Asphalt Pavement Analyzer Used to Assess Rutting Susceptibility of Hot-Mix Asphalt Designed for High Tire Pressure Aircraft

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Hot-mix asphalt (HMA) laboratory mix design is intended to determine the proportion of aggregate and binder that, when mixed and compacted under a specified effort, will withstand anticipated loading conditions. Current mix design procedures that use the Superpave® gyratory compactor rely on the engineering properties and volumetrics of the compacted mixture to ensure reliable performance; however, a definitive performance test does not exist. The asphalt pavement analyzer (APA) was evaluated as a tool for assessing HMA mixtures designed to perform under high tire pressure aircraft following FAA specifications. The APA used in this study was specially designed to test simulated high tire pressures of 250 psi, which are becoming more common for aircraft. Thirty-three HMA mixtures were included in the study. Each was designed with the Superpave gyratory compactor, according to preliminary criteria being developed by FAA. The study included some mixtures that contain excessive percentages of natural sand and that do not meet FAA criteria. These mixtures were included to provide relative performance for mixtures expected to exhibit premature rutting. APA testing with the high tire pressure APA resulted in rapid failure of HMA specimens compared with traditional APA testing at lower pressures. Data were analyzed, with a focus on the provision of acceptance recommendations for mixtures to support high tire pressures. A preliminary 10-mm rut depth criterion after 4,000 load cycles is recommended.

Rutting is a primary load-related distress in airport pavements subjected to high tire pressure aircraft loads. Hot-mix asphalt (HMA) for airport pavements has historically been designed with materials and compaction requirements that can withstand these loading conditions. The Marshall design procedure has been used by FAA for airport pavement. The design procedure includes meeting aggregate and binder requirements along with the laboratory mix design volumetric requirements to produce acceptable mixtures. Marshall stability and flow test values provide an empirical, threshold metric to help ensure a stable mixture under traffic, but this empirical test cannot assess performance. Performance can be assessed by either a damage model based on sophisticated testing of engineering and material properties or tests that mimic the traffic loads encountered in the field.

A new mix design procedure being implemented by FAA allows use of the Superpave® gyratory compactor in lieu of Marshall impact compaction to compact specimens during the mix design process (*1*). This new procedure includes the same aggregate and binder requirements and the same volumetric requirements as those that are currently part of the Marshall protocol, but no performance test is included in the protocol. Studies are currently being conducted to identify a companion performance test for the new mix design procedures, but one has not yet been adopted.

The asphalt pavement analyzer (APA) has been successfully used by several agencies as a test to determine HMA mixture suitability. It is one of the most widely accepted laboratory accelerated wheel trafficking devices available and one that attempts to mimic the action of a moving and heavily loaded, high tire pressure wheel of the type that simulates airfield traffic. Tests that simulate or mimic traffic action are often used in lieu of traditional laboratory testing because the action of a moving wheel load in which there is a rotation of principal stresses, and a transition from compression to extension is difficult to recreate with even sophisticated triaxial laboratory tests (*2*). For this reason, empirical tests such as the APA offer an alternative approach, which is favored by many.

The APA was first manufactured in 1996 (*3*). It places a loaded wheel on a pressured linear tube, centered on top of the specimen. The wheel is tracked in a forward and backward linear motion across the samples, resulting in plastic deformation, or rutting. The APA can be used to test either cylindrical or beam specimens.

Several studies have attempted to correlate APA laboratory rutting with field rutting. Williams and Prowell found that the APA test results correlated well with field results (*4*), as did a number of state departments of transportation (*5–8*). However, as the WesTrack Forensic Team Study demonstrated, a direct relationship between lab rutting and field rutting does not exist. For example, the WesTrack study showed that a laboratory rut depth of 6 mm after 8,000 cycles represented a field rut depth of 12.5 mm (*9*).

Choubane et al. reported appropriate ranking of mixes according to field performance (*7*). However, their study indicated APA test variability was statistically significant from test to test and among locations during a test. Recommendations from the study cautioned on using the APA as a pass or fail criterion based on the three mixes tested. AASHTO TP 63-07 indicated precision, and bias statements have yet to be determined for APA testing.

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OBJECTIVE

The objective of this study was to evaluate the ability of the APA to serve as a performance test to assess the potential for rutting under high tire pressure aircraft during the design of hot asphalt mixtures. HMA mixtures carefully designed to exhibit a wide range of rutting potential were included in the study. The ability of the APA to differentiate among these mixtures and its applicability as a mix design or quality assurance test, or both, were investigated. The actual rutting susceptibility of the mixtures tested under field conditions was not evaluated; however, mix variables known to contribute to rutting were controlled to provide relative performance correlations.

TEST PROCEDURE

The APA used in this study was specifically designed to simulate high tire pressures associated with aircraft. Two such high pressure APAs are known to exist in July 2011: one at the FAA William J. Hughes Technical Center in Atlantic City, New Jersey, and one at the Air Force Research Laboratory at Tyndall Air Force Base, Florida. Testing in this study was conducted at the FAA test facility. Mix design and specimen preparation were accomplished at the U.S. Army Engineer Research and Development Center (ERDC), Waterways Experiment Station in Vicksburg, Mississippi.

An APA tube or hose pressure of 250 psi under a wheel load of 250 lb was used for testing. Test temperature was 64°C as was the high temperature PG grade for the binder used in all mixtures. Cylindrical asphalt concrete specimens with a target air void content of 3.5% were prepared and tested. Air void content was selected as the midpoint of the allowable range in the FAA mix design procedure. Two replicate specimens were tested for each mix. The APA reports the average rut depth of the two specimens. Thirty-three mixtures were included in the study. The mixtures used one neat binder and three aggregate types. Some mixtures included natural sand.

Cyclic loads were applied by the APA at a rate of one cycle per second. The terminal rut depth of the specimens was set at 12 mm after 8,000 cycles; however, the test was terminated when the 12 mm 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.

MATERIALS

The asphalt binder used in this study was obtained from Ergon Asphalt and Emulsions, Inc. Tests by the distributor indicated the binder graded as a PG 64-22 and had a specific gravity of 1.038. Supplier-recommended mixing and compaction temperatures for the binder were 310°F (154°C) and 290°F (145°C), respectively, based on binder viscosity.

Aggregates used in this study consisted of material stockpiles at ERDC collected for a previous study, which evaluated the use of the Superpave gyratory compactor for airport mix design (*10*). These aggregates included limestone, granite, and chert gravel. The limestone aggregate was from a Vulcan Materials quarry in Calera, Alabama. The granite aggregate was from Granite Mountain Quarries in Little Rock, Arkansas. The chert gravel aggregate was from Green Brothers Gravel Company in Copiah County, Mississippi. Additionally, some mixtures were blended with selected percentages of natural sand, locally purchased from Mississippi Materials Corporation in Vicksburg, Mississippi.

Each aggregate type consisted of multiple stockpiles that were blended to meet the target gradations. Selected gradations were within the allowable range of size fractions incorporated in FAA specifications (*11*). Gradations referred to in this paper are designated as fine and coarse. Fine gradations are those near the upper limits of the gradation band. Coarse gradations are those near the lower limits of the gradation band. Some aggregate blends included 10% or 30% natural sand. These gradations are characterized by a hump in the grain size distribution near the 30- to 50-sieve sizes.

The percentages of aggregate with at least two fractured faces were 100%, 100%, and 97% for the limestone, granite, and chert gravel, respectively. Maximum percentages of flat and elongated aggregates were 1.6%, 1.0%, and 0.3% for the limestone, granite, and chert gravel, respectively.

The fine aggregate angularity for the limestone, granite, chert gravel, and mortar sand aggregates was determined by Method A of ASTM C1252. The limestone, granite, and chert gravel aggregates had a fine aggregate angularity of 47%, 47%, and 46%, respectively. The fine aggregate angularity of the mortar sand was 40%. This value is characteristic of rounded aggregate particles and is typical for natural sands (*12*).

Additional testing of the aggregates was performed with the Aggregate Imaging Measurement System (AIMS), which determines shape characteristics of aggregates through image processing and analysis techniques (*13*). AIMS is a computer-automated system that includes a lighting table where aggregates are placed, to measure their physical characteristics (shape, angularity, and texture). It is equipped with an autofocus microscope and a digital camera, and it is capable of analyzing the characteristics of aggregates sizes retained on the No. 100 sieve (0.15-mm sieve) up to aggregates retained on the 1-in. sieve (25.4 mm). Texture is measured by analyzing gray scale images captured at the aggregate surface by using the wavelet analysis method. Surface irregularities manifest themselves as variations in gray-level intensities that range from 0 to 255. Large variations in gray-level intensity mean a rough surface texture, whereas a smaller variation in gray-level intensity means a smooth particle. The wavelet transform analyzes the image as a two-dimensional signal of gray scale intensities, and it gives a higher texture index for particles with rougher surfaces. Angularity is measured by using the gradient analysis method, which basically quantifies the change in angles along the circumference of a particle. A higher change in angle means a more angular particle. Masad et al. gives detailed background information with AIMS operations and analysis methods (*13*). Six sizes of fractions for each of the three aggregate types were tested with AIMS. These fractions included aggregates retained on ½ in., ⅜ in., No. 4, No. 8, No. 16, and No. 30 U.S. standard sieves during a washed sieve analysis. Table 1 shows the average results for angularity and texture indices measured by AIMS.

MIX DESIGN

A Pine Instruments Company model AFGC125X gyratory compactor was used in the mix designs during this study to produce cylindrical asphalt concrete specimens with a diameter of 150 mm at a target height of 115 mm. Compaction was performed with a ram pressure of 87 psi (600 kPa) and an internal angle of gyration of 1.16° ± 0.02°. Asphalt mixtures were compacted to 70 gyrations at a rate of 30 revolutions per minute. Seventy gyrations is recommended for N_{design} for HMA mixtures designed for high tire pressure aircraft (*9*), but this is currently being evaluated by FAA. Three binder contents were used for the mix designs, in increments of 0.5% binder. Three

TABLE 1 Aggregate Data from AIMS Analysis

Sieve Size	Angularity			Texture		
	Limestone	Granite	Chert Gravel	Limestone	Granite	Chert Gravel
½ in.	2,607	3,200	2,721	359	535	153
⅜ in.	2,668	3,167	2,912	345	493	164
No. 4	2,841	3,461	2,960	274	362	130
No. 8	3,162	3,709	3,212	na	na	na
No. 16	3,164	3,907	3,348	na	na	na
No. 30	3,176	3,876	3,282	na	na	na

NOTE: Texture is measured only on coarse aggregate. na = not applicable.

replicate specimens were compacted at each binder content. The mix designs were able to bracket the design binder content by using only three trial percentages because of previous experience with these materials (*9*). The air void content and voids in mineral aggregate (VMA) were determined according to Asphalt Institute MS-02 procedures (*14*). The design or optimal binder content was selected as the binder content that resulted in a compacted specimen having 3.5% air voids.

Specimens produced for APA testing were compacted with the design binder content at a target height of 75 mm. The mass of binder and aggregate was proportioned so that the compacted specimen height would be near the target value. Reducing the mass of the material in the mold was expected to have some influence on the volumetric properties. The smaller sample size, along with inherent specimen variability, resulted in some specimens having higher or lower air voids than the target value of 3.5%. Table 2 shows the aggregate types, maximum size, and relative gradation, as well as the percentage of natural sand, the binder content, and the air void content for the APA test specimens. The mix designation is also listed and is used to identify these mixtures in this paper.

TABLE 2 Characteristics of APA Test Specimens

Aggregate Type	Maximum Aggregate Size (in.)	Gradation	Mortar Sand (%)	Optimum Binder Content	Air Voids 1	Air Voids 2	Mix Designation
Granite	½	Fine	0	6.7	3.73	3.68	1/2 FGN
			10	6.8	3.07	3.13	1/2 FGN10
			30	7.2	5.49	5.95	1/2 FGN30
		Coarse	0	6.3	3.76	3.95	1/2 CGN
			10	5.9	3.85	3.62	1/2 CGN 10
			30	6.8	4.89	3.52	1/2 CGN 30
	¾	Fine	0	6.2	2.37	3.02	3/4 FGN
			10	6.1	2.57	0.83	3/4 FGN 10
			30	7.0	2.54	3.17	3/4 FGN 30
		Coarse	0	5.9	4.70	6.30	3/4 CGN
			10	4.9	4.27	4.94	3/4 CGN 10
			30	7.1	5.03	4.56	3/4 CGN 30
Limestone	½	Fine	0	6.1	4.26	4.11	1/2 FLS
			10	5.2	3.69	3.50	1/2 FLS 10
			30	6.9	2.90	2.91	1/2 FLS 30
		Coarse	0	5.5	4.65	5.13	1/2 CLS
			10	5.0	4.05	3.58	1/2 CLS 10
			30	6.1	4.00	4.15	1/2 CLS 30
	¾	Fine	0	5.7	4.53	4.58	3/4 FLS
			10	4.8	3.90	4.40	3/4 FLS 10
			30	5.9	4.06	3.63	3/4 FLS 30
		Coarse	0	5.4	2.80	3.17	3/4 CLS
			10	5.4	2.04	2.50	3/4 CLS 10
			30	5.7	3.79	3.82	3/4 CLS 30
Chert gravel	½	Center	0	6.8	3.45	3.34	1/2 FGV
			10	6.2	2.50	2.28	1/2 FGV 10
			30	6.8	2.79	2.83	1/2 FGV 30
	¾	Fine	0	6.8	3.74	3.73	3/4 FGV
			10	5.9	2.90	2.89	3/4 FGV 10
			30	7.1	2.43	2.45	3/4 FGV 30
		Coarse	0	6.4	3.70	3.90	3/4 CGV
			10	5.3	3.34	3.16	3/4 CGV 10
			30	6.6	2.76	2.75	3/4 CGV 30

NOTE: Results from Superpave mix design at 70 gyrations (3.5% air voids).

APA RESULTS

General

The APA records the average rut depth of the two specimens with each load cycle into a Microsoft Excel spreadsheet. Average rut depth was plotted versus the number of load cycles to produce a curve of accumulated rutting. Figure 1 shows the number of load cycles versus APA rut depth for all 33 mixtures. As previously stated, the test was ceased after one of the two specimens reached the terminal rut depth of 12 mm. Values shown in Figure 1 are the average rut depth of the two specimens. The mix designation is not included on this figure because of the large number of data sets. Data from Figure 1 are extracted in subsequent figures with mix designations included for analysis.

During APA testing, a more rapid rutting rate took place during the initial load cycles. After about 1 mm of rut depth, specimen behavior was observed to be more closely linked to mixture characteristics as evidenced by variable rates of rut depth accumulation. Some mixtures had a slow rate of rut depth accumulation, whereas others failed quickly. The rate of rut depth accumulation seemed to become somewhat linear after approximately 2 mm of rutting. Rutting behavior in the APA followed the same general pattern as commonly observed in creep and repeated loading experiments with a primary and secondary flow. Tertiary flow was not observed during the experiments.

Although mix designations are not shown in Figure 1, analysis of the data indicates general trends in mix variables that affect the rate of rut depth accumulation. These mix variables are investigated in the following paragraphs.

An analysis was conducted to determine the effect of natural sand on the APA results. Figure 2 shows the APA results for mixtures containing no natural sand. These mixtures, as expected, were among the best performers in the APA test. Incorporating natural sand promotes rutting in HMA (*15, 16*). For mixtures containing no natural sand, the accumulation of rut depth is related to the aggregate type. Mixtures containing crushed chert gravel aggregate rutted much more quickly than did the other mixtures. The crushed gravel meets FAA requirements for the mass percentage of aggregate particles having at least two fractured faces (70% for coarse aggregate). However, these aggregates also have low levels of angularity and relatively smooth texture. Interparticle friction, although not directly measured, is accepted to be lower for chert gravel than for quarried aggregate. In addition, chert gravel mixtures commonly have a higher VMA than do quarried aggregate mixtures, resulting in more binder required to compact mixtures to equivalent air void content.

Mixtures containing crushed limestone aggregate performed best in the APA test. In general, the crushed granite mixtures rutted more quickly than did the crushed limestone mixtures. The crushed granite mixtures, on average, had a higher design binder content than did the crushed limestone mixtures. The differences in design binder content or binder demand are likely to be influenced by factors such as aggregate shape, texture, and breakdown during compaction or mixture VMA.

Figure 3 shows the APA results for mixtures containing 10% natural sand. These mixtures rutted more quickly than did those containing no natural sand. Again, mixtures produced with crushed gravel rutted more quickly than did other mixtures. Similarly, mixtures produced with crushed limestone performed best by demonstrating the greatest resistance to rutting.

Some mixtures contained 30% natural sand, a higher percentage of natural sand than is allowed by FAA specifications (maximum of 15%). The mixtures were included in the analysis because they were expected to rut quickly and could provide guidance for performance threshold levels within the specifications. All mixtures containing 30% natural sand failed quickly (fewer than 1,500 cycles) in the APA.

In general, the mixture variable with greatest influence on APA test results was the percentage of natural sand. High percentages of natural sand caused premature failure in the APA. Additionally, aggregate type influenced the APA test results. Mixtures of chert

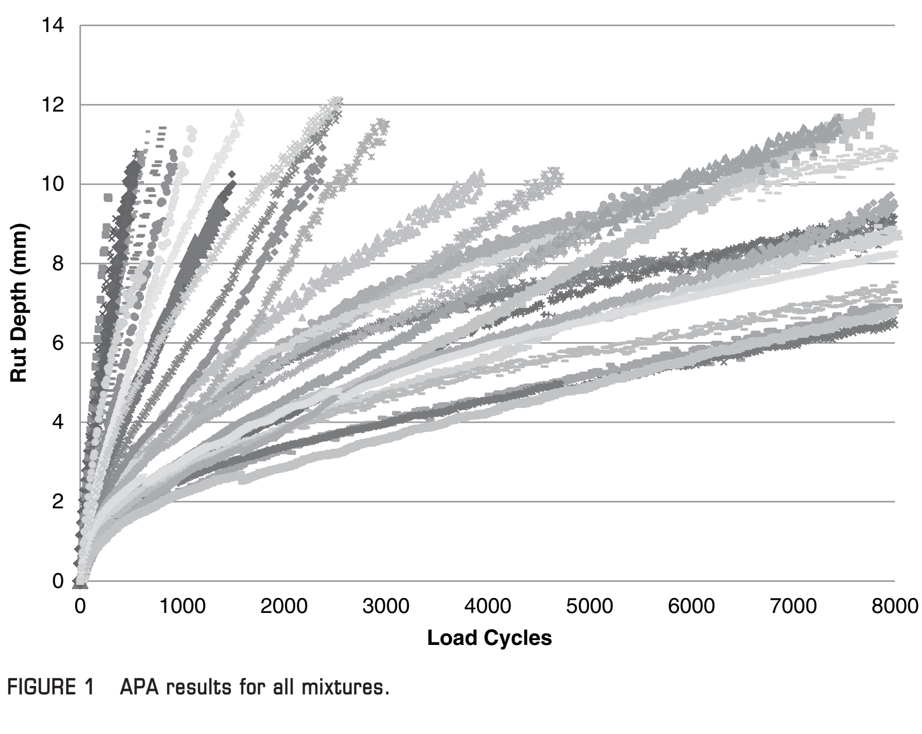

FIGURE 1 APA results for all mixtures.

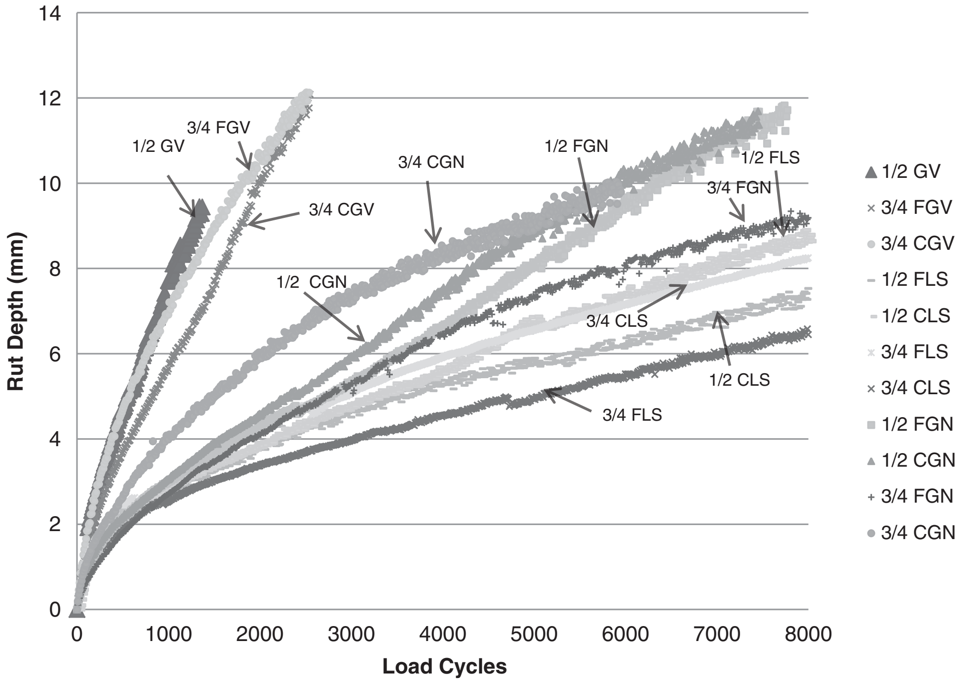

FIGURE 2 APA results for mixtures without natural sand.

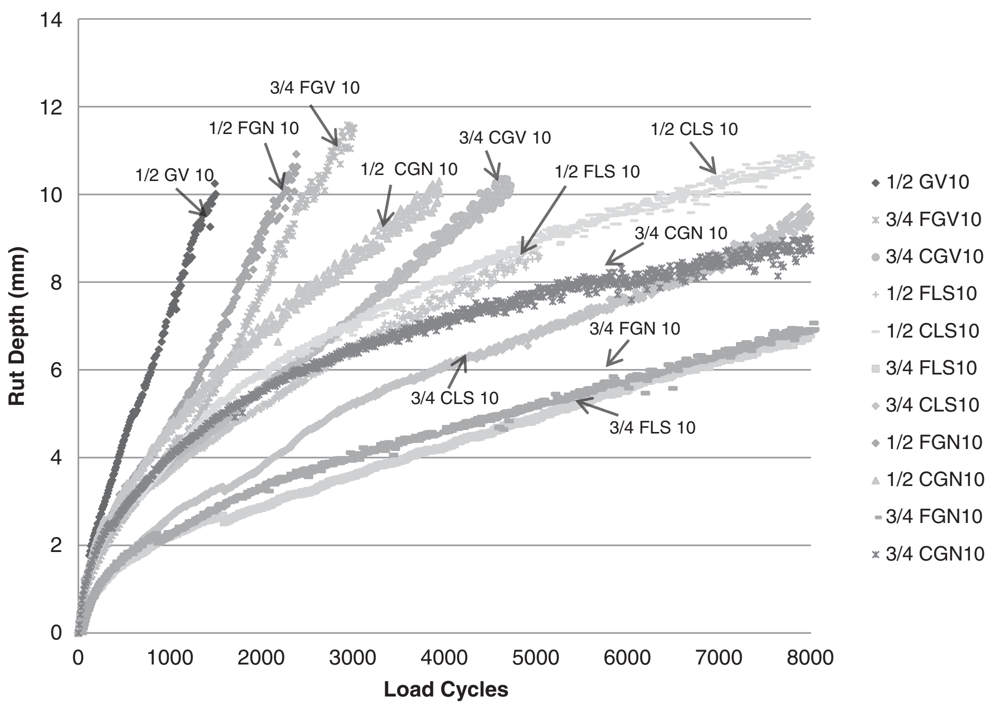

FIGURE 3 APA results for mixtures containing 10% natural sand.

gravel rutted more quickly than did mixtures with granite or limestone aggregate.

Statistical Considerations

Analyses were performed to evaluate the impact of mixture variables on rut depth accumulation considering statistical significance. All analyses were performed with SigmaStat software at a 95% confidence level. The analysis of variance (ANOVA) procedure, including the Tukey test for all paired comparison, was used to evaluate data sets. The number of load cycles to reach an average rut depth of 10 mm was used as a metric to quantify mixture behavior in these analyses. A rut depth of 10 mm was selected because it is near the maximum average rut depth reported in the APA samples.

The statistical analyses considered the following factors: (*a*) influence of aggregate type, that is, limestone, chert gravel, or granite; (*b*) influence of shape and textural factors (angularity, surface texture, and flat and elongated shape factors); and (*c*) impact of the presence and amount of field or natural sand (uncrushed). First, the influence of aggregate type on APA results was investigated. Granite, limestone, and chert gravel mixtures containing no natural sand require statistically different numbers of load cycles to reach 10 mm of rutting in the APA. The average number of load cycles required to reach 10 mm rutting for these respective mixtures was 6,530, 8,000, and 1,740. The value of 8,000 cycles is the terminal test value, and no data were extrapolated.

Further analyses on the influence of aggregate type on APA rutting were performed on the AIMS data. The indices of shape and angularity were investigated and considered to be the aggregate characteristics most closely related to rutting in HMA. Aggregate angularity was measured for three sizes of coarse aggregate and three sizes of fine aggregate for each aggregate type by AIMS. Coarse and fine aggregate were compared independently by ANOVA. Angularity was not found to be statistically different among the three size fractions within a specific aggregate type. The difference between the coarse aggregate fraction of limestone and chert gravel aggregates was not statistically significant. For each coarse size fraction, the granite aggregate was more angular than limestone. Granite was statistically more angular than chert gravel aggregate on ½-in. and No. 4 sieve sizes, but not the ⅜-in. sieve. Similarly, no statistically significant difference in angularity was detected between limestone and chert gravel fine aggregate. All size fractions of fine granite aggregate were statistically more angular than all size fractions of limestone or chert gravel aggregate.

Aggregate texture is measured only on coarse aggregate by AIMS. Statistical analyses of AIMS texture data indicate all sizes of chert gravel have a statistically lower texture index than does any size fraction of limestone or granite aggregate. For all equal size fractions, granite aggregate has a higher texture than limestone aggregate does.

In summary, the AIMS data rank the aggregates the same by both angularity and texture, with granite having the highest indices and chert gravel having the lowest indices, although the angularity of limestone and chert gravel are similar. Higher angularity and texture indices are expected to result in greater rutting resistance. On this basis, the degree of angularity and texture are consistent in regard to identifying chert gravel mixtures as the most rut susceptible, but inconsistent in predicting granite as the most rut-resistant mixtures. APA results indicate aggregate texture may be a better indicator of rutting resistance than is angularity. The lower resistance of the granite mixtures to APA rutting compared with limestone mixtures likely results from higher design binder contents. In fact, a Pearson product-moment correlation analysis considering the influence of aggregate angularity and texture, mixture binder content, and specimen air void content on APA rutting indicated that aggregate texture and binder content were the only statistically influential variables. Higher rut resistance resulted from increased aggregate texture and lower binder content.

The addition of neither 10% nor 30% natural sand to the mixtures affected the rank order of rutting sensitivity among the three aggregate types. For mixtures containing 10% natural sand, the mean number of load cycles resulting in 10 mm rut depth was 5,518, 7,033, and 2,850 for granite, limestone, and chert gravel mixtures, respectively. The trend of performance, according to the number of load cycles resulting in 10-mm rutting, was the same for mixtures containing no natural sand as for mixtures containing 10% natural sand. Limestone mixtures performed the best, whereas chert gravel mixtures performed the poorest. However, only limestone and chert gravel were statistically different from each other. For mixtures containing 30% natural sand, the numbers of load cycles to 10 mm rut depth were 490, 790, and 784, respectively. Each of these mixtures failed rapidly compared with mixtures with a higher percentage of crushed aggregate.

The effect of the percentage of natural sand contained in the mixtures on the number of load cycles to develop 10 mm of rutting was analyzed independently. The addition of 10% natural sand had no statistically significant impact on the number of load cycles to reach 10 mm rut depth for the granite aggregate. However, granite mixtures containing 30% natural sand were statistically different from mixtures containing either no natural sand or 10% natural sand. Similarly, statistical analyses of limestone mixtures revealed that mixtures containing no natural sand and 10% natural sand were not statistically different from each other, but both were different from mixtures containing 30% natural sand in regard to number of cycles to 10-mm rut depth. The addition of field sand had no statistically verifiable impact on load cycles to 10-mm rutting for chert gravel mixtures, regardless of the percentage of natural sand in the mix. The effect of neither maximum aggregate size nor relative gradation was statistically significant.

Selection of Interim Mixture Evaluation Criterion: Threshold Values

To establish interim mixture evaluation criteria for the APA, the number of load cycles to reach different rut depths was considered. Rut depths of 4 mm, 6 mm, 8 mm, and 10 mm were selected as possible failure thresholds. The number of load cycles required to reach these levels could be easily determined since the APA recorded the average rut depth after each load cycle. Figures 4 and 5 show the number of load cycles to achieve these threshold average rut depths. In some cases, mixtures did not reach an average rut depth of 8 or 10 mm before the test was terminated. A value of 8,000 cycles was denoted as the failure point for these mixtures, even though many more load cycles might have actually been required to obtain these rut depths.

The data were separated into two figures identified by the percentage of natural sand in the mixtures, allowing easier interpretation by reducing the total number of data points in one figure. Only data for mixtures containing no natural sand and 10% natural sand are presented. The mixtures containing 30% natural sand all failed rapidly in the APA. All but one of these mixtures reached 10-mm average rut depth before 1,000 cycles.

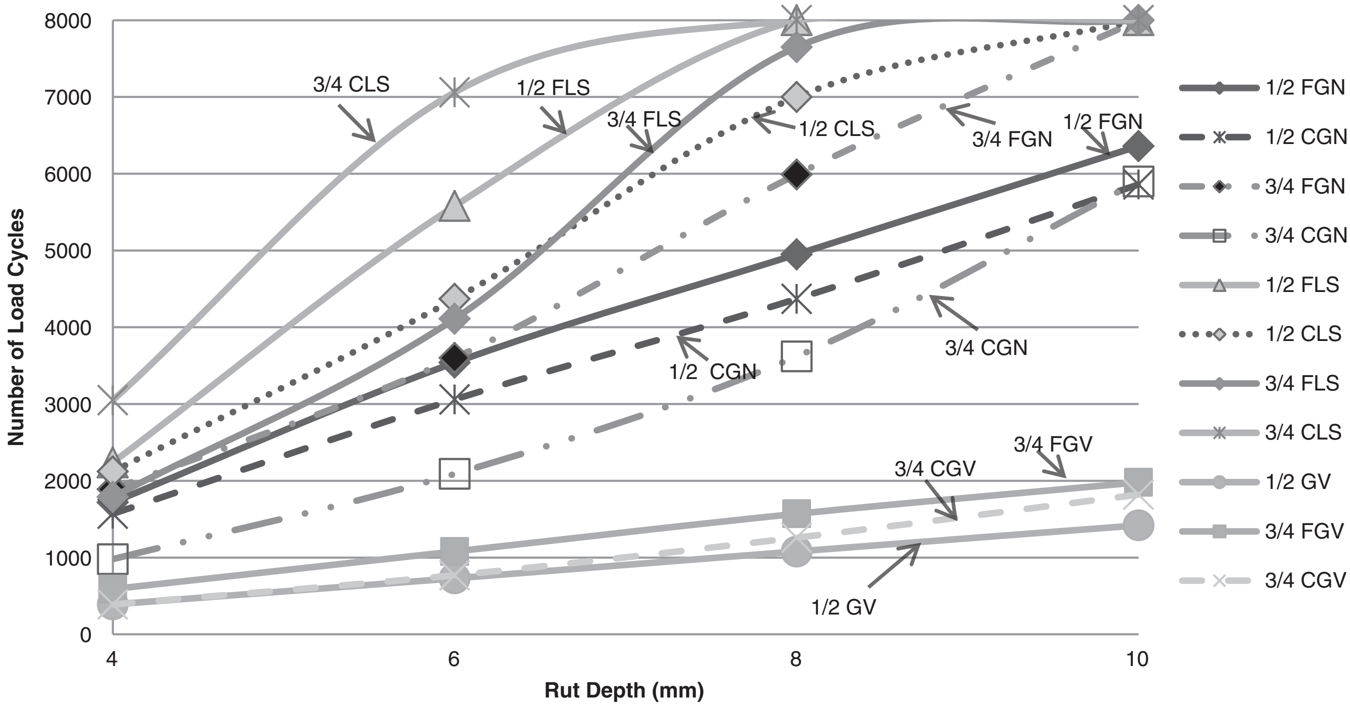

FIGURE 4 Number of load cycles versus target rut depths for mixtures without natural sand.

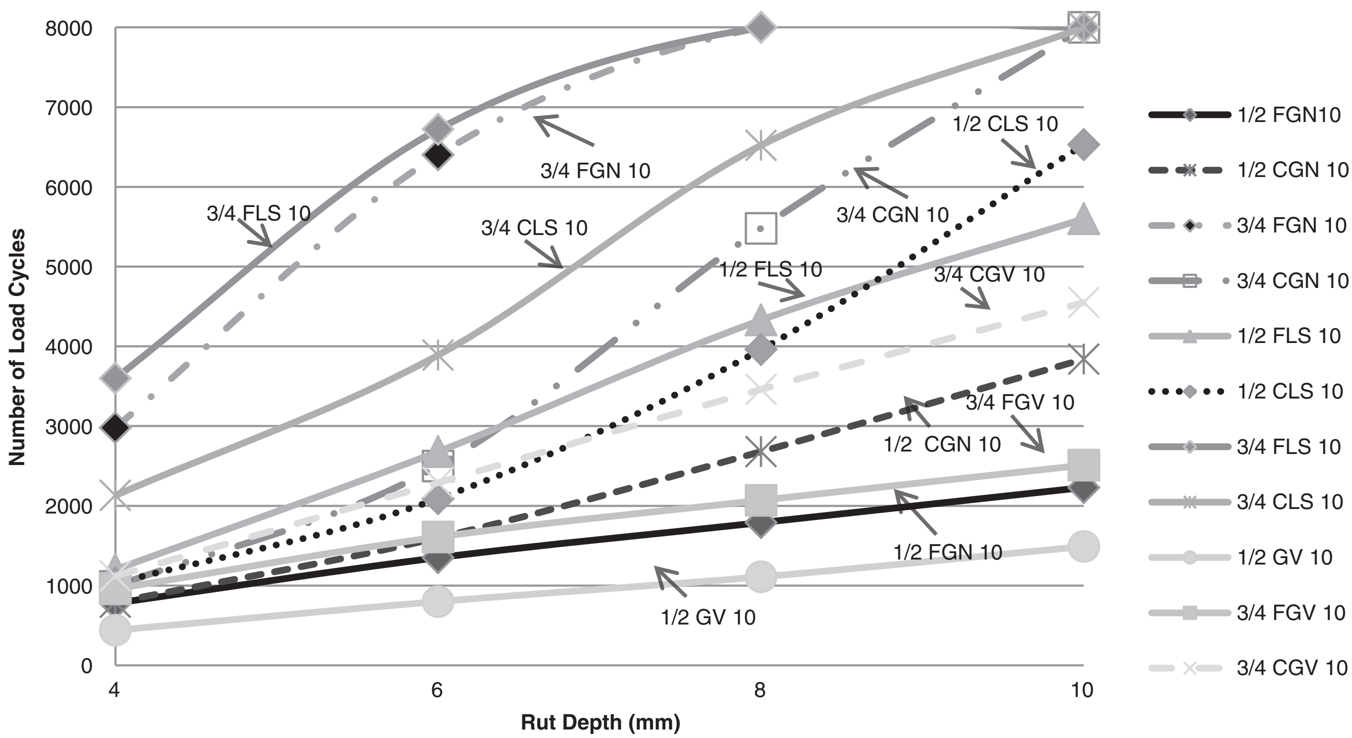

FIGURE 5 Number of load cycles versus target rut depths for mixtures with 10% natural sand.

The data in Figures 4 and 5 indicate a relatively linear rate of rut depth accumulation. Primary rutting (rapid accumulation) generally occurred until a rutting magnitude of about 4 mm. The tertiary phase of rutting was not reached before testing ended. Mixtures containing 30% natural sand rutted faster than mixtures containing either 10% or no field sand in all cases.

To provide perspective on these data, researchers compared these results with criteria for agencies that use the APA to accept HMA mixtures. These criteria were obtained from Williams et al. and are current as of 2005 (*3*). Other criteria, later than 2005, may exist but were not found in the literature search. Results from the APA test with a 250 psi hose pressure are expected to be significantly different from results used to develop criteria for highway pavements.

The majority of agencies require APA test specimens to be fabricated with a target air void content of 7%. Of the 21 states reported in the paper of Williams et al., only Alabama, Arkansas, and New Jersey test specimens at a different air void content, 4% air voids, which was the design air void content (*3*). Although higher air voids are more indicative of field-placed mixtures, much of the rutting at this air void content may be related to densification and not shear (*17*). Additionally, using the design air void content allows for performance testing of specimens produced from the mix design.

Several agencies vary the APA requirements based on the number of design equivalent single-axle loads. Others have a singular criterion or were listed as still evaluating the APA. Only five states included the APA in the specifications; others used the APA for comparative purposes. All agencies require the application of 8,000 load cycles during testing. The average maximum allowable rut depth specified is 5 mm. The lowest maximum rut depth is 3 mm (Arkansas and Delaware), while the highest maximum rut depth is 10 mm (Mississippi).

Comparison of results from this study with the agency criteria indicated that the high tire pressure APA is much more damaging than is the traditionally used APA. After application of 8,000 load cycles with 250 psi, no mixtures rutted less than 6 mm. Only four mixtures rutted less than 8 mm, while only nine mixtures rutted less than 10 mm. Aside from the mixtures containing 30% natural sand, all mixtures met or exceeded all FAA criteria for HMA mix design.

Since the APA is an empirical test that mimics loading, the most valid way to establish threshold values are through correlations with field studies. For example, the criterion recommended by the National Center for Asphalt Technology was less than 8.2 mm after 8,000 cycles at the location high-temperature PG grade (*18*). This criterion was developed through correlation of field data at the National Center for Asphalt Technology test track. The traffic used in the field test was 10,000,000 equivalent single-axle loads. These types of correlations indicate the large magnitude of damage each APA cycle induces compared with that of actual traffic. Ultimately, the rutting threshold established for the heavy wheel load (high tire pressure) APA must be correlated to field results. However, in the interim, it is important to establish a viable, realistic threshold acceptance on the rutting relationship between number of passes of the APA and rut depth. To do this, the following factors were considered: (*a*) number of applications of aircraft loading relative to highway truck loading, (*b*) tire pressure of airfield traffic relative to highway truck traffic, (*c*) greater wander of aircraft traffic compared with channelized highway traffic, and (*d*) established correlations of the type summarized in this discussion. Based on these factors, also considered were the results of the mixtures that were tested and the historical performance of these mixtures in airfield situations. The following paragraphs summarize the reasons for establishing the interim criterion.

Either 8 or 10 mm of rutting could be used as a criterion for maximum allowable APA rut depth when tested at 250 psi for airport pavements. The number of load cycles at which this level is reached has to be selected to correspond with mixture performance. The higher value will still produce a test that can be run in a reasonable timeframe (around 1 h) and has the ability to differentiate among mixtures.

To eliminate the mixtures containing 30% natural sand in this study, the criterion would need to be a maximum of 10-mm rut depth after 1,000 load cycles. However, this value is still inclusive of some mixtures. Although field performance is unknown, the mixtures containing chert gravel rutted significantly more quickly than did mixtures containing quarried aggregate. A criterion of less than 10-mm APA rut depth after 3,000 cycles would eliminate all but one of the chert gravel mixtures. This criterion would also eliminate one granite mixture containing 10% natural sand.

Based on the data from this study, a reasonable criterion for airport HMA designed for high tire pressure aircraft is less than 10-mm APA rut depth after 4,000 cycles when tested with 250 psi hose pressure. This criterion would eliminate 18 of the 33 mixtures in this study. However, 11 of the 18 mixtures that failed were not acceptable mixtures because they contained excessive natural sand. Of the other seven failed mixtures, five were chert gravel mixtures that may not be commonly used in airport HMA. Improvements of mixtures can be made by adjusting the gradation or binder content, and a key advantage of the APA is that the test can be performed in slightly more than 1 h and would be easily implemented for HMA mix design.

CONCLUSIONS

There is a pressing need for a performance test to accompany HMA mix design for airport pavements. Although the Marshall design method uses an empirical index test, a new design method using the Superpave gyratory compactor relies only on volumetric properties of the compacted mixture for acceptance. This study investigated the suitability of the APA as a test for characterizing HMA for airport pavements subjected to high tire pressure aircraft. From this study, the following conclusions are made:

- The most significant factor influencing APA rutting is excessive natural sand (30%). Mixtures containing excessive natural sand achieved 10-mm rut depth in fewer than 1,000 load cycles.
- Aggregate type influences APA test results as indicated by the ANOVA. Chert gravel mixtures rutted significantly more quickly than did mixtures containing granite or limestone aggregate. Mixtures containing limestone aggregate performed the best of those tested.
- Chert gravel aggregate had the lowest texture indices, according to AIMS testing. Aggregate texture is a better indicator than angularity of rutting resistance, according to the Pearson product-moment correlation analysis of APA test results.
- The APA test results were not significantly influenced by maximum aggregate size for the mixtures used in this study, according to the ANOVA.
- The APA test results were not significantly influenced by the relative gradation of the mixtures for those used in this study, according to the ANOVA.
- The APA test using a hose pressure of 250 psi rapidly damages HMA specimens. Most mixtures reached the terminal rut depth of 12 mm before 8,000 cycles were applied.

- None of the mixtures tested in this study had less than 6 mm rut depth after 8,000 cycles in the APA. The number of load cycles during the test will likely have to be reduced to produce criterion that will not eliminate a majority of mixtures.

RECOMMENDATIONS

Based on the results of this study, a preliminary criterion of less than 10 mm rut depth after 4,000 APA load cycles with 250 psi tire pressure is recommended for accepting HMA for high tire pressure aircraft during mix design. This recommendation is limited to the materials used in this study. Further testing should include more aggregate types representative of all regions of the United States. Additional binder types, specifically modified binders, should also be included in future studies. Further, mixtures with proven successful field performance should be evaluated with this criterion, along with mixtures that have been shown to rut easily. Further investigations should also determine the correlation of the APA test results with actual in-service pavements. Finally, the repeatability of the APA at high pressures should be investigated to develop tolerances for agency specifications.

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