will provide the information needed to develop such guidance. Specifically, the additional potential for rutting in WMA because of reduced aging and the stiffening of the binder during WMA production requires investigation. The purpose of this project was to evaluate the laboratory rutting performance of WMA and to compare the results to hot-mix asphalt (HMA) to formulate recommendations for full-scale evaluation of WMA under heavy aircraft loads at the FAA High Temperature Pavement Test Facility. The following summarizes the project's main findings presented in this report:

- Evaluating the rutting potential of the Massachusetts (MA)-Sasobit® (S) mixture provided a good reference point to compare the rutting resistance of other WMA mixtures since it has been demonstrated successfully as an airfield paving mixture.

- The Mississippi (MS) mixture is susceptible to rutting under aircraft loads. The rutting performance can be improved using WMA technology, but the mixture still would require a more rut resistant gradation or a modified asphalt binder to meet performance criteria.

- The New Jersey (NJ) mixture met the criteria for all the performance tests conducted. Resistance to rutting was generally improved using WMA technology. This mixture is expected to have good rutting performance under heavy aircraft loads when produced either as HMA or WMA.

- The repeated load, static creep, and asphalt pavement analyzer tests resulted in similar mixture rankings and indicated similar performance for HMA compared to WMA.

- The range of indirect tensile strength (IDT) values observed across all mixtures evaluated did not provide a clear distinction between high rutting potential mixtures and rut resistant mixtures. This may indicate that the IDT strength test parameters and perhaps the minimum IDT criteria need to be revisited to verify and refine these criteria and re-evaluate the use of IDT as an indicator of rutting performance.

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APPENDIX A—REPEATED LOAD TEST DATA

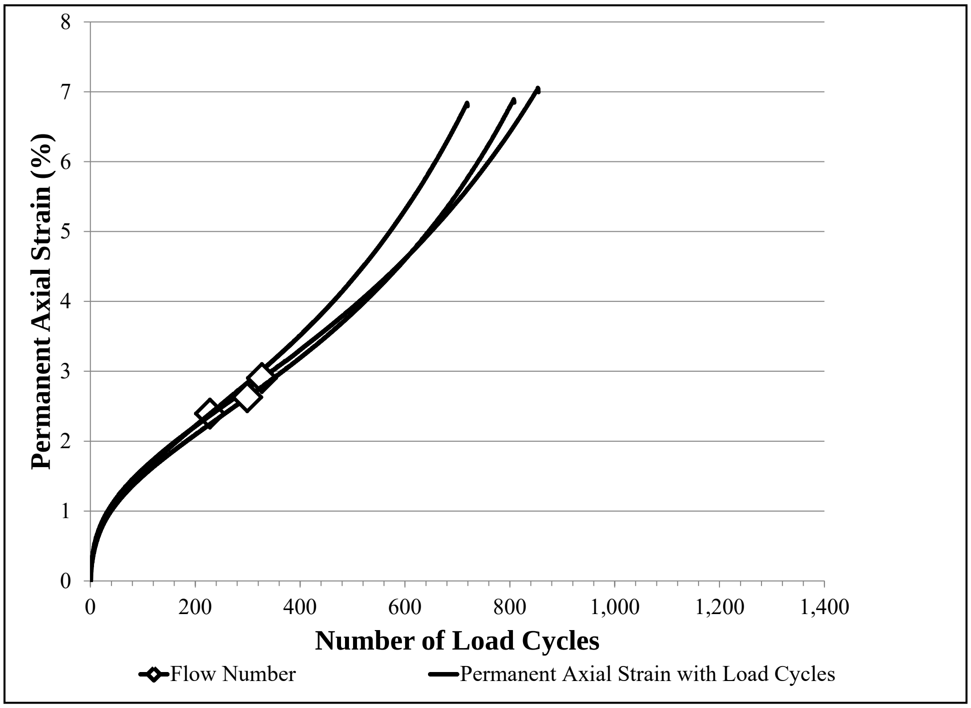


Figure A-1. The Flow Number (FN) Results for Three New Jersey HMA Mixture Samples

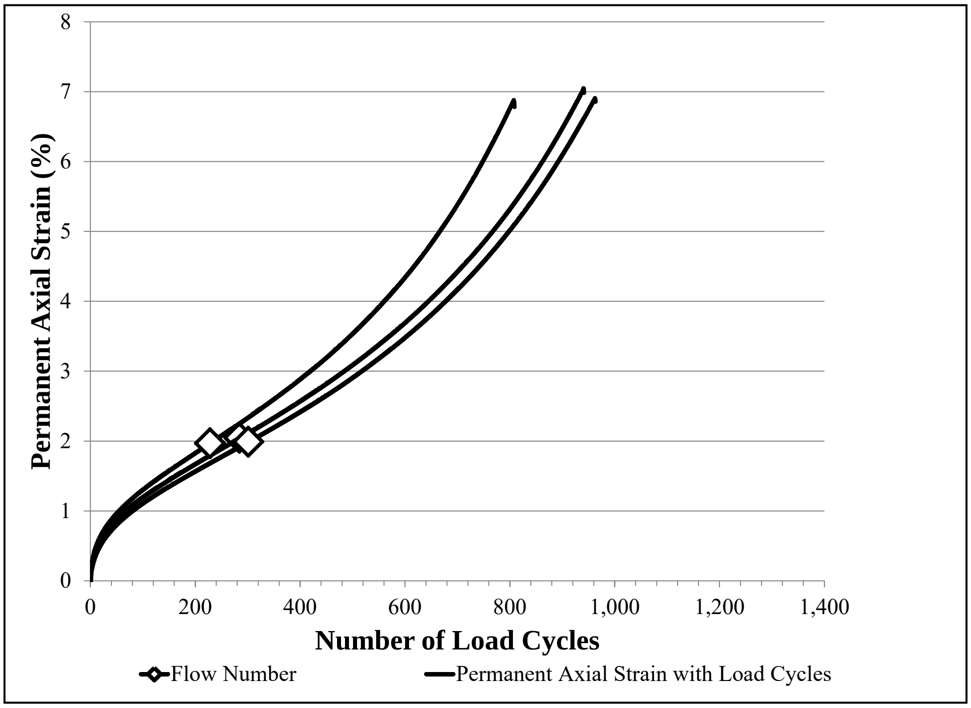


Figure A-2. The FN Results for Three New Jersey Evotherm® 3G Mixture Samples

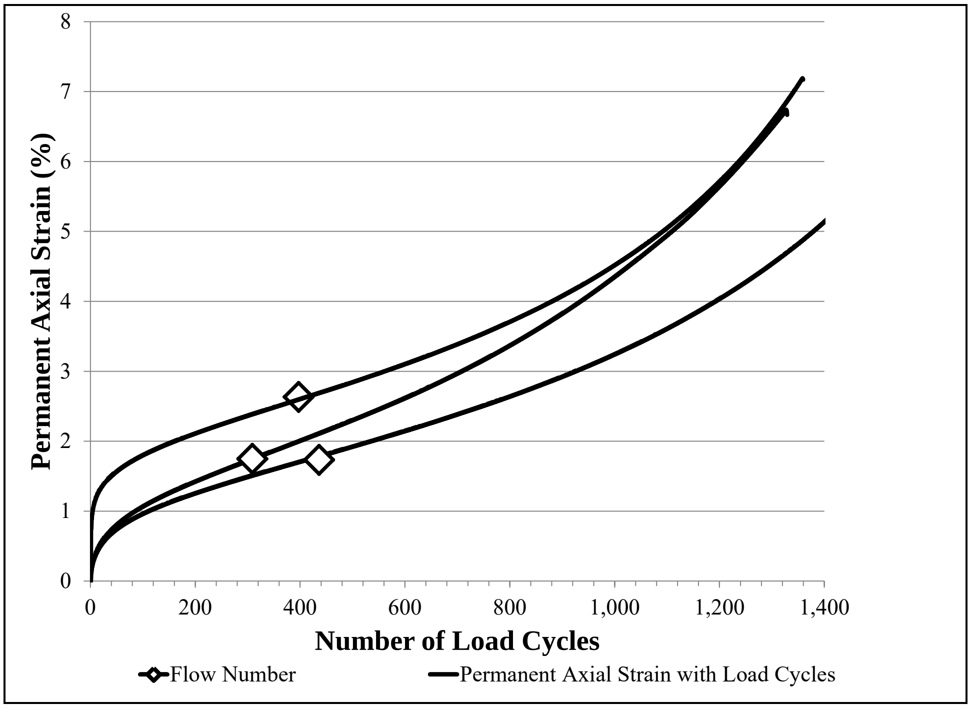


Figure A-3. The FN Results for Three New Jersey Sasobit® Mixture Samples

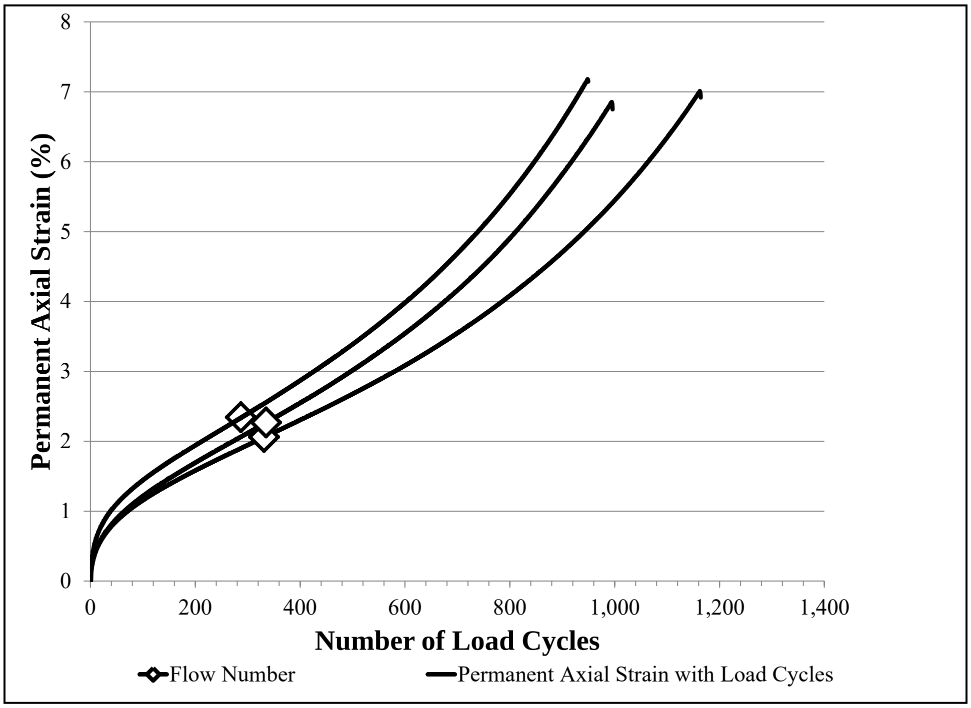


Figure A-4. The FN Results for Three New Jersey Foamed Asphalt Mixture Samples

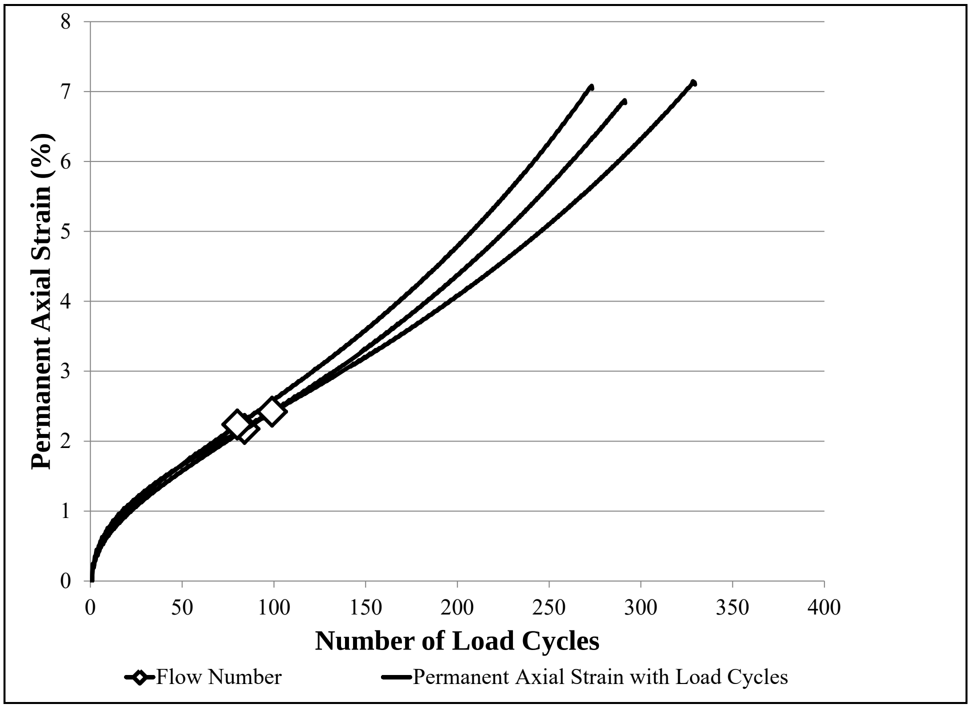


Figure A-5. The FN Results for Three Mississippi HMA Mixture Samples

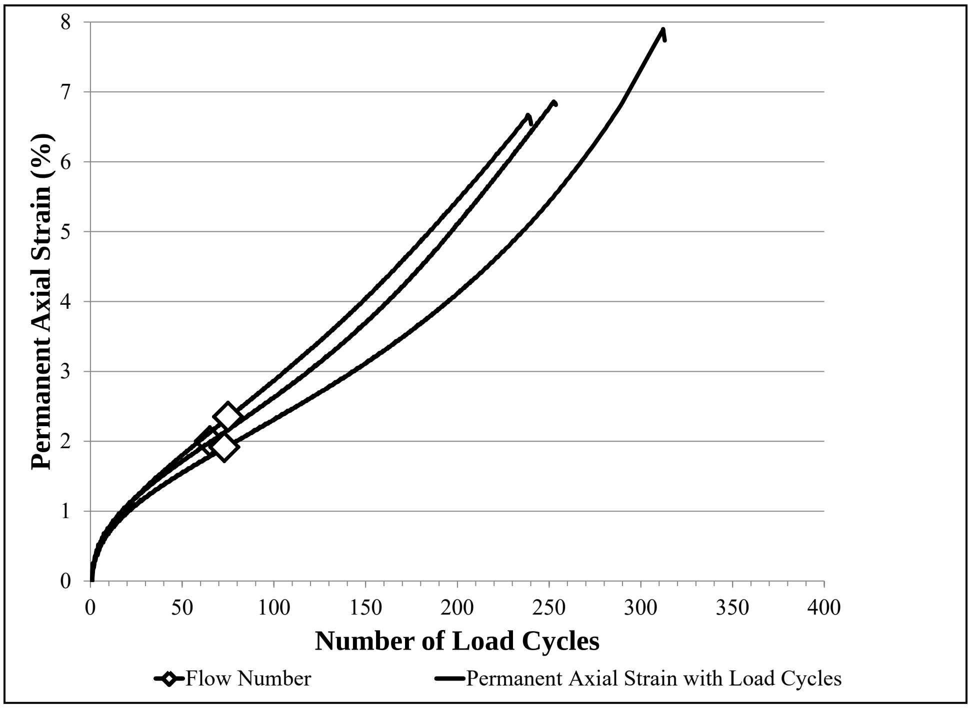


Figure A-6. The FN Results for Three Mississippi Evotherm® 3G Mixture Samples

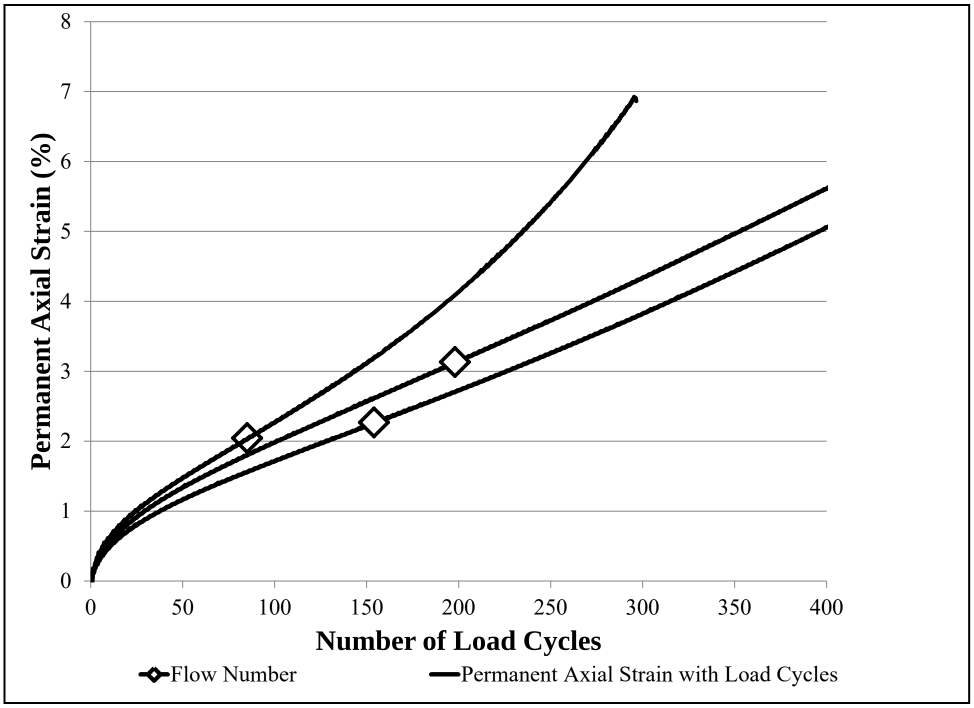


Figure A-7. The FN Results for Three Mississippi Sasobit Mixture Samples

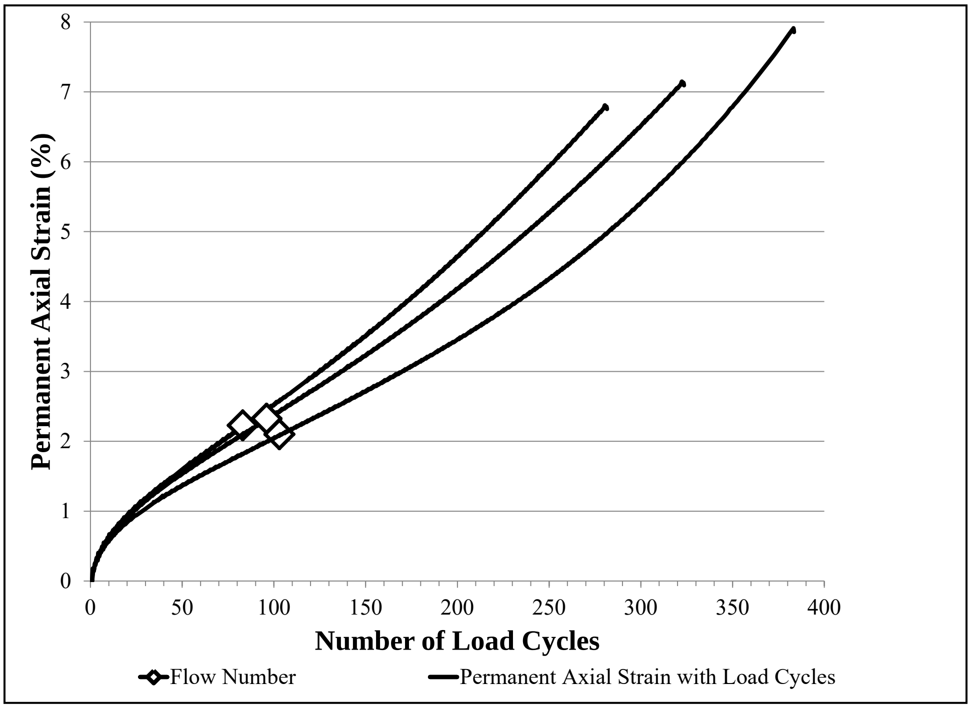


Figure A-8. The FN Results for Three Mississippi Foamed Asphalt Mixture Samples

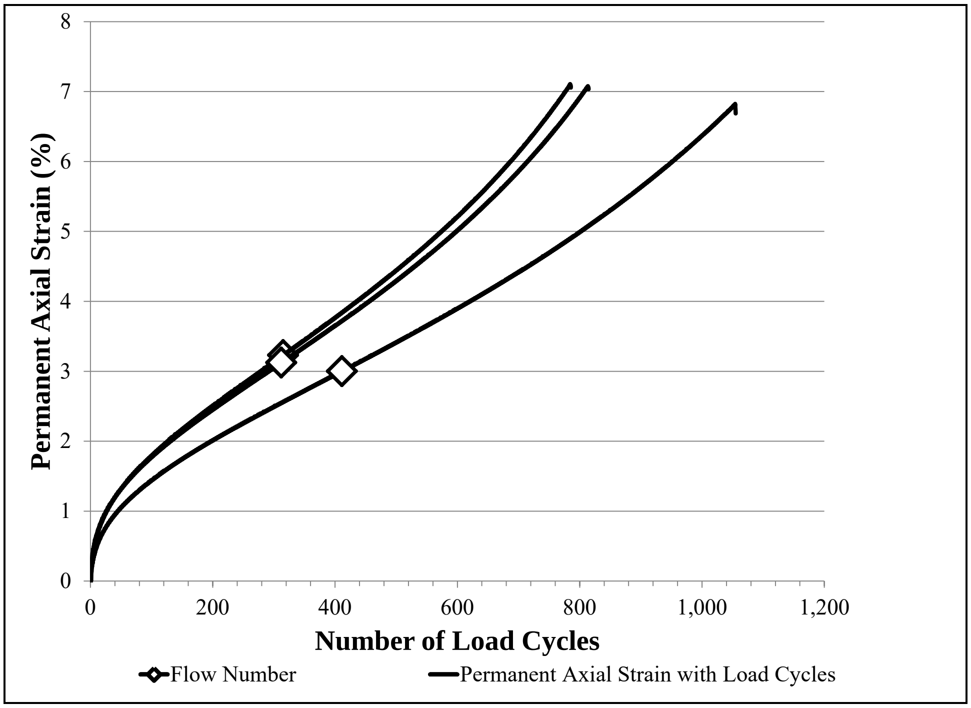


Figure A-9. The FN Results for Three Massachusetts Sasobit Mixture Samples

APPENDIX B—STATIC CREEP TEST DATA

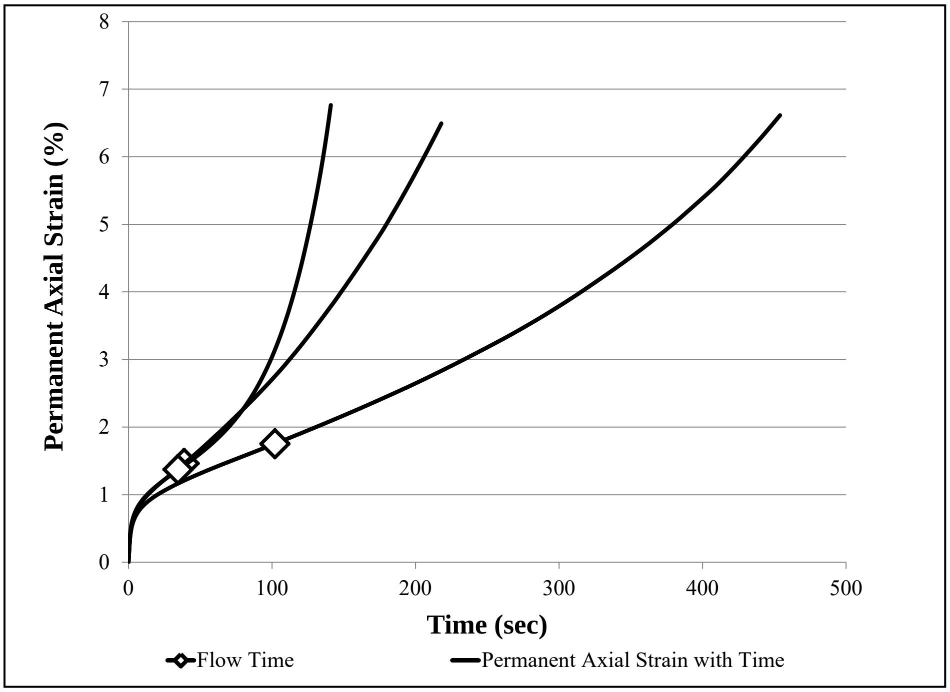


Figure B-1. The Flow Time (FT) Results for Three New Jersey Hot-Mix Asphalt (HMA) Mixture Samples

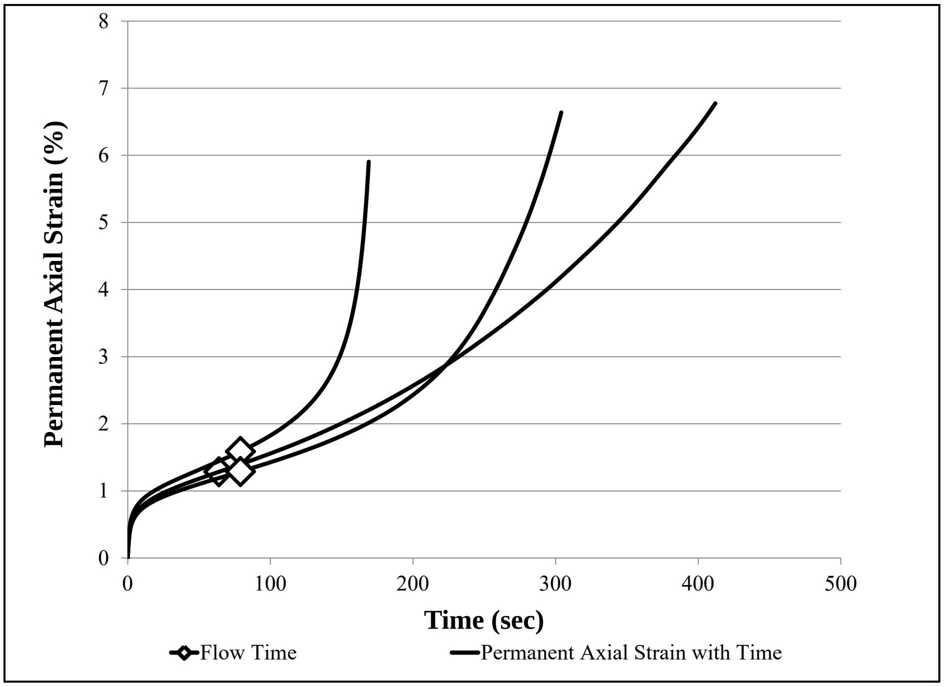
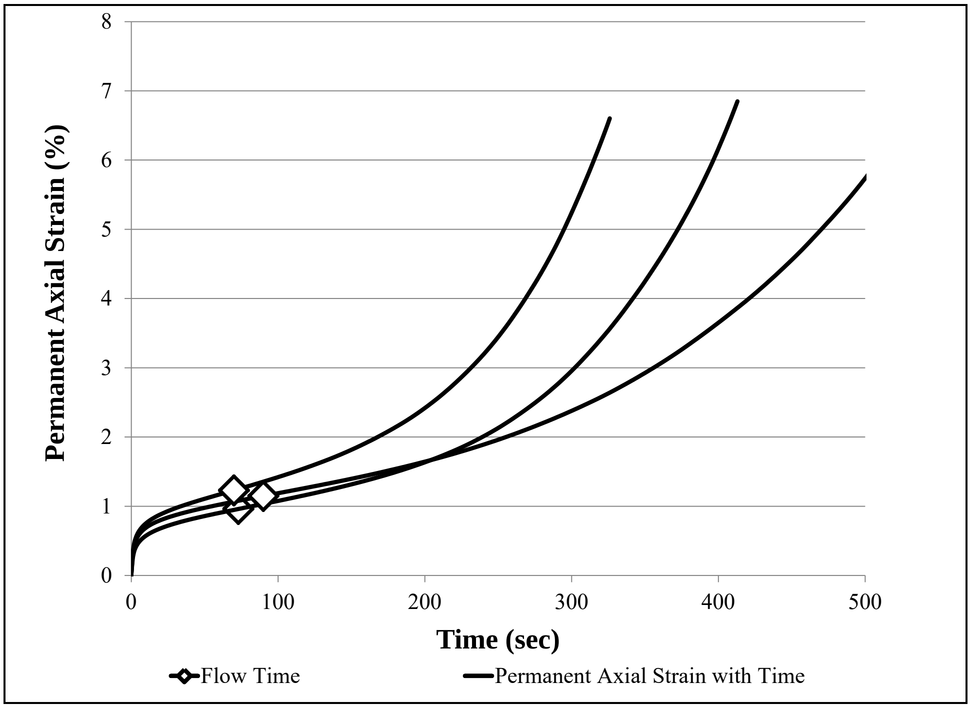


Figure B-2. The FT Results for Three New Jersey Evotherm® 3G Mixture Samples



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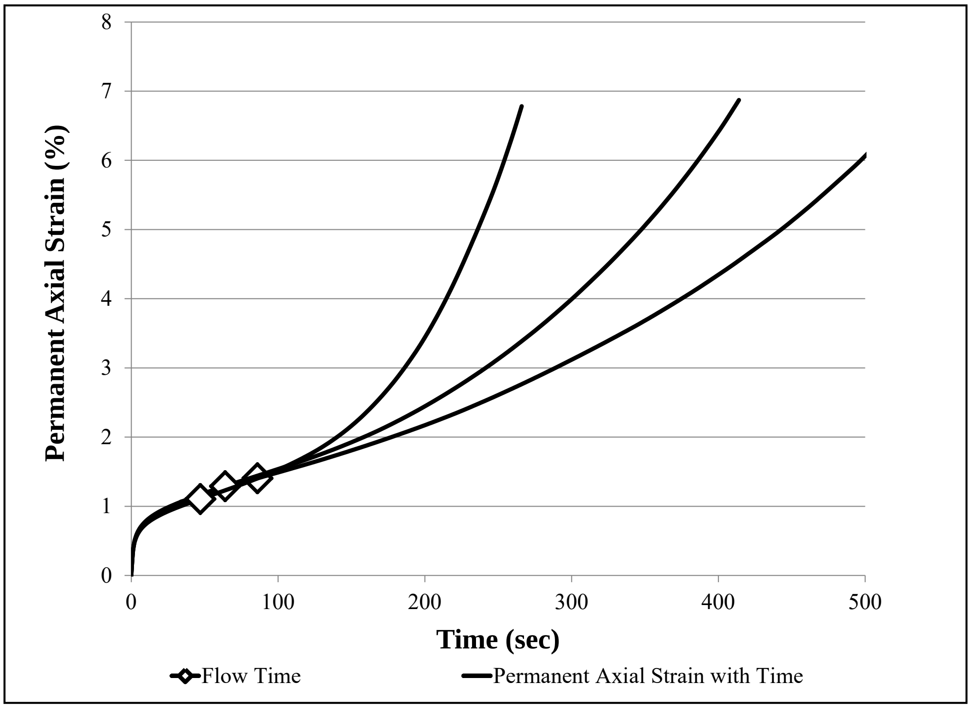

Figure B-4. The FT Results for Three New Jersey Foamed Asphalt Mixture Samples

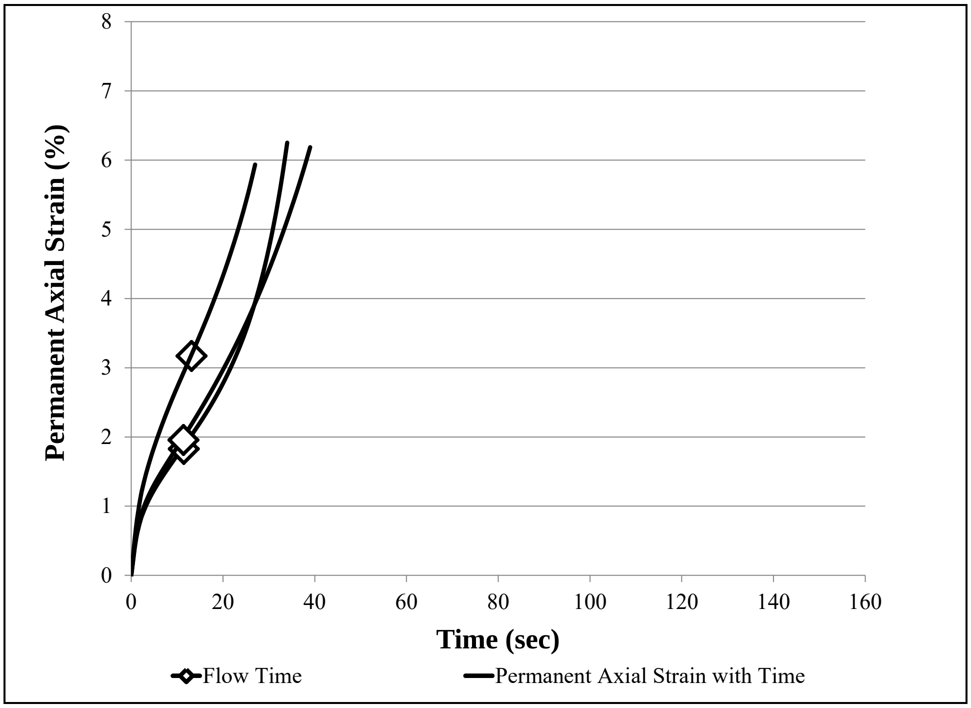

Figure B-5. The FT Results for Three Mississippi HMA Mixture Samples

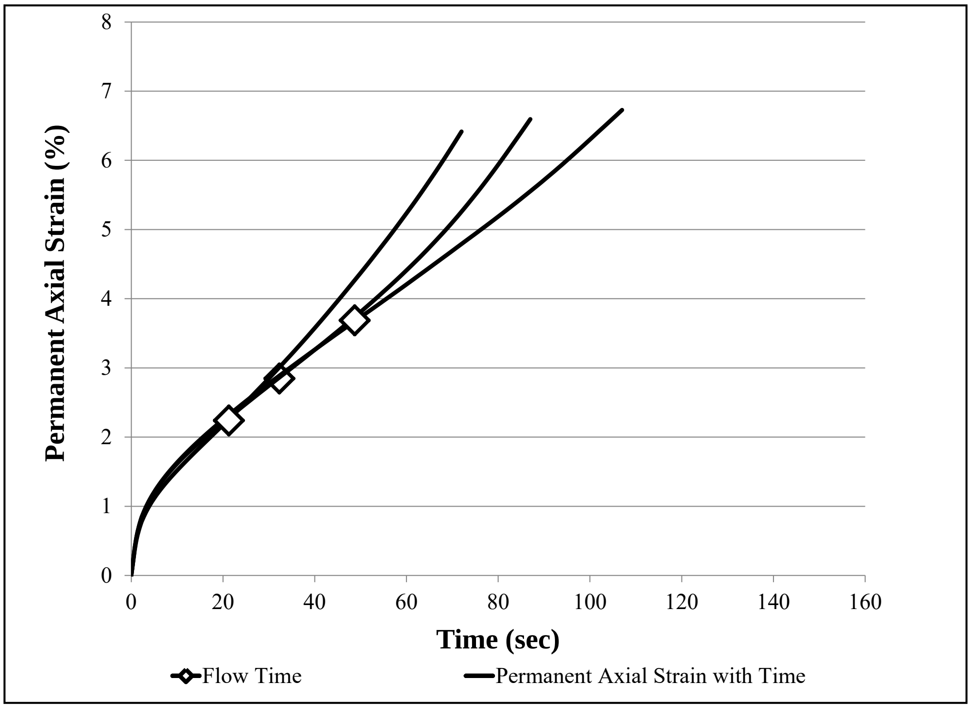

Figure B-6. The FT Results for Three Mississippi Evotherm 3G Mixture Samples

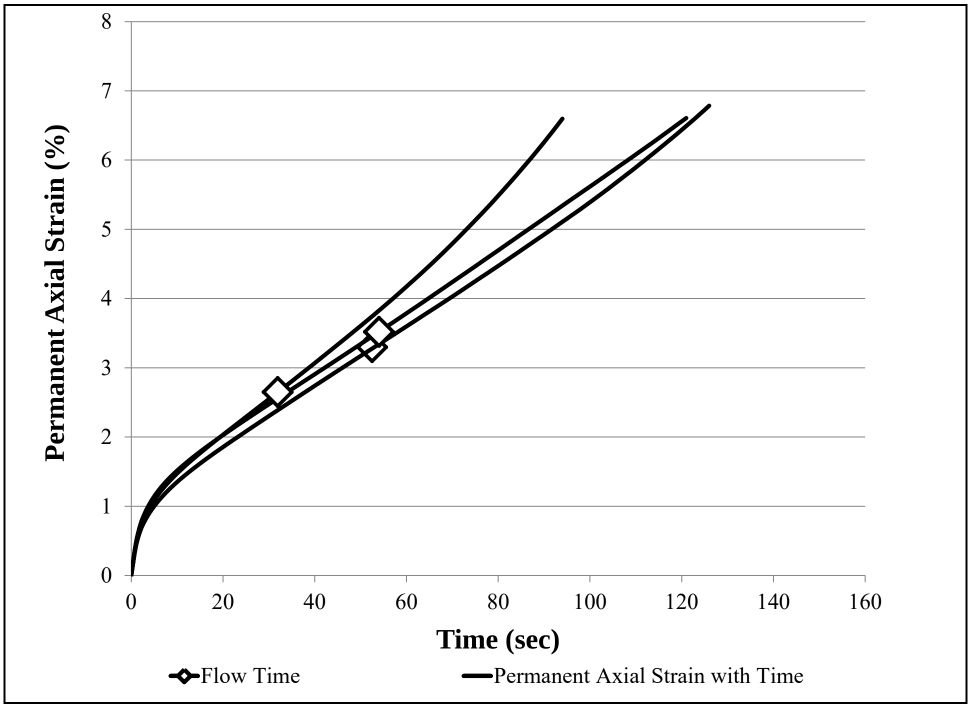

Figure B-7. The FT Results for Three Mississippi Sasobit Mixture Samples

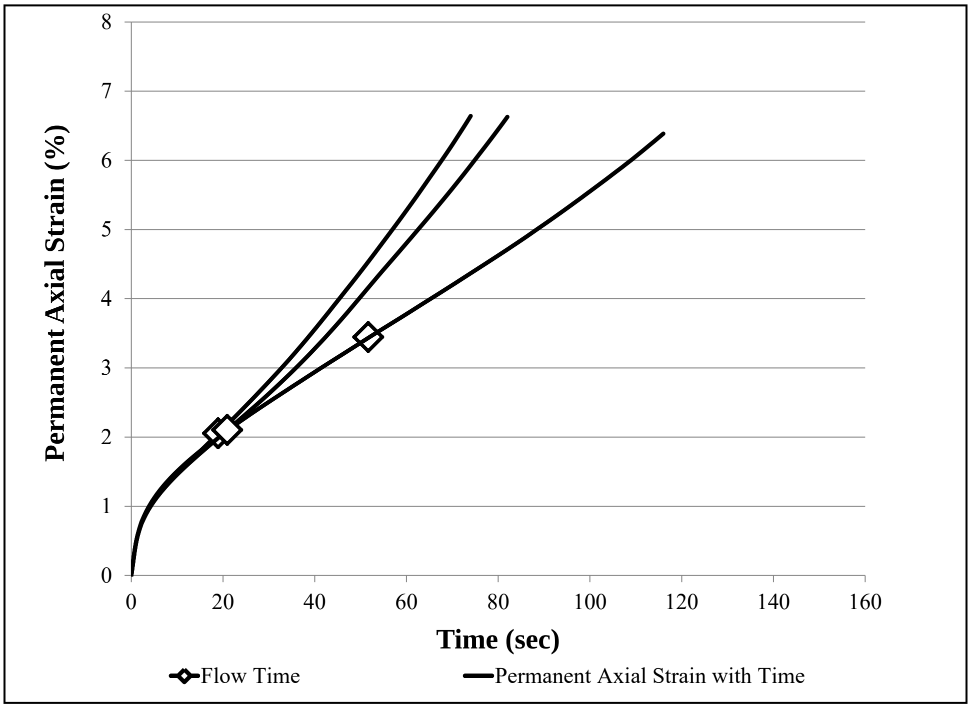

Figure B-8. The FT Results for Three Mississippi Foamed Asphalt Mixture Samples

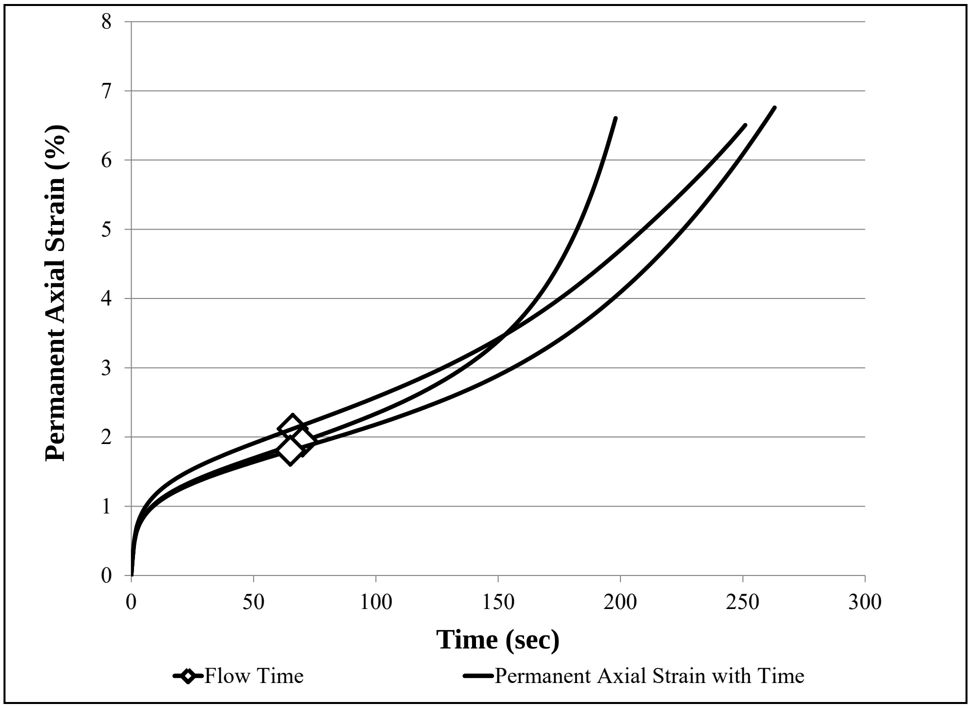

Figure B-9. The FT Results for Three Massachusetts Sasobit Mixture Samples

APPENDIX C—INDIRCT TENSILE TEST RESULTS

Table C-1. New Jersey Indirect Tensile Strength (IDT) Test Results

WMA Technology	Sample #	Height	Diameter	Dial Reading	Max Comp Load (N)	IDT Strength (kPa)
Evotherm® 3G	IT1	98.7	150.1	176	7451	320
	IT2	98.8	150.0	185	7832	336
	IT3	98.7	149.9	180	7621	328
	Average	98.7	150.0	180	7635	328
Sasobit®	IT1	98.7	150.1	185	7832	337
	IT2	98.9	150.0	185	7832	336
	IT3	98.9	150.0	187	7917	340
	Average	98.8	150.0	186	7860	338
Foamed Asphalt	IT1	98.7	150.0	194	8213	353
	IT2	98.9	150.0	164	6943	298
	IT3	99.0	150.0	179	7578	325
	Average	98.9	150.0	179	7578	325
HMA	IT1	99.0	150.0	173	7324	314
	IT2	98.8	150.0	172	7282	313
	IT3	98.9	150.0	170	7197	309
	Average	98.9	150.0	172	7268	312

HMA = Hot-mix asphalt
kPA = kilopascal
N = Newton
WMA = Warm-mix asphalt

Table C-2. Mississippi IDT Strength Test Results

WMA Technology	Sample #	Height	Diameter	Dial Reading	Max Comp Load (N)	IDT Strength (kPa)
Evotherm 3G	IT1	98.7	150.1	163	6901	297
	IT2	98.7	150.1	152	6435	277
	IT3	98.7	150	158	6689	288
	Average	98.7	150.1	158	6675	287
Sasobit	IT1	98.8	150	169	7155	307
	IT2	98.1	150	172	7282	315
	IT3	98.9	150.1	167	7070	303
	Average	98.6	150.0	169	7169	308

Table C-3. Mississippi IDT Strength Test Results (Continued)

WMA Technology	Sample #	Height	Diameter	Dial Reading	Max Comp Load (N)	IDT Strength (kPa)
Foamed Asphalt	IT1	96.6	150	184	7790	342
	IT2	98.8	149.9	162	6859	295
	IT3	98.9	150.1	175	7409	318
	IT4	98.7	150.1	172	7282	313
	Average	98.3	150.0	173	7335	317
HMA	IT1	98.6	150.1	163	6901	297
	IT2	98.4	150	160	6774	292
	IT3	98.4	150	155	6562	283
	Average	98.5	150.0	159	6746	291

Table C-4. Massachusetts IDT Strength Test Results

WMA Technology	Sample #	Height	Diameter	Dial Reading	Max Comp Load (N)	IDT Strength (kPa)
Sasobit	IT1	98.6	150.0	189	8002	344
	IT2	98.7	150.1	185	7832	337
	IT3	98.8	150.0	195	8256	355
	Average	98.7	150.0	190	8030	345

APPENDIX D—ASPHALT PAVEMENT ANALYZER TEST RESULTS

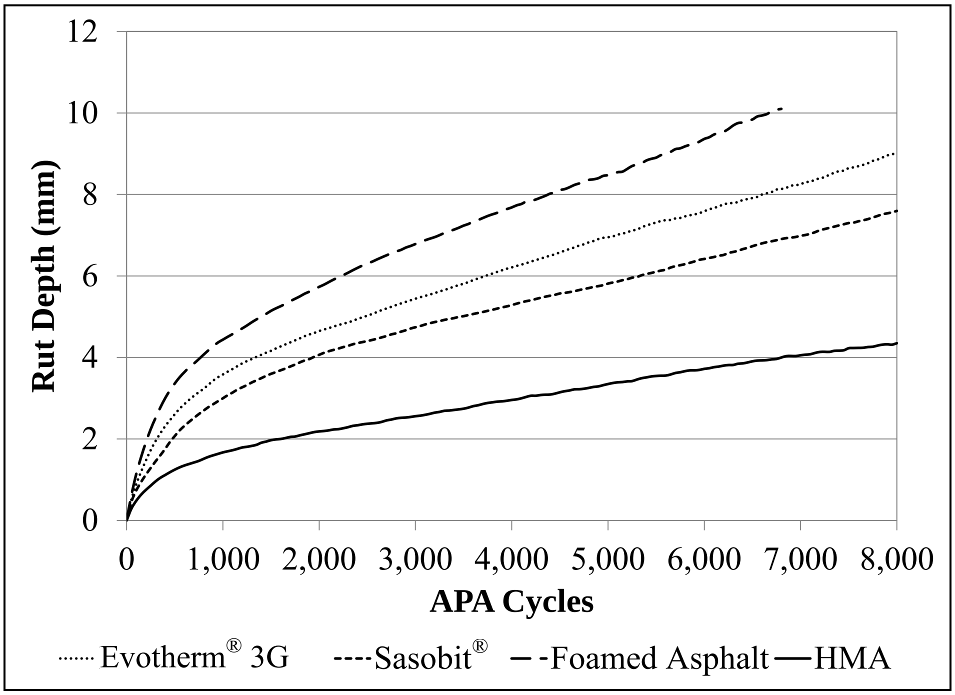

Figure D-1. New Jersey Asphalt Pavement Analyzer (APA) Test Results

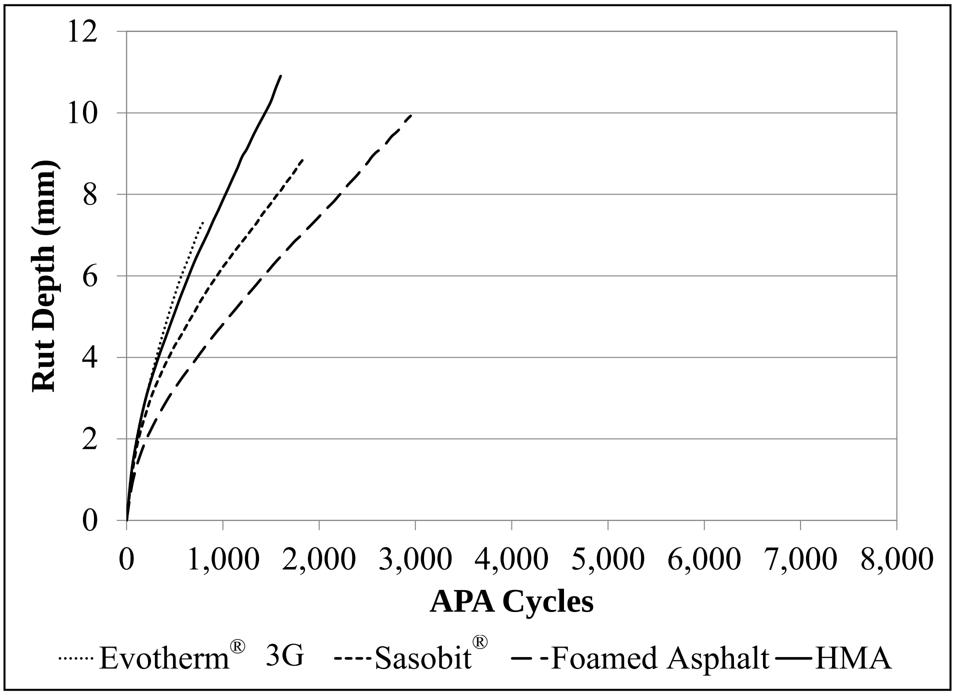

Figure D-2. Mississippi APA Test Results

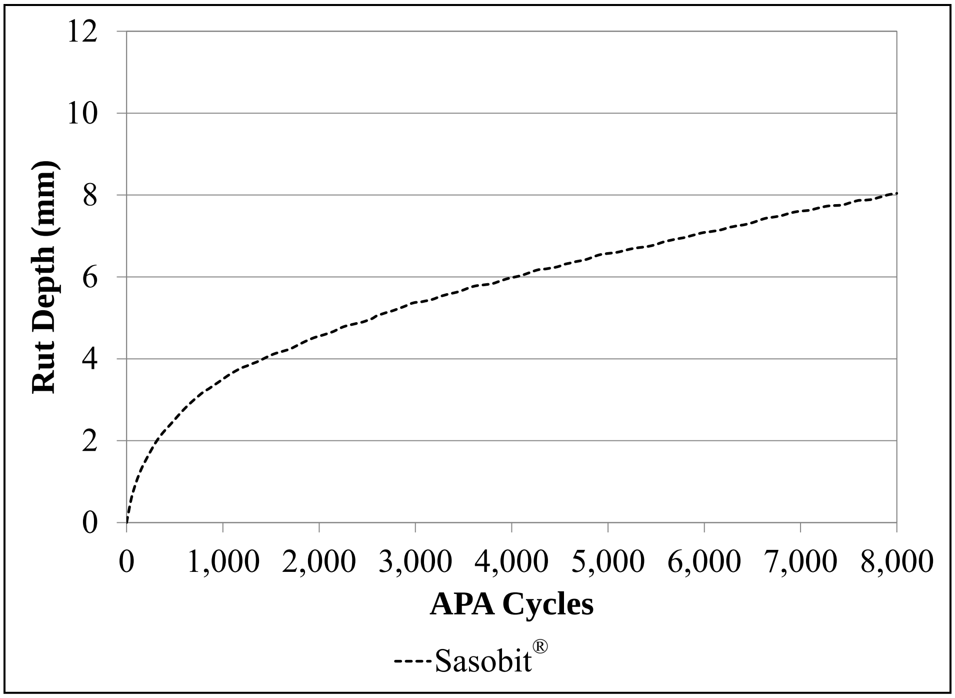

Figure D-3. Massachusetts APA Test Results