Selecting a Rutting Performance Test for Airport Asphalt Mixture Design

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ABSTRACT. *This paper presents results from a laboratory study to identify a performance-based acceptance test for hot asphalt mixtures when constructing airport pavements designed to accommodate high tire pressure traffic. Four performance tests, intended to screen for rutting susceptibility, were performed on twenty-six HMA mixtures using one neat binder. Eight of these mixtures were also prepared with a polymer-modified binder. Results from four candidate tests are presented: Asphalt Pavement Analyzer (APA), triaxial creep, triaxial repeated load, and dynamic modulus test. Preliminary criteria associated with these tests that can be used to screen or select airport HMA paving mixtures are proposed. The efficacy of the screening tests and associated criteria were evaluated by constructing and trafficking full-scale pavements using an accelerated pavement tester.*

KEYWORDS: *laboratory performance test, accelerated pavement testing airport HMA, rutting.*

*The oral presentation was made by Mr. Rushing.

1. Introduction

Rutting is a primary form of distress in hot mix asphalt (HMA) pavements. Airport pavements are particularly prone to rutting, because high pressure tires and heavy wheel loads can expose the HMA surface layer to high shear stresses resulting in vertical and lateral distortion. Aircraft manufacturers continue to develop aircraft with heavier wheel loads and higher tire pressures, necessitating continual refinement of material selection and design procedures to ensure that rutting does not become prevalent on HMA-surfaced airport pavements. Design procedures should include a rutting performance test as an indication of mixture quality. This paper describes a study to select a laboratory rutting test for airport HMA mixture design.

The Federal Aviation Administration (FAA) is preparing to adopt a new method for designing HMA mixtures that is based on compaction using a Superpave gyratory compactor (SGC). Studies concluded that 70 gyrations of the SGC is an appropriate compaction effort for the new method (Cooley et al., 2007, Christensen et al., 2010, Rushing 2011). A goal of the FAA is to include a laboratory performance test for the mixture at the conclusion of the design.

In 2002, National Cooperative Highway Research Program (NCHRP) Report 465 (Witczak, 2002) recommended the dynamic modulus (E*), repeated load (flow number), and static creep (flow time) as the top three candidate simple performance tests to accompany the Superpave highway mix design system for evaluating resistance to permanent deformation. The criteria for selecting candidate tests were accuracy, reliability, ease of use, and reasonable equipment cost. This series of tests has been termed the simple performance test procedure (Witczak, 2002). E* has been used for HMA materials characterization for highway pavement structural design using the Mechanistic-Empirical Pavement Design Guide, while the flow number (FN) and flow time (FT) have been considered potential performance tests that might be used to indicate rutting resistance. The ability of these tests to predict permanent deformation has been evaluated in several studies. In 2004, the NCHRP Project 9-19 panel recommended the dynamic modulus (E*) test as the primary simple performance test for permanent deformation (Witczak, 2007). The panel also recommended the FN test as a complementary procedure for evaluating the resistance of a HMA mix design to tertiary flow. Finally, the Asphalt Pavement Analyzer (APA) test has been evaluated and used by several agencies and contractors with good success, and preliminary performance criteria have been established by the National Center for Asphalt Technology (NCAT) (Zhang et al., 2002) and the WesTrack Forensic Team (1998). However, no guidance for the applicability of any of these tests to airport HMA exists.

Ahlrich (1996) performed repeated load tests using an axial stress of 1380 kPa (200 psi) with a confining stress of 276 kPa (40 psi) to assess the influence of aggregate properties on rutting performance of airfield HMA. These tests were performed on individual Marshall specimens having a diameter of 102 mm (4 in.) and a height of 64 mm (2.5 in.). The test temperature was 60°C (140°F). A total of 3,600 load cycles were applied to each specimen. Eighteen different HMA mixtures with a wide range of anticipated quality were prepared and tested, using three replicates. The average total strain in specimens for each mixture ranged from 1.5% to 8.5% after testing ceased. The majority of the mixtures experienced between 2 and 4% strain. Ahlrich also noted a significant improvement in rutting performance, particularly for lower quality mixtures, when using a polymer-modified binder. He concluded that the repeated load test can be used to evaluate the effects of aggregate property changes on mixture rutting performance for airport HMA.

Cooley et al. performed similar tests using deviator stress levels of 690, 1380, and 2413 kPa (100, 200, and 350 psi) with 276 kPa (40 psi) confinement (Cooley et al., 2007). Testing was performed on ten HMA mixtures from airports in the United States. The FN test was performed at the three different deviator stress levels with two to four different compaction efforts for each mixture. Changing the compaction effort produced specimens with varying asphalt contents. The asphalt content typically varied between 0.2 and 0.5% with a change in compaction effort. Higher asphalt contents typically reduced the rutting resistance during FN testing. In this study, the axial load pulse was repeated for 20,000 cycles or until failure occurred. The test temperature was the high pavement temperature determined from the local climate data. Testing was performed according to American Association of State Highway and Transportation Officials (AASHTO) TP 79. The data from this study shows that most mixtures achieved 20,000 cycles for 1380 kPa (200 psi) deviator stress at one or more asphalt contents (compaction effort). Increasing asphalt content or deviator stress caused sharp reductions in performance.

A complimentary research study funded by the FAA at the time of this research investigated alternative performance tests to identify an asphalt mixture’s rutting potential. The recommendation to the FAA was to use indirect tensile strength as a test for rutting potential (Advanced Asphalt Technologies 2013). This recommendation is based on previous work to use indirect tensile strength as a rutting performance test (Christensen et al., 2000, Christensen et al., 2004, Zaniewski and Srinivasan 2004).

2. Research plan

The objective of this study was to develop a procedure for testing airport HMA in the laboratory that can identify mixtures prone to permanent deformation, or rutting. A selected suite of potential performance tests was performed on HMA mixtures with an expected broad range of rutting performance potential with a goal to identify preliminary criteria for using the tests to screen airport HMA paving mixtures. One additional mixture was constructed at full scale and tested with an accelerated pavement test device to determine field performance. The ability of each performance test to appropriately rank mixture performance was considered to be a primary factor in test selection. This study provides recommendations on the selection of one or more simple performance tests that can be used in the laboratory design procedure to increase confidence in the ability of the designed HMA mixture to resist rutting in the field.

3. Asphalt mixtures

Aggregates were selected from a previous study used to define compaction requirements for using the SGC in mix design (Rushing, 2011). These included granite, limestone, and chert gravel, along with natural field sand. Aggregate blends were selected with the intent of providing a range of performance from very good to very poor in terms of rutting resistance. Aggregate properties specified by the FAA mix design procedure and others known to influence rutting susceptibility were measured. Coarse and fine gradations, with respect to the allowable FAA gradation, were included in the study. An example of representative gradations for the study is shown in Figure 1. Two asphalt binders were used in this study. Both were obtained from Ergon Asphalt and Emulsions, Inc. and were graded as a PG 64-22 neat binder and a PG 76-22 styrene-butadiene-styrene (SBS) polymer-modified binder.

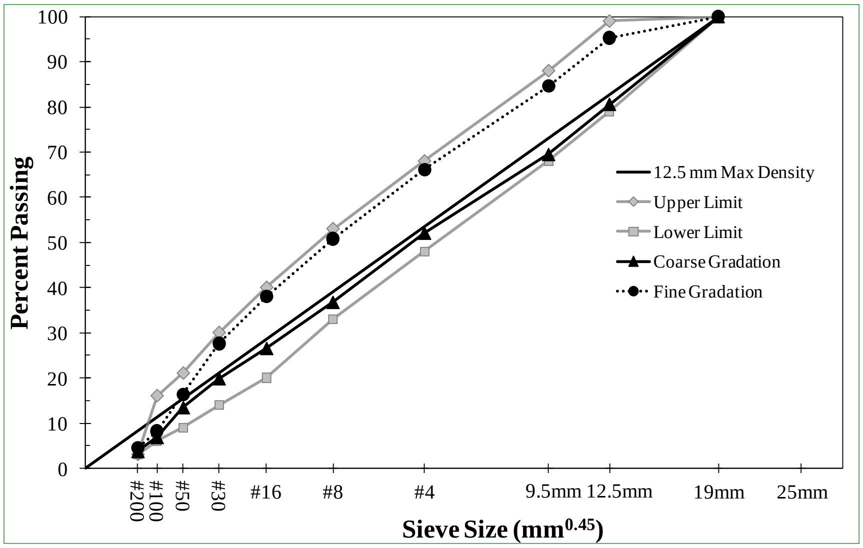


Figure 1. *Representative aggregate gradation*

Mix designs were performed according to FAA Advisory Circular 150/5370 10 E (Federal Aviation Administration, 2009). The design binder content for each mixture was determined by compacting specimens using at least three different binder contents. The compaction effort consisted of 70 gyrations. The theoretical maximum density was measured for each mixture following ASTM D 2041. The bulk specific gravity was determined following ASTM D 2726. The percentage of air voids in the specimen was determined following ASTM D 3203. The percentage of air voids was plotted versus the percentage of binder in the mixture to determine the percentage of binder required to compact the mixture to 3.5% air voids at the design compaction effort. The target air void content of 3.5% was selected because it is the center of the allowable design range in FAA specifications (2.8-4.2%). This percent binder was considered the design binder content. Specimens were prepared using this design binder content for further testing.

Twenty-six mixtures using a neat binder were designed and tested. Four of these mixtures did not meet FAA material requirements, because the percentage of natural sand exceeds 15%. Incorporating excessive natural sand is expected to produce mixtures that are more prone to rutting. These mixtures were included to produce acceptance limits for the potential performance tests. Eight additional mixtures were also prepared using a polymer-modified binder at the same binder content as the unmodified mixture. The nomenclature system used to identify each mix is given in

Table 1 along with the design and effective binder content. The mix designation was determined by the aggregate type, maximum aggregate size, gradation, and percent natural sand. For example, mix 1/2 FGN0 uses granite aggregate, has a maximum aggregate size of 1/2 in., is finely graded, and contains 0% natural sand.

4. Performance test methods

Performance tests selected for this study are among those most recommended by previous research and most widely accepted in the paving industry. Because the purpose of this study was to recommend one or more performance tests for implementation into construction specifications, certain considerations were made in selecting the test procedures and test specimen properties. The equipment required for testing should be commercially available, and some positive historical experience with the test methods or equipment was desirable. The test specimen geometric and volumetric properties were selected to be as simple as possible to prepare while still maintaining sufficient precision. Specimen geometries for the selected tests were the same as those used for the standard test protocols. For example, the APA must test specimens approximately

75 mm (3 in.) in height because of equipment limitations. Further, the height to diameter ratio for dynamic modulus or triaxial testing was maintained from accepted testing standards to ensure viability of the data. The air void content of the test specimens was selected to be approximately 3.5%, the design air void content. Some researchers prefer to use a higher air void content (e.g., 7%) for performance testing, because it more closely reflects the as-constructed properties of the HMA. However, using a different air void content from the mix design requires adjustment of the compaction effort and

Table 1. *Aggregate mix designations and design binder content*

Aggregate Type	Maximum Aggregate Size	Gradation	Natural Sand (%)	Design Binder Content (%)	Effective Binder Content (%)	Mix Designation
Granite	1/2 in. (12.5 mm)	Fine	0	6.7	6.0	1/2 FGN0*
			10	6.8	6.2	1/2 FGN10
			30	7.2	6.7	1/2 FGN30
		Coarse	0	6.3	5.6	1/2 CGN0*
			10	5.9	5.3	1/2 CGN10
			30	6.8	6.3	1/2 CGN30
	3/4 in. (19 mm)	Fine	0	6.2	5.5	3/4 FGN0
			10	6.1	5.5	3/4 FGN10
			30	7	6.5	3/4 FGN30*
		Coarse	0	5.9	5.2	3/4 CGN0
			10	4.9	4.3	3/4 CGN10
			30	7.1	6.6	3/4 CGN30
Limestone	1/2 in. (12.5 mm)	Fine	0	6.1	5.6	1/2 FLS0
			10	5.2	4.7	1/2 FLS10
		Coarse	0	5.5	5.0	1/2 CLS0*
			10	5	4.5	1/2 CLS10
	3/4 in. (19 mm)	Fine	0	5.7	5.2	3/4 FLS0
			10	4.8	4.3	3/4 FLS10*
		Coarse	0	5.4	4.9	3/4 CLS0*
			10	5.4	4.9	3/4 CLS10
Chert Gravel	1/2 in. (12.5 mm)	Center	0	6.8	5.3	1/2 GV0*
			10	6.2	4.8	1/2 GV10
	3/4 in. (19 mm)	Fine	0	6.8	5.3	3/4 FGV0
			10	5.9	4.5	3/4 FGV10
		Coarse	0	6.4	4.9	3/4 CGV0*
			10	5.3	3.9	3/4 CGV10

* Mixture also prepared and tested with polymer-modified binder.

Table 2. *Volumetric properties of test specimens*

Binder	Agg. Type	Sand (%)	Mix	RL1		RL2		SC1		SC2		DM1		DM2		DM3		APA1		APA2	
				VMA	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**
64-22	Granite	0	1/2 FGN0	16.6	3.1	17.2	3.8	17.6	4.2	17.8	4.5	16.6	2.6	16.7	2.8	16.9	3.0	17.5	3.7	17.5	3.7
			1/2 CGN0	16.2	3.2	15.9	2.9	16.2	3.2	16.0	2.9	15.8	2.7	15.7	2.6	16.3	3.3	16.7	3.8	16.9	4.0
			3/4 FGN0	14.8	4.4	14.7	4.4	15.7	5.4	13.6	3.1	14.2	1.1	13.9	0.7	14.6	1.5	15.3	2.4	15.9	3.0
			3/4 CGN0	16.1	5.4	14.7	3.9	15.4	4.7	15.2	4.5	14.3	2.4	15.2	3.4	14.7	2.9	16.3	4.7	17.7	6.3
		10	1/2 FGN10	17.9	3.9	17.8	3.9	18.2	4.4	17.7	3.7	18.2	4.3	17.4	3.4	17.1	3.1	17.1	3.1	17.2	3.1
			1/2 CGN10	15.4	2.9	16.1	3.6	16.6	4.2	16.1	3.6	16.1	3.6	16.6	4.2	16.5	4.1	16.3	3.9	16.1	3.6
			3/4 FGN10	17.2	4.8	16.5	3.9	15.9	3.3	15.5	2.8	14.8	2.0	14.8	2.0	15.6	2.9	15.3	2.6	13.8	0.8
			3/4 CGN10	13.7	3.2	13.1	2.5	14.1	3.6	15.1	4.8	14.8	4.5	13.3	2.7	14.4	4.0	14.7	4.3	15.3	4.9
		30	1/2 FGN30	19.7	4.5	20.7	5.7	21.0	6.1	21.1	6.3	21.2	5.9	19.4	5.4	19.5	5.6	20.5	5.5	20.9	6.0
			1/2 CGN30	19.1	4.9	18.0	5.0	18.8	4.8	19.3	5.1	18.3	4.9	18.7	4.7	19.4	5.1	19.1	4.9	18.0	3.5
			3/4 FGN30	18.9	4.2	19.2	4.5	19.2	4.5	18.4	3.6	17.8	3.4	18.1	4.2	17.7	3.9	17.0	2.5	17.6	3.2
			3/4 CGN30	19.9	3.5	19.5	4.6	19.1	4.2	18.9	3.8	19.6	3.9	19.2	4.1	20.1	5.2	19.9	5.0	19.5	4.6
	Gravel	0	1/2 GV0	16.1	3.9	16.3	4.0	16.0	3.6	16.1	3.8	15.5	3.2	15.8	3.5	15.5	3.1	15.8	3.5	15.7	3.3
			3/4 FGV0	16.2	3.9	15.8	3.5	15.5	3.2	16.2	3.9	15.9	3.6	15.8	3.5	15.3	2.9	16.0	3.7	16.0	3.7
			3/4 CGV0	15.0	3.3	14.8	3.1	15.2	3.5	15.5	3.9	14.5	2.7	14.4	2.6	14.4	2.6	15.3	3.7	15.5	3.9
		10	1/2 GV10	18.0	2.2	17.8	1.9	17.9	2.1	18.1	2.3	17.4	1.6	17.7	1.8	17.6	1.7	18.2	2.5	18.0	2.3
			3/4 FGV10	16.2	3.9	15.8	3.5	15.5	3.2	16.2	3.9	17.1	2.4	17.5	2.8	17.3	2.6	16.0	3.7	16.0	3.7
			3/4 CGV10	16.0	2.5	16.3	2.9	15.8	2.3	15.6	2.1	16.4	3.0	16.8	3.4	16.2	2.8	16.7	3.3	16.6	3.2
	Limestone	0	1/2 FLS0	16.4	3.0	17.2	4.0	16.7	3.4	17.7	4.6	17.5	4.4	17.3	4.1	17.0	3.8	17.4	4.3	17.3	4.1
			1/2 CLS0	15.5	3.5	15.3	3.3	15.7	3.8	14.9	2.8	15.2	3.2	14.7	2.7	16.9	5.2	16.5	4.7	16.9	5.1
			3/4 FLS0	17.5	5.3	17.5	5.3	17.2	4.9	17.2	4.9	15.9	3.5	17.0	4.8	16.1	3.7	16.8	4.5	16.9	4.6
			3/4 CLS0	14.1	1.4	14.1	1.9	14.5	1.4	14.5	1.4	15.3	2.8	14.6	2.0	15.1	2.6	15.3	2.8	15.6	3.2
		10	1/2 FLS10	15.3	3.1	14.6	3.0	14.8	3.6	14.6	2.9	15.2	3.5	15.1	3.5	15.3	3.7	15.3	3.7	15.1	3.5

				RL1		**RL2**		**SC1**		**SC2**		**DM1**		**DM2**		**DM3**		**APA1**		**APA2**	
Binder	**Agg. Type**	**Sand (%)**	**Mix**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**	**VMA**	**Va**
			1/2 CLS10	14.4	3.4	13.9	2.8	14.4	3.4	14.0	2.9	14.1	3.1	14.7	3.8	14.2	3.2	15.0	4.1	14.6	3.6
			3/4 FLS10	14.1	3.5	14.1	3.5	13.7	3.1	13.7	3.1	14.5	4.0	14.0	3.4	13.8	3.2	14.5	3.9	14.9	4.4
			3/4 CLS10	13.4	1.3	13.1	0.9	14.0	2.0	13.2	1.1	13.7	1.6	13.8	1.8	13.6	1.6	14.0	2.0	14.4	2.5
76-22	Granite	0	1/2 FGN0	16.7	3.1	16.3	2.7	17.3	3.9	16.5	3.0	16.6	3.0	16.9	3.4	16.6	3.1	17.6	3.8	18.4	4.8
			1/2 CGN0	16.1	3.1	16.4	3.4	16.6	3.6	16.3	3.2	16.2	3.2	16.7	3.8	16.6	3.5	17.6	4.7	17.1	4.2
		30	3/4 FGN30	18.1	3.3	19.4	4.8	19.9	5.3	18.9	4.2	17.7	2.7	18.3	3.5	19.3	4.7	19.3	5.3	18.4	4.2
	Gravel	0	1/2 GV0	15.6	3.2	15.2	2.8	15.3	2.9	15.5	3.2	15.5	3.1	15.6	3.2	15.6	3.2	16.3	4.0	15.8	3.5
			3/4 CGV0	14.9	3.2	15.8	4.3	15.1	3.4	15.2	3.5	14.3	2.5	14.9	3.2	14.6	2.9	16.1	4.5	16.0	4.4
	Limestone	0	1/2 CLS0	14.8	2.8	15.4	3.4	15.5	3.6	14.8	2.7	14.6	2.5	15.9	4.0	15.1	3.1	16.3	4.5	16.9	5.1
			3/4 CLS0	14.5	1.8	14.2	1.6	14.1	1.4	14.8	2.2	14.7	2.1	14.8	2.2	14.5	1.9	16.9	4.6	16.9	4.6
		10	3/4 FLS10	13.8	3.1	13.4	2.7	13.5	2.8	13.4	2.7	13.6	2.9	13.8	3.2	14.7	4.2	13.9	3.3	13.7	3.0

further burdens the designer as the researcher prepares specimens. Additionally, test specimens prepared at higher air void contents experience densification during the test, while specimens prepared and tested at the design air void content can be accurately ranked according to the mixture stability and hence reflects a more true assessment of rutting potential. Table 2 provides the measured VMA and air void content of the specimens used for performance testing. Specimen properties for each of the repeated load (RL), static creep (SC), dynamic modulus (DM), and APA tests are given. The following sections describe the details of the four performance tests used in this study.

4.1 *Static creep test*

The static creep triaxial test measures permanent deformation as a function of time when a constant load is applied to a cylindrical HMA specimen. Cumulative permanent deformation is reported as a function of loading time. NCHRP Report 465 provides a procedure for measuring the FT of HMA using static creep tests (Witczak, 2002). The procedure is based on application of creep loads on unconfined or confined cylindrical specimens, which are 100 mm (4 in.) in diameter and 150 mm (6 in.) in height and cored from gyratory compacted mixtures. The stress conditions are determined by the engineer.

The basic principles related to the creep test as stipulated in NCHRP report 465 for FT testing were applied in this study. Variations in stress conditions and test temperatures that apply more directly to airport pavements were considered. The confined test was selected in lieu of the unconfined compression test because it better simulates field conditions. Specifically, a confining stress of 276 kPa (40 psi) and a deviator stress of 1380 kPa (200 psi) were selected based on the work by Ahlrich (1996). The test temperature was selected to be the mean monthly pavement temperature (MMPT) as defined by Witczak (1996). A MMPT of 43°C (109°F) was used for Vicksburg, Mississippi, the selected climate.

The FT is 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 data to a Francken model and taking the second derivative to find the time of minimal rate of change.

The FT for each mixture occurred near the beginning of the secondary flow region for the set of testing conditions previously defined. These data were also analyzed to determine the number of load cycles at which tertiary flow begins. A graphical procedure was used to determine this point. First, a line was drawn along the slope of the secondary flow region. Next, a line was drawn following the slope of the tertiary flow region. The intercept of these lines is defined to be the tertiary flow value (TF) for these data. Additional details of this procedure are given in (Rushing and Little, 2013).

Another common method for analyzing creep test data is to plot the accumulated permanent strain versus time on a log-log scale. The secondary phase of the creep curve typically has a relatively linear shape. The data from the secondary phase of the curve plotted on a log-log scale can be fitted to Equation 1 to express permanent strain as a function of time where ε_p is the accumulated permanent strain, t is the loading time, and the material regression coefficients are a and m. Typically, decreasing m and a will improve resistance to permanent deformation (Leahy, 1989).

$$\varepsilon_p = a*t^m \qquad [1]$$

4.2 *Repeated load test*

The repeated load triaxial test measures permanent deformation as a function of number of axial load cycles applied to a cylindrical HMA specimen. The repeated load test is used to determine the FN for HMA in the asphalt mixture performance tester (AMPT) according to AASHTO TP 79-09. The procedure allows one to perform the test on an unconfined or confined cylindrical specimen, 100 mm (4 in.) in diameter by 150 mm (6 in.) in height and cored from gyratory compacted mixtures. The stress conditions are determined by the engineer.

The basic principles of the NCHRP 465-recommended FN test were used in this study (Witczak, 2002). A loading period of 0.1s along with a dwell time of 0.9s comprised the load pulse. A confining stress of 276 kPa (40 psi) and deviator stress of 1380 kPa (200 psi) were selected. The test temperature was 43°C (109°F).

The FN is defined as the number of load 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 the data to a Francken model and taking the second derivative to find the number of load cycles corresponding to the minimal rate of change.

Similar to the FT, the FN for each mixture occurred near the beginning of the secondary flow region in all cases for this set of testing conditions. The data were further analyzed to determine the number of load cycles where tertiary flow begins. The previously described graphical procedure was used to determine the tertiary flow value.

The accumulated permanent deformation can be mathematically expressed using the power-law model in Equation 2 where ε_p is the accumulated permanent strain, N is the number of load applications, and the material regression coefficients are a and b. The secondary region of strain accumulation typically provides a linear fit to the data plotted on a log-log scale. The data from the repeated load test were fitted to Equation 2 to determine the material regression coefficients, a and b. In general, resistance to permanent deformation increases as a or b decreases (Leahy, 1989).

$$\varepsilon_p = a^*N_b \tag{2}$$

4.3 *Dynamic modulus test*

AASHTO TP 62-07 provides the procedure for determining dynamic modulus. The procedure allows testing of unconfined or confined cylindrical specimens, 100-mm (4-in.) diameter by 150-mm (6-in.) high cored from gyratory compacted mixtures. The stress conditions are adjusted to result in 50 to 150 microstrain. Specimens are typically tested at five temperatures and six frequencies, resulting in thirty combinations of testing. The suggested test temperatures are -10, 4, 21, 37, and 54°C (15, 40, 70, 100, and 130°F). The suggested test frequencies are 25, 10, 5, 1, 0.5, and 0.1 Hz. For this study, testing was performed at 18 combinations of test conditions. No testing was performed at -10 or 4°C (15 or 40°F). The full range of test frequencies was performed at all test temperatures. Testing at low temperatures was not performed, because rutting was the primary pavement distress investigated in this study and because rutting in the HMA layer does not typically occur at low temperatures.

AASHTO PP 62-10 provides guidance on developing dynamic modulus master curves. The master curves are developed to enable material characterization on a single response scale. Data are typically shown as modulus over a range of reduced frequency at a reference temperature (Equation 3). The time-temperature superposition principle is used to shift the measured responses at various temperatures to this reduced frequency according to Equation 4. The selected reference temperature was 21°C (70°F). All dynamic modulus data were shifted to the reduced frequency by using Equation 5.

$$\log\left|E^*\right| = \delta + \frac{(\alpha)}{1+e^{\beta+\gamma\log f_r}} \tag{3}$$

where

$|E^*|$ = dynamic modulus (psi)
$\alpha, \beta, \delta, \gamma$ = fitting coefficients
f_r = reduced frequency (Hz)

$$\log f_r = \log f + a_1(T_R - T) + a_2(T_R - T)^2 \tag{4}$$

f = loading frequency at test temperature
a_1, a_2 = fitting coefficients
T_R = reference tempeature (°F)

T = test temperature (°F)

$$\log\left|\hat{E}*\right| = \delta + \frac{(\alpha)}{1+e^{\beta+\gamma\left[\log f + a_1(T_R - T) + a_2(T_R - T)^2\right]}} \quad [5]$$

4.4 *Asphalt pavement analyzer test*

The APA used in this study was designed specifically to simulate high tire pressures associated with aircraft. An APA tube or hose pressure of 1724 kPa (250 psi) under a wheel load of 1113 N (250 lb) was used for testing. These conditions are more severe than those typically used in APA testing and were selected to better represent aircraft loads. The test temperature, 64°C (147°F), was the high temperature performance grade (PG) grade for the neat binder. Mixtures containing polymer-modified binder were tested at the same temperature to quantify the benefit of using premium binders for a given climate. Cylindrical asphalt concrete specimens with a target air void content of 3.5% were prepared and tested. Two replicate specimens were tested for each mix. The APA reports the average rut depth of the two specimens.

The APA applied cyclic loads at a rate of one cycle per second. The terminal rut depth of the specimens was set at 12 mm (0.5 in.) after 8,000 cycles; however, the test was terminated when the 12-mm (0.5-in.) rut depth was achieved if this occurred before 8,000 cycles. Once one of the two specimens reached terminal rut depth, the test was stopped. However, since the APA reports the average rut depth for the two specimens, some average rut depths were less than 12 mm (0.5 in.).

5. Performance test results

Results from all four performance tests are given in Table 3. The data presented are the average of two specimens, except for the dynamic modulus data, which is the average of three specimens. Discussion of these data is presented in the following sections.

5.1 *Static creep test results*

The four index parameters extracted from creep data are given in Table 3. These parameters include the slope and intercept values from the data plotted on a log-log scale and the FT and tertiary flow values. The intercept values, *a*, ranged from 0.25 to 0.67. Slope values, *m*, ranged from 0.15 to 1.47. Typically, smaller slope and intercept values are indicative of greater rutting resistance. The mixtures with the poorest rutting performance in this study are those with 30% natural sand (exceeding construction specification limits of 15%). The intercept values for three of these mixtures were the lowest in the data set, falsely indicating greatest rutting resistance. The slope values for these mixtures ranged from 1.01 to 1.47, excluding the mixture with 30% natural sand with a polymer-modified binder, whose slope value was 0.61. Given that these mixtures are very susceptible to rutting, the intercept value does a poor job, while the slope value does a good job of differentiating these mixtures from other mixtures containing better quality aggregate. If mixtures are ranked according to the smallest intercept value, the five top performing mixtures are ½ FGN30, ¾ CGN30, ½ CGN30, ½ GV10, and ¾ CGV10. Intuitively, these mixtures are expected to provide poor rutting resistance. The slope values provide a strong association with rutting performance, since the slope of mixtures containing 30% natural sand was greater than the slope of any other mixtures. The improvement in rutting resistance from using a polymer-modified binder is also observed, with the slope of the ¾ FGN30 mixture reducing from 1.01 to 0.61 when the polymer-modified binder is used. A ranking of mixtures according to the lowest slope value includes ½ CLS0, ¾ CLS0, ½ FLS0, ½ FGN0, and ¾ FLS0 as the top performers.

The FT and TF values ranged from 3 to 130 and from 6 to 359, respectively, for mixtures containing neat binder. Higher values indicate greater rutting resistance. A ranking of the mixtures according to either of these values produces nearly identical results. In both cases, the mixtures with the poorest performance are those with 30% natural sand. The top five mixtures according to both values are ¾ CLS0, ½ CLS0, ½ FLS0, ½ FGN0, and ¾ FLS10. Either index value shows limestone mixtures to have the greatest rutting resistance. Gravel mixtures tended to have worse performance compared to other aggregate types. The ¾ FGN30 mixture with polymer-modified binder had a FT value of 18 and a TF value of 44. Other FT and TF values for mixtures with polymer-modified binder ranged from 95 to 564 and from 267 to 1,534, respectively. The improvement in rutting resistance by using a polymer-modified binder is clearly observed.

5.2 *Repeated load test results*

The four index parameters extracted from repeated load data are given in Table 3. These parameters include the slope and intercept values from the data plotted on a log-log scale and the FN and tertiary flow values. The intercept values, *a*, ranged from 0.15 to 0.39. Slope values, *b*, ranged from 0.25 to 0.71. Typically, smaller slope and intercept values are indicative of greater rutting resistance. The mixtures expected to have the poorest rutting resistance in this study are those with 30% natural sand. The intercept values ranged from 0.17 to 0.33 for these mixtures, similar to the range of the overall data set.

Table 3. *Performance test results*

				Repeated Load				Static Creep				Dynamic Modulus	APA
Binder	**Agg. Type**	**Sand (%)**	**Mix**	**a**	**b**	**FN**	**TF**	**a**	**m**	**FT**	**TF**	**0.1 Hz 64°C (MPa)**	**4,000 cycles Rut Depth (mm)**
64-22	Granite	0	1/2 FGN0	0.29	0.36	285	690	0.46	0.29	104	286	110	6.7
			1/2 CGN0	0.37	0.42	87	237	0.50	0.39	29	80	118	7.5
			3/4 FGN0	0.29	0.45	165	369	0.47	0.35	36	101	108	6.5
			3/4 CGN0	0.28	0.43	148	315	0.50	0.39	39	109	130	8.4
		10	1/2 FGN10	0.21	0.44	135	355	0.38	0.41	33	89	130	17.3[b]
			1/2 CGN10	0.18	0.41	221	646	0.41	0.42	32	79	128	10.1
			3/4 FGN10	0.22	0.40	231	544	0.39	0.34	57	159	144	4.6
			3/4 CGN10	0.29	0.35	255	592	0.45	0.39	40	98	141	7.2
		30	1/2 FGN30	0.26	0.65	21	44	0.25	1.47	4	6	29	--[a]
			1/2 CGN30	0.17	0.71	28	56	0.30	1.16	5	9	18	--[a]
			3/4 FGN30	0.25	0.60	22	54	0.54	1.01	3	7	17	--[a]
			3/4 CGN30	0.33	0.56	15	51	0.27	1.32	3	6	14	--[a]
	Gravel	0	1/2 GV0	0.29	0.44	110	244	0.39	0.47	28	70	96	22[b]
			3/4 FGV0	0.22	0.46	140	312	0.41	0.39	40	111	106	18.1[b]
			3/4 CGV0	0.21	0.44	186	399	0.46	0.43	30	71	114	16.8[b]
		10	1/2 GV10	0.18	0.44	186	459	0.34	0.45	27	74	106	22[b]
			3/4 FGV10	0.21	0.44	143	314	0.35	0.46	28	72	130	15.2[b]
			3/4 CGV10	0.15	0.49	165	391	0.34	0.47	25	63	131	8.9

				Repeated Load				Static Creep				Dynamic Modulus	APA
Binder	**Agg. Type**	**Sand (%)**	**Mix**	**a**	**b**	**FN**	**TF**	**a**	**m**	**FT**	**TF**	**0.1 Hz 64°C (MPa)**	**4,000 cycles Rut Depth (mm)**
	Limestone	0	1/2 FLS0	0.23	0.43	286	594	0.51	0.29	110	302	182	5.3
			1/2 CLS0	0.20	0.41	451	962	0.51	0.26	125	359	183	5.6
			3/4 FLS0	0.25	0.41	386	706	0.55	0.31	90	243	188	5.9
			3/4 CLS0	0.25	0.37	629	1,236	0.50	0.28	130	342	185	4.6
		10	1/2 FLS10	0.19	0.43	237	559	0.40	0.33	69	181	177	7.4
			1/2 CLS10	0.18	0.42	323	729	0.40	0.40	53	132	174	8.0
			3/4 FLS10	0.24	0.36	320	701	0.37	0.31	95	218	182	4.2
			3/4 CLS10	0.27	0.43	128	379	0.40	0.36	51	134	162	6.0
76-22	Granite	0	1/2 FGN0	0.32	0.30	813	1,793	0.47	0.15	402	1,435	150	5.5
			1/2 CGN0	0.37	0.28	951	2,242	0.44	0.27	188	533	142	4.7
		30	3/4 FGN30	0.22	0.50	172	296	0.30	0.61	18	44	117	--[a]
	Gravel	0	1/2 GV0	0.24	0.36	567	1365	0.39	0.33	95	267	141	6.1
			3/4 CGV0	0.30	0.33	842	1,875	0.45	0.33	106	284	143	4.4
	Limestone	0	1/2 CLS0	0.30	0.29	2,017	3,905	0.59	0.18	545	1,534	193	3.0
			3/4 CLS0	0.38	0.25	1,711	4,224	0.67	0.17	564	1,502	225	3.7
		10	3/4 FLS10	0.21	0.37	1,509	2,937	0.46	0.20	360	938	231	3.0

[a] Values not reported because specimens failed too early in testing

[b] Values extrapolated from available data because specimens failed before 4,000 APA cycles

The slope values for these mixtures ranged from 0.56 to 0.71, with the exception of the mixture with 30% natural sand with a polymer-modified binder, whose slope value was 0.50. Given that these mixtures are very susceptible to rutting, the intercept value does a poor job of differentiating these mixtures from other mixtures containing better quality aggregate. The slope values provide a much stronger association with rutting performance, since the slope of mixtures containing 30% natural sand was greater than the slope of any other mixtures. This is not surprising as the intercept is highly sensitive and often inversely related to slope. The improvement in rutting resistance due to polymer modification of the binder was consistently observed, with the average slope decreasing by 0.1 for mixtures with polymer-modification compared to their unmodified counterparts. A ranking of mixtures from least steep to most steep slope (best to poorest rutting resistance) included the top five performers as follows: ¾ CGN10, ½ FGN0, ¾ FLS10, ¾ FLS0, and ¾ FGN10. This ranking is intuitively correct, since quarried aggregates with a larger maximum size are known to provide better rutting resistance.

The FN and TF values ranged from 15 to 629 and from 44 to 1,236, respectively, for mixtures containing neat binder. Higher values indicate greater rutting resistance. In general, the TF values are a little more than twice the FN value for most mixtures. A ranking of the mixtures according to either of these parameters produces nearly identical results. In both cases, the mixtures with the poorest performance were those with 30% natural sand. The top five in the ranking considering both values are ¾ CLS0, ½ CLS0, ½ CLS10, ¾ FLS0, and ¾ FLS10. Either index value shows limestone mixtures to provide the greatest rutting resistance. Gravel mixtures tended to have worse performance compared to other aggregate types. The ¾ FGN30 mixture with polymer-modified binder had a FN value of 172 and a TF value of 296. Other FN and TF values for mixtures with polymer-modified binder ranged from 567 to 1,509 and from 1,365 to 4,224, respectively. The improvement in rutting resistance by using a polymer-modified binder is clearly observed.

5.3 *Dynamic modulus test results*

Dynamic modulus data are presented in Table 3 for one predicted result based on calculations from the master curves. The predicted stiffness value is for conditions of 64°C (147°F) using a frequency of 0.1 Hz. Rutting is more likely to occur at higher temperatures and under lower frequency loading conditions.

The dynamic modulus at 64°C (147°F) and 0.1 Hz was determined using Equation 5. The reduced frequency was determined using Equation 4 with the fitting parameters for each mixture and a reference temperature of 21°C (70°F). These test conditions were selected because 64°C (147°F) is the PG of the neat binder and 0.1 Hz loading is applicable for slow-moving aircraft traffic. Calculating the dynamic modulus at the PG temperature will allow one to determine appropriate dynamic modulus values for any climatic region. Since the objective of this study is to recommend test parameters that can be applied across any region of the United States, the evaluation of the dynamic modulus at a temperature related to the selected binder grade is reasonable. If modified binders are selected for their superior performance, the analysis of the test parameters should still take place at the high PG base grade for a selected climate to ensure the enhanced performance of the premium binder is measured.

The dynamic modulus at 64°C (147°F) and 0.1 Hz provides a reasonable ranking of mixture rutting performance. The mixtures with the lowest values are those containing high dosages of natural sand. The next three mixtures in the ranking from lowest performance are those with gravel aggregate, which is expected to be more rut-susceptible. The eight mixtures with limestone aggregate rank as best performers.

Similar rankings are noted for mixtures containing polymer-modified binder. The limestone mixtures performed the best, followed by granite mixtures and gravel mixtures. The mixture containing 30% natural sand had poorest performance. In all cases, the polymer-modified binder increased the dynamic modulus at 64°C (147°F) using a frequency of 0.1 Hz. This is an expected result since the polymer-modified binder has a higher PG, indicating greater stiffness at high temperature. Increased stiffness at high temperatures is one primary reason that polymer-modified binders are used to improve rutting performance.

5.4 *APA test results*

Although the APA tests were performed to 8,000 cycles, many specimens failed prematurely by exceeding a 12-mm (0.5-in.) rutting threshold. Rushing et al. (2012) recommended preliminary criterion of less than 10 mm (0.4 in.) of rutting for acceptance based on 4,000 cycles when testing at 1724-kPa (250-psi) hose pressure and 1113-N (250-lb) load. The APA rut depth after 4,000 cycles is presented in Table 3. Some mixtures exceeded 12-mm (0.47-in.) rutting after 4,000 cycles. The approximate rut depth at 4,000 cycles was extrapolated from available data for these mixtures. Mixtures containing 30% natural sand failed by 1,500 cycles, so approximated rut depths after 4,000 cycles could not be accurately determined. The best performers from the APA tests were mixtures containing limestone aggregate. The poorest performers were those having chert gravel aggregate. Using a polymer-modified binder gave better APA performance for all mixtures. For the chert gravel mixtures, the improvement in rutting performance changed the outcome of the test from fail to pass by using a premium binder.

6. Performance test assessment

6.1 *Selecting interim mixture evaluation criteria (threshold values)*

Since performance tests cannot accurately represent the complexities of a loaded asphalt concrete pavement, the most valid way to establish threshold mixture acceptance values for a test is through correlation with in-service pavement performance. In the interim, however, preliminary acceptance values were determined in this study from laboratory results. Selection of reasonable thresholds was based upon the test results and the properties of the mixture constituents known to contribute to rutting. Recommended threshold values for each performance test are given in Table 4 and discussed in the following paragraphs.

Rushing et al. (2012) recommended a maximum of 10-mm (0.4-in.) rutting after 4,000 APA cycles as an interim threshold value for accepting mixtures tested using the APA. This value was based on an analysis of rutting in thirty three mixtures. Rutting accumulation was relatively linear after about 2 mm (0.08 mm), and the 10-mm (0.4-in.) criterion allowed significant damage to occur to delineate poorly-performing mixtures from well-performing mixtures and to differentiate among mixtures. The recommended threshold value eliminates those mixtures seemingly prone to rutting, and is a reasonable threshold based on a review of available agency specifications for testing mixtures with the APA. This criterion rejects all mixtures containing 30% natural sand and all but one neat binder gravel mixtures (½ GV0, ¾ FGV0, ¾ CGV0, ½ GV10, ½ FGN10, ¾ FGV10, and ½ CGN10).

Table 4. *Potential performance test acceptance threshold values*

Repeated Load	Static Creep	Dynamic Modulus	APA
Maximum slope of 0.45 when data is plotted on a log-log scale or Minimum Flow Number (FN) of 200	Maximum slope of 0.45 when data is plotted on a log-log scale or Minimum Flow Time (FT) of 30 s	Minimum of 124 MPa (18 ksi) dynamic modulus at PG high temp and 0.1 Hz loading	Less than 10-mm rutting after 4,000 APA cycles using 1113-N (250-lb) load and 1724-kPa (250-psi) pressure

A similar approach was considered for identifying threshold values for the other performance tests considered in this study. The intercept values from the repeated load and static creep tests did not provide reasonable mixture rankings and were not considered. Further, since the tertiary flow values produced nearly identical rankings to FN or FT values, these parameters were not considered. The FN and FT parameters can be mathematically defined and are not as subjective as the tertiary flow values defined by the graphical procedure. The dynamic modulus at the high temperature PG for the selected climate under a 0.1-Hz load was selected for comparison.

The slope of the repeated load data on a log-log scale ranged from 0.25 to 0.71. The maximum slope for mixtures meeting current FAA requirements was 0.49 for the ¾ CGV10 mixture. The mixtures with the highest value of slope were those containing 30% natural sand. The slope of the data for the mixture with 30% natural sand using a polymer-modified binder was 0.505.

An acceptance criterion for repeated load slope values should eliminate those mixtures with excessive natural sand, even when a premium binder is used. This criterion should also reject mixtures that meet volumetric requirements but may be susceptible to rutting. For these reasons, a criterion of a maximum slope value of 0.45 was recommended. This criterion would eliminate all mixtures with 30% natural sand along with two neat binder gravel mixtures (¾ FGV0 and ¾ CGV10).

An alternative criterion for repeated load data would contain a minimum value for the FN. For these mixtures, the FN ranged from 15 to 2,017. The minimum FN for mixtures meeting current FAA criteria was 87 for the ½ CGN0 mixture. Mixtures containing 30% natural sand with the neat binder had FN values ranging from 15 to 28. The mixture with 30% natural sand using a polymer-modified binder had a FN of 172. A criterion that would eliminate mixtures potentially susceptible to rutting was a minimum allowable FN of 200. This criterion would eliminate all mixtures with excessive natural sand. It would also eliminate all neat binder gravel mixtures, half the remaining granite mixtures, and one limestone mixture (½ CGN0, ¾ FGN0, ¾ CGN, ½ FGN10, ½ GV0, ¾ FGV0, ¾ CGV0, ½ GV10, ¾ FGV10, ¾ CGV10, and ¾ CLS10).

This criterion is much more exclusive than the criterion based on the slope of the data. The FN is influenced by the primary flow region when rapid permanent deformation occurs, while the slope value is primarily governed by the secondary flow region. Further, the variability of FN values is greater than that of slope values.

The slope of the static creep data on a log-log scale ranged from 0.15 to 1.47. The maximum slope for mixtures meeting current FAA requirements was 0.47 for the ¾ CGV10 mixture. Mixtures containing 30% natural sand had a higher slope. The slope of the data for the mixture with 30% natural sand using a polymer-modified binder was 0.61.

An acceptance criterion for static creep slope values should eliminate those mixtures with excessive natural sand, even when a premium binder is used. This criterion should also reject mixtures that meet volumetric requirements but may be susceptible to rutting. For these reasons, a criterion of a maximum slope value of 0.45 was recommended. This criterion would eliminate all mixtures with 30% natural sand along with three neat binder gravel mixtures (½ GV0, ¾ FGV10, and ¾ CGV10).

An alternative criterion for static creep data would contain a minimum value for the FT. For these mixtures, the FT ranged from 3 to 564. The minimum FT for mixtures meeting current FAA criteria was 25 for the ¾ CGV10 mixture. The mixture with 30% natural sand using a polymer-modified binder had a FT of 18. A reasonable criterion is a minimum allowable FT of 30. This criterion would eliminate all mixtures with excessive natural sand. It would also eliminate four gravel and one granite mixture (½ CGN0, ½ GV0, ½ GV10, ¾ FGV10, and ¾ CGV10).

This criterion is slightly more exclusive than the criterion based on the slope of the data. The FT is influenced by the primary flow region when rapid permanent deformation occurs, while the slope value is primarily governed by the secondary flow region. Also, the FT value is more variable than the slope value as described later in this paper.

Dynamic modulus master curves are used to calculate responses at the high PG binder temperature of 64°C (147°F) using a 0.1-Hz load. Because mixture stiffness changes with temperature, the test protocol and associated criterion should be based on temperature as well. This temperature should reflect the climate for which a mixture is designed. A convenient method to select a test temperature is to use the high PG binder grade temperature required for a specific location. A singular minimum stiffness criterion can then be applied to all mixture testing.

The dynamic modulus calculated from master curves at the selected conditions ranged from 14.2 to 187.6 MPa (2.1 to 27.2 ksi). The dynamic modulus of the mixtures containing 30% natural sand with the neat binder ranged from 14.3 to 29.2 MPa (2.1 to 4.2 ksi). An acceptance criterion should exclude these mixtures. The next lowest dynamic modulus value was 13.9 ksi for the ½ GV0 mixture. The ¾ FGN30 mixture with the polymer-modified binder had a predicted dynamic modulus value of 116.8 MPa (16.9 ksi) at these conditions. An acceptance criterion of a minimum dynamic modulus of 124 MPa (18 ksi) when tested at the required PG temperature for the climate and using a 0.1-Hz load would reject all mixtures containing excessive natural sand. This criterion would also reject four gravel and three granite mixtures (½ GV0, ½ GV10, ¾ FGV0, ¾ FGN0, ½ FGN0, ¾ CGV0, and ½ CGN0).

7. Full-scale field testing

Data from full-scale field tests from ongoing research studies were used to evaluate the proposed laboratory performance test criteria. The first study, Field Trial 1, applied high tire pressure and wheel load (2,241 kPa and 142 kN (325 psi and 32 kips)) military jet aircraft traffic to an HMA surface at a constant elevated temperature of 43°C (109°F). The second study, Field Trial 2, applied heavy cargo aircraft traffic (980 kPa and 200 kN (142 psi and 45 kips)) to an HMA surface at ambient temperature (25°C (77°F)). Rutting performance at these two conditions was used to assess the preliminary threshold values for the mix design performance tests. The first study represents severe loading conditions that promote rutting (high tire pressure and elevated temperature). The second study represents moderate loading conditions where rutting is less likely to occur.

Both field studies incorporated an HMA pavement surface layer comprised of the same HMA mixture, which was expected to be somewhat susceptible to rutting because the aggregate was predominately chert gravel and natural sand. Only 40% of the aggregate by mass was comprised of a quarried aggregate with more rut resistant physical properties: higher levels of angularity and texture to better resist rutting.

The HMA consisted of an aggregate blend designed to meet Job Mix Formula (JMF) gradation requirements for a 19 mm (0.75 in.) maximum aggregate size mixture according to Item P-401, FAA AC 150/5370 10 E. The blend consisted of 45% crushed gravel, 40% limestone, and 15% natural sand (maximum allowed by specification). The aggregate sources and blend were selected based on materials available for plant production. The fine aggregate angularity value for this blend was 42.6%. Gradation and aggregate properties for the JMF aggregate blend and plant-produced blend can be found in Rushing et al., (2013).

The binder used for this project was an unmodified PG 67-22. Asphalt mixtures were designed using 75 gyrations in the SGC to achieve 4.0% air void content. The design compaction effort (75) was selected from military airfield construction specifications and is expected to result in a binder content nearly identical to that selected using the FAA draft design compaction effort of 70 gyrations. Theoretical maximum specific gravity (G_{mm}) of each mixture was determined on duplicate specimens according to AASHTO T 209, and the average value was reported. Bulk specific gravity (G_{mb}) of compacted cylindrical specimens was determined according to AASHTO T 331 and used to determine specimen air voids (V_a).

After the volumetric design was complete, test specimens were prepared with the HMA mixture for performance testing using all four potential test methods. Results from these tests compared against preliminary criteria are given in

Table 5. The HMA mixture used for field testing performs almost exactly at the minimum threshold criteria for each test method. Any mixture with poorer rutting resistance potential should fail to meet these criteria. Evaluating this mixture in the field study provides an indication of how well the criteria protect against using unsuitable mixtures in terms of rutting performance. All four test methods assessed the mixture as being borderline acceptable.

Asphalt for the full-scale tests was produced by APAC Mississippi, Inc. from a local drum mix plant in Vicksburg, Mississippi, and delivered to the construction facility at the ERDC. Samples of the mixtures were collected from elevated platforms at the plant to verify that the mix design had been achieved. Target production temperature for the HMA was 143°C (290°F).

Table 5. *Recommended performance test criteria*

		Recommended Criterion	Test Result
APA	Rut depth after 4,000 cycles	<10 mm	10.5 mm
Dynamic Modulus	Dynamic modulus at 64°C, 0.1 Hz	>124 MPa	123 MPa
Creep	Slope on log-log scale	<0.45	0.44
	Flow time	>30	34
Repeated Load	Slope on log-log scale	<0.45	0.45
	Flow number	>200 FN	199

The asphalt concrete pavement layer was constructed on the prepared base course using conventional paving equipment in two 50-mm (2-in.) lifts. The asphalt layer was placed with a Caterpillar AP655D asphalt paver. Breakdown rolling was performed using a Caterpillar CB-534D XW vibratory steel-wheel asphalt compactor. An Ingersol Rand PT125R pneumatic roller was used for intermediate rolling. The steel-wheel roller with no vibration was used for finish rolling. A CRS-2 asphalt emulsion tack coat was applied between lifts. In-place volumetric properties are provided in the descriptions of each full-scale test.

7.1 *Field trial 1*

For Field Trial 1, a flexible pavement structure was designed to withstand over 100,000 passes of a fully loaded F-15E fighter jet aircraft (approximately 142 kN (32 kip) wheel load and 2,241 KPa (325 psi) tire pressure) without failure according to DoD criteria (UFC 3-260-02). Failure for this analysis was defined as 25 mm (1 in.) of rutting in the subgrade or subbase. The resulting pavement structure consisted of 100 mm (4 in.) of asphalt concrete over 250 mm (10 in.) of limestone base course with a

California Bearing Ratio (CBR) of 100, over a 300-mm- (12-in.-) thick clay-gravel subbase course with a CBR of 30. The subgrade was high plasticity clay and had an average CBR of 15. The test item was 15.2 m (50 ft) long and 3.7 m (12 ft) wide.

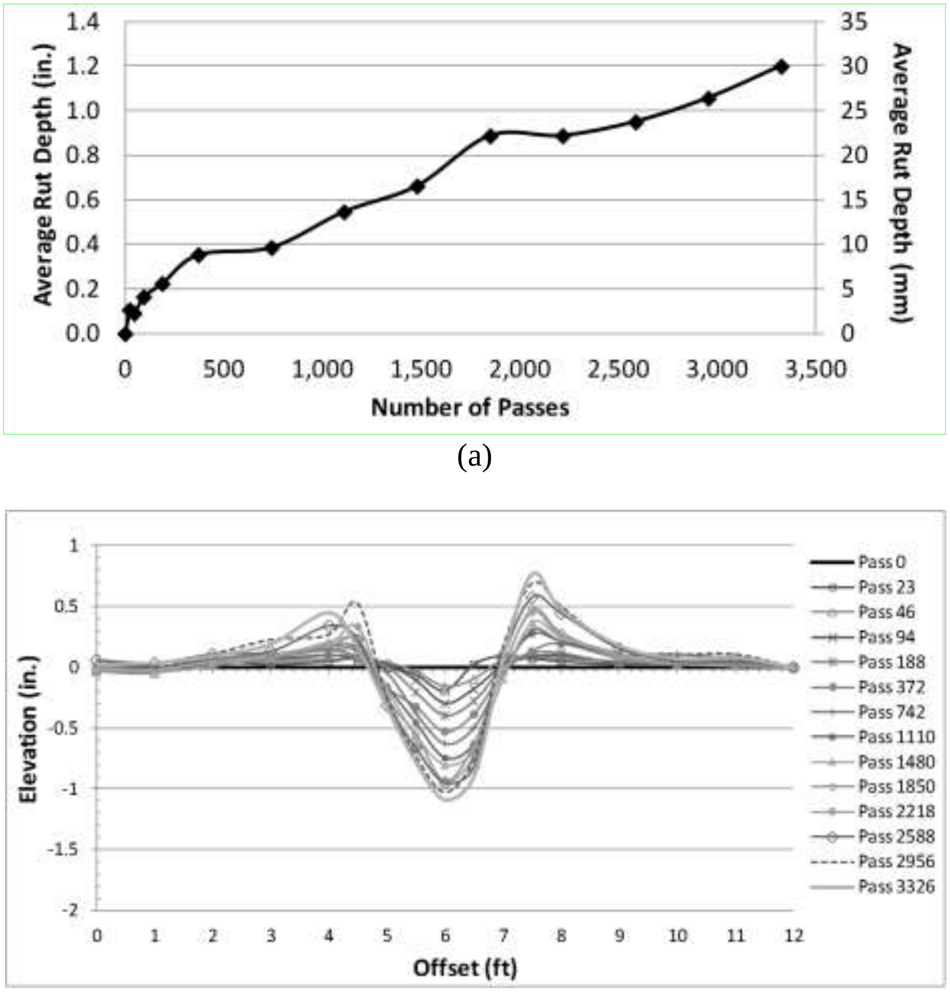
The average volumetric properties of the asphalt layer were determined from ten 100-mm- (4-in.-) thick cores. The average air void content of 3.8% was slightly below the target range of 4.0 to 6.0% for DoD specifications. The average VMA, VFA, and binder content were 14.3%, 73% and 5.3%, respectively. Simulated traffic was applied using a Heavy Vehicle Simulator-Aircraft (HVS-A) accelerated pavement test device. Insulated panels encapsulated the traffic area, and a heating unit provided a constant test temperature of 43°C (109°F) during traffic. A normally-distributed wander pattern was used to distribute traffic transversely within the center 81 cm (32 in.) of the pavement lane. A total of 3,326 traffic passes were applied over a period of 6 days. Figure 2a shows the average rut depth as a function of number of passes of the loaded tire for various data collection intervals. Figure 2b shows a typical cross section of the pavement surface after various traffic intervals.

Failure was defined as an average of 25-mm (1-in.) rutting in the pavement surface. This level of rutting was achieved after approximately 3,000 passes of the simulated traffic. The shape of the rut and the evidence of upheaval adjacent to the traffic area suggested that rutting was predominately in the asphalt concrete layer. Cores taken in and adjacent to the traffic lane after traffic was complete also support this claim.

7.2 *Field trial 2*

For Field Trial 2, a flexible pavement was designed that would withstand over 100,000 passes without failure (according to DoD criteria UFC 3-260-02) of a single wheel from a fully loaded C-17 cargo aircraft (approximately 200 kN (45 kip) wheel load and 980 kPa (142 psi) tire pressure). Failure for this trial was defined as 25 mm (1 in.) of rutting in the subgrade or subbase. The pavement structure consisted of 100 mm (4 in.) of asphalt concrete over 350 mm (14 in.) of limestone base course with a California Bearing Ratio (CBR) of 100, over a high plasticity clay subgrade with an average CBR of 8. The test item was 15.2 m (50 ft) long and 3.6 m (12 ft) wide.

The average volumetric properties of the asphalt layer were determined from ten 100-mm- (4-in.-) thick cores. The average air void content was 5.8%, typical for a newly-constructed pavement. The average VMA, VFA, and binder content were 15.8% 64%, and 5.2%, respectively. Simulated traffic was applied using the HVS-A. Insulated panels encapsulated the traffic area, and conditioned air provided a constant test temperature of 25°C (77°F) during traffic. A normally-distributed wander pattern was used to distribute traffic transversely within the center 122 cm (48 in.) of the pavement lane. A total of 180,000 traffic passes were applied over a period of 3 months, including

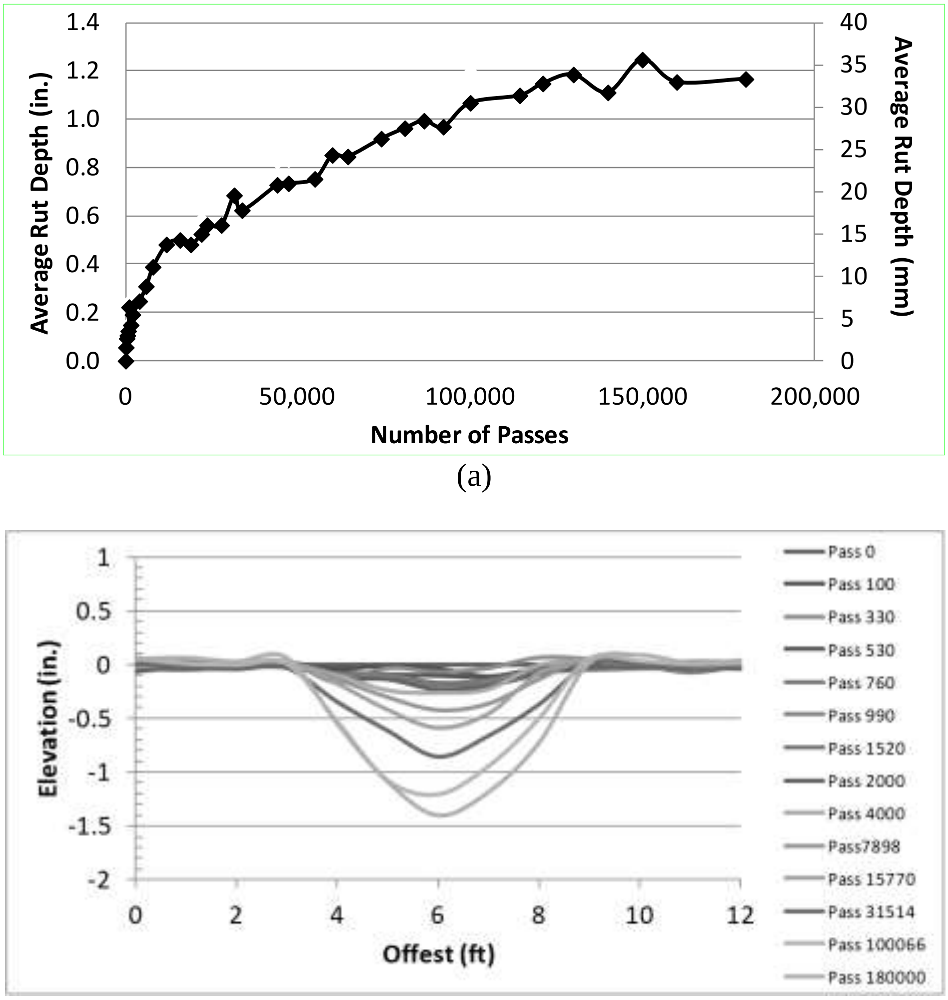


(a)

(b)

Figure 2. *Accumulated rutting during Field Trail 1*

intervals for equipment maintenance. Accumulated rut depth is shown versus the number of traffic passes in Figure 3a. A typical cross section of the pavement surface after various traffic intervals is shown in Figure 3b.



(a)

(b)

Figure 3. *Accumulated rutting during Field Trail 2*

Failure during trafficking was defined as an average of 25-mm (1-in.) rutting in the pavement surface. This level of rutting was achieved after approximately 75,000 passes. Traffic continued until the average total deformation was approximately 33 mm (1.3 in.). The shape of the rut was a wide, shallow bowl, suggesting that rutting was occurring in the structural sub-layers or the subgrade.

Results from the two field studies using the same asphalt mixture show very different rutting performance depending on the traffic and environmental conditions. Field Trial 1 represents an extremely severe condition that promotes high levels of rutting within the asphalt concrete layer. Applying 3,000 aircraft load applications at high temperatures is considered a reasonable, conservative method to test a mixture's rutting performance. An actual in-service pavement would not generally receive this level of traffic in such short duration. If one considers that the highest pavement temperatures only exist for about 3 months of the year, and only for an average of approximately 5 hours per day, then the actual number of hours that a pavement would experience such conditions would be about 450 hours per year. Assuming that most of the rutting occurs in the first year, the applied traffic represents approximately seven load applications per hour. This type of traffic is reasonable for an active military airfield housing fighter jets. Many facilities receive much lower traffic levels and would have better rutting performance.

On the other hand, Field Trial 2 represents moderate loading conditions. The tire pressure of the C-17 cargo aircraft is typical of many commercial aircraft, although it is also common for tire pressures of commercial aircraft to reach 1380 kPa (200 psi) or even higher. The gear load of the C-17 is heavy and requires a substantial pavement structure. The pavement structure in Field Trial 1 was more substantial than for Field Trial 2. Traffic with the C-17 tire required 180,000 passes to achieve 33 mm (1.3 in.) of rutting in the pavement. Very little of this rutting was thought to result from shear flow in the asphalt layer, although verification would require trenching the pavement to observe the cross-section. The lower tire pressure and moderate temperature improved performance considerably compared to Field Test 1. These results are included to show that an asphalt mixture, even with marginal properties, can exhibit adequate or even exemplary rutting performance when loading conditions are moderate.

8. Discussion

Based on the results of the full-scale field tests, the proposed criteria for mixture design performance tests are reasonable. They are conservative enough to eliminate any mixtures that would perform worse than the HMA tested in Field Trial 1 with very high tire pressure at elevated temperature. This performance was acceptable given that most pavements do not experience the type of traffic exposure used in the accelerated pavement test. Further, if traffic conditions did exist at a similar or higher level, a polymer-modified binder should be selected during design to provide better rutting performance.

Results from all four performance tests provided the same assessment of the mixture; which was questionable rutting performance according to the recommended acceptance criterion. Test results were nearly equal to the minimum thresholds for each test method. Since each test was capable of identifying the mixture as having some rutting susceptibility, selection of a performance test for use in mixture design specifications should include other factors such as the cost to perform the test, the time required to determine results, the complexity of the test and data analysis, and the variability of the test. The most desirable performance test is one that produces repeatable results in an economical manner.

Table 6 lists advantages and disadvantages of the different performance tests from this study.

A desirable performance test is one that produces precise and accurate results. Precision refers to the variability of the data produced by running the same test multiple times. The variability of each performance test was studied by preparing and testing twelve specimens of one selected mixture. The ½ FGN0 mixture was selected as a representative mixture for this evaluation since its performance was near the median values for the different mixtures tested in this study. Summary statistics for repeated load, static creep, and APA test parameters are shown in Table 7. The coefficient of variation was used as the comparative metric of performance. The coefficient of variation for dynamic modulus established by Bonaquist was adopted for this paper since a precision statement was recommended in NCHRP 702 (Bonaquist, 2011). The NCHRP study identified the coefficient of variation of low-stiffness mixtures to be between 15% and 24%, with higher variability in mixtures with larger nominal maximum aggregate sizes.

The intercept and slope values from the static creep test had the lowest coefficients of variation, followed by the slope value from the repeated load test. These parameters all had a coefficient of variation below 10%. The coefficient of variation of the TF value from the repeated load test (13%) was much lower than that of the creep test (26%), but the repeated load test FN value was more variable than the FT value from the creep test. The rut depth after 2,300 APA cycles was considered, because this was the number of load cycles achieved when failure occurred for the worst-performing specimen of the ½ FGN0 mixture. The APA rut depth after 2,300 cycles had a coefficient of variation of 20%.

The repeated load test, the static creep test, and the APA test all can be performed in two hours or fewer, allowing for testing of at least three replicates in one day. The APA can test six specimens simultaneously, providing even greater efficiency. The dynamic modulus test typically requires one day for each test temperature, resulting in multiple days to complete testing. To reduce test time, the dynamic modulus could be measured at one temperature (high PG grade) using a single frequency. In this case, the test time

Table 6. *Advantages and disadvantages of potential performance tests*

Performance Test	Parameter	Test Condition	Advantages	Disadvantages
Repeated Load	intercept	PG grade high temperature	Rapid test time	Coring and sawing required
	slope	276 kPa (40 psi) confinement	Slope value has low variability	Standard test equipment and software not available
	flow number	1380 kPa (200 psi) axial stress		
	tertiary flow	0.1 s load, 0.9 s rest		
Static Creep	intercept	PG grade high temperature	Rapid test time	Coring and sawing required
	slope	276 kPa (40 psi) confinement	Slope value has low variability	Standard test equipment and software not available
	flow time	1380 kPa (200 psi) axial stress		
	tertiary flow			
Dynamic Modulus	|E*|	Temperature and frequency sweep	Rutting prediction algorithms available for master curves	Coring and sawing required
		Unconfined		Requires multiple days to test
APA	cycles to 10-mm rut depth	PG Base Grade	Short test duration	Does not measure fundamental material property
		1724 kPa (250 psi)	Ability to test field cores	Equipment with high-pressure capacity may not be widely available
		1113 N (250 lb)		
		4,000 cycles	Ability to test specimens from mix design	

Table 7. Summary statistics of performance tests

Statistical Measure	**Static Creep**				**Repeated Load**				**APA RD at 2,300 Cycles**
	a	**m**	**FT**	**TF**	**a**	**b**	**FN**	**TF**	
Average	0.42	0.35	69	191	0.19	0.46	204	517	10
Min	0.39	0.30	52	128	0.11	0.41	143	438	7.3
Max	0.45	0.38	108	325	0.26	0.53	333	634	13.2
Stdev	0.02	0.02	14	50	0.05	0.04	50	67	2
Coeff. of variation	5%	7%	20%	26%	25%	9%	25%	13%	20%
Skewdness	0.126	-0.747	1.882	1.693	0.023	0.925	1.548	0.706	-0.145
Kurtosis	-0.963	-0.601	5.414	4.591	-1.078	-0.527	3.255	-0.969	-1.421
K-S dist	0.158	0.218	0.312	0.283	0.138	0.211	0.196	0.253	0.134

would be similar to the other methods. However, testing at high temperatures is difficult because permanent deformation can occur if the load levels are too high.

The repeated load test, the static creep test, and the dynamic modulus test also require one additional day for specimen preparation. The test specimens have to be cored and sawn to the test dimensions from gyratory-compacted specimens. Further, the unique size requirements of these test specimens do not allow one to use the same specimens that were prepared during the volumetric portion of the mixture design. Further, these performance tests cannot be directly used as quality assurance tests after construction, because the specimen height required for each of these tests (152 mm (6 in.)) is greater than a typical pavement lift thickness, and may be greater than the total pavement thickness. Any of these test methods will likely have different results if the tests are performed on multiple pavement layers stacked into a column. The APA test can be performed on specimens produced from the volumetric portion of the mixture design if they are sawn to reduce the height from 115 mm to 75 mm (4.5 to 3 in.).

The APA provides several advantages when used as a tool to identify rut potential. Ideally, the APA test criterion could eliminate excessive binder in mixtures of marginal quality during mixture design. A specific example is given in Figure 4. In this case, the design binder content was 5.0%. Increasing the binder content by 0.4% still produced a mixture that would pass the proposed criterion. However, when the binder content was increased by 0.9%, the mixture fails the proposed criterion.

Using mixture design specimens for APA testing eliminates a step in the testing procedure and improves efficiency. Additionally, the APA can be used as a quality assurance test on 152-mm- (6-in.-) diameter cores from a constructed pavement. For pavements greater than 75 mm (3 in.) thick, the specimens can be sawn to remove the lower portion. For pavements less than 75 mm (3 in.) thick, a spacer can be placed below the specimen. Because the critical shear stresses applied by the APA are thought to be most significant on the surface of the specimen, placing a spacer under a 50- to 65-mm (2- to 2.5-in.) specimen cored from a pavement surface lift should not greatly influence test results. The impact of specimen geometry should be investigated, however, before implementing a test protocol. APA performance from field cores may be different than from laboratory-produced mixtures.

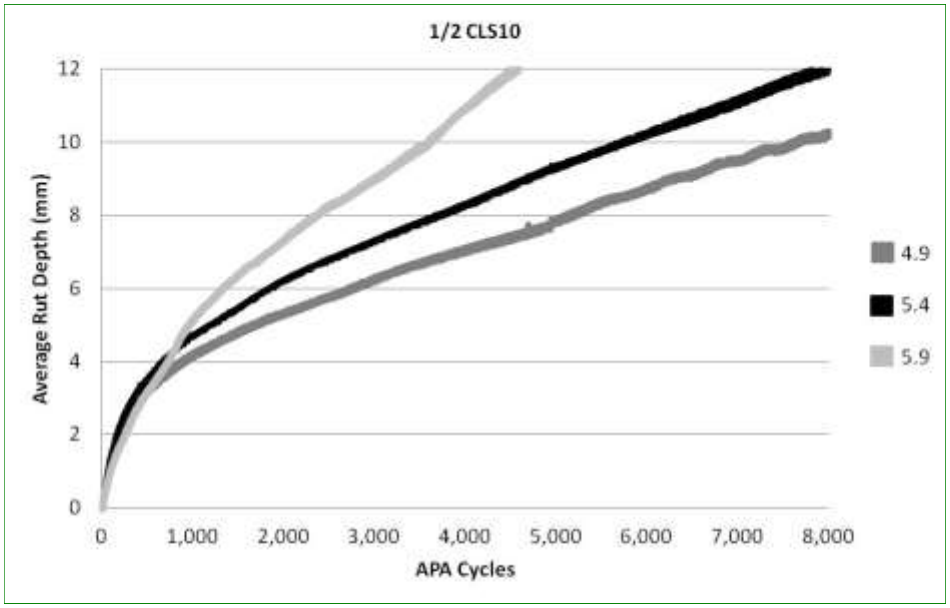


Figure 4. *APA test results from mixture design specimens for ½ CLS10 mixture*

For the reasons presented in the preceding paragraphs, among the tests considered, the APA test is best suited for a performance test as part of an HMA mixture design protocol and with potential for use in HMA construction quality assurance. The APA test equipment produces very similar rankings to the other performance tests evaluated by this study. The APA hose pressure can be adjusted to account for varying design aircraft at specific airport locations. The coefficient of variation of the APA test data is similar to that of FN, FT, and dynamic modulus data. The major disadvantage of the

APA is its purely empirical nature and limited availability with the high-pressure configuration. To fully implement the criterion, correlations should be developed between APA test results on laboratory-produced HMA, APA test results from plant-produced HMA, and in-service pavement rutting caused by high tire pressure aircraft.

9. Conclusions and recommendations

9.1 *Conclusions*

A performance test sensitive to asphalt mixture rutting potential is needed as part of a revised FAA mixture design protocol based on mixture volumetrics as defined by the SGC fabrication process. From this study, which assesses the efficacy of several performance test candidates to augment the volumetric-based SGC procedure and to screen for permanent deformation potential, the following conclusions are drawn:

- Using a polymer-modified binder significantly improved the rut-resistance of all mixtures as measured by each of the four performance tests. For airports experiencing frequent loading by aircraft with high tire pressures, using polymer-modified asphalt binders in the mixture may be necessary to prevent significant rutting from occurring.
- Repeated load tests on 100-mm- (4-in.-) diameter by 150-mm- (6-in.-) high cylindrical specimens using a confining pressure of 276 kPa (40 psi) and axial stress of 1380 kPa (200 psi) produce reasonable rankings of mixture performance. Under these test conditions, the onset of tertiary flow ranged from 237 to 1,236 load cycles for mixtures meeting FAA specifications and having a neat binder. Tertiary flow was achieved at approximately 50 load cycles for mixtures containing 30% natural sand. The onset of tertiary flow occurred between 1,365 and 4,224 load cycles for mixtures meeting FAA specifications and having a polymer-modified binder.
- Static creep tests on 100-mm- (4-in.-) diameter by 150-mm- (6-in.-) high cylindrical specimens using a confining pressure of 276 kPa (40 psi) and axial stress of 1380 kPa (200 psi) produce reasonable rankings of mixture performance. Under these test conditions, the onset of tertiary flow ranged from 63 to 359 seconds for mixtures meeting FAA specifications and having a neat binder. Tertiary flow was achieved at approximately 8 seconds for mixtures containing 30% natural sand. The onset of tertiary flow occurred between 533 and 1,534 seconds for limestone and granite mixtures meeting FAA specifications and having a polymer-modified binder. Tertiary flow began at 267 and

284 seconds, respectively, for the two gravel mixtures prepared using a polymer-modified binder.

- Most mixtures tested in the APA using a hose pressure of 1724 kPa (250 psi) reached the terminal rut depth of 12 mm before 8,000 cycles were applied. None of the mixtures with neat binder tested in this study had less than 6-mm- (0.25-in.-) rut depth after 8,000 cycles in the APA. The mixtures containing 30% natural sand reached 12-mm- (0.5-in.-) rutting within 1,500 APA cycles. The APA results from mixtures meeting FAA requirements ranged from achieving 12-mm- (0.5-in.-) rutting after approximately 1,500 APA cycles to having approximately 6.5-mm rutting after 8,000 APA cycles. Using a polymer-modified binder greatly enhanced rutting performance of the mixtures in the APA. Excluding the mixture containing 30% natural sand, the APA rut depth ranged from approximately 4 to 9 mm (0.16 to 0.39 in.) after 8,000 APA cycles for mixtures containing the polymer-modified binder.
- The slope of the linear portion of the static creep data plotted on a log-log scale is the performance index having the lowest coefficient of variation (7%). The slope of the repeated load data also has a very reasonable coefficient of variation (9%). These indices are less variable than the indices related to the onset of tertiary flow for these tests. The coefficient of variation of the dynamic modulus test is accepted to be approximately 14%. The APA has a coefficient of variation of 20%. The coefficient of variation should be a reasonable value for a selected performance tests to provide statistical confidence in the test results compared to the specified threshold values.
- The APA test is the only performance test evaluated by this study that can be performed on specimens produced by the SGC during mixture design because of the required specimen geometries. Additionally, the APA is the only performance test evaluated by this study that could be used for quality assurance on asphalt concrete paving projects because of specimen geometrical requirements. Currently, the APA with the high-pressure option is not widely used. This limits is applicability. However, it may become a viable option in the future.

9.2 *Recommendations*

Based on the results and conclusions from this study, the APA should be considered as a performance test to accompany mixture design for airport asphalt concrete with high tire pressure aircraft traffic. A preliminary criterion of less than 10-mm- (0.4-in.-) rutting after 4,000 APA cycles is recommended for mixture acceptance.

Further investigation is needed to correlate the performance test results with actual in-service pavement rutting. Future work should also include identifying an appropriate criterion for quality assurance testing of plant-produced mix using the selected performance test. The criterion for quality assurance may be different from the mixture design criterion because of changes to the mixture properties during plant production. Guidance for test frequency, location, conditions, and acceptance criterion should be developed.

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