Balanced Mix Design: Rutting Performance Tests

Phase I Interim Report

Appendix B

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Airport Asphalt Pavement Technology Program

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The Airport Asphalt Pavement Technology Program (AAPTP) is a cooperative agreement effort between the **National Asphalt Pavement Association** (NAPA) and the **Federal Aviation Administration** (FAA) to advance asphalt pavements and pavement materials. The AAPTP advances solutions for asphalt pavement design, construction, and materials deemed important to airfield reliability, efficiency, and safety. The program leverages NAPA's unique technology implementation capabilities with assistance from the FAA and industry to advance deployment and adoption of innovative asphalt material technologies.

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Credit: NAPA

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List of Acronyms and Abbreviations

AADTT	Average annual daily truck traffic
AAPTP	Airport Asphalt Pavement Technology Program
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ANC	Ted Stevens Anchorage International Airport
APA	Asphalt Pavement Analyzer
AV	Air voids
BMD	Balanced Mix Design
CC	Construction cycle
COV	Coefficient of variation
DOT	Department of Transportation
DTW	Detroit Metropolitan Wayne County Airport
EHEs	Equivalent highway ESALs
ERDC	U.S. Army Engineer Research and Development Center
ESAL	Equivalent single axle load
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FAARFIELD	FAA Rigid and Flexible Iterative Elastic Layered Design
FMFC	Field-mixed field-compacted
FMLC	Field-mixed laboratory-compacted
GA	General aviation
GAW	Gross aircraft weight
HMA	Hot mix asphalt
HT-IDT	High temperature indirect tensile
HVS	Heavy Vehicle Simulator
HVS-A	Heavy Vehicle Simulator, Airfields Mark VI
HWT	Hamburg wheel-track
IRT	Ideal rutting test
IDT	Indirect tensile
ILS	Interlaboratory study
JMF	Job mix formula
LMLC	Laboratory-mixed laboratory-compacted
LTPP	Long-Term Pavement Performance
MEHE	Million EHE
MESALs	Million ESALs
NAPA	National Asphalt Pavement Association
NAPTF	National Airport Pavement Test Facility
NAPMRC	National Airport Pavement and Materials Research Center
NBC	Marine Corps Air Station Beaufort

NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal maximum aggregate size
PANYNJ	Port Authority of New York and New Jersey
PG	Performance grade
PGH	High-temperature performance grade
PHL	Philadelphia International Airport
PMLC	Plant-mixed laboratory-compacted
PWL	Percent within limits
QA	Quality assurance
QC	Quality control
RAP	Reclaimed asphalt pavement
RT_{Index}	Rutting tolerance index
RTS	Reno Stead Airport
SFO	San Francisco International Airport
SMF	Sacramento International Airport
TPA	Tampa International Airport
TTI	Texas A&M Transportation Institute
TEB	Teterboro Airport
TC	Test cycle
VTRC	Virginia Transportation Research Council
UNR	University of Nevada, Reno
VMA	Voids in the mineral aggregate
WMA	Warm mix asphalt

Executive Summary

The Federal Aviation Administration (FAA) aims to address the rutting susceptibility of flexible pavements as part of its implementation of the Balanced Mix Design (BMD) method. The prospective BMD framework for flexible airfield pavements is expected to include rutting and cracking performance specifications at the mix design level as well as during production. This project, entitled “Balanced Mix Design: Rutting Performance Tests,” focused on the rutting tests and specifications.

The research plan to fulfill the BMD rutting project objective and deliverables comprised two main phases with a total of eight tasks. Phase I of the project consisted of reviewing and analyzing existing data to select test methods, establishing testing conditions, and developing preliminary airfield rutting criteria. The second phase was aimed at refining the preliminary rutting criteria and recommending revisions to current specifications to incorporate the findings from this study. This interim report summarizes the findings and the main approach to achieving the objectives of Phase I and developing the research plan for Phase II of the study.

Chapter 1. Introduction

Rutting, or permanent deformation, is one of the major distress types in asphalt concrete (AC) pavements, particularly under slow-moving or stacking heavy traffic coupled with high pavement temperatures. Rutting can be further exacerbated by high wheel loads and/or tire pressures, which are higher for airfield pavements than for highways. With the new larger and heavier generation of aircraft, aircraft manufacturers tend to increase tire pressure in order to increase payload or add more wheels to maintain the load limit on each wheel (Wang, Li, Garg, & Zhao, 2020; White, 2016; Rushing & Garg, 2017). The gross aircraft weight (GAW), along with the relative gear configuration, dictates the load distribution per wheel, which in most cases exceeds the wheel load of a highway truck. The pavement-tire interaction and resulting stress state depend primarily on the tire pressure. For large commercial aircraft, wheel loads commonly range from 14,000 to 77,000 lb, with tire pressures between 150 and 240 psi. In comparison, a truck trailer typically has a 4,500-lb wheel load and a tire pressure range of 85 to 110 psi (FAA, 2022; Song & Garg, 2010; Christensen, Bahia, & McQueen, 2008).

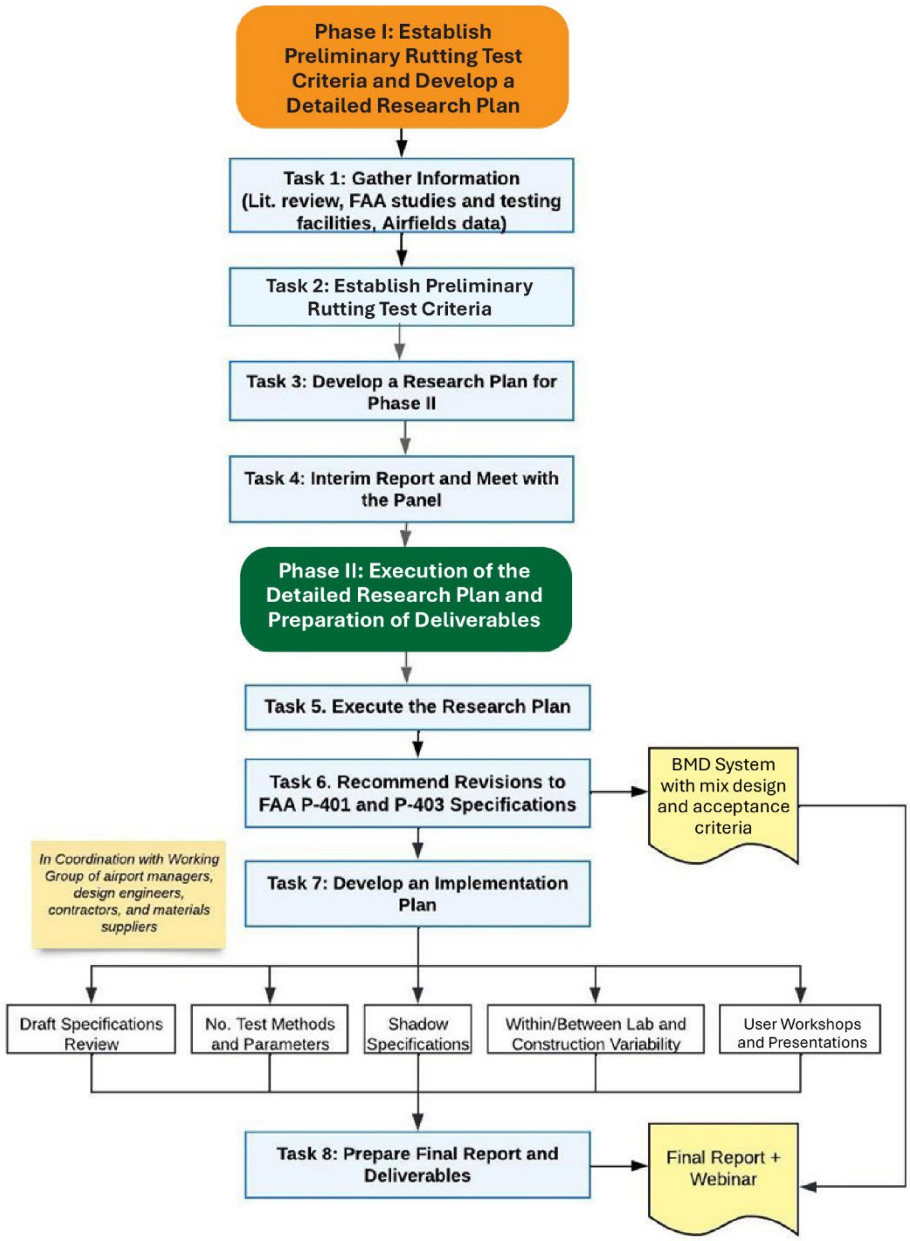
The Federal Aviation Administration (FAA) aims to address the rutting susceptibility of flexible pavements as part of its implementation of the Balanced Mix Design (BMD) method. The prospective BMD framework for flexible airfield pavements is expected to include rutting and cracking performance specifications at the mix design level as well as during production. This project, entitled "Balanced Mix Design: Rutting Performance Tests," focuses on the rutting tests and specifications, while the cracking specifications for asphalt mixtures are developed in parallel by a separate research team.

The research plan to fulfill the BMD rutting project objective and deliverables comprises two phases with a total of eight tasks (Figure 1). Phase I of the project consists of reviewing and analyzing existing data to select test methods, establishing testing conditions, and developing preliminary airfield rutting criteria. The second phase aims at refining the preliminary rutting criteria and recommending revisions to current specifications to incorporate the findings from this study.

The current FAA advisory circular 150/5370-10H, *Standard Specifications for Construction of Airports,* includes three types of asphalt mixtures: Items P-401, P-403, and P-404. The P-401 specifications are used for surface courses of airfield pavements subjected to aircraft loading with a GAW greater than 30,000 lb (13,600 kg). This asphalt mixture may also be used as a stabilized base layer.

The P-403 specifications are used for the surface layer of small maintenance and repair projects less than 3,000 tons (2,721 tonnes); for pavements subjected to GAW of 30,000 lb (13,600 kg) or less; for pavements intended to be used for roads, shoulder sections, or blast pads and for other pavements not subjected to full aircraft loading; and for courses other than surface course, including stabilized base course, asphalt binder courses, and/or truing and leveling courses (FAA, 2018).

The P-404 specifications are used for surface courses at locations that need a fuel-resistant asphalt mix pavement. On select projects, asphalt mixtures following State departments of transportation (DOTs) designs are accepted for use on FAA projects. These State DOT mixtures are allowed on non-primary airports with aircraft weighing less than 60,000 lb (27,216 kg).



Source: University of Nevada, Reno

Figure 1. Flowchart of BMD Rutting Project Tasks

A main difference between the P-401 and P-403 specifications is the use of reclaimed asphalt pavement (RAP). While it is not allowed in P-401, RAP is allowed on the shoulder surface course mixes and in any intermediate or lower courses (up to 30 percent RAP). Moreover, the acceptance of each lot of plant-produced material from Item P-401 is defined based on the percentage of material within specification limits (PWL). Straight acceptance limits are used for Item P-403. It should be noted that materials meeting P-401 specifications will also meet P-403 specifications, while the reverse is not true (FAA, 2018).

According to FAA specifications, asphalt mixtures are designed based on the Asphalt Institute's *MS-2 Asphalt Mix Design Methods,* 7th edition, in which samples are prepared and compacted with the Marshall compactor (FAA, 2018; Asphalt Institute, 2014). The specifications also include job mix formula (JMF) options for the Superpave Gyratory mix design method, based on the prevalent mix design method used in the local project area.

The FAA has done a significant amount of rigorous research on rutting of airfield pavements and rutting test methods to address increases in traffic volumes, aircraft weights, and tire pressures. This has led to integration of the Asphalt Pavement Analyzer (APA) and Hamburg wheel-track (HWT) rutting tests with design criteria in the current P-401 and P-403 specifications (Rushing & Garg, 2017; Song & Garg, 2010; FAA, 2018; Rushing, Little, & Garg, 2012; Rushing, Little, & Garg, 2014; AASHTO, 2020; AASHTO, 2022d).

Table 1 summarizes the current rutting test criteria for Items P-401 and P-403 for pavements serving aircraft 60,000 lb or more (FAA, 2018). Criteria are provided for the APA test results per the American Association of State Highway and Transportation Officials (AASHTO) T 340 at 64 °C under 250 psi, as well as under 100 psi hose pressure. Where APA is not available, test criterion is provided for the HWT test per AASHTO T 324 at 50 °C.

To make the BMD implementation as efficient as possible, key factors considered in this project when evaluating test methods and criteria for mix design, control strip, and quality assurance (QA) included the following:

- Specimen geometry.
- Specimen target air voids (AV) level.
- Sample preparation (cutting, gluing, etc.).
- Conditioning/aging temperature and time.
- Test temperature.
- Test loading conditions.

The recommendations for rutting test specifications aim to improve or address the current limitations in terms of the following:

- Testing asphalt mixtures at a single test temperature regardless of the geographical location of the project (i.e., climatic conditions) or the location of the asphalt mixture within the pavement structure.

- Using a single rutting test criterion regardless of the aircraft traffic mix and volume.
- Allowing agencies to send their compacted mix design samples to be tested at mix-design AV rather than 7±0.5 percent if APA was not available in the area. Previous airfield research studies that led to current FAA rutting test criteria conducted the APA at mix-design AV (Rushing & Garg, 2017; Rushing et al., 2012; AASHTO, 2020). On the other hand, current standard test methods mentioned in the FAA advisory circular (i.e., AASHTO T 340 and AASHTO T 324) require preparing the samples at 7±0.5 percent AV (AASHTO, 2020; AASHTO, 2022d).

Table 1. Current FAA Advisory Circular 150/5370-10H Rutting Specifications for Airports Serving Aircraft Weighing 60,000 lb or More (FAA, 2018; AASHTO, 2020; AASHTO, 2022d)

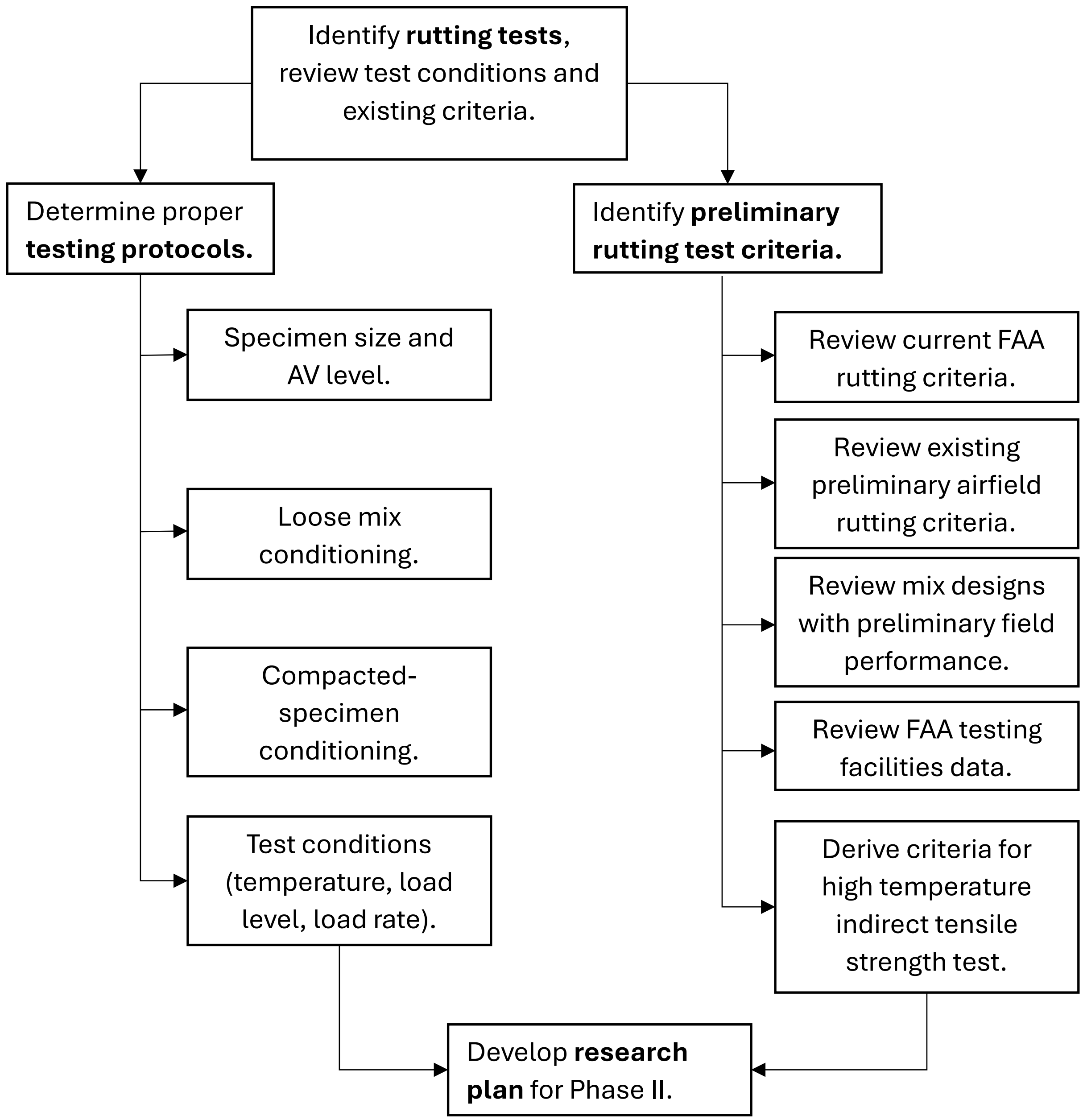
Rutting Test	AV	Test Criteria (P-401 or P-403)
APA at 250 psi Hose Pressure and 64 °C Test Temperature, AASHTO T 340	7±0.5%	Rut depth ≤10 mm at 4,000 passes
APA at 100 psi Hose Pressure and 64 °C Test Temperature (may be used in the interim), AASHTO T 340	7±0.5%	Rut depth ≤5 mm at 8,000 passes
HWT at 50 °C (where APA is not available), AASHTO T 324	7±0.5%	Rut depth ≤10 mm at 20,000 passes

Chapter 2. Phase I Scope of Work

The Phase I tasks, with corresponding inputs and outputs illustrating the relationship and dependence of information from each, are shown in Table 2. This interim report summarizes the findings from Task 1 through Task 3. The flowchart in Figure 2 summarizes the main approach followed to achieve the objectives of Phase I and develop the research plan for Phase II.

Table 2. Phase I Task Breakdown Summarizing Associated Inputs and Outputs by Task

Task	Inputs	Outputs
Task 1 Gather Information	1. Airfield and highway data literature review. 2. FAA studies on airfield pavement performance and laboratory rutting tests review. 3. Asphalt mixtures performance review.	1. Available rutting test methods and specifications or laboratory criteria. 2. Handling, conditioning, aging, and testing protocols. 3. Validation of rutting tests. 4. Correlation between rutting tests. 5. Rutting performance of FAA mixtures.
Task 2 Verify and Establish Preliminary Test Criteria	1. Task 1 inputs and outputs. 2. Candidate rutting tests. 3. Candidate airfield pavement identification. 4. Field performance data review.	1. Selection, planning, and sampling of materials from airfield projects. 2. Collection of mix designs and QA data. 3. Proposed preliminary test criteria.
Task 3 Develop Phase II Research Plan	1. Task 1–2 inputs and outputs. 2. Project team research approach refinements identified. 3. Proposed rutting test methods. 4. Proposed handling, conditioning, aging, and testing protocols. 5. Proposed asphalt mixtures for laboratory evaluation.	1. Updated Phase II research plan based on Tasks 1–2 findings, with activities to execute experimental design detailed. 2. Proposed laboratory testing details and data analysis. 3. Updated schedule for delivering final deliverables.
Task 4 Prepare Interim Report	1. Tasks 1–3 inputs and outputs. 2. Regular team meetings. 3. Project reporting and meeting requirements.	1. Interim report documenting Phase I Tasks 1–3 for Project Panel review and consideration. 2. Project Panel meeting.



Note: Bold items refer to different sections in this report.

Source: University of Nevada, Reno

Figure 2. Phase I Overall Scope of Work

Chapter 3. Rutting Tests

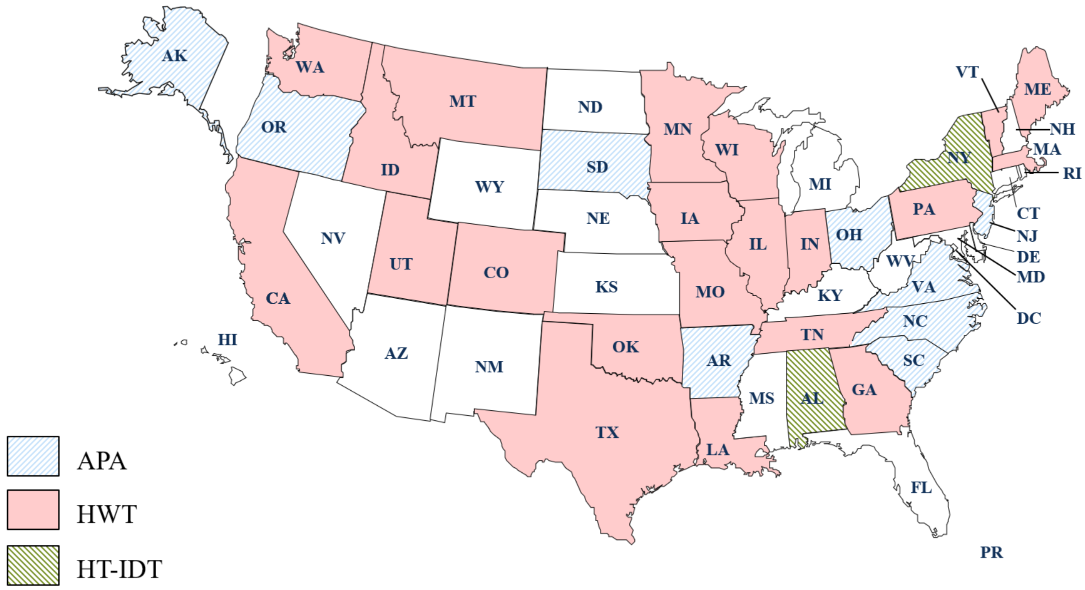
Table 3 presents the four main rutting mechanical tests under two different modes of testing (i.e., monotonic and repeated loading) identified by the research team to be candidates for mix design and/or QA during production of airfield AC pavements. Factors like efficiency, practicality, common availability and affordable cost, repeatability, sensitivity to mixture components, simulation of rutting mechanism, and correlation with field performance and other rutting mechanical tests were considered (Rushing et al., 2014; Zhou, Crockford, Zhang, Epps, & Sun, 2019; Christensen & Bonaquist, 2007; West, Rodezno, Leiva, & Yin, 2018; Hajj, Hand, Chkaiban, & Aschenbrener, 2019; Hajj, Aschenbrener, & Nener-Plante, 2022).

Table 3. Candidate Rutting Mechanical Tests

Test	Standard Test Method	Mode of Testing	Outcome
APA	AASHTO T 340-10 (AASHTO, 2020)	Repeated loading	Rut depth
HWT	AASHTO T 324-22 (AASHTO, 2022d)	Repeated loading	Rut depth, number of passes to failure, rutting resistance index, corrected rut depth
HT-IDT	ASTM D6931-17 (ASTM, 2017b) ALDOT-458 (Alabama DOT, 2022)	Monotonic	IDT strength
IRT	ASTM D8360-22 (ASTM, 2022)	Monotonic	RT_{Index}

IDT = indirect tensile; HT-IDT = high temperature indirect tensile test; IRT = ideal rutting test; RT_{Index} = rutting tolerance index.

Current implementation of rutting mechanical tests varies among the State DOTs (Figure 3) (Yin, 2020; NAPA, n.d.; AASHTO, 2021). As of October 2022, the HWT and APA tests have been implemented by 22 and 9 States, respectively. Two States use the high temperature indirect tensile (HT-IDT) strength test, while several other States are currently investigating its use as part of BMD (e.g., Maine DOT, New York State DOT) (ASTM, 2017b; Alabama DOT, 2022; ASTM, 2022). Moreover, the ideal rutting test (IRT) that was recently published as a standard test method (ASTM D8360-22) has not been implemented but is currently being considered along with other rutting mechanical tests by several State DOTs (ASTM, 2022).



Alabama DOT implemented both HWT and HT-IDT.

Source: National Asphalt Pavement Association

Figure 3. Rutting Tests Implemented as Current State of Practice

Asphalt Pavement Analyzer (APA)

The APA, first manufactured in 1996, operates by running a loaded wheel in a forward and backward linear motion on a pressured linear tube centered on top of the sample. Accordingly, the rutting or permanent deformation of cylindrical or beam specimens can be quantified. Several studies, including those by State DOTs, identified a good correlation between the APA laboratory data and field rutting (Jackson & Baldwin, 2000; Brown, et al., 2002; Buchanan, White, & Smith, 2004; Choubane, Page, & Musselman, 2000; Kandhal & Cooley, 2003). Nonetheless, laboratory-measured APA rut depths may not necessarily translate to the same field rut depth value. For example, WesTrack data showed that a laboratory test rut depth of 6 mm after 8,000 cycles corresponds to a field rut depth of 12.5 mm after 4.5 million equivalent single axle loads (MESALs) (Rushing et al., 2012). In addition to those by State DOTs, several additional research studies have employed the APA to evaluate the susceptibility of airfield asphalt mixtures to rutting, as per the test conditions in Table 4 and findings in Table 5 (Rushing & Garg, 2017; Rushing et al., 2014; Shang, Takahashi, & Maekawa, 2013; Rushing, McCaffrey, & Warnock, 2014; Varamini, Corun, Bennert, Esenwa, & Kucharek, 2018; Garg, Kazmee, & Ricalde, 2021; Batioja-Alvarez & Garg, 2021). These research studies were used to establish the current rutting test criteria implemented in the FAA advisory circular (Rushing & Garg, 2017; FAA, 2018; Rushing et al., 2012; Rushing et al., 2014).

Table 4. Summary of Previous Airfield Research Studies with APA Test

Reference	Compacted Mixture Conditioning	Test Temperature, °C	Hose Pressure, psi	Wheel Load, lb	Sample Type	AV%	Criterion
Rushing, et al. (2012); (2014)	–	64 (PGH of neat binder)	250	250	LMLC	3.5	≤10 mm at 4,000 cycles
Shang, et al. (2013)	6 hr at test temperature	60	100	100	–	–	–
Rushing, McCaffrey, & Warnock (2014)	–	PGH (64 or 70)	250	250	FMLC	2.3–5.6	≤10 mm at 4,000 cycles
Rushing & Garg (2017)	24 hr at test temperature	58 or 64	250	250	LMLC	3.5	≤10 mm at 4,000 cycles
Varamini et al., (2018)	6 hr at test temperature	64	100	100	LMLC	5.0	≤5 mm at 8,000 cycles
Garg et al. (2021); Batioja-Alvarez & Garg (2021)	6–24 hr at test temperature	64	250	250	LMLC, FMLC, FMFC	In situ (FMFC) and 5.0 (LMLC, FMLC)	≤10 mm at 4,000 cycles

PGH = high-temperature performance grade; FMFC = field-mixed field-compacted; FMLC = field-mixed laboratory-compacted; LMLC = laboratory-mixed laboratory-compacted.
– = Not available.

Table 5. Findings from Previous Airfield Studies with APA Test

Reference	Overall Findings
Rushing et al. (2012)	• Set criterion excluded 18 of the 33 tested asphalt mixtures. Of the 18 failing samples, 11 were not acceptable due to excessive natural sand, and 5 out of the remaining 7 failing samples included chert gravel aggregates, which are not commonly used in airport pavements. • Similar general pattern of rutting progression between the APA and creep repeated loading tests with primary and secondary flow.
Shang et al. (2013)	• Japanese airfield mixtures with 70–90% of loose unit weight of coarse aggregate had low rut depth. Both the coarsest and the finest blends had higher rut depths. • The percent of loose unit weight of coarse aggregate had more influence than the Bailey method ratios on the rutting resistance of asphalt mixtures.

Reference	Overall Findings
Rushing et al. (2014)	• Modified binder enhanced the APA performance for all asphalt mixtures. • The best performers were asphalt mixtures containing limestone aggregate. The poorest performers were those having chert gravel aggregate. • Increasing the optimum binder content by 0.4% still passed the set criteria, however the mixture failed with an additional 0.9% binder content. • Criterion validated with two field trials: one with excessive and one with moderate load/climatic conditions.
Rushing, McCaffrey, & Warnock (2014)	• 5.9 mm and 7.2 mm rut depths for two asphalt mixtures after 4,000 cycles APA at 250 psi corresponded to 3.5 mm rutting after 4,000 cycles at 100 lb load and 100 psi hose pressure.
Rushing & Garg (2017)	• Good correlation between the rut depth at 100 psi hose pressure after 8,000 cycles and the rut depth at 250 psi after 4,000 cycles.
Varamini et al. (2018)	• Fuel-resistant mix showed better rutting resistance than P-401 mix.
Garg et al. (2021); Batioja-Alvarez & Garg (2021)	• WMA mixture with hybrid foam additive exhibited the highest APA rut depth among all sections consistently with field-measured rutting. • APA rut depth of the FMLC samples at 4,000 and 8,000 cycles correlated well with the HVS number of passes. • APA was found to be sensitive to AV using FMFC samples.

WMA = warm mix asphalt; HVS = Heavy Vehicle Simulator; FMLC = field-mixed laboratory-compacted; FMFC = field-mixed field-compacted.

Laboratory mechanical tests with high variability involve fabricating and testing more samples, along with an ambiguous delineation between poor- and good-performing mixtures (Zhou et al., 2019). Therefore, the repeatability of a test needs to be verified, especially when the test is to be employed for QA purposes. Table 6 summarizes the repeatability of the APA test rut depth reported in literature in terms of the coefficient of variation (COV) (NAPA, n.d.; Taylor, Moore, & Moore, 2022; Hajj & Aschenbrener, 2021; Sebaaly, Schlierkamp, Diaz, Hajj, & Souliman, 2015; Sebaaly & Bazi, 2004; Boz, et al., 2023). The tabulated COVs are based either on testing two- or three-wheel replicates, where each replicate is composed of two cylindrical specimens. The within-laboratory COV reported in some studies ranged between 2 and 38 percent, compared to a maximum between-laboratory COV of 29.6 percent. Notably, the reported COV values were similar for the different AV levels: 3, 5, and 7 percent (Sebaaly et al., 2015; Sebaaly & Bazi, 2004).

Table 6. Review of Repeatability Test Results for APA Rut Depth

Reference	Within-Laboratory COV, %	Between-Laboratory COV, %	Number of Replicates[1]
National Asphalt Pavement Association (NAPA) BMD Guide (7% AV, 64 °C) (NAPA, n.d.)	20	–	3
National Center for Asphalt Technology (NCAT) Report 22-01 (7% AV, 64 °C) (Taylor et al., 2022)	18.3	29.6	2 or 3
New Jersey DOT (7% AV, 64 °C) (Hajj & Aschenbrener, 2021)	10	20	3
Nevada DOT (60 °C) (Sebaaly et al., 2015; Sebaaly & Bazi, 2004) • 3% AV • 7% AV • 11% AV	 2.2–27.9 3.2–27.5 2.5–26.4	 – – –	 2 2 2
Virginia Transportation Research Council (VTRC) Study (7% AV, 64 °C) (Boz et al., 2023)	3.5–38	–	2

[1]Each replicate is composed of two cylindrical specimens loaded under one APA wheel.
– = Not available.

A suitable laboratory mechanical test has to be sensitive to the main asphalt mixture components and volumetric properties. Table 7 summarizes the findings from past studies on the impact of single-factor variation on the APA rut depth of asphalt mixtures with polymer-modified and unmodified asphalt binders (Sebaaly et al., 2015; Sebaaly & Bazi, 2004). Based on the data in Table 7, the following observations can be made:

- For the same aggregate source and gradation, the APA rut depth was sensitive to the asphalt binder type (i.e., polymer modification).
- The APA rut depths were least sensitive to the single variation in either percent passing No. 4 sieve or percent passing No. 200 sieve.
- In general, the APA rut depth increased with the increase in asphalt binder content. Nonetheless, for some asphalt mixtures this was only true when asphalt binder contents differed by 1.1 percent (i.e., JMF minus 0.55 percent versus JMF plus 0.55 percent).
- The APA rut depth increased with the increase in AV level.

Table 7. Sensitivity of APA Rut Depth at 60 °C to Asphalt Mixture Characteristics (Sebaaly et al., 2015; Sebaaly & Bazi, 2004)

Factor	Northern Nevada Mixtures (Same Aggregate Source and Gradation)		Southern Nevada Mixtures (Same Aggregate Source and Gradation)	
Asphalt Binder Type	PG 64-28 Polymer Modified	PG 64-22	PG 76-22 Polymer Modified	PG 70-16
Impact of Asphalt Binder Type (polymer modified versus unmodified)	↓		↓	
Lower Percent Passing No. 4 Sieve (JMF minus two times standard deviation)	↔	↔	↔	↔
Higher Percent Passing No. 4 Sieve (JMF plus two times standard deviation)	↔	↔	↓	↓
Lower Percent Passing No. 200 Sieve (JMF minus two times standard deviation)	–	–	–	–
Higher Percent Passing No. 200 Sieve (JMF plus two times standard deviation)	↔	↑	↔	↔
Lower Asphalt Binder Content (JMF minus 0.55%)	↔	↔	↓	↓
Higher Asphalt Binder Content (JMF value plus 0.55%)	↔	↑	↑	↑
Lower AV (3% versus 7%)	–	↓	–	↓
Higher AV (11% versus 7%)	↑	↑	↑	↑

PG = performance grade.
↔ = No statistically significant effect on the mixture rut depth at a 5% significance level.
↓ = Statistically significant reduction in the mixture rut depth at a 5% significance level.
↑ = Statistically significant increase in the mixture rut depth at a 5% significance level.
– = Not available.

Hamburg Wheel-Track (HWT)

The HWT test typically performed per AASHTO T 324 is widely adopted to assess the rutting susceptibility of asphalt mixtures as part of mix design specifications. Two sets of cylindrical laboratory compacted specimens or field cores are submerged in water at the test high temperature on two sides of the testing equipment and subjected to repetitive passes of steel wheels. The steel wheel with a 158-lb load runs at 52 passes per minute to generate a rutting curve (AASHTO, 2022d). The resulting rutting curve generally consists of three phases: post-compaction phase, creep phase, and stripping phase (Yin, Chen, West, Martin, & Arambula-Mercado, 2020). Airfield mixtures have been evaluated for rutting potential using the HWT test, as summarized in Table 8 and Table 9 (Batioja-Alvarez & Garg, 2021; Garg, Kazmee, Ricalde, & Parsons, 2018; Ling, et al., 2020).

Table 8. Summary of Previous Airfield Research Studies with HWT

Reference	Compacted Mixture Conditioning	Test Temperature, °C	Sample Type	AV%	Criterion
Garg et al. (2018)	45 min in water bath.	–	FMFC	–	12.5 mm after 20,000 cycles
Ling et al. (2020)	45 min in water bath.	40, 50	FMFC	7	–
Batioja-Alvarez & Garg (2021)	45 min in water bath.	50	FMLC FMFC	5 (FMLC) in situ (FMFC)	10 mm after 20,000 passes

– = Not available.

Table 9. Findings from Previous Airfield Studies with HWT

Reference	Overall Findings
Garg et al. (2018)	• The WMA field cores with PG 64-22 showed the highest HWT rut depth followed by HMA cores with similar binder grade. The results were consistent with the accelerated pavement testing results. • Asphalt mixtures with PG 76-22 polymer modified asphalt binder accumulated minor rutting in the HWT relative to mixtures with PG 64-22 unmodified asphalt binder. The results were consistent with the laser profile data of the mixtures from the HVS test sections.
Ling et al. (2020)	• HWT rut depth significantly increased between 40 °C and 50 °C test temperatures. • HWT showed improved rutting resistance of stone matrix asphalt samples compared to conventional asphalt mixtures.
Batioja-Alvarez & Garg (2021)	• There was consistency between HWT rut depth and APA results for laboratory-prepared samples. • The variability in the evaluated field cores increased the magnitude and variability in the HWT rut depths.

Table 10 summarizes some of the repeatability reported in the literature for the HWT test rut depth (NAPA, n.d.; Taylor et al., 2022; Mateos & Jones, 2017; Yin, Taylor, & Tran, 2020; Azari, 2014; Hajj, Aschenbrener, & Nener-Plante, 2021). The highest within-laboratory COV was observed in the California DOT round-robin study (Mateos & Jones, 2017). COVs of 18 percent and 35 percent were reported for rut depths up to 3 and 6 mm, respectively. On the other hand, the between-laboratory COV, shown in Table 10, ranged between 23 percent and 37 percent for rut depths up to 3 and 6 mm, respectively.

Table 10. Review of Repeatability Test Results for the HWT Test Rut Depth at 20,000 Cycles

Reference	Within-Laboratory COV, %	Between-Laboratory COV, %	Number of Replicates[a]
California DOT[b] (7% AV, 45–55 °C) (Mateos & Jones, 2017)	18 and 35	23 and 37	2
Louisiana Department of Transportation & Development (design AV, 50 °C) (Hajj et al., 2021)	<20	–	2
NAPA BMD Guide (7% AV, 40–70 °C) (NAPA, n.d.)	10–30	–	2
NCAT Report 22-01 (7% AV, 50 °C) (Taylor et al., 2022)	9.4	25.9	2
NCAT Report 20-02 (7% AV, 50 °C) (Yin et al., 2020)	0.2–51.7	–	2
NCHRP Project 10-87 (7% AV, 50 °C) (Azari, 2014)	14.2	26.0	2
Texas DOT (7% AV, 50 °C) (Hajj et al., 2021)	30	–	–

[a]Each replicate was composed of two cylindrical specimens loaded under one HWT wheel.
[b]COV for rut depth up to 3 and 6 mm, respectively.
NCHRP = National Cooperative Highway Research Program.
– = Not available.

The sensitivity of the HWT test to different mixture factors is summarized in Table 11. A higher binder grade, the addition of hydrated lime, and lower asphalt binder content resulted in statistically lower HWT test rut depths at a 5 percent significance level (p=0.05). However, the sensitivity of the HWT rut depth to AV level was not statistically verified (Yildirim, et al., 2007; Walubita, et al., 2014; Kassem, Bayomy, Jung, Alkuime, & Tousif, 2019).

Table 11. Sensitivity of HWT Test Rut Depth to Asphalt Mixture Characteristics (Yildirim, et al., 2007; Walubita, et al., 2014; Kassem et al., 2019)

Factor	Impact on HWT Rut Depth After 20,000 Cycles
Higher Asphalt Binder Grade	↓
Addition of Hydrated Lime	↓
Different Aggregate Gradation	↔
Different Aggregate Minerology	↔
Higher AV	↑ (Not verified with statistical analysis.)
High Asphalt Binder Content: • 5.75% vs 4.25% and 5.75% vs 5.0% • 5.0% vs 4.25%	 ↑ ↔

↔ = No statistically significant effect on the mixture rut depth at a 5% significance level.
↓ = Statistically significant reduction in the mixture rut depth at a 5% significance level.
↑ = Statistically significant increase in the mixture rut depth at a 5% significance level.

High Temperature Indirect Tensile (HT-IDT) Strength

Although the HT-IDT strength test has not been widely implemented by many State DOTs, there has been a growing interest in adopting this simple, low-investment test using commonly available and existing equipment. The indirect tensile (IDT) strength test has been used to simultaneously evaluate fatigue and rutting resistance of asphalt mixtures at intermediate and high temperature, respectively, using the same equipment and basic procedure (Advanced Asphalt Technologies, 2011; Bennert, Haas, & Wass, 2018). In 2000, a promising relationship was documented between asphalt mixture rutting resistance and HT-IDT test data. This was further validated by Zaniewski and Srinivasan (2004). The HT-IDT test was recommended, in NCHRP Report 673, at a critical representative pavement temperature in order to assess the rutting resistance of asphalt mixtures (Advanced Asphalt Technologies, 2011). Preliminary test criteria were provided based on the correlation of the test with FHWA's Accelerated Loading Facility and were further validated in 2007.

In 2018, the HT-IDT strength test was correlated to APA test data and examined by Bennert et al. (2018) as a surrogate test to evaluate the rutting potential of asphalt mixtures within performance-related specifications for the New Jersey DOT. Moreover, the HT-IDT was identified as one of the two main rutting tests for BMD performance evaluation and QA testing within the BMD/QA framework developed in 2021 by Zhou et al. (2021). As per Zhou et al. (2021), the HT-IDT quantifies the cohesion component of the shear strength without the friction angle, which is a main component of the mixture shear strength. Accordingly, the HT-IDT was identified as a simple and practical mechanical test to evaluate the rutting resistance of asphalt mixtures using the IDT equipment of AASHTO T 283, which is typically available at relevant laboratories (AASHTO, 2022c). In a 2023 study, the HT-IDT was evaluated as one of three rutting monotonic tests for further implementation by the Virginia DOT in its BMD and acceptance specifications. The HT-IDT was subsequently identified by Boz et al. (2023) as the most suitable surrogate test for APA to screen rutting potential of asphalt mixtures .

Field-mixed field-compacted (FMFC) and field-mixed laboratory-compacted (FMLC) samples of hot mix asphalt (HMA) and warm mix asphalt (WMA) from FAA's accelerated pavement testing facility were evaluated with HT-IDT, as shown in Table 12 and Table 13 (Garg et al., 2021; Batioja-Alvarez & Garg, 2021; Garg et al., 2018). In general, it was observed that the HT-IDT is sensitive to asphalt mixture type (i.e., HMA versus WMA) and AV level.

Table 14 summarizes some of the repeatability reported in the literature for the HT-IDT strength test. A maximum COV of 15.1 percent was observed (NAPA, n.d.; Hajj & Aschenbrener, 2021; Boz et al., 2023; Bennert et al., 2018). Bennert et al. (2018) showed the HT-IDT test method to be sensitive to asphalt mixture volumetrics, composition, binder grade, and aging.

Table 12. Summary of Previous Airfield Studies with HT-IDT Test

Reference	Compacted Mixture Conditioning	Test Temperature	Sample Type	AV%	Criterion
Garg et al. (2018)	–	40 °C	FMLC FMFC	3.5% (FMLC) in situ (FMFC)	–
Garg et al. (2021); Batioja-Alvarez & Garg (2021)	30 min in 40 °C water bath	40 °C	FMLC FMFC	5% (FMLC) in situ (FMFC)	≥60 psi

– = Not available.

Table 13. Findings from Previous Airfield Studies with HT-IDT Test

Reference	Overall Findings
Garg et al. (2018)	• The WMA field cores of Lane 2 with PG 64-22 exhibited the minimum HT-IDT strength, followed by the HMA cores of Lane 4 with same binder grade. The results were consistent with accelerated pavement testing and HWT test results. • HT-IDT strength was sensitive to AV as demonstrated with FMFC samples.
Garg et al. (2021); Batioja-Alvarez & Garg (2021)	• Higher HT-IDT strength was observed for HMA samples when compared to WMA samples, possibly due to the stiffening of the asphalt binders with short-term aging and higher production temperature. • HT-IDT strength for the WMA FMFC mixtures was uniformly 40% lower than that of their replicated FMLC mixtures. • The HT-IDT strength results were not conclusive when compared to the results of the accumulated rutting measured on the FAA testing facility sections. • The HT-IDT strength test was identified as a practical surrogate rutting test due to its simplicity and observed low variability (COV ≤18%).

Table 14. Review of Repeatability Test Results for HT-IDT Test Strength Test

Reference	Within-Laboratory COV, %	Between-Laboratory COV, %	Number of Replicates
Bennert et al. (2018) (3.5%, 5%, and 6.5% AV; 44 °C[a])	6	–	3
NAPA BMD Guide (environmental temperature[a]) (NAPA, n.d.)	<10	–	≥3
NCAT Report 20-02 (7% AV; 50.2 °C[b]) (Yin et al., 2020)	1.3–15.1	–	–
New Jersey DOT (environmental temperature[a]) (Hajj & Aschenbrener, 2021)	8.2	11.8	3
VTRC Study (7% AV, 54.4 °C[c]) (Boz et al., 2023)	2.2–21.6	–	3

[a]10 °C below the Long-Term Pavement Performance Bind (LTPPBind) v3.1 yearly 7-day average maximum pavement temperature 20 mm below the pavement surface at 50% reliability.

[b]9 °C lower than the LTPPBind yearly 7-day average maximum pavement temperature 20 mm below the pavement surface.

[c]Seven-day average maximum high temperature at 50% reliability in Virginia through the pavement depth computed using LTPPBind.

– = Not available.

Srinivasan (2004) identified factors with statistically significant effect (at a 5 percent significance level) on the HT-IDT strength at 60 °C. Table 15 suggests that aggregate gradation (i.e., course versus fine), percentage of sand in the mixture, and the asphalt binder grade and content have a significant effect on the HT-IDT strength of asphalt mixtures. The HT-IDT strength increased by 2.5 and 3.0 psi when the sand content was reduced by 40 percent and the PG 70-22 was substituted with PG 76-22, respectively. Among the evaluated factors, the asphalt binder grade showed the most significant effect on HT-IDT strength. Accordingly, it was concluded that the HT-IDT strength is correlated mostly to the asphalt mixture cohesion, which is mainly tied to the asphalt binder property rather than the angle of internal friction or aggregate property (Srinivasan, 2004).

Table 15. Sensitivity of HT-IDT Strength Test to Asphalt Mixture Characteristics (Srinivasan, 2004)

Factor	Impact on HT-IDT Strength
Finer Gradation	↓
Higher NMAS (9.5 mm vs 19 mm)	↔
Higher Sand Content (0% vs 40%)	↓
Higher Binder Content by 0.5%	↓
Higher Binder Grade	↑
Gradation and Sand Content Interaction	↔
Gradation and Binder Grade Interaction	↔
NMAS and Binder Content Interaction	↔
Sand Content and Binder Grade Interaction	↔

NMAS = nominal maximum aggregate size.
↔ = No statistically significant effect on the mixture rut depth at a 5% significance level.
↓ = Statistically significant reduction in the mixture rut depth at a 5% significance level.
↑ = Statistically significant increase in the mixture rut depth at a 5% significance level.

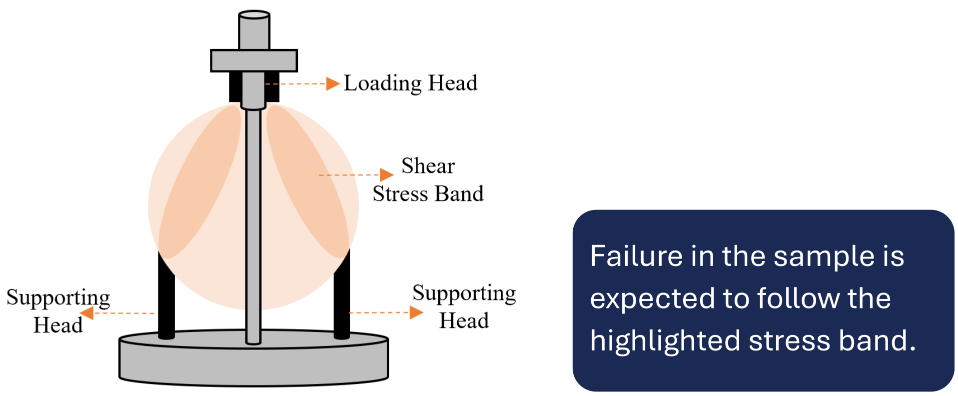
Ideal Rutting Test (IRT)

The HWT and APA tests, currently the most common rutting tests implemented by State DOTs, are not suitable for QA testing during production. A rapid shear rutting test for QA is therefore needed. The rationale behind the IRT for implementation is its simplicity, efficiency, practicality, low cost, repeatability, sensitivity to mixture components, simulation of rutting mechanism, and correlation with field rutting performance (Zhou et al., 2019; ASTM, 2022).

The IRT is similar to the ideal cracking test but is run at high temperature with a different bottom fixture to generate shear failure in the specimen. The main concept of IRT was derived from the three-point flexural bending test of a beam, where a center load in the middle will generate shearing stress on either half of the beam. The IRT relies on a circular specimen rather than a beam specimen, where the shear forces propagate from the loading point at the top to the supports on either side of the specimen.

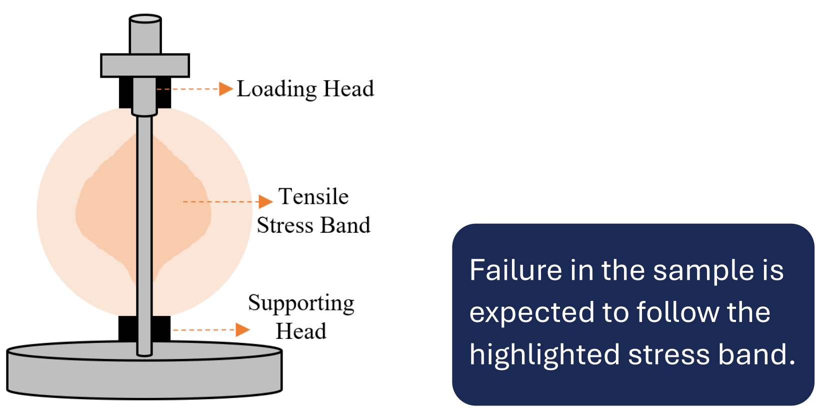
The stress distributions of the specimen subjected to shear loading in the IRT fixture have been examined and compared with the HT-IDT sample (Luo, Hu, Zhou, Crockford, & Karki, 2022). This was done based on the analytical solution derived by Luo et al. (2022) for the specific shearing fixture and two-dimensional plane of the test. The stress distribution in the IRT sample shows how the sample will fail in shear mode based on the left and right stress bands between the maximum shear stress at the loading and supporting head area (Figure 4). In the case of the HT-IDT sample, shear stresses are observed at the top and bottom of the specimen before attenuating fast without showing any shear stress bands within the specimen (Figure 5). The stress band observed in the HT-IDT sample corresponds to tensile stresses, suggesting how the sample will fail in tension mode (Table 16) (Luo et al., 2022).

The IRT was published as a national standard test method, ASTM D8360-22, in October 2022 (ASTM, 2022). Table 17 summarizes some of the existing literature for the IRT along with criteria for RT_{Index} (Zhou et al., 2019; NAPA, n.d.; ASTM, 2022; Boz et al., 2023; Advanced Asphalt Technologies, 2011; Zhou, Hu, & Newcomb, 2020; Zhou, Steger, & Mogawer, 2021). Table 18 summarizes findings from previous highway studies with IRT (Boz et al., 2023; Zhou et al., 2019; Zhou et al., 2020; Zhou et al., 2021).



Data source: Luo et al., 2022. Graphic source: University of Nevada, Reno

Figure 4. Stress Bands in IRT Test Sample



Data source: Luo et al., 2022. Graphic source: University of Nevada, Reno

Figure 5. Stress Bands in HT-IDT Test Sample

Table 16. Stress Distribution in IRT and HT-IDT Test Samples (Luo et al., 2022)

Stress	IRT Sample	HT-IDT Sample
Shear Stress	10 psi to 43 psi (shear stress band between loading and supporting head)	0 psi (no shear stress band)
Tensile Stress	3 psi (no tensile stress band)	10 psi (tensile stress band along the vertical axis)

Table 17. Summary of Previous Highway Studies with IRT (Advanced Asphalt Technologies, 2011)

IRT	Compacted Mixture Conditioning	Test Temperature, °C	Sample Type	AV%	Criteria
ASTM D8360-22 Standard Test Method (ASTM, 2022)	150±10 min in an environmental chamber or 45±5 min in a water bath	50±15[a]	LMLC PMLC FMFC	7±0.5	–
NAPA (NAPA, n.d.)	2 hr at the test temperature	50±15[a]	–	7±0.5	–
VTRC Study (Boz et al., 2023)	2 hr at the test temperature	54.4[b]	PMLC	7±0.5	RT_{Index} ≥59 (AADTT≤299) RT_{Index} ≥72 (300≤AADTT≤999)
Zhou et al. (2019)	–	50	LMLC PMLC FMFC	7±0.5	–
Zhou et al., (2020)	30 min fan/30 min at 50 °C water bath (for QC)	50	PMLC	7±0.5	RT_{Index} ≥65
Zhou et al. (2021)	–	50	LMLC PMLC	7±0.5	RT_{Index} ≥60 (mixtures with PG 64-XX or lower) RT_{Index} ≥65 (mixtures with PG 70-XX) RT_{Index} ≥75 (mixtures with PG 76-XX or higher)

PMLC = plant-mixed laboratory-compacted; AADTT = average annual daily truck traffic; QC = quality control.
[a]Test temperature depends on LTPPBind or the target high test temperature based on local climate data of the project.
[b]54.4 = 7-day average maximum high temperature at 50% reliability in Virginia through the pavement depth computed using LTPPBind.
– = Not available.

Table 18. Findings from Previous Highway Studies with IRT

Reference	Overall Findings
VTRC Study (Boz et al., 2023)	• IRT and HT-IDT were validated to screen the rutting potential of asphalt mixtures meeting Virginia DOT mixture volumetric and gradation requirements, along with initial performance criteria. • A fair correlation existed between the IRT and APA test results (R2 = 60%) with most of the data points for the IRT tests within the confidence interval limits at 95%. • A different state of strain existed within the body of the specimen between IRT and HT-IDT samples based on digital image correlation. • IRT ranked as second-best test after the HT-IDT with respect to repeatability, discrimination potential, performance ranking, sensitivity to mixture properties, correlation with binder Jnr parameter, and agreement with fundamental rutting tests (i.e., dynamic modulus, flow number, stress sweep rutting).
Zhou et al. (2019)	• The IRT has been introduced as a simple and practical rutting performance test for mix design and acceptance purposes. • The IRT has shown to be sensitive to key AC mixture components and volumetric properties. • The IRT showed very good correlation with field rutting data from WesTrack, MnROAD, and in-service Texas sections.
Zhou et al. (2020)	• Good correlation has been reported between the IRT and APA test data. • The 30 min fan/30 min water bath conditioning has been recommended after immediate Superpave compaction of IRT samples for a practical QC timeframe.
Zhou et al. (2021)	• Acceptance criteria have been developed for IRT along with strategies to meet the criteria (e.g., stiffer binders, angular aggregates, less binder content, less natural sand). • IRT implementation in BMD and acceptance framework has been demonstrated through case studies.

Jnr = binder non-recoverable creep compliance parameter; WesTrack = a pavement testing facility sponsored by the Federal Highway Administration in Nevada; MnROAD = a pavement test track owned and operated by the Minnesota DOT.

The IRT variability has been assessed in previous studies, and a summary of reported COVs for RT_{Index} is presented in Table 19 (Zhou et. al, 2019; NAPA, n.d.; Yin et al., 2020). A maximum within-laboratory COV of 26.4 percent was reported by Boz et al. (2023), suggesting similar repeatability characteristics between HT-IDT and IRT. Lower COVs of 6.7 percent and 10 percent were reported for the RT_{Index} by Zhou et al. (2019) and NAPA, respectively (NAPA, n.d.). Zhou et al. (2019) referred to the IRT as a very repeatable and simple test, with three replicates enough to obtain an accurate shear strength of the asphalt mixture, while showing sensitivity to main mixture components. Higher RT_{Index} values for lower asphalt binder content, higher amount of recycled materials in the mixture, stiffer asphalt binder, more rough aggregates, extended loose mix aging, and lower AV have been reported. It should be noted that the sensitivity analysis findings presented in

Table 20 were solely based on laboratory experimental data without further statistical analysis of variance between the results (Zhou et al., 2019).

Table 19. Review of Repeatability Test Results for RT_{Index}

Reference	Within-Laboratory COV, %	Between-Laboratory COV, %	Number of Replicates*
NAPA BMD Guide (7% AV, 50 °C) (NAPA, n.d.)	10	–	3
NCAT Report 20-02 (7% AV, 50.2 °C) (Yin et al., 2020)	17.9	–	3
VTRC Study (7% AV, 54.4 °C*) (Boz, et al., 2023)	0.6-26.4	–	3
Zhou et al. (7% AV, 50 °C) (Zhou et al., 2019)	6.7	–	3

*7-day average maximum high temperature at 50% reliability in Virginia through the pavement depth computed using LTPPBind.

– = Not available.

Table 20. Sensitivity of IRT to Asphalt Mixture Characteristics (Zhou et al., 2019)

Factor	Impact on RT_{Index}
Higher Asphalt Content (+0.5%)	Lower RT_{Index}
Different Asphalt Binder Grades	RT_{Index} PG 76-22 > PG 70-22 > PG 64-28 > PG 64-22
Higher RAP (up to 20%) and RAS (5%) Content	Higher RT_{Index}
Replacing 40% of Regular Granite Aggregates with River Pea Gravel	Lower RT_{Index}
Extended Aging of Loose Mix (4, 8, and 24 hr Before Compaction at 135 °C)	Higher RT_{Index}
Higher AV% (4, 7, and 9%)	Lower RT_{Index}

RAS = recycled asphalt shingles.

Chapter 4. Rutting Protocols

One of the key elements required to establish test acceptance criteria is having laboratory testing protocols that best simulate actual field conditions for airfield pavements. These test parameters involve selecting the proper compaction method, AV level, specimen size and preparation method (cutting, coring, etc.), loose mix aging temperature and time, compacted-specimen conditioning, test temperature, and load level and rate reflecting actual flexible airfield pavement conditions. Accordingly, the testing protocols have been classified into four main categories:

- Specimen characteristics including specimen AV level, size, and preparation method.
- Conditioning of loose mix prior to compaction.
- Conditioning of compacted specimen at relative test temperature.
- Test conditions including test temperature, load level, and load rate.

Table 21 presents the testing parameters selected by the research team for the rutting mechanical tests of flexible airfield pavements. Each selected parameter is justified in the following sections either based on the analysis of previous literature or based on the analysis of actual airfield sections data.

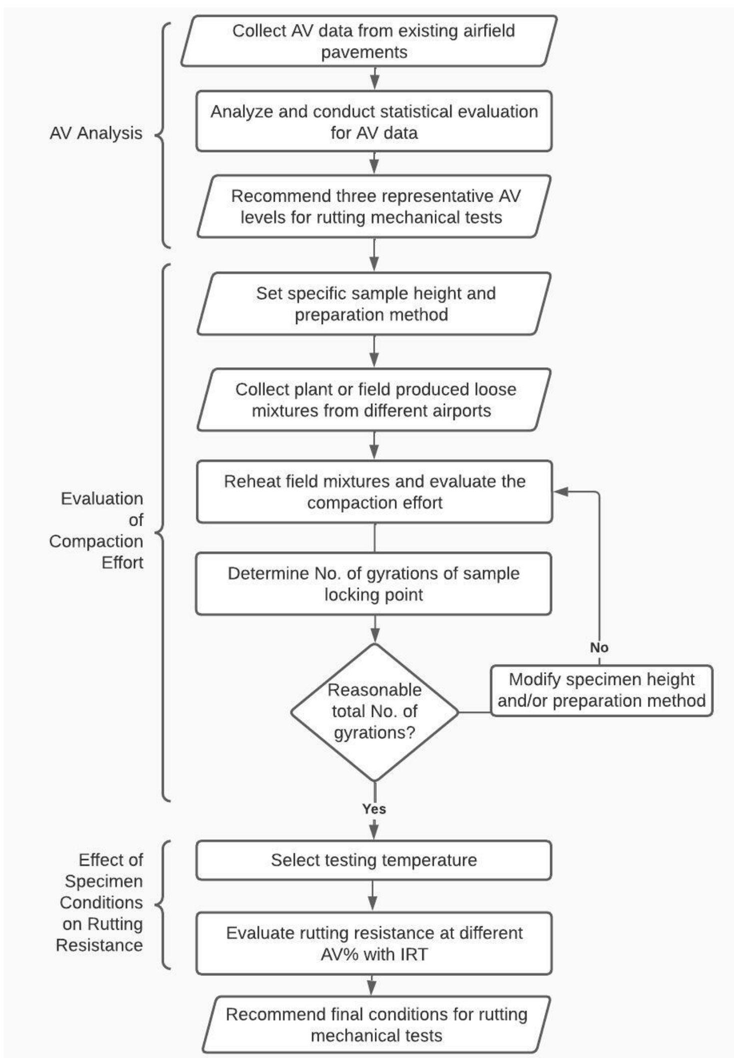
Table 21. Summary of Selected Rutting Test Protocols for Airfield Asphalt Mixtures(FHWA, n.d.-f)

Category	Factor	Project Recommendation
Specimen Characteristics	AV level	• 5±0.5% (cut from 165 mm specimens) • 7±0.5% (directly molded)
	Specimen size	• APA: 150 by 75±2 mm • HWT, HT-IDT, IRT: 150 by 62±1 mm
Loose Mix Conditioning	Laboratory-prepared, loose mix short-term oven aging	2 hr at compaction temperature
	Laboratory-prepared, loose mix reheating	See protocol in Figure 10
	Plant-mixed, loose mix reheating	See protocol in Figure 11
	Lag time, laboratory-prepared, loose mix compaction	Sample mixing and compaction same day
Compacted Specimen Conditioning	Dwell time	Maximum 7 days
	Pre-test conditioning to bring the sample to test temperature	Wet conditioning in temperature-controlled water bath
Test Conditions	Test temperature	LTPPBind Online environmental PG (no bumping), 12.5 mm rut depth, 50% reliability, at surface
	Test load level	• APA: 250 psi (250 lb) and 100 psi (100 lb) • HWT: 158 lb
	Test load rate	HT-IDT and IRT: 50 mm/min

Lag time = duration between asphalt mixture sampling and sample compaction; dwell time = duration between asphalt mixture compaction and mechanical testing.

Specimen Characteristics

With the aim of making BMD as efficient as possible, some testing parameters need to be considered when ultimately recommending test methods and criteria for mix design and QA. Some of the main parameters highlighted in this section include AV level, specimen geometry, and preparation method. As per the experimental plan in Figure 6, the quality control (QC) data of plant-mixed laboratory-compacted (PMLC) samples along with in-place density measurements were analyzed for multiple existing airfield sections in order to select representative AV levels for the rutting mechanical tests (Hajj, et al., 2025). The laboratory compaction efforts needed to reach the recommended AV levels were evaluated under different specimen heights using plant-produced asphalt mixtures collected from airfield pavements.



Source: University of Nevada, Reno

Figure 6. Experimental Plan to Select Specimen AV Level and Size

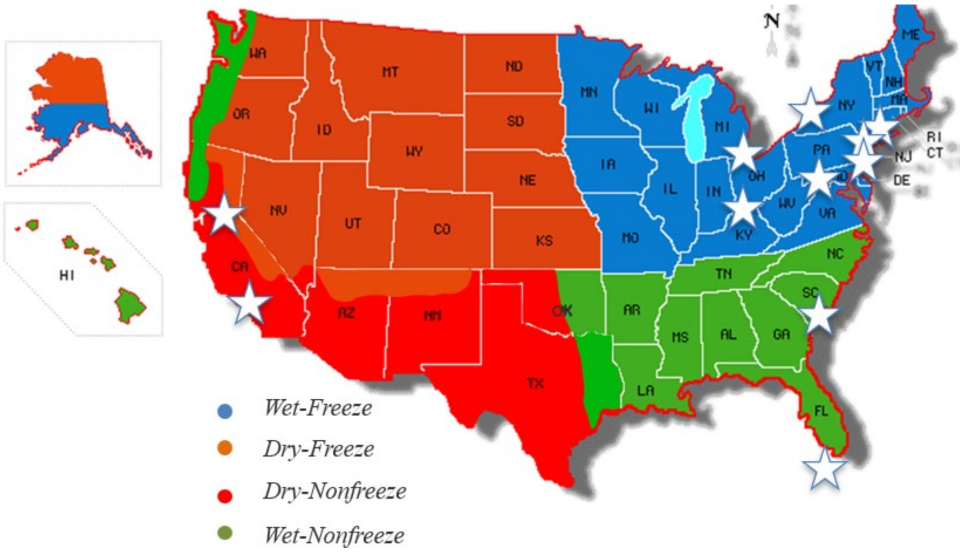
The final recommendations for test specimen conditions are verified using IRT testing of different airfield mixtures by examining the sensitivity of the test to AV levels and specimen preparation methods (ASTM, 2022). The IRT was mainly conducted to depict any significant impact of different specimen preparation methods on relative sample results and to examine the effect of different AV levels on the rutting resistance of the mixture.

AV Level

Specimen AV level is generally known to impact mechanical test results. Thus, it becomes critical to select specimen AV levels that mimic in-place AVs in airfield AC pavements for laboratory mechanical testing. To this end, asphalt mixture AV data on PMLC specimens, as well as in-place asphalt density data, for an array of airport projects, were acquired and analyzed by the research team. The detailed analysis can be seen in the technical memorandum entitled "Analysis of In-Place Density Data from Airfield Projects" dated December 8, 2022 (Hajj, et al., 2025).

Rutting in airfield AC pavements is typically observed in the mat or in close proximity to a longitudinal joint that is being traversed by aircraft due to wander effects. Rutting at or next to a joint is primarily driven by the lower in-place density (i.e., higher percentage of AV in the asphalt mixture) at this location than the rest of the mat. Thus, both in-place asphalt mat and joint density are considered in this analysis to recommend a suitable specimen AV level(s) for laboratory mechanical testing.

Eleven airports around the United States with 12 airfield AC pavement projects were evaluated in this analysis. Figure 7 illustrates the geographical distribution of the evaluated airports located within three of the Long-Term Pavement Performance (LTPP) climatic zones (Schwartz, et al., 2015). Table 22 summarizes the airports considered along with their respective FAA identification code, category and hub size per the FAA classification, maximum GAW, and LTPP climatic zone (Schwartz, et al., 2015; FAA, 2023; Airport-Data.com, n.d.; FAA, 2021a; FAA, 2024).



Data source: Schwartz et al., 2015. Graphic source: University of Nevada, Reno.

Figure 7. Geographical Location of Airports on the LTPP Climate Zone Map

Table 22. Characteristics of Airports Used in AV Analysis (Schwartz, et al., 2015; FAA, 2023; Airport-Data.com, n.d.; FAA, 2021a; FAA, 2024)

Airport	State	Airport Code	Classification/ Hub[a]	GAW, lb[b, c]	LTPP Climatic Zone
Buffalo Niagara International Airport	NY	BUF	Primary/Small	≥100,000	Wet-Freeze
Hollywood Burbank Airport	CA	BUR	Primary/Medium	≥100,000	Dry-Nonfreeze
Ronald Reagan Washington National Airport	VA	DCA	Primary/Large	≥100,000	Wet-Freeze
Detroit Metropolitan Wayne County Airport	MI	DTW	Primary/Large	≥100,000	Wet-Freeze
Key West International	FL	EYW	Primary/Small	≥100,000	Wet-Nonfreeze
Blue Grass Airport	KY	LEX	Primary/Small	≥100,000	Wet-Freeze
Marine Corps Air Station Beaufort	SC	NBC	GA/Nonprimary hub	-	Wet-Nonfreeze
Newark Liberty International Airport	NJ	EWR	Primary/Large	≥100,000	Wet-Freeze
Philadelphia International Airport	PA	PHL	Primary/Large	≥100,000	Wet-Freeze
Sacramento International Airport	CA	SMF	Primary/Medium	≥100,000	Dry-Nonfreeze
Teterboro Airport	NJ	TEB	GA/Nonprimary hub	≥100,000	Wet-Freeze

[a]FAA, CY 2021 Enplanements at All Airports (primary, non-primary commercial service, and general aviation), Last updated: Monday, September 19, 2022.
[b]FAA, Aeronautical Information Services.
[c]Airport-Data.com.
GA = general aviation.

Table 23 summarizes the 12 airfield AC pavement projects along with their respective construction date and pavement sections. The asphalt mixture type, binder performance grade (PG), gradation, nominal maximum aggregate size (NMAS), and RAP content are also included in Table 23. While asphalt mixtures are identified as either P-401 or P-403, the following modifications from the FAA standard specifications are noted (FAA, 2018):

- The Marine Corps Air Station Beaufort (NBC) was designed at 4.0 percent AV per the Naval Facilities Engineering Command Specifications Section 32 12 15.13. However, the NBC mixtures still met the main P-401 specifications including gradation, number of gyrations, voids in the mineral aggregate (VMA), tensile strength ratio, and binder content.
- The EWR and TEB airfield mixtures are designed per the Port Authority of New York and New Jersey (PANYNJ) Specification Section 321218, which includes the requirements of FAA advisory circular 150/5370 Item P-401 with FAA approved modifications.

The AV database of asphalt mixtures from 12 different airfield AC pavement projects is categorized into the following three datasets (Hajj, et al., 2025):

- Dataset 1: Laboratory QC and acceptance data with a total of 1,563 data points (PMLC).
- Dataset 2: Mat cores with a total of 858 data points (FMFC).
- Dataset 3: Joint cores with a total of 760 data points (FMFC).

Table 23. Characteristics of Airfield Asphalt Mixtures Used in AV Analysis

Airfield Project	Const. Date	Section	Mixture Type	Mix Design	Binder PG	Gradation	NMAS, mm	RAP, %
BUF	May–Aug 2017	*Runway* *Runway*	P-401 (surface) P-401 (base)	Marshall Marshall	64E-22 64S-22	Grad 2 (401-3.3) Grad 1 (401-3.3)	12.5 19.0	0 0
BUR	Feb 2021	*Taxiway* *Taxiway*	P-401 (surface) P-401 (base)	Superpave Superpave	76-22 70-10	Grad 1 (401-3.3) Grad 1 (401-3.3)	19.0 19.0	0 0
DCA	Apr–May 2010	*Runway/ Taxiway*	P-401 (surface)	Marshall	76-22	Grad 1 (401-3.3)	19.0	0
DTW	Jul–Oct 2020	*Apron Deicing Facility*	P-401 (surface) P-403 (surface)	Marshall Marshall	76-22P 64-22	Grad 2 (401-3.3) Grad 2 (403-3.3)	12.5 12.5	0 30
EYW	Jan 2018; Jun 2020–Sept 2021	*Runway*	P-401 (surface)	Superpave	76-22 (PMA)	Grad 2 (401-3.3)	12.5	0
		Taxiway	P-401 (surface)	Superpave	76-22 (PMA)	Grad 2 (401-3.3)	12.5	0
LEX	Sept 2020	*Runway/ Taxiway*	P-401 (surface)	Superpave	76-22 (SBS)	Grad 1 (401-3.3)	19.0	0
NBC	Mar–Oct 2020	*Runway*	P-401 (surface)	Superpave	76-22 (PMA)	Grad 2 (401-3.3)	12.5	0
		Runway	P-401 (intermediate)	Superpave	76-22 (PMA)	Grad 2 (401-3.3)	12.5	20
		Shoulder	P-401 (surface)	Superpave	76-22 (PMA)	Grad 2 (401-3.3)	12.5	20

Airfield Project	Const. Date	Section	Mixture Type	Mix Design	Binder PG	Gradation	NMAS, mm	RAP, %
EWR 1	May–Sept 2021	*Runway*	Modified P-401 (surface)	Marshall	76-22	Mix 3[a]	12.5	0
		Runway	Modified P-401 (surface)	Marshall	76-22	Mix 3[a]	19.0	0
EWR 2	Aug–Sept 2022	*Taxiway*	Modified P-401 (surface)	Marshall	82-22	Mix 2[a]	19.0	0
PHL	Dec 2017–May 2018	*Runway*	P-401 (surface)	Marshall	82-22	Grad 1 (401-3.3)	19.0	0
		Runway	P-401 (base)	Marshall	70-22	Grad 1 (401-3.3)	19.0	20
SMF	Dec 2016–Mar 2017	*Taxiway*	P-401 (surface)	Marshall	64-28PM	Grad 1 (401-3.3)	19.0	0
TEB	Jul–Aug 2022	*Runway*	Modified P-401 (surface)	Marshall	64-22	Mix 3[a]	19.0	0

Const. = Construction.
[a]PANYNJ Specification Section 321218.

Based on the analyzed airfield projects data, the following AV levels for laboratory mechanical testing were identified for further evaluation. The advantages and challenges associated with each AV level are summarized in Table 24.

- Based on in-place mat density:
  - AV level matching the observed median of mat core data for the percentage of AV in the asphalt mixtures (i.e., 4.1 percent). AV level of 4.0±0.5 percent is selected, or
  - AV level matching the 75th percentile of mat core data for percentage of AV in the asphalt mixtures (i.e., 5.2 percent). AV level of 5.0±0.5 percent is selected.
- Based on in-place joint density:
  - AV level matching the 75th percentile of joint core data for percentage of AV in the asphalt mixtures (i.e., 7.7 percent). AV level of 7.0±0.5 percent is selected to stay consistent with the AV level specified in current standard test methods (e.g., AASHTO T 324, AASHTO T 340, ASTM D8360) (AASHTO, 2022d) (AASHTO, 2020) (ASTM, 2022).

Table 24. Potential Advantages and Disadvantages for Identified AV Levels(Hajj, et al., 2025)

Identified AVs, %	Advantages	Disadvantages/Challenges
4.0±0.5	• Performance testing is done at an AV level consistent with the asphalt mix design. • Performance testing is implemented during production for acceptance and/or consistency of the asphalt mixture. ○ Lab QC/QA: PMLC samples are used for both volumetrics and performance testing (if Superpave mix design method used). ○ Cores: mat cores are used for both in-place density and performance testing.	• Target AV level may not be achieved within a reasonable number of gyrations. • Damage to the aggregate particles or structure when compacting asphalt mixtures having large NMAS to target AV level and relatively thin compacted samples. • Core thickness is less than the recommended sample thickness for the performance test.
5.0±0.5	• Percent of in-place mat AV data below the upper limit of 5.5% is 77.6%. • Target AV level is likely to be achieved within a reasonable number of gyrations; thus, reducing the potential for damaging aggregate particles or structure.	• AV level different than the mix design target AV level. • Trial and error are needed to achieve target AV level. • Potential to have statistically similar AVs between a sample compacted to 5.0±0.5% AV and another sample compacted to 7.0±0.5% AV.
7.0±0.5	• AV level is consistent with several standard test methods for performance testing. • Industry has the experience and knowledge in fabricating samples to target AV level. • Findings and data are leveraged from past and existing research studies. • Percent of in-place mat and joint AV data below the upper limit of 7.5% is 97.7 and 71.8%, respectively. • Performance testing is implemented during production for acceptance and/or consistency of the asphalt mixture. • Cores: joint cores are used for both in-place density and performance testing.	• AV level different than the mix design target AV level. • Trial and error are needed to achieve target AV level.

Specimen Size

The laboratory compaction effort required to reach each of the recommended target AV levels for a certain specimen thickness was evaluated in the Superpave Gyratory Compactor. This was done to avoid excessive compaction effort in the laboratory, which may cause aggregate breakdown or damage to the mix skeleton during compaction. This issue may typically be encountered in cases of low target AV (e.g., 4 percent or 5 percent AV) and/or mixtures with large NMAS.

Excess compaction effort in the Superpave Gyratory Compactor was evaluated based on the locking point concept. The gyratory locking point was determined following the common Georgia DOT method, which defines the locking point as the number of gyrations at which the same specimen height repeats three consecutive times (Polaczyk, Huang, Shu, & Gong, 2019). Plant-produced asphalt mixtures from four different airfield projects (Table 25) were sampled to examine the compaction effort. The mix type along with the airport code, construction date of the project, asphalt binder grade, and aggregate NMAS are summarized in Table 25 for each of the four used mixtures.

Table 25. Airfield Characteristics of the Evaluated Materials

Airport	Airport Code	Mixture Type	Construction Date	Binder PG	NMAS, mm
Sacramento International Airport	SMF	P-401 surface	Sept 2022	PG 76-22M	12.5
Reno Stead Airport	RTS	P-401 surface (bottom lift)	Oct 2022	PG 64-28NV[1]	12.5
Newark Liberty International Airport	EWR	P-401 surface (modified per PANYNJ specification)	Aug–Sept 2022	PG 82-22	19.0
Teterboro Airport	TEB	P-401 surface (modified per PANYNJ specification)	July–Aug 2022	PG 64-22	19.0

[1]PG 64-28NV is a polymer-modified asphalt binder used by the Nevada DOT on all roadways in the northern part of the State. The "NV" extension indicates that the asphalt binder meets the agency's PG "plus" specifications that include the standard Superpave PG system (Nevada DOT, 2014).

Compaction effort depends on the combination of the final specimen height and target AV level. Hence, specimens with 60 mm thickness were initially evaluated targeting an AV level of 7±0.5 percent. The number of gyrations required to reach the set AV range at 60 mm varied between 162 and 172 gyrations for one of the airfield mixtures, which is equivalent to four times the calculated locking point of 44. With the aim of reducing the required gyrations, the 60 mm height was substituted with 62 mm, which is a common specimen height currently adopted for several rutting resistance tests including HWT, HT-IDT, and IRT (ASTM, 2017b; ASTM, 2022). The results of the four airfield mixtures suggest that 7±0.5 percent AV can be achieved within a reasonable number of gyrations at 62 mm, where the locking point was not reached during compaction in most cases, as shown in Table 26 and Table 27.

Table 26. SMF and RTS Airfield Mixture Compaction Data

Mixture	SMF				RTS		
Final Height, mm	60		62		62		
Locking Point (Gyration No.)	42	45	42	47	Not Reached		
Total Gyrations	162	172	101	72	58	41	36
Final AV%	6.6	6.4	7.2	7.0	7.0	7.5	7.1

Table 27. EWR and TEB Airfield Mixture Compaction Data

Mixture	EWR						
Final Height, mm	62						
Locking Point (Gyration No.)	39	Not Reached				43	44
Total Gyrations	79	41	63	51	79	101	111
Final AV%	7.0	7.3	7.2	6.5	6.5	5.6	5.4
Mixture	**TEB**						
Final Height, mm	62						
Locking Point (Gyration No.)	42	48	Not Reached			42	49
Total Gyrations	46	58	28	36	45	146	98
Final AV%	7.4	6.7	6.5	6.6	7.1	5.0	5.1

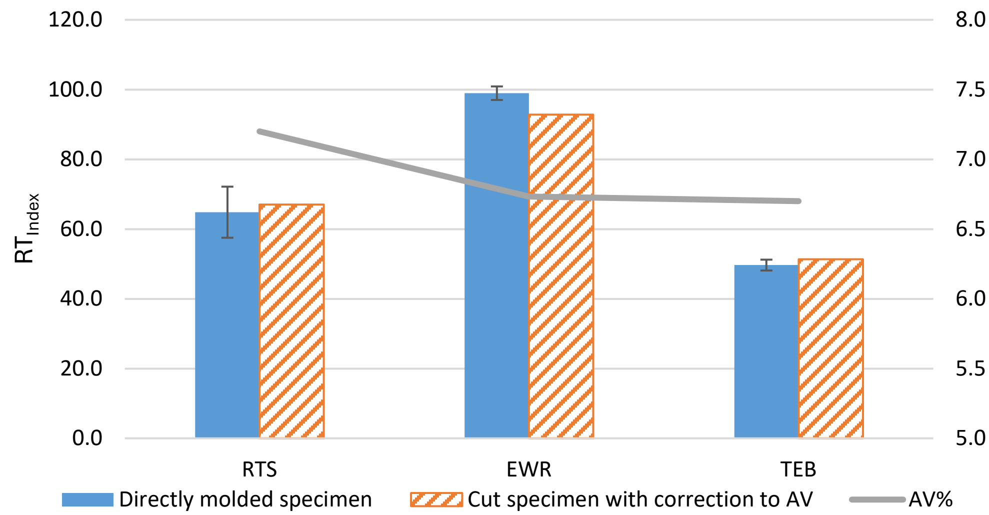
The number of gyrations needed to reach the second recommended AV level of 5±0.5 percent at 62 mm height reached, in some cases, three times the reported locking point, as shown in Table 27. A lower compaction effort was favored by the research team, hence the alternative of cutting 62 mm specimens from thicker samples of 165 mm height was further investigated to reach lower AV levels. The 165 mm specimen height was the minimum height needed to cut two samples from the large specimen, while keeping in mind compacted-height limitations for some equipment (i.e., gyratory compactors).

The range of required gyrations is summarized in Table 28 using various specimen preparation methods for three airfield mixtures. Due to the AV variability among compacted specimens, the number of gyrations in Table 28 was estimated at each AV level based on developed linear regressions of compacted specimens. It can be inferred that cutting 62 mm specimens from larger specimens eliminated the excess compaction effort and allowed the three target AV levels to be achieved within a reasonable number of gyrations (i.e., less than three times the locking point). Based on the tabulated results, the research team concluded that specimens targeting 7±0.5 percent AV can be directly molded to 62 mm, whereas specimens targeting 4 percent or 5 percent AV should be cut from 165 mm samples for further testing.

Table 28. Number of Gyrations to Target AV Levels

Airport Mixture	Directly Molded	Cut from 165 mm-Thick Sample		
	AV = 7.0±0.5%	AV = 7.0±0.5%	AV = 5.0±0.5%	AV = 4.0±0.5%
RTS	49	35	65	80
EWR	64	24	39	47
TEB	42	19	33	40

The influence of specimen preparation method (i.e., directly modeled to 62 mm versus cut from a 165-mm-thick sample) was verified experimentally using the IRT results of the three evaluated asphalt mixtures (Figure 8). Any potential influence of specimen preparation method on rutting test results is expected to mostly be captured with the IRT. A 7±0.5 percent AV was targeted for the directly molded specimens. The RT_{Index} values of the cut specimens were corrected (using the mixture-specific relationship between the specimen's RT_{Index} and AV values) to match the exact AV level reached with the directly molded samples (i.e., 7.2 and 6.7 percent AV) for comparison purposes.



Source: University of Nevada, Reno

Figure 8. Effect of Cutting at 7±0.5% AV on RT_{Index} (Error bars represent mean plus or minus one standard deviation.)

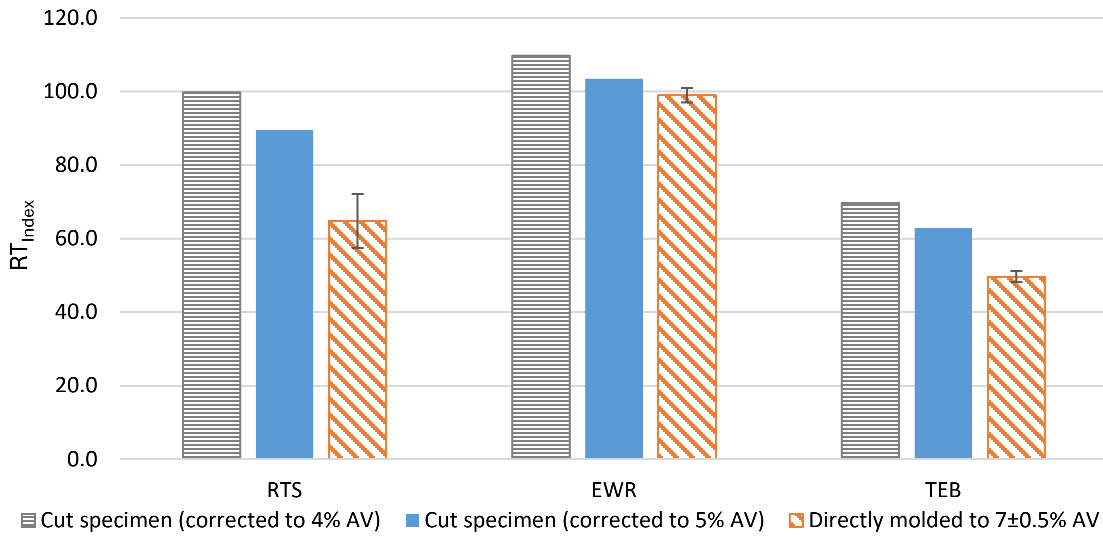
Based on the data in Figure 8, no bias in the measured RT_{Index} was observed due to the sample preparation method. The difference in the RT_{Index} values between directly molded and cut specimens was within the 11 percent maximum COV observed between the replicates. It should be noted that the observed COV of 11 percent is consistent with the reported COV in the literature (Table 19) (Zhou et al., 2019; NAPA, n.d.). Thus, it can be concluded that either directly molded or cut specimens can be used to measure the asphalt mixture resistance to rutting.

Figure 9 summarizes the IRT results for each of three evaluated asphalt mixtures at the three target AV levels: 7 percent, 5 percent, and 4 percent. Within each asphalt mixture, a reduction in the RT_{Index} was observed with the increase in AV level. When comparing the RT_{Index} of each asphalt mixture at 4 and 5 percent AV levels, the results ranged within a maximum COV of 8 percent, which is less than the maximum COV of 11 percent reported within the replicates at the same AV level. The ranking of the asphalt mixtures based on RT_{Index} remained consistent at all three AV levels.

Based on the presented data, the following two AV levels for future rutting testing in this study were selected: 7±0.5 percent and 5±0.5 percent. The latter (i.e., 5 percent AV) corresponded to the 75th percentile of the mat core AV data and showed similar IRT results to the 4 percent AV samples.

In summary, for the APA test, specimens are 150 by 75±2 mm directly molded to 5±0.5 percent and 7±0.5 percent AV levels. In the case of HWT, HT-IDT, and IRT, specimens are

150 by 62±1 mm directly molded to 7±0.5 percent AV and cut from 165-mm-tall specimens to reach 5±0.5 percent AV.



Source: University of Nevada, Reno

Figure 9. RT_{Index} Results at Varying AV Levels

Loose Mix Conditioning

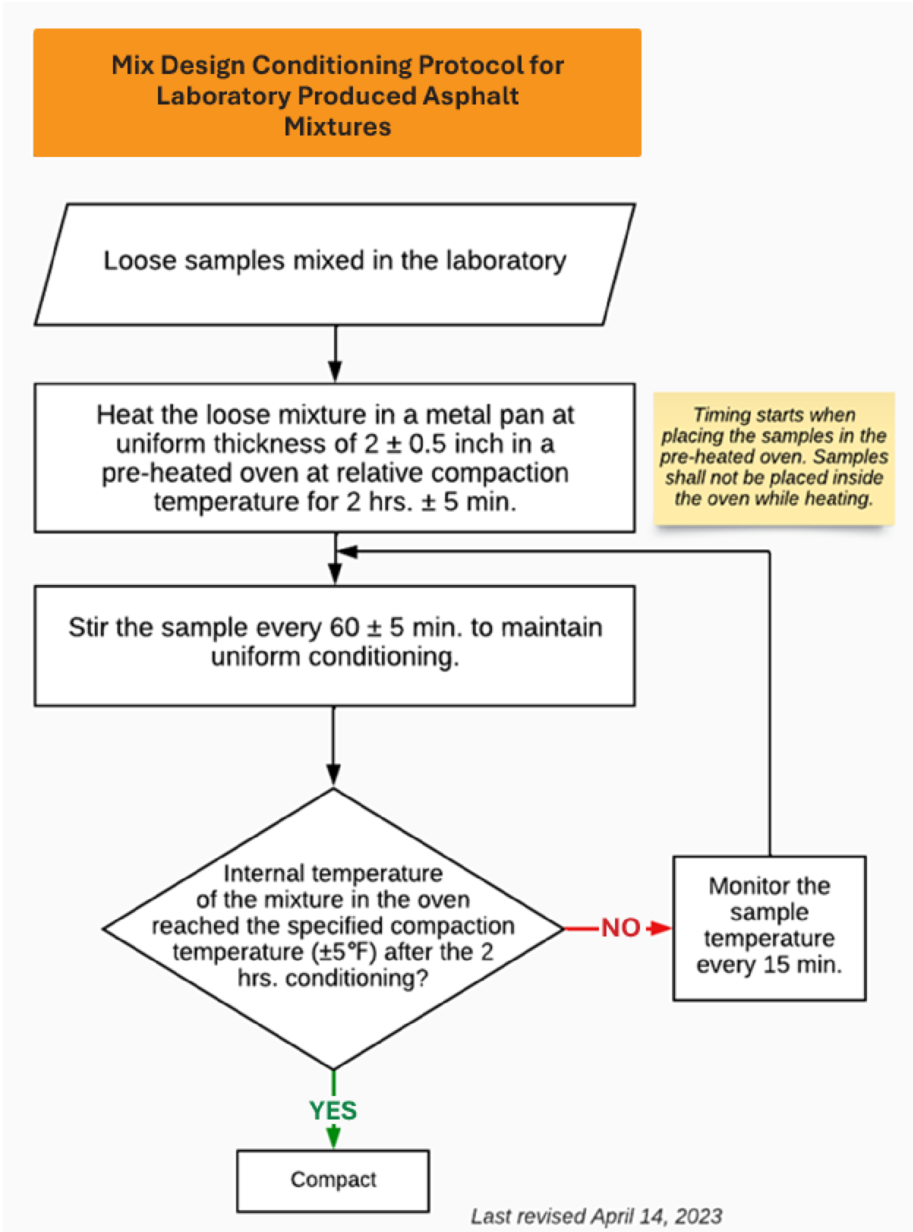
The loose mix conditioning prior to sample compaction needs to be clearly defined for laboratory-prepared and plant- or field-produced asphalt mixtures. Accordingly, two detailed flowcharts are presented for both specimen types as part of handling and conditioning/reheating protocols. Both protocols were discussed and coordinated with the BMD cracking team to maintain consistency in handling and sample preparation within and between both research teams.

Laboratory-Prepared Loose Asphalt Mixtures

Figure 10 shows the adopted protocol for short-term conditioning of laboratory-prepared loose asphalt mixtures in a forced-draft oven. A short-term conditioning of 2 hr at compaction temperature was selected for this effort following a review of common practices and literature (Luo et al., 2022).

While the selected 2-hr duration is consistent with the latest version of AASHTO R 30-22, conditioning temperatures of 116 °C and 135 °C were specified for WMA and HMA, respectively (AASHTO, 2022b). Nonetheless, AASHTO R 30-22 notes that "for modified binders, the agency should consider the manufacturer's recommendations for compaction temperatures as the conditioning temperature." These recent changes in AASHTO R 30-22 are based on the findings from the National Cooperative Highway Research Program (NCHRP) project 09-49, which originally recommended 2 hr at compaction temperature for short-term conditioning (Epps Martin, et al., 2014). However, Epps Martin, et al. (2014) proposed the fixed compaction temperatures for HMA and WMA that were adopted by AASHTO mainly due to a presumed difficulty in accurately defining the compaction temperature for each project. In this study, the compaction temperature was selected instead for the following reasons:

- To avoid conditioning different asphalt binder grades at different stiffnesses or viscosities. Conditioning asphalt binders at their respective compaction temperatures provides an approximately equal stiffness condition for different asphalt binder grades.
- To maintain consistency and improve efficiency of the short-term conditioning procedure by eliminating the need to bring the sample to compaction temperature after conditioning and before compaction. Thus, avoiding different conditioning durations and reducing conditioning time during sample preparation.

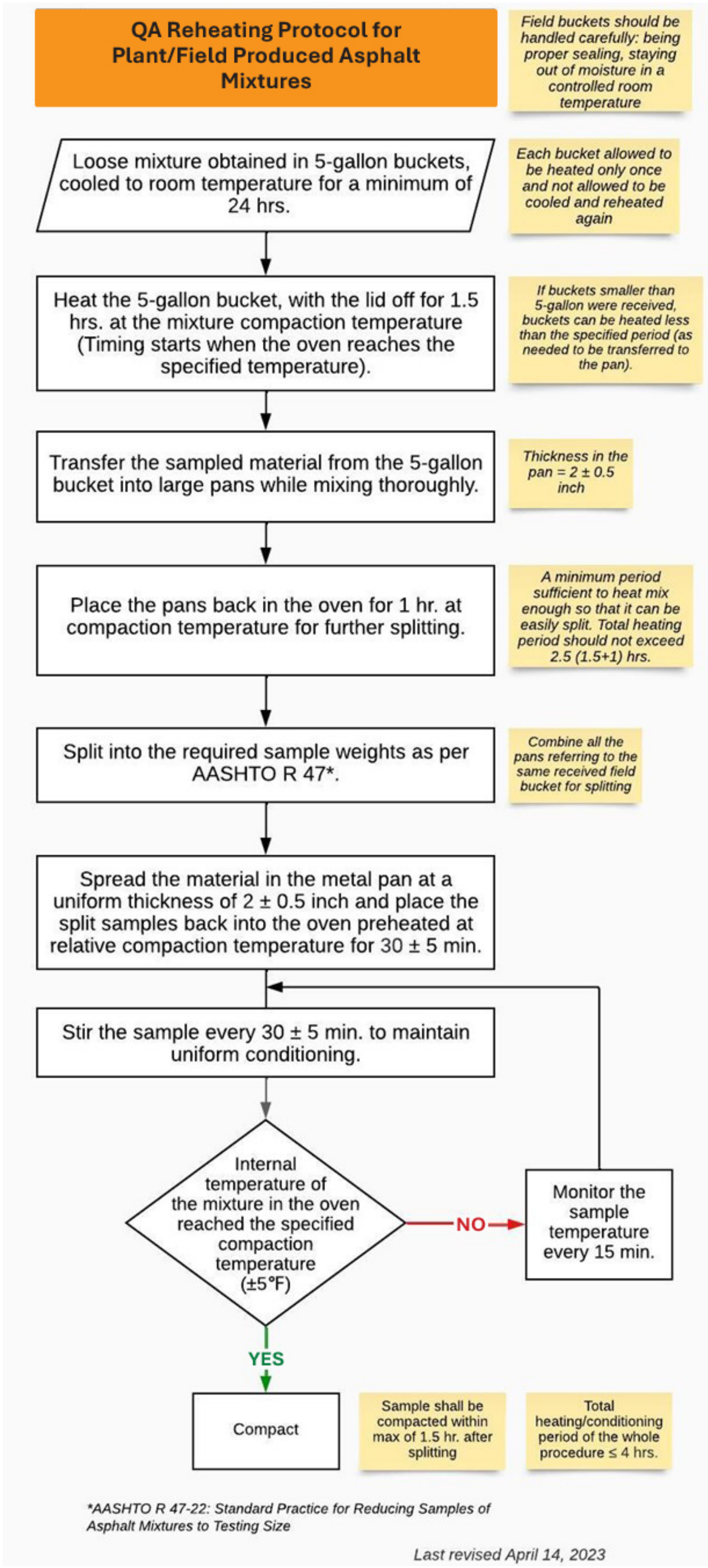


Source: University of Nevada, Reno

Figure 10. Short-Term Conditioning Protocol for Laboratory-Prepared Loose Asphalt Mixtures

Plant- or Field-Produced Asphalt Mixtures

The literature documented on the sequence of steps to reheat plant- or field-produced loose asphalt mixtures was reviewed, including current State DOT standard practice (MaineDOT, 2021; Texas DOT, 2021; Arizona DOT, 2015). Consequently, a well-detailed protocol was developed to include details for handling, splitting, and reheating plant- or field-produced asphalt mixtures. The set protocol aims to minimize unnecessary stiffening of the asphalt mixture due to oxidation with a maximum total reheating period of 4 hr. Figure 11 shows a flowchart of the detailed protocol adopted in this study.



Source: University of Nevada, Reno

Figure 11. Reheating Protocol for Plant- or Field-Produced Loose Asphalt Mixtures

- Step 1. Heat the loose asphalt mixture in a metal pan at uniform thickness of 50±12 mm in a preheated oven at relative compaction temperature with the lid off for 1.5 hr ±5 min.
- Step 2. Transfer the sampled material from the 5-gal bucket into large pans while mixing thoroughly.
- Step 3. Place the pans back in the oven for 1 hr at compaction temperature for further splitting.
- Step 4. Split the material into required sample weights as per AASHTO R 47 (AASHTO, 2022e).
- Step 5. Spread the material in the metal pan at a uniform thickness of 50±12 mm and place the split samples back into the oven preheated at relative compaction temperature for 30±5 min.
- Step 6. Stir the samples every 30±5 min to maintain uniform conditioning.
- Step 7. Monitor the sample temperature every 15 min.
- Step 8. Compact the sample if the internal temperature of the loose asphalt mixture in the oven reached the specified compaction temperature (±15 °C).

It should be noted that both field- and plant-produced asphalt mixtures are included in the developed protocol and project experimental plan. Field-produced asphalt mixtures refer to asphalt loose mixtures sampled on site during the paving job (e.g., behind the paver or paving truck). On the other hand, plant-produced asphalt mixtures refer to asphalt loose mixtures sampled at the plant during production.

Lag Time

Lag time refers to the duration between asphalt mixture sampling and sample compaction. Considering that different lag times between laboratories may create discrepancy in test results, the prospective FAA rutting specifications would need to define and identify lag time. For the purpose of this study, mixing and compacting will occur within the same day for laboratory-mixed laboratory-compacted (LMLC) samples. On the other hand, the lag time for PMLC specimens will be further evaluated and set throughout the project experimental plan.

Chapter 5. Compacted Specimen Conditioning

Wet vs. Dry Conditioning

The compacted specimen conditioning, which aims to bring the specimen to the target test temperature prior to testing, is defined in the standard rutting test methods with two different alternatives: wet or dry conditioning (AASHTO, 2020; AASHTO, 2022d; ASTM, 2017b; Alabama DOT, 2022; ASTM, 2022). Table 29 summarizes the conditioning time for compacted specimens as defined by the corresponding standard procedures for the various rutting tests. In general, less time is needed when wet conditioning is adopted.

Several studies reported similar rutting test results for compacted specimens when subjected either to dry (i.e., in a temperature-controlled chamber) or wet (i.e., in a water bath) conditioning (Bennert, Haas, Wass, & Berger, 2021; Zhou et al., 2020). Thus, wet conditioning will be followed in this study to reduce the time needed to complete testing. This helps in saving time when testing asphalt mixtures during production.

A dummy sample with inserted temperature probe will be placed in the conditioning water bath to verify that the sample reached the target test temperature at the end of the conditioning period prior to testing. Figure 12 shows a dummy sample in the HWT test water bath.

Table 29. Dry vs. Wet Conditioning for Compacted Asphalt Mixtures (AASHTO, 2020; AASHTO, 2022d; ASTM, 2017b; Alabama DOT, 2022; ASTM, 2022)

Rutting Test	Test Method	Dry Conditioning	Wet Conditioning
APA	AASHTO T 340-10	6–24 hr	6–24 hr
HWT	AASHTO T 324-22	–	45 min
HT-IDT	ASTM D6931-17 (ALDOT-458)	≥4 hr (2 hr ±10 min)	30–120 min
IRT	ASTM D8360-22	150±10 min	45±5 min

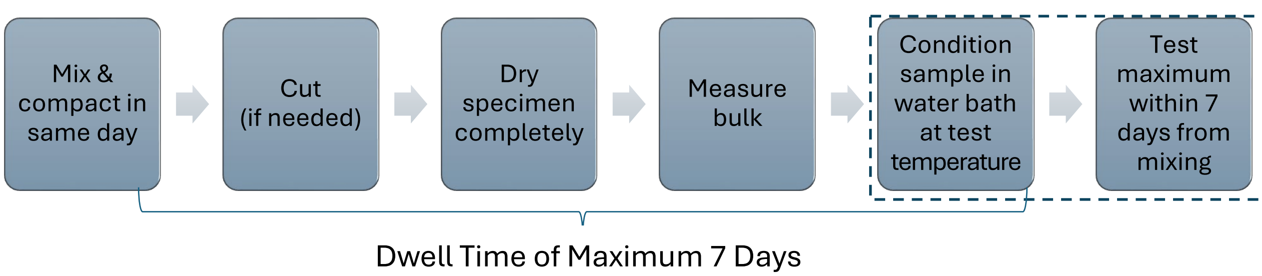
– = Not applicable.

Source: University of Nevada, Reno

Figure 12. Dummy Sample with Temperature Probe When Conditioning Compacted Asphalt Mixtures in HWT Test Water Bath

Dwell Time

Another parameter that will be included in the future FAA rutting specifications is the dwell time, which refers to the duration between asphalt mixture compaction and mechanical testing. The survey responses reported in NCHRP Synthesis 552 on the maximum allowable storage time during performance test specimen fabrication process were reviewed (Sias, Dave, & Myers McCarthy, 2020). The timeframe shown in Figure 18 was set by the research team allowing for a maximum dwell time of 7 days from sample compaction to mechanical testing.



Source: University of Nevada, Reno

Figure 13. Dwell Time and Timeframe for Testing

Chapter 6. Test Conditions

Test Temperature

The aim is to account for varying climatic conditions when developing rutting specifications for airfield asphalt mixtures used around the United States. Thus, the research team proposes the use of an environmental temperature tied to the geographical location of the airfield pavement rather than a fixed temperature for rutting tests. Table 30 summarizes the environmental test temperatures recommended by NCHRP Project 09-33 (Advanced Asphalt Technologies, 2011). Several alternatives for environmental testing temperatures for different airfield pavements were explored and are summarized in Table 31. The airfield pavements are at airports identified in this study for materials sampling (FHWA, n.d.-f). The true and final asphalt binder PG were determined using LTPPBind Online software for a reliability level of 50 percent and 98 percent, a 12.5 mm target rut depth, and surface as well as 20 mm below surface. Figure 14 and Figure 15 compare the determined PGs for different scenarios to the true and final PG at pavement surface with 98 percent reliability, respectively.

Table 30. NCHRP 09-33 Suggested Environmental Temperature for Rutting Tests (Advanced Asphalt Technologies, 2011)

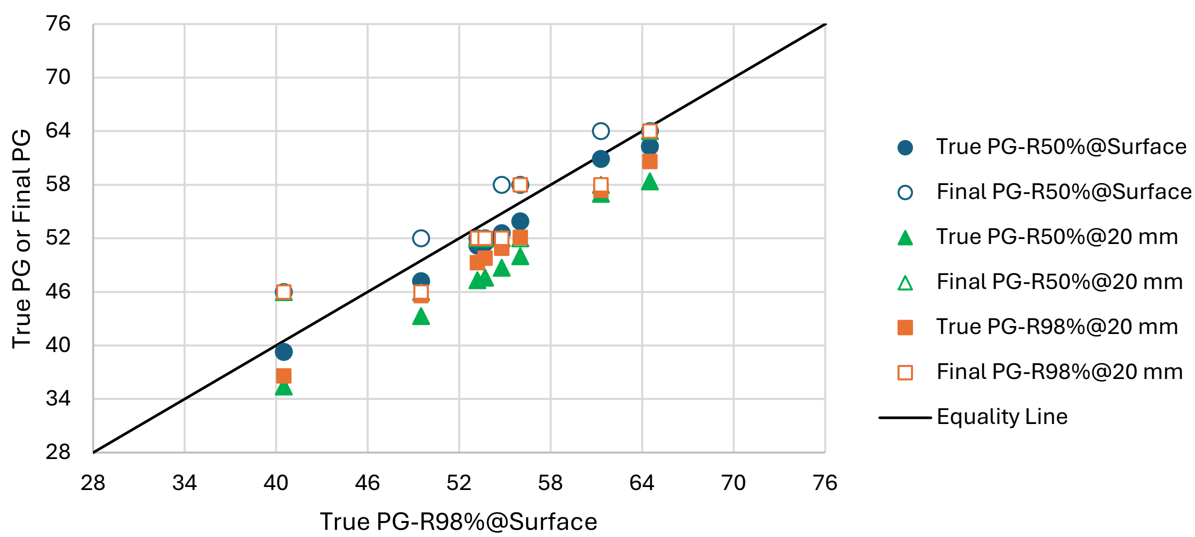
Rutting Test	Test Temperature
APA	Typical: 64 °C Suggestion: asphalt binder PGH for ≥3 MESALs
HWT	50±1 °C
HT-IDT	10 °C below the average, 7-day maximum pavement temperature, 20 mm below surface at 50% reliability (LTPPBind 3.1)
IRT	–

– = Not available.

Table 31. Alternatives for Environmental Testing Temperatures (FHWA, n.d.-f)

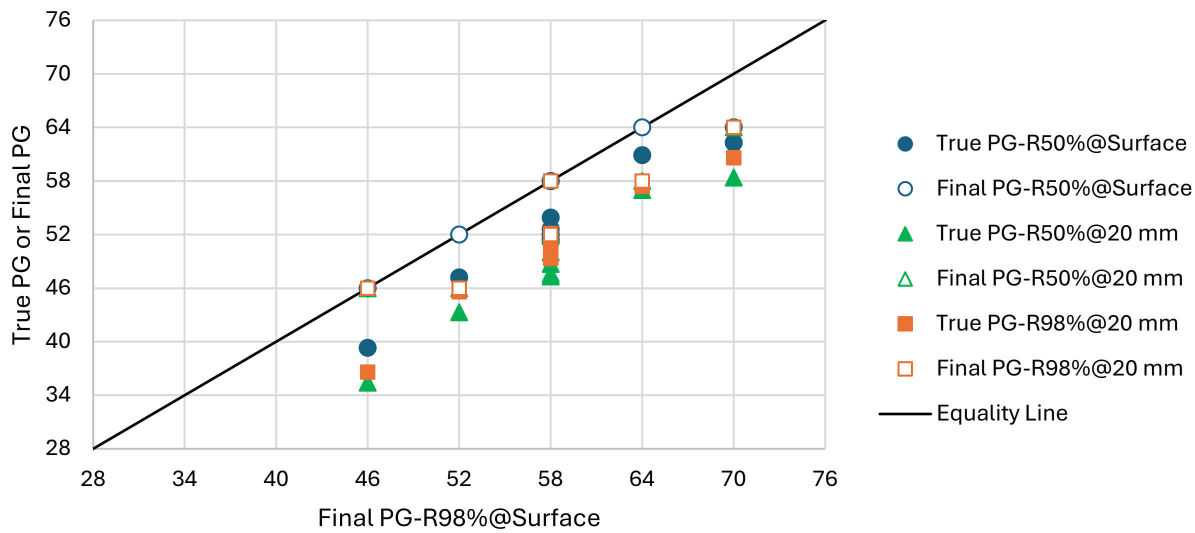
Airport	Airport Code	50% Reliability				98% Reliability			
		At Surface		20 mm Below Surface		At Surface		20 mm Below Surface	
		True PG	Final PG	True PG	Final PG	True PG	Final PG	True PG	Final PG
Sacramento International Airport	SMF	62.3	64	58.4	64	64.5	70	60.6	64
Detroit Metropolitan Wayne Country Airport	DTW	47.2	52	43.3	46	49.5	52	45.6	46
Reno Stead Airport	RTS	51.2	52	47.3	52	53.2	58	49.3	52
Newark Liberty International Airport	EWR	52.6	58	48.7	52	54.8	58	50.9	52
Teterboro Airport	TEB	51.5	52	47.6	52	53.7	58	49.8	52
Philadelphia International Airport	PHL	53.9	58	50.0	52	56.0	58	52.1	58
Tampa International Airport	TPA	60.9	64	57.0	58	61.3	64	57.4	58
San Francisco International Airport	SFO	39.3	46	35.4	46	40.5	46	36.6	46

Note: 12.5 mm target rut depth.



Source: University of Nevada, Reno

Figure 14. Comparison Between True or Final PG and True PG at Pavement Surface and 98% Reliability



Source: University of Nevada, Reno

Figure 15. Comparison Between True or Final PG and True PG at Pavement Surface and 98% Reliability

Based on the presented data and considering the findings from NCHRP 09-33, a rutting test temperature corresponding to the LTPPBind Online environmental PG (no bump), with 12.5 mm target rut depth, at the pavement surface with 50 percent reliability is recommended. The recommended test temperature was in most cases warmer than or within 2 °C of the true PG at the pavement surface with 98 percent reliability. The following factors were taken into consideration when recommending the rutting test temperature:

- Rutting in the AC layer is likely to be confined to the top 50 mm and is most critical under pavement high temperatures, which are higher at or near the surface.
- Exiting equipment capabilities and limitations for testing temperatures.

Test Load Level and Tire Pressure

The following section will discuss the load level and tire pressure selected for further laboratory mechanical testing relative to actual aircraft data. The load level and tire pressure constitute the main parameters that control the laboratory tests with repeated loading (i.e., APA and HWT). On the other hand, monotonic laboratory testing (i.e., HT-IDT and IRT) will be controlled by the rate of loading, which will be discussed in the subsequent section.

The APA has been commonly evaluated in the literature for highway pavements under 100–120 lb wheel load relative to 158 lb for the HWT machine (Kandhal & Cooley, 2003; Moore & Prowell, 2006). Compared to a maximum gross weight of 80,000 lb for an 18-wheeler truck, airfield pavements are designed for aircraft gross weights ranging from 2,000 lb for small general aviation (GA) airports to 1,322,750 lb for large commercial airports (FAA, 2021b). However, large commercial aircraft with heavy gross weights are fitted with multiple-wheel landing gear systems to help distribute their weight across a wider area. For example, the Antonov 225, the world's heaviest plane with a maximum takeoff weight of about 2,905,000 lb, has a 32-wheel landing gear configuration that results in a wheel load of only 19,634 lb. The final aircraft wheel load is calculated as a function of GAW, gear type, and number of main gears per aircraft.

A review of current aircraft loading characteristics was conducted from the FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) pavement design software database (FAA, 2021b). The FAARFIELD vehicle library contains the most common commercial airplanes, including generic aircraft, Airbus, Boeing, GA models, and many others (FAA, 2021b). An example of some Boeing aircraft characteristics are summarized in Table 32. The Boeing aircraft wheel loads ranged from 26,363 to 79,800 lb. The average wheel load was 44,082 lb with a standard deviation of 12,247 lb. Moreover, the 25th, 50th, 75th, and 99th percentiles of the wheel-load distribution were 34,497, 43,304, 52,082, and 75,777 lb, respectively.

The reported aircraft wheel loads are far greater than the typical loaded truck wheel load of 11,000 lb (on average four times larger). Hence, it is reasonable to assume an increase in the testing load level by at least fourfold to represent aircraft loading conditions (e.g., use of APA 400 lb for airfield application relative to 100 lb for highway application). However, this increase would result in several implementation challenges, including the effect of loading magnitude relative to specimen size as well as equipment capacity and cost. Considering APA and HWT testing machines, the research team will be aligned with the commercially available equipment for nationwide implementation. This includes the APA machine under 100 lb, the HWT under 158 lb, and the new APA upgrade for airfield pavements under 250 lb that will be further discussed (AASHTO, 2020; AASHTO, 2022d).

Table 32. Boeing Aircraft Characteristics (FAA, 2021b)

Aircraft	Gear Type	Gross Load, lb	Gear Load/ Landing Gear, lb	Wheel Load, lb
B737-100	D	111,000	52,725	26,363
B737-200	D	116,000	55,100	27,550
B717-200 HGW	D	122,000	57,950	28,975
B737-500	D	134,000	63,650	31,825
B737-300	D	140,000	66,500	33,250
B737-400	D	150,500	71,488	35,744
B737-700	D	155,000	73,625	36,813
B737-800	D	174,700	82,983	41,491
B737-900	D	174,700	82,983	41,491
B727-200 Advanced Option	D	210,000	99,750	49,875
B757-200	2D	256,000	121,600	30,400
B707-320C	D	336,000	159,600	79,800
B767-200	2D	368,000	174,800	43,700
B767-300 ER	2D	388,000	184,300	46,075
B767-400 ER	2D	451,000	214,225	53,556

Aircraft	Gear Type	Gross Load, lb	Gear Load/ Landing Gear, lb	Wheel Load, lb
B777-200	3D	547,000	259,825	43,304
B777-200 ER	3D	658,000	312,550	52,092
B777-300	3D	662,000	314,450	52,408
B747-SP	2D/2D5	703,000	166,963	41,741
B777-300 ER	3D	777,000	369,075	61,513
B747-200/300	2D/2D2	836,000	198,550	49,638
B747-400	2D/2D3	877,000	208,288	52,072
B747-400ER	2D/2D4	913,000	216,838	54,209

D = dual wheels; 2D = 4 wheels; 3D = 6 wheels.

As for the tire/hose pressure, a hose pressure of 100 psi and wheel load of 100 lb were predominant in the literature of the APA test (Kandhal & Cooley, 2003; Moore & Prowell, 2006). The literature included several research studies recommending the APA at 120 psi and 120 lb wheel load, based on good correlation with field rutting data. However, these latter test parameters were not widely implemented due to practical and economic reasons. Some field laboratories may not have enough resources to equip themselves with large air compressors, since many air compressors would not consistently supply 120 psi of air pressure (Kandhal & Cooley, 2003; Moore & Prowell, 2006).

For airfield pavements, the new set of APA test conditions of 250 psi hose pressure and 250 lb were introduced to simulate actual aircraft characteristics (Rushing et al., 2012). Table 33 is an example from a series of tables in the FAARFIELD library for Airbus aircraft, where the tire pressure reaches a maximum between different aircraft types of 241 psi for the A350-900 aircraft type (FAA, 2021b). A statistical summary including 253 aircraft tire pressures had an average of 164 psi and a standard deviation of 58 psi. The tire pressure distribution ranged between 30 and 241 psi, with 25th, 50th, 75th, and 99th percentiles of 126, 185, 208, and 234 psi. In contrast with the wheel load, the laboratory tire pressure can closely simulate actual aircraft characteristics based on the analyzed dataset. The range of tire pressure observed for different aircraft justifies the APA testing under 250 psi hose pressure for airfield surface layers, similar to the pressure level adopted in previous airfield research studies (Rushing & Garg, 2017; Rushing et al., 2012; Rushing et al., 2014; FAA, 2021b).However, further investigation is needed for deeper AC layers in the pavement structure, such as the case of an asphalt binder or base course. Thus, previous research studies that included field measurements and modeling of the state of stresses under aircraft loading were reviewed.

Table 33. Airbus Aircraft Characteristics (FAA, 2021b)

Airplane Name	Gross Taxi Weight, lb	Tire Pressure, psi	Percent GAW on Gear	Dual Tire Spacing, cm	Tandem Tire Spacing, cm	Tire Contact Area, cm^2
A350-900	601,650	241	0.475	173.5	204.0	1913
A350-1000	681,000	220	0.475	139.7	140.0	1581
A340-600 WV103	807,325	234	0.361	139.7	198.1	2009
A340-600 WV103 Belly	807,325	222	0.230	117.6	198.1	1349
A340-600 WV000	807,325	234	0.361	139.7	198.1	2009
A340-600 WV000 Belly	807,325	222	0.230	117.6	197.9	1349
A340-600 WV001	813,950	234	0.361	139.7	198.1	2030
A340-600 WV001 Belly	813,950	222	0.230	117.6	197.9	1360
A340-500 WV102	822,775	234	0.355	139.7	198.1	2014
A340-500 WV102 Belly	822,775	222	0.240	117.6	198.1	1435
A340-500 WV003	827,175	234	0.357	139.7	198.1	2040
A340-500 WV003 Belly	827,175	222	0.235	117.6	198.1	1414
A340-500 WV101	840,400	234	0.355	139.7	198.1	2061
A340-500 WV101 Belly	840,400	222	0.240	117.6	198.1	1465
A340-600 WV101	840,400	234	0.359	139.7	197.9	2084
A340-600 WV101 Belly	840,400	222	0.231	117.6	198.1	1410
A380-800 WV007	1,084,675	218	0.190	134.9	169.9	1525
A380-800 WV007 Belly	1,084,675	218	0.285	00.0	00.0	1525
A380-800 WV000	1,239,000	218	0.190	134.9	169.9	1742
A380-800 WV000 Belly	1,239,000	218	0.285	00.0	00.0	1742
A380-800 WV001	1,239,000	218	0.190	134.9	169.9	1742
A380-800 WV001 Belly	1,239,000	203	0.285	00.0	00.0	1870
A380-800 WV002	1,258,850	203	0.190	134.9	169.9	1901
A380-800 WV002 Belly	1,258,850	218	0.285	00.0	00.0	1770
A380-800 WV006	1,267,658	218	0.190	134.9	175.0	1782
A380-800 WV006 Belly	1,267,658	218	0.285	00.0	00.0	1782

The most common non-uniform contact stress distribution is based on the contact stress measurements under heavy aircraft tire load reported by Rolland (2009). The peak contact stresses beneath two edge ribs are assumed equal to 2.2 times the tire inflation pressure, while the peak contact stresses under central ribs are assumed equal to 1.18 times the tire inflation pressure. Two research studies found in the literature are presented in Table 34 showing the vertical stress distribution within airfield pavement structures, either based on three-dimensional finite element modeling or field measurements (i.e., pressure cells) (Wang, Al-Qadi, Portas, & Coni, 2013; Wang, Li, & Garg, 2017). The vertical stresses tabulated at varying depths of the airfield pavement structure indicate stresses as high as 145 and 189 psi (>100 psi) at 39 percent and 43 percent depth-to-thickness ratios. Hence, testing deeper asphalt layers with the APA under 250 psi hose pressure still represents the actual stress state observed in both the airfield pavement structures presented herein. However, these observations were reported based on data from a limited number of test sections, and the APA 100 psi hose pressure may still be representative of the actual stress state for other airfield pavement structures.

Table 34. Stress Distribution Within Airfield Pavement Structure

	Three-Dimensional Finite Element Model (Wang et al., 2013)		Field Measurements (Pressure Cells) (Wang et al., 2017)	
Depth, mm	Depth-to-Thickness Ratio, %	Vertical Pressure, psi	Depth-to-Thickness Ratio, %	Vertical Pressure, psi
0.0	0	447 (203 psi tire pressure)	0	409 (186 psi tire pressure)
50.8	39	145	14	384
149.9	–	–	43	189

– = Not available.

Performing the APA test under 250 psi pressure requires laboratories to upgrade their existing 100 psi APA equipment. The upgrade cost is estimated at $30,000 for APA Junior equipment (two-wheel loaded wheel tester) and higher for standard APA equipment (three-wheel loaded wheel tester). These costs are associated with additional components, parts, labor, software updates (if needed), and other related items. Otherwise, agencies will have to purchase the new-generation APA Juniors with the capability of running the APA test under both hose pressures of 100 psi and 250 psi.

Since APA equipment at 100 psi is currently the most commonly used and widely accessible, and some laboratories may have limited resources to upgrade their equipment, the research team plans to continue testing sampled asphalt mixtures using the APA at both 100 psi and 250 psi. The research team aims to determine any potential correlation between the APA at the two different pressure levels. Additionally, the possibility of testing at 100 psi and higher temperatures will be explored to simulate potential increases in stress levels in airfield pavements.

Test Load Rate

Traffic speed and number of loading repetitions differ significantly between highway and airfield pavements. While 70 mph represents typical highway traffic speed, airfields are subjected to a wider range of speeds across different airfield sections (Rushing & Garg, 2017), as shown in the following list:

- Speed ≥45 mph for central portions of runways.
- Speed 15 to <45 mph for taxiways and runway ends without aircraft stacking.
- Speed 5 to <15 mph for taxiways and runway ends with occasional aircraft stacking.
- Speed <5 mph for taxiways and runway ends with frequent aircraft stacking.

Moreover, airfield pavements experience a lower number of load repetitions compared to highways, which are typically quantified in terms of equivalent single axle loads (ESALs). Highways with moderate to heavy traffic are typically subjected to 10 to 30 MESALs over 20 years. Whereas airfields can be subjected to total annual departures ranging from 50,000 operations (e.g., Reno Stead, a reliever airport) up to 335,000 operations (e.g., Newark, a primary large airport) (FAA, 2023; Airport-Data.com, n.d.; FAA, 2021a). Setting new frequencies for the APA and HWT test machines (i.e., passes/min) can be challenging for many contractors when evaluating highway and airfield asphalt mixtures using the same laboratory equipment. It is worth noting that the aforementioned differences between highways and airfields, in terms of speed and load repetitions, can be further addressed through rutting test limits and/or test temperature. Therefore, the experimental plan of this project will conform to the common wheel pass frequency for the APA and HWT specified in the standard test method of 60 and 52 passes/min, respectively (AASHTO, 2022d; NAPA, n.d.).

For HT-IDT and IRT monotonic tests, a load rate of 50 mm/min has been commonly used for both tests in previous research studies and standard test methods (Christensen & Bonaquist, 2007; ASTM, 2017b; ASTM, 2022; Alabama DOT, 2022; Advanced Asphalt Technologies, 2011; Hajj, et al., 2025). The use of the HT-IDT began in the 1990s, when researchers investigated triaxial testing for assessing the rut resistance of asphalt mixtures. As a result, an abbreviated test protocol was developed for HT-IDT performed at 3.75 mm/min and 20 °C below the critical pavement temperature for rutting (i.e., annual 7-day average maximum pavement temperature 20 mm below pavement surface) (Christensen & Bonaquist, 2007). The test conditions were adopted to approximately simulate the rheological conditions existing in the pavement at the critical high temperature, as per the authors, while allowing a reasonably slow loading rate that could be run easily in the laboratory. The HT-IDT results at 3.75 mm/min have shown very good correlations with the Superpave Shear Tester (SST) AASHTO T 320 results as well as with some field rutting data (Christensen & Bonaquist, 2007; Christensen, Bennert, Bonaquist, & McQueen, 2010). However, Christensen and Bonaquist explored a simplified procedure to expedite the failure so that the test could be run at room temperature after proper conditioning. Thus, the new loading rate of 50 mm/min was investigated at 10 °C higher than the preceding test temperature (Christensen & Bonaquist, 2007). Subsequently, the HT-IDT results indicated excellent correlation between both loading rates at different temperatures, with the strength values at 50 mm/min being slightly higher than those determined using the original protocol at 3.75 mm/min. Therefore, Christensen and Bonaquist recommended in 2007 the HT-IDT strength test with the loading rate of 50 mm/min to be conducted at 9 °C below the critical pavement temperature for rutting (Christensen & Bonaquist, 2007). Afterward, NCHRP Project 09-33 recommended performing the HT-IDT test at 10 °C below the critical pavement temperature, while slightly bumping the criteria derived from the original protocol at 3.75 mm/min (Advanced Asphalt Technologies, 2011).

Chapter 7. Rutting Test Criteria

This section reviews and explores different approaches for establishing rutting test criteria for airfield pavements. These alternatives include reviewing rational for the current FAA rutting test criteria and summarizing previous APA airfield criteria; associating mix design data with initial field performance of existing airfield pavements; analyzing data from FAA testing facilities; and refining highway HT-IDT criteria for airfield conditions based on the tire resistivity model and equivalent highway ESALs (EHEs).

Review of Current FAA criteria

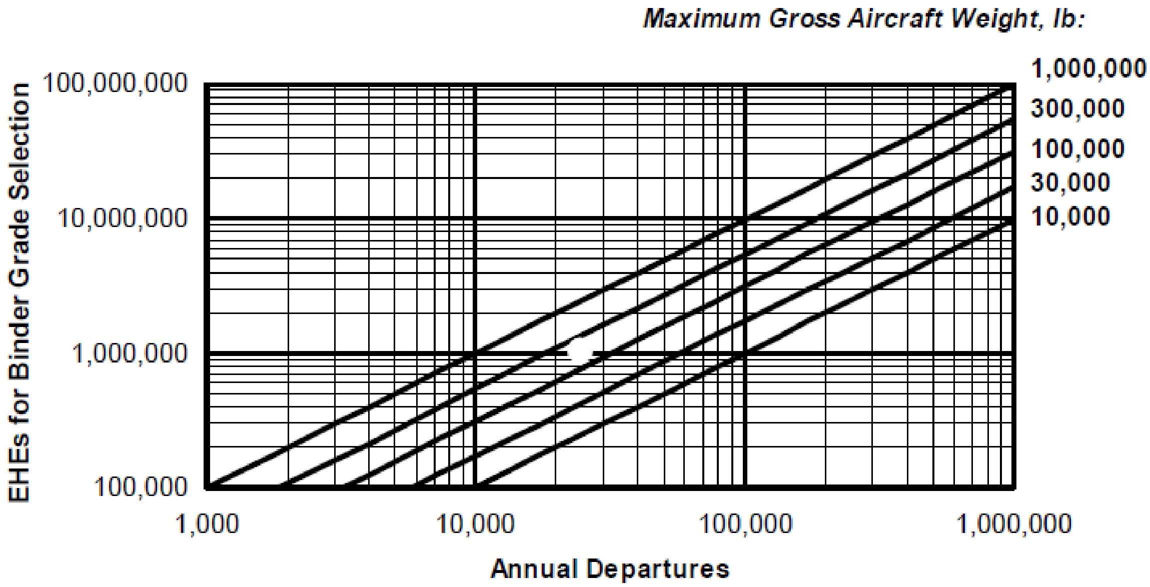
In 2010, Christensen et al. developed a set of preliminary APA criteria for airfield asphalt mixtures (Table 35) (Christensen et al., 2010; Christensen, 2013). The APA test was conducted at 250 psi hose pressure, 250 lb load, and at the average 7-day maximum pavement temperature 20 mm below the surface with 50 percent reliability (LTPPBind 3.1) (FHWA, n.d.-f). The APA rut depth criteria were developed as a function of the traffic in terms of the EHEs that determined using the methodology in the Airport Asphalt Pavement Technology Program (AAPTP) 04-02 study (Christensen et al., 2008). The EHE was defined in the AAPTP 04-02 study as an alternative for highway ESALs to select appropriate binder PG for airfield pavements. Following the AAPTP 04-02 recommendations, the EHE can be calculated based on the GAW and number of arrivals/departures using Figure 16 (Christensen et al., 2008). The EHE estimation was based on thorough research accounting for all the differences between airfields and highways mentioned in this methodology (VMA, surface area, design compaction, etc.) along with other major components such as high tire pressure, reliability, traffic growth, and annual departures (Christensen et al., 2008).

Table 35. Preliminary APA Test Criteria for Airfield Asphalt Mixtures (Christensen et al., 2010; Christensen, 2013)

EHE Traffic Level (MESALs)	Maximum APA Rut Depth at 8,000 Cycles (mm)[1]
<3	–
3 to <10	8
10 to <30	6
30 to <100	5
100 to <300	4
≥300	3

[1]Rut depth at 250 psi and at a temperature equal to average 7-day maximum pavement temperature 20 mm below surface with 50% reliability (LTPPBind 3.1).

– = Not applicable.



Source: Airport Asphalt Pavement Technology Program

Figure 16. EHE Calculation as a Function of Annual Departures and Maximum GAW (Christensen, Bahia, & McQueen, 2008)

In 2012, Rushing et al. initiated an effort for using the APA during mix design to examine the rutting potential of airfield asphalt mixtures under high tire pressure (Rushing et al., 2012). To evaluate the APA suitability at the mix design and QA stages, the study incorporated different HMA designs with a wide range of rutting resistance (Rushing et al., 2012). The evaluated asphalt mixtures included three aggregate types (limestone, granite and chert gravel) where different stockpiles were blended for each aggregate type to target blend gradations within the FAA specifications. Fine- and coarse-blend gradations were targeted, with some including 10 percent and 30 percent mortar sand. The asphalt mixtures were designed to 3.5 percent AV at 70 gyrations using a PG 64-22 asphalt binder.

A total of 33 LMLC samples were evaluated using the APA (Rushing et al., 2012). Test specimens were 150 mm in diameter by 75 mm tall with a target AV of 3.5 percent. The APA was run at the asphalt binder PGH of 64 °C with a 250-psi hose pressure and 250-lb wheel load to simulate aircraft high tire pressure, along with a rate of one cycle per second. APA rut depths as a function of loading cycles are shown in Figure 17. During the initial load cycles, the APA rut depth of the evaluated asphalt mixtures accumulated at a high initial rate. After 1 mm rut depth, the rates of rutting progression started deviating according to the asphalt mixture characteristics, then became linear after approximately 2 mm rutting. The study noticed a similar general pattern of rutting progression between the APA and creep repeated-loading tests with primary and secondary flow, without capturing the tertiary flow. For 0-percent and 10-percent natural sand, asphalt mixtures with crushed limestone aggregates exhibited highest rutting resistance, followed by crushed granite mixtures and crushed chert gravel. The asphalt mixtures with 30-percent natural sand, which exceeds the maximum allowed by FAA of 15 percent, failed quickly as expected with less than 1,500 cycles (Rushing et al., 2012).

When setting the criterion, Rushing et al. (2012) targeted 8- or 10-mm maximum rut depth and a number of cycles that would result in a reasonable test duration (around 1 hr) for ease of future implementation, while still allowing differentiation between the performance of different mixtures. A criterion of 10 mm APA rut depth after 4,000 cycles under 250 psi high-tire-pressure aircraft was recommended. This maximum threshold would have excluded 18 of the 33 tested asphalt mixtures. Eleven of the 18 failing mixtures were unacceptable due to excessive natural sand, and 5 of the remaining 7 mixtures included chert gravel aggregates that are not commonly used in airport pavements. Rushing et al. (2012) recommended adjustments for asphalt binder content and gradation as key components to improve rutting behavior of asphalt mixtures.

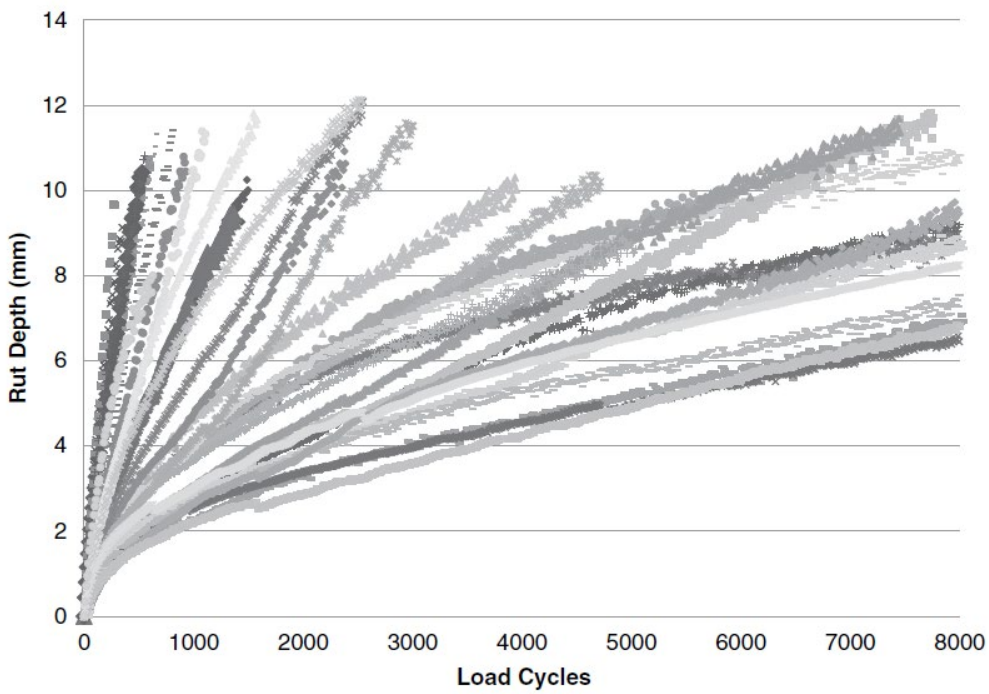


Figure 17. APA Test Results at 250 psi for Airfield Asphalt Mixtures

Source: Reproduced from *Asphalt Pavement Analyzer Used to Assess Rutting Susceptibility of Hot-Mix Asphalt Designed for High Tire Pressure Aircraft*, by J. F. Rushing, D. N. Little, and N. Garg in *Transportation Research Record*, 2296(1), 97–105. Reprinted with permission.

In 2014, Rushing et al. expanded the experimental matrix for APA testing of airfield pavements with eight additional asphalt mixtures prepared using a PG 76-22 polymer-modified asphalt binder (Rushing et al., 2014). The asphalt mixtures used the same asphalt binder content of the corresponding PG 64-22 asphalt mixtures. The samples were tested with APA under similar conditions and a test temperature of 64 °C. The study showed that the polymer-modified asphalt binder enhanced the APA performance for all evaluated asphalt mixtures and made the chert gravel mixtures pass the set criterion of 10 mm rut depth after 4,000 cycles.

In an attempt to validate the established APA test criterion, the same airfield mixture was used in two field experiments, one under severe conditions and the other under moderate conditions for load and temperature (Table 36) (Rushing et al., 2014). The employed asphalt mixture consisted of 45 percent crushed aggregates, 40 percent limestone, and 15 percent natural sand with an unmodified PG 67-22. The APA rut depth of the PMLC samples was 10.5 mm after 4,000 cycles. In terms of field performance, different field observations were reported for the same mixture under different climatic and traffic conditions from both field experiments. Finally, the proposed maximum APA rut depth of 10 mm after 4,000 cycles was validated by eliminating any mix with field performance worse than Field Trial 1. Rushing et al. considered that most airfield pavements do not experience in real life such accelerated loading, high tire pressure, and constant elevated temperature as in Field Trial 1 (Rushing et al., 2014).

Table 36. Field Trial Validation for APA 250 psi Test Criteria at 4,000 Cycles (Rushing et al., 2014)

Test Conditions and Results	Field Trial 1 (Severe Conditions)	Field Trial 2 (Moderate Conditions)
Wheel Load, lb	32,000	45,000
Tire Pressure, psi	325	142
Temperature, °C	43	25
Number of Passes to 25.4 mm Surface Rutting	3,000	75,000

Note: APA rut depth at 250 psi of PMLC mixture = 10.5 mm after 4,000 cycles.

As part of the same study in 2014, Rushing et al. investigated the capability of the APA test to eliminate asphalt mixtures with excessive asphalt binder content. Asphalt mixtures with 0.4 percent increase in the optimum binder content still passed the set criteria for APA at 250 psi. However, the asphalt mixture failed the APA test criteria at 250 psi when an additional 0.9 percent asphalt binder content was used (Rushing et al., 2014).

Consequently, the APA rutting test was considered suitable for asphalt mix design with potential use for QA due to its simple procedure, adequate ranking of asphalt mixtures, and efficiency to test field cores with 76 mm thickness or less. The recommended APA criterion under 250 lb load and 250 psi hose pressure at 64 °C was further used in several airfield applications, including asphalt mixture sampled from March Air Reserve Base in California, from the Accelerated Pavement Test Facility at the U.S. Army Engineer Research and Development Center (ERDC), and from Columbus Air Force Base (Rushing, McCaffrey, & Warnock, 2014).

In 2018, an APA rut depth criterion of 5 mm after 8,000 cycles and 100 psi was derived from the correlation with the APA rut depths at 250 psi established using the FAA National

Airport Pavement and Materials Research Center (NAPMRC) test cycle (TC) 1 data (Figure 18) (Garg, 2018).

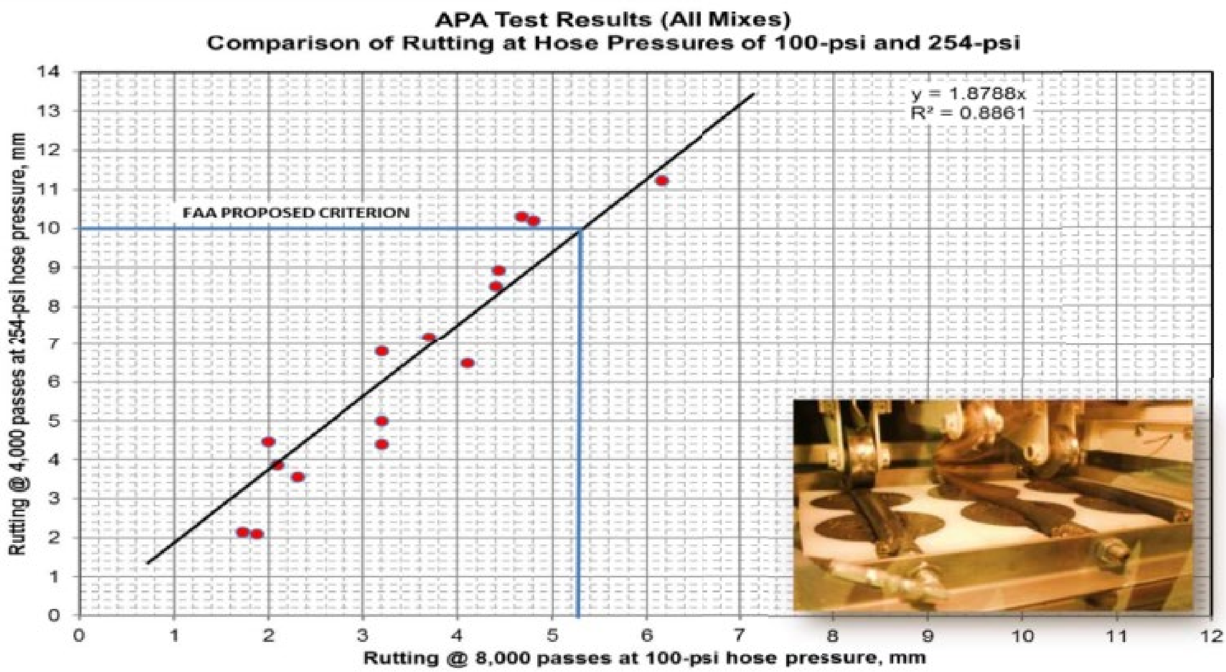


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Figure 18. Correlation Between APA 100 and 250 psi Test Data (NAPMRC TC1)

Source: Navneet Garg, *FAA Research on Pavement Design and Materials for New Generation Aircraft,* presentation at Airport Engineering Seminar, University of North Carolina Charlotte Professional Development Program (Garg, 2018). Used with permission.

As for the maximum HWT rut-depth criteria of 10 mm after 20,000 cycles, no literature has been found on the rationale behind developing the set value for airfields. Therefore, the experimental plan of this project includes verifying and/or refining current HWT rut depth criteria for airfield conditions.

Review of Preliminary Airfield Pavement Performance

Correlating results of laboratory mechanical tests with field performance of airfield pavements is a necessary step prior to the implementation of rutting performance specifications. Thus, mix design and rutting test data for existing airfield pavements were gathered along with their corresponding initial field performance after several years of service. Table 37 summarizes the reviewed airfield mixtures. Unfortunately, the detailed mix designs and pavement structures were not provided for most of the tabulated airfield projects. Considering that these asphalt mixtures were labeled as P-401 mix type, a general assumption could be made that they were used as surface layer.

Table 37. Characteristics of Evaluated Airfield Mix Designs

Mix ID	Airport	State	Mix Type	NMAS, mm	In-Place Years of Service
1	Philadelphia International Airport (PHL)	Pennsylvania	P-401	–	–
2	Philadelphia International Airport (PHL)	Pennsylvania	P-401	–	–
3	Philadelphia International Airport (PHL)	Pennsylvania	P-401	–	–
4	Newark Liberty International Airport (EWR)	New Jersey	P-401	12.5	–
5	Newark Liberty International Airport (EWR)	New Jersey	P-401	12.5	–
6	Newark Liberty International Airport (EWR)	New Jersey	P-401	12.5	–
7	Hollywood Burbank Airport (BUR), Taxiway D7, G Infield, Delta Ramp (PG 76-22M)	California	P-401	19.0	2.5
8	Hollywood Burbank Airport (BUR), Taxiway D7, G Infield, Delta Ramp (PG 70-10)	California	P-401	19.0	2.5
9	Blue Grass Airport (LEX), Runway 4-22 and Taxiway A Rehab Runway 4-22 Departure (PG 76-22M)	Kentucky	P-401	19.0	2.7
10	Sacramento International Airport (SMF), Taxiway Delta, Whiskey, Yankee Rehab (PG 76-22M)	California	P-401	19.0	2.7

–= Not available.

Each airfield mixture with APA or HWT laboratory data has been linked with either satisfactory or unsatisfactory feedback regarding its field performance (Table 38). The APA test was performed at 64 °C, whereas the HWT test was run at 50 °C following the current FAA specifications (FAA, 2018). Interestingly, some of the tabulated APA data corresponds to samples at mix design AV, while others correspond to 7±0.5 percent AV. The observed AV discrepancy between different samples is caused by one of the previously mentioned limitations of the current FAA specifications. In fact, some laboratories test their mix-design samples (i.e., at mix-design AV) with the APA, because current APA airfield criteria were based on previous research performed on samples at mix-design AV. Thus, a side note in the FAA advisory circular allows contractors to send their mix-design samples for APA testing. Other laboratories, however, follow the APA and HWT standard test methods (AASHTO T 340 and AASHTO 324) referred to in the FAA specifications, which require testing the samples at 7±0.5 percent AV (AASHTO, 2020; AASHTO, 2022d).

Based on the data in Table 38, the 100 psi APA rut depth after 8,000 cycles ranged from 1.55 to 2.98 mm at mix-design AV with an average of 2.42 mm, and from 2.15 to 3.01 mm at 7 percent AV with an average of 2.71 mm. One of the airfield mixtures included HWT rut depth of 4.56 mm after 20,000 cycles at 7±0.5 percent AV. It can be inferred that all presented airfield mixtures with acceptable preliminary field performance had significantly lower rut depths than current APA 100 psi and HWT FAA criteria.

Table 38. Airfield Mix Design Data with Preliminary Field Performance

Mix ID	Specimen AV%	Specimen Type	APA Rut Depth at 64 °C and 8,000 Cycles (mm)[1] (Criteria ≤5 mm)	HWT Rut Depth at 50°C and 20,000 Cycles (mm) (Criteria ≤10 mm)	Acceptable Preliminary Field Performance (Yes or No)?
1	3.5±0.5	LMLC	1.55	–	Yes
2	3.5±0.5	LMLC	2.90	–	Yes
3	3.5±0.5	LMLC	2.09	–	Yes
4	3.5±0.5	PMLC	2.31	–	Yes
5	3.5±0.5	PMLC	2.70	–	Yes
6	3.5±0.5	PMLC	2.98	–	Yes
7	7±0.5	LMLC	2.96	–	Yes
8	7±0.5	LMLC	3.01	–	Yes
9	7±0.5	LMLC	2.15	–	Yes
10	7±0.5	LMLC	–	4.56	Yes

[1]APA test was run according to AAHTO T 340 under 100 psi hose pressure and 100 lb.
–= Not available.

Review of FAA Testing Facility Data

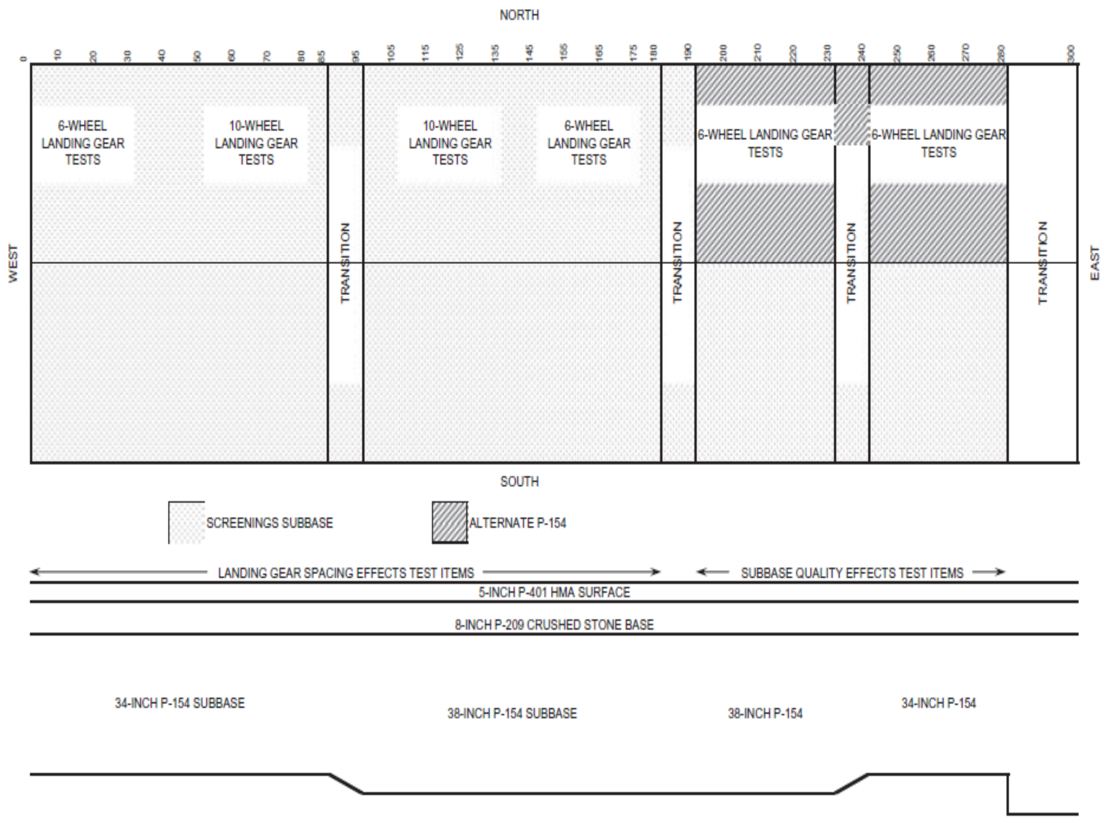
The FAA testing facilities data were reviewed by means of rutting laboratory test data and field measurements of the accelerated tested sections. The FAA full-scale pavement testing facilities include NAPMRC and the National Airport Pavement Test Facility (NAPTF) (FAA, n.d.-d; FAA, n.d.-a; FAA, n.d.-e). The Heavy Vehicle Simulator, Airfields Mark VI (HVS-A), with a maximum wheel load of 100,000 lb and significant wander capabilities, is used on NAPMRC test sections. In contrast, the NAPTF is trafficked with the National Airport Pavement Test Vehicle (NAPTV), a rail-based vehicle with two loading carriages that can be configured with up to 10 wheels per carriage, a maximum wheel load of 75,000 lb, and a controlled aircraft-simulation wander. It is worth mentioning that the NAPTF is a fully enclosed test track, whereas the NAPMRC has four outdoor and two indoor test lanes with an automated heating system in the HVS-A that can replicate high pavement temperatures in summer, even during winter time (FAA, n.d.-d; FAA, n.d.-a; FAA, n.d.-e). Prior to the performance data analysis, the NAPTF indoor construction cycles (CCs) were verified to perceive representative climatic conditions (i.e., not controlled continuously at low or intermediate temperatures). The temperature sensor data of construction cycles 5 and 7 (CC5 and CC7) were reviewed by the FAA BMD rutting research team to reach a maximum pavement temperature around 43 °C, allowing rutting progressive accumulation.

The different CCs of the NAPTF were reviewed for rutting test data relevant to any of the four rutting tests considered in this project (i.e., APA, HWT, HT-IDT, and IRT). The first two CCs with flexible test sections (CC1 and CC3) involved only Marshall stability test data, thus no further analysis was conducted on CC1 and CC3. As for CC9, while laboratory test data were received from the FAA NextGen Pavement Materials Laboratory, the final traffic report with measured field rutting and section profiles are not yet available. Hence, this effort focused mainly on the analysis of the data from CC5 and CC7, and the findings are summarized as follows.

NAPTF CC5

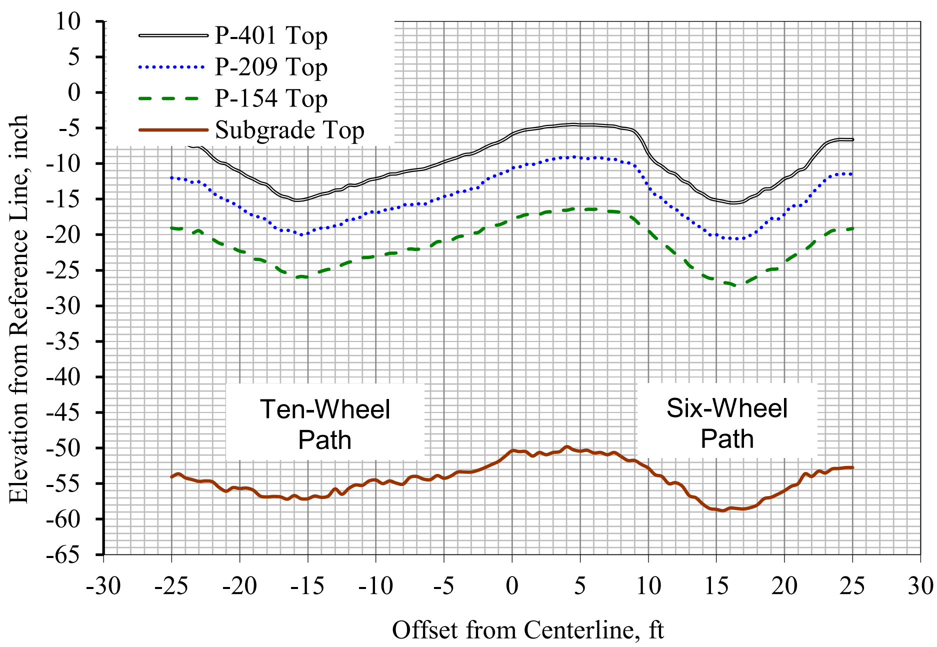
The north and south test sections of CC5, shown in Figure 19 with 12.7-cm-thick AC surface layer, were trafficked with either a 10-wheel landing gear configuration (center to center spacing of 290 cm between the 6- and 4- wheel landing gears) under 50,000 lb wheel load or with a 6-wheel landing gear configuration (designated as the subbase quality effects test items) under 59,000 lb wheel load (FAA, n.d.-b). The tire pressure during traffic testing was maintained at 243 psi for all test sections. AC cores were extracted after 12,408 passes from the trafficked area without any significant sign of rutting in the AC layer. This has been observed as well in the pavement trench profiles (example shown in Figure 20), where rutting was mainly associated with permanent deformation in unbound aggregate layers. Therefore, the P-401 layer showed adequate rutting resistance in the field under the particular conditions of NAPTF CC5 (FAA, 2010).

Loose field samples from the P-401 mixture used in CC5 were tested with the APA under 100 psi hose pressure at 5±0.5 percent AV. APA test results are shown in Figure 21, with a rut depth of 0.42 mm and 5.55 mm after 8,000 cycles was measured at 25 °C and 64 °C test temperature, respectively (Garg, Bennert, & Brar, 2009). The P-401 mixture of the CC5 failed the current FAA APA test criteria of 5 mm after 8,000 cycles even at 5 percent rather than 7 percent AV. Considering the significant amount of rutting in the CC5 unbound layers (refer to Figure 20), the P-401 mixture did not exhibit high rutting in the field. Should less rutting have occurred in the unbound layers, the P-401 mixture would have been expected to rut more significantly in the field and be consistent with the failing APA test results.



Source: Federal Aviation Administration

Figure 19. FAA NAPTF CC5 Test Sections (FAA, n.d.-b)



Source: Federal Aviation Administration

Figure 20. Pavement Layer Profile Measurements—LFC1 Test Section NE&SE (East Face) (FAA, 2010)

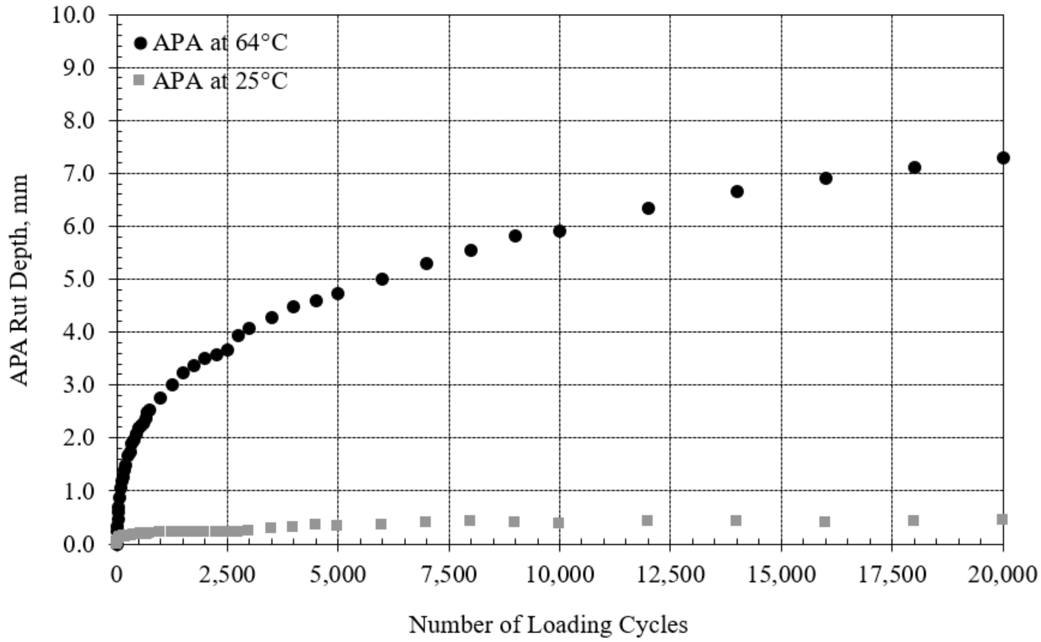


Figure 21. APA 100 psi Hose Pressure and 100-lb Load Rut Depth at 8,000 Cycles

Source: Reproduced from *Performance of Hot Mix Asphalt Surface under High Tire Pressure Aircraft Landing Gear Configuration at the FAA National Airport Pavement Test Facility*, by N. Garg, T. Bennert, and H. Brar in Advanced Testing and Characterization of Bituminous Materials (1st ed., Vol. 2, pp. 1311–1320), edited by A. Loizos, M. N. Partl, T. Scarpas, & I. L. Al-Qadi. Reprinted with permission.

NAPTF CC 7

The NAPTF CC7 was divided into two test areas, designated as North and South, corresponding to perpetual pavement test area with AC varying from 12.7 to 38.1 cm thick and an overload test area with a 7.6-cm AC layer, respectively (FAA, n.d.-c). The perpetual pavement North sections were subjected to 255 psi tire pressure at 2.5 mph with a 55,000 to 65,000-wheel load in a 3D gear (6 wheels) configuration. On the other hand, the South sections were trafficked with D (dual wheels), 2D (4 wheels), and 3D (6 wheels) gear configurations at 200 psi and 2.5 mph speed with wheel loads ranging from 34,500 up to 62,500 lb.

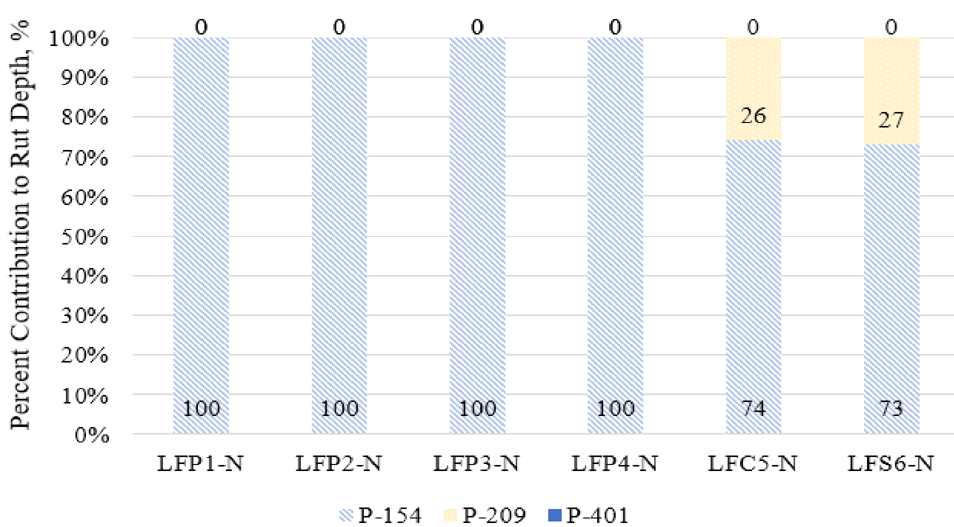
Post-traffic APA data at 64 °C are presented in Table 39 for the P-401 layer based on 150 mm cores extracted from the non-trafficked area away from upheaval (General Dynamics, 2019b). It is worth noting that the pre-trafficked APA rut depth was reported in the CC7 test report as 4 mm after 4,000 passes. As expected, the APA rut depth under 100 psi was lower than the 250 psi test. The APA rut depth under 250 psi was 195 percent, 37 percent, and 135 percent higher than the 100 psi rut depth for north side cores at –5 offset, north side cores at –25 offset, and south side cores, respectively. A comparative analysis of both binder grades indicates that the PG 64-22 rutted 29 percent and 49 percent more than the PG 76-22 asphalt mixture, under 100 psi and 250 psi hose pressure, respectively.

Table 39. Summary of APA Rut Depth (mm) at 4,000 Cycles and 64 °C for North and South Sides (General Dynamics, 2019b)

Wheel Location	AV%	Left	Center	Right
		North Side (PG 76-22)		
100 psi (–5 OS)	8.4	2.31	2.65	2.43
250 psi (–5 OS)	9.5	4.88	8.06	8.89
100 psi (–25 OS)	6.7	3.32	3.34	3.68
250 psi (–25 OS)	5.4	4.57	4.96	4.65
		South Side (PG 64-22)		
100 psi	5.0	3.63	4.22	3.62
250 psi	5.9	9.43	8.50	5.58

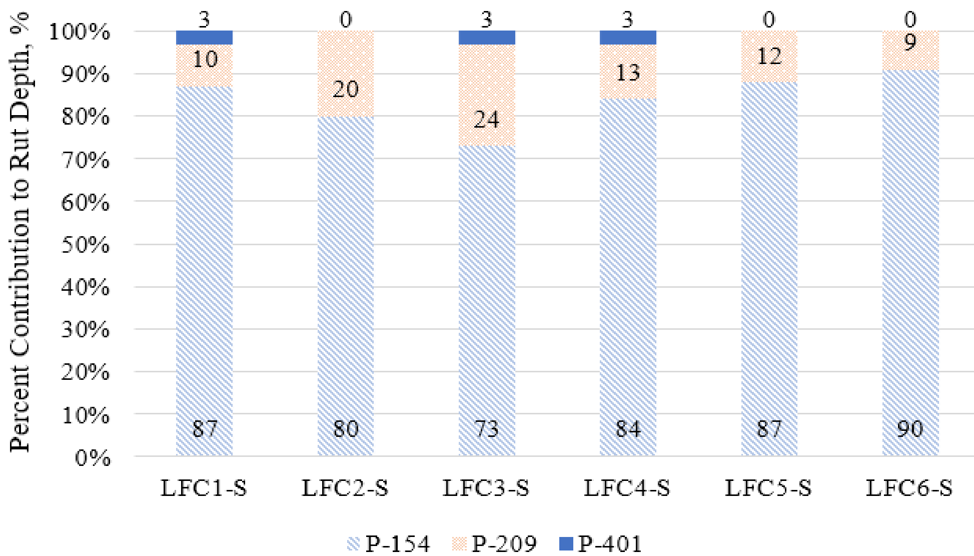
OS = cores offset from centerline.

As expected, the APA rut depth increased in Table 39 under 250 psi, compared to 100 psi, while still meeting the FAA current criteria of 10 mm after 4,000 cycles. Based on the analyzed heavy falling weight deflectometer, trenching profiles and multi-depth deflectometer sensors, rutting in the perpetual pavement test sections (LFP-1N and LFP-2N) was mainly contributed by the subbase. Both subbase and subgrade contributed to rutting in test sections LFP-3N and LFP-4N (General Dynamics, 2019a; Garg, Li, & Brill, 2020). No contribution from the AC layer to the total rut depth was reported for the North test sections (Figure 22), compared to a minor AC rutting in the South sections (Figure 23). Interestingly, the pre-trafficked and post-trafficked laboratory rutting data of the CC7 P-401 mixture met the FAA criteria of a maximum 10-mm APA rut depth after 4,000 cycles under 250 psi hose pressure. This could have been reflected in the field with the high rutting resistance of this asphalt mixture observed in CC7 test sections.



Source: University of Nevada, Reno

Figure 22. Percent Contribution to Rut Depth of CC7 North (General Dynamics, 2019a)



Source: University of Nevada, Reno

Figure 23. Percent Contribution to Rut Depth of CC7 South(General Dynamics, 2019a)

NAPMRC TC1

Two indoor (one HMA and one WMA) and four outdoor lanes (two HMA and two WMA) were constructed in the NAPMRC TC1. Each lane incorporated the same mix and was subdivided into three test sections, North, Center, and South, which were subjected to 254, 254, and 210 psi tire pressure maintained at 49, 32, and 49 °C, respectively(Garg et al., 2018; Garg, 2018; FAA, n.d.-e). The HVS-A testing was performed on top of a 127-mm AC layer at a speed of 3 mph with a 61,300-lb bidirectional single wheel load. The same PG 76-22 was employed for both indoor lanes (one HMA and one WMA) and two outdoor lanes (one HMA and one WMA). The two additional outdoor lanes (one HMA and one WMA) were designed with a PG 64-22 binder. The pavement sections were designed using FAARFIELD with a target to limit distresses to the surface layer with no failure to occur in the unbound materials.

Table 40 outlines the pavement test sections along with the number of passes to 25.4 mm total rut depth. Regardless of the pavement temperature and tire pressure, both HMA and WMA test lanes with PG 64-22 were found to be the worst-performing test lanes by means of number of passes to failure. On the other hand, curing and environmental aging increased the asphalt rutting resistance in the field due to the stiffening of asphalt mixtures. This was shown with the outdoor test sections with PG 76-22 outperforming the indoor sections with the same binder grade. The effect of mix type between HMA and WMA was more pronounced with PG 76-22, where the rutting resistance of PG 76-22 HMA slightly exceeded the resistance of respective WMA test sections (Garg et al., 2021). Garg et al. inferred that the magnitude and rate of rutting progression was mostly influenced by the pavement temperature. None of the center sections trafficked at 32 °C with PG 76-22 reached the failure criterion until the end of HVS-A trafficking at 5,022 passes (Garg et al., 2018).

Table 40. NAPMRC TC1 Sections and Number of Passes to Failure (25.4-mm Rut Depth) (Garg et al., 2018)

Test Sections	North (49 °C, 254 psi)	Center (32 °C, 254 psi)	South (49 °C, 210 psi)
WMA PG 76-22[a]	601	> 5,022	876
WMA PG 64-22[a]	166	2,962	248
HMA PG 76-22[a]	861	> 5,022	767
HMA PG 64-22[a]	146	2,616	281
WMA PG 76-22[b]	470	> 5,022	801
HMA PG 76-22[b]	667	> 5,022	924

[a]Outdoor sections.

[b]Indoor sections.

Note: Wheel load = 61,300 lb.

PMLC and FMFC samples from NAPMRC TC1 test sections were evaluated experimentally using the APA test at 64 °C and the HT-IDT test at 50 mm/min after conditioning the sample for 4 to 5 hr at 40 °C (Garg, 2018). Good correlation has been found between HT-IDT and APA test data per test conditions in Table 41, where the maximum rut depth of 10 mm after 4,000 cycles corresponds to a minimum HT-IDT of 30 psi, as per Figure 24. Figure 25 suggests that the minimum HT-IDT limit of 30 psi corresponds to 25.4 mm field rutting after 150 HVS-A passes. Promising correlations between the APA and HT-IDT with HVS number of passes, outlined respectively in Figure 25 and Figure 26, validate the suitability of both rutting tests to assess the rutting resistance of airfield mixtures.

Table 41. NAPMRC TC1 Laboratory Test Conditions (Garg et al., 2018; Garg, 2018)

Factors	HT-IDT	APA
Test Temperature, °C	40	64
Loading Rate, mm/min	50	–
Loading Pressure, psi	–	254
AV Level (PMLC), %	3.5	3.5
AV Level (FMFC), %	2.1–5.3	Not available

– = Not applicable.

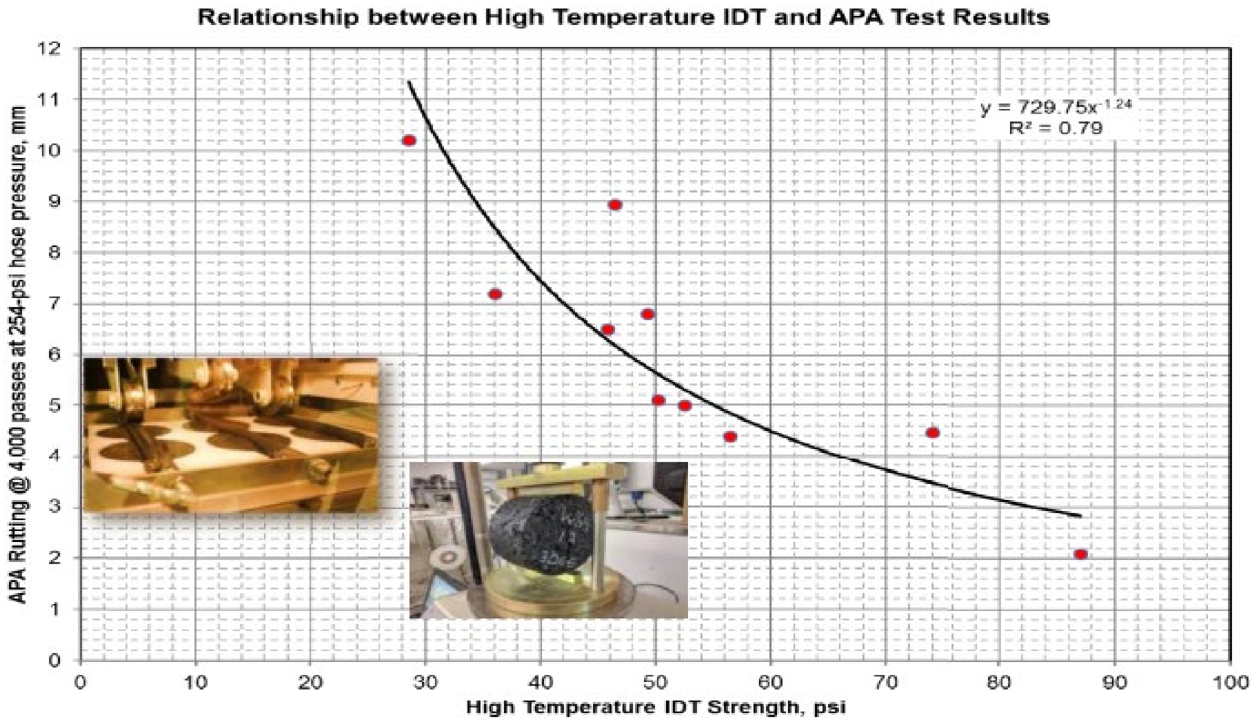


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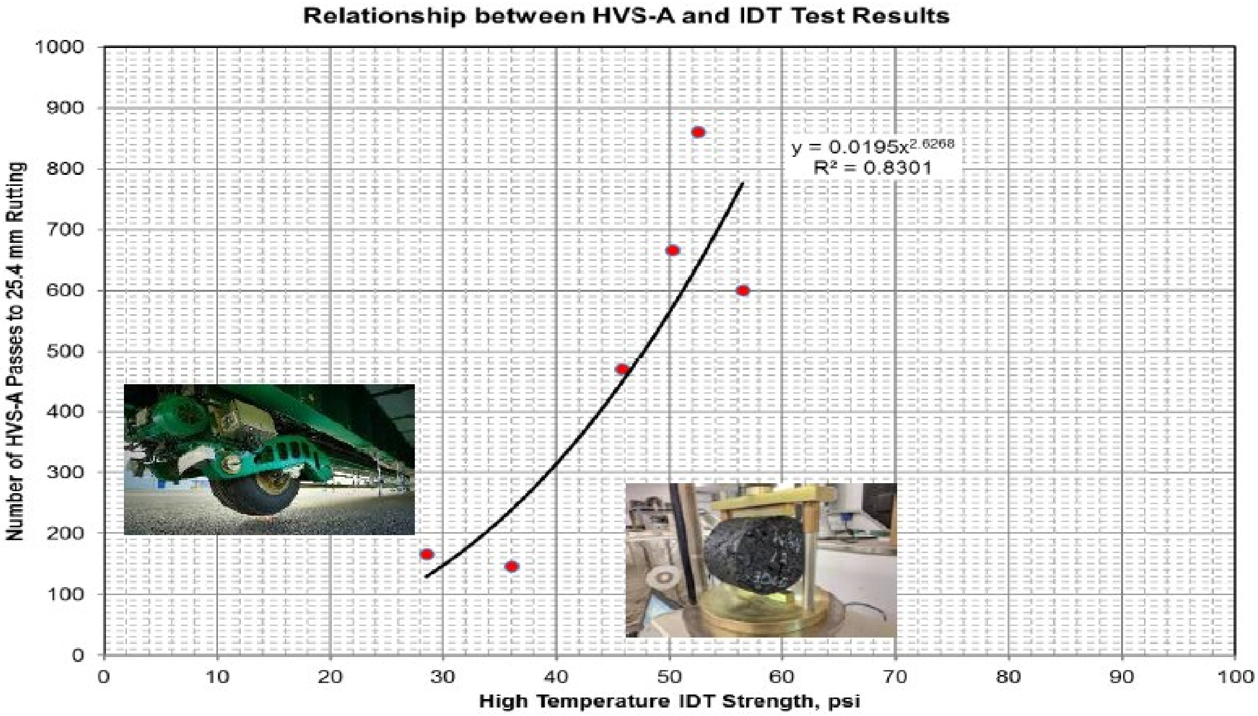
Figure 24. NAPMRC TC1 HT-IDT Results vs. APA 250 psi Rut Depth After 4,000 (Cores and Laboratory-Compacted)

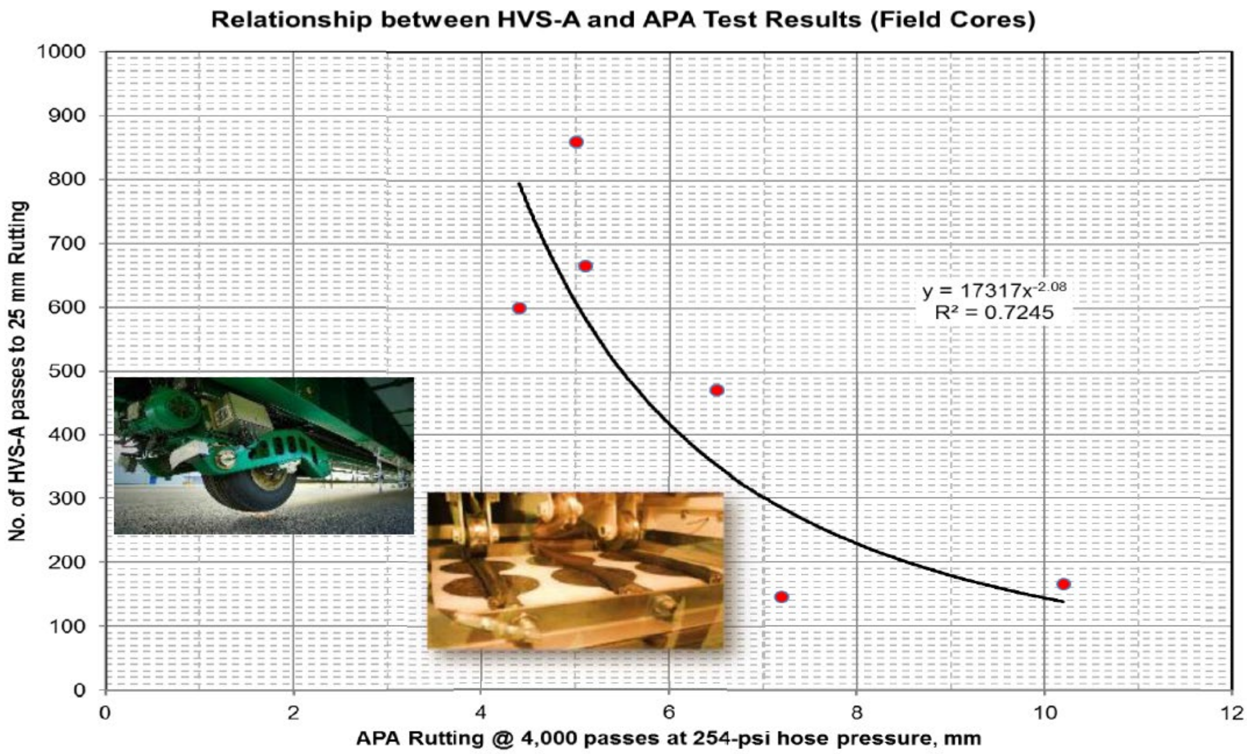
Source: Navneet Garg, *FAA Research on Pavement Design and Materials for New Generation Aircraft,* presentation at Airport Engineering Seminar, University of North Carolina Charlotte Professional Development Program (Garg, 2018). Used with permission.



Source: Navneet Garg

Figure 25. NAPMRC TC1 HT-IDT Core Results vs. Number of HVS-A Passes to 25.4 mm Rutting

Source: Navneet Garg, *FAA Research on Pavement Design and Materials for New Generation Aircraft,* presentation at Airport Engineering Seminar, University of North Carolina Charlotte Professional Development Program (Garg, 2018). Used with permission.



Source: Navneet Garg

Figure 26. NAPMRC TC1 APA 250 psi Rut Depth After 4,000 vs. Number of HVS-A Passes to 25.4 mm Rutting (Cores)

Source: Navneet Garg, *FAA Research on Pavement Design and Materials for New Generation Aircraft,* presentation at Airport Engineering Seminar, University of North Carolina Charlotte Professional Development Program (Garg, 2018). Used with permission.

Chapter 8. HT-IDT Criteria Based on EHE

Background

The tire resistivity model was initiated in NCHRP Projects 09-25 and 09-31 to evaluate the effect of different asphalt mixture properties on the relative resistance of the mixture to rutting (Christensen & Bonaquist, 2006). Field rutting data from the Minnesota Road Research Facility (MnROAD), NCAT, and WesTrack projects were used to calibrate the rutting resistivity model (Advanced Asphalt Technologies, 2011). The model was further refined in the NCHRP 09-33 project. Equation 1 shows the latest version of the model, which gives the allowable traffic as a function of the asphalt mixture composition, compaction, and AV to maintain a certain rut depth in the field (Advanced Asphalt Technologies, 2011).

$$\boldsymbol{TR = 9.85 \times 10^{-5}(PNK_s)^{1.373}\, V_{QC}{}^{1.5185} V_{IP}{}^{-1.4727} M} \qquad \textbf{Equation 1}$$

Where:

TR = MESALs to an average rut depth of 7.2 mm (50-percent confidence level).

= MESALs to a maximum rut depth of 12 mm (95-percent confidence level).

P = resistivity, s/nm = $\frac{(|G^*|/\sin\delta)S_a{}^2 G_a{}^2}{49VMA^3}$

$(|G^*|/\sin\delta)$ = Estimated aged performance grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPPBind, Version 3.1 (units of Pa); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short-term projects of 1 to 2 years.

S_a = specific surface of aggregate in mixture, m^2/kg ≈ the sum of the percent passing the 75-, 150-, and 300-micron sieves, divided by 5.0 ≈ 2.05 + (0.623 × percent passing the 75-micron sieve).

G_a = bulk specific gravity of the aggregate blend.

VMA = voids in the mineral aggregate for the mixture as determined during QA testing, percent.

N = Design gyrations.

K_s = speed correction = $(v/70)^{0.8}$ where v is the average traffic speed in km/hr.

V_{QC} = AV content determined during QA testing at design gyrations, percent.

V_{IP} = in-place AV content, volume percent.

M = 7.13 for mixtures containing typical polymer-modified asphalt binders, 1.00 otherwise.

A simplified version of the model after inserting the resistivity and all different parameters can be found in Equation 2 to give an alternate form for allowable traffic (Advanced Asphalt Technologies, 2011):

$$\boldsymbol{TR = 4.71 \times 10^{-7}(|G^*|/\sin\delta)^{1.373} S_a^{\;2.746} G_a^{\;2.746} VMA^{-4.119} N_{eq}^{\;1.373} K_s^{\;1.373} V_{QC}^{\;1.5185} V_{IP}^{\;-1.4727} M} \qquad \textbf{Equation 2}$$

The maximum allowable traffic from the rutting resistivity model was correlated to the HT-IDT values measured at an average of 4 percent AV (Figure 27) (Advanced Asphalt Technologies, 2011). A good correlation was observed and allowed for deriving the HT-IDT strength criteria for different highway traffic levels. Considering that the HT-IDT suggested protocol to test at 50 mm/min loading rate and 10 °C below the critical high pavement temperature generates HT-IDT strength values 10 percent higher than the original protocol followed in Figure 27, the plotted HT-IDT values were adjusted by 10 percent to derive the proper criteria (Christensen & Bonaquist, 2007; Advanced Asphalt Technologies, 2011). Accordingly, minimum HT-IDT values were recommended for each traffic level in Table 42, where the traffic level used to estimate the HT-IDT strength was the midpoint of each traffic range (i.e., 6.5 MESALs for a range of 3–10 MESALs, 20 MESALs for 10–30 MESALs, and 65 MESALs for greater than 30 MESALs).

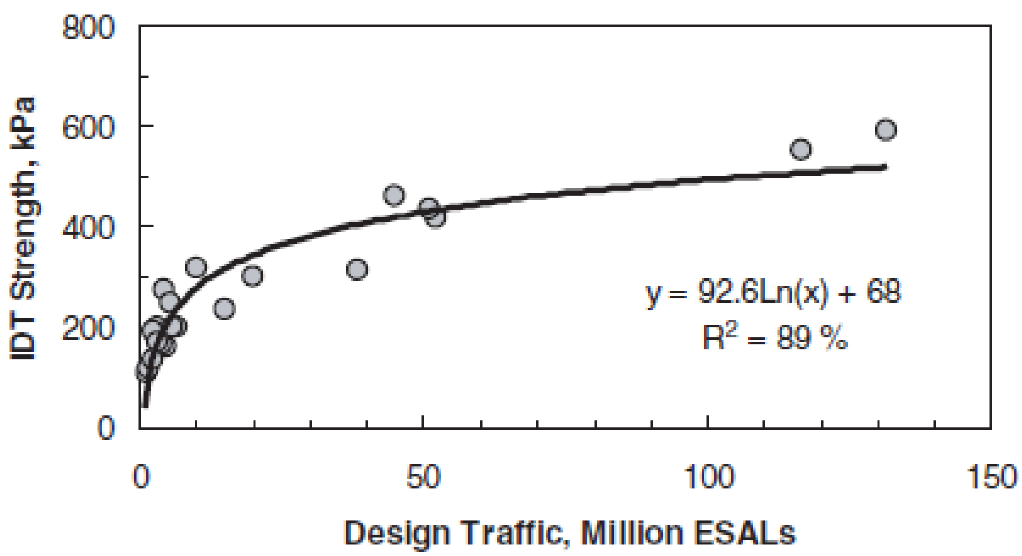


Figure 27. Plot of HT-IDT Strength vs. Estimated Allowable MESALs for NCHRP 09-25 and 09-31 Data

Source: Reproduced from *NCHRP Report 673: A Manual for Design of Hot-Mix Asphalt with Commentary*, produced by Advanced Asphalt Technologies, 2011, for the National Cooperative Highway Research Program, Transportation Research Board, National Academies Press. Reproduced with permission of the Cooperative Research Programs. No endorsement is implied.

Table 42. Minimum HT-IDT Strength Criteria as a Function of Highway Traffic Level (Advanced Asphalt Technologies, 2011)

Traffic Level, MESALs	Minimum Highway HT-IDT Strength, psi[a, b]
<3	–
3 to <10	39 (270 kPa)
10 to <30	55 (380 kPa)
≥30	73 (500 kPa)

[a]Specimens compacted to N_{design} (AV close to 4.0%), tested at 10 °C below average, 7-day maximum pavement temperature, 20 mm below surface at 50% reliability determined using LTPPBind, Version 3.1.

[b]Specimens wrapped tightly in plastic or placed in a heavy-duty, leakproof plastic bag and conditioned in a water bath at test temperature for 2 hr ±10 min.

– = Not applicable.

Application of the Rutting Resistivity Model to Airfield Mixtures

Differences in asphalt mixture composition, vehicle speed, and laboratory and field compaction between highways and airfields can have a significant effect on the rutting resistance of AC pavements. This can be quantified using the rutting resistivity model shown in Equation 2. The model input parameters will be further modified in the next section to account for special airfield pavement conditions relative to highway pavements. This will further help in computing the final ratio of the allowable traffic between airfield and highway pavements. The following are the six input parameters modified in the developed rutting resistivity model:

- VMA.
- Aggregate surface area.
- Design compaction effort.
- Vehicle speed.
- AV percent of QA laboratory-compacted samples.
- In-place AV percent.

This methodology is similar to the approach followed in the AAPTP 04-02 project to quantify the EHEs for airfield pavements (Christensen et al., 2008). The six aforementioned parameters were quantified for highways and airfields, respectively, to get the ratio of $\frac{TR_{Airfield}}{TR_{Highway}}$ (i.e., $\frac{Airfield\ Allowable\ ESAL}{Highway\ Allowable\ ESAL}$) as per Equation 3 and Equation 4. The parameters were summarized and then justified for both pavement types in Table 43 and Table 44, respectively, leading to a ratio of $\frac{TR_{Airfield}}{TR_{Highway}} = 0.22$. In other words, the allowable traffic for airfield mixtures is 22 percent of the allowable traffic of highway mixtures, considering the modified parameters between both pavement types. This was expected due to the higher VMA, lower surface area, lower design compaction effort, lower speed, and lower QA AV percent in the case of airfield pavements.

$$\frac{TR_{Airfield}}{TR_{Highway}} = \left(\frac{VMA_2}{VMA_1}\right)^{-4.199} \left(\frac{S_{a2}}{S_{a1}}\right)^{2.746} \left(\frac{N_2}{N_1}\right)^{1.373} \left(\frac{V_{s2}}{V_{s1}}\right)^{1.098} \left(\frac{V_{QC2}}{V_{QC1}}\right)^{1.5158} \left(\frac{V_{IP2}}{V_{IP1}}\right)^{-1.4727} \quad \textbf{Equation 3}$$

$$\frac{TR_{Airfield}}{TR_{Highway}} = \left(\frac{16}{15}\right)^{-4.199} \left(\frac{5.79}{6.72}\right)^{2.746} \left(\frac{75}{88}\right)^{1.373} \left(\frac{24}{70}\right)^{1.098} \left(\frac{3.6}{4}\right)^{1.5158} \left(\frac{4.3}{7}\right)^{-1.4727} = \mathbf{0.22} \quad \textbf{Equation 4}$$

Table 43. Ratio of Airfield to Highway Rutting Resistivity Models (FAA, 2018; AASHTO, 2022a)

Parameter	VMA, %	S_a, m²/kg	N	V_s, km/hr	V_{QC}, %	V_{IP}, %
Airfield	16	5.79	75	24	3.6	4.3
Highway	15	6.72	88	70	4	7
Exponent	-4.199	2.746	1.373	1.098	1.5158	-1.4727
$\frac{TR_{Airfield}}{TR_{Highway}}$	0.76	0.66	0.80	0.31	0.85	2.05
	0.22					

Table 44. Modified Parameters Between Highways and Airfields

Parameter	Airfield	Highway
Specification	Advisory circular 150/5370-10H (FAA, 2018).	AASHTO M 323-22 (AASHTO, 2022a).
VMA	P-401/403 VMA specification 1% higher than highway (Superpave).	Superpave highway specification for VMA 1% lower than P-401/403.
	Minimum specification of 16 for 9.5-mm NMAS.	Minimum specification of 15 for 9.5-mm NMAS.
S_a	P200 FAA specification of 3–6%.	P200 Superpave specification of 2–10%
	Relationship between mineral filler content and S_a.	Relationship between mineral filler content and S_a.
	Additional fines generated during production.	Additional fines generated during production.
N_{eq}	One Marshall blow is approximately equal to one Superpave gyration (in terms of rut resistance) (Christensen et al., 2008).	One Marshall blow is approximately equal to one Superpave gyration (in terms of rut resistance) (Christensen et al., 2008).
	75 gyrations/blows in FAA specification.	Average Marshall blows (75) and Superpave gyrations (100) for highways 3–30 MESALs.
V_s	Critical minimum speed on taxiways and runway ends without aircraft stacking (15 mph).	Typical highway speed (70 mph).
V_{QC}	3.6% = mean of lab QA dataset from airfield analysis.	4.0% = typical highway lab QC/QA AV%.
V_{IP}	4.3% = mean of mat core dataset from airfield analysis.	7.0% = typical highway in-place density.

HT-IDT Strength Criteria

Subsequently, the $\frac{TR_{Airfield}}{TR_{Highway}}$ can be used to convert the highway HT-IDT criteria to airfield applications in Table 45, based on the following steps:

- Set allowable airfield MESALs for each traffic range.
- Convert to highway MESALs (dividing airfield traffic by 0.22).
- Calculate minimum HT-IDT strength for each range based on the relationship between HT-IDT and TR (Figure 27): HT-IDT Strength = 92.6 ln (TR) +68 (Advanced Asphalt Technologies, 2011).

In summary, using Table 45, the HT-IDT strength criteria can be determined for a given airfield EHE. The following section describes the steps for using the proposed method for estimating the HT-IDT strength criteria.

Table 45. Highway-Based Estimated Airfield HT-IDT Strength Criteria

Allowable Airfield MESALs (EHE)	Assumed Allowable Airfield MESALs for Calculation	Converted Highway MESALs	Minimum HT-IDT Strength Criteria, psi[a,b]
<3	1.4	6.5	39 (270 kPa)
3 to <10	6.5	29.5	61 (420 kPa)
10 to <30	20	90.9	78 (535 kPa)
≥30	65	295.5	95 (655 kPa)

[a]Specimens compacted to N_{design} (AV close to 4.0%), tested at 10 °C below average, 7-day maximum pavement temperature, 20 mm below the pavement surface at 50% reliability determined using LTPPBind, Version 3.1.

[b]Specimens wrapped tightly in plastic or placed in a heavy-duty, leakproof plastic bag and conditioned in a water bath at test temperature for 2 hr ±10 min.

The minimum HT-IDT values proposed in Table 45 were compared to the minimum threshold of 30 psi derived from the NAPMRC test data in Figure 24 (Garg, 2018). It should be mentioned that both HT-IDT thresholds (i.e., Table 45 and 30 psi from Figure 24) are recommended at similar AV levels (i.e., mix-design AV) and test temperatures (10 °C below environmental critical temperature). The minimum HT-IDT of 30 psi from NAPMRC data corresponded in Figure 25 to 150 HVS passes, which is slightly below the minimum of 39 psi recommended in Table 45 for a traffic level of less than 3 million EHE. It should be noted that the correlation derived in Figure 25 between the minimum HT-IDT of 30 psi and 150 HVS passes was solely based on data points from NAPMRC test sections. However, NAPMRC test sections were continuously trafficked at high pavement temperature, which does not reflect actual airfield pavement conditions (Garg et al., 2018; Garg, 2018).

Application of the Proposed Procedure

The sequence of steps below summarizes the procedure for selecting an HT-IDT strength criterion for an airfield mixture, along with an example.

- Step 1. Calculate total annual departures and GAW.

Total annual operations and GAW data were collected from the Airport Data and Information Portal and Aeronautical Information Services available on the FAA website, as per the example in Table 46 (FAA, 2023; Airport-Data.com, n.d.; FAA, 2024).

Table 46. Air Traffic for Airfield Case Studies (FAA, 2023; Airport-Data.com, n.d.; FAA, 2024)

Airport	Total Annual Operations	Runway: Max GAW, lb (Dual Double Tandem 2D/2DS)					
Detroit Metropolitan Wayne County Airport (DTW)	286,702	03L/21R: 1,000,000	03R/21L: 750,000	04L/22R: 750,000	04R/22L: 350,000	09L/27R: 350,000	09R/27L: 350,000
Newark Liberty International Airport (EWR)	336,538	04L/22R: 1,000,000	04R/22L: 1,000,000	11/29: 1,000,000	–	–	–
Philadelphia International Airport (PHL)	268,884	08/26: 145,000[a]	09L/27R: 350,000	09R/27L: 350,000	17/35: 300,000	–	–
Reno Stead Airport (RTS)	49,800	08/26: 90,000	14/32: 85,000	–	–	–	–
Sacramento International Airport (SMF)	132,773	17L/35R: 961,000	17R/35L: 961,000	–	–	–	–
San Francisco International Airport (SFO)	299,744	01L/19R: 877,000	01R/19L: 877,000	10L/28R: 877,000	10R/28L: 877,000	–	–
Tampa International Airport (TPA)	212,973	01L/19R: 850,000	01R/19L: 850,000	10/28: 380,000	–	–	–
Ted Stevens Anchorage International Airport (ANC)	216,208	07L/25R: 900,000	07R/25L: 1,300,000	15/33: 900,000	–	–	–
Teterboro Airport (TEB)	86,372	01/19: 100,000	06/24: 100,000	–	–	–	–

[a]2D gear
– = Not available.

- Step 2. Calculate EHE (Figure 16).

Considering that air traffic mix data was not available per runway or taxiway, the total annual operations for the airport (i.e., including air carrier, air taxi, GA local, GA itinerant, and military operations) was multiplied by 75 percent and coupled with the maximum GAW to compute the EHE from Figure 16. An example can be seen in Table 49 (Christensen et al., 2008).

Table 47. EHE Calculation for Airfield Case Studies

Airport	Maximum GAW, lb	Annual Departures	EHE, MESALs
Detroit Metropolitan Wayne County Airport (DTW)	1,000,000	215,027	21
Newark Liberty International Airport (EWR)	100,000	252,404	8
Philadelphia International Airport (PHL)	350,000	201,663	11
Reno Stead Airport (RTS)	90,000	37,350	1.2
Sacramento International Airport (SMF)	961,000	99,580	10
San Francisco International Airport (SFO)	877,000	224,808	18
Tampa International Airport (TPA)	850,000	159,730	12
Ted Stevens Anchorage International Airport (ANC)	900,000	162,156	12
Teterboro Airport (TEB)	100,000	64,779	2

- Step 3. Input the determined EHE from Step 2 in the “Allowable Airfield MESALs” column in Table 48.

Table 48. New HT-IDT Criteria for Airfields

Allowable Airfield MESALs (EHE Range)	Minimum HT-IDT Strength Criteria[a,b]
<3	39 psi (270 kPa)
3 to <10	61 psi (420 kPa)
10 to <30	78 psi (535 kPa)
≥30	95 psi (655 kPa)

[a]Specimens compacted to N_{design} (AV close to 4.0%), tested at 10 °C below average, 7-day maximum pavement temperature, 20 mm below the pavement surface at 50% reliability determined using LTPPBind, Version 3.1.
[b]Specimens wrapped tightly in plastic or placed in a heavy-duty, leakproof plastic bag and conditioned in a water bath at test temperature for 2 hr ±10 min.

- Step 4. Select the corresponding minimum HT-IDT strength value for each airfield, as per the example in Table 47.

Table 49. HT-IDT Criteria for Airfield Case Studies

Airport	Maximum GAW, lb	Annual Departures	EHE, MESALs	HT-IDT, psi Criteria
Detroit Metropolitan Wayne County Airport (DTW)	1,000,000	215,027	21	78
Newark Liberty International Airport (EWR)	100,000	252,404	8	61
Philadelphia International Airport (PHL)	350,000	201,663	11	78
Reno Stead Airport (RTS)	90,000	37,350	1.2	39
Sacramento International Airport (SMF)	961,000	99,580	10	78
San Francisco International Airport (SFO)	877,000	224,808	18	78
Tampa International Airport (TPA)	850,000	159,730	12	78
Ted Stevens Anchorage International Airport (ANC)	900,000	162,156	12	78
Teterboro Airport (TEB)	100,000	64,779	2	39

Chapter 9. Summary

The summary of the preliminary rutting criteria defined in the previous sections based on different methodologies is presented in Table 50 along with the relative AV level, load level, test temperature, and traffic level, if applicable.

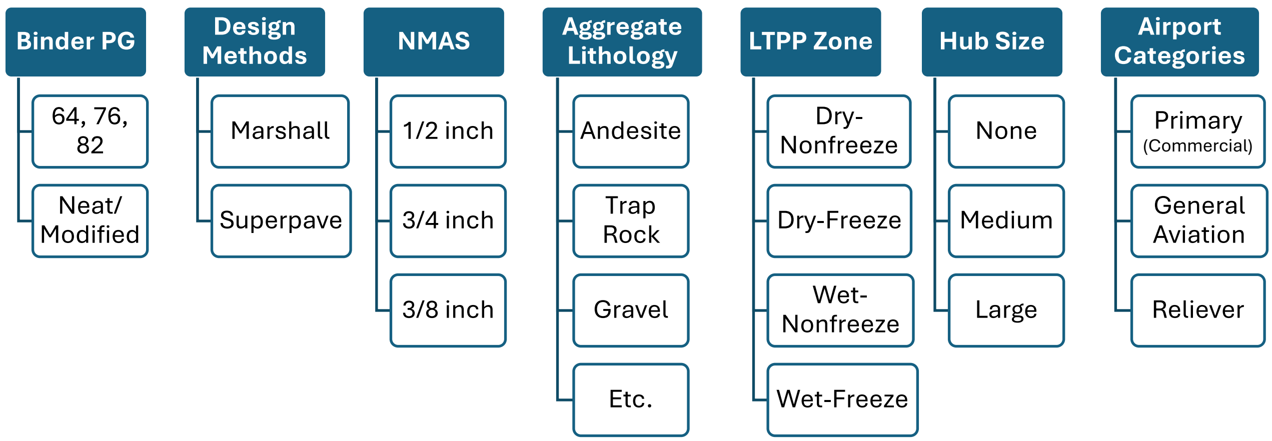
Table 50. Summary of Airfield Rutting Preliminary Test Criteria

Rutting Test	Test Temperature	AV	EHE (MESALs)[a]	Test Criteria	Note
APA at 250 psi and 250 lb, AASHTO T 340	64 °C	7±0.5%	–	Rut depth ≤10 mm at 4,000 passes	Current FAA criteria (FAA, 2018)
		5±0.5%	–	Rut depth ≤5 mm at 4,000 passes	NAPTF CC7 (General Dynamics, 2019a)
	Average 7-day maximum pavement temperature 20 mm below surface with 50% reliability (using LTPPBind 3.1)	7±0.5%	<3	–	Previous airfield criteria from literature (Christensen, 2013)
		7±0.5%	3 to <10	Rut depth ≤8 mm at 8,000 passes	
		7±0.5%	10 to <30	Rut depth ≤6 mm at 8,000 passes	
		7±0.5%	30 to <100	Rut depth ≤5 mm at 8,000 passes	
		7±0.5%	100 to <300	Rut depth ≤4 mm at 8,000 passes	
		7±0.5%	≥300	Rut depth ≤3 mm at 8,000 passes	
APA at 100 psi and 100 lb, AASHTO T 340	64 °C	7±0.5%	–	Rut depth ≤5 mm at 8,000 passes	Current FAA criteria (FAA, 2018)
	64 °C	Design AV%	–	Rut depth ≤3 mm at 8,000 passes	Table 38[b]
	64 °C	7±0.5%	–	Rut depth ≤3 mm at 8,000 passes	
	64 °C	5±0.5%	–	Rut depth ≤6 mm at 8,000 passes	NAPTF CC5 (Garg et al., 2009)
	64 °C	7±0.5%	–	Rut depth ≤4 mm at 4,000 passes	NAPTF CC7 (General Dynamics, 2019a)
HWT	50 °C	7±0.5%	–	Rut depth ≤10 mm at 20,000 passes	Current FAA criteria (FAA, 2018)
	50 °C	7±0.5%	–	Rut depth ≤ 5 mm at 20,000 passes	Table 38[b]
HT-IDT	40 °C	Design AV%	–	Strength ≥30 psi (207 kPa)	NAPMRC TC1 (Garg, 2018)
	10 °C below average, 7-day maximum pavement temperature, 20 mm below the pavement surface at 50% reliability (using LTPPBind 3.1)	Design AV%	<3	Strength ≥39 psi (270 kPa)	Rutting resistivity model and EHE (Christensen et al., 2008; Advanced Asphalt Technologies, 2011)
		Design AV%	3 to <10	Strength ≥61 psi (420 kPa)	
		Design AV%	10 to <30	Strength ≥78 psi (535 kPa)	
		Design AV%	≥30	Strength ≥95 psi (655 kPa)	

[a]EHE = MESALs determined based on annual departure and maximum GAW.
[b]Airfield mix designs with preliminary field performance.
– = Not applicable.

Chapter 10. Research Plan

The primary goal when developing the research plan was to increase the variety of materials included in the testing matrix to encompass a wide range of factors. These factors include asphalt binder grade, modification type, mix design method, NMAS, and aggregate lithology. The plan illustrated in Figure 28 provides an overview of the testing materials sampled from several airfield projects located throughout the United States.

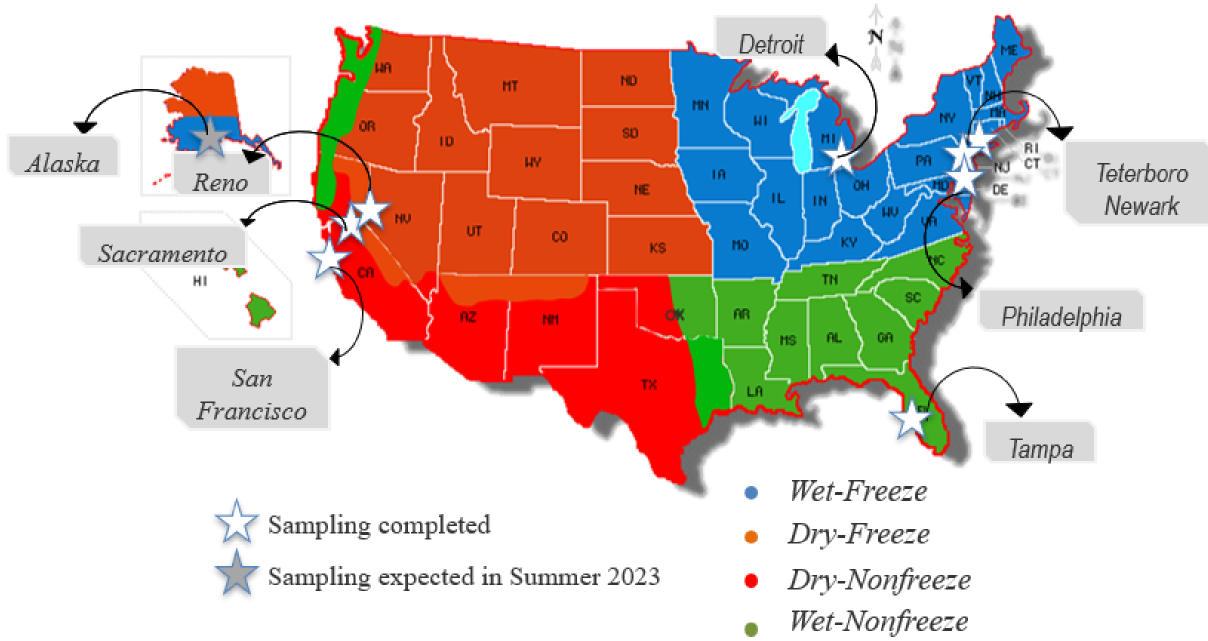


Source: University of Nevada, Reno

Figure 28. Materials Testing Matrix

Materials

The team has collected raw materials, field- and plant-produced mixtures, and field cores from various airfield projects in different LTPP climatic zones (Schwartz, et al., 2015). This has been done to ensure a diverse range of materials for testing purposes. The locations of these airfield projects are highlighted on the map in Figure 29. A summary of the airfield projects included in the study can be found in Table 51 along with their airport code, construction date, category, and hub size (according to the FAA classification), maximum GAW, and LTPP climatic zone. This information was gathered to provide a complete understanding of the conditions and factors affecting the pavement performance in various locations across the United States.



Source: University of Nevada, Reno

Figure 29. Airports Identified for Sampling Materials (Schwartz, et al., 2015)

Table 51. Characteristics of Airports Identified for Sampling (FAA, 2023; Airport-Data.com, n.d.; FAA, 2024; FAA, 2021b)

Airport	Airport Code	Construction Date	Classification/ Hub[1]	GAW (lb)[2,3,4]	LTPP Climatic Zone	Sampled (Yes or No)
Detroit Metropolitan Wayne County Airport	DTW	July 2022	Primary/Large	≥100,000	Wet-Freeze	Yes
Newark Liberty International Airport	EWR	Aug-Sept 2022	Primary/Large	≥100,000	Wet-Freeze	Yes
Philadelphia International Airport	PHL	May 2018	Primary/Large	≥100,000	Wet-Freeze	Yes
Reno Stead Airport	RTS	Oct 2022	Reliever/–	<100,000	Dry-Freeze	Yes
Sacramento International Airport	SMF	Sept 2022	Primary/Medium	≥100,000	Dry-Nonfreeze	Yes
San Francisco International Airport	SFO	Spring 2023	Primary/Large	≥100,000	Dry-Nonfreeze	Yes
Tampa International Airport	TPA	Oct 2022	Primary/Large	≥100,000	Wet-Nonfreeze	Yes
Ted Stevens Anchorage International Airport	ANC	–	Primary/Medium	≥100,000	Wet-Freeze	No
Teterboro Airport	TEB	July-Aug 2022	GA/–	<100,000	Wet-Freeze	Yes

– = Not applicable.

Moreover, Table 52 summarizes the asphalt mixture characteristics of sampled airfield projects, including the corresponding asphalt mixture type, binder PG, gradation, and

NMAS. While none of the sampled projects included RAP, all projects were identified as P-401 except for the following slight modifications (FAA, 2018):

- The EWR and TEB airfield mixtures are designed per PANYNJ Specification Section 321218, which includes the requirements of FAA advisory circular 150/5370 Item P-401 with FAA approved modifications.
- The TPA airfield mixture is designed as a fuel-resistant P-404 mixture, which is expected to exhibit an improved rutting resistance.

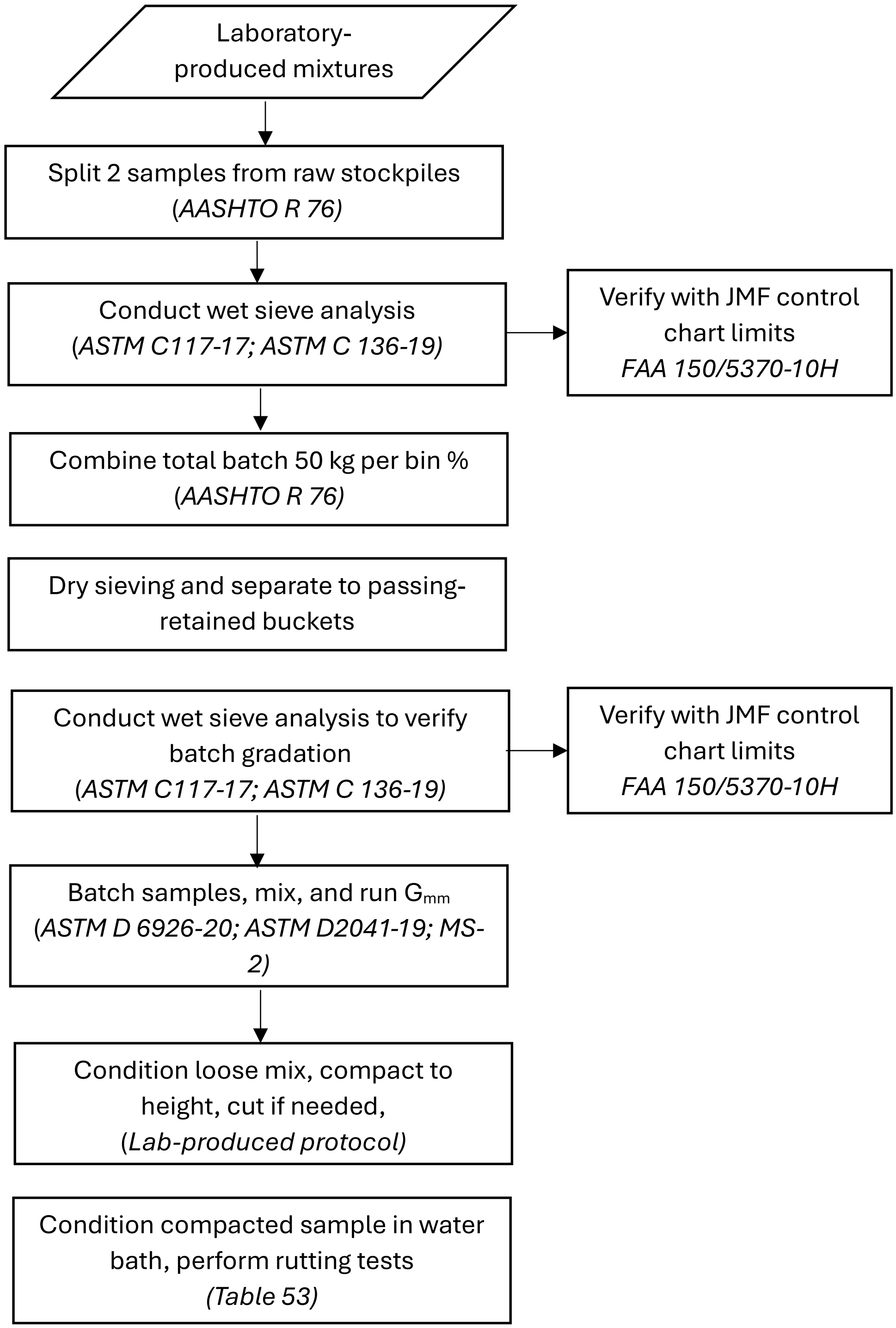
Table 52. Asphalt Mixture Characteristics of Sampled Projects (FAA, 2018)

Airport	Mix Type	PG	Gradation	Aggregate Lithology	NMAS, mm
DTW	P-401 Surface	76-22P	Grad 2 (401-3.3)	–	12.5
EWR	Modified P-401 Surface	82-22	Mix 2 (PANYNJ Specification Section 321218)	Gneiss from Braen Stone, Sparta, NJ	19
PHL	P-401 Surface	82-22	Grad 1 (401-3.3)	Trap Rock from Dyer Quarry, Birdsboro, PA	19
RTS	P-401 Surface (bottom lift)	64-28NV	Grad 2 (401-3.3)	Andesite, Lockwood, NV	12.5
SMF	P-401 Surface	76-22M	Grad 2 (401-3.3)	Alluvial sand and gravel from Western Aggregates	12.5
SFO	P-401 Surface	76-22 M	Grad 1 (401-3.3)	Wilson Quarry, Aromas, CA	19
TPA	P-404 Surface	82-22 fuel resistant	Grad 3 (401-3.3)	–	9.5
TEB	Modified P-401 Surface	64-22	FAA Mix 3 (PANYNJ Specification Section 321218)	Gneiss from Tilcon, Mount Hope, NJ	19

– = Not available.

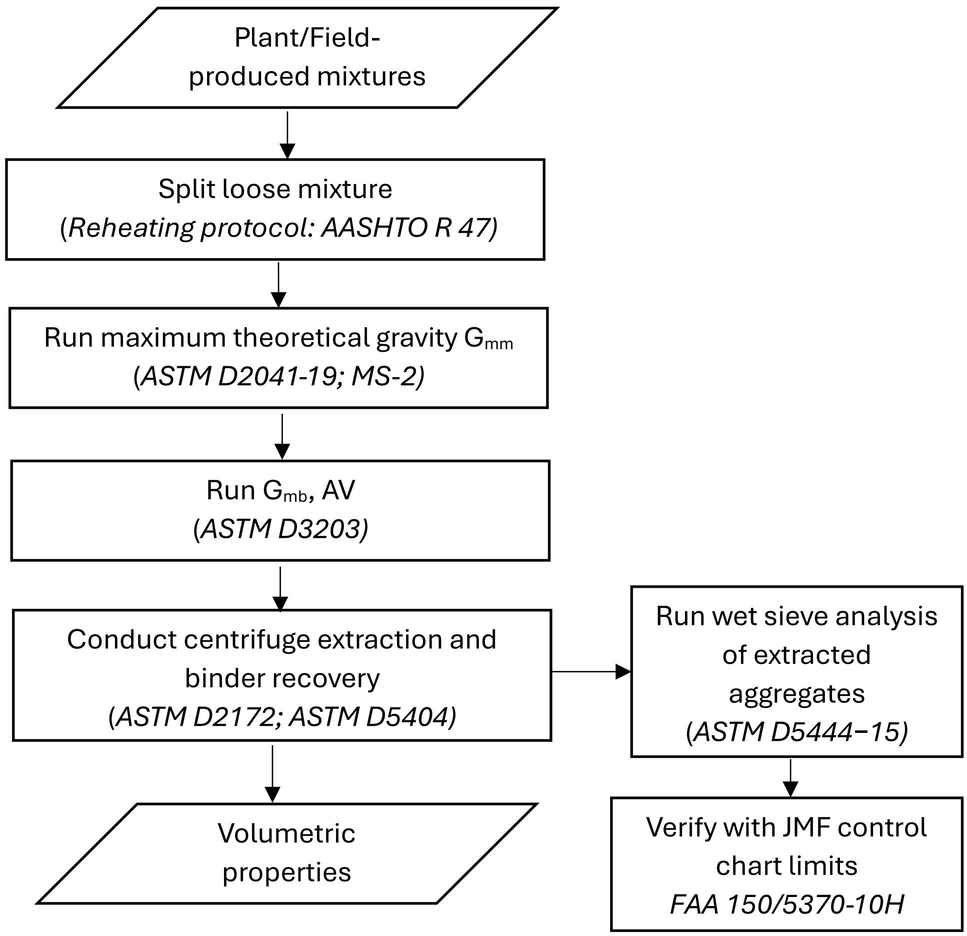
Laboratory Experimental Matrix

The developed laboratory experimental plan has been detailed to ensure high consistency with minimal variability in testing results between different entities of the research team. The first target in the experimental plan is to verify that the field- and plant-produced asphalt mixtures as well as the raw materials conform to the JMF within acceptable production tolerance prescribed by the FAA specifications (FAA, 2018). The laboratory experimental plans for the LMLC and for the PMLC and FMLC samples are illustrated in Figure 30 and Figure 31, respectively. The plant- and field-produced mixtures will be verified using the centrifuge extraction method to confirm the asphalt binder content and the gradation of the extracted aggregates. Once the extracted aggregate gradation is confirmed to meet the production tolerance of the JMF, the gradation will also be verified through sieve analysis of two samples split from the raw aggregate stockpiles. The aggregate stockpiles can be then blended for a total of 50 kg following the mix deign bin percentages and sieved into passing-retained control buckets. The aggregate gradation from the passing-control buckets will be verified against the JMF control chart limits for every 50 kg blend prior to batching samples. The batched samples can then be mixed, compacted, conditioned, and subjected to rutting mechanical tests as per Table 53.



Source: University of Nevada, Reno

Figure 30. Laboratory Experimental Plan for LMLC Samples (FAA, 2018; ASTM, 2020a; ASTM, 2020b; ASTM, 2019b; ASTM, 2019a)



Source: University of Nevada, Reno

Figure 31. Laboratory Experimental Plan for PMLC/FMLC Samples (FAA, 2018; Asphalt Institute, 2014; AASHTO, 2022c; ASTM, 2020a; ASTM, 2019a; ASTM, 2019b; ASTM, 2017a; ASTM, 2010; ASTM, 2015; ASTM, 2021)

Table 53. Rutting Test Experimental Matrix (FHWA, n.d.-f)

Parameter	Rutgers		TTI		UNR		Rutgers		TTI	
Test	APA (100 psi)		APA (250 psi)		HWT		HT-IDT		IRT	
Test Temperature	LTPPBind Online Environmental PG (no bumping), 12.5 mm rut depth, 50% reliability, at surface									
Loose Mix Conditioning	Based on developed LMLC loose mix conditioning protocol (2 hr at compaction temperature)									
AV Level, %	5±0.5	7±0.5	5±0.5	7±0.5	5±0.5	7±0.5	5±0.5	7±0.5	5±0.5	7±0.5
Specimen Diameter, mm	150	150	150	150	150	150	150	150	150	150
Specimen Height, mm	75	75	75	75	165	62	165	62	165	62
Cutting (Yes/No)	No	No	No	No	Yes	No	Yes	No	Yes	No
Final Specimen Height, mm	75	75	75	75	62	62	62	62	62	62
Number of Samples per Mix per Combination	6	6	6	6	4	4	3	3	3	3
Total Number of Samples per Mix	12		12		8		6		6	

TTI = Texas A&M Transportation Institute; UNR = University of Nevada, Reno.

The experimental rutting tests will be conducted under various predefined conditions, which can be found in Table 53. As previously mentioned, to maintain consistency while testing between the three laboratories within the research team, the extracted and raw aggregate gradations will always be verified against the JMF control chart limits. The following two types of control charts are currently defined in the FAA advisory circular, with action and suspension limits to monitor the compliance during production (FAA, 2018):

- Control chart limits for individual measurements: utilize the JMF target values as indicators of central tendency for each measurement.
- Control chart limits based on range: based on a range of two measurements to control process variability.

The rutting test experimental matrix incorporates the five rutting mechanical tests performed by three AASHTO-accredited laboratories within the research team:

- Western Regional Superpave Center laboratory at the University of Nevada, Reno (UNR).
- Center for Advanced Infrastructure and Transportation at Rutgers University.
- Texas A&M Transportation Institute (TTI).

The rutting tests are defined at the set AV levels, along with the test temperature, specimen size, specimen preparation method, and number of replicates for each condition.

Table 54 summarizes the current progress of the laboratory experimental plan by means of sampling, mix verification, and rutting mechanical tests for all nine airfield projects identified for sampling (Table 51). Additional projects will be coordinated for future sampling in the next paving season to complement the laboratory experimental plan of the project as found necessary.

Table 54. Current Progress of Laboratory Experimental Plan

Airport	Sampling			PMLC/FMLC			LMLC
	Raw Materials	PMLC/ FMLC	FMFC	Mix Verification	Rutting Tests	Mix Verification	Rutting Tests
DTW	–	✓	–	✓	–	–	–
EWR	✓	✓	✓	✓	–	In Progress	In Progress
PHL	–	✓	–	✓	–	–	–
RTS	✓	✓	✓	✓	–	✓	In Progress
SMF	–	✓	–	✓	–	–	–
SFO	✓	✓	✓	✓	–	–	–
TPA	✓	✓	–	✓	–	–	–
ANC	–	–	In Progress[1]	✓	–	–	–
TEB	✓	✓	✓	✓	–	✓	In Progress

– = Not started.

✓ = Completed.

[1]Identifying sampling core locations from existing rutted sections of ANC Airport is based on an ongoing analysis of airfield mix design, acceptance, and field rutting data received from the Alaska Department of Transportation and Public Facilities.

Airfield Construction Project (Subtask 3.2)

As part of Phase II, the research team will coordinate with the FAA, BMD cracking team, local airport(s), and contractor(s) to select at least one field project to demonstrate the proposed BMD framework. This will assist in depicting any potential implementation issues with new specifications at the mix design level as well as during production. The lessons learned and findings from the field demonstration project will help in refining the prospective P-401/P-403 specifications (FAA, 2018). Several parameters will help in selecting the field project, including the following:

- Critical climate and/or traffic conditions for rutting and cracking mechanisms.
- Availability of the required laboratory equipment to perform specified laboratory mechanical tests.
- Ease of sampling raw materials, plant mixtures and cores during production for further laboratory evaluation.
- Resources to monitor the field performance after a few years of service.

Preliminary Interlaboratory Study on Rutting Tests (Subtask 3.3)

Controlling the variability of laboratory mechanical tests can be tackled by considering the test variability while setting the corresponding rutting criteria for each test. Considering the different modes of loading and mechanisms between different rutting tests, the variability is expected to differ for each of the rutting tests. This can be considered by conducting a preliminary interlaboratory study (ILS) among the three laboratories and the FAA Technical Center based on ASTM E691, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method" (ASTM, 2021). The following three round-robin studies will be considered:

- Send raw materials to the different laboratories to prepare samples and test.
- Send loose mixtures to the different laboratories to compact samples and test.
- Send prepared samples to the different laboratories to test.

A ruggedness test to determine the control of test method conditions will be discussed prior to the ILS. The ILS will be performed after setting the final rutting tests and relative criteria. The type of ILS selected will depend on the prospective rutting specification that will be recommended at the end of Phase II.

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