University Transportation Research Center - Region 2

Final Report

Determine Viscoelastic Mechanical Properties of Warm Mix Asphalt (WMA)-Reclaimed Asphalt Pavement (RAP) Mixes under High Stresses in Airfield Flexible Pavements and Its Impact on Design Life

Performing Organization: Rowan University

June, 2014

Sponsor(s):
New Jersey Department of Transportation (NJDOT)
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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract

The introduction of larger aircrafts on flexible airfield pavements has led to a need for asphalt mixtures capable of sustaining such heavy loads. This laboratory and analytical study investigated the mechanical responses of a number of modified asphalt mixtures to identify their potential for use in airfield aprons and taxiways that are subjected to heavy, static or slow-moving aircraft loads. The mixtures analyzed in this study consisted of a P-401 mixture (used as baseline); a warm mix asphalt (WMA) with 35% reclaimed asphalt pavement (RAP) added to the aggregate portion; a SMA mixture; two HMA mixtures with two different modified binder grades (PG82-22 and PG70-22); a dense-graded asphalt (DGA) mixture; and a BRIC mixture. The airfield flexible pavement section constructed at the Federal Aviation Administration's (FAA) National Airport Pavement Test Facility Construction Cycle – 1 was modeled using the three-dimensional finite element analysis (FEA) software ABAQUS™. Laboratory-compacted specimens of each modified asphalt mixture were tested using AASHTO standards to determine volumetric properties and mechanical responses. The effects of static and dynamic aircraft loading were evaluated in ABAQUS™ using the material properties of the mixtures determined in the laboratory. Flow time and overlay tester results were found to be closely related to the performance of the modified asphalt mixtures. Higher flow time values resulted in lower stresses and deflections in the asphalt surface course. Higher cycles to failure resulted in lower tensile strains at the bottom of the surface course. The rutting performance of all mixtures analyzed in this study, except for HMA PG70-22 and DGA mixtures was comparable to the performance of the baseline (FAA P-401) mixture. Based on the overlay test results, it was found that all of the mixtures analyzed in this study, except for the SMA, exceeded the minimum threshold value and might be comparable to the baseline (FAA P-401) mixture. Based on the findings of this study, it appears that a number of mixtures more commonly used in highway pavements, including modified mixtures, warm mix asphalt, and reclaimed asphalt pavement perform similarly to or even outperform the FAA standard asphalt mixture. The results of this initial study support the idea that an opportunity exists for airports to implement emerging asphalt paving materials without compromising the pavement design life.

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ABSTRACT

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INTRODUCTION

The introduction of newer aircraft types has resulted in the need for constructing airfield pavements capable of withstanding heavier loads. The asphalt layer in flexible airfield pavements are currently designed with stiff, dense-graded mixtures according to the Federal Aviation Administration (FAA) P-401 specifications (*1*, *2*). These specifications, developed to provide guidance on the production of asphalt concrete for airfield applications, require the production and placement of dense-graded hot mix asphalt mixtures with 25 mm maximum aggregate size and PG 64-22 or PG 76-22 binders.

Current Flexible Pavement Mixtures

In recent years, asphalt mixtures for highway pavements have been modified to improve performance related to permanent deformation, fatigue, thermal cracking, and aging resistance. These include a variety of polymer-modified mixtures, warm mix asphalt, reclaimed asphalt pavement, and mixtures designed with aggregate gradations to resist heavy loads such as stone matrix asphalt.

Polymer-modified binders have been used in airfield flexible pavements to accommodate the effects of high ambient temperature and heavier aircrafts. Polymer-modified binders were introduced to increase the stiffness of the asphalt at higher temperatures which should further reduce the likelihood of rutting and shoving. The ability of polymer-modified asphalts to improve asphalt pavement resistance to permanent deformation is well documented (*1, 3, 4, 5*). In cases where high-quality aggregates are used, polymer modification for the purpose of permanent deformation resistance may not be necessary (*4*). The fatigue life of asphalt mixtures might either increase or decrease with the use of modified binders (*6*, *7*). Studies have shown that modified asphalt mixtures may reduce the number of strain cycles to failure. However, it was found that same modifier used with different asphalt increased the fatigue life (*8*).

The highway industry has used reclaimed asphalt pavement (RAP) as a mechanism for producing stiffer mixtures by adding it to the aggregate portion of asphalt mixtures. Flexible pavements containing RAP have been evaluated by the U. S. Army Corps of Engineers in airfield applications (*9*), and the addition of RAP has been reported to increase the dynamic modulus of airfield asphalt mixtures (*10*). With the increase in stiffness, the concern of the mixture resistance to long-term fatigue cracking arises.

Another form of modification to the asphalt mixture is the implementation of alternative gradations. Stone matrix asphalt (SMA) is gap-graded hot mix asphalt (HMA) that is designed to maximize rutting resistance and durability by using a structural basis of stone-on-stone contact (*11*). Originally developed in Europe to resist rutting and studded tire wear, SMA has been used in highway applications in the U.S. since 1990 (*12*). Because the aggregates are all in contact, the mixture's rut resistance relies on aggregate properties rather than asphalt binder properties (*10*). SMA is generally more expensive than a typical dense-graded HMA (about 20 to 25 percent) because it requires more durable aggregates, higher asphalt content and, typically, a modified asphalt binder and fibers. In the right situations it should be cost-effective because of its increased rut resistance and improved durability (*11*). SMA has also been successfully used for airfield applications in China (*13*), Norway, Australia, Belgium, Germany, Italy, Mexico, and the U.S. (*14*). The U.S. Air Force has also constructed SMA runways in Germany and Italy (*15, 16*), and it has been documented to exhibit performance similar to that of the P-401 mixes (*17*).

Emerging Asphalt Mixture Technologies

Warm mix asphalt (WMA) is an emerging technology which has been used extensively in the construction of highway pavements and was recently constructed on runway 4R/22L at the Boston Logan International Airport (*18*). WMA was also paved at the Stevens Anchorage International Cargo Airport (on the taxiways) and at the Chicago O'Hare International Airport (on the runways and taxiways). WMA is produced by altering HMA with water-, organic-, or chemical-based additives. The additives result in reduced HMA production and construction temperatures by as much as 75°C. The goal with WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA, but at substantially reduced production temperatures (*19*). Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving (*20*).

Another emerging asphalt technology is the performance-based mixture known as bottom rich intermediate course (BRIC). This mixture type was originally designed to be placed between a concrete structural layer and an HMA overlay to retard the development of cracking due to joint movement (*21*). More recently, the BRIC mixtures have been applied in flexible highway perpetual pavements. The overall flexible section of the perpetual pavement is thinner compared to pavements using thick granular base courses. Because the total thickness of asphalt bound layers is greater, the potential for traditional bottom-up fatigue cracking and structural rutting are minimized, and pavement distress may be limited to the surface lift (*22*). When damage is limited to the surface, all distresses can be quickly remedied from the surface and encourage a longer-life pavement (*23*). Due to the different loading configuration and frequency applied in an airfield pavement, the BRIC was analyzed as a surface lift in this study.

OBJECTIVES

This study investigated how the mechanical responses of a broad range of asphalt mixtures compare under static and dynamic airfield loads using laboratory-measured viscoelastic properties as well as fatigue cracking initiation and propagation of the mixtures. The main objectives of this study are as follows:

- to measure the flow time, viscoelastic properties, and cycles to failure under shear stress using the overlay tester of a broad range of asphalt mixtures;
- to determine mechanical responses in terms of stresses, strains and deflections under these static and dynamic aircraft loading through a finite element analysis (FEA);
- to determine the relative pavement life of different mixtures using the Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design tool, FAARFIELD (*24*).

Accomplishing the objectives will allow for the comparison of the mechanical responses and predicted life of various asphalt airfield pavement subjected to heavy, standing and slow moving aircrafts.

SCOPE

This study focuses on evaluating mechanical responses (stresses, strains, and deflections) and pavement life of asphalt mixtures used as surface course in airfield pavements especially in taxiways and aprons where aircrafts are standing or slow moving (4.8 km/hr.). Mixtures analyzed in this study include those modified by addition of polymers, lower production and compaction temperatures, addition of reclaimed asphalt pavement to the aggregate portion, or by implementing alternative aggregate gradation. Laboratory testing of laboratory-compacted specimens was conducted to determine the flow time and cycles to failure using the overlay tester. Stresses, strains and deflections in the surface course were obtained using the three-dimensional (3-D) FEA software, ABAQUS™ (*25*). The FAARFIELD software was used to compare the design life of the different mixes for an airfield pavement.

MATERIALS AND EXPERIMENTAL METHODS

A total of seven modified asphalt mixtures were tested and analyzed in this study. One of the mixes met all the FAA P-401 mixture specifications (*2*) and was considered to be the baseline case. The other six modified asphalt mixtures consisted of WMA with 35% RAP added; an SMA mixture; two HMA mixtures with two different modified binder grades (PG82-22 and PG70-22); a dense-graded asphalt (DGA) mixture; and a BRIC mixture. Table 1 introduces the features of these mixture and their volumetric properties, while Figure 1 shows their aggregate gradations.

TABLE 1 Range of Asphalt Mixtures Analyzed in Study

Mixture Design Properties	Asphalt Mixtures						
	FAA P-401 (Baseline)	WMA-RAP	SMA	HMA PG82-22	HMA PG70-22	DGA	BRIC
PG Grade	76-22	64-28	76-22	82-22	70-22	70-28	70-28
Asphalt Content (%)	5.02	5.25	4.87	5.41	4.83	6.42	8.40
RAP (%)	0	35	0	0	0	0	0

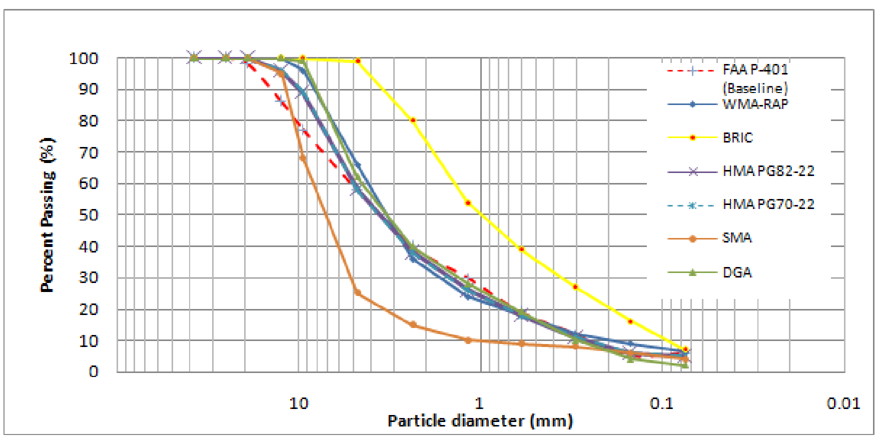

FIGURE 1 Aggregate gradation for mixtures investigated.

LABORATORY TESTING

There have been numerous efforts on the development of asphalt performance tests relating laboratory-measured parameters to predicted distresses for highway pavements. The flow time test has been recognized as one of the tests to measure the fundamental properties of asphalt and is a variation of the simple compressive creep tests introduced by the National Cooperative Highway Research Program (NCHRP) Project 9-19 (*25*). Flow time is defined as the time when the minimum rate of change in strain occurs during the creep test. It is determined by differentiation of the strain versus time curve (*27*). The test measures the viscoelastic response of asphalt concrete (AC) specimens under a static stress level. In NCHRP Project 9-19 (*26*), the flow time was found to correlate well with the rutting resistance of mixtures used in experimental highway field sections at MNRoad (*28*), WesTrack (*29*), and the FHWA Accelerated Load Pavement Testing Facility (*30*). Laboratory data acquired from this static creep test can then be used to determine viscoelastic properties of specific asphalt mixtures.

The flow time was determined for mixtures in accordance with AASHTO TP79-11 *(31)*. During this uniaxial static creep test, the specimen is subjected to a constant compressive load of 600 kPa at a test temperature of 52.5^{o} C. This temperature was based on 50% reliability at a depth of 50 mm in the pavement surface lift for a site in New Jersey obtained from LTPPBind (*32*)., LTPPBind is a widely available tool that provides users with the ability to apply regional temperature and traffic conditions to select Superpave performance-grade asphalt binders. Specimens are prepared according to AASHTO PP 60 (*33*). The test may be conducted with or without confining pressure (*31*) and for this study the test was performed without confining pressure to simulate the most severe loading scenario. Flow time was conducted for 1000 seconds. The resulting axial strain is measured as a function of time and numerically differentiated to calculate the flow time, defined as the time corresponding to the minimum rate of change of axial strain.

The most recent test that can be conducted in the AMPT is the overlay test in accordance with the Texas Department of Transportation (TxDOT) test procedure Tex-248-F (*34*). The overlay test measures the mixture's resistance to crack propagation and correlates well with the field cracking performance for both composite pavements and flexible pavements (*35*, *36*). The specimens can be prepared from either field cores or from Superpave Gyratory Compactor (SGC) molded specimens. Specimens were prepared in accordance with AASHTO T-312 (*37*). Specimens used for overlay testing must meet a relative density specification of 93±1% (7±1% Va) in accordance with AASHTO T-209 (*38*) and AASHTO T-166 (*39*), after being trimmed to test sample size. The test was performed at 25^{o}C with a minimum opening width of 0.625 mm. Specimen failure was deifned as 93% reduction of initial load. Typically, failure criteria are 300 cycles for dense-graded mixtures and 750 cycles for fine graded crack-attenuated mixtures. Therefore, the main parameter for comparison among mixtures is their number of cycles to failure.

LABORATORY TESTING RESULTS

Figure 2 was generated to illustrate a typical flow time curve for the FAA P-401 mix.

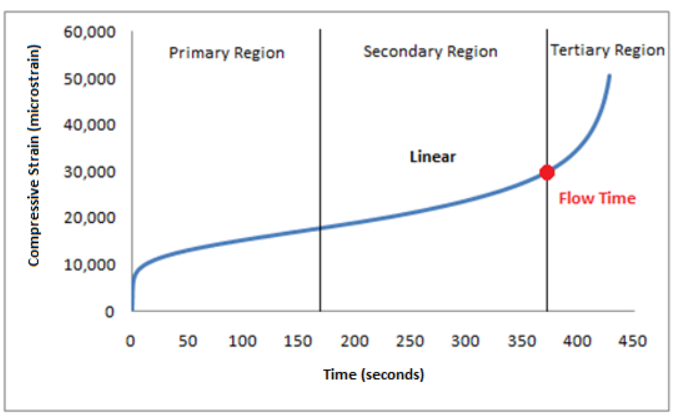

FIGURE 2 Typical flow time test result.

The plot is divided into three basic regions or stages of deformation: primary, secondary, and tertiary. The primary region is where the strain rate decreases sharply and is associated with a densification type of permanent deformation. This behavior continues until the mixture reaches an optimum density level that is followed by the secondary region of the curve where the strain rate remains almost constant under the applied static load. As loading continues within the secondary region, densification will continue until a point is reached where the mixture becomes unstable and significant deformation occurs reaching the tertiary region. The time corresponding to the start of the tertiary zone is referred to as the flow time. Flow time can therefore be considered as the time when the rate of change of compliance is the lowest. The slope represents the rate of change in permanent deformation as a function of the change in loading time. High flow times and lower slopes are considered desirable for resistance to rutting.

Table 2 summarizes the results obtained from the flow time testing of each mixture, while Figure 3 represents the flow time test curves (strain vs. time) for all mixtures.

TABLE 2 Flow Time Test Results

Flow Time Phases		Asphalt Mixtures Tested						
		FAA P-401 (Baseline)	**WMA-RAP**	**SMA**	**HMA PG82-22**	**HMA PG70-22**	**DGA**	**BRIC**
Primary to Secondary	***Time (sec)***	171	84	121	111	23	50	892
	Microstrain (με)	17,913	25,379	29,068	19,055	16,671	25,540	15,136
Secondary to Tertiary	***Flow Time (sec)***	385	213	206	262	53	106	4,011
	Microstrain (με)	31,721	39,202	36,808	30,302	25,424	35,243	39,661
Difference	***Time (sec)***	214	130	85	152	30	56	3,119
	Microstrain (με)	13,808	13,823	7,740	11,247	8,753	9,703	24,525

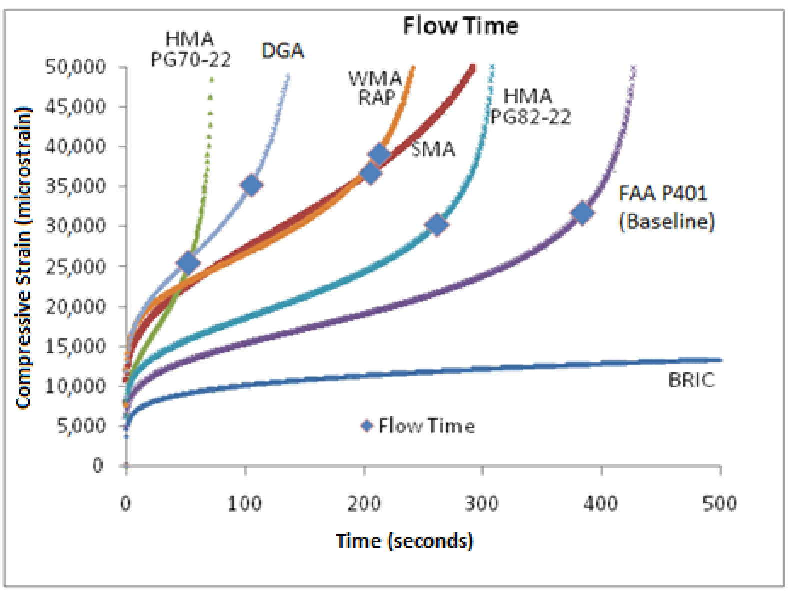

FIGURE 3 Flow time curves measured in the study.

As shown in Table 2, the strain measured for some mixtures are relatively similar; however, the flow time values varied widely. For example, the BRIC and the WMA-RAP mixtures produced 39,661 με and 39,202 με, respectively, while the flow time was 4011 sec for BRIC and 213 sec for

WMA-RAP. This finding may be attributed to the contribution of microstrain resulting from binder and aggregate interlock properties. The difference between values from primary to secondary flow and secondary to tertiary flow captured the actual different behaviors of the analyzed mixtures (24,525 με and 13,823 με for BRIC and WMA-RAP, respectively).

Based on the correlation between flow time and rutting performance (higher flow time, higher rutting resistance), the baseline mixture (FAA P-401) exhibited a better rutting performance overall when compared to the other mixtures, except for the BRIC. As shown in Figure 3, the flow time curve associated with the BRIC mixture was truncated at 500 sec. This mixture had a very low slope and the highest flow time of 4,011 sec, indicating that the mixture has the best rutting performance when compared to the FAA P-401 and the other mixtures.

The FAA P-401, WMA-RAP, SMA, and BRIC mixtures were further investigated for fatigue cracking potential by using the overlay tester. Figure 4 represents a typical output from the AMPT overlay test.

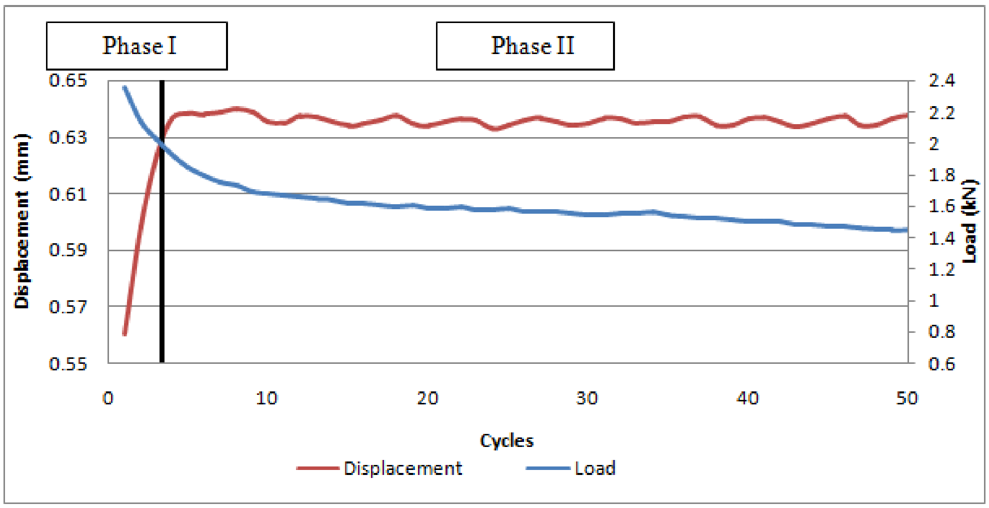

FIGURE 4 Typical AMPT overlay test output.

Three phases can be detected from the data generated from the AMPT overlay test:

- **Phase I: Crack initiation and early propagation**

The load decreases rapidly as the crack starts to propagate through the specimen. At this stage the displacement increases to the minimum amount of 0.635 mm.

- **Phase II: Late crack propagation**

This phase is monitored as a slow decrease in maximum load. Phase II occurs before and up to the cycle when 93% of load (initial) reduction is reached.

- **Phase III: Specimen failure** - In this phase the crack has propagated completely through the specimen or 93% of load reduction has occurred.

Table 3 summarizes the data collected through lab testing including initial and final loads, percent initial load reduction, and cycles to failure. The main parameter for comparison among mixtures is their number of cycles to failure. As specified in the test specifications, the test was stopped at either 93% load reduction or 1,200 cycles, whichever came first.

TABLE 3 Cycles at Each Phase for All Specimens

Asphalt Mixture	Initial Load (kN)	Final Load (kN)	Reduction (%)	Cycles to failure
FAA P-401	3.414	0.923	83	1,200
WMA-35% RAP	2.412	0.756	93	728
SMA	3.124	1.039	93	255
BRIC	1.987	0.773	77	1,200

As mention previously, typically, failure criteria are 300 cycles for dense-graded mixtures and 750 cycles for fine graded crack-attenuated mixtures (*34*). As shown in Table 3, the FAA P-401 and BRIC mixtures exceeded the threshold limits. Both mixtures reached 1,200 cycles before the initial load was reduced by 93%. Except for the SMA mixture, all mixtures performed extremely well with more than 300 cycles to failure.

LINEAR VISCOELASTIC PROPERTIES OF THE MIXTURES

The flow time curve was utilized to determine the viscoelastic properties of the mixtures analyzed in this study. For example, the creep compliance was determined from the 100-second creep curve using the following equation (Eq. 1).

$$J(t) = \frac{\gamma(t)}{\tau} \quad \text{(Eq. 1)}$$

Where
J (t) = creep compliance, 1/kPa;
γ(t) = strain, %; and
τ = creep shear stress, kPa.

If the material is linear viscoelastic, the recovery curve can be predicted using the following equation (Eq. 2). The recovery curve at any time, *t*, can be calculated by superposition of the strain from the positive creep stress at time *t* = 0 to time *t* = *t* seconds and a negative creep stress from time *t* = 1 second to *t* = *t* seconds.

$$\gamma_{recoverable}(t) = \tau J(t) - \tau J(t-1) \quad \text{(Eq. 2)}$$

The creep compliance can be calculated by fitting Eq. (1) or Eq. (2) to the measured data from the laboratory-tested materials. In order to determine the linear viscoelastic parameters (A, B, C, D, and E), the two-mode Prony series linear viscoelastic Kelvin-Voigt model in Eq. 3 was used in order to be consistent with the inputs required in ABAQUS™ FEA software. The ABAQUS™ program uses nonlinear least-squares fit to automatically determine the Prony series parameters when creep data is provided as inputs.

$$J(t) = A + B\left(1 - e^{\frac{-t}{C}}\right) + D(1 - e^{\frac{-t}{E}}) \quad \text{(Eq. 3)}$$

AIRFIELD PAVEMENT ANALYSIS

Finite element analysis has been used in a number of applications to investigate and model both highway and airfield pavements (*40*). The FEA software, ABAQUS™, has been used to model flexible pavements in several studies. The 3D analysis tool is commonly used to evaluate a pavement's mechanical responses in terms of stresses and deflections in the layers. In this study, ABAQUS™ was used to model the airfield flexible pavement and to assess the mechanical responses of the surface lift (or layer), in order to provide a comparison of the behaviors of the various emerging modified asphalt mixtures. The airfield flexible pavement cross-section, materials, and material properties used in this study were the same as the pavement structure that was tested at the FAA National Airport Pavement Test Facility (NAPTF) (*41*). This is an exclusive, fully enclosed facility dedicated to full-scale traffic testing of airport pavements under realistic aircraft loads. Figure 4 shows the typical dual tandem wheel configuration loads of an A340 (4a), tire pressure of 1,448 kPa, dimensions (4b), and material properties (4c).

Material	Thickness (mm)	Density (kg/m^3)	Poisson's Ratio	Elastic modulus (MPa)
Asphalt Surface	127	-	-	-
Stabilized Asphalt-Treated Base P-401	127	2,403	0.35	2,758
Subbase P-209	216	2,162	0.35	261
Medium Strength Subgrade	2,438	93	0.4	72

(a) **(b)** **(c)**

Figure 5 (a) Aircraft carriage, (b) wheel configuration, and (c) material properties and structural profile.

The model geometry consists of the four layers with each layer assumed to be perfectly bonded. The pavement cross-section is comprised of a 127 mm of asphalt surface, over 127 mm of P-401 asphalt treated base layer, 216 mm of P-209 crushed aggregate subbase layer, and 2,438 mm of medium-strength subgrade. For the surface course the material properties used as input were dynamic modulus, Poisson's ratio, density, and viscoelastic properties obtained through laboratory testing.

Finite Element Model

The finite element mesh developed for this study had the following dimensions: 14 m in x-direction (length), 3 m in the y-direction (height), and 3 m in the z-direction (width) and models the section at the NAPTF. The model featured 3D reduced integration elements (C3D8R) and was reduced in size by the use of symmetry and asymmetric boundary conditions. The degree of mesh refinement is one of the most significant factors for estimating accurate mechanical responses in the pavement. A finer mesh was created near the loads to capture the most significant stress and strain gradients. The boundary conditions also have a significant influence on response predictions and the model was constrained along the bottom in all directions and on the sides to restrain its movement in the x- and z-directions. The asphalt surface layer was modeled as viscoelastic while the base, subbase, and subgrade were assumed to be linear elastic. A standing aircraft load was modeled by applying pressure loads to four rectangular contact areas with uniform tire pressure of 1,448 kPa representing the wheel configuration shown in Figure 4. A typical aircraft wheel imprint is of elliptical shape; however, according to Huang (*42*), creating a rectangular element with equivalent contact area is a valid assumption and thus, the wheel imprint was modeled to be 0.3 m by 0.5 m.

Validation of the Finite Element Model

In order to validate the FEM, the mechanical responses from a simplified version of the flexible airfield pavement analyzed in this study were compared to those from a closed form solution (an elastic layer analysis was performed using KENLAYER (*42*)). The simplified model consisted of the same configuration described previously, applied statically on the flexible airfield pavement cross-section. The creep data from the flow time test was used as an input to both the ABAQUS™ and KENLAYER models in order to characterize the behavior of the surface layer.

The supporting structure was assumed to be elastic and Young's elastic modulus was used to represent the stiffness of the base, subbase, and subgrade. The validation resulted in stresses and deflections generated by both analysis tools that were within 4% error.

Modeling of Dynamic Loading

The FEM was then run simulating a dynamic wheel load, modeled as a pressure load moving across the surface of the pavement. The most common application of wheel loads in a finite element analysis is by applying pressure loads to a circular or rectangular equivalent contact area with a uniform tire pressure (*43*). A pressure load equal to 24,948 kg was applied to each contact area, which was created to be the same size as the wheel imprint of a large airplane. The contact area was approximated as a rectangle. The dynamic load was simulated by moving the four wheel loads across the surface to represent a slow moving (4.8 km/hr.) aircraft on an apron or taxiway (*43*). The amplitude of tire pressure acting on each element was varied with time to simulate the advancement of the aircraft. Figure 5 presents a schematic of the FEM and the moving load. As the load moves across from point A to point B, the pressure amplitude of each element changes accordingly.

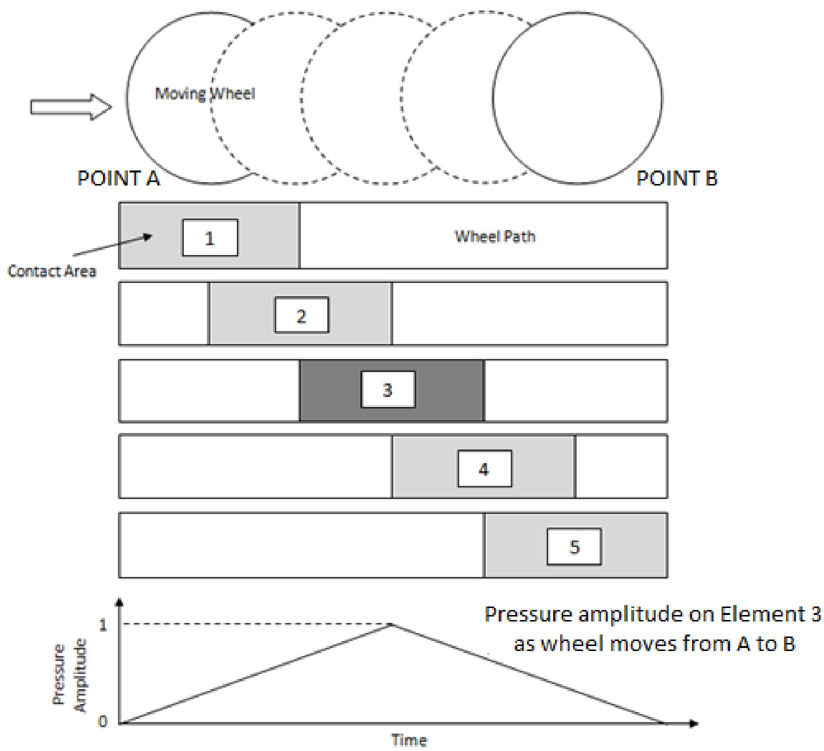

FIGURE 6 Schematic representation of ABAQUS™ modeling of moving load (*43*)

MECHANICAL RESPONSES UNDER STATIC AND DYNAMIC LOAD

The mechanical responses evaluated using ABAQUS™ are summarized in Table 5. A relative comparison of the stresses and deflections at the top of the surface layer, and strains at the bottom of the surface layer was made for the FAA P-401 and the other mixtures.

TABLE 4 Mechanical Responses from Finite Element Analysis

Asphalt Mixtures	3D FEA (ABAQUS ™)											
	Static Load						Dynamic Load					
	Stress (kPa)	Deflection (mm)	Strain (mm/mm)	% variation from P-401			Stress (kPa)	Deflection (mm)	Strain (mm/mm)	% variation from P-401		
				Stress	Deflection	Strain				Stress	Deflection	Strain
FAA P-401 (Baseline)	1,334	3.030	0.001165	Baseline	Baseline	Baseline	1,037	1.046	0.0002111	Baseline	Baseline	Baseline
WMA-RAP	1,364	3.084	0.001183	2.0%	1.8%	2%	1,114	1.265	0.0002157	6.0%	19.9%	2%
SMA	1,355	3.078	0.001641	1.6%	1.6%	41%	1,096	1.207	0.000377	5.7%	15.3%	79%
HMA PG82-22	1,349	3.063	0.001128	1.1%	1.1%	-3%	1,073	1.186	0.0002019	3.5%	13.3%	-4%
HMA PG70-22	1,404	3.198	0.001218	5.3%	5.5%	5%	1,211	1.532	0.0002251	16.8%	46.4%	7%
DGA	1,373	3.084	Not available	1.9%	1.8%	Not available	1,162	1.288	Not available	12.0%	23.1%	Not available
BRIC	1,309	3.020	0.0006842	-1.9%	-0.3%	-41%	1,006	1.011	0.0001077	-3.0%	-3.4%	-49%

Table 5 shows that the static and dynamic stresses of the WMA-RAP and SMA mixtures are within 2% and 6%, respectively, of the FAA P-401 mix. Deflections from the static and dynamic FEA of the WMA-RAP and SMA are within 2% and 20%, respectively, of the FAA P-401 mix. The HMA PG70-22 and DGA mixtures produced the highest static and dynamic stresses (within 6% and 17%, respectively), and deflections (within 6% and 46%, respectively) compared to the baseline mixture. The HMA PG82-22 mixture generated static and dynamic stresses and deflections within 4% and 14%, respectively, higher than the baseline mixture. The BRIC asphalt mixture exhibits lower stresses and deflections than the FAA P-401 mixture, which is indicative of better long-term resistance to the aircraft loading. Overall, the findings are consistent with the flow time results obtained through laboratory testing of the same mixtures.

BRIC is also producing lower strains at the bottom of the AC layer compared to the FAA P-401 mixture. The SMA mixture resulted in the highest increase in strains for both the static (41%) and dynamic (79%) analyses. The HMA 82-22 produced a slight decrease in strains (up to 4%). The WMA-RAP and the HMA 70-22 mixtures produced a slight increase in strains, within 7% for both static and dynamic analyses.

Analysis of Relative Pavement Life

The FAARFIELD program (*24*) uses layered elastic theory to provide airfield pavement life predictions and was used in this study to compare mixtures on the basis of the predicted design life. FAARFIELD failure models relate a computed structural response to the number of coverages (repetition of maximum strain) a pavement structure can carry. For flexible pavement design, FAARFIELD uses the maximum vertical strain at the top of the subgrade and the maximum horizontal strain at the bottom of the asphalt surface layer to predict pavement structural life. The heaviest aircraft (Dual Tan-400) available in the software was applied in the analysis and consisted of a gross weight of 181,437 kg, a tire pressure of 1,379 kPa, and a load frequency of 1000 annual departures. The dynamic complex modulus (|E*|) determined for each mixture was used as the material property inputs to FAARFIELD and was estimated from the flow time test results for the high temperature (52.5^{o} C) and measured through laboratory testing for the lower temperature (25^{o} C). The stiffness values are summarized in Table 6.

TABLE 5 Dynamic Modulus Data Used as Inputs in FAARFIELD

Material Property	Asphalt Mixtures						
	Baseline (FAA P-401)	WMA-RAP	SMA	HMA PG82-22	HMA PG70-22	DGA	BRIC
Dynamic Modulus at 52.5^{o} C, |E*| (MPa)	103.7	57.0	60.4	81.5	77.6	55.5	135.4
Dynamic Modulus 25^{o} C, |E*| (MPa)	1,996	1,935	851	2,128	1,822	Not available	4,901

The estimation of the |E*| at 52.5^{o} C was done by taking the inverse slope of the creep compliance curve at 0.67 seconds which is the time the load takes to move across the wheel imprint (0.5 m long) at 4.8 km/hr. The stiffness values presented below are significantly lower than the default stiffness value of 1,379 MPa assumed in FAARFIELD because they are estimated based on testing at high temperatures of 52.5^{o}C. The dynamic modulus at 25^{o} C was obtained from laboratory testing.

The stiffness of the underlying pavement layers, which are assumed to be elastic in the 3D FEA and FAARFIELD analyses, were not adjusted based on temperature since the changes in stiffness due to temperature will not affect the relative rutting performance of the surface mixtures. Also, the stiffness of the stabilized-asphalt treated base is fixed as a default value at 2,760 MPa in the FAARFIELD software.

Since the FAA P-401 mixture was considered the baseline, it was assigned a pavement life factor of 1.0. The performance associated with the modified mixtures was compared to the performance of the baseline mixture and the predicted results are shown in Figure 7 and 8.

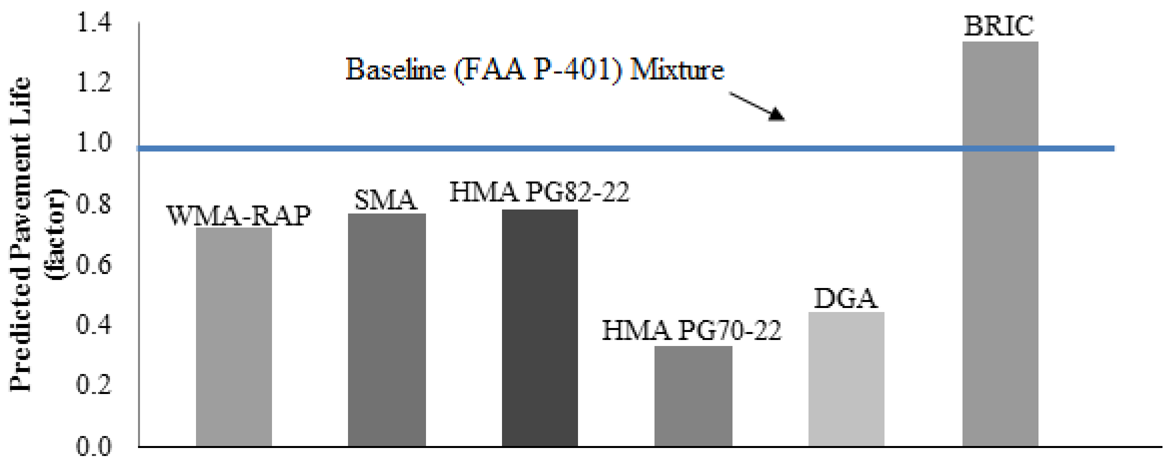

FIGURE 7 Relative predicted pavement life from FAARFIELD analysis (|E*| at 52.5ºC).

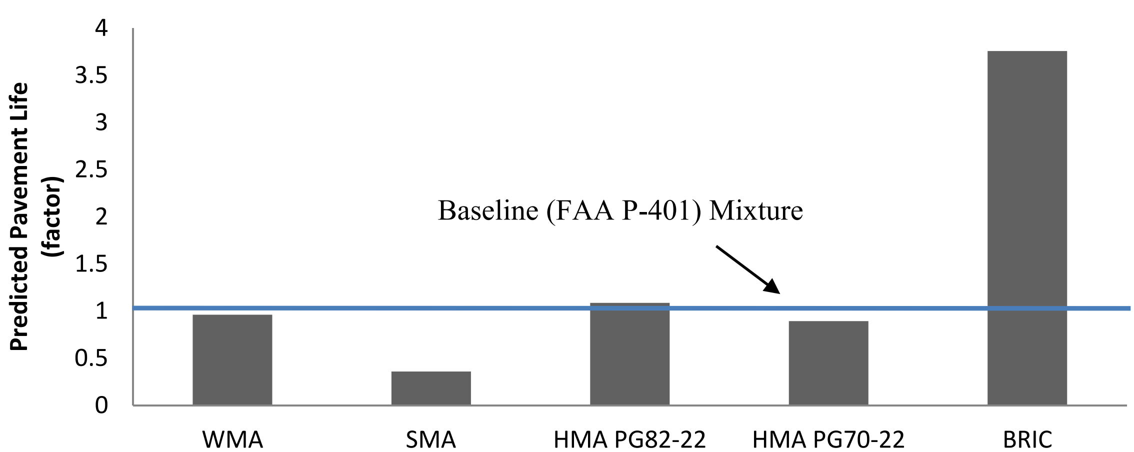

FIGURE 8 Relative predicted pavement life from FAARFIELD analysis (|E*| at 25ºC).

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Figure 7 shows the BRIC mixture has approximately 30% more life as compared to the FAA P-401 mixture. The predicted lives of the WMA-RAP, SMA, and HMA PG 82-22 mixtures were 65%, 69%, and 70%, respectively, of the performance of the baseline mixture. The HMA

PG70-22 and DGA mixtures were predicted to perform less than half the amount of time of the FAA P-401 mixture. The data showed that relatively slight increases in stresses and deflections (up to 2%) in the static analysis for the WMA-RAP, SMA, and HMA PG82-22 mixtures resulted in a life reduction of approximately one-third that the life of the FAA P-401. A life reduction of approximately two-thirds was observed for the HMA PG70-22 and DGA mixtures, where the stresses and deflections estimated from the static analysis were between 3% and 6% higher than the baseline mixture.

Figure 8 shows the BRIC mixture has approximately four times more life than the FAA P-401 mixture. The predicted lives of the WMA-RAP, HMA 82-22, and HMA 70-22 were comparable to the standard FAA P-401 mixture. However, the SMA mixture performed the worst resulting with a predicted life reduction of approximately 70%.

SUMMARY OF FINDINGS

This study was conducted to evaluate and compare the mechanical responses of a number of modified asphalt mixtures subjected to both static and dynamic aircraft loads typical of aprons and taxiways. The findings from the FEA and FAARFIELD analyses are summarized as follows:

1. Higher flow time values resulted in lower stresses and deflections in the asphalt surface course. Flow time was found to be closely related to the performance of the modified asphalt mixtures.
2. Most of the mixtures produced mechanical responses that were comparable to the baseline mixture for both static and dynamic loading. The HMA PG70-22 and DGA mixtures were less comparable in that they produced the highest stresses and deflections, along with the lowest flow time values.
3. The BRIC asphalt mixture was predicted to perform better than the FAA P-401 mixture based on the mechanical responses. This mixture had the highest flow time, highest cycles to failure, lowest stresses and deflections. It was also predicted to perform to the longest service life by approximately 30% more than the FAA P-401.
4. The WMA-RAP, SMA, and HMA PG 82-22 mixtures were predicted to have comparable performance life to that of the FAA P-401. Overall, the estimated mechanical responses were relatively similar to the mechanical responses of the FAA P-401 mixture.
5. The HMA PG70-22 and DGA mixes were not predicted to have comparable rutting performance to the FAA P-401, yielding shorter service lives and lower flow time values.
6. All of the mixtures, except for the SMA, exceeded the threshold limits for cycles to failure according to the TxDOT specifications.
7. Higher cycles to failure obtained through the overlay test resulted in lower tensile strains at the bottom of the surface course. The results from the overlay test were found to be closely related to the performance of the modified asphalt mixtures.
8. The BRIC and HMA 82-22 mixtures showed a better fatigue cracking performance compared to the FAA P-401. Both mixtures had lower strains and better performance life than the FAA P-401.
9. The WMA-RAP and HMA 70-22 mixtures predicted a slight increase in strains and to have a relatively similar performance life to that of the FAA P-401.
10. The SMA mixture produced the highest increase in strains and shortest performance life compared to the FAA P-401 mixture.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this study:

1) A combined approach with FEA and layered elastic analysis was effective for discerning the performance potential of various asphalt mixtures for airfield pavements.
2) It was found that the rutting performance of all mixtures analyzed in this study, except for the HMA PG70-22 and DGA mixtures was comparable to the performance of the baseline (FAA P-401) mixture.
3) Based on the overlay test results, it was found that all of the mixtures analyzed in this study, except for the SMA, exceeded the minimum threshold value and might be comparable to the baseline (FAA P-401) mixture. The FEA confirmed that except for the SMA, all mixtures performed better or were comparable to the FAA P-401. It was also determined that mechanical responses and performance under static and dynamic heavy aircraft load of the BRIC mix may outperform the baseline mix possibly both for rutting and fatigue cracking.
4) The flow time test was found to produce results that can be correlated to the mixture performance and can be used to evaluate new mixture applications in flexible taxiway and apron pavements where rutting or shoving is the primary distress.
5) Overall, the overlay test was also found to correlate well with the mixture fatigue cracking performance.
6) There is a potential for the airfield industry to consider modified binders and other emerging mixture technologies, such as WMA-RAP. Also, the use of BRIC mixture as surface lift in airfield taxiways and aprons should be further investigated since this mixture appears to exhibit the most potential for improving surface rutting and fatigue cracking performance.

It is recommended to use this study as basis of a more in-depth analysis of WMA-RAP and BRIC mixtures used as surface lift to investigate the effects of a larger variety of aircraft wheel configurations. Also, to confirm the results of this study and validate the analysis, an analysis should be initiated to compare the mechanical responses obtained from the FEA with the actual field data. Future studies may also consider the effects of temperature gradients throughout the surface and underlying bituminous layers on the overall stiffness of the pavement and its resistance to rutting and fatigue cracking.

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