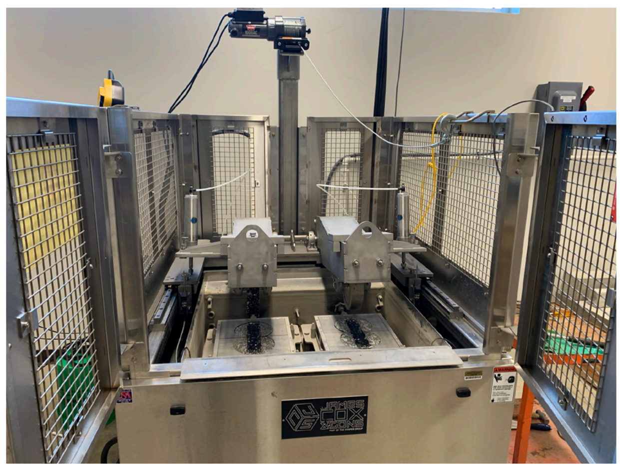
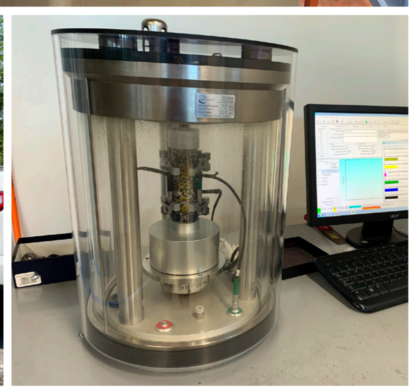
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Development of Volumetric Acceptance and Percent Within Limits (PWL) Criteria for Stone Matrix Asphalt (SMA) Mixtures in Indiana





Jusang Lee, John E. Haddock, Jongmyung Jeon

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AUTHORS

Jusang Lee, PhD, PE
Asphalt Pavement Research Engineer
Office of Research and Development
Indiana Department of Transportation

John E. Haddock, PhD, PE
Professor of Civil Engineering
Director of the Indiana Local Technical Assistance Program
Lyles School of Civil Engineering
Purdue University
(765) 496-3996
jhaddock@purdue.edu
Corresponding Author

Jongmyung Jeon, PhD
Research Associate
Lyles School of Civil Engineering
Purdue University

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16. Abstract

SMA is designed based on SMA volumetric properties in terms of air voids content (Va), voids in the mineral aggregate (VMA), and adequate stone-on-stone contact. For construction quality assurance (QA) purposes, INDOT currently accepts SMAs based on aggregate gradation and asphalt binder content. Thus, there is a discrepancy between SMA design criteria and construction acceptance. To better align design and construction, it is necessary to consider SMA volumetric properties in the use of QA. For HMA mixtures, INDOT has already transitioned from volumetric QA acceptance procedures to PWL. Today, SMA still uses adjustment points, which are not based on robust statistics, for QA acceptance.

SMA QA samples and QA data sets were collected from projects constructed in 2019 and subsequently tested in the laboratory. The Hamburg Wheel Track Test (HWTT) was performed on the 2019 QA samples to evaluate SMA rutting performance. Additionally, the PWL method for HMA was applied to the 2019 SMA QA data to see if the HMA PWL method will work for SMA. Possible SMA QA measurements were compared to past QA data and HMA QA measurements. In addition, Voids in the Coarse Aggregate (VCA) was evaluated as a possible SMA QA measurement. Finally, using the suitable QA measurements for SMA, a PWL parameter study was performed to find PWL that provide a Pay Factor (PF) equivalent to the current SMA Adjustment Point (AP) PF. The current SMA QA measurements (binder content, gradation, and density) are recommended for Indiana's SMA PWL. Based on the results of applying PWL to SMA QA data for the last four years, SMA PWL specification limits are recommended. Also, the SMA PF equations are suggested to get the SMA PWL to have PF equivalent to the current AP PF.

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EXECUTIVE SUMMARY

Introduction

The stone matrix asphalt (SMA) mixture design process is based on volumetric properties, but for quality assurance (QA) purposes, the Indiana Department of Transportation (INDOT) currently accepts SMA based on aggregate gradation and binder content. Thus, there is a discrepancy between the design criteria and the mixture acceptance. This suggests that the feasibility of using volumetric properties as SMA QA measurements needs to be investigated. However, INDOT has transitioned from using single test value volumetric properties to accept hot-mix asphalt (HMA) mixtures to using percent-within-limits (PWL) criteria for HMA QA procedures. This leaves a wide gulf in the QA procedures for HMA and SMA, as the latter still uses adjustment points that are not based on robust statistics. Since PWL procedures rely heavily on a statistical assumption of normality, robust statistical analysis is needed for the development of updated SMA PWL specifications, which will provide a better understanding of the data and maximize its interpretation and use.

SMA QA samples and QA data sets were collected from projects constructed in 2019 and subsequently tested in the laboratory. The Hamburg Wheel Track Test (HWTT) was performed on 2019 QA samples to evaluate SMA rutting performance. Additionally, the PWL for HMA was applied to the 2019 SMA QA data to see if the HMA PWL method would work for SMA. Possible SMA QA measurements were compared to past QA data and HMA QA measurements. Additionally, voids in the coarse aggregate (VCA) were evaluated as a possible SMA QA measurement. Finally, using the suitable QA measurements for SMA, a PWL parameter study was performed to find PWLs that provide a pay factor (PF) equivalent to the current SMA adjustment point (AP) PF.

Findings

The study reviewed the INDOT SMA QA and developed a new SMA QA PWL. First, possible SMA QA measurements were reviewed using past QA data and HMA QA measurements. In addition, VCA was evaluated as a possible SMA QA measurement. A PWL parameter study was performed using the selected QA measurements to find PWL providing pay factors similar to the current SMA AP PFs.

Reviewing VCAs and QAs in the 2019 SMA mix designs indicated that the Indiana SMA had negligible VCA problems. In addition, because of the VCA practicality limitation requiring significant efforts (i.e., in-place loose mix sampling, gyratory compactions, G_{mb} measurements, etc.) to obtain in-place VCA, the study determined not to include VCA in QA measurements. The outstanding rutting performance of SMA was confirmed by HWTT using the selected SAM QA core samples obtained from the projects constructed in 2019. The HMA PWL application using the 2019 SMA volumetric properties resulted in numerous failed QA SMAs, mainly due to the large V_a deviations caused by significant V_a sensitivity to the steel slags. Consequently, the SAC decided to exclude V_a and V_{be} (closely related to V_a) from the possible SMA QA measurements. Thus, it was determined that the study should use the current SMA QA measurements (i.e., binder content, gradation, and density) for the SMA PWL development. The study developed a framework to develop SMA PWL, which results in contractor payments equivalent to those being paid with the current SMA AP system. A PWL parameter study was successfully performed using reasonable specification limits obtained from the SAC, the limit optimization with respect to the AP percent material failure, the bonus-penalty scale adjusted pay factors, pay factor equations in terms of PWLs, and measurement-weight factors.

Implementation

The current SMA QA measurements (i.e., binder content, gradation, and density) are recommended for Indiana's SMA PWL. Therefore, PFs may be calculated for the binder content; 2.36-mm, 600-µm, and 75-µm sieves; and density. To get the SMA PWL to have PF equivalent to the current AP PF, the SMA PF is calculated using the following equations.

Estimated PWL greater than 90:

$$PF = ((0.50 \times PWL) + 55.0)/100$$

Estimated PWL greater than 50 and equal to or less than 90:

$$PF = ((0.75 \times PWL) + 32.5)/100$$

A weight factor of 35% for binder content, 30% for gradation, and 35% for density is recommended. The composite PF of each lot may be calculated as follows:

$$\text{Lot PF} = 0.35(PF_{\%Binder}) + 0.10(PF_{2.36mm}) + 0.10(PF_{600\mu m}) + 0.10(PF_{75\mu m}) + 0.35(PF_{Density})$$

Based on the results of applying PWL to SMA QA data for the last 4 years, the following SMA PWL specification limits are recommended.

Specification Limits		
Mixture		
	LSL	**USL**
Binder Content, %	DMF -0.5	DMF +0.5
Percent passing 2.36-mm sieve	DMF -5.0	DMF +5.0
Percent passing 600-µm sieve	DMF -4.0	DMF +4.0
Percent passing 75-µm sieve	DMF -2.5	DMF +2.5
In-Place Density		
	LSL	**USL**
Roadway Core Density (%Gmm), %	91.0	n/a

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1. INTRODUCTION

Stone matrix asphalt (SMA) is a stable and durable asphalt mixture that was originally developed in Germany in the 1960s to overcome asphalt pavement rutting and durability problems. Considered a premium product, SMAs have a gap-graded aggregate structure and rely on stone-on-stone contact to provide rut resistance and a rich asphalt binder content mortar to ensure durability. Most of the voids between the large aggregates are filled with the mortar, which is comprised of fine aggregates, mineral filler, and asphalt binder.

The primary advantage of SMA is extended pavement life, with improved pavement performance as compared to conventional dense-graded hot-mix asphalt (HMA) mixtures (National Asphalt Pavement Association, 2002). It has been documented that SMA pavements experience little to no measurable rutting due to the stone skeleton, and improved cracking resistance mainly due to their relatively high asphalt binder content (AASHTO Subcommittee on Construction, 2003). SMA pavements have also shown improved noise reduction levels and better friction resistance, due to a relatively rough texture (National Asphalt Pavement Association, 2002).

In the early 1990's the Federal Highway Administration (FHWA) established a technical group to study guidelines for design, construction and implementation of SMA (National Asphalt Pavement Association, 2002). By 1997, more than 28 states, including Indiana, were already implementing SMA. In the late 1990s, when the Indiana Department of Transportation (INDOT) began using SMA, HMA was accepted based on binder content and gradation testing. Thus, this basis was also adopted as the acceptance method for SMA. In the early 2000s, INDOT transitioned HMA to acceptance by volumetric properties, and then later to percent-within-limits (PWL), also based on volumetric properties (Gulen et al., 2009). However, SMA continued to be accepted using binder content and gradation.

PWL is defined as the percentage of a given material lot falling between the lower and upper specification limits, with a "lot" being some previously specified amount of material, usually further reduced to a previously specified number of sublots. Thus, PWL uses a statistical determination of the consistency and quality of the contractors' products. PWL-based pay factors encourage contractors to consistently produce quality work. Using sample data and the assumption of sampled population normality, the area under the curve is used to estimate the percentage of the population that falls within the selected limits. Thus, the portion of a given lot that falls within the limits can also be determined. Once upper and lower specifications limits are identified from the job mix formula (JMF) and mean and standard deviation determined from the samples, lower and upper specification limits are computed assuming normal distributions properties as shown in Figure 1.1.

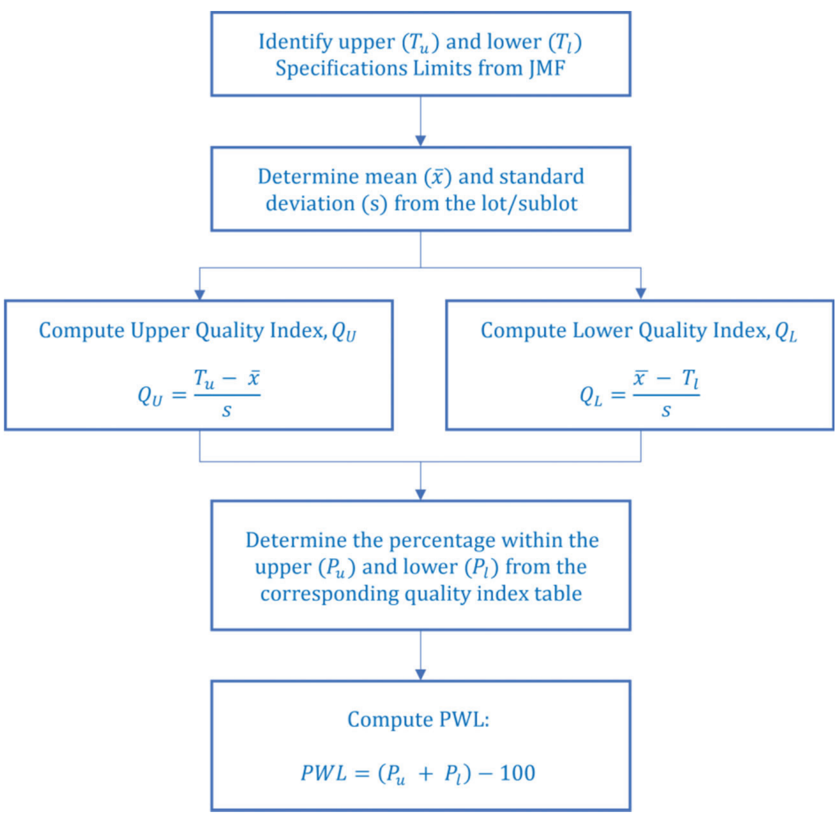


Figure 1.1 PWL computation procedure.

1.1 Problem Statement

INDOT transitioned from volumetric QA acceptance procedures to PWL in early 2000. As of 2022, SMA uses adjustment points, which are not based on robust statistics, for QA acceptance. In general, a robust statistical evaluation can provide a better understanding of the data, maximizing their interpretation and use. As PWL procedures rely heavily on a statistical assumption of normality, a robust statistical analysis in the development of updated SMA PWL specifications is needed. In addition, PWL encourages the production of consistent products by incentivizing producers to manufacture products close to targets and with low variability.

1.2 Research Objectives

The primary objective of this research was to develop a PWL-based payment system for SMA. The study followed the following tasks to meet this objective.

- Determine appropriate QA measurements for SMA.
- Determine SMA-appropriate specification limits, pay factor calculation equations, and weight factors.
- Convert adjustment points to PWL in a payment method equivalent to what is currently used for SMA.

2. REVIEW OF PERCENT WITHIN LIMITS

2.1 Review of Percent-Within-Limits System

2.1.1 Distribution of Data and Variability

PWL uses the measured sample average and standard deviation of a given asphalt mixture property to estimate the percent of mixture production falling within the specification limits (Sebaaly et al., 2015). According to the Transportation Research Board (TRB) definition, PWL is the "percentage of the lot falling above the lower specification limit (LSL), beneath the upper specification limit (USL), or between the USL and LSL (PWL may refer to the population value or the sample estimate of the population value, i.e., PWL = 100-PD, where PD is the percent defect)." The PWL process assumes asphalt properties are normally distributed. The mean and the standard distribution of the properties are calculated using Equations 2.1 and 2.2.

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad \text{(Eq. 2.1)}$$

Where:
$\bar{X}$ = average value of the mixture property for the lot;
X_i = sublot mixture property value; and
n = number of sublot samples in the lot.

$$s = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \qquad \text{(Eq. 2.2)}$$

Where:
s = mixture property standard deviation of the lot;
X_i = sublot mixture property value;
$\bar{X}$ = average value of the mixture property for the lot; and
n = number of sublot samples in the lot.

Quality Index (QI) is a measure of mixture quality. It can be calculated using the average and standard deviation. The Lower/Upper Quality Index for each mixture property is calculated by subtracting the Lower/Upper Specification Limit from the lot average of each mixture property and dividing the result by the standard deviation of the lot mixture property as shown in Equations 2.3 and 2.4.

$$Q_U = \frac{USL - \bar{x}}{s} \qquad \text{(Eq. 2.3)}$$

Where:
Q_U = Upper Quality Index;
USL = Upper Specification Limit;
$\bar{x}$ = average value of the mixture property for the lot; and
s = standard deviation of the lot mixture property.

$$Q_L = \frac{\bar{x} - LSL}{s} \qquad \text{(Eq. 2.4)}$$

Where:
Q_L = Lower Quality Index;
LSL = Lower Specification Limit;
$\bar{x}$ = average value of the mixture property for the lot; and
s = standard deviation of the lot mixture property.

The QI indicates the distance in sample deviation units. The sample average is offset from the specification limit. A positive QI is the number of standard deviation units the sample average falls within the specification limit, while a negative QI represents the number of sample standard deviation units the sample average falls outside the specification limits (Sebaaly et al., 2015).

2.1.2 Percent Within Limits

The calculated Q_L and Q_U are used to identify the data percentages falling above the LSL and below the USL, respectively (Sebaaly et al., 2015). Tables of the limit-percentages are available in Indiana Test Method (ITM) 588. The total data percent falling between the LSL and USL is estimated using Equation 2.5.

$$PWL_T = PWL_L + PWL_U - 100 \qquad \text{(Eq. 2.5)}$$

Where:
PWL_T = percent within the upper and lower specification limits;
PWL_L = percent above the lower specification limit, based on Q_L; and
PWL_U = percent below the upper specification limit, based on Q_U.

TABLE 2.1
Asphalt mixture properties used for pay adjustments

Agency	Binder Content	V_a	VMA	Gradation	Density
Arizona	O	O		9.5-mm (3/8″), 2.36-mm (#8), 600-µm (#30), 75-µm (#200)	O
California	O			12.5-mm (1/2″), 2.36-mm (#8), 75-µm (#200)	O
Colorado	O			9.5-mm (3/8″), 4.75-mm (#4), 2.36-mm (#8), 600-µm (#30), 75-µm (#200)	O
Florida	O	O		2.36-mm (#8), 75-µm (#200)	O
Illinois		O	O		O
Kansas		O			O
Kentucky	O	O	O		O
Michigan	O	O	O		O
New York					O
Ohio	O	O		12.5-mm (1/2″), 4.75-mm (#4), 2.36-mm (#8), 75-µm (#200)	O
Texas	O		O		O
Utah	O			top size, 2.36-mm (#8), 300µ-m (#50), 75-µm (#200)	O
Washington	O	O		top size, 4.75-mm (#4), 2.36-mm (#8), 75-µm (#200)	O

2.2 Other Payment Systems

Asphalt mixture payment systems for 13 departments of transportation (DOTs) were reviewed in 2020, and their QA measurement properties are summarized in Table 2.1. In general, these DOTs use volumetric properties, aggregate gradation, and in place mixture density as properties measured to determine PWL and make pay adjustments.

For PWL calculation and pay adjustment, DOTs are currently using QA measurements, including in-place density (for all 13 DOTs), binder content (10 DOTs), Va (8 DOTs), gradation (7 DOTs), and VMA (4 DOTs). All DOTs using gradation as a QA measurement use the 2.36- and 0.075-mm sieves. When calculating the PWL PF, each DOT sets a weight for every factor according to the perceived effect each factor has on pavement performance. Table 2.2 summarizes these weight factors. The Colorado DOT puts the most weight on density (60%), including joint density, while most DOTs use an in-place density weight factor of 35% to 45% and 55% to 65% for mixture properties. DOTs with QA gradation measurements put the most weight on the 0.075-mm sieve.

Owner agencies should set the LSL and USL for each QA measurement according to the anticipated production or construction quality.

Table 2.3 shows the LSL and USL for various QA mixture property measurements for PWL calculation. Kansas, Michigan, and Washington DOTs use only an LSL for in-place density.

TABLE 2.2
Asphalt mixture property weight factors

Agency	Property	Weight
California	Binder content 12.5-mm (1/2") sieve 2.36-mm (#8) sieve 75-µm (#200) sieve In-place density	30 5 10 15 40
Colorado	Binder content Gradation In-place density joint Density	25 15 45 15
Florida	Binder content Va 2.36-mm (#8) sieve 75-µm (#200) sieve In-place density	20 25 5 10 40
Kentucky	Binder content Va VMA In-place density joint Density	5 25 25 30 15
Michigan	Binder content Va VMA In-place density	15 30 15 40
New York	Binder content Va VMA In-place density	10 35 20 35
Washington	Binder content Va 4.75-mm (#4) sieve 2.36-mm (#8) sieve 75-µm (#200) sieve In-place density	24 12 3 9 12 40

TABLE 2.3
Asphalt mixture properties specification limits

Agency	Binder Content, %		Va, %		VMA, %		Gradation, %			In-Place Density, %	
	LSL	USL	LSL	USL	LSL	USL	Sieve, mm	LSL	USL	LSL	USL
Arizona	-0.5	+0.5	-2.0	+1.5	–	–	9.5 2.36 0.600 0.075	-6.0 -6.0 -5.0 -2.0	+6.0 +6.0 +5.0 +2.0	91	96
California	-0.45	+0.45	–	–	–	–	12.5 2.36 0.075	-6.0 -5.0 -2.0	+6.0 +5.0 +2.0	92	96
Colorado	-0.3	+0.3	–	–	–	–	9.5 4.75 2.36 0.600 0.075	-6.0 -5.0 -5.0 -4.0 -2.0	+6.0 +5.0 +5.0 +4.0 +2.0	92	96
Kansas	–	–	3.0	5.0	–	–	–	–	–	92	–
Michigan	-0.4	+0.4	3.0	5.0	14	16	–	–	–	92	–
New York	–	–	–	–	–	–	–	–	–	92	97
Utah	–0.35	+0.35	–	–	–	–	Top 2.36 0.300 0.075	-6.0 -5.0 -3.0 -2.0	+6.0 +5.0 +3.0 +2.0	90.5	95.5
Washington	–	–	2.5	5.5	–	–	Top 4.75 2.36 0.075	-6.0 -5.0 -4.0 -2.0	+6.0 +5.0 +4.0 +2.0	91	–

3. STONE MATRIX ASPHALT IN INDIANA

3.1 Stone Matrix Asphalt Specification

Not all INDOT SMA specifications are described here. Full details of INDOT's SMA specification can be found in the *INDOT Standard Specifications*, Section 410 (INDOT, 2022).

3.1.1 Mixture Design

INDOT SMAs are designed in accordance with ITM 220, AASHTO M 325 and R 46, except that the number of design gyrations in the Superpave Gyratory Compactor (SGC) is 75 for all equivalent single axle load (ESAL) categories. Since the strength of SMA is in the stone-on-stone aggregate skeleton, SMA coarse aggregates must be durable enough. Therefore, the maximum allowable percent loss in the Los Angeles abrasion test is 30%. Because of the aggregate requirement, steel slag is widely used as the SMA coarse aggregates. Steel slag bulk specific gravity (G_{sb}) is approximately 3.000, significantly higher than about 2.600 G_{sb} of the typically coarse limestone and dolomite aggregates in Indiana's HMAs. Accordingly, the SMA bulk-specific gravities (G_{mb}) tend to be larger than the HMA G_{mb}.

According to the report, *Designing and Constructing SMA Mixtures* published by the National Asphalt Pavement Association (2002) and other state DOT specifications, the minimum desired asphalt binder content (P_b) for SMAs is 6% by total mixture weight. The requirement is for general SMAs, unlike the Indiana SMAs having high steel slag contents. INDOT does not specify a minimum binder content for SMAs. An average P_b of 33 Indiana SMA mix designs used between 2019 and 2021 is 6.2%, and 12 mix designs (36.4%) are below the minimum P_b requirement. However, the difference in compound G_{sb} between the Indiana SMA and HMA 9.5 mm is approximately 10% due to the high G_{sb} of SMA steel slag contents. Therefore, the Indiana SMA P_b should be increased by 10% to fairly compare the P_b to the requirement, assuming the compound G_{sb}s are reasonably the same for the general SMA and the Indiana HMA 9.5 mm. Then, an average Indiana SMA P_b becomes 6.78%, and none of the mix designs have P_b below the requirement. Besides, according to Appendix X2 of *AASHTO R 46, Standard Practice for Designing Stone Matrix Asphalt (SMA)* (INDOT, 2022), a minimum P_b should be 5.5% for the case of the Indiana SMA using the steel slag. All the 33 mix designs having minimum P_b 5.7% meet the AASHTO R 46 minimum P_b requirement.

When designing SMA, INDOT also considers the voids-in-the-coarse-aggregate (VCA) along with volumetric properties such as V_a and VMA. Voids-in-the-coarse-aggregate in the dry-rodded condition (VCA_{DRC}) must be less than voids-in-the-coarse-aggregate of the mixture (VCA_{MIX}) to ensure adequate stone-on-stone contact in the mixture. The VCA application to QA is discussed in Chapter 3.4.2.

3.1.2 Mixture Acceptance

Volumetric properties such as V_a and Volume of Effective Binder (V_{be}) are the QA measurements of HMA, whereas SMAs use binder content and gradation for the mix QA. In particular, for the gradation, the acceptance tolerances of the percentages of materials passing each of the 2.36-, 0.600-, and 0.075-mm sieves are specified. Detailed SMA acceptance tolerances for binder content and gradation are specified in *INDOT Standard Specifications*, Section 410.09 (INDOT, 2022). The SMA volumetric properties are reviewed and discussed for the possibility of their QA application in Chapter 3.4.3.

3.1.3 Adjustment Points

In early 2000, INDOT adopted the PWL QA system to improve the HMA quality. As of 2022, INDOT still uses the adjustment point (AP) system for SMA QA. APs are to calculate a quality assurance adjustment quantity for SMA lots (lots are defined as 2,400 t of SMA surface mixture and are further sub-divided into sublots not exceed 600 t of SMA surface mixture). Binder content APs for the lot shall be two points for each 0.1% above the tolerance or four points for each 0.1% below the tolerance. Gradation APs for the lot shall be the sum of points calculated for up to 1% out of tolerance and the points calculated for greater than 1% out of tolerance using Table 3.1. When test results for the mixture furnished exceed the allowable range, APs are assessed in Table 3.2.

3.2 Percent-Within-Limits Applied to SMA

3.2.1 SMA Quality Assurance Data

SMA QA samples and QA data sets (14 projects, 18 mixture designs, 172 lots, and 688 sublots) were collected from projects constructed in 2019. The SMA QA measurements are binder content, gradation, and In-place density, which differ from the HMA QA PWL volumetric measurements, including laboratory V_a and V_{be}. The INDOT Central HMA Acceptance Laboratory performed HMA QA testing on extra SMA QA samples (7 projects, 11 mixture designs, 72 lots, and 309 sublots) left over after the SMA QA testing was complete. The normal distributions of the SMA volumetric properties are shown in Figure 3.1, with the HMA acceptance tolerances shaded Figure 3.1 for comparison. The average laboratory V_a value was 3.44%, which does not meet the target V_a of 4.0%, with a standard deviation of 1.82, a significant deviation. Figure 3.1(a) shows that about 40% of the lots are distributed outside the HMA V_a tolerance. For the laboratory V_{be}, approximately 83% of the lots for SMA 12.5-mm are within the tolerances, while about 45% of the SMA 9.5-mm lots have below the minimum requirement of 13%.

3.2.2 SMA Adjustment Points (APs)

SMA APs were reviewed using the QA results of 172 lots. The average quality assurance adjustment was 0.986, with a range from 0.756 to 1.000. According to the *INDOT Standard Specification*, Section 410.19 (INDOT, 2022), if the total APs for a lot are greater than 15, the pavement will be evaluated by the INDOT Division of Materials and Tests. There was no lot among the 172 lots that failed this criterion.

3.2.3 SMA Percent-Within-Limits

The HMA PWL was applied to SMA using V_a, V_{be}, and in-place density. PWLs were calculated from a total

TABLE 3.1
SMA adjustment points for gradation

Adjustment Points	Sieve Size, mm							
	25.0	19.0	12.5	9.5	4.75	2.36	0.600	0.075
For each 0.1% up to 1.0% out of tolerance	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.3
For each 0.1% above 1.0% out of tolerance	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.6

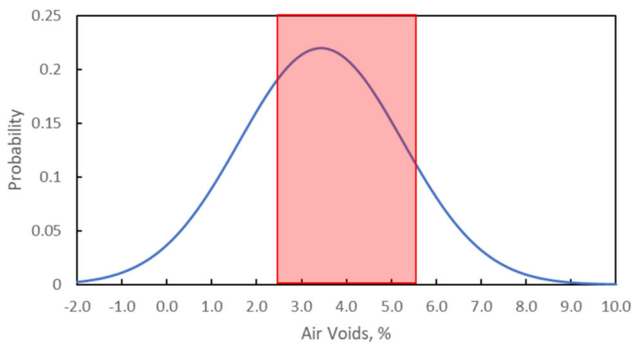
TABLE 3.2
SMA adjustment points for range

Sieve Size and Binder Content	Adjustment Points (for each 0.1% out of range)
2.36-mm (#8)	0.1
0.600-mm (#30)	0.1
0.075-mm (#200)	0.1
Binder Content, %	1.0

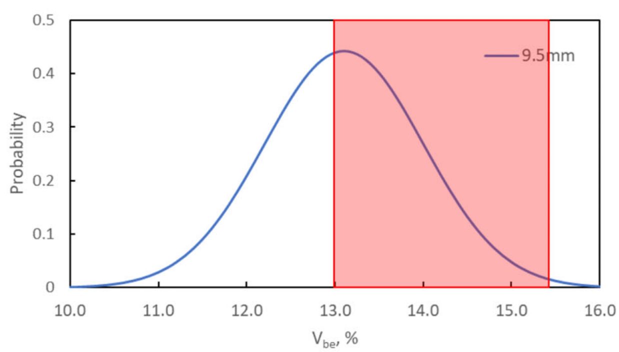
of 72 lots, and their PFs determined. The average PWLs for laboratory V_a, V_{be}, and in-place density are 45.3, 76.0, and 95.2, respectively. The PWL range for laboratory V_a and V_{be} is 0.0 to 100.0, while the in-place density PWL ranges from 52 to 100. The average PF is 0.977, excluding failed lots. The PF ranges from 0.91 to 1.03.

INDOT Standard Specifications, Section 401.19 (2022), states that if a lot PWL for any one of the three properties is less than 50, a sublot has a laboratory V_a less than 1.0%, or greater than 8.0%, or a sublot has a laboratory V_{be} more than 3.0% above design minimums, the lot will be referred to the INDOT Division of Materials and Tests for adjudication as a failed material. Among the 72 lots used for the analysis, 41 had failed PWL. Most failures were due to laboratory V_a (37 of 72). There were a few laboratory V_{be} failures (11 of 72) and no in-place density failures, as shown in Table 3.3. The failure contribution pattern was strongly related to the QA measurement deviations from the tolerances, as shown in Figure 3.1. As noted earlier, the laboratory V_a values are distributed well outside the HMA tolerance, which resulted in most of the failed PWL lots.

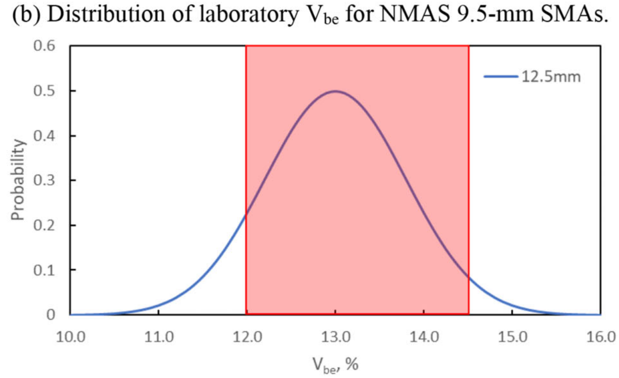
Given these results, if the current HMA PWL were to be used for SMA PWL on future projects, a significant number of SMA PWL failed lots would likely occur. Since INDOT considers current SMAs to be providing adequate service, it is, therefore, necessary to determine SMA QA measurements and adjust PWL accordingly, in order to develop an SMA PWL which provides a payment system reflecting Indiana SMA production quality.



(a) Distribution of laboratory V_a.



(b) Distribution of laboratory V_{be} for NMAS 9.5-mm SMAs.



(c) Distribution of laboratory V_{be} for NMAS 12.5-mm SMAs.

Figure 3.1 Distributions of volumetric properties.

3.3 Laboratory Performance of Indiana SMA

Permanent deformation can be a primary distress in asphalt pavements. Permanent deformation is a failure mode in asphalt pavements due to unrecoverable deformation that can often manifest in the form of wheel path surface depressions referred to as rutting (Lee et al., 2019). Rutting can impact ride quality and can significantly reduce the service life of affected pavement sections. Severe cases of rutting can detrimentally impact driver safety to standing water in deeper ruts, thus increasing the possibility of vehicle hydroplaning (Kim et al., 2018). Therefore, asphalt mixtures require some minimum level of rut resistance. Over many years, various laboratory test methods have been developed to evaluate asphalt mixture rut resistance. The three main test methods are the flow number test, the Asphalt Pavement Analyzer (APA) and the Hamburg Wheel Tracking Test (HWTT). In this study, the HWTT was adopted to evaluate SMA rut resistance.

3.3.1 Hamburg Wheel Tracking Test

The HWTT is perhaps the most widely used laboratory test method for evaluating asphalt mixture

TABLE 3.3
PWL application results

2019 SMA	Total	Pass	Fail	Laboratory V_a	Laboratory V_{be}	In-Place Density
No. of Lots	72	31	41	37	11	0
Percentage of Lots	100.0	43.1	56.9	51.4	15.3	0.0

rut resistance. The standard test procedure is AASHTO T324-19, *Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*. Compacted slab specimens or two cylindrical specimens are placed in the machine, submerged in a heated water bath, and tested in accordance with the method (Figure 3.2). The HWTT is a destructive test method that measures the rut depths of compacted asphalt specimens that are subjected to continuous loading imposed by a 47 mm wide, 705 N steel wheel for 20,000 passes. The recorded rut depth provides a direct indication of a mixture's rutting resistance and the stripping inflection point (SIP). The SIP is estimated from the rut depth data and is thought to be an indication of a mixture's moisture damage susceptibility (Lee et al., 2019). The standard test method allows the testing of laboratory-prepared specimens, typically compacted using an SGC to a target V_a of 7.0 $\pm$ 0.5%. Field-cored specimens do not have a V_a requirement and can be tested at the in-situ V_a (Sel et al., 2014).

Figure 3.2 INDOT HWTT set up.

3.3.2 Test Specimen Selection

For this study, 248 QA field cores (150 cores from 12.5-mm SMAs, 98 cores from 9.5-mm SMAs) were collected from six SMA projects constructed in 2019. Although the current INDOT SMA QA method does not measure laboratory V_a and V_{be}, these two properties were measured for this study. Figures 3.3 and 3.4 show the distributions of V_{be} as a function of the in-place density of the 9.5-mm and 12.5-mm mixture field cores. The V_{be} of the 9.5-mm mixtures ranges from 10.9% to 15.4%, while the 12.5-mm mixture V_{be} ranges from 10.4% to 15.9%. The in-place densities of the mixtures are distributed from 89.8% to 98.6% and 88.2% to 98.1% for the 9.5- and 12.5-mm mixtures, respectively. The standard deviations of laboratory V_{be} and in-place density of the 12.5-mm mixture cores are 0.86 and 2.11, respectively, both of which are larger than the standard deviations of 9.5-mm mixture cores, which were 0.70 and 1.90, respectively.

SMA is considered to be a premium asphalt mixture type, well known for its excellent rut resistance, believed to be due to stone-on-stone contact. Rutting tends to be sensitive to both binder content and V_a. Asphalt mixtures with high binder contents or high V_a are typically more susceptible to rutting than are mixtures with lower binder contents and V_a. Therefore, in this study, field core samples with high binder contents or high V_a were selected for HWTT testing, as such specimens are expected to be more susceptible to rutting. For the 9.5-mm SMA field cores, a core pair, one with a V_a of 10.2%, the other 10.0%, and the second core pair, one with a V_{be} of 15.4%, and the second 15.1%, were selected for testing. One 12.5-mm

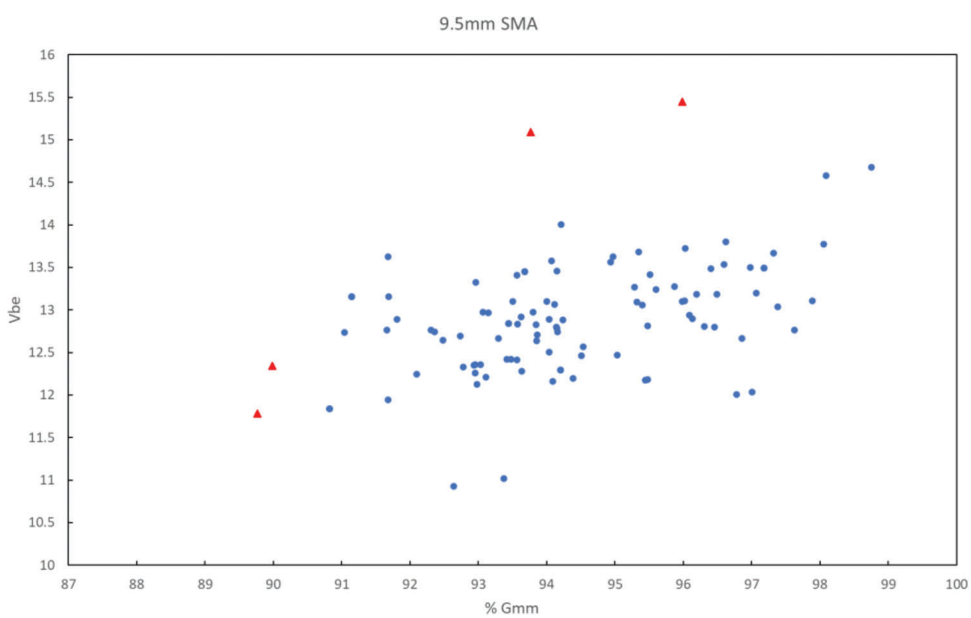


Figure 3.3 Distribution of 9.5-mm SMA QA samples.

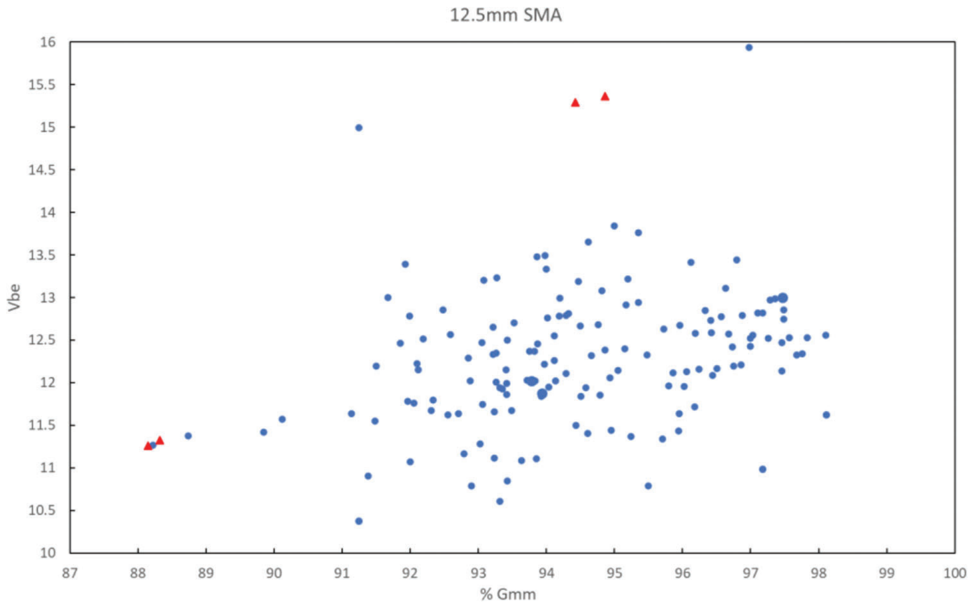


Figure 3.4 Distribution of 12.5-mm SMA QA samples.

TABLE 3.4
Field core specimen volumetric properties

Sample ID	9.5-mm Density			9.5-mm V_{be}			12.5-mm Density			12.5-mm V_{be}		
	a	b	Ave.	a	b	Ave.	a	b	Ave.	a	b	Ave.
Density	89.77	89.99	89.88	93.77	95.99	94.88	88.15	88.32	88.24	94.86	94.43	94.65
V_{be}	11.78	12.34	12.06	15.09	15.45	15.27	11.26	11.32	11.29	15.36	15.29	15.32

SMA core pair had V_a values of 11.8% and 11.7%, while the second 12.5-mm core pair had V_{be} values of 15.4% and 15.3%. Table 3.4 shows the laboratory V_{be} and in-place density of each core pair, along with the averages. The HWTT test results of these cores are shown highlighted as red triangles in Figure 3.3 and Figure 3.4.

3.3.3 Hamburg Wheel Tracking Test Results

The HWTT results are shown in Figure 3.5. All four specimens meet the typical maximum rut depth of 12.5 mm at 20,000 passes when tested at 50°C. The largest rut depth, 6.84 mm, is seen in the high V_a 9.5-mm mixture core. The second largest rut depth also occurred in the 9.5-mm mixture core, this time the high binder content core. The 12.5-mm mixture cores show half as much rutting as the 9.5-mm cores. Figure 3.5. The results indicate both mixtures should have adequate rut resistance when put into service.

Additionally, the 12.5-mm mixtures appear to have better rut resistance than the 9.5-mm mixture, perhaps due to the larger coarse aggregate particles in this mixture. Finally, it is observed that SMA rut resistance may be more sensitive to V_a than to binder content, as the high V_a field cores for both SMAs show larger rut depths than do the respective high binder content cores. It should be noted that the observations were made from the HWTT results of the limited number of SMA core samples.

3.4 Determination of SMA Quality Assurance Measurements

3.4.1 Air Voids Content as a Quality Assurance Measurement

Air voids content is a fundamental factor in volumetric mixture design, a process of controlling the aggregate gradation and adjusting the binder content to achieve a target V_a. According to AASHTO M325 and R46, SMA is designed to have 4% V_a. However, the QA results discussed in Section 3.2.3 show that air voids were widely dispersed from the 4% target value. These high air voids content deviations caused numerous PWL failures. The SMA V_a dispersion compared to the HMA V_a distribution from 2018-HMA QA data can clearly be seen in Figure 3.6. The average HMA V_a and standard deviation for 566 material lots were 3.999% and 0.956%, respectively. Statistically, the data indicate that HMA mixtures have significantly lower

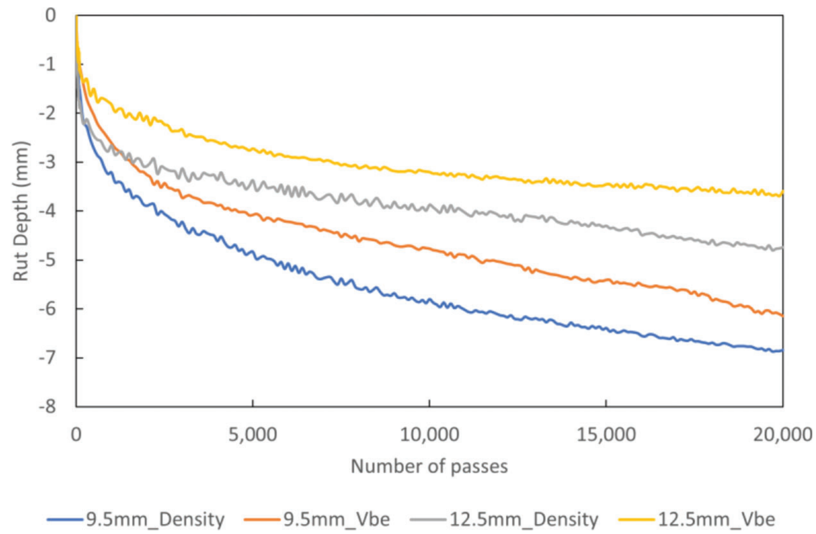


Figure 3.5 Hamburg test results.

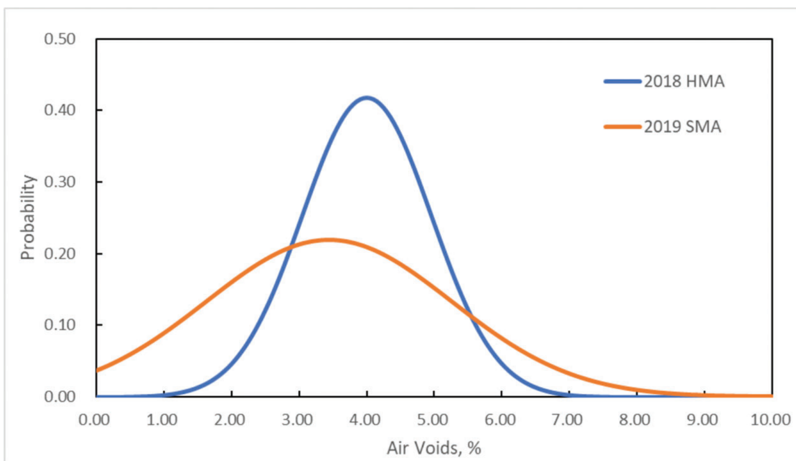


Figure 3.6 Distributions of V_a for HMA and SMA.

deviations than the SMAs (p-value of 3.08E-10) as shown in Figure 3.6

The wide variation in SMA V_a is thought to be caused by aggregate variability. As discussed in Section 3.1.1, because SMA requires more durable aggregates than HMA, steel slag is typically used as coarse aggregate for INDOT SMAs. Steel slag has a high G_{sb}, 3.000 or higher, much higher than that of typical limestone aggregates used in HMA. Additionally, SMA gradations require higher proportions of coarse aggregate than HMA (see *INDOT Standard Specifications*, Section 410.05). It is known that SMA G_{mb} is sensitive to changes in steel slag contents. Therefore, when QA-sampling SMAs, high V_a variability can occur if the samples are segregated, and the steel slag is not uniformly distributed in each sample used for the determination of G_{mm} and G_{mb}. Because of this limitation, the SAC has decided to exclude V_a from possible SMA QA measurements. Consequently, V_{be} was also ruled out since V_{be} is a function of V_a.

3.4.2 Voids in Coarse Aggregate (VCA)

VCA is one of the important factors affecting the performance of SMA that is considered in the mix design process. SMA utilizes stone-on-stone contact to support heavy traffic. The stone contact is ensured by voids in the coarse aggregate (VCA) in the SMA mix-design process. VCA is the volume between the coarse aggregate particles. The mix design specifies that VCA in rodded dry aggregates (VCA_{DRC}) in accordance with AASHTO T19 should be higher than VCA in mix (VCA_{MIX}) using Equation 3.1.

$$VCA(MIX) = 100 - \left(\frac{Gmb}{Gca} \times Pca\right) \qquad \text{(Eq. 3.1)}$$

Where,
G_{mb} = mixture bulk specific gravity;
G_{ca} = coarse aggregate bulk specific gravity; and
P_{ca} = coarse aggregate percent in the mixture, by total mixture mass.

To understand SMA production quality with respect to VCA, the in-place VCA_{MIXs} ($VCA_{\text{IN-PLACE MIXs}}$) calculation was performed for the 2019 SMA QA using their volumetric measurements explained in Chapter 3.2.1. Among 1,178 sublots, 61 sublots (5.2%) had $VCA_{\text{IN-PLACE MIX}}$ higher than VCA_{DRC}. The finding generally confirms that Indiana SMAs meet the overall VCA requirements regarding the mix production quality. Ultimately the finding indicates that the SMAs have acceptable stone-on-stone contacts.

It should be noted that quantifying the $VCA_{\text{IN-PLACE MIXs}}$, requires significant effort (i.e., in-place loose mix sampling, gyratory compactions, G_{mb} measurements, etc.) to be used as a QA measurement. Considering the production quality satisfaction of Indiana's SMA in terms of the $VCA_{\text{IN-PLACE MIXs}}$ and the significant effort requirement, the study does not recommend VCA as an SMA QA measurement.

3.4.3 Quality Assurance Measurements for SMA

For the SMA PWL development, the study concluded using the existing SMA QA measurements (binder content, aggregate gradation, and density) instead of the volumetric properties for the following reasons.

- Indiana's SMAs have a high air void variability, in part due to sensitivity to steel slag gravity variations.
- Most SMAs (94.8%) meet the VCA requirements.

The Study Advisory Committee (SAC) agreed that there is no need to change the current QA measurement since INDOT has not experienced any major SMA performance problems. The agreement is supported by the HWTT result in Chapter 3.3, confirming Indiana SMA rutting performance outstands.

4. SMA PWL DEVELOPMENT

4.1 Approach Method

The study primarily aims to develop SMA PWL requirements that will result in contractor payments equivalent to those being paid with the current SMA AP system. To that end, the research team developed a methodology for developing the AP-equivalent PWL, as shown in Figure 4.1. First, an average AP pay factor is determined using QA measurements from INDOT projects using the most up-to-date SMA specification. The AP PF is then set as a target for the PWL PF. Finally, the PWL parameter (i.e., specification limits, PF equations, and weight factors) study is performed to find the best parameter set providing the closest PF to the target.

4.2 QA Data Collection and Analysis

The research team collected and reviewed SMA QA data from 2016 to 2021, including 43 projects, 52 mixture designs, 424 lots, and 1,696 sublots, as shown in Table 4.1. The SMA QA measures and calculates deviations from the requirements of binder content (ΔP_b), percent passing the 2.36-, 0.600-, and 0.075-mm sieves, and in-place density. The average values of ΔP_b and density are -0.03% and 93.8%, respectively, while the average values of $\Delta 2.36$, $\Delta 0.600$, and $\Delta 0.075$-mm sieves are -0.03%, 0.02%, and -0.22%, respectively.

AP PFs by year were reviewed, as shown in Figure 4.2. Generally, the AP PF decreased over the years. It should be noted that INDOT changed the SMA design gyration number to 75 for all Equivalent Single Axle Load (ESAL) categories in 2018. To evaluate the effect of design gyration change on the AP PF, the statistical difference between the QA data of the two groups (Group 1: 2016–2017, Group 2: 2018–2021) was t-tested. The P-value between the two groups was 0.0357, which means the gyration change significantly affected AP PFs at a confidence level of 95%. Therefore, the PWL development study excluded the 2016–2017 QA data from the QA data set.

The average and standard deviation of AP PFs for 4 years from 2018 to 2021 are 0.986 and 0.0032, respectively. A t-test was performed between adjacent years to determine whether to consider the weight for the most recent year in calculating the average PF for 4 years. Table 4.2 shows the t-test results of AP PF values between the adjacent years of the last 4 years. There were no significant differences (i.e., p-values > 0.05) between the adjacent years at the 95% confidence level. Accordingly, the average PF for the 4 years was calculated without a specific year weight, and its value is 0.986.

In addition to the AP PFs by year, the AP PFs by contractors for 4 years were explored. AP PFs of four major contractors who performed SMA projects for 4 years were selected. As shown in Figure 4.3, there was no trend in AP PFs among the contractors. The lowest 4-year average AP PF among them was 0.978, and the highest average PF was 0.986. The standard deviation of the AP PFs was 0.0035, indicating minimal variation.

The AP PF is calculated as follows:

$$Pay\,factor = 1 - \frac{Adjustment\,points}{100} \qquad \text{(Eq. 4.1)}$$

As described earlier, APs are determined by how far each QA measurement value deviates from an acceptable tolerance. The more deviations, the larger APs and the smaller the PF. The SMA QA measurement (i.e., binder content, gradation, and in-place density) contribution to APs is shown in Figure 4.4. As can be seen in the plot, the gradation AP contribution has decreased over the years, while in-place density appears to have made the most considerable contribution to APs. In particular, the contribution of the in-place density APs in 2020 and 2021 was substantial.

4.3 Percent-Within-Limits Parameter Study Using SMA Quality Assurance Measurements

A PWL parameter study was performed using the SMA QA measurements to determine the best fit to

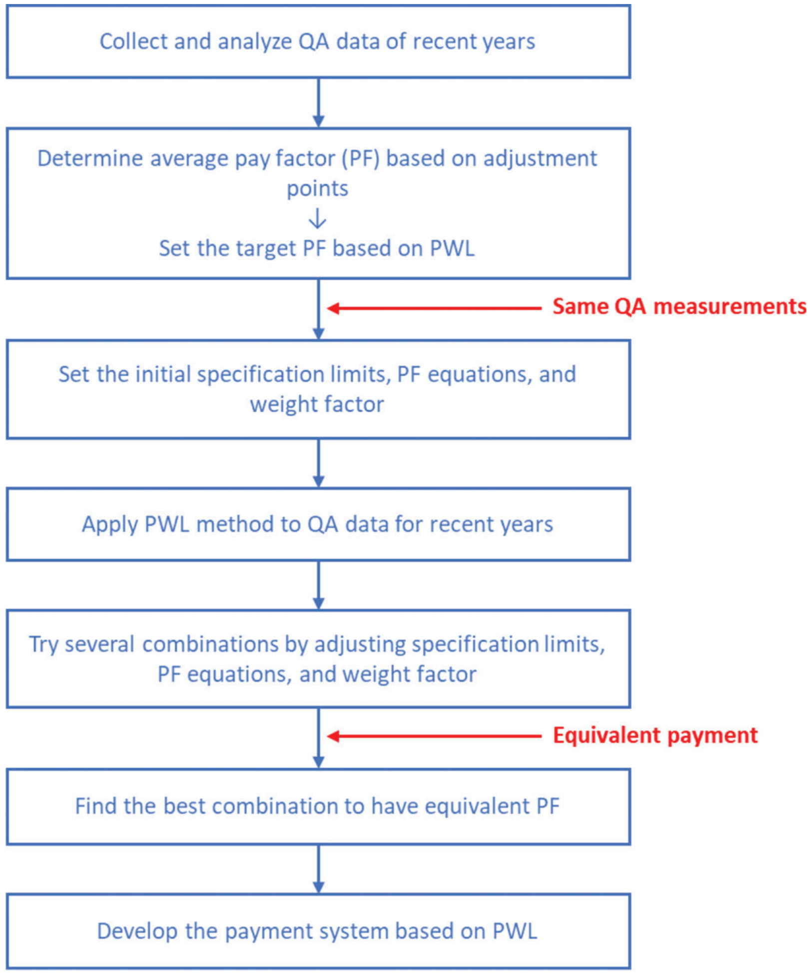


Figure 4.1 SMA percent-within-limits developmental approach.

TABLE 4.1
SMA QA data information

Year	2016–2017	2018	2019	2020	2021	Total
Number of projects	5	11	14	4	9	43
Number of designs	7	14	18	4	9	52
Number of lots	64	89	172	53	46	424
Number of sublots	320	356	688	212	184	1,696

current SMA AP results, such as the percent material failure and PF. The parameters include the upper and lower specification limits, the PWL equations, the PWL weight factors, and the PF scale adjustment.

4.3.1 Setting Percent-Within-Limits Parameters

First, PWL upper and lower specification limits, as shown in Table 4.3, were set based on the *INDOT Standard Specifications*, Section 410. The specification binder content acceptance tolerance for ranges from ±0.3% to ±0.7%, depending on the number of tests. The median of the range (±0.5%) was selected for use in the study. As shown in Figure 4.4, gradation had the lowest impact on APs, as compared to binder content and in-place density. Thus, among the tolerances for 2.36-, 0.600-, and 0.075-mm sieves, which vary depending on the number of tests performed, the smallest values of ±4.0%, ±2.0%, and ±1.5% were set as initial limits, respectively. In-place density shows the greatest influence on APs among QA measurements. Therefore, 91%, two percentage points lower than the target density value of 93%, was set to apply PWL to SMA QA data.

The HMA PWL PF equations, as specified in the *INDOT Standard Specifications*, Section 401.19, were used for initial SMA PWL PF calculations, as shown in Equations 4.2, 4.3, and 4.4.

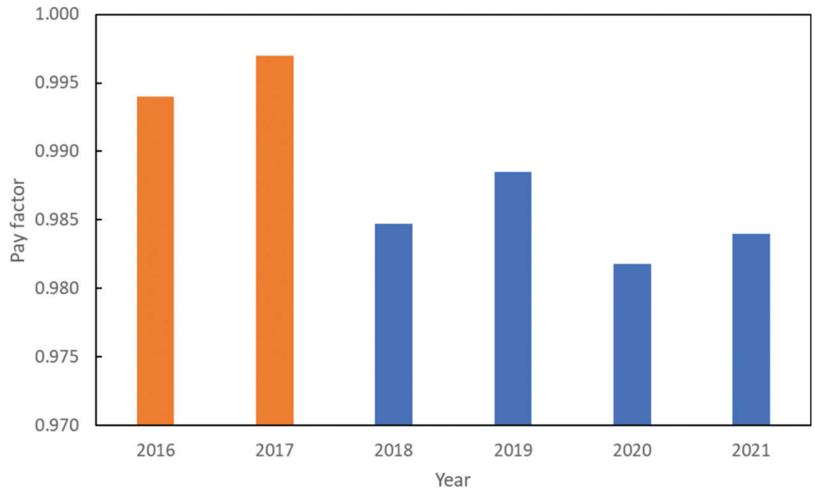


Figure 4.2 Pay factors by year.

TABLE 4.2
P-values of each adjacent years

Year	2018–2019	2019–2020	2020–2021
P-value	0.290	0.175	0.774

Estimated PWL greater than 90:

$$PF = ((0.50 \times PWL) + 55.00)/100 \quad \text{(Eq. 4.2)}$$

Estimated PWL greater than 70 and equal to or less than 90:

$$PF = ((0.40 \times PWL) + 64.00)/100 \quad \text{(Eq. 4.3)}$$

Estimated PWL greater than or equal to 50 and equal to or less than 70:

$$PF = ((0.85 \times PWL) + 32.50)/100 \quad \text{(Eq. 4.4)}$$

Unlike SMA PF, the QA measurements for the HMA PF are V_a, V_{be}, and in-place density. The composite HMA PF, considering the weight of each property, is calculated by Equation 4.5, and the weight factors for V_a, V_{be}, and in-place density are 30%, 35%, and 35%, respectively.

$$\text{Lot PF} = 0.30(PF_{VOIDS}) + 0.35(PF_{Vbe}) + 0.35(PF_{DENSITY}) \quad \text{(Eq. 4.5)}$$

The SMA PF weight factors were chosen as 35%, 30%, and 35% weights for binder content, gradation, and in-place density, respectively. The weight factor for the gradation was evenly distributed to the three sieve sizes as expressed in Equation 4.6.

$$\text{Lot PF} = 0.35(PF_{\%Binder}) + 0.1(PF_{2.36mm}) + 0.1\left(PF_{600\mu m}\right) + 0.1\left(PF_{75\mu m}\right) + 0.35\left(PF_{Density}\right) \quad \text{(Eq. 4.6)}$$

4.3.2 Specification Limits Based on Failed Cases

The PWL using the 2018–2021 SMA QA was calculated, and the parameter set was evaluated in terms of the percent of material failures. According to the Sections 401.19 and 410.19 of the INDOT Standard Specifications, if a lot PWL and AP are less than 50 and greater than 15, respectively, the lot is considered to fail. The SMA AP with the QA had three failed lots out of a total of 360 lots, whereas the PWL parameter set resulted in 123 failed lots (34.2%). Therefore, adjusting the PWL parameters to have a lower failure percentage was necessary.

As a breakdown of the failure cases in QA measurements, among the 123 failed lots, eight lots failed due to binder content, ten lots for the 2.36-mm sieve, 88 lots for the 0.600-mm sieve, 48 lots for the 0.075-mm sieve, and three lots for in-place density. The failure cases for binder content and in-place density were relatively low. On the other hand, there were many failed cases due to gradation. Therefore, to reduce the failure rate, the specification limits of the gradation parameters were adjusted, as shown in Table 4.4. As a first trial, the specification limits for 2.36-, 0.600-, and 0.075-mm were set to $\pm 5.0\%$, $\pm 3.0\%$, and $\pm 2.0\%$, respectively. As a result of the adjustment, the number of failed lots decreased from 123 to 65 (i.e., from 34.2% to 18.1%).

To further lower the failure lots, the specification limits for gradation were readjusted a second time. Since there were only two failed lots due to the 2.36-mm sieve, only the specification limits for the 0.600- and 0.075-mm sieves were readjusted to $\pm 4.0\%$ and $\pm 2.5\%$. As a result of the second adjustment, the number of failed cases decreased to 29 and the failure percentage to 8.1%. If the specification limit is continuously relaxed to reduce failed cases, SMA quality can be sacrificed. A failed rate of less than 10% was judged to be an acceptable value, and this second specification limit readjustment was accepted as the final SMA PWL

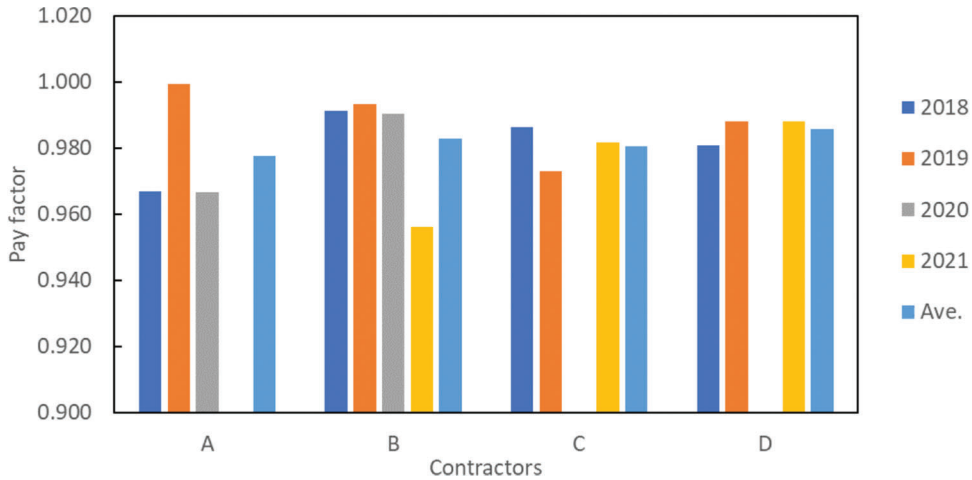


Figure 4.3 Pay factors by contractor.

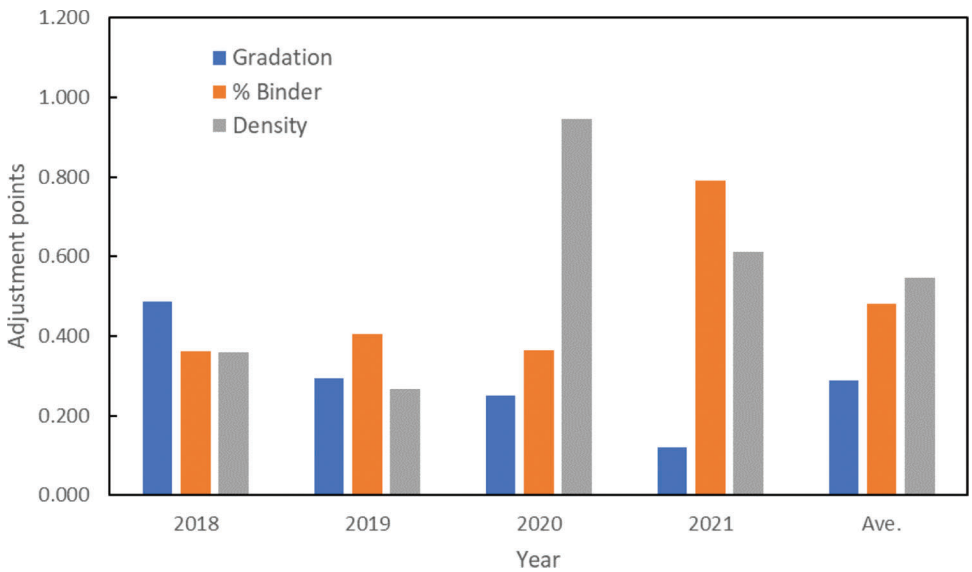


Figure 4.4 Adjustment points for each SMA quality assurance measurement.

TABLE 4.3
Chosen specification limits

QA Measurement	USL	LSL
Binder content, %	+0.5	-0.5
2.36-mm, %	+4.0	-4.0
0.600-mm, %	+2.0	-2.0
0.075-mm, %	+1.5	-1.5
In-place density, %	–	91.0

parameter set. Table 4.4 summarizes the PWL parameter study in terms of material failures.

Comparing material failure cases between the current AP and the selected PWL is critical to confirm the consistency of screening the failures from both QA systems. AP had three failed lots among 360 lots between 2018 and 2021. Among the three failed cases under APs, Case 1 failed with inadequate binder content, and Cases 2 and 3 failed with insufficient in-place density, as shown in Table 4.5. With the selected PWL application, all the cases had failures for the same causes as the APs, as shown in Table 4.6. It was concluded that PWL could reasonably filter the failed SMA materials as the AP does.

4.3.3 Target Pay Factor Value Through Scale Adjustment

There is a difference in PF between AP and PWL, where PWL pays bonuses for good quality work and AP does not. The AP PF ranges from 0.85 to 1.0 and the PWL PF varies from 0.75 to 1.05, adding a bonus of up to 5% for good quality. Therefore, it is necessary to consider the difference in scale between the two methods in the process of converting PF from AP to PWL. In the first case, adjusting only for the maximum PF difference due to the 5% bonus, the PWL PF is equivalent to 0.986, and the average AP PF is 1.035. In the second case, when adjusting not only the

TABLE 4.4
Failed cases according to specification limits

Trial	Specification Limits (Binder Content, 2.36-mm, 0.600-mm, 0.075-mm, Density)	Number of Failed Lots	Percent Failed Cases (%)	Number of Individuals Failed Lots (Binder Content, 2.36-mm, 0.600-mm, 0.075-mm, Density)
Initial	±0.5%, ±4.0%, ±2.0%, ±1.5%, 91%	123	34.2	8, 10, 88, 48, 3
1	±0.5%, ±5.0%, ±3.0%, ±2.0%, 91%	65	18.1	8, 2, 41, 18, 3
2 (selected)	±0.5%, ±5.0%, ±4.0%, ±2.5%, 91%	29	8.1	8, 2, 12, 6, 3

Note: Red text indicates those limits re-adjusted.

TABLE 4.5
Failed cases under APs

	Adjustment								
	Accept Tolerance			Range					
Case	Gradation	Binder Content	Density	2.36-mm	0.600-mm	0.075-mm	Binder Content	Total	PF
1	0.0	20.0	0.4	0.0	0.0	0.0	4.0	24.4 > 15	Fail
2	0.6	0.0	22.0	0.0	0.0	0.0	0.0	22.6 > 15	Fail
3	0.8	0.0	19.0	0.0	0.0	0.0	0.0	19.8 > 15	Fail

Note: Red text indicates failed materials.

TABLE 4.6
Failed cases under PWL

	PWL										
	Binder Content		2.36-mm		0.600-mm		0.075-mm		Density		Total
Case	PWL_B	PF_B	$PWL_{2.36}$	$PF_{2.36}$	$PWL_{0.600}$	$PF_{0.600}$	$PWL_{0.075}$	$PF_{0.075}$	PWL_D	PF_D	PF_{TOTAL}
1	32 < 50	Fail	100.00	1.05	73.00	0.93	100.00	1.05	100.00	1.05	Fail
2	97.00	1.04	100.00	1.05	100.00	1.05	84.00	0.98	21 < 50	Fail	Fail
3	100.00	1.05	100.00	1.05	100.00	1.05	86.00	0.98	24 < 50	Fail	Fail

Note: Red text indicates failed materials.

maximum PF difference but also the difference between 0.75 and 0.85, which are the minimum PFs of the two methods, the PWL PF equivalent to 0.986 is 1.022. When adjusting the PF scale considering both the minimum and maximum, PWL PF decreases when AP PF is smaller than the intersection value of AP and PWL, as shown in Figure 4.5. Conversely, when AP PF is larger than the intersection value, PWL PF increases. Figure 4.5 shows an example of how they change for four lots after scaling. The increase or decrease of PF according to scaling was also examined. As shown in Table 4.7, when converting to the PWL without adjusting the scale, 11.7% of the PF decreased, and 88.3% of the PF increased.

Additional adjustments were also attempted. In the first case, 53.1% of the PF decreased, 22.2% increased, and 24.7% did not change. In the second case, 41.7% of the PF decreased, 33.9% increased, and 24.4% showed the same value. Adjusting the scale considering both sides showed the best balance of increases and decreases after converting PF from AP to PWL. In other words, a balance was achieved between better quality and poorer quality jobs, with incentives and disincentives applied appropriately. Therefore, the second case was adopted, and the target PF was set to 1.022.

4.3.4 Equation for Equivalent Pay Factor

Based on the previously determined specification limits and weight factor, the calculated PWL PF is 1.031 using Equations 4.2, 4.3, and 4.5, which are PF calculation equations for the current HMA. This is slightly higher than the target PF of 1.022. Accordingly, the equations were adjusted to lower the PF value, as shown in Figure 4.6. As shown in Table 4.8, the PFs estimated by the adjusted Equations A and B are 1.026 and 1.023, respectively. Although the PF by Equation B is closer to 1.022, the target PF, it receives a disincentive since the PF is less than 1, even though the PWL value is 90. Also, the difference in PF between the two equations is negligible. Therefore, Equation A was adopted for the SMA PWL.

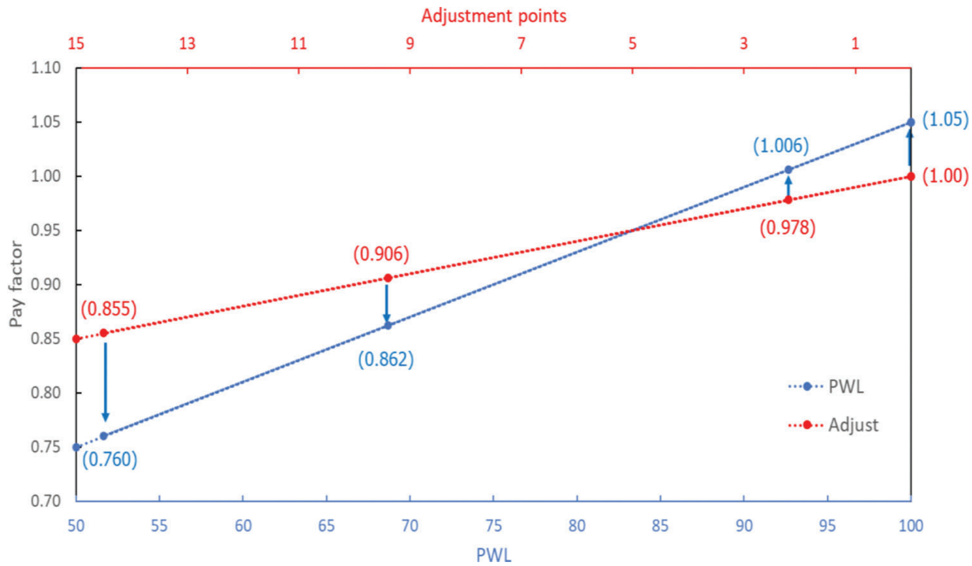


Figure 4.5 Scale adjustment considering both the top and bottom.

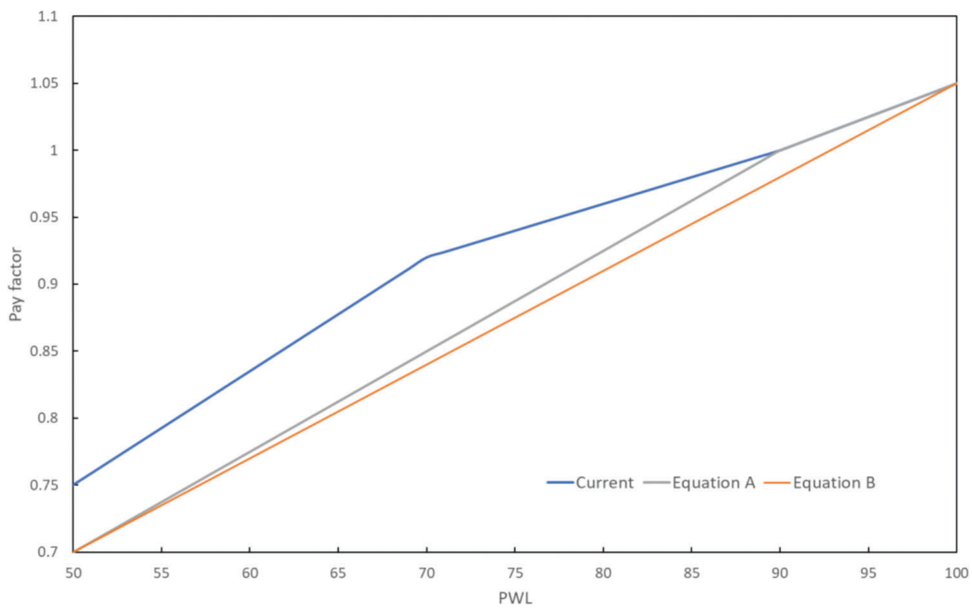


Figure 4.6 Equations for pay factor.

TABLE 4.7
Changes resulting from scale adjustments

After Converting	Before Scale Adjustment	Scale Adjusted by 1.05	Scale Adjusted by 0.75 and 1.05
Number of Decreases	42 (11.7%)	191 (53.1%)	150 (41.7%)
Even	0 (0%)	89 (24.7%)	88 (24.4%)
Number of Increases	318 (88.3%)	80 (22.2%)	122 (33.9%)

TABLE 4.8
Pay factor values according to equations

Trial	Equation	Pay Factor
Initial	PWL > 90, (0.50*PWL + 55.0)/100 70 < PWL ≤ 90, (0.40*PWL + 64.0)/100 PWL ≤ 70, (0.85*PWL + 32.5)/100	1.031
A (Selected)	PWL > 90, (0.50*PWL + 55.00)/100 PWL < 90, (0.75*PWL + 32.5)/100	1.026
B	(0.75*PWL + 35.0)/100	1.023

TABLE 4.9
Specification limits

Specification Limits		
Mixture		
	LSL	**USL**
Binder Content, %	DMF -0.5	DMF +0.5
Percent passing 2.36-mm sieve	DMF -5.0	DMF +5.0
Percent passing 0.600-mm sieve	DMF -4.0	DMF +4.0
Percent passing 0.075-mm sieve	DMF -2.5	DMF +2.5
Density		
	LSL	**USL**
Roadway Core Density (%Gmm), %	91.0	n/a

4.4 Pay Factor Using Percent-Within-Limit for SMA

Pay factors are calculated for the binder content, 2.36-, 0.600-, and 0.075-mm sieves, and density. The PWL for each lot will be determined in accordance with ITM 588. The pay factor for each property is calculated using Equations 4.7 and 4.8.

Estimated PWL greater than 90:

$$PF = ((0.50 \times PWL) + 55.0)/100 \quad \text{(Eq. 4.7)}$$

Estimated PWL greater than or equal to 50 and equal to or less than 90:

$$PF = ((0.75 \times PWL) + 32.5)/100 \quad \text{(Eq. 4.8)}$$

A composite pay factor for each lot based on test results for mixture properties and density is determined by a weighted equation (Equation 4.9).

$$\text{Lot PF} = 0.35(PF_{\%Binder}) + 0.1(PF_{2.36mm}) + 0.1(PF_{600\mu m}) + 0.1(PF_{75\mu m}) + 0.35(PF_{Density}) \quad \text{(Eq. 4.9)}$$

The specification limits for the binder content, gradation, and in-place density will be those shown in Table 4.9.

5. SUMMARY AND CONCLUSIONS

The study reviewed the INDOT SMA QA and developed a new SMA QA PWL. First, possible SMA QA measurements were reviewed using past QA data and HMA QA measurements. In addition, VCA was evaluated as a possible SMA QA measurement. A PWL parameter study was performed using the selected QA measurements to find PWL providing pay factors similar to the current SMA AP PFs. The study findings are summarized below.

- According to the PWL systems of 13 state agencies reviewed in the study, Ohio DOT was the only agency having an SMA QA separated from HMA QA. All 13 agencies use gradations, adopting the 2.36- and 0.075-mm sieves, and in-place density commonly as QA measurements.
- Reviewing VCA in the 2019 SMA mix designs and QAs indicated that the Indiana SMA had negligible VCA problems. In addition, because of the VCA practicality limitation requiring significant efforts (i.e., in-place loose mix sampling, gyratory compactions, G_{mb} measurements, etc.) to obtain in-place VCA, the study determined not to include VCA in QA measurements.
- The outstanding rutting performance of SMA was confirmed by HWTT using the selected SMA QA core samples obtained from the projects constructed in 2019.
- The HMA PWL application using the 2019 SMA volumetric properties resulted in the numerous failed QA SMAs, mainly due to the large V_a deviations caused by significant V_a sensitivity to the steel slags. Consequently, the SAC decided to exclude V_a and V_{be} (closely related to V_a) from the possible SMA QA measurements. Thus, it was determined that the study used the current SMA QA measurements (i.e., binder content, gradation, and density) for the SMA PWL development.
- The study developed a framework to develop SMA PWL resulting in contractor payments equivalents to those being paid with the current SMA AP system.
- A PWL parameter study was successfully performed using reasonable specification limits obtained from the SAC; the limit optimization with respect to the AP percent material failure; the bonus-penalty scale adjust pay factors; pay factor equations in terms of PWLs; and measurement-weight factors.

6. RECOMMENDATION

Based on the results of this study, SMA QA PWL recommendations are as follows.

- The current SMA QA property measurements (binder content, gradation, and density) should continue to be used in the INDOT SMA PWL.
- SMA PWL specification limits should be those shown in Table 6.1, based on the results of applying PWL to SMA QA data from the last 4 years and SAC's recommendations.

TABLE 6.1
Recommended SMA PWL limits

QA Measurement	USL (%)	LSL (%)
Binder content	+0.5	-0.5
2.36-mm	+5.0	-5.0
0.600-mm	+4.0	-4.0
0.075-mm	+2.5	-2.5
In-place density	–	91

- SMA pay factors should be calculated using the following equations.

Estimated PWL greater than 90:

$$PF = ((0.50 \times PWL) + 55.0)/100$$

Estimated PWL greater than or equal to 50 and equal to or less than 90:

$$PF = ((0.75 \times PWL) + 32.5)/100$$

- Weight factors of 35% for asphalt binder content, 30% for gradation, and 35% for in-place mixture density should be used. The composite pay factor of each lot may be calculated as shown in the following equation.

$$\text{Lot PF} = 0.35(PF_{\%Binder}) + 0.1(PF_{2.36mm}) + 0.1\left(PF_{600\mu m}\right) + 0.1\left(PF_{75\mu m}\right) + 0.35\left(PF_{Density}\right)$$

- A periodic QA parameter refinement with reviewing the QA results (i.e., every 5 years) is essential to keep improving the Indiana SMA qualities.
- There is an ongoing NCHRP study on the performance-related specification (PRS) linking the QAs to performances. It is recommended that INDOT follows up on the study to develop an SMA PRS in the future.

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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