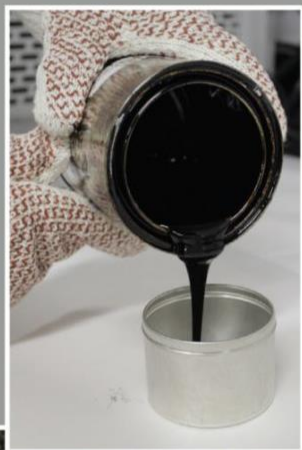

NCAT Report 19-02

FHWA DEMONSTRATION PROJECT FOR ENHANCED DURABILITY OF ASPHALT PAVEMENTS THROUGH INCREASED IN-PLACE PAVEMENT DENSITY, PHASE 2

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August 2019

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FHWA Demonstration Project for Enhanced Durability of Asphalt Pavements Through Increased In-Place Pavement Density, Phase 2

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Notice

Quality Assurance Statement

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16. Abstract
Based on prior studies, a 1 percent increase to in-place asphalt pavement density achieved through improved compaction was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent. A 1 percent increase in in-place density was estimated to extend the service life by 10 percent, conservatively.

Recognizing the importance of in-place density in building cost effective asphalt pavements, a Federal Highway Administration (FHWA) Demonstration Project was initiated for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. The objective of this Demonstration Project was to determine the benefit of additional compaction and show that additional density could be obtained through improved techniques. Many States also added additional compaction equipment and evaluated other methods that could help obtain additional in-place density.

Phase 2 of this Demonstration Project included two major components: (1) a literature review to identify how much in-place density is enough and (2) the construction of field demonstration projects in eight States. The literature review identified best practices for sufficient in-place density for long-life asphalt pavements and provided examples of specifications from the State highway agencies (SHAs) that have successfully achieved the sufficient in-place density for asphalt pavements.

Six of the eight States participating in Phase 2 improved in-place density by at least 0.5 percent on their demonstration projects. All the participating States averaged greater than or equal to 94.0 percent in-place density in at least one test section. Many of the States constructed more than two pavement sections for a total of 28 sections. Many variables were evaluated, including mixture type, construction equipment, and procedures between States and within States. A summary of the methods that States used to obtain increased in-place density generally fell into one of five categories: (1) improving the agency's specification by including or increasing incentives and increasing the minimum percent in-place density requirements; (2) making engineering adjustments to the asphalt mixture design to obtain slightly higher optimum asphalt content (although not part of the original goal of the demonstration project); (3) improving consistency as measured by the standard deviation; (4) following best practices; and (5) using new technologies.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Transportation Officials
AC	Asphalt Content
ADOT&PF	Alaska Department of Transportation and Public Facilities
AI	Asphalt Institute
BC	Base Course
COV	Coefficient of Variation
D/A	Dust/Asphalt Ratio
DOT	Department of Transportation
FHWA	Federal Highway Administration
Gmb	Bulk Specific Gravity of the Mixture
GPS	Global Positioning System
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
IR	Infrared Imaging
LCCA	Life Cycle Cost Analysis
LSL	Lower Specification Limit
Maine DOT	Maine Department of Transportation
MDOT SHA	Maryland Department of Transportation State Highway Administration
MDOT	Michigan Department of Transportation
MTV	Material Transfer Vehicle
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NMAS	Nominal Maximum Aggregate Size
NPV	Net Present Value
NYSDOT	New York State Department of Transportation
Pbe	Effective Binder Content
PCS	Primary Control Sieve
PennDOT	Pennsylvania Department of Transportation
PWL	Percent Within Limits
QA	Quality Assurance
QC	Quality Control
RAP	Reclaimed Asphalt Pavement
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
TDOT	Tennessee Department of Transportation
Gmm	Theoretical Maximum Density
WC	Wearing Course
WMA	Warm Mix Asphalt
WSDOT	Washington State Department of Transportation
USL	Upper Specification Limit
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate

ABSTRACT

Based on prior studies, a 1 percent increase to in-place density (or 1 percent decrease in air voids) achieved through improved compaction was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent. In addition, a 1 percent increase in in-place density was estimated to extend the service life by 10 percent, conservatively.

Recognizing the importance of in-place density in building cost effective asphalt pavements, a Federal Highway Administration (FHWA) Demonstration Project was created for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. The objective of this Demonstration Project was to determine the impact of additional compaction on in-place density and how additional density could be obtained through improved techniques. Many States added additional compaction equipment and evaluated other methods that can help obtain additional in-place density.

Phase 2 of this Demonstration Project included two major components: 1) a literature review to identify how much in-place density is enough, and 2) the construction of field demonstration projects in eight States. The literature review identified best practices for sufficient in-place density required for long-life asphalt pavements and provided examples of specifications from the State highway agencies (SHAs) that have successfully achieved the required in-place density level.

The field demonstration projects were intended to support SHAs in evaluating their current density requirements for acceptance. Six of the eight States participating in Phase 2 improved in-place density by at least 0.5 percent on their demonstration projects. All the participating States averaged greater than or equal to 94.0 percent in-place density in at least one test section. Many of the States constructed more than two pavement sections for a total of 28 sections. Many variables were evaluated, including mixture type, construction equipment, and procedures between States and within States. A summary of the methods that States used to obtain increased in-place density generally fell into one of five categories: (1) improving the agency’s specification by including or increasing incentives and increasing the minimum percent in-place density requirements; (2) making engineering adjustments to the asphalt mixture design to obtain slightly higher optimum asphalt content (although not part of the original goal of the demonstration project); (3) improving consistency as measured by the standard deviation; (4) following best practices; and (5) using new technologies.

1 INTRODUCTION

In-place density is one of the most important factors that can significantly influence the long-term performance of an asphalt pavement (Asphalt Institute, 2007). A small increase in in-place density can potentially lead to a significant increase in the pavement service life. Based on past studies reviewed in a previous report by Tran et al. (2016), a 1 percent increase to in-place asphalt pavement density (or a 1 percent decrease in in-place air voids) was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent. In addition, a correlation between in-place air voids and the service lives of asphalt overlays with in-place densities between 91 percent and 96 percent of the theoretical maximum density (Gmm) suggested that a 1 percent increase in in-place density would extend the service life by 10 percent.

To illustrate the effect of in-place density on the life cycle cost of asphalt pavements, a life cycle cost analysis (LCCA) was conducted on two pavements in which the same asphalt overlay would be constructed to 93.0 percent and 92.0 percent (densities) of Gmm. Using the 10 percent increase in service life, the LCCA results revealed that the State highway agency (SHA) would see a cost savings in terms of net present value (NPV) of $88,000 on a $1,000,000 paving project (8.8 percent) by increasing the minimum required density by 1 percent of Gmm (Tran et al., 2016). This savings does not consider potential savings from other costs such as operation, maintenance, and road user costs.

Since in-place density is important to building cost effective asphalt pavements, a Federal Highway Administration (FHWA) Demonstration Project was initiated for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. The FHWA Demonstration Project was the partnership between State highway associations, the National Asphalt Pavement Association (NAPA), and the contractors that built the demonstration sections.

The FHWA Demonstration Project includes three phases. Phase 1 was completed in 2017 and documented in a previous report by Aschenbrener et al. (2017), which included a detailed literature review and documentation of demonstration projects constructed in 10 States. Phases 2 and 3 were an extension of the Phase 1 effort. This report summarizes activities, observations and lessons learned from Phase 2 of the Demonstration Project. Additionally, more information on success stories related to SHA density specifications is included. Phase 3 will be documented in a future report when all demonstration sections have been constructed.

2 OBJECTIVE AND SCOPE

The overall objective of the Demonstration Project was to achieve increased in-place density that is expected to improve asphalt pavement performance. The Phase 2 effort built upon the Phase 1 objectives. The objectives for Phases 1 (Aschenbrener et al., 2017) and 2 are listed below.

- Phase 1: 1) a literature review to serve as an educational component regarding the best practices for increasing density, and 2) the construction of ten field demonstration projects.

- Phase 2: 1) documentation of successful SHA density specifications, and 2) the construction of nine additional field demonstration projects.

The FHWA identified nine SHAs for participation in Phase 2 of the Demonstration Project through an application process. Successful applicants received assistance for construction. Consideration for applications was given to those SHAs that could benefit most from increased compaction requirements as well as a distribution of SHAs in varied geographic and climatic regions.

Seven of the nine SHAs selected for Phase 2 of the Demonstration Project hosted an Enhanced Durability through Increased In-Place Pavement Density Workshop prior to the construction of their demonstration project. An eighth SHA hosted the workshop after construction of its demonstration project. The workshop was developed and delivered jointly by the Asphalt Institute and FHWA. The target audience was the SHA, contractors, equipment suppliers, and academia. The workshop included the use of currently recognized best practices as well as new materials and technologies.

Eight of the nine SHAs selected for Phase 2 have constructed field demonstration projects in their States with the other SHA planning to construct its field demonstration project in early 2019. This report documents the eight completed field demonstration projects. The remaining field demonstration project will be documented in a future summary report for Phase 3.

Each field demonstration project included a control and one or more test sections. The control section was built by the contractor to achieve the required in-place density based on its routine construction practices. At least one test section was built as part of the agreement with FHWA, and the goal of this section was to use improved paving and compaction techniques to increase density. The contractor was encouraged to employ techniques that did not require additional rollers or a higher asphalt content, which would result in significantly increased cost. In some States, additional test sections were constructed by the SHAs and contractors to evaluate other techniques, which generally included additional rollers to improve density or other ideas of interest that they believed would work best in their situation. During the field construction, on-site technical assistance was provided to the participating SHAs by staff from the National Center for Asphalt Technology (NCAT).

The field demonstration projects were intended to support SHAs in evaluating their current density requirements for acceptance. The demonstration projects would allow SHAs to partner with their paving contractors to try those techniques that would work best for their situation and allow the FHWA to share these success stories with others. The FHWA would use the results from the demonstration projects to provide information and education to SHAs in reviewing, updating, and improving their current field density acceptance criteria for asphalt pavements.

It should be recognized that although increased density can improve performance, it cannot overcome all issues. For example, improvements to in-place density cannot overcome performance issues with asphalt mixtures constructed with high levels of segregation, moisture susceptible aggregates, and/or unacceptable volumetric properties. Increased density will not have the same benefit in those situations.

3 DEFINITIONS

Definitions for consistency of the discussion in this paper come from *The Asphalt Handbook* (2007), *Hot Mix Asphalt Materials, Mixture Design and Construction* (2009), and the *Hot-Mix Asphalt Paving Handbook* (2000).

- **Compaction**. Compaction is the process by which the asphalt mixture is compressed and reduced in volume. Compaction reduces air voids and increases the unit weight or density of the mixture.
- **Density**. The density of a material is simply the weight of the material that occupies a unit volume of space. Increased density is achieved through the compaction process. For example, an asphalt mixture containing limestone aggregate may have a compacted density of 147 lb/ft^3 (2.36 g/cc). The density, or unit weight, is an indication of the degree of compaction of the mixture. Pavement materials made with different aggregates can have significantly different densities. An asphalt mixture with lightweight aggregate, for example, might have a compacted density of 85 lb/ft^3 (1.36 g/cc).
- **% Density**. The percent density referred to in this report is a physical measurement of density expressed as a percentage of maximum theoretical specific gravity (G_{mm}). Although some projects expressed the density in other manners, density is expressed relative to G_{mm} in this report.
- **Pass**. A pass is defined as the roller passing over one point in the mat one time. For this report, a lightly different definition was used as provided at the beginning of Chapter 6.
- **Coverage**. Coverage is defined as the roller making enough passes to cover the complete width of the mat being placed one time. Repeated coverages are applied until the target density is achieved.
- **Rolling pattern**. Often referred to as a roller train, the rolling pattern is a generic term used to quantify the types and number of rollers and the specific sequence or order in which they operate for a particular mix type, thickness, and width. In some cases, the rolling pattern is referred to for each individual roller to establish the number of passes to obtain the optimum density. Regardless if the rolling pattern is defined as the train or an individual roller, the key is to determine and maintain consistent speed, amplitude and frequency on each pass, both forwards and backwards.
- **Breakdown rolling**. The breakdown roller is the first compactor to roll the freshly laid asphalt mixture.
- **Intermediate rolling**. Intermediate (or secondary) rolling should closely follow breakdown rolling while the asphalt mixture is still hot and compactable. Intermediate rolling is used to increase the density from that provided during breakdown rolling up to the required minimum density.
- **Finish rolling**. Finish rolling is conducted primarily to remove roller marks and provide aesthetic improvement of the surface, although in some instances it is still possible to increase density.
- **Echelon rolling**. In echelon rolling, two rollers are operating with one being slightly behind the other. The two rollers are staggered and offset from each other. With

echelon rolling, the two rollers may complete one full lane-width of coverage as they each complete one pass.

4 BACKGROUND AND LITERATURE REVIEW

The long-term performance and life cycle cost of asphalt pavements can be improved if higher in-place density is achieved in a cost-effective manner. The key findings of a literature review conducted in Phase 1 were documented by Aschenbrener et al. (2017) and include the best practices and new technologies that can help achieve density. A summary of the best practices and new technologies for improving in-place density follows (Aschenbrener et al., 2018).

- Lift thickness, mix design and field verification
    - Fine-graded Superpave mixes can be used in place of coarse-graded Superpave mixes to improve field compaction without affecting the long-term performance of asphalt pavements (Epps et al., 2002; Timm et al., 2006).
    - During pavement design, the lift thickness should be designed to be a minimum of three and four times the intended nominal maximum aggregate size (NMAS) for fine- and coarse-graded mixes, respectively. The thicker the lift, the more room for compaction. Lift thickness is related to potential density, not to rutting (Brown et al., 2004).
    - For some SHAs, mix design requirements have been refined to encourage increasing effective binder volume. More information is provided in an FHWA tech brief (FHWA, 2010a). In addition, an example is provided with Superpave 5 (Hekmatfar et al., 2013). Some of these requirements should only be used after local experience. These changes can improve field compaction while ensuring mixture resistance to premature distresses such as rutting, cracking and moisture damage.
    - After a mix design is completed in the laboratory, it should be verified and properly adjusted at the start of production as materials in the field may be different and/or more variable than those used in the laboratory and field-acceptance criteria may be different from those used for the asphalt mixture design.
- Field compaction
    - The underlying layers should be properly constructed and inspected to provide sufficient, consistent support for achieving higher in-place density.
    - Appropriate compaction equipment should be selected and properly operated during paving. The rolling pattern should be optimized to achieve both in-place density and consistency (Beainy et al., 2014; Scherocman, 2006). Paving operations should be balanced to improve the ability to obtain density and consistency (NAPA, 1996).
    - It is important to understand how weather conditions can affect the mix temperature. If needed, the MultiCool software can be used to estimate the available time for compaction (Timm, 2017).
- Measurement and payment
    - The in-place field density should be compared with Gmm from field-produced samples. Useful information regarding the bulk specific gravity of the mixture (G_{mb}) and Gmm is presented in an FHWA Tech Brief (FHWA, 2010b).

- Incentive specifications can be adopted to yield higher in-place density. A good SHA specification should include an asphalt mixture design procedure that can result in workable and compactable mixtures with an incentive that is obtainable for in-place density (Santucci, 1998; Nodes, 2006).
- The Pennsylvania Department of Transportation (PennDOT) and New York State Department of Transportation (NYSDOT) obtained good in-place density results using the minimum lot average specification and the percent within limits (PWL) specification, respectively (Aschenbrener et al., 2017). Their specifications result in projects with an average of 94.0 percent density. A discussion of their specifications and test results is presented later in Chapter 5.

- New technologies
  - Warm-mix asphalt (WMA) can be utilized to improve compaction, especially for projects requiring longer haul times and/or those constructed in cold weather temperatures and conditions (Prowell et al., 2012).
  - Intelligent compaction (IC) can be implemented to make it easier to optimize, automate, and monitor compaction parameters such as rolling pattern, frequency, drum impact spacing, amplitude, temperature, and number of coverages to achieve higher in-place density and consistency (Chang et al., 2011; Chang et al., 2014).
  - Infrared (IR) imaging can be deployed to measure the real-time mat temperature and adjust to improve temperature consistency and in-place density (Willoughby et al., 2001).
- Others
  - Best practices should be followed to achieve optimal compaction for longitudinal joints (Benson et al., 2006). Through a cooperative agreement with FHWA, the Asphalt Institute website has more detailed information about specifying and constructing longitudinal joints. Echelon paving and paving super-wide are gaining more interest recently as they can help eliminate the need of constructing longitudinal joints.
  - Tack coats should be applied sufficiently, as determined based on residual asphalt content, and uniformly to improve compaction. A good tack coat application will assist compaction and provide an improved bond, resulting in better long-term performance (FHWA, 2016).

5 HOW MUCH DENSITY IS ENOUGH?

A question remains regarding the appropriate minimum and maximum specification requirements for in-place density. To provide background in answering this question, a combination of approaches was used. A literature review was conducted as well as an examination of several SHA specifications.

5.1 Literature Review

Linden et al. (1989) provided information based on three separate sources: the existing literature on the subject, a questionnaire survey of 48 SHAs on compaction practices and performance data from the Washington State Department of Transportation (WSDOT) pavement management system. All three sources show some correlation between the degree of compaction and the performance of asphalt pavement. Overall, a 1 percent decrease in percent density tends to produce about a 10 percent loss in pavement life when below the base percent density level of 93.0. Minimum density levels desirable for construction are shown in Table 1 and support the information in Finn et al. (1980).

Table 1. Minimum Percent Density Levels Desirable for Construction (Finn et al., 1980)

Expected Design Traffic	Top 2 Inches	Deeper Than 2 Inches
Light Traffic	92.0	93.0
Moderate to Heavy Traffic	93.0	94.0

Mallela et al. (2013) conducted a calibration study to implement the AASHTO Mechanistic-Empirical Pavement Design Guide for Colorado DOT. There was a correlation of the pavement performance and the in-place percent density as shown in Table 2. There was a large drop off in performance for those pavements with an in-place percent density below 93.0.

Table 2. In-place Percent Density Versus Percent of Service Life (Mallela et al., 2013)

In-place Percent Density	Percent of Service Life
93.0 to 95.0	100
90.0 to 92.0	65
87.0 to 89.0	35
Less than 87.0	15

Terrel et al. (1994) conducted work for the Strategic Highway Research Program (SHRP). They described the concept of pessimum air voids, which is the range of air void contents within which most asphalt mixtures are typically compacted (between about eight and ten percent air voids). Above this level, the air voids become interconnected and moisture can flow out under a stress gradient developed by traffic loading. Below this value, the air voids are disconnected and are relatively impermeable and thus do not become saturated with water. In the pessimum range, water can enter the voids but cannot escape freely and is subjected to pore pressure buildup upon repeated loading. The recommendation was to obtain percent density during construction above 92.0.

Cooley et al. (2001) developed critical field permeability and pavement density values for coarse-graded Superpave pavements. In a follow-up study, Brown et al. (2004) studied the relationship of in-place air voids, lift thickness, and permeability in hot-mix asphalt pavements. The maximum acceptable permeability was determined to be 125 x 10^{-5} cm/second and the specified minimum percent density level was typically 92.0 to 93.0. It is generally understood that pavements with densities below that level tend to be permeable to water. However, the relationship between density and permeability is also greatly influenced by other simple gradation characteristics, such as nominal maximum aggregate size (NMAS) and the relative coarseness or fineness of the gradation. In order to have acceptable permeability, the minimum percent density values are shown in

Table ***3***.

Table 3. Minimum Percent Density for Various NMAS Based on Permeability (Mallick et al., 2003)

NMAS (mm)	Minimum Percent Density
19.0	94.0
12.5	92.8
9.5	90.5
4.75	88.0

An NCHRP Synthesis (Hughes, 1989) was published at a period when many agencies were using method specifications for compaction. At the time, specifying agencies were moving in the direction of using end-result specifications with density measurements. Because compaction is so important to performance, the author provided a recommendation: realistic target values for density using a statistically-based, end-result specification should have an average percent density of 93.0 and a standard deviation of 1.5.

The Asphalt Institute (2007) reports that a target percent density less than 92.0, densification is considered inadequate and the National Center for Asphalt Technology's (NCAT's) *Hot Mix Asphalt Materials, Mixture Design, and Construction, Third Edition* (Brown et al., 2009) has recommendations for percent density. There is considerable evidence to show that the initial in-place voids for dense graded mixtures should be no higher than approximately 8.0 percent. This is to minimize water permeability and binder aging.

Decker (2017) reported that in-place density of asphalt mixtures is the single most important property of the asphalt mixture in the pavement and collected specific information on the current state-of-the-knowledge and agency practices. He received responses from all 50 State DOTs and the District of Columbia DOT. A total of 60 agency responses were received, including a few multiples from the same State and from five Canadian provinces. A total of 38 responses were received from private industry personnel. He found that 89 percent of the respondents had a lower specification limit ranging from 91.0 to 93.0 percent with 57 percent of the respondents indicating a lower specification limit of 92.0 percent. About 77 percent of the respondents indicated an upper specification limit between 97.0 and 98.0 percent, and 58 percent of the respondents reported an upper specification limit of 97.0 percent.

5.1.1 Summary

The literature review examined the percent density of asphalt pavement at the time of construction. Researchers used a wide variety of techniques. In general, however, there is consensus in more recent research that the percent density of the mat should be greater than about 92.0, and 93.0 to 94.0 would be preferred after construction (McDaniel, 2018). The next step was to identify SHA success stories with percent density specifications that minimized the amount of test results below the 92.0 threshold on the construction project.

5.2 Success Stories Identified as Part of FHWA Demonstration Project, Phase 1

5.2.1 Pennsylvania Department of Transportation

The Pennsylvania Department of Transportation (PennDOT) was identified as a success story for using the minimum lot average quality measure. In fact, PennDOT had a minimum individual sublot requirement. With one test per sublot, PennDOT required the minimum of each test to be greater than or equal to 92.0 percent G_{mm} with its Restricted Performance Specification. The density is measured with cores. Results from the 2015 statewide average density for wearing and binder asphalt mixtures are shown in Figure 1. For the non-PWL projects constructed in 2016, the statewide average percent density was 94.3 and the standard deviation was 1.53.

PennDOT started using the PWL quality measure in some construction projects in 2016. For the PWL projects constructed in 2016, the statewide average percent density was 94.1 and the standard deviation was 0.95. The statewide average density was above 94 percent regardless of the type of specification; however, the consistency of results as measured by the standard deviation improved greatly with the PWL quality measure. It should be noted that this may have been a function of the number and/or types of projects (more consistent existing base conditions) that were initially selected for the new PWL quality measure and may not be totally dependent on the use of the PWL quality measure.

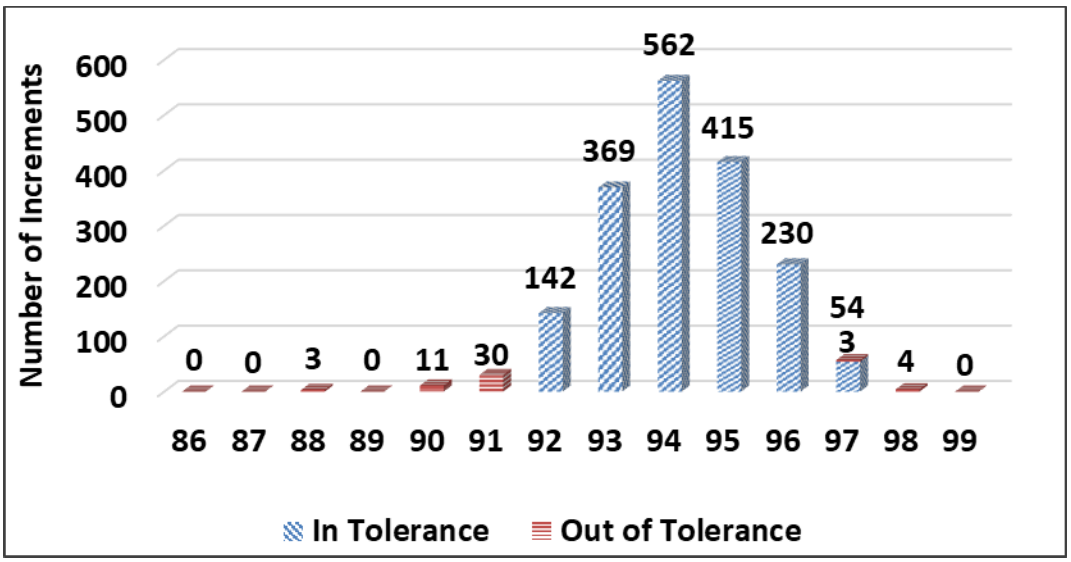


Figure 1. Results of PennDOT's Minimum Sublot Quality Measure in 2015

5.2.2 New York State Department of Transportation

The New York State Department of Transportation (NYSDOT) was identified as another success story for using the PWL quality measure. The NYSDOT 50 Series is used on Interstates and principal arterials with full or partial control of access. The density is measured with cores. The lower specification limit and upper specification limits were set at 92.0 and 97.0 percent G_{mm}, respectively. There is a five percent incentive available on density alone. The same specification has been used since 2002. For 2015, the statewide average percent density was 94.1, as shown in Figure 2. This was consistent with the data from 2002–2014. As observed by NYSDOT, contractors understand that PWL quality measure requires a focus on consistency in addition to the average density and are focusing on being more consistent. The standard deviation of projects statewide was 0.83.

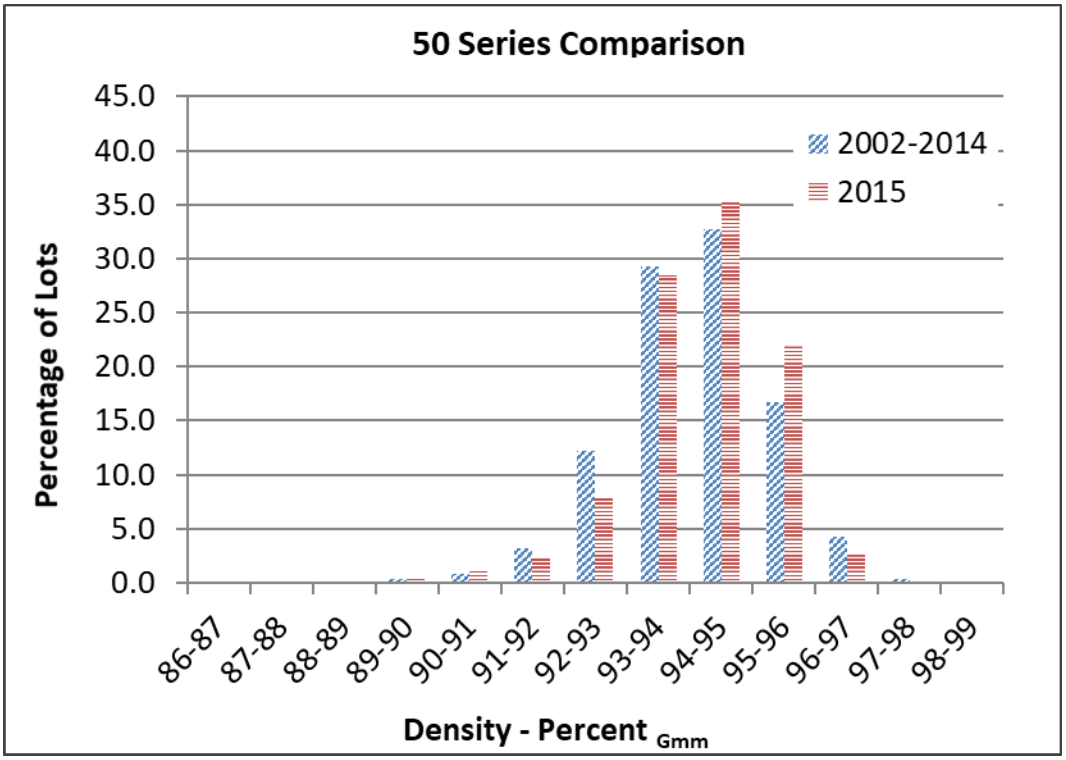


Figure 2. Results of NYSDOT's PWL Quality Measure

5.3 Additional Success Stories Identified as Part of FHWA Demonstration Project, Phase 2

Building upon the success stories identified in the FHWA Density Demonstration Project, Phase 1, more case studies were added for this Phase 2 report. Some of these SHAs participated in Phase 1 or 2 of the FHWA Density Demonstration Project, but not all. These SHAs were primarily identified as a result of a specification mining effort (Aschenbrener et al., 2017).

Further, more details of the specifications were gathered from seven SHAs identified as success stories. There are likely more than seven SHAs, but these are the agencies identified to date. Again, the purpose of the success stories was to identify SHAs with percent density specifications that minimized the amount of test results below the 92.0 threshold. The seven SHAs are:

- Alaska Department of Transportation and Public Facilities (ADOT&PF);
- Maine Department of Transportation (Maine DOT);
- Maryland Department of Transportation State Highway Administration (MDOT SHA);
- Michigan Department of Transportation (MDOT);
- New York State Department of Transportation (NYSDOT);
- Pennsylvania Department of Transportation (PennDOT); and
- Tennessee Department of Transportation (TDOT).

In addition to these seven SHAs, an eighth was added that was not considered to be a best practice so its requirements could be used for comparison purposes. The eighth SHA will be referred to as "Example State."

SHAs typically have more than one density specification. The various density specifications are used for different types of asphalt mixtures, highways, and/or projects. These success stories represent the SHAs' most stringent density specification. The information associated with the use of the density specification is shown in Table 4. Each of the eight SHAs used its electronic data management system to collect percent density results from all the acceptance tests on a project, and then all the projects for a given period such as a construction season. The averages and standard deviations were calculated for each lot and then the results from each lot were averaged and presented for each SHA. The period is also shown on Table 4. The period is often one construction season, although some of the data is from multiple construction seasons.

Table 4. Project Information and Time Period for Density Data

SHAs	Year of Data	Mix Type	Type of Projects	Acceptance Testing
Example State	2016	Type C	N/A	Agency only
ADOT&PF	2015	Type II 19mm & Superpave 12.5 mm	Interstate and principal arterial	Agency only
Maine DOT	2013 to 2017	9.5, 12.5 and 19 mm	All mainline projects	Agency only
MDOT SHA	2017	Dense Graded	N/A	Contractor validated by agency
MDOT	2015	9.5, 12.5 and 19 mm	All projects greater than 5,000 tons	Agency only
NYSDOT	2015	Series 50 9.5, 12.5 and 19 mm	Full or partially controlled roadways	Agency only
PennDOT	2017	High level wearing surface 9.5, 12.5 & 19 mm	N/A	Agency only
TDOT	2015 to 2017	D-mix (3/8" NMAS)	Interstate and SR Freeways	Agency only

N/A: Not Available

Each pavement is not constructed uniformly; that is, the entire pavement is not constructed to a single percent density value. There is variability from roller patterns, mixture properties, and temperatures, among others. Each construction project is built with a range of percent density values. Based on the literature review, the percent density of an asphalt pavement should be greater than 92.0 and possibly even 93.0 after construction. A threshold of 92.0 was used for this analysis.

An example of the histogram from one of the SHAs is shown in Figure 3. The histogram shows the variation in percent density results from multiple projects within the period. The distribution of percent density results is shown along with the percentage of results below a threshold of 92.0. From Figure 3, there were 5.8 percent of the test results below 92.0. Histograms similar to Figure 3 were developed for each of the eight SHAs.

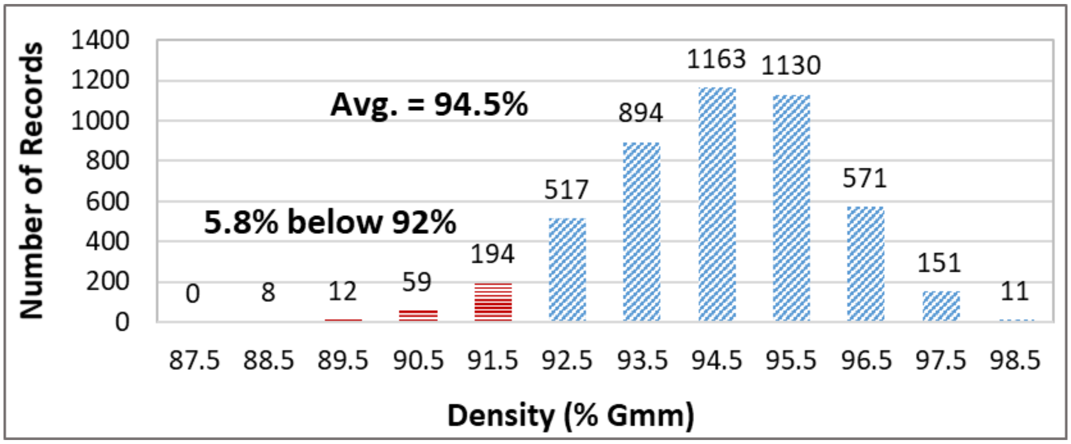


Figure 3. Histogram of Percent Density Results from Maine DOT

In-place asphalt density specifications from the eight SHAs were examined to determine the actual field outcomes produced from each specification. The density specifications from each SHA and a summary of the project results during a period selected by the SHA are shown in

Table *5*. Seven of the eight SHAs were selected because they had less than 6.0 percent of their percent density results below the 92.0 percent threshold. Key information is provided below.

- Five SHAs (AKDOT&PF, Maine DOT, MDOT, NYSDOT and PennDOT) use a percent within limits (PWL) quality measure with a lower specification limit ranging from 92.0 to 93.0 percent. Only 3.1 to 5.8 percent of the results were below the threshold of 92.0.
- One SHA (MDOT SHA) uses a minimum lot average quality measure with a minimum individual sublot requirement of 92.0 percent. Only 5.3 percent of the results were below the threshold of 92.0.
- One SHA (TDOT) uses a minimum lot average quality measure with a minimum specification limit of 92.0. Unfortunately, this resulted in 11.0 percent of the results below the threshold of 92.0. This quality measure was not quite as effective as the PWL quality measure or the minimum lot average quality measure with a minimum individual sublot requirement.
- Seven SHAs use incentives for density ranging from 2.0 to 5.0 percent, for the density quality characteristic alone.
- For the six SHAs with less than 6.0 percent of their density results below the threshold of 92.0, their average percent density ranged from 94.0 to 94.9.

Table 5. Percent Density Specifications and Results from Projects

SHAs	Quality Measure	Limits (Percent G_{mm})	Incentive for Only Density	Max. Incentive (Percent G_{mm})	Avg. (Percent G_{mm})	Std. Dev. of Lots	Less than 92 Percent G_{mm}
Example State	Lot Avg.	91.5 to 95.0	1.50%	92.8	92.6	N/A	25.30%
ADOT&PF	PWL	93.0 to 100.0	5.00%	Approx. 96.0	94.9	1.76	5.60%
Maine DOT	PWL	92.5 to 97.5	2.50%	Approx. 93.5	94.5	1.2	5.80%
MDOT SHA	Lot Avg. & Ind. Sublot	92.0 to 97.0	5.00%	94	94	1.03	5.30%
MDOT	PWL	92.5 to 100.0	2.00%	Approx. 94.5	94.4	1.03	5.50%
NYSDOT	PWL	92.0 to 97.0	5.00%	Approx. 94.0	94.2	1.01	5.00%
PennDOT	PWL	92.0 to 98.0	2.00%	Approx. 94.0	94.4	1.46	3.10%
TDOT	Lot Avg.	92.0 to 97.0	2.00%	94	93.9	N/A	11.00%

Information from the eighth SHA, Example State, was provided as a contrast. Example State has a minimum lot average quality measure with a minimum of 91.5. This resulted in a statewide average percent density of 92.6 with over 25 percent of the results below 92.0. Since the maximum incentive is achieved at 92.75 percent, the statewide average makes sense. Contractors often have a philosophy of "roll until it meets." Example State's pay adjustment begins decreasing above 93.25. Considering the potential impacts of rounding, over 40 percent of the percent density results were below 92.4. Example State has a large percentage of results below the generally recognized threshold.

In order to serve as a guide to those SHAs interested in making improvements to their density requirements, additional information on the density specifications is shown in

Table ***6***. Generally, a minimum of five test results per lot is needed for accurate payment; however, using lots with 10 or more test results will provide improved statistical accuracy for pay determinations. The Example State and ADOT&PF met this guideline with eight and ten, respectively. The most common frequency of density testing was every 250 to 500 tons. All of the SHAs use cores, and they all use G_{mm} values from plant-produced material obtained within the lot. These are all considered best practices.

Table 6. Additional Percent Density Specification Information

SHAs	Lot Size (tons)	Sublots per Lot	Frequency (tons)	Measuring Gmb	Measuring G_{mm}
Example State	2,000	8	250	6-in. cores: 1 per sublot	Avg. of 5 tests: Every 500 tons
ADOT&PF	5,000	10	500	6-in. cores: 1 per sublot	Ind. test: 1 per lot
Maine DOT	4,500	6	750	6-in. cores: 1 per sublot	Ind. test: 1 per sublot
MDOT SHA	Daily production	5 min.	500 max.	4 or 6-in. cores: 2 per sublot	Ind. test: Daily value
MDOT	5,000	5	1000	6-in. cores: 1 per sublot	Ind. test: 1 per sublot
NYSDOT	1,000	4	250	6-in cores: 1 per sublot	Ind. test: 1 per lot
PennDOT	2,500	5	500	6-in cores: 1 per sublot	Ind. test: Daily value
TDOT	1,000	5	200	4 or 6-in. cores: 1 per sublot	Daily Avg.: 2 tests per day

The longitudinal joint density is a very important part of a percent density requirement. Information on longitudinal joint density requirements for each SHA identified in this study is shown in Table 7. Most notable is that the lower limit for the percent density at the joint is 2.0 percent or less, lower than the percent density requirement in the mat. Again, incentives are an important aspect of the percent density requirements for longitudinal joints.

Table 7. Longitudinal Joint Density Specification Information

SHAs	Quality Measure	Limits (% G_{mm})	Incentive for Only Joint Density
Example State	None	N/A	N/A
ADOT&PF	Lot Avg.	Greater than 91.0	$1.50 per L.F. (approx. 6.25%)
Maine DOT	PWL	Greater than 91.0	2.00%
MDOT SHA	None	N/A	N/A
MDOT	Lot Avg.	Greater than 90.5	$1.00 per L.F. (approx..4.0%)
NYSDOT	Under Development	N/A	N/A
PennDOT	PWL	Greater than 90	$5000 per Lot (approx.. 2.5%)
TDOT	Lot Avg.	Greater than 91.0	1.25%

N/A: Not Available

5.4 A Success Story from State 1

State 1 participated in the Phase 2 demonstration project. The States participating in the demonstration project were not identified and kept anonymous, because the information gathered was the important part. State 1 has a percent density specification that uses a quality measure of PWL with a lower specification limit of 91.0. Percent density results from over 9,300 cores taken from projects constructed during the 2017 construction season are shown in Figure 4. The statewide average percent density was 93.2 with 20.0 percent of the results below the threshold of 92.0.

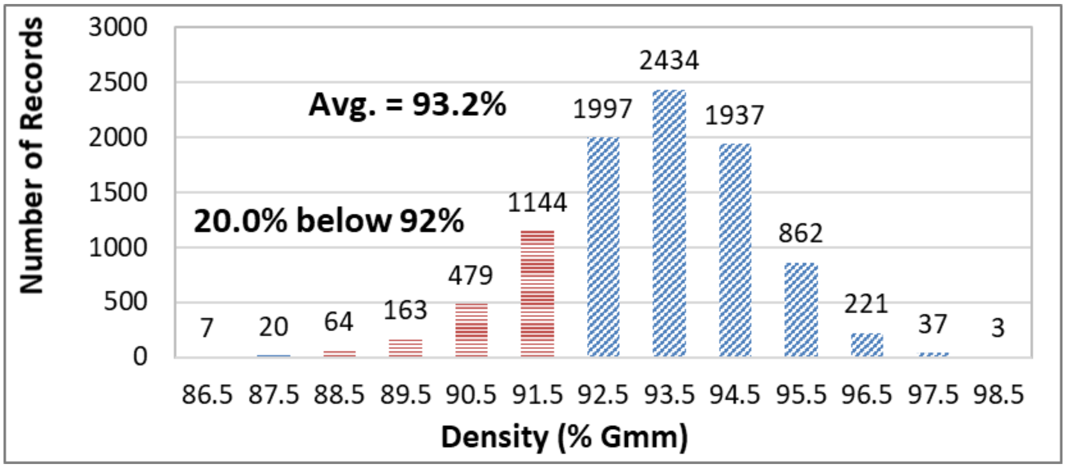


Figure 4. Histogram of Percent Density Results from State 1 during 2017 Construction Season

For the density demonstration project, State 1 used a PWL quality measure with a lower specification limit of 92.0 for the entire project. Percent density results from over 1,100 cores are shown in Figure 5. There were 5.7 percent of the percent density results below the threshold of 92.0, and there was quite an improvement by increasing the lower specification limit from 91.0 to 92.0.

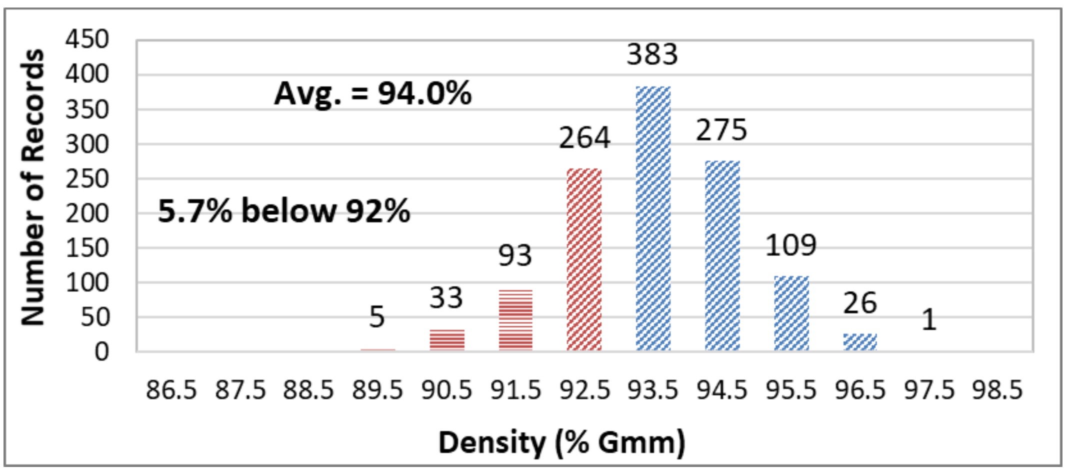


Figure 5. Histogram of Percent Density Results from State 1 during the FHWA Density Demonstration Project

5.5 Summary

As determined from the literature review, percent density should be greater than 92.0 and perhaps even 93.0 at the time of construction. With the variability of materials and construction, several SHAs have been successful at averaging just over 94.0 to minimize the amount of percent density results below 92.0. Successful SHAs have done this with either the PWL or minimum lot average quality measure with a minimum individual sublot requirement. More have used the PWL quality measure. Incentives are included in all of the specifications. Longitudinal joint density is important to pavement performance and should also be included.

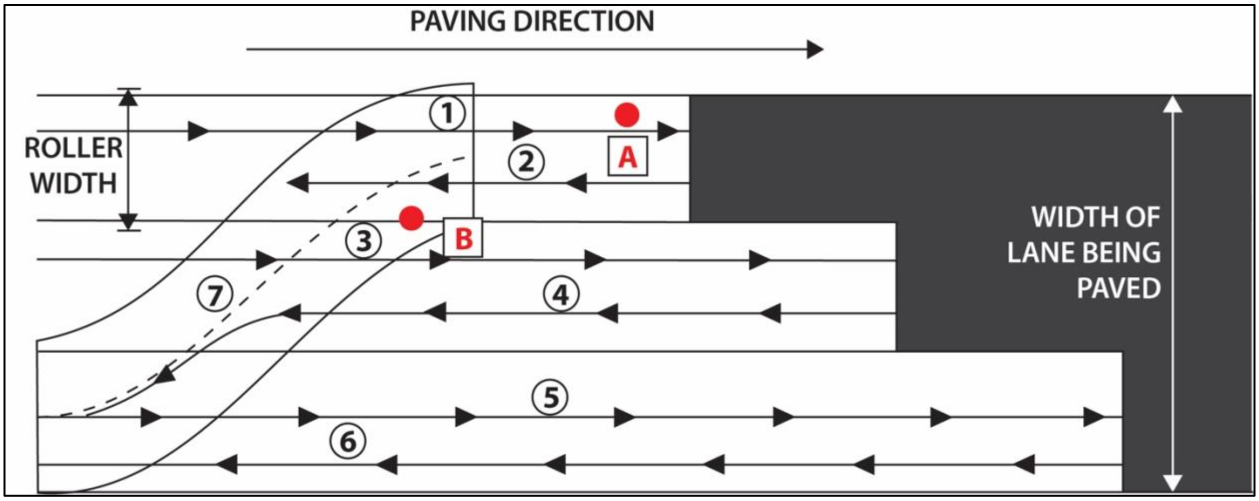
6 FIELD DEMONSTRATION PROJECTS

Nine SHAs were selected through an application process for Phase 2 of FHWA's demonstration project for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. Eight SHAs completed construction of their field demonstration projects and will be summarized here. The States participating in the demonstration project were not identified and kept anonymous, because the information gathered was the important part. The one SHA not included in this report had significant delays in its construction project and will be reported along with Phase 3. Each demonstration project was required to have a preconstruction meeting to discuss proposed procedures for building the test sections. The SHAs and contractors generally partnered for planning control and test sections to evaluate the ability to obtain increased density with enhanced compaction to improve pavement durability.

The contractor was to build a control section using its standard compaction techniques and then build a test section with improved compaction techniques using the same equipment used for construction of the control section. If desired, the SHA could have the contractor construct additional test sections using additional equipment, changes in materials, mixture proportioning, lift thicknesses, improved procedures, or other means to achieve improved in-place density.

The following terms are constantly used throughout the entire report and are defined as follows:

- **Pass**. A pass is defined as the roller passing over one point in the mat one time. When observing a rolling pattern as shown on Figure 6, the number of passes can be quite variable depending on where the point is selected. One point may get two passes (Point A) whereas another point may get five passes (Point B). So, for the purposes of this study, the number of passes was reported as those that a roller made as part of the rolling pattern. In this document the reported passes, are the total number of passes a roller made behind the paver as part of the rolling pattern before it was moved to another section.
- **Finish rolling**. Finish rolling is conducted primarily to remove roller marks and provide aesthetic improvement of the surface, although in some instances it is still possible to increase density. As part of this study, the number of passes from the finish roller was generally not included a smaller roller operating in static mode was often used to remove roller marks. This was done such that the number of passes to obtain density was not skewed.



Note: This is a recommended rolling pattern where each roller pass should proceed straight into the compacted mix and return in the same path. After the required number of passes are completed, the roller should move to the outside of the pavement on cooled material and repeat the process.

Figure 6. Definition of Roller Passes

In this chapter, the results from each of the eight demonstration projects are discussed. As part of the FHWA demonstration project, each SHA agreed to prepare a report to document its findings. A summary from each of the SHA reports is provided here.

6.1 State 1

6.1.1 Project Description

The demonstration project was located on a high-volume, four-lane divided interstate highway. The project length was approximately five miles and a total of over 100,000 tons of asphalt mixture. A total of five lifts were placed directly over the top of a cement treated base. The first three lifts were 3.5-inches thick, the fourth was 2-inches thick and then a wearing surface was placed. The project began in August of 2018 and continued into the following year. Only the first 3.5-inch lift was evaluated for this report.

For this project, the SHA approved a new specification for field density to be used on the entire project as the test section. The experimental sections were defined as:

- Control section (entire 2017 construction season), used density results from the entire 2017 construction season for the entire State. This specification used PWL with a lower specification limit (LSL) of 91.0 percent. This was a unique selection of a control section, but one that was used by this State.
- Test section 1 (increased lower limit on the PWL specification), used the combined results from two separate projects constructed near each other by the same contractor with the same mixture design and equipment. A new PWL specification with an LSL of 92.0 percent was used.

6.1.2 Asphalt Mixture Design

The gradation used was a 19.0-mm NMAS on the fine side of the primary control sieve. The primary control sieve and control point are defined in AASHTO M 323 (47 percent passing on the 4.75 mm sieve for 19.0 mm NMAS). The asphalt mixture was designed with the Marshall method with 75 blows. The optimum binder content was 5.5 percent selected at 5.0 percent air voids. 25 percent fractionated reclaimed asphalt pavement (RAP) was used, and the added virgin binder content was 4.4 percent. A summary of the Marshall mixture design gradation and volumetric properties as well as the mix design criteria are presented in Table 8 and Table 9. No laboratory performance testing (cracking, moisture susceptibility, or rutting) were conducted as part of this mixture design. The designed t/NMAS for this project was 4.7 for the lower lifts, and the PG grade of binder was a PG 64-28 for the lower lifts and PG 70-22 modified with SBS for the upper lifts.

Table 8. Mixture Design Aggregate Gradation and Corresponding Criteria, Percent Passing – State 1

Sieve Size	Gradation	Criteria	
		Min	Max
25.4 mm (1”)	100	100	
19.0 mm (¾”)	99	90	100
12.5 mm (½”)	87		
9.5 mm (⅜”)	77	62	77
4.75 mm (#4)	56		
2.36 mm (#8)	38	38	47
1.18 mm (#16)	22		
0.60 mm (#30)	13		
0.45 mm (#40)	11	11	19
0.30 mm (#50)	9		
0.15 mm (#100)	5		
0.075 mm (#200)	5.2	2.5	6.0

Table 9. Mixture Design Volumetric Properties and Corresponding Criteria – State 1

Mixture Design Properties	Mixture Design	Field Acceptance Criteria
AC (%)	5.5	NA
Air voids, (%)	4.8	4.8–5.2
VMA (%)	15.8	15–18
D/A Ratio	1.1	0.8–1.2
Stability, lbf	3740	2000 Min
Flow	13	8–16

NA: Not Applicable

6.1.3 Field Verification of the Asphalt Mixture Design

The asphalt mixture design was verified during field production based on asphalt content, selected sieve size, and air voids content per the agency’s standard requirements. The results indicated that the gradation and air voids contents were very similar to those from the mixture design. The results of the mixture volumetric properties and gradations came from four sublots per lot and are shown in Table 10. At the time of NCAT's visit, the contractor and SHA personnel indicated that the mixture was slightly adjusted with an increase in binder content, and that improvements in materials processing (crushing and stockpiling) were also made. It can be observed that the target binder content was increased to 5.7 percent compared to the 5.5 percent from the JMF and the percent passing the No. 200 sieve increased to 5.9 compared to 5.2 from the JMF.

Table 10. Production Mixture Properties – State 1

Agency Acceptance Property	Section		Target	Tolerance	
	Avg	Std Dev		Min	Max
AC (%)	5.66	0.20	5.7	5.2	6.2
Air Voids (%)	4.5	0.29	4.8	2.8	6.3
3/8 inch	80.8	4.57	77	71	83
No. 8	37.8	1.89	36	30	42
No. 40	13.5	0.58	11	6.0	16
No. 200	6.9	0.32	5.9	3.9	7.9

6.1.4 Density Measurement and Specifications

For the entire project, a new PWL specification with an LSL of 92.0 percent was used. The LSL was 1 percent higher than the current standard: from 91.0 to 92.0 percent. For acceptance, the in-place air voids were determined by comparing the in-place density measured from cores to the theoretical maximum density. The average in-place density was obtained from 10 cores taken from each lot. The in-place density results averaged 94.0 percent (6.0 percent air voids) with a standard deviation of 0.87 percent.

6.1.5 Experimental Section Construction and Results

The base was a 12-inch cement treated granular base and was to be overlaid with 3.5 inches of asphalt mixture. Paver speed was estimated to be between 10 to 15 feet per minute. There were only a few paver stops longer than two minutes when it was required to take samples with steel plates placed under the paver.

An SS-1H diluted (1:1) emulsion was applied at a bar rate of 0.15 gallons per square yard to seal and protect the cement treated surface. Asphalt was delivered to the site in belly dump trucks and deposited in a windrow. The mixture was transferred from the windrow to the paver using a Barber Green BG-650 windrow elevator. A Caterpillar AP 1055D paver was used to lay the mixture. A 14-ton Caterpillar CB66B roller operating in high frequency vibratory mode was used as the breakdown roller. An 11-ton Caterpillar CB10 roller, operating in low frequency and low amplitude setting, was used as the intermediate roller. Finally, a static steel drum roller (12-ton CAT CB54B) was used as finishing roller.

The asphalt plant was located about 20 miles from the paving site and the hauling time was estimated to be about 30 minutes. The plant was a drum plant with separate cold bins for fractionated RAP.

Temperature at the beginning of paving was 62 degrees F with a steady breeze. Temperatures behind the paver ranged from 295 to 305 degrees F and the overall look of the mat after placement was uniform without any type of defects. The breakdown roller operated directly behind the paver. The first pass was performed over the joint from the cold side (outside lane) in static mode. The roller then operated in vibratory mode and applied 13 passes. The intermediate roller also applied vibration and completed 15 passes. The finishing roller applied only static compaction and completed 9 to 11 passes. Compared to typical projects built by the contractor in 2017 (control section), there were about 20 percent more passes used on this project (test section).

For QC, mat densities were checked by the contractor using a Troxler 3440 nuclear density gauge. For acceptance, the agency reported an average of 6.0 percent air voids (94.0 percent density) with a standard deviation of 0.87 percent from 10 cores per lot.

This SHA had a unique comparison of control and test sections. Figure 7 shows a comparison of in-place density during 2017, which can be considered as the control section. Additionally, it shows the in-place density for this project during 2018 with the increased density specification, which can be considered as the test section. The statewide average percent density in 2017 was 93.2 with 20.0 percent of the results below the threshold of 92.0, while in 2018, the average percent density was 94.0 with 5.7 percent of the results below the threshold of 92.0 for the two projects. In addition, the statewide standard deviation of lots for the percent in-place air voids decreased from 1.36 to 0.86 percent, which shows a significant effect of the change in the specification with higher density.

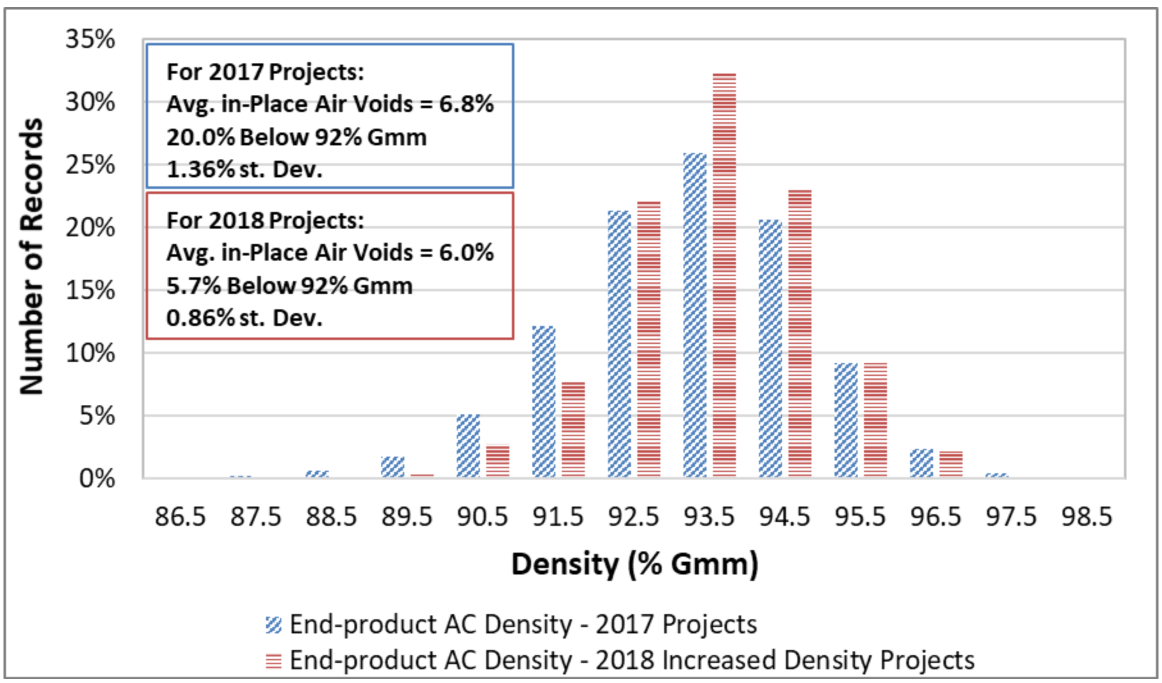


Figure 7. In-place Density Comparison of Control and Test Sections – State 1

6.1.6 Utilization of New Technologies

Intelligent compaction technologies were available in all the rollers for the operator to know the location (GPS technology) and the number of passes applied to a segment of the pavement. WMA allows effective compaction to occur at lower mix temperatures. No other new technologies such as the MOBA Pave-IR System or rolling density meter were used as part of this project.

6.1.7 Summary of State Findings

For State 1, the percent density increased by 0.8 percent with the new specification. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
  - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
  - There were 13 vibratory passes from the breakdown roller and at least another 15 vibratory passes of the intermediate roller. This was an increase of approximately 20 percent more passes than typically used for the projects in 2017, which were considered the control section.
  - The standard deviations of density results for each lot improved from 1.36 to 0.87. This was attributed to improvements to the aggregate crushing and handling process and more uniform roller patterns.
  - The construction season was extended with the use of WMA.
- Observations for specification development (agencies):
  - The asphalt mixture design was adjusted to include 0.2 percent more asphalt binder.
  - The field density acceptance specification was PWL. The LSL was increased from 91.0 to 92.0 percent and the upper specification limit (USL) was 96.5 percent.
  - The specification had incentives of up to $2 per ton per lot.

6.2 State 2

6.2.1 Project Description

The demonstration project was 5.7-miles long and located on a medium-volume, two-lane State highway. The condition of the pavement prior to milling consisted of low to moderate severity longitudinal and transverse cracks at 20 to 100-foot intervals, low to moderate severity alligator cracking generally in the wheel paths, and no significant permanent deformation.

The project scope required the contractor to remove four inches of the existing pavement by cold milling and replace with two inches of 19.0 mm-NMAS binder course mixture followed by a two-inch layer of 12.5-mm NMAS wearing course mixture. The entire project consisted of approximately 4,380 tons of HMA.

The following experimental sections were established at the beginning of the project:

- Control section (typical binder and wearing courses), used the typical binder course as one control section, and the typical wearing course as a second control section.
- Test section 1 (warm-mix asphalt), used Evotherm warm-mix asphalt in the binder (BC) and wearing (WC) courses.
- Test section 2 (additional asphalt content), used higher binder content, +0.2 percent, in the binder and wearing courses.

6.2.2 Asphalt Mixture Design

A total of six asphalt mixtures were used in the demonstration project, namely, three binder course and three wearing course mixtures. Both binder and wearing course mixtures include one conventional asphalt mixture, one Evotherm WMA, and one “Plus AC” asphalt mixture which had 0.2 percent more asphalt. Table 11 and

Table ***12*** summarize the mix design aggregate gradation and volumetric properties of both binder and wearing course mixtures used in the control and test sections. SBS polymer modified asphalt binder meeting State 2 specifications for PG 76-22M (based on AASHTO M332) was used for both the binder and wearing course mixtures.

Binder course mixtures were coarse-graded 19.0 mm NMAS mixtures. The primary control sieve and control point are defined in AASHTO M 323 (47 percent passing on the 4.75 mm sieve for 19.0 mm NMAS). Wearing courses were coarse-graded 12.5 mm NMAS mixtures. The primary control sieve and control point are defined in AASHTO M 323 (39 percent passing on the 2.36 mm sieve for 12.5 mm NMAS). These mixtures included 24 percent RAP. The t/NMAS ratio for binder mixtures was 2.7 and for wearing mixtures was 4.0.

Design aggregate gradations for control binder and wearing course mixtures were chosen first, then the gradations were kept constant for the Evotherm WMA and "Plus AC", while the design asphalt content was increased by 0.1 percent for Evotherm WMA and another 0.1 percent for "Plus AC" asphalt mixture. Thus, the "Plus AC" binder and wearing course mixtures contained 0.2 percent more asphalt binder as compared to the control mixtures. At the laboratory compactive effort of N_{design} 75 gyrations, design air voids content of 3.5 percent were targeted for all six mixtures. Other design volumetric properties (Gmm, VMA, and VFA) were found to be relatively consistent with a minimal variation among the three mixture types. The minimum VMA for 19.0 mm NMAS binder course mixture in this State is 12.5 percent and 13.5 percent for 12.5 mm NMAS wearing course mixtures. The specified VFA ranges from 69 to 80 percent for all mixture types.

Table 11. Mixture Design Aggregate Gradation, Percent Passing – State 2

Sieve Size	Control		Evotherm WMA		"Plus AC"	
	Binder	Wearing	Binder	Wearing	Binder	Wearing
25.4 mm (1")	100	100	100	100	100	100
19.0 mm (¾")	97	100	97	100	97	100
12.5 mm (½")	86	93	86	93	86	93
9.5 mm (⅜")	72	80	72	80	72	80
4.75 mm (#4)	42	45	42	45	42	45
2.36 mm (#8)	32	35	32	35	32	35
1.18 mm (#16)	23	27	23	27	23	27
0.60 mm (#30)	18	22	18	22	18	22
0.30 mm (#50)	10	12	10	12	10	12
0.15 mm (#100)	6	7	6	7	6	7
0.075 mm (#200)	4.1	5.0	4.1	5.0	4.1	5.0

Table 12. Mixture Design Volumetric Properties – State 2

Mixture Design Properties	Control		Evotherm WMA		"Plus AC"	
	Binder	Wearing	Binder	Wearing	Binder	Wearing
D/A Ratio	0.87	1.02	0.85	1.00	0.84	0.98
Pbe (%)	4.7	4.9	4.8	5.0	4.9	5.1
AC (%)	4.8	5.0	4.9	5.1	5.0	5.2
Gmm	2.468	2.448	2.464	2.441	2.480	2.441
VMA (%)	14.3	14.6	14.5	15.0	14.7	15.1
VFA (%)	76	76	76	77	76	77
Air Voids (%)	3.5	3.5	3.5	3.5	3.5	3.5

6.2.3 Field Verification of the Asphalt Mixture Design

Table 13 and

Table ***14*** present the aggregate gradations and volumetric properties of the plant produced mixtures. Compared to the JMF (shown in Table 11 and

Table ***12***), the plant mixtures appeared to have slightly finer gradations, resulting in a slightly higher dust ratio. Further, the extracted percent AC of Evotherm WMA BC, Evotherm WMA WC, and "Plus AC" BC were slightly different from that of the JMF. Specifically, percent AC of Evotherm WMA BC and "Plus AC" BC increased by 0.1 percent more than JMF percent AC value, while percent AC of Evotherm WMA WC also decreased by 0.1 percent. In general, these differences resulted in slight reductions in VMA, slight increases in VFA, and 0.2 to 0.6 percent reduction in percent AV.

Table 13. Agency Acceptance Plant Mix Aggregate Gradation, Percent Passing – State 2

Sieve Size	Control		Evotherm WMA		"Plus AC"	
	Binder	Wearing	Binder	Wearing	Binder	Wearing
25.4 mm (1")	100	100	100	100	100	NA
19.0 mm (¾")	97	100	96	100	96	NA
12.5 mm (½")	85	95	84	92	85	NA
9.5 mm (⅜")	71	80	72	79	72	NA
4.75 mm (#4)	42	45	42	43	42	NA
2.36 mm (#8)	32	35	32	35	31	NA
1.18 mm (#16)	22	27	22	25	22	NA
0.60 mm (#30)	18	22	19	21	18	NA
0.30 mm (#50)	10	12	9	11	10	NA
0.15 mm (#100)	6	7	6	7	5	NA
0.075 mm (#200)	4.2	5	4.6	5.1	4.2	NA

NA: Not Applicable

Table 14. Agency Acceptance Plant Mix Volumetric Properties – State 2

Mixture Design Properties	Control		Evotherm WMA		"Plus AC"	
	Binder	Wearing	Binder	Wearing	Binder	Wearing
D/A Ratio	0.92	1.05	0.97	1.05	0.87	NA
Pbe (%)	4.6	4.8	4.8	4.8	4.8	NA
Extracted AC (%)	4.8	5.0	5.0	5.0	5.1	NA
Gmm	2.473	2.453	2.465	2.452	2.467	NA
VMA (%)	14.0	14.3	14.1	14.4	13.9	NA
VFA (%)	76	77	78	78	80	NA
Air Voids (%)	3.3	3.3	3.1	3.3	2.9	NA

NA: Not Applicable

6.2.4 Density Measurement and Specifications

Table 15 presents the average air voids of the field cores obtained from the binder and wearing course experimental sections and their respective coefficient of variation (COV) values. Values are averages of 15 cores for each experimental section. The CoV varied from 23.5 to 35.8 percent.

For the binder course, increased densities (i.e., reduced air voids) are clearly observed for Evotherm WMA and "Plus AC" sections. On the other hand, for the wearing course, Evotherm WMA mixtures showed comparably higher density or lower field air voids (e.g., 4.4 vs. 3.5 percent), while the "Plus AC" mixtures showed only a slight reduction in air voids (e.g., 4.4 vs. 4.1 percent) as compared to the control section. This observation indicates that the increased density techniques used in this study were effective in improving mixture density (lower in-place air voids) for the binder and wearing course mixtures. The improvement in density was greater in the binder course mixtures than the wearing coarse mixtures. It is worth noting that five out of the six sections achieved much higher field densities (i.e., lower air voids) than both conventional and proposed density requirements (i.e., 92 and 93.5 percent of Gmm), respectively, except for the control section for the binder course mixture.

Table 15. Air Void Content of Field Cores Using Agency Acceptance Data

Mixture	Layer	Density (%Gmm)	Std. Dev.	COV (%)
Control HMA	BC	92.2	2.56	32.8
	WC	95.6	1.03	23.5
Evotherm WMA	BC	95.2	1.43	29.8
	WC	96.5	1.25	35.8
"Plus AC" HMA	BC	94.5	1.93	35.0
	WC	95.9	1.05	25.5

6.2.5 Experimental Section Construction and Results

Prior to the new overlay mixture placement, the existing asphalt surface was milled at approximately four inches in depth. The dry milled surface was then cleaned by a power broom in preparation for tack coat application. SS-1 anionic emulsion asphalt was spread on the milled surface by a spray truck at an application rate of 0.045 g/sy. Throughout the test sections, no levelling course was needed or placed.

A Caterpillar paver (model: CAT AP1055) was used throughout the entire construction. A Roadtec Shuttle Buggy (model: SB-2500) material transfer vehicle (MTV) was used during the binder course construction and was later replaced with a Weiler E2850 full-size MTV for the wearing course construction. Surface temperature of the uncompacted asphalt mat behind the paver were periodically monitored. The average mat temperatures of the six different sections ranged from 240 to 275 degrees F. Ambient temperature during paving started at 40 degrees F.

Two slightly different models of steel rollers were utilized for the compaction process. A 10-ton CAT CB 534D roller was primarily used as a breakdown roller and a 7-ton CAT CB 434D was used as a finishing roller. On average, the breakdown roller applied seven to nine passes of compaction over a 100 to 150-foot long span of asphalt mat with vibration (high frequency, low amplitude setting). The finishing roller generally followed the breaking roller at an interval (i.e., five to ten minutes behind the breakdown roller) while applying five to seven passes of finish compaction in the static mode.

6.2.6 Utilization of New Technologies

WMA technology was utilized in two experimental sections. No other new technologies such as the MOBA Pave-IR System, intelligent compaction, or rolling density meter were used as part of this project.

6.2.7 Summary of State Findings

Increased densities (i.e., reduced air voids) were observed for Evotherm WMA and “Plus AC” BC sections as compared to the control BC section. Evotherm WMA WC mixtures showed comparably lower air voids (e.g., 4.4 vs. 3.5 percent), while the “Plus AC” WC mixtures showed only a slight reduction in air voids (e.g., 4.4 vs. 4.1 percent) compared to the control WC section. Improvement in density and reduction in variability (lower standard deviation) was greater in the binder course mixtures than the wearing coarse mixtures.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
    - The roller pattern for the test sections was seven to nine vibratory passes for the breakdown roller and five to seven static passes with the finishing roller.
- Observations for specification development (agencies):
    - The field acceptance PWL specification had an LSL of 92.0 percent density on the control sections and a proposed 93.5 percent density on the experimental sections.
    - The specification had disincentives only.

6.3 State 3

6.3.1 Project Description

The demonstration project was 10 miles long and located on a high-volume, four-lane State highway. The condition of the pavement prior to milling consisted of low to moderate severity longitudinal and transverse cracks at 20 to 100-foot intervals, low to moderate severity alligator cracking generally in the wheel paths, and no significant permanent deformation.

The project scope required the contractor to remove 2 inches of the existing pavement by cold milling and replace it with 2.5 inches of new asphalt mixture. The entire project consisted of approximately 31,000 tons of HMA with approximately 500 tons utilized for each of the test sections.

The following experimental sections were established at the beginning of the project:

- Control section (standard rolling), used one steel-drum vibratory roller and a pneumatic roller.
- Test section 1 (additional roller), used a second vibratory roller for a total of three rollers.
- Test section 2 (additional roller and additional passes), used a total of three rollers, and more passes were added.
- Test section 3 (additional roller and additional passes), used a total of three rollers, and more passes were added compared to test section 2.

6.3.2 Asphalt Mixture Design

The mixture design for this project was a slightly coarse-graded 12.5 NMAS mix with a PG 58-28 asphalt binder compacted to 100 gyrations, and is shown in Table 16 and

Table ***17***. The primary control sieve and control point are defined in AASHTO M 323 (39 percent passing on the 2.36 mm sieve for 12.5 mm NMAS). The mixture had 19 percent RAP. The design asphalt content for the control and test sections was 5.2 percent with a design air void content of 4.1 percent with a VMA of 14.7 percent. For this project, the t/NMAS ratio was 5.0.

Table 16. Mixture Design Aggregate Gradation and Corresponding Criteria, Percent Passing – State 3

Sieve Size	Gradation	Criteria	
		Min.	Max.
19.0 mm (¾”)	100	100	
12.5 mm (½”)	99	90	100
9.5 mm (⅜”)	87		
4.75 mm (#4)	55		
2.36 mm (#8)	38	28	58
1.18 mm (#16)	27		
0.60 mm (#30)	20		
0.30 mm (#50)	15		
0.15 mm (#100)	10		
0.075 mm (#200)	7.3	2	10

Table 17. Mixture Design Volumetric Properties and Corresponding Criteria – State 3

Mixture Design Properties	Mixture Design	Field Acceptance Criteria
AC (%)	5.2	NA
Air voids (%)	4.1	3.5–4.5
VMA (%)	14.7	≥14.0
VFA (%)	72.0	65–75
D/A Ratio	1.37	0.8–1.6

NA: Not Applicable

6.3.3 Field Verification of the Asphalt Mixture Design

The asphalt mixture design was verified during field production based on asphalt content and volumetric properties per the SHA's standard requirements. The results indicated that the air voids content, asphalt content, and VMA were very similar to those from the mixture design. The results of the mixture volumetric properties are shown in Table 18.

Table 18. Agency Acceptance Production Mix Properties – State 3

Test Sections	**Control** Constructed July 27	**Test Section 1** Constructed July 28	**Test Sections 2 & 3** Constructed Aug. 21	Specification
Gmm	2.497	2.492	2.493	NA
AC (%)	5.17	5.26	5.34	4.9–5.5
Air Voids (%)	4.4	3.9	4.0	2.9–5.3
VMA (%)	14.5	14.3	14.4	13.5–15.9

6.3.4 Density Measurement and Specifications

The SHA uses a PWL specification with a lower specification limit of 92.0 percent and an upper specification limit of 96.0 percent of the theoretical maximum density of the plant-produced mixture. The in-place density was measured by the nuclear gauge correlated to five cores. A lot is defined as the entire quantity of the specific mixture for the project.

The density test results in

Table ***19*** show that there were some differences in the in-place density from the control to the three test sections. The control section and test section 1 were very similar in density and test section 2 was approximately 2 percent higher than the control section. The average densities from the nuclear gauge readings are shown in

Table ***19*** and Figure 8. The gauge readings were performed by the SHA. As can be seen, there was not an increase in density between the control and test section placed on July 28, 2018. Test sections 2 and 3 were added due to the inconsistent roller patterns and an increase in density was achieved.

Table 19. Agency Acceptance Density (Percent Gmm) Results – State 3

Test Sections	**Control** Constructed July 27	**Test Section 1** Constructed July 28	**Test Section 2** Constructed Aug. 21	**Test Section 3** Constructed Aug. 21
Average	92.9	92.5	94.0	94.7
Standard Deviation	1.6	1.8	1.3	1.1
Number of Tests	12	20	40	37
Minimum	90.6	88.9	91.5	92.7
Maximum	96.2	94.9	96.7	97.2

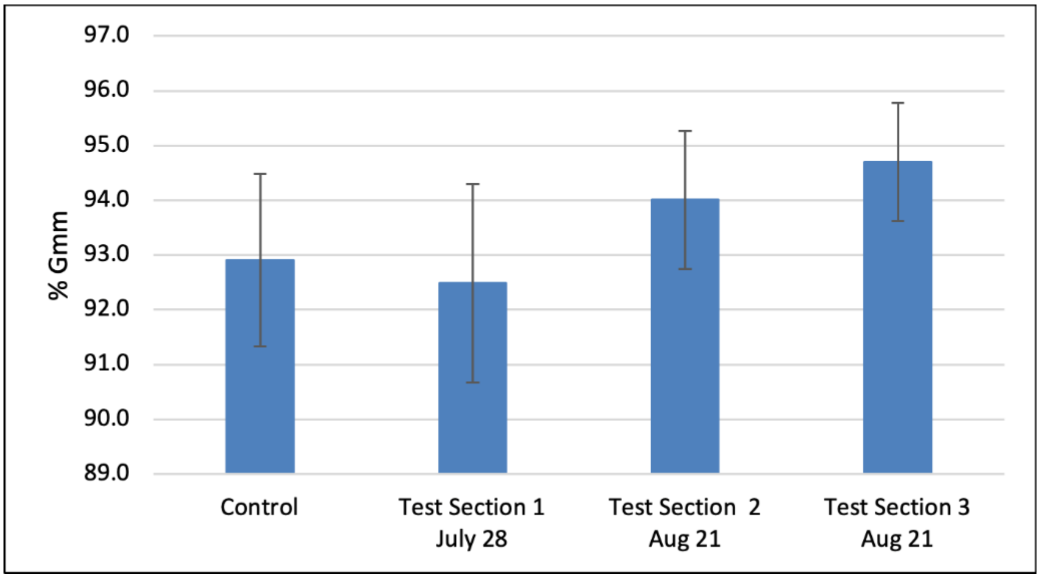


Figure 8. Comparison of Percent Density Results from Each Experimental Section – State 3

6.3.5 Experimental Section Construction and Results

The mixtures were delivered to the site in belly dump trailers and placed in windrows. The mixture was then picked up by a BOMAG Cedarapids MS-2 windrow elevator material transfer vehicle (MTV). A BOMAG Cedarapids asphalt paver CR 552 placed the mixture, and compaction was performed using three rollers. The breakdown roller was a 14-ton Caterpillar CB64 (high frequency, low amplitude setting), followed by a pneumatic 7-ton Caterpillar CW 34, and the finish roller was a 12-ton Caterpillar CB54. For the test sections, a 12-ton HYPAC C784A was added after the breakdown roller.

The weather during construction of the control section was clear and air temperature generally ranged from 80 to 85 degrees F. For the test sections on August 21, the weather was clear and air temperature ranged from 80 to 85 degrees F. These were very good conditions for paving. The traffic in this area is quite heavy due to the camping and vacation traffic.

The paving site was 15 miles from the asphalt plant, which resulted in a haul time of about 30 minutes. The surface on which the test sections were to be placed had been milled giving it a rough surface texture that helped ensure a good bond between the overlay and underlying layers. A CSS-1H tack was applied at 0.1 gallons per square yard with a 50/50 dilution. Paving speed was determined by measuring the distance moved over a period of 25 minutes. The average speed over this period was 28.8 feet per minute. Paving slowed on several occasions due to trucks being held up in the traffic control.

Placement of the control section began around 7:30 am on July 27. The control section was approximately 2,800 feet in length and was two lanes of paving, each 16 feet wide. There were approximately five passes from the vibratory breakdown roller and seven passes from the pneumatic intermediate roller. Densities were monitored using a Troxler 3440 nuclear gauge.

The first attempt at paving the test section was on July 28. The densities in these sections with the extra roller did not yield an increase in density. Rolling patterns were inconsistent for this test section. It was decided another attempt would be made with two more test sections on August 21. These new test sections were monitored more closely with a new roller pattern put in place to achieve a higher density.

Placement of test section 2 was on August 21 and began around 11:00 am. Test section 2 was approximately 2,200 feet in length. An extra roller was used after the breakdown roller for the test sections. The roller pattern for test section 2 was seven vibratory passes for the breakdown roller, five vibratory passes and two static passes for the additional roller, and seven static passes with the 12-ton pneumatic roller. The additional roller was not in echelon, so the roller train was extended.

Test section 3 was also placed on August 21 and began after the completion of test section 2. Test section 3 was approximately 2,800 feet in length. Test section 3 contained two extra static passes than test section 2 with the Hypac C784A vibratory steel drum roller. The roller pattern for this test section was seven vibratory passes for the breakdown roller, five vibratory passes and four static passes for the additional roller, and seven static passes with the pneumatic roller. The additional roller was not in echelon, so the roller train was extended.

6.3.6 Utilization of New Technologies

No new technologies such as the MOBA Pave-IR System, WMA, intelligent compaction, or rolling density meter were used as part of this project.

6.3.7 Summary of State Findings

The density test results showed that there were some differences in the density results from the control section when compared to the density results from test sections 2 and 3. For test section 2, the extra roller with the extra roller passes yielded a result of 1.1 percent increase in density compared to the control section. For test section 3, the extra roller with two more static passes than test section 2 had a 1.8 percent increase in density than the control section.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
  - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
  - The roller pattern for the test sections was seven vibratory passes for the breakdown roller, five vibratory passes and two static passes for the additional

roller, and seven static passes with the pneumatic roller. This was an increase from the control section, which had five vibratory passes from the breakdown roller and seven passes from the pneumatic roller.
- Observations for specification development (agencies):
  - The field acceptance PWL specification had an LSL of 92.0 percent density and a USL of 96.0 percent.
  - The specification had incentives and disincentives.
  - The USL of 96.0 percent will be increased for future projects.

6.4 State 4

6.4.1 Project Description

The demonstration project was 3.5-miles long and located on a rural, minor-arterial road with one 12-foot lane in each direction and a 9-foot shoulder on each side. It was a two-lane, undivided road. The existing pavement was comprised of 6.25 to 11 inches of dense-graded asphalt mixture. The pavement was in fair condition with medium to high severity alligator cracking, low severity longitudinal cracking, low to medium severity reflective cracking, and low severity patching. The surface lift thickness was 2 inches for the project and all four experimental sections. The project used approximately 10,000 tons of asphalt mixture. Each section was planned to be 1000 feet in length. These sections were paved on September 13, 2017.

The project scope included one control section and three test sections.

- Control section (standard compaction practices), used the State's normal paving practices using two vibratory rollers and a static finishing roller.
- Test section 1 (additional vibratory roller), used an additional vibratory breakdown roller.
- Test section 2 (additional asphalt binder with standard compaction practices), used an additional 0.2 percent asphalt binder based on a lower gyration mixture design with the roller pattern used for the control section.
- Test section 3 (additional asphalt binder with an additional vibratory roller), used an additional 0.2 percent asphalt binder based on a lower gyration mixture design with the rollers and pattern used for test section 1.

6.4.2 Asphalt Mixture Design

The mixture used on this project was a coarse-graded 9.5 NMAS design with a PG 64S-22 binder compacted to 65 gyrations. The primary control sieve and control point are defined in AASHTO M 323 (47 percent passing on the 2.36 mm sieve for 9.5 mm NMAS). The optimum asphalt binder content was 4.8 percent. There was 27 percent RAP. The Superpave mixture design volumetric properties and gradation values and criteria are presented in

Table ***20***. Note that AASHTO M323 allows for the increase in the allowable D/A Ratio at the agency's discretion. For this project, the t/NMAS ratio was 5.3.

Table 20. Mixture Design Aggregate Gradation and Validated Contractor QC Results for Mixtures Used in the Experimental Sections, Percent Passing – State 4

Sieve Size	Criteria		Lab Mix Design	Control Mix	Difference from Design
	Min	Max			
19.0 mm (¾”)			100	100	0.0
12.5 mm (½”)	100		98	97	-0.5
9.5 mm (⅜”)	90	100	90	89	-0.6
4.75 mm (#4)		90	60	60	+0.7
2.36 mm (#8)	32	67	36	42	+6.3
1.18 mm (#16)			23	29	+6.3
0.60 mm (#30)			17	21	+4.2
0.30 mm (#50)			11	16	+5.0
0.15 mm (#100)			9	12	+3.0
0.075 mm (#200)	2	10	7.0	8.1	+1.1

6.4.3 Field Verification of the Asphalt Mixture Design

QC and acceptance testing were conducted during the construction of these experimental sections. Gradation, asphalt content, and volumetric data from the sections are summarized in Table 21.

Table 21. Mixture Design Volumetric Properties and Validated Contractor QC Results for Mixtures Used in Experimental Sections – State 4

Mixture Property	Design Criteria	Lab Mix Design	Avg. Control Mix, QC	Avg. High Percent AC Mix, QC
AC (%)		4.8	4.8	5.14
Air Voids (%)	4.0	4.0	2.8	N/A
VMA (%)	≥ 15.0	15.3	14.7	N/A
VFA (%)	65–78	73.9	81.2	N/A
D/A Ratio	0.6–1.2	1.48	1.63	N/A

6.4.4 Density Measurement and Specifications

For dense-graded mixtures, the SHA uses a minimum and maximum lot average specification with a minimum of 92.0 percent and a maximum of 97.0 percent of the theoretical maximum density of plant-produced mixture. There is also a minimum individual sublot of 91.0 percent. Cores are used for acceptance. Incentives for density alone can be 5 percent.

Seven, six-inch field cores were randomly selected and taken for each experimental section. The summary of the in-place density of the four experimental sections is shown in

Table ***22*** and graphically in Figure 9 as measured by the SHA. The results from the control and test sections were all well above 94 percent.

Table 22. Experimental Section Core Densities from Validated Contractor QC Results – State 4

Summary	Avg. % (Gmm)	St. Dev.	Min (% Gmm)	Max (% Gmm)
Control	95.8	0.75	94.5	96.8
Test Section 1: Control + Roller	95.7	0.58	94.9	96.5
Test Section 2: Control + AC	96.5	0.64	95.5	97.3
Test Section 3: Control + AC + Roller	97.1	0.26	96.8	97.5

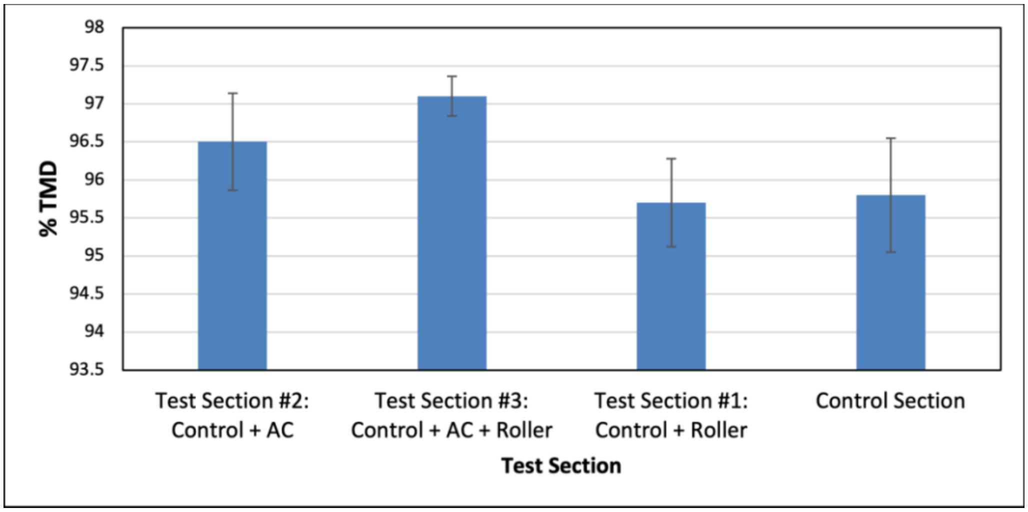


Figure 9. Comparison of Percent Density Results from Each Experimental Section – State 4

6.4.5 Experimental Section Construction and Results

Paving was conducted at night. End-dump trucks delivered the asphalt mixture to the Roadtec MTV, which remixed the product before transferring into the paver. The paver was a CAT AP1055E equipped with a hopper insert to hold additional material and minimize segregation. The compaction equipment consisted of a 12-ton CAT CB54XW tandem steel-wheel roller used as a breakdown roller in vibratory mode, and the other three rollers used for intermediate and finish rolling were a 12-ton Hamm HD+120. Paver speed was measured and assumed to be constant throughout the project. The paver traveled 400 feet in 16.5 minutes, equating to about 24 feet per minute. There were no stops during construction, nor were there any noticeable slowdowns.

Mixtures were placed as an overlay on top of the existing pavement. However, the existing pavement had been improved using a wedge (layer used to improve pavement profile) and level course in the weeks before construction of the surface lift. The wedge and level course appeared to be in excellent shape. A CRS-1 tack was used to bind the surface course to the wedge and level course. The application rate was stated to be 0.03 gallons per square yard. The weather was clear and ranged from 60 to 70 degrees F during paving operation, and mix temperature was around 310 degrees F behind the screed during placement.

For the control section, the breakdown roller was a 12-ton CAT CB54, which made seven vibratory passes, and the intermediate roller was a 12-ton Hamm HD+120, which made seven vibratory passes. In test section 1, the additional roller was a Hamm HD+120, which added five vibratory passes. In test sections 2 and 3, there was an additional 0.2 percent asphalt content.

Test section 2 had the same roller pattern as the control section. Test section 3 had the same roller pattern as test section 1.

6.4.6 Utilization of New Technologies

No new technologies such as the MOBA Pave-IR System, WMA, intelligent compaction, or rolling density meter were used as part of this project.

6.4.7 Summary of State Findings

First, it should be noted that the densities from the control and test sections were all well above 94.0 percent. The additional 0.2 percent asphalt content had a significant effect on in-place density. The sections that utilized an extra roller yielded less variability, measured by the standard deviation of the in-place density, than the sections that did not use an extra roller. However, it cannot be said that the extra roller significantly improved mat density when compared to the control section. The extra asphalt increased the average in-place density from the control section to test sections 2 and 3 by 0.7 percent and 1.3 percent, respectively. In both mixtures, the additional roller did not provide enough improvement to determine that the additional compactive effort yield statistically significant improvement over the sections without additional compaction. However, the overall density was greater than 95.0 percent, which is excellent and does not need to be increased. Further, it should be noted that the overall variability was reduced by including an extra roller in both test section 1 and test section 3, and this finding could help contractors in States with PWL specifications.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
    - The roller pattern for the test sections was seven vibratory passes for the breakdown roller, seven vibratory passes for the intermediate roller, and five vibratory passes for the additional roller
- Observations for specification development (agencies):
    - The field acceptance specification, as per the State standard specifications, is a minimum lot average of 92.0 percent density and maximum of 97.0 percent. There is also a minimum individual sublot of 91.0 percent.
    - The specification had incentives and disincentives with a maximum incentive of 5.0 percent for density alone.
    - A longitudinal joint density specification is being developed.

6.5 State 5

6.5.1 Project Description

The demonstration project was located on a 25-mile section of a State route. It was a two-lane roadway with intermittent passing lanes throughout. This project was constructed as a 2-inch mill-and-fill. Before milling, the pavement exhibited some low to medium severity cracking. It was estimated that the existing structure consisted of approximately 7 to 8 inches of asphalt over concrete pavement. The thickness of the older concrete pavement was not known.

The project included a control and three test sections; the control and first two test sections were 10,000 tons each and the third test section was approximately 23,000 tons. The demonstration project was constructed from mid-September through October of 2017. The experimental sections included:

- Control section (standard mixture and roller train), used a standard mixture design and had a PWL specification with an LSL of 92.0 percent density.
- Test section 1 (increased compactive effort), used the same mixture design as the control section with the addition of two rollers.
- Test section 2 (modified mixture design), used a mixture design in which the optimum asphalt content was selected at 3 percent air voids.
- Test section 3 (performance acceptance), used a design similar to the control section but with an extra 0.1 percent asphalt content. Mixture performance testing was used for acceptance.

6.5.2 Asphalt Mixture Design

Three different mixture designs were used for this project. All three were coarse-graded 12.5mm NMAS Superpave mix designs with a PG 70-22 binder. The primary control sieve and control point are defined in AASHTO M 323 (39 percent passing on the 2.36 mm sieve for 12.5 mm NMAS). The control section, test section 1, and test section 3 all contained 30 percent RAP, while test section 2 contained 25 percent of the same RAP. The RAP asphalt content was 4.5 percent by total weight of the mixture. Gradation and mix design information is shown in Table 23 and

Table ***24***. The t/NMAS was 4.0. Mixture performance testing was used for the mixture design and acceptance for test section 3. This included the I-FIT for cracking and the Hamburg wheel-tracking device for rutting and moisture damage.

Table 23. Mixture Design Aggregate Gradation and Corresponding Criteria, Percent Passing – State 5

Sieve Size	Criteria		Mixture Used for Control Section and Test Section 1	Mixture used for Test Section 2	Mixture used for Test Section 3
	Min	Max			
19.0 mm (¾”)	100		100	100	100
12.5 mm (½”)	90	100	94	92	94
9.5 mm (⅜”)	90	100	89	86	89
4.75 mm (#4)			60	58	59
*2.36 mm (#8)	28	58	34	32	32
1.18 mm (#16)			23	22	22
0.60 mm (#30)			16	15	15
0.30 mm (#50)			11	11	11
0.15 mm (#100)			7	8	7

*Denotes primary control sieve (PCS). PCS control point is 39 percent.

Table 24. Mixture Design Volumetric Properties and Corresponding Criteria – State 5

Mixture Property	Mixture Design Criteria	Mixture used for Control Section and Test Section 1	Mixture used for Test Section 2	Mixture used for Test Section 3
Ndes	NA	80	60	60
Air Voids (%)	NA	4.0	3.0	4.0
AC (%)	NA	5.0	5.7	5.1
VMA (%)	≥14.0	14.3	14.6	14.3
VFA (%)	65–75	72.0	79.7	72.0
D/A Ratio	0.8–1.6	1.2	1.1	1.2

NA: Not Applicable

6.5.3 Field Verification of the Asphalt Mixture Design

QC testing was performed by the contractor based on a lot size of 3,000 tons as specified in the contractor's QC plan. The contractor's results were validated by the agency. Asphalt content and volumetric properties were tested once every sublot, or 750 tons such that there were four sublots per lot. The tolerance for asphalt content was target ±0.3 percent, the tolerance for laboratory compacted air voids was target ±1.0 percent, and the tolerance for VMA was target -0.5 and +2.0 percent. The results from each lot are shown in Table 25.

Table 25. Validated QC Asphalt Content and Volumetric Results – State 5

Mix Section	Lot Number (Four Tests Per Lot)	Asphalt Content (%)	Laboratory Compacted Air Voids (%)	VMA (%)	VFA (%)
Control	3 Lots	5.0	3.8	14.0	73.2
Test Section 1	3 Lots	5.0	4.1	14.2	71.1
Test Section 2	4 Lots	5.6	3.7	14.3	73.7
Test Section 3	8 Lots	5.1	3.8	14.3	73.6

6.5.4 Density Measurement and Specifications

The agency uses a PWL specification with an LSL of 92.0 percent and a USL of 96.0 percent. The percent density was based on the theoretical maximum density of the plant-produced mixture. The in-place density was measured with cores. For in-place density, two field cores were taken in each 750-ton sublot, which yielded a total of eight cores per lot. This resulted in about 24 cores for each experimental section. The validated QC results for in-place density are shown in Table 26 and Figure 10. The higher optimum binder content of Test Section 2 asphalt mixture could be responsible for the higher level of compaction, compared to the other sections.

Table 26. Validated QC In-Place Density Results by Lot – State 5

Experimental Section	Lot Number (Note: Eight Cores Per Lot)	Average Density (% Gmm)	Std. Dev.
Control	3 Lots	92.0	1.3
Test Section 1	3 Lots	94.5	1.0
Test Section 2	4 Lots	95.0	1.3
Test Section 3	8 Lots	93.7	1.3

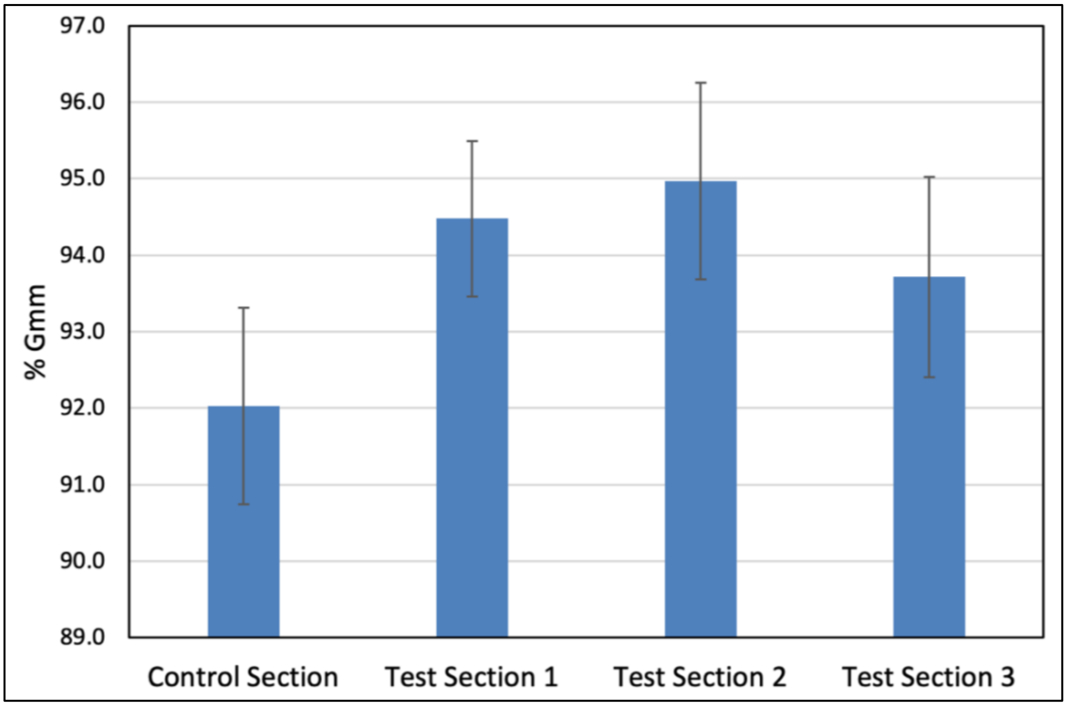


Figure 10. Comparison of Percent Density Results from Each Experimental Section – State 5

6.5.5 Experimental Section Construction and Results

The mixtures were delivered to the site using a cycle of 10 to 12 end-dump trucks. The mixture was then transferred to the Caterpillar AP1055F paver using a Weiler E2850 material transfer vehicle. Four rollers were used during the construction of the control section. Two additional rollers were added for a total of six for test section 1. For the construction of test section 2 and test section 3, four rollers were used as with the control section. Table 27 shows the rollers used for each experimental section.

Table 27. Rollers Used for Each Experimental Section – State 5

Roller Sequence	Control Section	Test Section 1	Test Section 2	Test Section 3
Breakdown Roller A	Volvo DD118HF (12 ton)	Volvo DD120C (12 ton IC)	Volvo DD120B (12 ton)	Volvo DD120B (12 ton)
Breakdown Roller B	Caterpillar CB54 XW (12 ton)	Caterpillar CB54 XW (12 ton)	Caterpillar CB54 XW (12 ton)	Caterpillar CB54 XW (12 ton)
Breakdown Roller C	Not Used	Volvo DD120B (12 ton)	Not Used	Not Used
Breakdown Roller D	Not Used	Volvo DD118HF (12 ton)	Not Used	Not Used
Intermediate Roller	Volvo DD120B (12 ton)	Sakai GW750-2 Vibratory Pneumatic (10 ton)	Volvo DD118HF (12 ton)	Volvo DD118HF (12 ton)
Finishing Roller	Hypac C776C (10 ton)	Hypac C776C (10 ton)	Volvo DD120B (12 ton)	Volvo DD120B (12 ton)

An SS-1 tack coat was applied to the milled surface at a rate of 0.10 gallons per square yard. The laydown temperature for the four sections was between 300 and 325 degrees F, and the average laydown speed was approximately 30 feet per minute. However, there were times when the paver had to stop because trucks were getting stuck in the line of vehicles waiting for the pilot car.

Four rollers were used for compaction of the control section. The two breakdown rollers operated in echelon (Volvo DD118HF and Caterpillar CB54 XW), performing four vibratory passes then one static pass on each side of the mat. Both the intermediate and finishing rollers used the same rolling pattern, which was three vibratory passes and two static passes across the entire mat. The amplitude of the breakdown and intermediate rollers was set at 5 of 8. The finishing roller was set to low amplitude.

Test section 1 was placed for five days of production. Two rollers were added to this test section compared to the control section. This yielded four breakdown rollers all operating in echelon. The rolling pattern for each of the breakdown rollers was the same as for the control section with one exception. The amplitude was changed from 5 to 6 after the first day to help compaction. The intermediate roller was a vibratory, pneumatic roller (Sakai GW750-2) with the tires inflated to 90 psi. It performed seven vibratory passes across the mat. Soap was added to the water on the roller to eliminate pickup by the tires, and no pickup was observed. The finish roller used the same pattern as the control section with three vibratory passes and two static passes across the entire mat.

Construction of test section 2 was completed over seven days. There were a couple of plant issues during production, which delayed construction a few days. Four rollers were used for this section with the same rolling patterns as the control section with two exceptions. The amplitude setting on the breakdown rollers was left at a setting of 6 and not changed back to 5 as with the control section. The finishing roller had to delay rolling due to roller marks being left when the mixture was compacted too hot.

Test section 3 was placed over 15 days. The same rolling pattern used for test section 2 was used for test section 3.

6.5.6 Utilization of New Technologies

A vibratory pneumatic roller was used. Mixture performance testing was conducted as part of the mixture design and acceptance process. No other new technologies such as the MOBA Pave-IR System, WMA, intelligent compaction, or rolling density meter were used as part of this project.

6.5.7 Summary of State Findings

All three test sections had higher densities compared to the control section. The addition of the two extra rollers for test section 1 yielded a 2.5 percent increase in density compared to the control section. Test section 3 had 1.7 percent higher density compared to the control section using essentially the same rolling pattern and 0.1 percent added binder. Test section 2, with 0.7 percent more binder than the control section, had the highest density as expected.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
  - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
  - The roller pattern for the test sections was four vibratory passes and one static for each of the breakdown rollers, and three vibratory passes and two static passes for the intermediate roller. Additional breakdown rollers were used in one of the test sections.
- Observations for specification development (agencies):
  - The field acceptance specification is PWL with an LSL of 92.0 percent.
  - The specification had incentives and disincentives.
  - Based on results from the construction of these experimental sections, changes may include:
    - Utilizing the t/NMAS criteria.
    - Adjusting the mixture design criteria for a higher asphalt content by using lower gyrations and/or designing at a lower air voids.
    - Adding mixture performance tests as part of the asphalt mixture design and/or acceptance.

6.6 State 6

6.6.1 Project Description

The State route was five lanes with four travel lanes and a two-way, left-turn lane in the middle. The project length was two miles, and it was in a mountainous part of the State. The pavement would be classified as being in fair condition, as a majority of the alligator cracking was defined as low to medium severity with low extent. The cracking percent appeared to be influenced by transverse cracking and block cracking, as those distresses were defined as medium to high severity with low to medium extent. The overlay treatment was a 3-inch mill and was to be overlaid with 2.5-inches of asphalt. The remaining depth of the existing pavement was unknown and the remaining wearing course thickness was not specified by the SHA.

The experimental sections involved the same roller patterns and compactive efforts with two different mixture designs.

- Control section (coarse gradation): used a coarse gradation as it was used very often within the State and by the contractor.
- Test section 1 (fine gradation): used a fine gradation that was designed to determine how gradation affected density.

Each mixture was placed continuously in a lane for the entire length of the two-mile project. Placement of the fine mixture began May 29, 2018, and was completed after three working nights on June 3. The initial 500 tons of the coarse mixture were used in a test strip on June 4, 2018 and construction was completed on the night of June 10, 2018.

6.6.2 Asphalt Mixture Design

Both mixtures used on this project were 12.5 mm NMAS designs with PG 64-28 binder compacted to 100 gyrations. The primary control sieve and control point are defined in AASHTO M 323 (39 percent passing on the 2.36 mm sieve for 12.5 mm NMAS). The optimum binder contents for the fine and coarse mixtures were 5.1 percent and 5.3 percent, respectively. However, the effective binder contents were within 0.1 percent of each other. Based on the expected surface area of a coarse versus fine gradation, it was interesting to note that the coarse gradation had a higher binder content. Both mixtures had 15 percent RAP and utilized foaming WMA technology. The Superpave mixture design volumetric, gradation values, and criteria for these mixes are presented in Table 28 and Table 29. The t/NMAS was 5.0. Additional mixture performance testing was conducted on the coarse and fine gradation plant-produced materials to further evaluate the acceptability of the fine gradation.

Table 28. Mixture Design Aggregate Gradation and Corresponding Criteria, Percent Passing – State 6

Sieve Size	Fine Mixture			Coarse Mixture		
	Gradation	Criteria		Gradation	Criteria	
		Min	Max		Min	Max
19.0 mm (¾”)	100	100		100	100	
12.5 mm (½”)	96	90	100	95		
9.5 mm (⅜”)	90	64	90	88		90
4.75 mm (#4)	67			58		
2.36 mm (#8)	43	41	58	35	28	58
1.18 mm (#16)	29			23		
0.60 mm (#30)	21			17		
0.30 mm (#50)	15			13		
0.15 mm (#100)	12			10		
0.075 mm (#200)	6.5	2	10	6.5	2	10

Table 29. Mixture Design Volumetric Properties and Corresponding Criteria – State 6

Mixture Design Property	Fine Mixture Design	Coarse Mixture Design	Mixture Design Criteria
AC (%)	5.1	5.3	
Air Voids (%)	4.0	4.0	4.0
VMA (%)	15.1	15.3	14.5–16.0
VFA (%)	73.5	73.8	68–75
D/A Ratio	1.4	1.3	0.6–1.4

6.6.3 Field Verification of the Asphalt Mixture Design

Contractor’s QC and agency acceptance testing were conducted during the construction of these experimental sections. Ten samples were taken from each mixture during production. The results of the volumetric properties and gradations for the fine mixture are shown in Table 30 and Table 31, respectively, and the results of the volumetric properties and gradations of the coarse mixture are shown in Table 32 and *Tolerance range for VMA is different for samples 9 and 10. Max VMA = 17.5

Table *33*, respectively.

The contractor struggled to maintain volumetric properties for the fine mixture, as shown in the VFA results. Although VFA failed to meet specifications in seven of the ten samples, every sample had passing VMA and only two air void results failed. The contractor also struggled to keep the dust content within tolerance limits. Five of the ten gradation samples had dust contents that were too high and two of the D/A ratio results failed. Note that the failing results related to dust content were all found in the first six samples. It seems that the contractor was able to get the production under control after a few nights of paving.

The contractor did not seem to have the same issues with production limits for the coarse mixture as they did for the fine mixture. This is most likely due to the fact that the coarse mixture was a typical mixture that the contractor was more experienced with. Samples 9 and 10 were taken on the final night of paving, June 10, and the VMA tolerance specifications were different for that night from the other nights. Both samples from that night had dust contents that were too low, which produced D/A ratios that were under the minimum limit. Other than those last two samples, the asphalt contents were all on the higher end of the tolerance.

Table 30. Fine Mixture Volumetric Properties from Agency Testing – State 6

Property	Sample Number										Tolerance	
	1	2	3	4	5	6	7	8	9	10	Min	Max
Air Voids (%)	2.9	2.8	2.0	3.6	3.8	4.1	5.5	3.4	3.1	3.7	2.6	5.4
VMA (%)	14.7	14.8	14.6	14.9	14.7	15.2	16.0	15.3	15.0	14.9	13.5	16.7
VFA(%)	80.3	81.3	86.4	76.0	74.1	73.2	65.4	77.5	79.1	74.9	68.0	75.0
AC (%)	5.2	5.0	5.4	5.2	5.1	4.9	4.7	5.1	5.2	5.0	4.6	5.6
D/A Ratio	1.6	1.5	1.7	1.7	2.0	1.8	1.2	1.3	1.4	1.6	1.1	1.7

Table 31. Fine Mixture Gradation Results from Agency Testing, Percent Passing – State 6

Gradation	Sample Number										Tolerance	
	1	2	3	4	5	6	7	8	9	10	Min	Max
19.0 mm (¾”)	100	100	100	100	100	100	100	100	100	100	95	100
12.5 mm (½”)	96	95	97	96	96	95	94	94	94	94		
9.5 mm (⅜”)	89	85	90	88	88	89	84	85	87	85	82	98
4.75 mm (#4)	65	61	65	64	62	65	57	59	61	61	60	74
2.36 mm (#8)	41	38	41	40	39	40	33	37	38	38		
0.075 mm (#200)	8.1	7.5	9.1	8.2	9.2	8.5	5.6	6.5	7.1	7.5	5.1	7.9

Table 32. Coarse Mixture Volumetric Properties from Agency Testing – State 6

Mixture Property	Sample Number										Tolerance	
	1	2	3	4	5	6	7	8	9*	10*	Min	Max
Air Voids (%)	4.8	4.1	3.4	4.3	4.5	4.5	5.3	4.2	5.4	5.2	2.6	5.4
VMA (%)	16.6	15.9	15.8	16.9	16.5	16.5	16.6	16.0	17.9	17.3	13.7	16.9
VFA (%)	71.3	74.1	78.8	73.2	72.9	73.0	68.7	73.6	70.1	69.8	68.0	75.0
AC (%)	5.7	5.7	5.8	5.7	5.9	6.1	5.7	5.7	6.0	6.0	4.8	5.8
D/A Ratio	1.1	1.2	1.1	1.3	1.1	1.1	1.1	1.3	0.7	0.8	1.0	1.6

*Tolerance range for VMA is different for samples 9 and 10. Max VMA = 17.5

Table 33. Coarse Mixture Gradation Results from Agency Testing – State 6

Gradation	Sample Number										Tolerance	
	1	2	3	4	5	6	7	8	9	10	Min	Max
19.0 mm (¾")	100	100	100	100	100	100	100	100	100	100	95	100
12.5 mm (½")	95	94	94	95	96	97	94	97	95	95		
9.5 mm (⅜")	85	83	83	88	87	88	86	84	82	84	60	96
4.75 mm (#4)	59	54	54	59	56	61	59	60	55	57	51	65
2.36 mm (#8)	34	33	33	37	33	37	36	38	34	35		
0.075 mm (#200)	5.7	6.1	6.0	6.5	5.5	5.6	5.3	6.4	4.0	4.3	5.1	7.9

6.6.4 Density Measurement and Specifications

The agency uses a PWL specification with an LSL of 92.0 percent and a USL of 97.0 percent. The percent density was based on the theoretical maximum density of the plant-produced mixture. The in-place density was measured with cores. A summary of the density results from both mixtures is shown in Table 34 and Figure 11. The average densities were very similar between the coarse and fine mixtures, but the variability of the coarse mixture was almost 30 percent lower than that of the fine mix. This is most likely due to the lack of experience the contractor had with the fine mixture. There were no differences in the densities of the two mixtures and both mixtures far exceeded the LSL of 92.0 percent G_{mm}. Densities of both mixtures were very good, as they approached the average of 94.0 percent that is considered excellent. It seemed the fine mixture would be a good alternative for the SHA to consider.

Table 34. Comparison of Core Densities Between Two Mixtures Using Acceptance Testing – State 6

Experimental Mixture	Number of Cores	Avg. Density (% Gmm)	Std. Dev.	Tolerance (%)
Fine Mixture	10	93.7	1.4	92–97
Coarse Mixture	10	93.9	1.0	

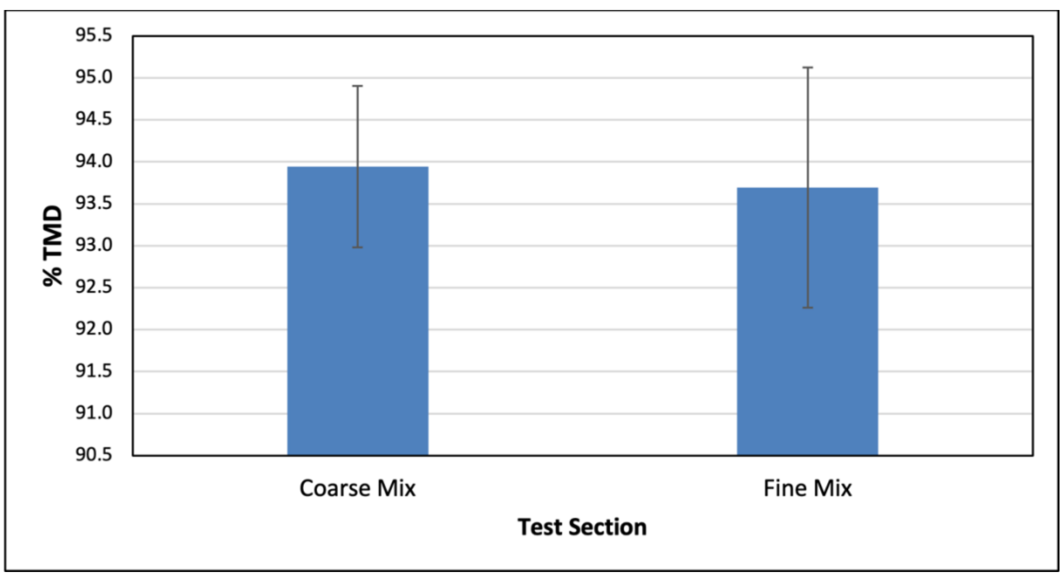


Figure 11. Comparison of Percent Density Results from Each Experimental Section – State 6

6.6.5 Experimental Section Construction and Results

This section was paved at night. The mixture was delivered to the site in belly dump trucks and deposited as windrows and transferred from the windrows to the paver using a Roadtec SB2500D material transfer vehicle. A CAT AP 1055D paver was used to place the mixture. Two vibratory rollers (both were 12-ton Hamm HD+ 140i High Frequency) were used as the breakdown and intermediate rollers.

Paver speed was recorded on the paver and varied throughout the project. During the beginning of the night of June 3 when the fine mixture was being produced, the paver was operating around 10 feet per minute, and as the night progressed, the average speed increased to approximately 17 feet per minute. There were a few long (≥ 5 min) paver stops and construction issues on both nights. Overall, paving operations on both nights were satisfactory. A SS1 tack was used to bind the overlay to the milled surface at a bar rate of 0.08 gallons per square yard.

The same roller pattern was used for each experimental section. Each roller applied nine passes. The breakdown roller applied all nine passes in vibratory mode at a high amplitude. The finishing roller, which was actually operating as an intermediate roller, also operated in vibratory mode and applied nine passes. The finish roller was intended to provide additional compaction and smooth out roller marks.

The fine mixture was the first one to be paved. The temperature of the mixture in the windrows averaged around 275 degrees F according to the SHA personnel on site. 1800 tons of WMA were placed from 11:15 pm to 9:00 am in this lane. There were only a few notable construction issues. When the breakdown roller was at Sta. 29+00 it was noticed that the paver had outrun the breakdown roller by almost 1,100 ft. The paver speed was 22 feet per minute during this portion of the project. Nuclear gauge densities in this area averaged about 1-2 pounds per cubic foot lower than the rest of the project. The paver subsequently slowed down to allow the breakdown roller time to catch up. This issue did not occur again that night. At Sta. 48+75 the finishing roller operator left the job site, and there was only one roller for about 30 minutes. The only significant paver stop occurred at Sta. 76+00. The paver ran out of mixture because it was traveling too fast and there were no trucks with mixture nearby. This stop lasted for 20 minutes.

Mat densities were checked by the contractor using a Troxler 3440 nuclear density gauge. The lowest gauge reading, according to the gauge operator, was 89 percent G_{mm} that night, but that the average reading behind the finishing roller was 93 percent. Densities behind the breakdown roller averaged 89-90 percent.

The coarse mixture began at mile post 2.00 (Sta. 115+39) and was first placed in the turn lane in the southbound direction. Only 500 tons were produced on the night of June 4. The paving and roller operations were the same for the coarse mixture as they were for the fine mixture. The paver averaged 14 feet per minute on the first night. The contractor deliberately went slowly because it was a test strip for the coarse mixture, which only included 500 tons. Mixture was delivered to the site at 10:55 pm and mainline paving was completed by 3:00 am.

The average mixture temperatures in the windrows were approximately 260 degrees F. This was lower than the previous night because the paver was operating at a slower pace. Average mat densities were 92-93 percent behind the finishing roller. No major issues were noted.

6.6.6 Utilization of New Technologies

Both mixtures utilized WMA technologies. Mixture performance testing was conducted to further compare the mixtures with fine and coarse gradations. No other new technologies such as the MOBA Pave-IR System, intelligent compaction, or rolling density meter were used as part of this project.

6.6.7 Summary of State Findings

These density results showed that mixtures with both coarse and fine gradations could be used to achieve excellent mat density. The coarse mixture had a significantly higher average asphalt content. Additionally, this project also demonstrated the need for familiarity with the production and placement of the mixture to yield good results. It was believed that the contractor could easily gain experience with the fine gradation.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
  - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
  - The roller pattern for the test sections was nine vibratory passes for the breakdown roller and nine vibratory passes for the intermediate roller.
- Observations for specification development (agencies):
  - The field acceptance used a PWL specification with an LSL of 92.0 percent and a USL of 97.0 percent.
  - The specification had incentives and disincentives.
  - Fine gradations would be a viable option.

6.7 State 7

6.7.1 Project Description

The demonstration project was located on a rural, two-lane State highway. There were several sections scattered along this roadway that were to be milled and repaved, while other sections required no work. The existing pavement exhibited some low to medium severity transverse and fatigue cracking. The fatigue cracking seemed to be more severe throughout the eastbound lane compared to the westbound lane. There were also numerous potholes, which were filled prior to placing the surface. The thickness for all paving was 2.0 inches. These sections were paved during the day in May of 2018.

Three different experimental sections were placed for this study.

- Control section (standard mixture design), used the SHA's standard mixture design with a standard rolling pattern.

- Test section 1 (pneumatic roller added), used the same mixture design as the control section, and a pneumatic roller was added to the standard rolling pattern.
- Test section 2 (modified mixture design), used a modified mixture design in which the optimum asphalt content was selected at 4.0 percent air voids instead of the 4.5 percent typical for this SHA. This produced a mixture that had 0.2 percent additional binder compared to the control section. The standard rolling pattern was used.

It should be noted that this was State 7's second attempt at constructing a demonstration project. The first attempt was constructed in October of 2017. Something was amiss with the density data. This was based on observations of the field compactive effort provided by the rollers and the laboratory density results from cores measured by an independent third-party laboratory. The SHA decided to try another demonstration project. It appeared that this SHA had a weak validation process.

6.7.2 Asphalt Mixture Design

The mixture design used for this project was a slightly coarse 12.5-mm NMAS Superpave mixture design using 100 design gyrations with a PG 70-22 binder. The primary control sieve and control point are defined in AASHTO M 323 (39 percent passing on the 2.36 mm sieve for 12.5 mm NMAS). Although the primary control sieve (PCS) for the mixture design was right on the 39 percent limit between a coarse and fine gradation, the validated contractor QC results showed that the mixture was slightly coarse. The mixture contained 10 percent RAP. Mixture design information for the control section and test section 1 is shown in Table 35 and

Table **36**. Test section 2 used the same aggregate structure while adding 0.2 percent additional binder by selecting optimum as a lower air voids. The t/NMAS was 4.0.

Table 35. Mixture Design Aggregate Gradation, Percent Passing – State 7

Sieve Size	Gradation	Criteria	
		Min	Max
19.0 mm (¾”)	100	100	
12.5 mm (½”)	94	90	100
9.5 mm (⅜”)	84	90	100
4.75 mm (#4)	58		
*2.36 mm (#8)	39	28	58
1.18 mm (#16)	28		
0.60 mm (#30)	22		
0.30 mm (#50)	18		
0.15 mm (#100)	9		
0.075 mm (#200)	5.8	2	10

*Denotes primary control sieve (PCS). PCS control point is 39 percent.

Table 36. Mixture Design Volumetric Properties – State 7

Mixture Design Properties	Mixture Design	Mixture Design Criteria
Ndes	100	NA
Air Voids (%)	4.5	4.5%
AC (%)	5.1	NA
VMA (%)	15.0	≥14.0
VFA (%)	70.0	65–75
D/A Ratio	1.29	0.8–1.6

NA: Not Applicable

6.7.3 Field Verification of the Asphalt Mixture Design

QC testing was performed by the contractor based on a lot size of 3,000 tons. These results were validated by the agency. Asphalt content and volumetric properties were tested once every sublot, or 750 tons such that there were four sublots per lot. The tolerance for asphalt content was ± 0.3 percent. The tolerance for laboratory compacted air voids was ±1.5 percent, and the tolerance for VMA was -0.5 and +2.0. percent. The results from each sublot are shown in Table 37 and Table 38.

Table 37. Validated QC Aggregate Gradation, Percent Passing – State 7

Sieve Size	Mix Design	Control 5/9/18		Test Section 1 5/11/18		Test Section 2 5/14/18	
19.0 mm (¾")	100	100	100	100	100	100	100
12.5 mm (½")	94	92	93	99	92	93	93
9.5 mm (⅜")	84	84	85	85	83	82	85
4.75 mm (#4)	58	60	55	58	59	56	57
*2.36 mm (#8)	39	37	37	39	38	39	39
1.18 mm (#16)	28	27	30	30	27	28	27
0.60 mm (#30)	22	22	21	21	21	21	20
0.30 mm (#50)	18	18	17	19	17	16	18
0.15 mm (#100)	9	8	21	8	8	10	9
0.075 mm (#200)	5.8	6.5	6.3	5.2	5.4	6.2	5.2

Table 38. Validated QC Asphalt Content and Volumetric Results – State 7

Mixture Design Properties	Mix Design	Control 5/9/18		Test Section 1 5/11/18		Test Section 2 5/14/18	
Air Voids (%)	4.5	3.3	3.5	3.8	3.4	3.6	2.3
AC (%)	5.1	5.0	4.9	5.1	5.0	5.1	5.2
VMA (%)	15.0	13.7	13.7	14.3	13.8	14.2	13.3
VFA (%)	70.0	75.9	74.5	74.8	72.1	74.6	82.7

6.7.4 Density Measurement and Specifications

For this particular project with lower tonnage, the density specification was a minimum and maximum lot average of 92.0 and 96.0 percent, respectively. For larger quantities, this SHA used a PWL specification for in-place density. One field core was taken in each 750-ton sublot at a random location. Each experimental section included two sublots, so the contractor took two cores per experimental section. Additionally, four extra cores were taken at random locations from each mixture for testing at NCAT. The in-place density results are shown in Table 39 and

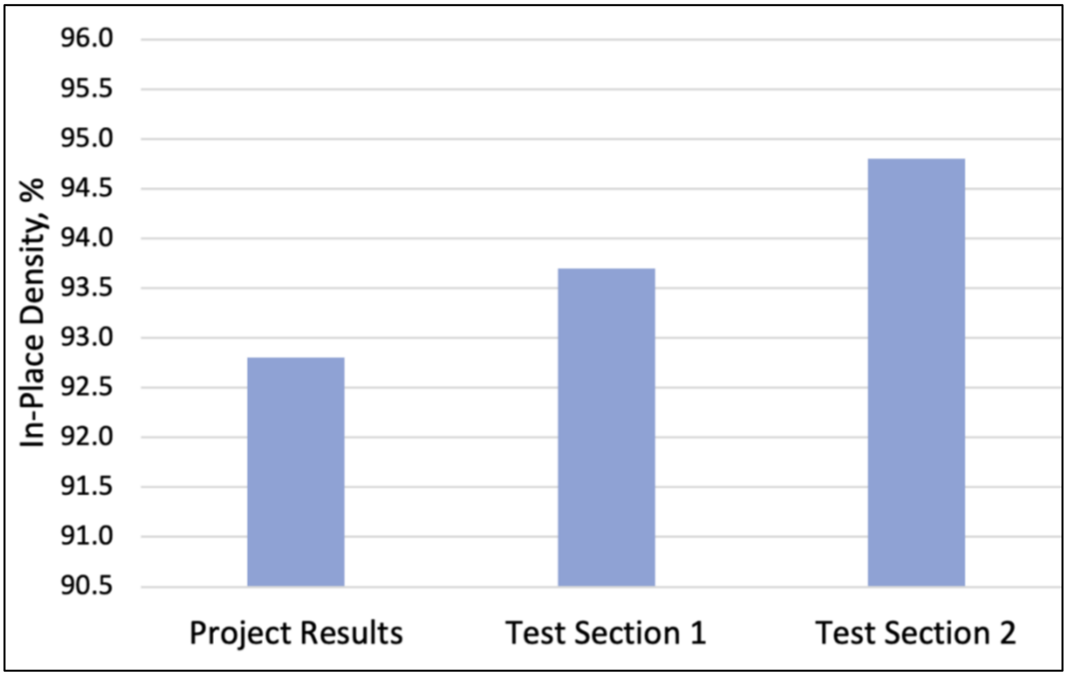


Figure **12**.

The control section averaged 93.8 percent density. Additional lots from the project were analyzed and averaged 92.8 percent density. It seems that the added attention of the experimental project resulted in a 1.0 percent increase in density in the control section. The 92.8 will be used as the control section as it was probably more representative of what was normally done.

Table 39. Validated QC In-Place Density Results by Lot – State 7

Mixture	Source	Average Density (% Gmm)	Std. Dev.
Project Results	Contractor's Cores	92.8	-
Control Section	Contractor Cores (2)	94.0	-
	NCAT Cores (4)	93.8	1.3
	All Cores (6)	93.8	1.1
Test Section 1	Contractor Cores (2)	93.7	-
	NCAT Cores (4)	93.3	1.3
	All Cores (6)	93.5	1.2
Test Section 2	Contractor Cores (2)	94.8	-
	NCAT Cores (4)	94.2	1.2
	All Cores (6)	94.4	1.0

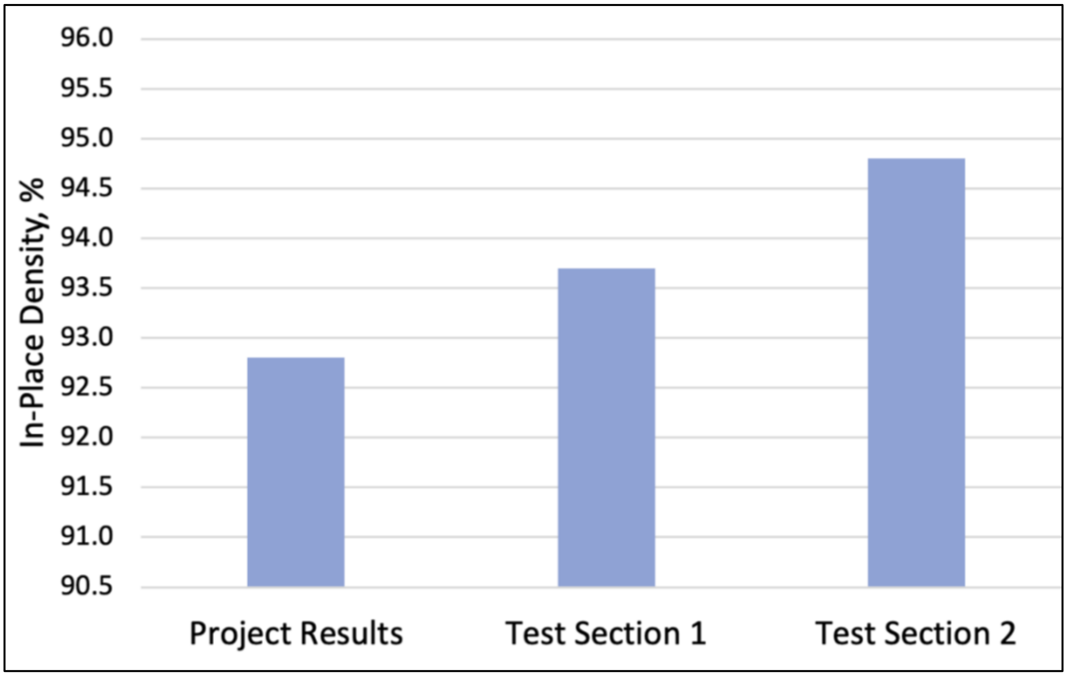


Figure 12. Comparison of Percent Density Results from Each Experimental Section – State 7

6.7.5 Experimental Section Construction and Results

The mixtures were delivered to the site using a cycle of six end-dump trucks and then transferred to a Caterpillar AP1055F paver using a Roadtec SB 2500e MTV. Three rollers were used during the construction of the control section. The breakdown roller was a Volvo DD120C (14 ton), the intermediate roller was a Caterpillar CB64 (14 ton), and a Hamm HD12 (3 ton) was used as the finish roller. A pneumatic roller (10-ton Sakai GW750) was added for test section 1. For the construction of test section 2, the same rollers and patterns from the control section were used.

A CSS-1 tack coat was applied to the milled surface at a spray rate of 0.10 gallons per square yard. The mat received good tack coverage. The laydown temperature for the four sections was between 300 and 330 degrees F, and the average speed was approximately 25 feet per minute.

The control section was placed on May 9 and 10, 2018 with three rollers. The breakdown roller operated in vibratory mode at an amplitude of 3 and a frequency of 3,400 vibrations per minute. The rolling pattern was four passes on each side of the mat with another pass back up the middle for a total of nine passes per paving width. The intermediate roller applied this same rolling pattern and stayed close to the breakdown roller. The contractors termed this as "shadow rolling." The finishing roller then was used to remove roller marks and had no consistent pattern.

Test section 1 was placed on May 11, 2018 in the westbound lane. This test section used the same mixture and equipment as the control section but with a pneumatic roller added as an intermediate roller. The breakdown and intermediate vibratory steel-drum rollers operated closer together compared to the control section. Some would term this rolling in echelon. For this test section, the pneumatic roller acted as a true intermediate roller. The steel drum rollers applied nine passes per paving width, while the pneumatic roller added seven passes per paving width. The target temperature range before application of the pneumatic roller was 170–200°F. The same finishing roller used on the control section was then used to remove the roller marks.

Test section 2 was paved on May 14, 2018 in the eastbound lane adjacent to test section 1. This mixture was design to 4.0 percent air voids instead of 4.5 percent. The same rolling pattern used for the control section was used for test section 2, but the pneumatic roller was not used.

6.7.6 Utilization of New Technologies

No new technologies such as the MOBA Pave-IR System, WMA, intelligent compaction, or rolling density meter were used as part of this project.

6.7.7 Summary of State Findings

The control section averaged 2 percent higher density compared to the LSL of 92.0 percent. However, test section 1 exhibited slightly higher results compared to the control section. This suggested that the addition of the pneumatic roller (which was also an additional roller) had little effect on density for this mix. Further, the contractor and roller operator were not familiar with the use of the pneumatic roller, which may have also had an impact. Test section 2, which had a slightly higher optimum asphalt content, exhibited higher densities, about 1.7 percent, compared to the control section.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
    - The roller pattern for the test sections was nine vibratory passes for the breakdown roller and nine vibratory passes for the intermediate roller. A pneumatic roller added seven passes per paving width on one of the test sections.
- Observations for specification development (agencies):
    - Validated contractor's density results are used in the acceptance decision by the SHA. This SHA had a weak validation process. Cores tested at NCAT showed significantly lower density than what the contractor provided on the original demonstration project.
    - The SHA used higher optimum binder content by changing the design air voids.
    - This SHA had two density specifications: one for projects with higher quantities that utilized PWL, and one for lower quantities that utilized minimum lot average. The threshold for selecting the type of density specification was changed so the PWL specification for higher quantities was used more often.
    - A longitudinal joint density specification was implemented.

6.8 State 8

6.8.1 Project Description

This project was approximately 10 miles long and built along a transition from a rural to urban State highway. At the start of the project limits, it was a two-lane undivided highway that widened to two lanes and then three lanes in each direction. The existing asphalt pavement consisted of 4 to 6 inches of asphalt pavement placed over 8 to 9 inches of cement treated base with a variable aggregate subbase. This project was placed as a 3-inch mill-and-fill. Low to medium severity cracking was observed on the existing pavement prior to milling, but very few distresses were seen after milling. The project was constructed from June through August of 2018 with the experimental sections paved in mid-June.

There were three different experimental sections.

- Control section (IC screens were covered), was placed in the northbound passing lane. The control section used a standard mixture design. This project also required the use of intelligent compaction (IC) as a QC tool. However, for the control section, the IC screens were covered so that the operator could not see the real-time data provided by the IC system.
- Test section 1 (IC screens were uncovered), were placed in the southbound passing lane. Test section 1 used the same mixture design as the control section but had a higher density requirement with a greater incentive.
- Test section 2 (IC screens were uncovered), also used the same mixture design as the control section but with an even higher density requirement and greater incentive than test section 1.

6.8.2 Asphalt Mixture Design

The mixture design was a fine-graded,19.0-mm NMAS Superpave mixture design with 85 gyrations with a PG 64-10 binder. The primary control sieve and control point are defined in AASHTO M 323 (47 percent passing on the 4.75 mm sieve for 19.0 mm NMAS). The WMA technology Cecabase was used along with Ad-here XL-9000 as an antistrip and was added at a rate of 0.75 percent to the liquid binder. The mixture contained no recycled materials, only local granite and sand. Mixture design information is shown in Table 40 and Table 41. The t/NMAS was 4.0.

Table 40. Mixture Design Aggregate Gradation, Percent Passing – State 8

Sieve Size	Gradation	Mixture Design Criteria	
		Min	Max
25.4 mm (1”)	100	100	
19.0 mm (¾”)	97	92	100
12.5 mm (½”)	88	82	94
9.5 mm (⅜”)	80		
*4.75 mm (#4)	58	53	63
2.36 mm (#8)	40	35	45
1.18 mm (#16)	28		
0.60 mm (#30)	18	14	22

0.30 mm (#50)	11		
0.15 mm (#100)	5		
0.075 mm (#200)	3.5	1.5	5.5

*Denotes primary control sieve (PCS). PCS control point is 47 percent.

Table 41. Mixture Design Volumetric Properties – State 8

Mixture Design Properties	Mixture Design	Mixture Design Criteria
Ndes	85	--
Air Voids (%)	4.2	--
AC (%)	5.0	4.7–5.5
VMA (%)	13.5	≥ 13.0
VFA (%)	68.9	65–75
D/A Ratio	1.17	0.6–1.2

6.8.3 Field Verification of the Asphalt Mixture Design

QC testing was performed by the contractor based on its quality control plan, and the agency performed the acceptance testing. Asphalt content and volumetric properties were tested once every 750 tons. For each night of construction, three sublots were tested. This yielded three sets of results for each night of paving. The average results from each night are shown in Table 42 and Table 43. For example, the average asphalt content from the three tests conducted on test section 1 was 4.8 percent. It was noted that the reported binder content, VMA and air voids content appeared unusual and at this point, there is not an explanation. Basically, a reduction in VMA would be expected on all sections when the binder content was reported more or less constant and a significant reduction in air voids content was also reported.

Table 42. Agency Acceptance Aggregate Gradation, Percent Passing – State 8

Sieve Size	Mix Design	Control Night 1 6/3/18	Control Night 2 6/10/18	Test Section 1 6/11/18	Test Section 2 6/12/18
25.4 mm (1")	100	100	100	100	100
19.0 mm (¾")	97	97	98	97	98
12.5 mm (½")	88	88	88	88	87
9.5 mm (⅜")	80	82	81	82	80
*4.75 mm (#4)	58	58	59	58	57
2.36 mm (#8)	40	36	43	36	36
1.18 mm (#16)	28	25	32	25	26
0.60 mm (#30)	18	18	22	18	17
0.30 mm (#50)	11	11	14	11	10
0.15 mm (#100)	5	5	7	5	5
0.075 mm (#200)	3.5	3.0	4.2	3.0	2.7

Table 43. Asphalt Content and Volumetric Properties – State 8

Mixture Design Properties	Mix Design	Control Night 1 6/3/18	Control Night 2 6/10/18	Test Section 1 6/11/18	Test Section 2 6/12/18
Air Voids (%)	4.2	2.4	2.4	3.3	3.6
AC (%)	5.0	5.0	5.1	4.8	4.8
VMA (%)	13.5	13.4	13.7	13.6	13.8

VFA (%)	68.9	62.7	62.8	64.7	65.2

6.8.4 Density Measurement and Specifications

The agency used a minimum and maximum lot average specification with limits of 91.0 and 97.0 percent, respectively. In-place density was measured with cores. The theoretical maximum density of plant-produced mixture was used to calculate the percent density. For the demonstration projects, in-place density was measured with 10 field cores taken per night by the contractor. The in-place density results from these cores are shown in Table 44 and Figure 13. Results from the control and test section 1 were above 94 percent.

Table 44. Agency Acceptance In-Place Density Results by Lot – State 8

Section	IC Screens	Density Range, %	Median Density, %	Average Density, %	Std. Dev. of Density, %
Control Night 1	Covered	91.0–97.0	94.0	94.2	0.9
Control Night 2				94.9	0.6
Test Section 1	Uncovered	92.0–96.0	94.0	94.4	0.7
Test Section 2	Uncovered	93.0–97.0	95.0	93.5	1.1

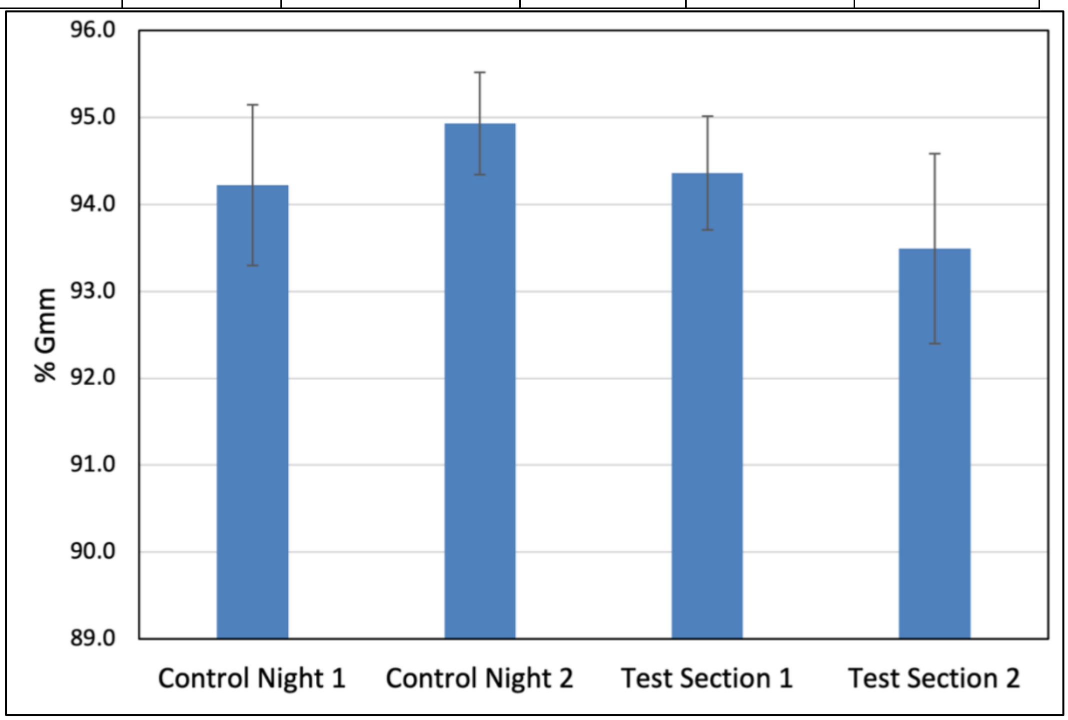


Figure 13. Comparison of Percent Density Results from Each Experimental Section – State 8

6.8.5 Experimental Section Construction and Results

This section was paved at night. The mixtures were delivered to the site using a cycle of 27 live-bottom trucks. The mixture was placed in windrows and then loaded into the paver using a Weiler E550A elevator machine. Two different pavers were used during construction. For the control section, a Caterpillar AP 1000F rubber-tire paver was used. When swapping to the test mixtures in the southbound passing lane, a Caterpillar AP 1055F track paver was used. Since the southbound passing was wider than the northbound passing lane, it was decided that the AP

1055F would work better since it was outfitted with a more rigid screed when extended. Three rollers were used during the construction of each mix. Several different models were used as shown in Table 45. The intermediate roller could also operate in vibratory mode.

Table 45. Rollers Used for Each Mix – State 8

Roller Sequence	Control Night 1	Control Night 2	Test Section 1	Test Section 2
Breakdown Roller	Hamm HD+120i (14 ton)	Hamm HD+120i (14 ton)	Hamm HD+120i (14 ton)	Hamm HD+140i (15 ton)
Intermediate Roller	Sakai GW750 (10 ton pneumatic)	Sakai GW750 (10 ton pneumatic)	Sakai GW750 (10 ton pneumatic)	Sakai GW750 (10 ton pneumatic)
Finishing Rollers	Hamm HD+70i (8 ton)	Hamm HD+140i (15 ton)	Hamm HD+120i (14 ton)	Hamm HD+140i (15 ton)

An SS-1h was applied to the milled surface as a tack coat prior to mix placement. The mat received good coverage and did not track significantly. The average laydown speed was approximately 30 feet per minute. The operating temperature range of each roller was tracked by the contractor each night and is shown in Table 46.

Table 46. Roller Operating Ranges – State 8

Mixture Identification	Date Mix Placed	Total Tons Placed	Temp. Range for Mix Delivery, °F	Temp. Range for Breakdown Roller, °F	Temp. Range for Intermediate Roller, °F	Temp. Range for Finish Roller, °F
Control Night 1	6/03/2018	2267	280-290	250-280	170-195	130-155
Control Night 2	6/10/2018	1891	285-295	250-265	170-190	140-160
Test Section 1	6/11/2018	2300	285-305	260-285	180-200	130-160
Test Section 2	6/12/2018	2300	275-295	265-285	180-200	130-145

The control section was placed in the northbound passing lane on the nights of June 3 and 10, 2018. Although the screens for the roller's intelligent compaction were to be covered, data was still to be collected for quality control and future analyses. Three rollers were used for compaction of the control section. The breakdown roller operated in vibratory mode at a frequency of 2,700 vibrations per minute. The rolling pattern was three passes on each side of the mat and then back up the middle for a total of seven passes. The intermediate pneumatic roller applied four static passes on each side of the mat, then the last pass was typically back up the middle for a total of nine passes. The finishing roller applied the same pattern as the breakdown roller, also in vibratory mode. It should be noted that the contractor's roller operators were very experienced with the IC. It is unknown how much effect covering the screens had.

Test section 1 was placed on the night of June 11, 2018 in the southbound passing lane. This test section used the same mixture as the control section. The breakdown and intermediate rollers were the same as both control section nights; the only difference was the finishing roller model. A lighter model was used for test section 1 based on the density results from the two control section nights. Since the average density was approximately 95 percent for the control section in the second night, the contractor wanted to use a lighter finishing roller since the maximum lot average went from 97 percent to 96 percent. The same rolling patterns as the control section were used for all three rollers on test section 1. However, for this mixture, the IC screens were uncovered so the operators could use their data in real-time, unlike the control section.

Test section 2 was paved on the night of June 12, 2018 in the southbound passing lane. This mixture had a minimum lot average of 93.0 percent density. To accomplish this, the contractor decided to add the heavier roller back as the finishing roller and added an extra pass to each side with the intermediate roller. Therefore, the breakdown roller still had 7 passes, but the intermediate roller had 11 passes. The IC screens were uncovered as with test section 1.

6.8.6 Utilization of New Technologies

WMA and intelligent compaction were utilized in this project. No other new technologies such as the MOBA Pave-IR System or rolling density meter were used as part of this project.

6.8.7 Summary of State Findings

The test sections had lower densities compared to the control section, but it is important to keep in mind that the control and test section 1 had densities greater than 94 percent which is extremely good. However, the incentive for the contractor on this project encouraged the contractor to obtain higher densities and keep standard deviations low to receive the full 7.5 percent incentive. In that regard, the results for both control nights and test section 1 were very favorable, and the contractor received full incentive for those nights. Test section 2 did not perform as well relative to the higher incentive; that mix had the highest standard deviation and the lowest density. The standard deviations were low for all four nights of paving, with the highest being 1.1 percent on test section 2. Standard deviations at or below 1 percent are also among the best in the country.

Operators were very familiar with the IC screens from past projects. Covering the screens was not entirely representative of having no IC as the operators had been “trained” or were experienced from past projects. However, the operators did comment that the screens were helpful to keep track of passes.

Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - Passes are reported to be the total number of passes a roller made behind the paver before it was moved to another section.
    - The roller pattern for the test sections was 7 vibratory passes for the breakdown roller, 11 static passes for the intermediate pneumatic roller, and the finishing roller applied the same pattern as the breakdown roller, also in vibratory mode.
- Observations for specification development (agencies):
    - The field acceptance specification was a minimum of 91.0 percent for the control section and it was increased to a minimum of 92.0 percent for test section 1 and a minimum of 93.0 percent for test section 2.

- The specification had incentives and disincentives.
- IC seemed to be effective at producing highly acceptable density and standard deviation results. It should be noted that the contractor was very accustomed to using IC and covering the screens may not have had a large impact. Further, standard deviations at 1.0 and lower are excellent as they have rarely been observed throughout this demonstration project.

7 OBSERVATIONS

Density can be improved through focused efforts on field compaction. Six of the eight States improved in-place density by at least 0.5 percent on their demonstration projects. All of the States averaged greater than or equal to 94.0 percent in at least one test section, which is excellent. One State already raised the lower specification limit by one percent and provided evidence of improvement in the standard deviation and higher in-place density due to that change. Another State compared a coarse-graded mixture and a fine graded mixture with no significant difference in density. Based on the observations from these demonstration projects, techniques were identified to improve density that will be of interest to agencies and contractors. They are presented here in no particular order.

7.1 Overview

There was at least one test section constructed within each of the eight States that participated in Phase 2 of FHWA's *Demonstration Project for Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. Many of the SHAs constructed more than one test section, and a total of 28 experimental sections were constructed. There were many variables including mixture type, construction equipment, and procedures between States and within States, making it very difficult to compare the density results between various pavement sections. The number of variables that were intentionally changed within a State was much less than the number of changes between States. This was expected, as it was a demonstration project and not a formal experiment. As a demonstration project, each State (the contractor and agency) was empowered to focus on changes to improve density that they thought would be most beneficial for their situation. So, it was much easier to compare the changes made within a State to show the effect of these changes on performance.

A summary of the asphalt mixture data along with in-place density is provided in Table 47. The observed effect of each of these variables is provided in the following paragraphs. Note: 9.5-mm mixtures below 47 percent passing the 2.36-mm sieve were coarse-graded and 12.5-mm mixtures below 39 percent passing 2.36-mm sieve were coarse-graded. The primary control sieve and control point as defined in AASHTO M 323 were used to make this determination.

Table 47. Summary of Mixture Properties on In-Place Density

State-Section Number	NMAS (mm)	Fine- or Coarse-Graded	Thick to NMAS	Num of Gyr	Mix Design AC (%)	Mix Design Air Voids (%)	Prod Air Voids (%)	Mix Design VMA (%)	Prod VMA (%)	Density (% of Gmm)
1-TS1	19.0	Fine	4.7	-	5.5	4.8	4.5	15.8	-	94.0
2-C1B	19.0	Coarse	2.7	75	4.8	3.5	3.3	14.3	14.0	92.2
2-C2W	12.5	Coarse	4.0	75	5.0	3.5	3.3	14.6	14.3	95.6
2-TS1B	19.0	Coarse	2.7	75	4.9	3.5	3.1	14.5	14.1	95.2
2-TS2W	12.5	Coarse	4.0	75	5.1	3.5	3.3	15.0	14.4	96.5
2-TS3B	19.0	Coarse	2.7	75	5.0	3.5	2.9	14.7	13.9	94.5
2-TS4W	12.5	Coarse	4.0	75	5.2	3.5	-	15.1	-	95.9
3-C	12.5	Coarse	5.0	100	5.2	4.1	4.4	14.7	14.5	92.9
3-TS1	12.5	Coarse	5.0	100	5.2	4.1	3.9	14.7	14.3	92.5
3-TS2	12.5	Coarse	5.0	100	5.2	4.1	4.0	14.7	14.4	94.0
3-TS3	12.5	Coarse	5.0	100	5.2	4.1	-	14.7	-	94.7
4-C	9.5	Coarse	5.3	65	4.8	4.0	2.8	15.3	14.7	95.8
4-TS1	9.5	Coarse	5.3	65	5.0	-	-	-	-	95.7
4-TS2	9.5	Coarse	5.3	65	5.0	-	-	-	-	96.5
4-TS3	9.5	Coarse	5.3	65	5.0	-	-	-	-	97.1
5-C	12.5	Coarse	4.0	80	5.0	4.0	3.8	14.3	14.0	92.0
5-TS1	12.5	Coarse	4.0	80	5.0	4.0	4.1	14.3	14.2	94.5
5-TS2	12.5	Coarse	4.0	60	5.7	3.0	3.7	14.6	14.3	95.0
5-TS3	12.5	Coarse	4.0	60	5.1	4.0	3.8	14.3	14.3	93.7
6-C	12.5	Coarse	5.0	100	5.1	4.0	4.6	15.1	16.6	93.7
6-TS1	12.5	Fine	5.0	100	5.3	4.0	3.5	15.3	15.0	93.9
7-C	12.5	Coarse	4.0	100	5.1	4.5	3.4	15.0	13.7	92.8
7-TS1	12.5	Coarse	4.0	100	5.1	4.5	3.6	15.0	14.1	93.5
7-TS2	12.5	Coarse	4.0	100	5.3	4.0	2.9	-	13.8	94.4
8-C (Night 1)	19.0	Fine	4.0	85	5.0	4.2	2.4	13.5	13.4	94.2
8-C (Night 2)	19.0	Fine	4.0	85	5.0	4.2	2.4	13.5	13.7	94.9
8-TS1	19.0	Fine	4.0	85	5.0	4.2	3.3	13.5	13.6	94.4
8-TS2	19.0	Fine	4.0	85	5.0	4.2	3.6	13.5	13.8	93.5

7.2 Gradation Type

A 1 percent improvement in density means much more to the long-term performance for a coarse gradation with a larger NMAS than a finer gradation with a smaller NMAS. The breakdown of gradations used by each State is shown below.

- Three States used fine gradations (States 1, 6, and 8), and
- Six States used coarse gradations (States 2, 3, 4, 5, 6, and 7).

For the most part, the test sections within each State did not attempt to evaluate the effect of changing the aggregate gradation. One reason for this may be that it is very difficult to quantify a change in gradation. One State (State 6) did make a change in gradation but there was not a significant effect of the change in gradation on the measured density, as the density of both the fine and coarse gradation were very near 94.0 percent.

Many think that fine-graded mixtures are more workable and easier to compact than coarse-graded mixtures, but the data in Table 47 indicate that good or poor density could be obtained with either fine-graded or coarse-graded mixtures. Based on this data, it appeared that rolling procedures could generally be adjusted to obtain adequate density when mixture variables such as air voids, NMAS, and laboratory compaction level were varied. There were many other factors, such as mixture volumetric properties, that likely had a greater effect on in-place density than the aggregate gradation.

7.3 Nominal Maximum Aggregate Size

The breakdown of the NMAS used by the States is shown below.

- One State used 9.5-mm NMAS (State 4),
- Five States used 12.5-mm NMAS (States 2, 3, 5, 6, and 7), and
- Two States used 19-mm NMAS (States 1 and 8).

Changing the NMAS also changed the t/NMAS when the layer thickness remained the same. This made it difficult to make a direct comparison between two different NMASs. Generally, it is desirable that the t/NMAS be at least 3.0 for fine-graded mixtures and at least 4.0 for coarse-graded mixtures. The t/NMAS used on the demonstration projects generally followed the best practice guidelines. The t/NMAS on the demonstration projects were:

- Five States with t/NMAS ≥ 4.0 (States 1, 2, 5, 7, and 8), and
- Three States with t/NMAS ≥ 5.0 (States 3, 4, and 6).

7.4 Asphalt Mixture Design

Superpave asphalt mix design requirements are defined in AASHTO standards. There are several factors in an asphalt mixture that might affect the compacted density. The two biggest factors are likely gyration level during laboratory compaction and the level of air voids used for selecting the optimum asphalt content. Engineering adjustments to these standards can be made, but it is recommended to follow the guidelines in the FHWA Tech Brief (2010). If the design gyrations are reduced and gradation is not changed, the VMA will increase and the asphalt to achieve design air voids will increase. If a new mix design is done at a different design gyration level, the design amount of asphalt will be the same within normal design variability.

Some States obtained higher density by adding additional asphalt binder to the mixture and others obtained higher density by increasing compaction with rollers. These two approaches of reducing the in-place air voids do not have the same effect on performance. It is important that a satisfactory mixture be designed and produced to ensure good performance and that this mixture be compacted to the adequate density in the field. As a word of caution, adding additional asphalt solely for compaction changes the mixture properties, and this adjusted mix should only be used if laboratory test results have shown that this adjusted mixture is satisfactory (i.e., performance tests measuring permanent deformation tests).

Three of the eight States made engineering adjustments to the AASHTO Superpave mixture design to obtain higher optimum AC, including States 2, 5, and 7. These States increased the asphalt binder content by 0.2 to 0.7 percent. Engineering adjustments to obtain a slightly higher optimum asphalt content included adjusting gyrations (State 5) and lowering design air voids (States 2, 5, and 7).

The gyration level for State 5 was varied, and in this case, the increase in density was 1.7 percent. State 5 also combined the gyration level reduction (from 100 to 60 gyrations) with lower design air voids to obtain an increase in density of 3.0 percent.

Another factor in mixture design that has a significant effect on density is the design air void level. A pavement section designed with lower design air voids will be easier to compact than one with higher design air voids for the same gradation. Two States that looked at varying the laboratory air voids without significantly changing other mixture properties or compaction procedures were States 5 and 7. The results from State 7 showed that lowering the design air voids from 4.5 to 4.0 percent without changing the gradation resulted in an approximate 0.6 percent increase in the in-place density. The results from State 5 showed that lowering the design air voids from 4.0 to 3.0 percent in combination with lower gyration levels resulted in an approximate 3.0 percent increase in the in-place density.

When adjusting the mixture design criteria, it is extremely important to adjust the field density requirement. For instance, if an agency does make engineering adjustments to increase the optimum asphalt content, then the agency should also adjust the percent density requirement.

7.5 Field-Produced Mixture Properties

The asphalt mixture design properties have an effect on in-place compaction but this effect can likely be better evaluated based on mixture properties during field production. Random variation, breakdown of aggregates, and other issues happen during production that can make the mixture properties different than that shown in the design. These laboratory properties of the asphalt mixture during production should correlate better with in-place density than the design properties. The asphalt mix design was adequately verified by each of the States and adjustments were made as needed to ensure the production gradations and mixture volumetric properties met the specification requirements.

7.6 Placement and Compaction

The placement and compaction data along with in-place density results are provided in Table 48. MTVs have been shown to provide improved smoothness and reduced segregation and were used on five (States 2, 3, 5, 6, and 7) of the eight demonstration projects.

The number of compaction rollers varied from as few as two rollers on one of the demonstration projects and up to six compaction rollers on another demonstration project (State 5). This was a tremendous difference in compactive effort. The reported number of passes is equal to the total number of passes a roller made behind the paver before it was moved to another section. A summary of some key observations follows.

- The total number of passes on the test section was as follows:
    - One of the eight States used < 15 passes (State 2),
    - Four of the eight States used 15 to 20 passes (States 5, 6, 7, and 8), and
    - Three of the eight States used > 20 passes (States 1, 3, and 4).
- When vibratory or oscillatory rollers were used, generally all of the passes used the vibratory or oscillatory mode. In some cases, there was a final one or two passes that were static. Two of the eight States used the vibratory mode of the roller with less than 10 passes in the control section (States 2 and 5).
- Two of the eight States used breakdown rollers in echelon (States 5 and 7).
- Four of the eight States used pneumatic rollers (States 3, 5, 7 and 8).
- One of the eight States used vibratory pneumatic rollers (State 5).

Overall, the results showed that the amount of rolling significantly affected the in-place density. An additional roller was helpful in increasing density. Two of the eight States used an additional roller to successfully obtaining higher in-place density (States 4 and 5).

Table 48. Summary of Effect of Placement, Compaction, and New Technologies

State–Section	MTV	Compaction Rollers*	Passes (Total)	New Tech.	Density (% of Gmm)	Lot Std. Dev.
1-C	No	Same as TS1	≈ 20% less than TS1	Varied	93.2	1.36
1-TS1	No	2 steel wheel	28 vibratory	IC and WMA	94.0	0.87
2-C1B	Yes	1 steel wheel	9 vibratory	-	92.2	2.56
2-C2W	Yes	1 steel wheel	9 vibratory	-	95.6	1.03
2-TS1B	Yes	1 steel wheel	9 vibratory	WMA	95.2	1.43
2-TS2W	Yes	1 steel wheel	9 vibratory	WMA	96.5	1.25
2-TS3B	Yes	1 steel wheel	9 vibratory	-	94.5	1.93
2-TS4W	Yes	1 steel wheel	9 vibratory	-	95.9	1.05
3-C	Yes	1 steel wheel, 1 pneum.	5 vibratory and 7 pneumatic	None	92.9	1.6
3-TS1	Yes	2 steel wheel, 1 pneum.	No clear rolling pattern	None	92.5	1.8
3-TS2	Yes	2 steel wheel, 1 pneum.	12 vibratory, 2 static, 7 pneumatic (21)	None	94.0	1.3
3-TS3	Yes	3 steel wheel, 1 pneum.	12 vibratory, 4 static, 7 pneumatic (23)	None	94.7	1.1
4-C	No	2 steel wheel	14 vibratory	None	95.8	0.75
4-TS1	No	3 steel wheel	19 vibratory	None	95.7	0.58
4-TS2	No	2 steel wheel	14 vibratory	None	96.5	0.64
4-TS3	No	3 steel wheel	19 vibratory	None	97.1	0.26
5-C	Yes	3 steel wheel	11 vibratory and 4 static (15) echelon used	None	92.0	1.3
5-TS1	Yes	4 steel wheel, 1 pneum.	16 vibratory, 4 static and 7 vibratory pneumatic (27) echelon	None	94.5	1.0
5-TS2	Yes	3 steel wheel	11 vibratory and 4 static (15) echelon	None	95.0	1.3
5-TS3	Yes	3 steel wheel	11 vibratory and 4 static (15) echelon	None	93.7	1.3
6-C	Yes	2 steel wheel	18 vibratory	WMA	93.9	1.0
6-TS1	Yes	2 steel wheel	18 vibratory	WMA	93.7	1.4
7-C	Yes	2 steel wheel	18 vibratory	None	92.8	1.1
7-TS1	Yes	2 steel wheel, 1 pneum.	18 vibratory and 7 pneumatic (25)	None	93.5	1.2
7-TS2	Yes	2 steel wheel	18 vibratory	None	94.4	1.0
8-C (Night 1)	No	1 steel wheel, 1 pneum.	7 vibratory and 9 pneumatic (16)	IC and WMA	94.2	0.9
8-C (Night 2)	No	1 steel wheel, 1 pneum.	7 vibratory and 9 pneumatic (16)	IC and WMA	94.9	0.6
8-TS1	No	1 steel wheel, 1 pneum.	7 vibratory and 9 pneumatic (16)	IC and WMA	94.4	0.7
8-TS2	No	1 steel wheel, 1 pneum.	7 vibratory and 11 pneumatic (18)	IC and WMA	93.5	1.1

*Finish roller was generally not included as it was often a smaller roller operating in static mode to remove roller marks.

7.7 Measuring and Reporting Density

The primary property that is important during compaction is the percent air voids in the in-place mixture. Reporting density as percent of Gmm directly provides the air voids in the compacted mix. Other methods of specifying and measuring density only provide an indirect measure of the air voids and in some cases can be misleading. All of the eight States reported density as a percent of Gmm or the air voids in the compacted mix.

7.8 Field Acceptance Specification

Agency specifications play a key role in the amount of density obtained on a project. Here are a few key observations from the demonstration projects based on the agency specifications.

- The contractor is required to meet the specifications and often does so in the most efficient manner in order to be the low bidder. Simply asking for higher density, three of the eight States (States 1, 7, and 8) achieved higher in-place density. Although this would not work in all of the States, some States could simply raise the minimum density requirements and the contractors could adjust their compaction methods to meet specifications.
- Consistency is an important factor. Four of the eight States (States 1, 2, 4, and 8) demonstrated improvements in the standard deviation, and showed that achieving standard deviations below 1.00 was possible.
- Incentives can be a valuable part of the specification to gain improvements in density. Six of the eight States (States 1, 3, 4, 5, 6, and 8) used incentives. Several States noted the importance of the incentive to the success of their improvements in density.

7.9 New Technologies

Several States evaluated new technologies to help ensure good compaction. The technologies used included warm-mix asphalt and intelligent compaction. The number of States using each of the technologies was:

- WMA was used by three of the eight States (States 1, 6, and 8), and
- IC was used by two States (States 1 and 8).

The IC has the potential to improve the quality of large projects but may not be very effective when used in small sections such as those in this project. This technology generally provided information that would have been useful in making adjustments as work progresses, so it would be most useful for larger projects. WMA was found to be effective with allowing effective compaction at cold-weather paving (potentially extending the paving season).

8 SUMMARY OF OBSERVATIONS

8.1 Observations from Phase 2

Density can be improved through focused efforts on field compaction. Six of the eight States participating in Phase 2 improved in-place density by at least 0.5 percent on their demonstration projects. Eight of the eight States averaged greater than or equal to 94.0 percent in at least one test section, which is excellent. When averaging 94.0 percent or greater, there is not much need for additional improvement. A summary of the methods used to obtain increased density seemed to fall into one of the following six categories.

1. The agency's specification was improved by including or increasing incentives and examining the minimum percent density requirements. Two States increased their upper specification limit and three States increased the lower acceptance limit to 92.0 percent. Two States improved or implemented a longitudinal joint density specification and two States improved the density specification for secondary roads. In one State, the contractor's results were used in the acceptance decision, leading to a strengthened validation process.
2. There was a significant difference in the number of rollers used for compaction between States. Some States used as little as two compaction rollers while others used as many as four or five. The number of passes for each roller varied considerably among States. There is a strong correlation between the rolling effort and the agency's requirements. Some States were able to obtain high density in the range of 95.0 to 97.0 percent of Gmm while other States only obtained density in the range of 90 to 91 percent. As expected, using fewer rollers and fewer vibratory passes generally resulted in lower in-place density, and using more rollers resulted in higher in-place density. Each demonstration project was monitored for aggregate breakage and none was observed.
3. Engineering adjustments made to the asphalt mix design to obtain slightly higher optimum asphalt content were successful at achieving higher in-place densities. Also, reducing the number of gyrations during mix design resulted in increased density in the field. Some States obtained higher density by increasing the optimum asphalt binder content with engineering adjustments. A combination of engineering adjustments used in one State provided the highest increase in field density. Mixture performance testing is also important when making changes to the mixture design criteria to ensure that the new asphalt content will not create a mixture susceptible to rutting.
4. Consistency is one of the most important factors in improving in-place density. Consistency can be generally defined as consistency in temperatures, paver speeds, roller patterns, and all of the other factors that impact density and standard deviation of density measurements. Improving consistency as measured by the standard deviation was accomplished by four of the eight States with standard deviation results below 1.00. In one State, improvements in materials processing (crushing and stockpiling) also reduced variability of density results.
5. Following best practices is important. There was a lot of attention on the construction of the control and test sections. Since this was part of an experiment, there was more attention to best practices than there would normally have been. In many States, the results in the control section were greater than that of the statewide average results that would normally be expected. When examining the improvement in density from the control to the test section, the increases could have been even greater. Improvement in density reported from each of the demonstration projects was likely even better than documented in this report.

6. Using new technologies was helpful. The technologies used included warm-mix asphalt and intelligent compaction. All of these new technologies showed some promise. The use of intelligent compaction (roller pattern tracking or mapping) provided density results with lower standard deviation than without. Some increases in density were also observed (in two States) due to the use of intelligent compaction. In one case, the use of WMA extended the paving season by six weeks.

8.2 Follow-Up from FHWA Demonstration Project, Phase 1

In Phase 1, some metrics from the in-place density achieved in the test sections include:

- 8 of 10 SHAs improved percent densities by at least one percent.
- 7 of 10 SHAs obtained an average percent density greater than 94.0.
- 6 of 10 SHAs obtained an average percent density greater than 95.0.

These projects were constructed in 2016. As time has passed, nine of the ten SHAs have made changes to their density specifications. These changes were tracked and are summarized below.

- **Method of measuring density.** One SHA was measuring density with a nuclear gauge that was not correlated to cores. They are now correlating the gauge to cores.
- **Reference density.** One SHA was using the bulk specific gravity of the laboratory compacted sample (G_{mb}) as the reference and has now changed to G_{mm} as the reference.
- **Density of pavement to meet requirements.** Four SHAs increased their minimum density requirements. These SHAs had minimum percent density requirements at 91.0 or below. Decker (2017) found that 89 percent of the respondents had minimum requirements on percent density ranging from 91.0 to 93.0 with 58 percent of the respondents at 92.0.
- **Upper specification limit.** One SHA increased its upper specification limit from 96.0 percent to 98.0 percent. This provided contractors more room with higher in-place densities before the disincentive of exceeding the upper limit. Decker (2017) found about 77 percent of the respondents indicated maximum requirements were between 97.0 and 98.0 and 58 percent were at 97.0.
- **Quality Measure.** Two SHAs changed their quality measure from minimum lot average to PWL. PWL includes the standard deviation of the test results, which is impacted by the contractors' target and consistency.
- **Consistency.** Two SHAs decreased the standard deviation used in their specification. Although not common, standard deviations less than 1.0 were achievable.
- **Incentives.** Three SHAs increased the incentive for density. One SHA budgeted an additional $1 million per year for density incentives. Nationally, 37 SHAs have incentives ranging from 1 to 10 percent for density alone with an average incentive of 2.9 percent (Aschenbrener et al., 2017).
- **Mixture design changes.** Five SHAs made engineering adjustments to their asphalt mixture design procedure such that there was a higher optimum asphalt content. This was not an intended part of the demonstration project. It should be noted that many SHAs are changing Superpave mixture design requirements to get a higher optimum

asphalt content. When making these adjustments, it is important to: 1) make sure the asphalt mixture is rut resistant and 2) review the density specification.

- **New technologies.** Two SHAs used new technologies that relate to in-place density. They were the dielectric profiling system and the paver mounted thermal profiler. These SHAs did not observe an improvement in percent density based on the new technology, but it was found to be a good quality control or troubleshooting tool.

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