Developing Representative Test Specimen Conditions for Rutting Mechanical Test Methods of Airfield Pavements

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September 22, 2023

Abstract

The Federal Aviation Administration (FAA) is considering implementation of a balanced mix design method (BMD) for asphalt concrete (AC) of airfield pavements in a future specification update. One of the key elements towards implementing BMD, is setting adequate conditions for laboratory mechanical testing that best simulate actual field conditions. In this study, representative air void (AV) levels were identified for laboratory mechanical testing by analyzing quality control (QC) data of plant-mixed laboratory-compacted (PMLC) samples along with in-place density measurements for multiple existing airfield pavements. The laboratory compaction effort in the Superpave Gyratory Compactor (SGC) required to reach the recommended AV levels were evaluated for different specimen heights. The specimen height and AV level were then experimentally verified with the Ideal Rutting test (ASTM D8360-22) for these airfield mixtures. Based on analysis of field density, laboratory compaction effort, and mechanical test data, it was recommended to test 62 mm thick gyratory specimens at 7±0.5% AV (directly molded) or at 5±0.5% AV (after cutting), which should help capture the different aspects of the asphalt mixture's resistance to rutting in terms of aggregate skeleton and binder properties.

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Word Count: 9324 words

Submitted [07/02/2023]

ABSTRACT

The Federal Aviation Administration (FAA) is considering implementation of a balanced mix design method (BMD) for asphalt concrete (AC) of airfield pavements in a future specification update. One of the key elements towards implementing BMD, is setting adequate conditions for laboratory mechanical testing that best simulate actual field conditions. In this study, representative air void (AV) levels were identified for laboratory mechanical testing by analyzing quality control (QC) data of plant-mixed laboratory-compacted (PMLC) samples along with in-place density measurements for multiple existing airfield pavements. The laboratory compaction effort in the Superpave Gyratory Compactor (SGC) required to reach the recommended AV levels were evaluated for different specimen heights. The specimen height and AV level were then experimentally verified with the Ideal Rutting test (ASTM D8360-22) for these airfield mixtures. Based on analysis of field density, laboratory compaction effort, and mechanical test data, it was recommended to test 62 mm thick gyratory specimens at 7±0.5% AV (directly molded) or at 5±0.5% AV (after cutting), which should help capture the different aspects of the asphalt mixture's resistance to rutting in terms of aggregate skeleton and binder properties.

Keywords: Asphalt Mixture Performance, Airfield Pavement, Mechanical Testing, Field Density, Rutting.

INTRODUCTION AND BACKGROUND

Airfield pavements are targeted at an improved performance level, with less permanent deformation or rutting, for safety and takeoff/landing smoothness. This can be achieved by implementing new specifications for airfield pavements based on the latest state-of-the-art methodology of designing asphalt mixtures, the Balanced Mix Design (BMD). There have been significant efforts to implement BMD for highway pavements (*1*-*3*). The Federal Aviation Administration (FAA) is considering the implementation of a BMD framework in their subsequent specifications update for the P-401 and P-403, asphalt concrete (AC) mixtures of airfield pavements (*4*). The prospective BMD framework will incorporate rutting and cracking performance criteria based on laboratory mechanical testing. However, the laboratory mechanical testing and criteria need to be thoroughly tailored to airfield conditions, in terms of test temperature, wheel load, specimen air void (AV) level, tire pressure, etc. Accordingly, test criteria commonly used for rutting and cracking resistance of highway pavements will need to be re-evaluated for airfield pavement conditions.

One of the key elements to derive these test criteria is to establish representative laboratory testing conditions that best simulate actual field conditions for airfield pavements. These test conditions involve selecting proper AV level, specimen size and preparation method (cutting, gluing, etc.), aging temperature and time, and test temperature reflecting actual climatic field conditions. In-place density of AC pavements is an important contributor to the pavement service life. Higher in-place density or lower percent AV in the pavement has been associated with improved mixture performance (*5*-*7*). The FAA acceptance criteria for AC pavements includes meeting target percentage of AV on plant-mixed laboratory-compacted (PMLC) specimens, along with mat and joint density on field cores sampled on a sublot basis (*4*). Therefore, percentage of AV in asphalt mixtures for PMLC samples, mat cores, and joint cores are used for acceptance in the current FAA Standard Specifications for Construction of Airports, AC 150/5370-10H (*4*). While the target percentage of AV for mix design is set at 3.5% for items P-401 and P-403, the acceptance limits during production and after construction differ slightly between the two mixture types. Item P-401 is intended to be used for the surface course of airfield flexible pavements subjected to aircraft loadings of gross weights greater than 30,000 pounds; and the acceptance of each lot of plant-produced material is defined based on the percentage of material within specification limits (PWL). Item P-403 is intended to be used as a base or leveling course, shoulder surface, or surface for pavements designed to accommodate aircraft of gross weights less than or equal to 30,000 pounds. Table 1 summarizes the specification tolerance limits for both mix items P-401 and P-403 (*4*).

Table 1. Tolerance limits for P-401 and P-403 mixtures per AC 150/5370-10H FAA specifications.

Mix Item	Percentage of AV				Notes
	PMLC Samples	Mat Cores (Surface Course)	Mat Cores (Base Course)	Joint Cores	
P-401 (401-6.3)	2–5%	≤ 7.2%	≤ 8.0%	≤ 9.5%	PWL
P-403 (403-6.2)	2–5%	–	≤ 6.0%	≤ 8.0%	–

SCOPE OF WORK

With the aim of making the BMD as efficient as possible, there are some testing parameters that need to be considered when ultimately recommending test methods and criteria for mix design, control strip, quality control (QC), and acceptance. Some of the main parameters highlighted in this manuscript include AV level, specimen geometry and preparation along with the aging protocol and testing temperature. As per the experimental plan in Figure 1, the QC data of PMLC samples along with the in-place density measurements were analyzed for multiple existing airfield sections in order to select representative AV levels for further laboratory rutting mechanical testing. Thereafter, the laboratory compaction effort required to reach the recommended AV levels was evaluated under different specimen heights using plant-produced asphalt mixtures collected from airfield pavements. The final recommendations on test specimen conditions were verified based on rutting test results using the Ideal

Rutting Test (Ideal-RT, ASTM D8360-22) for different airfield mixtures, by investigating the sensitivity of the test to different AV levels and specimen preparation methods (*8*). The Ideal-RT was mainly conducted to depict any significant impact of different specimen preparation methods on relative sample performance, and to examine the effect of different AV levels on the rutting resistance of the mixture.

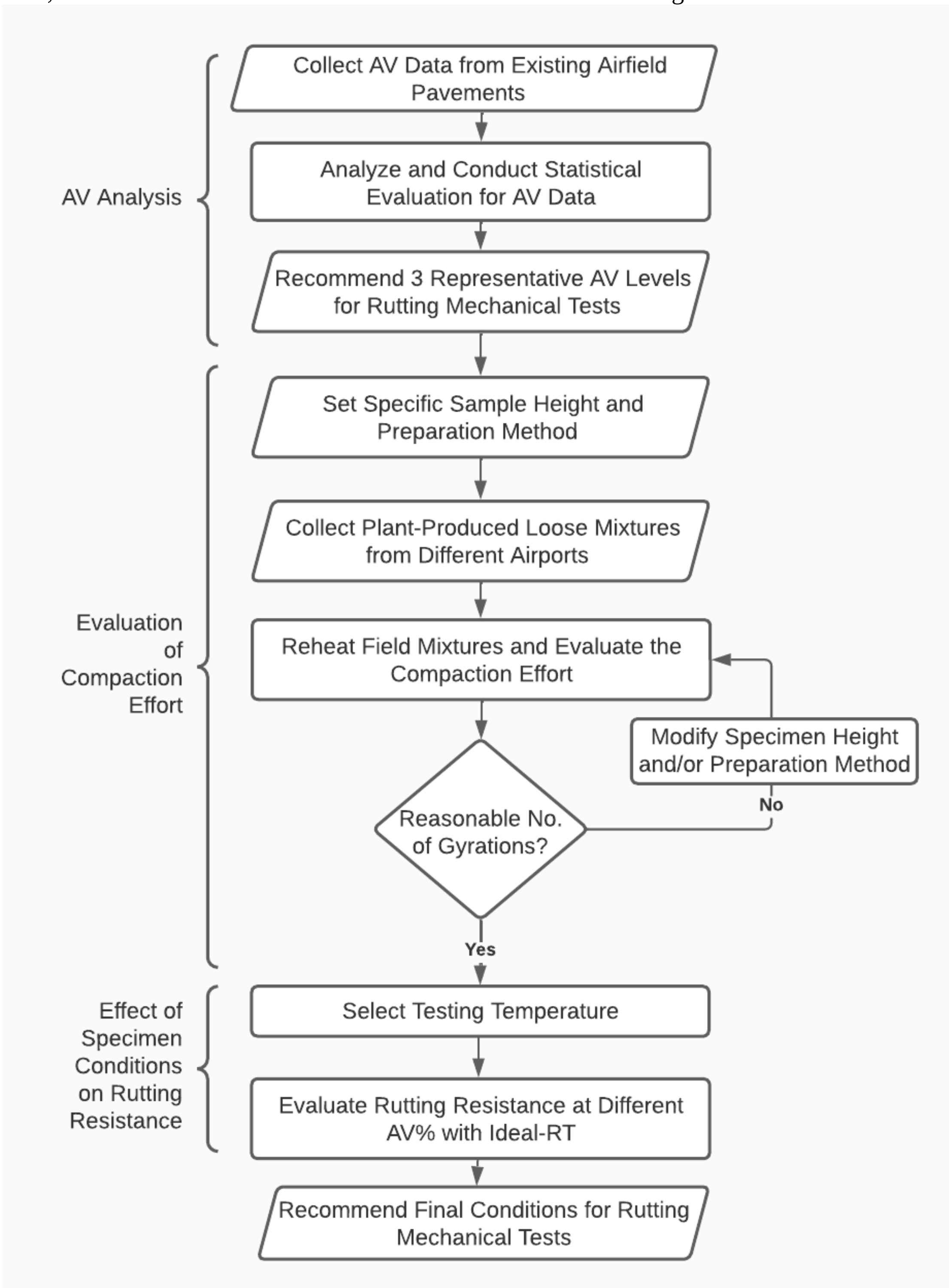

Figure 1. Flowchart of the experimental plan.

AIR VOIDS ANALYSIS

It is commonly agreed that the specimen AV level is known to have an impact on mechanical testing results. Thus, specimen AV levels that mimic the in-place percentage of AV in airfield AC pavements need to be established 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 following terminology is used in this paper in accordance with AC 150/5370-10H (*4*):

- Air voids (AV): refers to the percentage of AV in the asphalt mixture determined in accordance with ASTM D3203 for compacted specimens prepared in accordance with ASTM D6926 (*9,10*).
- In-place density: refers to the percent compaction of field cores taken from the mat or joint. The percent compaction (density) of each core sample is determined by dividing the bulk specific gravity of the sample (determined in accordance with ASTM D2726) by the theoretical maximum density (TMD) (*11*). The percentage of AV in the core sample can then be calculated as 100 minus the percent compaction.

Rutting in airfield AC pavements is observed in the mat or in close proximity to a longitudinal joint that is being traversed by aircrafts due to the wander effect. The footprint of the landing gear impression in the asphalt surface indicates a possibility that aircraft can still be driving on the longitudinal joint based on the statistical wander measured in the field. 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. Poor joint construction can lead to additional consolidation and rutting and affect drainage and operation. 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.

Analyzed Airfield Pavements

Eleven airports around the United States with twelve airfield AC pavement projects were evaluated in this analysis. Figure 2 illustrates the geographical distribution of the evaluated airports located within three of the Long-Term Pavement Performance (LTPP) climatic zones (*12*). Table 2 summarizes the considered airports along with their respective FAA identification code, category and hub size per the FAA classification, maximum aircraft gross weight, and LTPP climatic zone (*12*-*15*).

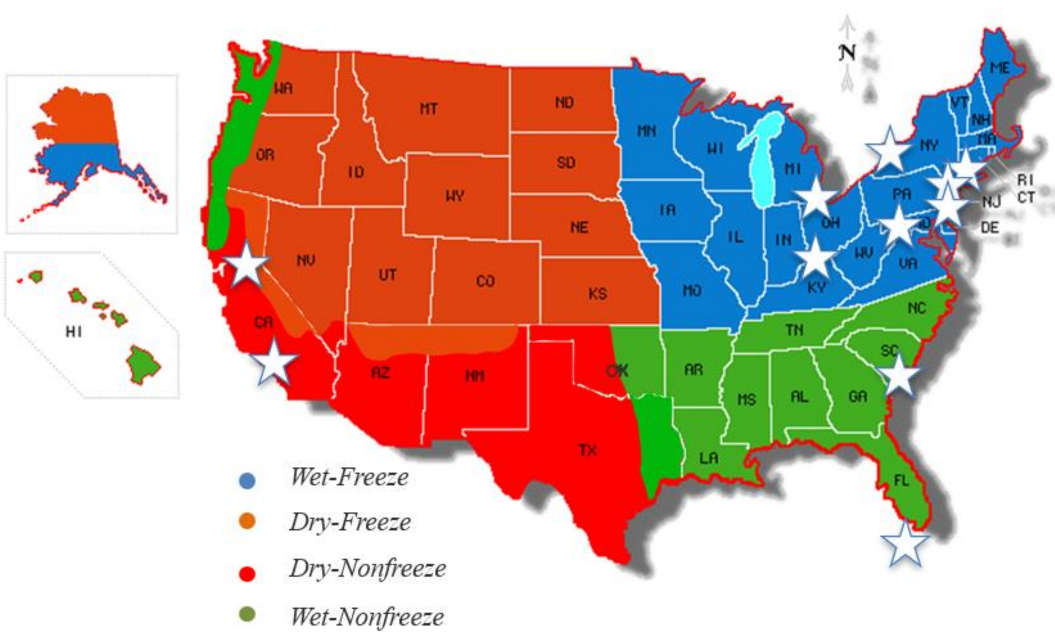

Figure 2. Geographical location of airports on the LTPP climate zone map.

Table 2. Characteristics of airports used in the evaluation.

Airport	State	Airport Code	Classification/Hub[a]	Aircraft Gross Weight[b,c]	LTPP Climatic Zone
Buffalo Niagara Int.	NY	BUF	Primary/Small	≥ 100,000	Wet-Freeze
Burbank Bob Hope	CA	BUR	Primary/Medium	≥ 100,000	Dry-Nonfreeze
DCA Ronald Reagan	VA	DCA	Primary/Large	≥ 100,000	Wet-Freeze
Detroit Metro Wayne	MI	DTW	Primary/Large	≥ 100,000	Wet-Freeze
Key West Int.	FL	EYW	Primary/Small	≥ 100,000	Wet-Nonfreeze
Lexington Blue Grass	KY	LEX	Primary/Small	≥ 100,000	Wet-Freeze
MCAS Beaufort	SC	NBC	GA/Nonprimary Hub	-	Wet-Nonfreeze
Newark Liberty	NJ	EWR	Primary/Large	≥ 100,000	Wet-Freeze
Philadelphia Int.	PA	PHL	Primary/Large	≥ 100,000	Wet-Freeze
Sacramento Int.	CA	SMF	Primary/Medium	≥ 100,000	Dry-Nonfreeze
Teterboro	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, February 27, 2023. https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/cy21_all_enplanements
[b] FAA, Aeronautical Information Services. https://nfdc.faa.gov/nfdcApps/services/ajv5/airportDisplay.jsp?airportId.
[c] Airport-Data.com. https://www.airport-data.com/usa-airports/search.php.
GA=General Aviation.

Table 3 summarizes the twelve 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), reclaimed asphalt pavement (RAP) content, and design compaction effort are also included in Table 3. While asphalt mixtures are identified as either P-401 or P-403, the following modifications from the FAA Standard Specifications are noted (*4*):

- The Marine Corps Air Station (MCAS) Beaufort (NBC) was designed at 4.0% 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 mineral aggregates (VMA), tensile strength ratio (TSR), and binder content.
- The EWR and TEB airfield mixtures are designed per the Port Authority of New York and New Jersey (PANYNJ) Specifications Section 321218, which includes the requirements of FAA AC 150/5370 Item P-401 with FAA approved modifications.

The field acceptance data for the evaluated asphalt mixtures (Table 3) were acquired and analyzed as shown in the following sections.

Table 3. Characteristics of airfield asphalt mixtures used in the evaluation.

Airfield Project	Construction Date	Section	Mixture Type	Binder PG	Gradation	NMAS (inch)	RAP (%)	Design Compaction
BUF	May–Aug 2017	*Runway* *Runway*	P-401 (surface) P-401 (base)	64E-22 64S-22	Grad 2 [a] Grad 1 [a]	1/2 3/4	0 0	75 Blows 75 Blows
BUR	Feb 2021	*Taxiway* *Taxiway*	P-401 (surface) P-401 (base)	76-22 70-10	Grad 1 [a] Grad 1 [a]	3/4 3/4	0 0	75 Gyrations 75 Gyrations
DCA	Apr–May 2010	*Runway/ Taxiway*	P-401 (surface)	76-22	Grad 1 [a]	3/4	0	75 Blows
DTW	Jul–Oct 2020	*Apron Deicing Facility*	P-401 (surface) P-403 (surface)	76-22P 64-22	Grad 2 [a] Grad 2 [a]	1/2 1/2	0 30	75 Blows 75 Blows
EYW	Jan 2018; Jun 2020 –Sept 2021	*Runway* *Taxiway*	P-401 (surface) P-401 (surface)	76-22 (PMA) 76-22 (PMA)	Grad 2 [a] Grad 2 [a]	1/2 1/2	0 0	75 Gyrations 75 Gyrations
LEX	Sept 2020	*Runway/ Taxiway*	P-401 (surface)	76-22 (SBS)	Grad 1 [a]	3/4	0	75 Gyrations
NBC	Mar–Oct 2020	*Runway* *Runway* *Shoulder*	P-401 (surface) P-401 (intermediate) P-401 (surface)	76-22 (PMA) 76-22 (PMA) 76-22 (PMA)	Grad 2 [a] Grad 2 [a] Grad 2 [a]	1/2 1/2 1/2	0 20 20	75 Gyrations 75 Gyrations 75 Gyrations
EWR 1	May–Sept 2021	*Runway* *Runway*	Mod. P-401 (surface) Mod. P-401 (surface)	76-22 76-22	Mix 3 [b] Mix 3 [b]	1/2 3/4	0 0	75 Blows 75 Blows
EWR 2	Aug–Sept 2022	*Taxiway*	Mod. P-401 (surface)	82-22	Mix 2 [b]	3/4	0	75 Blows
PHL	Dec 2017–May 2018	*Runway* *Runway*	P-401 (surface) P-401 (base)	82-22 70-22	Grad 1 [a] Grad 1 [a]	3/4 3/4	0 20	75 Blows 75 Blows
SMF	Dec 2016–Mar 2017	*Taxiway*	P-401 (surface)	64-28PM	Grad 1 [a]	3/4	0	75 Blows
TEB	Jul–Aug 2022	*Runway*	Mod. P-401 (surface)	64-22	Mix 3 [b]	3/4	0	75 Blows

[a] 401-3.3/403-3.3
[b] PANYNJ Specifications Section 321218.
NMAS=nominal maximum aggregate size; RAP=reclaimed asphalt pavement; PANYNJ=Port Authority of New York and New Jersey.

Acceptance Data

For each airfield AC pavement project, job mix formula (JMF), laboratory QC, acceptance data, and field reports for mat and joint cores density data were obtained and analyzed to determine the percentage of AV in asphalt mixtures. All of the evaluated airfield projects were designed per the FAA specifications at 3.5% AV, except for NBC, EWR, and TEB that were designed at 4.0% AV.

Figure 3 shows the calculated percentage of AV in the asphalt mixtures using PMLC samples (i.e., lab QC and acceptance), in-place asphalt mat density (i.e., mat cores), and in-place asphalt joint density (i.e., joint cores). The average percentage of AV for each project ranges from 3.3 to 4.0%, 3.3 to 5.3%, and 4.5 to 7.9% for lab QC and acceptance, mat cores, and joint cores, respectively. For lab QC and acceptance data, the average percentage of AV in asphalt mixtures are within 0.7% of the design AV (i.e., JMFs). The comparison of observed densities between the lab QC and acceptance samples and mat cores indicates an average increase in AV of 0.7% for mat cores data from nine airfield projects. This indicates a slightly higher compaction effort in the laboratory when compared to the compaction effort applied in the field during construction. Nonetheless, a higher deviation in AV values between laboratory and field compacted samples has been reported for highway pavements in the literature (*16*). Yan et al. reported an average AV of 6.6% in the field compared samples compared to the 4.0% design AV for 15 projects constructed in Minnesota between 2018 to 2020 (*16*).

Furthermore, a good agreement between laboratory and field compaction data was observed for BUR and TEB airfield projects (Figure 3), with mat cores AV being only 0.1% greater than the measured AVs on lab QC and acceptance samples. Notably, the mat cores from the EWR 2 airfield project had 0.5% less AV than the laboratory compacted samples, which can be attributed to good field compaction practices followed during construction. As expected, the joint cores consistently showed higher percentage of AV than mat cores and lab QC and acceptance data. Moreover, the 95% confidence intervals (CI) suggest higher variability in the percentage of AV from the joint cores when compared to those from the mat cores, while the least variability is observed for PMLC samples (i.e., lab QC and acceptance).

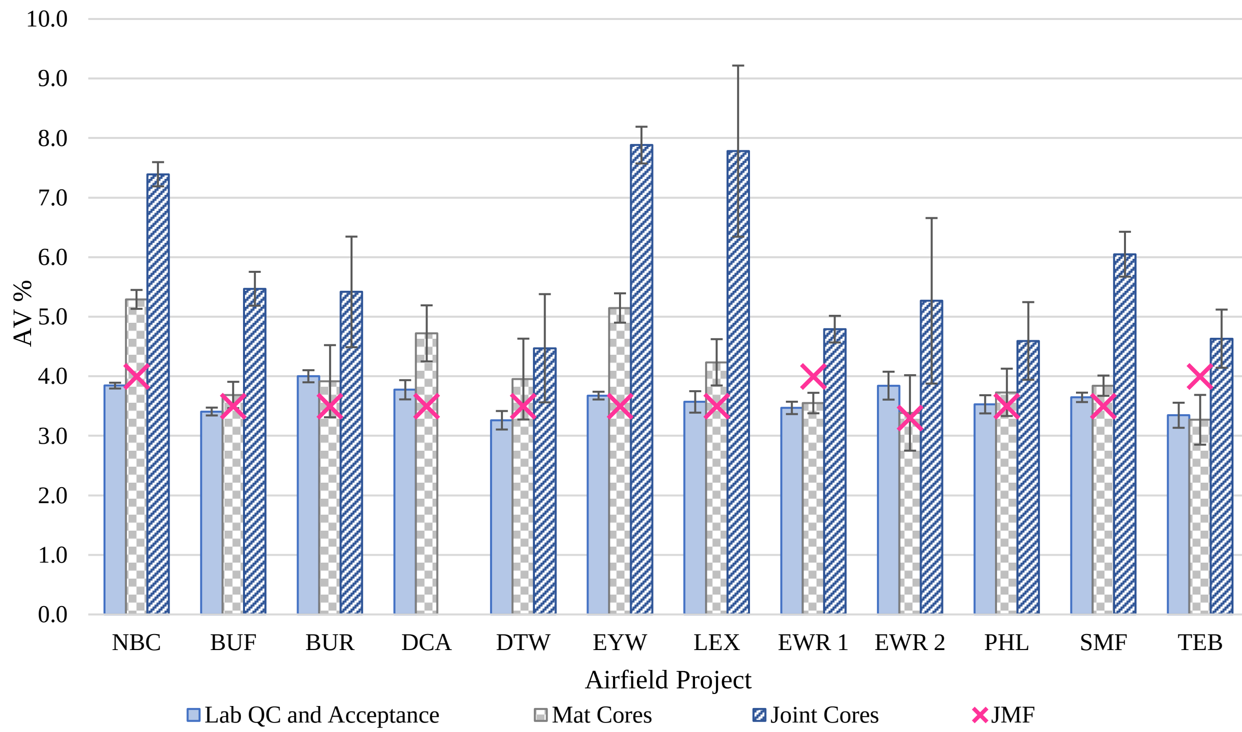

Figure 3. Summary of percentage of AV in asphalt mixtures (error bars represent the mean plus or minus 95% confidence interval).

Combined Data Analysis

The percentage of AV database from asphalt mixtures of the twelve airfield AC pavement projects are categorized into the three following data sets:

- Data set 1: Lab QC and acceptance data with a total of 1,563 data points.
- Data set 2: Mat cores with a total of 858 data points.
- Data set 3: Joint cores with a total of 760 data points.

An additional data set that combines mat and joint cores data from all twelve airfield AC pavement projects may be included in the analysis. However, grouping the mat and joint cores data into one data set should be based on pavement area (i.e., weighted by mat and joint pavement surface area). Each of the three data sets was analyzed using Minitab Statistical Software (Minitab® 17.1.0) in order to generate descriptive statistical parameters (e.g., mean, median, mode, standard deviation, skewness, kurtosis, etc.) (*17*). Three histograms along with fitted normal curves were developed for each data set (i.e., lab QC and acceptance, mat cores, and joint cores) and are presented in Figure 4 to Figure 6.

Each data set was subjected to the Anderson-Darling normality test, which compares the empirical cumulative distribution function (ECDF) of the sample data with the expected distribution in case of normal data. The null hypothesis of population normality is rejected if the observed difference is adequately large at the 95% confidence level (*18*). In order to pass the Anderson-Darling normality test at the 95% confidence level, the values in data sets 1 and 2 have to be mathematically transformed by raising the percentage of AV in asphalt mixtures to the power 1.5 and by applying square root, respectively. Whereas, for data set 3, the quality tools analysis on Minitab software with individual distribution identification indicated that none of the mathematical transformation will be able to fit the percentage of AV in asphalt mixtures for joint cores into a normal distribution with a $p\text{-value} \geq 0.05$. This was nearly expected based on the bimodal distribution of the original data for joint cores in Figure 6, delineating two different peaks in the respective histogram. It is worth noting that previous distribution of field density data has been reported in the literature with left-skewed and leptokurtic (i.e., kurtosis > 3) properties, rather than normal distribution (*19*).

Moreover, the joints AV of data set 3 was analyzed using two different groups, including Beaufort, Key West, and Lexington projects with high joints AV as group 1. However, no common factor nor a normal distribution was depicted within the projects of each group. Therefore, the joints data points were recombined into one data set representing all evaluated airfield projects. Despite that the transformed data set 3 did not pass the normality test ($p\text{-value} < 0.05$), Figure 7 denotes that most of the transformed data (i.e., after square root transformation) falls within the 95% confidence band of the normal probability plot.

The basic statistics of the three AV data sets are summarized in Table 4 to better evaluate the shape of the probability distributions. The skewness values suggest that the distribution of AV percentage in asphalt mixtures for data set 1 is slightly left-skewed, compared to a slightly right-skewed distributions for data sets 2 and 3. Moreover, the kurtosis value for lab QC and acceptance data (i.e., data set 1) is very close to 3, which corresponds to the kurtosis value of a normal distribution. Finally, a small positive (i.e., kurtosis > 3) and negative (i.e., kurtosis < 3) excess kurtosis was observed for data sets 2 and 3, respectively, indicating that the peak of distribution is slightly taller or shorter than the normal distribution.

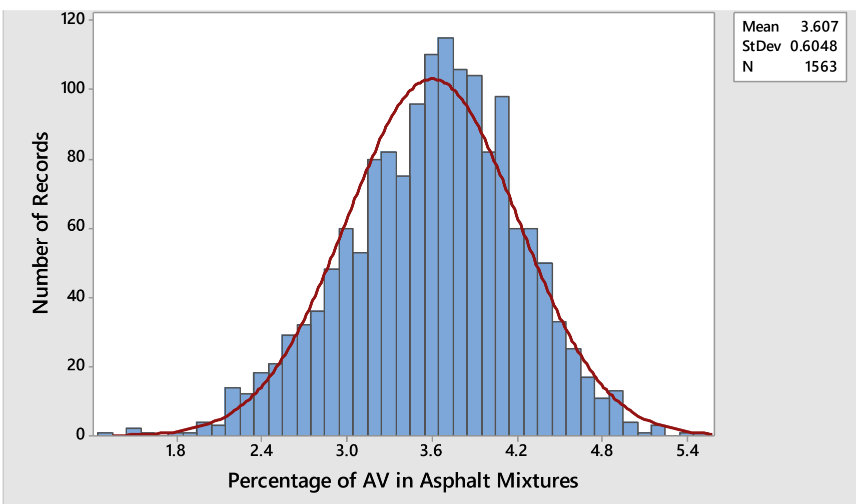

Figure 4. Histogram of percentage of AV in asphalt mixtures for data set 1 (combined lab QC and acceptance data).

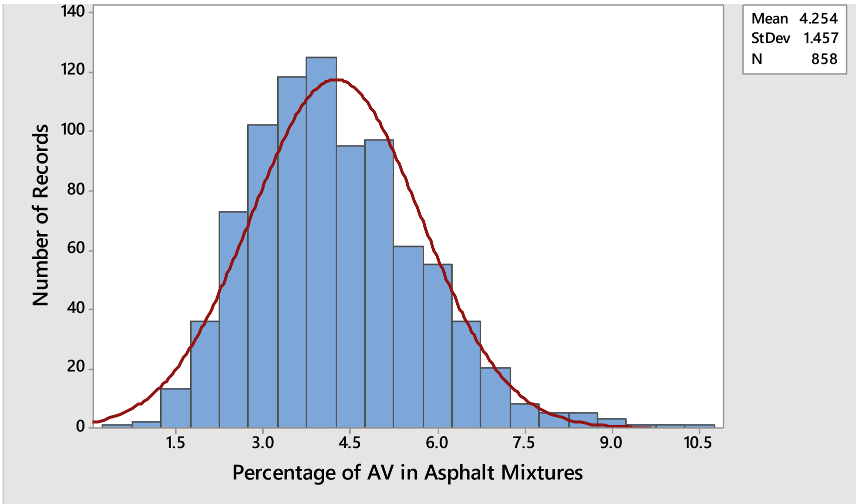

Figure 5. Histogram of percentage of AV in asphalt mixtures for data set 2 (combined mat cores data).

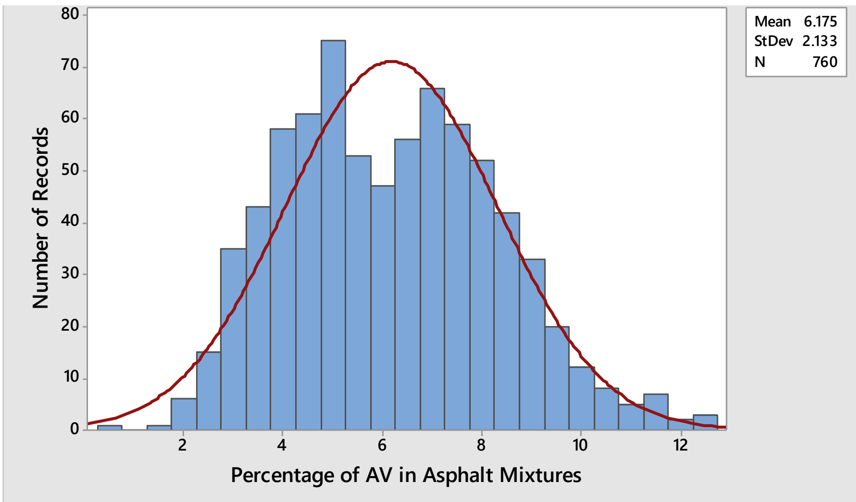

Figure 6. Histogram of percentage of AV in asphalt mixtures for data set 3 (combined joint cores data).

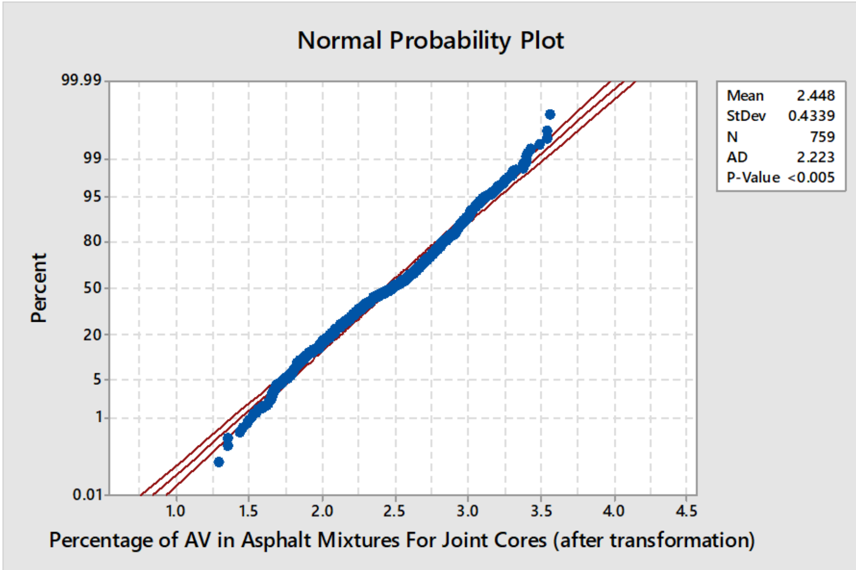

Figure 7. Normal probability plot for the square root of percentage of AV in asphalt mixtures for data set 3 (combined joint cores data).

Table 4. Basic statistics for percentage of AV data sets.

Data Set	Mean, %	Standard Deviation, %	Skewness	Kurtosis
1 (Lab QC and acceptance)	3.6	0.605	-0.27	3.06
2 (Mat Cores)	4.3	1.457	0.60	3.53
3 (Joint Cores)	6.2	2.133	0.30	2.60

Table 5 shows the average percentage of AV for each of the three data sets before and after transformation to better fit for normal distribution. The original average percentage of AV in asphalt mixtures are 3.6, 4.3, and 6.2 for lab QC and acceptance, mat cores, and joint cores, respectively. A decrease of 0.2% in the average percentage of AV in asphalt mixtures is observed for the mat and joint cores after square root transformation of the respective data.

Table 5. Average percentage of AV in asphalt mixtures.

Data Set	Before Transformation to better fit for normal distribution	After Transformation to better fit for normal distribution
1 (Lab QC and acceptance)	3.6%	3.6%
2 (Mat Cores)	4.3%	4.1%
3 (Joint Cores)	6.2%	6.0%

A useful characterization of the evaluated data sets is to calculate the percentiles of each distribution for the percentage of AV. Table 6 shows the results for the 25th, 50th (i.e., median), 75th, and 99th percentiles. The median for each of the data sets is very comparable to the average value before and after transformation. The 75th percentile of the percentage of AV in asphalt mixtures was calculated to be 4.0, 5.2, and 7.7% for lab QC and acceptance, mat cores, and joint cores data, respectively. The 99th percentile covering most of the data points was determined to be 4.9, 8.7, and 11.5% for lab QC and acceptance, mat cores, and joint cores data, respectively.

Table 6. Percentiles of percentage of AV in asphalt mixtures.

Percentile	Percentage of AV		
	Data Set 1 (Lab QC and acceptance)	Data Set 2 (Mat Cores)	Data Set 3 (Joint Cores)
25^{th}	3.2%	3.2%	4.5%
50^{th} (Median)	3.7%	4.1%	6.1%
75^{th}	4.0%	5.2%	7.7%
99^{th}	4.9%	8.7%	11.5%

Test Method Precision

The precision of the ASTM D3203 test method can be computed by a procedure described in ASTM D4460, which depends on the precision of test methods for bulk specific gravity and TMD (*20*). Consequently, the precision limits for percent AV are in AASHTO T 269 "Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures." (*21*). Table 7 summarizes the one-sigma limit (1s) and the difference two-sigma limit (d2s) determined for single and multi-operator conditions. The 1s is the standard deviation of AV population data indicating the variability of a large group of individual AV values obtained under similar conditions (*22*). The d2s provides a maximum acceptable difference between two AV results on test portions of the same material. The d2s index equals the difference between two individual AV values that would be equaled or exceeded in the long run in only 5% of the time under the normal and correct operation of the test method. The d2s index is determined by multiplying the 1s by a factor of $2\sqrt{2}$, which represents the 95% confidence interval (*22*).

The AV precision limits in Table 7 need to be considered in order to ensure that samples compacted to different target AV ranges present statistically different AV levels. In other words, when d2s criteria is considered, the difference in AV between the two data sets need to be outside the limits to signify that the AVs on the two data sets are statistically different at the 95% confidence level. Thus, assuring the selection of two distinct target AV levels for laboratory mechanical testing of compacted asphalt mixtures.

Table 7. Precision limits for percentage of AV (AASHTO T 269).

Precision	Standard Deviation, 1s (%)	Acceptable Range of Two Results, d2s (%)
Single Operator (repeatability)	0.21	0.59
Multi Operator (reproducibility)	0.40	1.13

AV Levels Recommendations

Based on the analyzed airfield projects data, the following AV levels for laboratory mechanical testing were identified for further evaluation:

- Based on in-place mat density:
  - AV level matching the observed median of mat cores data for the percentage of AV in the asphalt mixtures (i.e., 4.1%)→ AV level of 4.0±0.5% is selected, or
  - AV level matching the 75^{th} percentile of mat cores data for percentage of AV in the asphalt mixtures (i.e., 5.2%)→ AV level of 5.0±0.5% is selected.
- Based on in-place joint density:
  - AV level matching the 75^{th} percentile of joint cores data for percentage of AV in the asphalt mixtures (i.e., 7.7%)→ AV level of 7.0±0.5% is selected to keep it consistent with the AV level specified in current standard test methods (e.g., AASHTO T 324, AASHTO T 340, ASTM D8360) (*8, 23-24*).

While 7.0% AV is recommended to represent in-place joint density, either 4.0% or 5.0% AV is to be selected to represent in-place mat density. A percentage of AV tolerance of ±0.5% is recommended on the samples used for mechanical tests. This tolerance may be increased (e.g., ±1.0%) when samples used for acceptance during production (e.g., field cores). Per Table 7, the difference between the identified AV level to represent in-place mat density (i.e., 4.0±0.5% or 5.0±0.5%) and the one representing in-place joint density (i.e., 7.0±0.5%) is greater than the single operator d2s precision limit for percentage of AV. In other words, two samples compacted by a single operator to 4.0% (or 5.0%) AV and 7.0% AV are considered to have statistically different AVs even when considering the 0.5% tolerance. However, in the case of multi-operator, there is a chance that two samples compacted to 5.0±0.5% and 7.0±0.5% have statistically similar AVs. This is demonstrated in the difference between 5.5% (i.e., 5.0+0.5%) and 6.5% (i.e., 7.0–0.5%) being within the multi-operator d2s precision limit for percentage of AV (i.e., 6.5% – 5.5% = 1.0% < 1.13%).

The three AV levels identified for laboratory mechanical testing (two from in-place mat density and one from joint density) are assessed in Table 8 by means of the percent of data covered within each AV range using the ECDF (empirical cumulative distribution function). Moreover, Table 9 summarizes the advantages and disadvantages for implementing each of the identified AV levels. While evaluating the data, one should keep in mind that the main goal is to implement mechanical tests as part of the BMD framework for asphalt mixture design, verification, and acceptance during production.

Based on the potential advantages and disadvantages identified in Table 9, a laboratory experiment to study the feasibility of using the identified AV levels was conducted using select mechanical tests. The objective of this experiment was to verify whether target AV levels can be achieved within a reasonable number of gyrations without damaging the aggregates particles or structure. In particular, the study should look at the effort needed in the Superpave gyratory compactor (SGC) (i.e., number of gyrations) to reach the target AV levels for asphalt mixtures having a NMAS of 0.5 inch and 0.75 inch. The selection of the mechanical tests to be included as part of this experiment needed to consider the specified thickness of the test specimen relative to the NMAS of the asphalt mixture.

Table 8. Selected AV levels for laboratory mechanical testing.[a]

AV Level[b]	Data Set	AV_{LL} ≤ Percent of Data ≤ AV_{UL}	Percent of Data ≤ AV_{UL}
4.0±0.5%	Lab QC and acceptance	53.4	93.5
	Mat Cores	27.6	60.0
5.0±0.5%	Lab QC and acceptance	6.5	99.9
	Mat Cores	17.6	77.6
7.0±0.5%	Mat Cores	4.8	97.7
	Joint Cores	16.7	71.8

[a]AV_{LL} = AV lower limit; AV_{UL} = AV upper limit.
[b]The ±0.5% tolerance may be increased (e.g., ±1.0%) for mechanical test samples used for acceptance during production.

Table 9. Potential advantages and disadvantages for identified AV levels.

Identified AVs	Advantages	Disadvantages/Challenges
4.0 ± 0.5%	▪ Mechanical testing is done at an AV level consistent with the asphalt mix design. ▪ Mechanical testing is implemented during production for acceptance and/or consistency of the asphalt mixture. o Lab QC and acceptance: PMLC samples are used for both volumetrics and mechanical testing (if Superpave mix design method used). o Cores: mat cores are used for both in-place density and mechanical 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 mechanical 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 mechanical 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. ▪ Mechanical testing is implemented during production for acceptance and/or consistency of the asphalt mixture. o Cores: joint cores are used for both in-place density and mechanical testing.	▪ AV level different than the mix design target AV level. ▪ Trial and error are needed to achieve target AV level.

EVALUATION OF COMPACTION EFFORT

The laboratory compaction effort required to reach each of the recommended target AV level for a certain specimen thickness was evaluated in the SGC. This was done in order to avoid excessive compaction effort in the laboratory, which may cause aggregate breakdown or damage to the mix skeleton during compaction. This issue may be encountered typically in case of low target AV (e.g., 4% and 5%) and/or mixtures with large NMAS. Plant-produced AC mixtures from four different airfield projects shown in Table 11, were sampled to examine the compaction effort. The mix type along with the airport code, construction date of the project, binder grade, and aggregates NMAS were tabulated for each of the four mixtures. The first two mixtures were classified as FAA P-401, while the other two mixtures (i.e., EWR and TEB) were designed per the Port Authority of New York and New Jersey (PANYNJ) Specifications Section 321218, which includes the requirements of FAA AC 150/5370 Item P-401 with FAA approved modifications (*4*).

Table 10. Airfield characteristics of the experimental plan.

Airport	Airport Code	Mix Type	Construction Date	Binder PG	NMAS, inch
Sacramento International Airport	SMF	P-401 Surface	Sept 2022	PG 76-22M	1/2
Reno Stead Airport	RTS	P-401 Surface (Bottom lift)	Oct 2022	PG 64-28NV	1/2
Newark Liberty International Airport	EWR	P-401 Surface (Modified per PANYNJ specifications)	Aug-Sept 2022	PG 82-22	3/4
Teterboro Airport	TEB		July-Aug 2022	PG 64-22	3/4

The plant-produced loose asphalt mixtures were reheated per the flowchart in Figure 8, then compacted to the set specimen height and target AV range described in the following sections, to assess the relative compaction effort needed. Excess compaction effort in the SGC was evaluated based on the locking point concept. The literature documented on the sequence of steps to reheat plant/field-produced loose asphalt mixtures was reviewed including current Departments of Transportation (DOTs) standard practices (*25*-*27*). Consequently, a protocol was developed to include details for handling, splitting, and reheating plant/field-produced asphalt mixtures. The established protocol aims to minimize unnecessary stiffening of the asphalt mixture due to oxidation with a maximum total reheating period of four hours. The gyratory locking point was determined following the common Georgia Department of Transportation (GDOT) method, which defines the locking point as the number of gyrations at which the same specimen height repeats for three consecutive times (*28*).

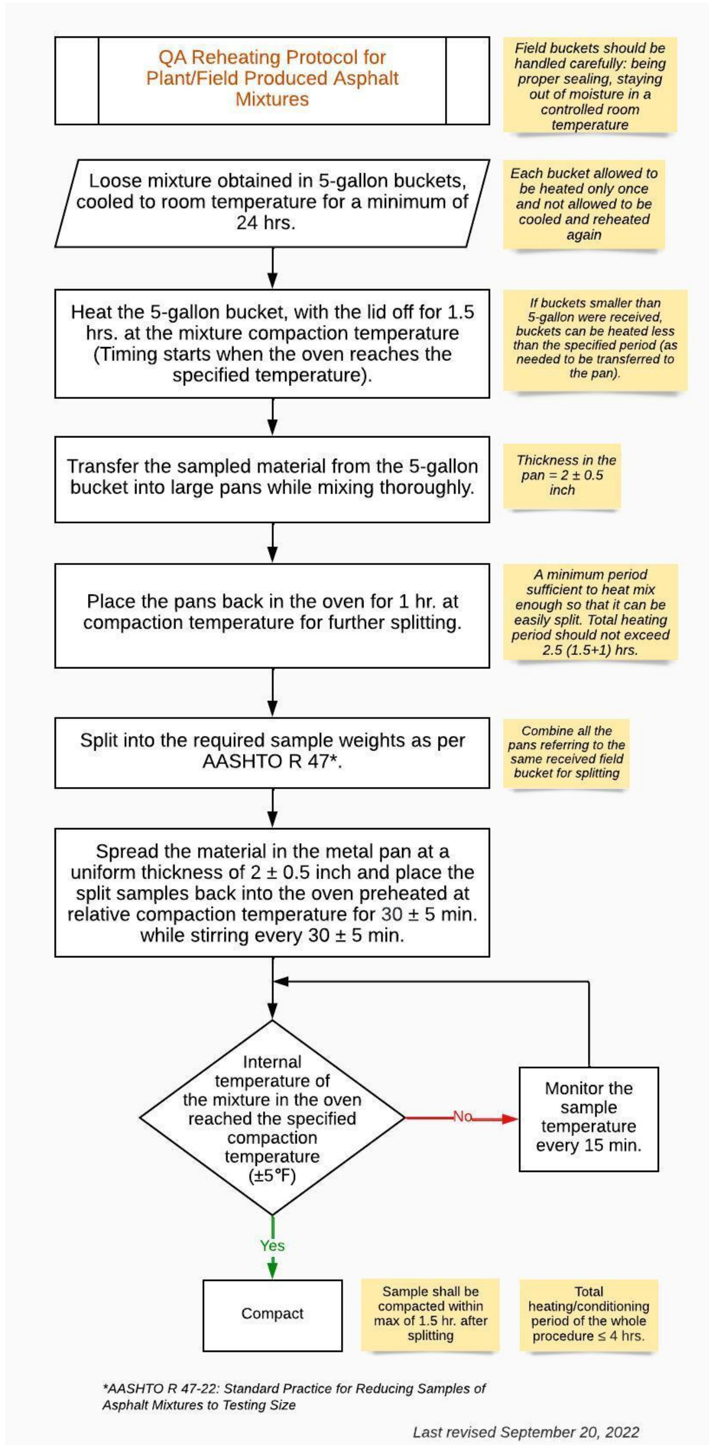

Figure 8. Reheating protocol for plant-produced loose asphalt mixtures.

Directly Molded Specimens

It is commonly believed that the required compaction effort depends on the combination of the final specimen height and the target AV level, hence the specimens at 60 mm thickness were initially evaluated targeting 7±0.5% AV. The number of gyrations required to reach the set AV range at 60 mm varied between 162 and 172 gyrations for the SMF mixture (Table 11), which significantly exceeds the reported locking point. The compaction curve is plotted based on the height and the number of gyrations recorded by the SGC machine during compaction. The excess compaction effort can be clearly seen in Figure 9, where the sample was subjected to 120 gyrations after the locking point, to reach 6.6% AV at 60 mm height, which may be associated with a high likelihood of damage for the aggregate skeleton. 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: Hamburg Wheel Track Test (HWTT), High Temperature Indirect Tensile Test, and Ideal-RT *(8,23)*. The results of the four airfield mixtures in Table 11 andTable 12 suggest that the 7±0.5% AV can be achieved within reasonable number of gyrations at 62 mm, where the locking point was not reached during compaction in most cases. Larger Superpave gyratory samples have been found to be easier to compact relative to small specimens (*29*). Yan et al. emphasized on the profound effect of specimen size on the compaction curve, where the packing fraction increases with the specimen size (*29*). Additionally, more uniformity in the AV level within the sample has been reported by Masad et al. with lower number of gyrations (*30*).

Table 11. SMF and RTS airfield mixtures compaction data.

Mix	**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

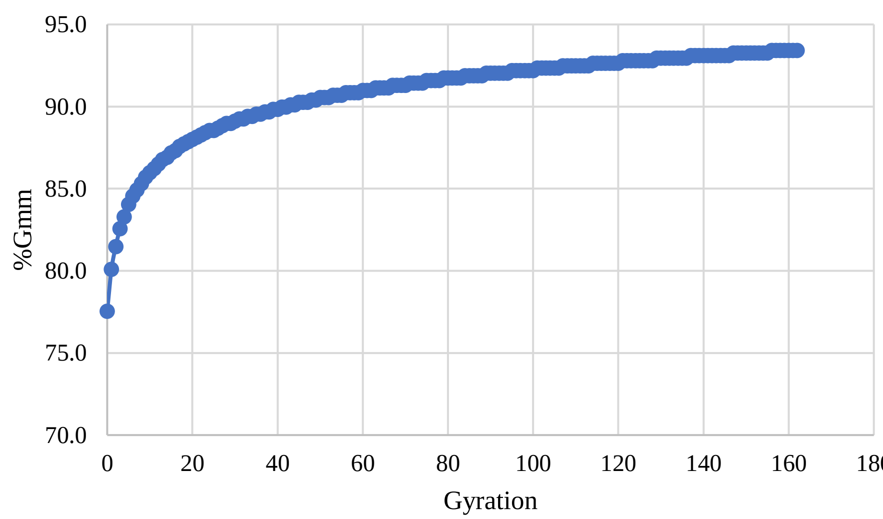

Figure 9. Compaction curve for 60 mm SMF specimen targeting 7±0.5% AV.

The number of gyrations to reach the second recommended AV level of 5±0.5% was assessed for EWR and TEB mixtures. As expected for lower AV, the sample was subjected to significantly higher number of gyrations to get the target density, ranging between 98 and 146 gyrations. However, a lower compaction effort was favored by the research team, hence the alternative of cutting 62 mm specimens from thicker samples at 165 mm height was further investigated to reach lower AV levels as per the following sections. Moreover, cutting and coring processes have been associated with substantial reduction of AV heterogeneity in the vertical direction of the compacted sample (*31*). In particular, AV heterogeneity has been significantly reported in case of slender asphalt specimens (i.e., tall specimens) due to the cone effect inducing higher AV in the middle of the directly molded sample.

Table 12. EWR and TEB compaction data.

Mix	**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
Mix	**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

Comparative Results with Cut Specimens

It is recognized believed that the cutting technique may delay sample preparation in the laboratory, however efficiency was optimized in this research by cutting two specimens at 62±2 mm height, out of a single thick SGC sample. Therefore, the thick sample was compacted to 165 mm in order to ensure two specimens cut from the cylindrical specimen, after removing the top and bottom surface, if needed. However, the cutting technique needs to be verified to maintain similar mixture rutting resistance, otherwise the prospective criteria and performance analysis would need to be adjusted between directly molded and cut specimens. In this regard, replicate specimens targeting 7±0.5% AV were compared after direct molding to 62 mm as well as after cutting from 165 mm molded samples. Accordingly, specimens from three airfield mixtures including: RTS, EWR, and TEB projects were produced in the laboratory with two different procedures (i.e., direct molding versus cutting out of a larger specimen) to analyze the relative compaction curve, followed by performance evaluation at several AV levels in the following section. A total of nine specimens were tested for each asphalt mixture:

- Three specimens directly molded to 62 mm targeting 7±0.5% AV.
- Three specimens cut to 62±2 mm from thicker sample (165 mm) targeting 7±0.5% AV on the cut specimens: to depict any significant performance difference with directly molded specimens.
- Three specimens cut to 62±2 mm from thicker sample (165 mm) targeting 4±0.5% AV on the cut specimens: to verify the required compaction effort for a lower AV level.

Considering that cut specimen did not reach the exact target AV, while most replicates ranged within the AV allowable range, linear interpolations were employed to estimate the number of gyrations needed to reach the exact target AV (i.e., 4%, 5%, or 7%). The range of required gyrations is summarized in Table 13 using various specimen preparation methods for the three airfield mixtures. It can be inferred that the alternative of cutting eliminated the excess compaction effort and the three target ranges of AV can be achieved at 62 mm after cutting with reasonable number of gyrations. Based on the tabulated results, the research team concluded that specimens targeting 7±0.5% AV can be directly molded to 62 mm, whereas specimens targeting 4% or 5% AV should be cut from 165 mm samples for future testing. However, the non-uniformity of the AV level within the sample should be considered prior to cutting. In fact, targeting 4 or 5% AV on final cut specimens may require compacting the 165 mm samples to a slightly higher AV level based on AV distribution reported in the literature within the sample (*29,30,32*). Accordingly, trial and error compacted samples may be needed to reach the target AV level on the final cut specimens.

Table 13. Estimated number of gyrations for different AV levels

Airport mix	Estimated No. of Gyrations			
	Directly molded	Cut from 165 mm thick sample		
Target AV%	7.0	7.0	5.0	4.0
RTS	49	35	65	80
EWR	64	24	39	47
TEB	42	19	33	40

EFFECT OF SPECIMEN CONDITIONS ON RUTTING RESISTANCE

After selecting representative AV levels and specimen size associated with reasonable compaction effort, the susceptibility of the mixture to rutting was examined by means of the Rutting Tolerance Index (RT Index ASTM D8360-22). The objectives of the rutting resistance evaluation were to:

1. Capture any significant impact of different specimen preparation methods (i.e., direct molded vs cut) on relative sample performance.
2. Investigate the effect of different AV levels on the rutting resistance and relative ranking of the mixtures based on the RT Index.

The presented rutting resistance evaluation will assist in setting final test specimen conditions, in terms of selecting between 4±0.5% or 5±0.5% AV level and investigating the effect of cutting on sample rutting performance. The RT Index is a parameter derived from the Ideal-RT which was published recently as a national standard for practice (ASTM D8360-22) (*8*). The Ideal-RT was introduced in 2019 by Zhou et al. as a QC rutting test with a simple shear fixture practical for routine laboratory use, while adequately manifesting the shearing principle of the rutting mechanism (*33,34*). The Ideal-RT consists of the same apparatus and specimen size of Ideal Cracking Test (Ideal-CT), run at high temperature with a different bottom fixture to generate shear failure in the specimen. The main concept of Ideal-RT was derived from the three-point bending test of a beam, where a center load in the middle will generate shearing stress on either half of the beam. The Ideal-RT relies on a circular specimen as shown in Figure 10, rather than beams, where the shear forces propagate from the loading point at the top to the fixture base supports on either side of the specimen.

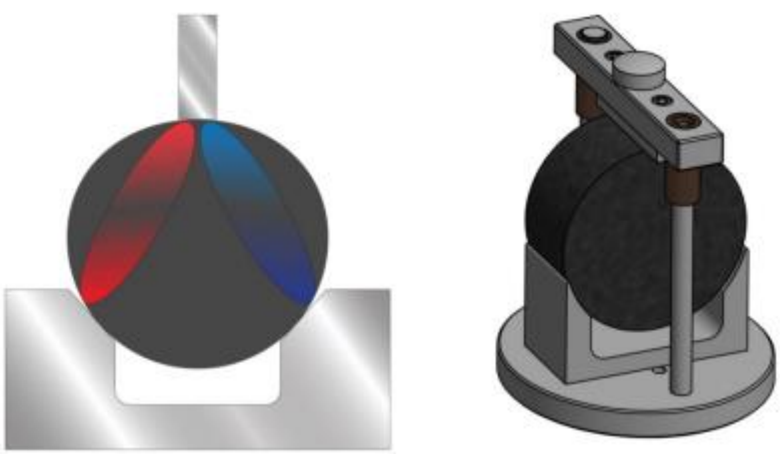

Figure 10: Ideal-RT apparatus showing shear planes caused by compression at the top of the fixture (*33*).

The tested cylindrical specimen can have a diameter of 100 or 150 mm and thicknesses varying between 38, 50, 62, 75 mm, etc., while the authors recommended a 150±2 mm diameter and 62±1 mm height for mixtures with NMAS of ¾" or smaller (*8,33,34*). The test is run with a compression loading rate of 2 inch/min at the target high test temperature, which is generally in the range of 50±15°C. The same preselected high temperature of the HWTT or Asphalt Pavement Analyzer test can be adopted for the Ideal-RT. However, a test temperature founded on the climatic conditions was recommended in this study based on the geographical location of the airport where the asphalt mixture is used, rather than a fixed test temperature. Following to a thorough review of several alternatives to derive a representative test temperature, the final selection adopted in this study corresponds to the final binder environmental grade (i.e., no grade bumping for speed) derived from the LTPPBind Online software at the surface of the pavement, with 50% reliability, and a target of ½ inch rut depth (*35*). Consequently, the testing temperatures was 52°C for RTS and TEB, comparing to 58°C for EWR airport. In summary, the RT Index derived from the Ideal-RT run at the proper high temperature, relies on the shear strength determined from the measured peak load, where greater shear strength indicates better rutting resistance of asphalt mixes.

Rutting Test Results and AV Effect

The Ideal-RT was run on different specimen types from the RTS, EWR, and TEB airfield mixtures including:

- Specimens directly molded to 62 mm targeting 7±0.5% AV.
- Specimens cut to 62±2 mm from thicker sample (165 mm) targeting 7±0.5% AV.
- Specimens cut to 62±2 mm from thicker sample (165 mm) targeting 4±0.5% AV.

Considering that the density of some cut specimen did not exactly reach the target AV, regression equations were developed for each mixture between the RT Index and specimen AV level measured after cutting. Therefore, the sensitivity of the Ideal-RT to AV was plotted in Figure 11 for the cut specimens of each airfield mixture, where a steeper slope indicates higher susceptibility of the rutting performance to AV. The EWR and TEB mixtures showed similar susceptibility to AV with parallel slopes, whereas RTS mixture got a steeper slope which may be referred to the soft base binder used in the polymer modified PG 64-28NV of the mixture.

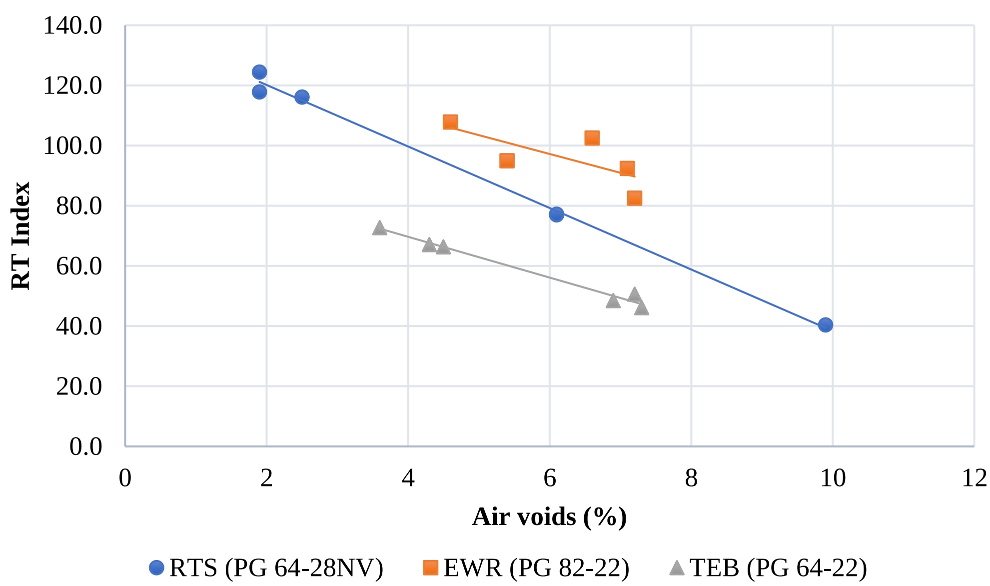

Figure 11. Regressions of RT Index with AV for cut specimens.

The RT Index results of the three mixtures at different AVs are shown in Figure 12, along with the error bars representing the sample standard deviation for directly molded specimens. The results at 4%

and 5% AV were estimated using the linear regressions of the cut specimens developed in Figure 11, hence no error bars were shown for these 2 AV levels. The RT Index values were shown to increase as expected with lower AVs, while maintaining similar performance ranking among the mixtures. Consistently at 4, 5, and 7% AV, the EWR rutting resistance outperformed the other two project mixtures, followed by the RTS, then TEB mixtures. The observed trend is consistent with the asphalt binders used in the three mixtures including a PG 82-22 (polymer modified), PG 64-28NV(polymer modified), and a neat PG 64-22, for EWR, RTS, and TEB, respectively.

However, the deviation in the mixture performance was more pronounced at higher AV (i.e., 7%) relative to 4 and 5% AV, where the RT Index of the EWR mixture (PG 82-22) was 10, 16, and 53% higher than RTS (PG 64-28NV) at 4, 5, and 7% AV, respectively. Compared to the TEB (PG 64-22), the RT Index of the EWR increased 57, 64, and 99% at 4, 5, and 7% AV, respectively. Interestingly, the RT Index was able to capture the effect of the polymer modification in the binder, particularly at 7±0.5% AV range. On the other hand, the Ideal-RT results at lower AV levels (i.e., 4 and 5% AV) highlight the effect of the aggregates structure. This observation can be correlated with the confinement effect applied during mechanical testing, where the impact of the binder grade and rheological properties can be less notable at higher confinement pressures (or lower AV%).

Subsequently, the presented data support the significance of evaluating the mixture performance at different AV levels, however the RT Index at 4 and 5% AV for all three mixtures ranged within a maximum coefficient of variation (COV) of 8%. Noting that a maximum COV of 11% was reported within the replicates of this study, and a typical COV < 10% was reported per previous studies on the repeatability of the Ideal RT (*33*,*36*). In view of the presented results and discussion, the research team selected the following two AV levels for future mechanical testing: 7±0.5% and 5±0.5%, where the latter showed similar results to the 4% AV and corresponded to the 75th percentile of the mat cores AV data.

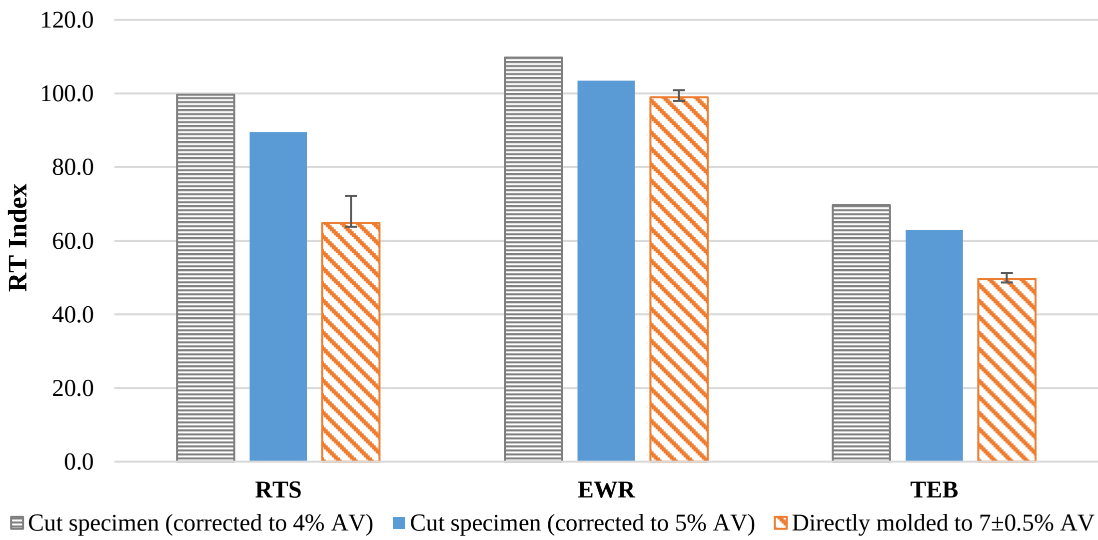

Figure 12. RT Index results at varying AV levels.

Effect of Cutting and Multi-lab Variability of Rutting Performance

The specimen preparation at low AV involved cutting from thicker samples, assuming that the cutting process does not significantly alter the rutting performance results. In particular, testing directly molded and cut specimens was conducted to depict any significant influence of AV non-uniformity (within 165 mm thick specimens) on selected rutting test results. This was verified experimentally as shown in Figure 13, including the Ideal-RT results of the three mixtures with different specimen preparation methods (directly molded vs. cut specimens) along with the error bars (i.e., one standard deviation) for the directly molded specimens. The directly molded specimens targeted a range of 7±0.5% AV, and the RT Index of the cut specimens were corrected per the regressions developed in Figure 11, in order to match the exact AV level reached with the directly molded samples (i.e., 7.2 and 6.7% AV) for higher consistency. The same rutting resistance ranking was denoted in both specimen types, suggesting similar RT Index values for directly molded and cut specimens. In fact, the cutting process did not show any bias data towards consistently higher or lower RT Index, and the values between directly molded and cut specimens ranged within the 11% maximum COV reported in this research. Based on the similar results between both specimen types, it can be concluded that Ideal-RT can be consistently conducted either on directly molded or on cut specimens, if needed, without any significant difference in the relative rutting performance.

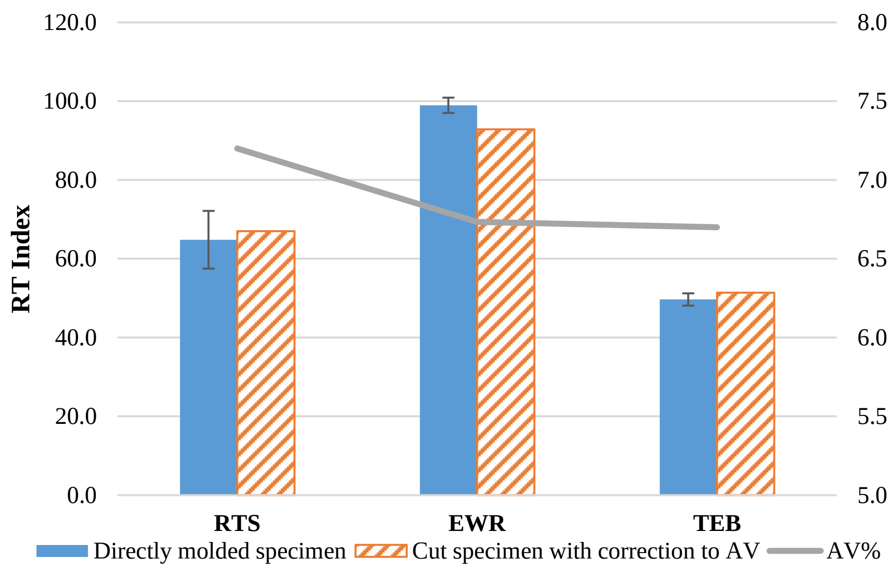

Figure 13. Effect of cutting at 7±0.5% AV on RT Index.

The second experiment was performed on directly molded, as well as on cut specimens targeting 5±0.5% AV. The results for EWR and TEB airfield mixtures are graphed in Figure 14, along with the error bars of the directly molded specimens. Similar to the aforementioned evaluation in Figure 13, the RT Index of the cut specimens were corrected per the regressions developed in Figure 11, in order to match the exact AV level reached with the directly molded samples (i.e., 5.5 and 5.1% AV) for higher consistency. As per Figure 14, the directly molded specimens had a COV of 8% and <1% within the replicates of EWR and TEB mixtures, respectively. Furthermore, it is worth mentioning that the directly molded and cut specimens were each prepared and tested by different entities, as outlined in the graph. Thus, the multi-lab variability between directly molded and cut specimens ranged between 6% and 8% for EWR and TEB mixtures, respectively, which is lower than the maximum single operator COV of 11% reported for the presented set of data. Despite the excess compaction effort of the directly molded specimens, the RT Index did not considerably change between both specimen types at the range of 5±0.5% AV. Additionally, the Ideal RT outcome validates the regression between the RT Index and AV on cut specimens, previously developed for each mixture in Figure 11. This was observed based on the consistency between direct measurement of the RT Index (directly molded specimens at 5±0.5% AV) and estimated results for the cut specimens.

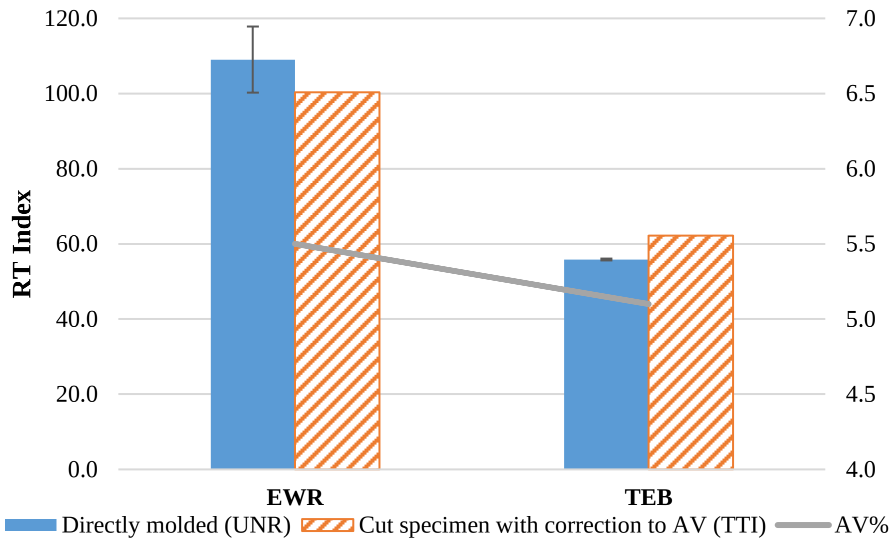

Figure 14. Effect of cutting at 5±0.5% AV and multi-lab variability of RT Index.

FINDINGS AND CONCLUSION

This study aimed at developing specific test specimen conditions for rutting mechanical tests of airfield asphalt mixtures as part of a prospective implementation of the BMD methodology in the FAA P-401/P-403 specifications. One of the key elements towards implementing BMD, is setting adequate and practical conditions for laboratory mechanical testing that best simulate actual airfield conditions. These conditions include setting selecting proper AV level, specimen size and preparation (cutting, gluing, etc.), aging temperature and time, and representative test temperature for evaluating airfield mixtures. Based on the analysis of QC and acceptance AV data of PMLC samples and in-place density of mat and joint cores from existing airfield pavements, representative AV levels were recommended for future laboratory testing. The first AV level suggested corresponded to 5±0.5% AV which matches the 75th percentile of mat cores data for percentage of AV in the asphalt mixtures. Whereas the 7±0.5% AV range was further suggested based on in-place joint density, where rutting has been reported as being driven by lower in-place density. The proper specimen size and specimen preparation method were selected for each AV level, while avoiding excessive compaction in SGC and crushing the aggregates. The rutting test results, in terms of RT Index, at varying AV levels indicate that the 7±0.5% AV range was able to differentiate the mixture susceptibility to rutting better than lower AV levels. Moreover, the recommended cutting technique was verified to maintain similar performance results relative to the directly molded specimens, while noting same test results between specimens cut at 4±0.5% and 5±0.5% AV levels. It was finally recommended testing 62 mm height specimens at 7±0.5% AV (directly molded) and at 5±0.5% AV (after cutting), which should help with capturing the different aspects of the mixture rutting resistance in terms of aggregates skeleton and binder properties.

ACKNOWLEDGMENTS

The authors greatly acknowledge the Airport Asphalt Pavement Technology Program (AAPTP), established though the Cooperative Agreement effort between National Asphalt Pavement Association (NAPA) and the Federal Aviation Administration (FAA).

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: E. Hajj, T. Bennert, F. Zhou, and A. Hand; data collection: C. Decker, H. Patel, F. Zhou, and N. Elias; analysis and interpretation of results: E. Hajj, T. Bennert, F. Zhou, and N. Elias; draft manuscript preparation: N. Elias. All authors reviewed the results and approved the final version of the manuscript.

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