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FHWA DEMONSTRATION PROJECT FOR ENHANCED DURABILITY OF ASPHALT PAVEMENTS THROUGH INCREASED IN-PLACE PAVEMENT DENSITY, PHASE 3

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AASHTO	American Association of State Highway Transportation Officials
AC	Asphalt Content
ADOT&PF	Alaska Department of Transportation and Public Facilities
AI	Asphalt Institute
AV	Air Voids
BC	Base Course
COV	Coefficient of Variation
CTDOT	Connecticut Department of Transportation
D/A Ratio	Dust/Asphalt Ratio
DOT	Department of Transportation
FHWA	Federal Highway Administration
G_{mb}	Bulk Specific Gravity of the Mixture
G_{mm}	Theoretical Maximum Density
GPR DPS	Ground Penetrating Radar Density Profiling System
GPS	Global Positioning System
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
INDOT	Indiana Department of Transportation
IR	Infrared Imaging
JMF	Job Mix Formula
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
MDT	Montana Department of Transportation
MoDOT	Missouri Department of Transportation
MTV	Material Transfer Vehicle
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NJDOT	New Jersey Department of Transportation
NMAS	Nominal Maximum Aggregate Size
NPV	Net Present Value
NYSDOT	New York State Department of Transportation
Pbe	Effective Binder Content
PCS	Primary Control Sieve
PD	Percent Defective
PennDOT	Pennsylvania Department of Transportation
PMTP	Paver-Mounted Thermal Profiler
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
WC	Wearing Course
WMA	Warm Mix Asphalt
WSDOT	Washington State Department of Transportation
USL	Upper Specification Limit
VFA	Voids Filled with Asphalt
VRAM	Void Reducing Asphalt Membrane
VMA	Voids in the Mineral Aggregate

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

Phase 3

Abstract

Achieving appropriate in-place density is critical to the long-term performance of an asphalt pavement, as a small change can significantly affect pavement service life. Thus, 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 benefit of additional mat compaction and show that additional density could be obtained through improved techniques. Many states supplemented the compaction equipment or made changes in the mix design process to obtain additional density.

The FHWA Demonstration Project included three phases. Phase 1 was completed in 2017 with demonstration projects constructed in 10 states (Aschenbrener et al., 2017). Phases 2 and 3 were an extension of the Phase 1 effort. Phase 2 was completed in 2018 with demonstration projects constructed in 8 states (Aschenbrener et al., 2019). This report documents activities and observations from Phase 3 of the Demonstration Project in 11 states, including (1) a summary of a detailed literature review conducted in Phase 1, (2) success stories related to SHA density specifications started in Phase 2, (3) lessons learned from the three phases of the Demonstration Project, and (4) strategies to overcome some obstacles to achieving higher in-place density.

Based on the lessons learned from this Demonstration Project, there will be challenges as state highway agencies embrace the idea to increase the in-place density requirements in their specifications as contractors and agencies will have to go through a learning curve. However, with appropriate strategies, training, and education, the challenges can be overcome to achieve increased in-place density.

Chapter 1: Introduction

Achieving appropriate in-place density is critical to the long-term performance of an asphalt pavement, as any small change can significantly affect the pavement service life. As little as a 1 percent increase can improve the fatigue performance of asphalt pavements between 8 and 44 percent and rutting resistance by 7 to 66 percent. A 1 percent increase, between 91 percent and 96 percent of the theoretical maximum density (G_{mm}), would extend the service life of asphalt overlays by 10 percent. The life extension benefit of higher in-place density can, in turn, result in a significant cost savings. For example, a state highway agency (SHA) can potentially save $88,000 in life cycle cost on a $1,000,000 resurfacing project by increasing the minimum required density by 1 percent, from 91 to 92 percent (Tran et al., 2016).

Recognizing the importance of in-place density, 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 a successful partnership between state highway agencies, the National Asphalt Pavement Association, and the contractors that built the demonstration sections.

The FHWA Demonstration Project included three phases. Phase 1 was completed in 2017 with demonstration projects constructed in 10 states (Aschenbrener et al., 2017). Phases 2 and 3 were an extension of the Phase 1 effort. Phase 2 was completed in 2018 with demonstration projects constructed in 8 states (Aschenbrener et al., 2019). This report documents activities and observations from Phase 3 of the Demonstration Project. The report also includes a summary of a detailed literature review conducted in Phase 1, success stories related to SHA density specifications started in Phase 2, and lessons learned from the three phases of the Demonstration Project.

Chapter 2: Objective and Scope

The overall objective of the Demonstration Project was to achieve increased in-place density that can result in improved asphalt pavement performance. The Phase 3 effort built upon the objectives of previous phases as listed below (Aschenbrener et al., 2017).

- Phase 1: 1) a literature search 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. Only eight were reported as one of them had construction delays. The ninth one was then included in Phase 3.
- Phase 3: 1) documentation of successful SHA density specifications started in Phase 2, and 2) the construction of ten additional field demonstration projects.

Ten SHAs participated in Phase 3 of the Demonstration Project with grants provided by FHWA for constructing test sections. These SHAs were selected through an application process with consideration given to those that could benefit most from increased compaction requirements in various geographic and climatic regions. One of the SHAs participating in the Phase 2 study had their project delayed due to various design challenges. That demonstration project is reported in this Phase 3 report; thus, this report includes results from eleven demonstration projects.

Seven of the ten SHAs participated in an *Enhanced Durability through Increased In-Place Pavement Density Workshop* developed and delivered jointly by the Asphalt Institute and FHWA. The target audience of the workshop was the SHA, contractors, equipment suppliers, and academia. The workshop covered best practices as well as new materials and technologies.

All SHAs participating in Phase 3 constructed field demonstration projects in their states in 2018. 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 their 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 (AC), 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 local state. 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 project 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 this demonstration project to provide guidance and/or motivation to SHAs in reviewing, updating, and improving their current field density acceptance criteria for asphalt pavements.

While 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 mixtures, and/or unacceptable volumetric properties. Increased density will not have the same benefit in those situations.

Chapter 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.
- **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 first passes of the (breakdown) roller over the freshly laid asphalt mix.
- **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.

Chapter 4: Best Practices for Improving In-Place Density

Higher in-place density can be achieved in a cost-effective manner by following best practices and employing new technologies to improve the long-term performance and life cycle cost of asphalt pavements. The best practices and new technologies for improving in-place density are briefly discussed below (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 selected 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 guidance is provided in an FHWA tech brief (FHWA, 2010a). 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 G_{mm} from field-produced samples. Useful information regarding the bulk specific gravity of the mixture (G_{mb}) and G_{mm} 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 achievable for in-place density (Santucci, 1998; Nodes, 2006).

  - Utilizing good specifications, the Pennsylvania Department of Transportation (PennDOT) and New York State Department of Transportation (NYSDOT) could obtain good in-place density results using the minimum lot average specification and the percent within limits (PWL) specification, respectively (Aschenbrener et al., 2017).

- 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 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 surface 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). The Asphalt Institute website has more detailed information about specifying and constructing longitudinal joints.
  - Tack coats should be applied sufficiently 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).

Chapter 5: Acceptance Practices for Increased In-Place Density

A question remains regarding the appropriate minimum and maximum specification requirements for in-place density. To provide guidance in answering this question, a literature review was conducted followed by an examination of several SHA specifications.

5.1 Literature Review

The key findings of the literature review are summarized below.

- Based on the correlations between pavement performance and in-place density, pavement service life is significantly reduced when in-place density is below 93.0 percent. Linden et al. (1989) reported that a one percent decrease in density can result in about a ten percent loss in pavement life, and Mallela et al. (2013) suggested a 35 percent reduction in service life for pavements with an in-place density between 90.0 and 92.0 percent when compared with those having an in-place density between 93.0 and 95.0 percent.
- Water can enter permeable pavements and cause issues that reduce service life. To avoid water-induced issues, Terrel et al. (1994) suggested that asphalt pavements were relatively impermeable when the in-place density was above 92.0 percent. However, the relationship between density and permeability can be greatly influenced by other factors, such as nominal maximum aggregate size (NMAS) and the relative coarseness or fineness of the gradation. A minimum in-place density was recommended for various NMAS gradations in previous reports (Cooley et al. 2001, Brown et al. 2004).
- Other authors also recommended a minimum in-place density for asphalt pavements. Based on historical data, Hughes (1989) suggested that realistic target values for density should have an average percent density of 93.0 and a standard deviation of 1.5 for use by agencies that started using end-result specifications with density measurements in the late 1980s. In addition, the Asphalt Institute (2007) reported that a target density less than 92.0 percent was considered inadequate, and Brown et al. (2009) suggested that the initial in-place voids for dense graded mixtures should not be less than approximately 92.0 percent to minimize water permeability and binder aging. Finally, based on a survey of state highway agencies, Decker (2017) reported that 89 percent of the respondents had minimum requirements on in-place density ranging from 91.0 to 93.0 percent with 58 percent of the respondents specifying 92.0 percent while about 77 percent of the respondents indicated that maximum requirements were between 97.0 and 98.0 percent with 58 percent specifying 97.0 percent.

In summary, there is consensus in more recent research using various evaluation techniques that the in-place density of the mat should be greater than 92.0 percent, and 93.0 to 94.0 would be preferred after construction (McDaniel, 2018). The next step was to identify SHAs that have successfully adopted in-place density specifications that minimize the number of test results below the 92.0 threshold on their construction projects.

5.2 Successful Acceptance Practices by Participating SHAs for Increased Density

The purpose of the success stories was to identify SHAs with in-place density specifications that minimized the amount of test results below the 92.0 percent threshold. The following twelve SHAs, some of which participated in the FHWA Density Demonstration Project, have been identified as success stories to date, and details of their specifications and historical data are gathered for analysis.

- State highway agencies with lot average specifications
    - Maryland Department of Transportation State Highway Administration (MDOT SHA)
    - Montana Department of Transportation (MDT)
    - Tennessee Department of Transportation (TDOT)
- State highway agencies with PWL specifications
    - Alaska Department of Transportation and Public Facilities (ADOT&PF)
    - Indiana Department of Transportation (INDOT)
    - Maine Department of Transportation (Maine DOT)
    - Michigan Department of Transportation (MDOT)
    - Missouri Department of Transportation (MoDOT)
    - New Jersey Department of Transportation (NJDOT)
    - New York State Department of Transportation (NYSDOT)
    - Pennsylvania Department of Transportation (PennDOT)
    - Puerto Rico Highway and Transportation Authority (PRHTA)

In addition to the twelve SHAs, a thirteenth was added that was not considered to be a best practice so its requirements could be used for comparison purposes. The thirteenth SHA is referred to as “Example State” in this report.

While SHAs typically have more than one in-place density specification applicable to various types of asphalt mixtures, highways, and/or projects, the SHAs’ most stringent density specification was analyzed, and the information associated with its use in specific projects is shown in Table 1. Each of the twelve SHAs used their data management system, often times electronic, to collect percent density results from all the acceptance tests on a project, and data for one or more construction seasons are provided by the SHAs for this analysis, as shown in Table 1. In addition, it should be noted that each pavement is not likely to be constructed with absolute uniformity as there is variability from roller patterns, mixture properties, and temperatures, among others. Thus, for each set of data, the average and standard deviation were calculated for each lot and then the results from each lot were averaged and presented for each SHA. The results were then compared with the 92.0 percent threshold as discussed in the literature review.

Table 1. Project Information and Time Period for Density Data

SHA	Year of Data	Mix Type	Type of Project	Acceptance Testing
Example State	2016	Type C	N/A	Agency only
MDOT SHA	2017	Dense Graded	N/A	Contractor validated by agency
MDT	2007 to 2018	9.5, 12.5 & 19 mm	All projects	Agency only
TDOT	2015 to 2017	D-mix (3/8" NMAS)	Interstate and SR Freeways	Agency only
ADOT&PF	2015	Type II 19mm & Superpave 12.5 mm	Interstate and principal arterial	Agency only
INDOT	2018	Superpave5	All projects with 9.5 and 19-mm mixes	Agency only
Maine DOT	2013 to 2017	9.5, 12.5 & 19 mm	All mainline projects	Agency only
MDOT	2015	9.5, 12.5 & 19 mm	All projects greater than 5,000 tons	Agency only
MoDOT	2018	4.75, 9.5, 19 & 25 mm	All projects greater than 5,000 tons	Contractor validated by agency
NJDOT	2018	4.75, 9.5, 19 & 25 mm	All projects	Agency only
NYSDOT	2015	Series 50 9.5, 12.5 & 19 mm	Full/partially controlled roadways	Agency only
PennDOT	2017	High level wearing surface 9.5, 12.5 & 19mm	N/A	Agency only
PRHTA	2017-2019	Superpave	All projects	Agency only

N/A: Not Available

For each of the SHAs, a histogram similar to Figure 1 was developed. The histogram shows the variation in percent density results from multiple projects within the five-year period from 2013 to 2017. The distribution of percent density results is shown along with the percentage of results below the 92.0 percent threshold. Based on Figure 1, there were 5.8 percent of the test results below 92.0 percent. This is an example of a very good specification.

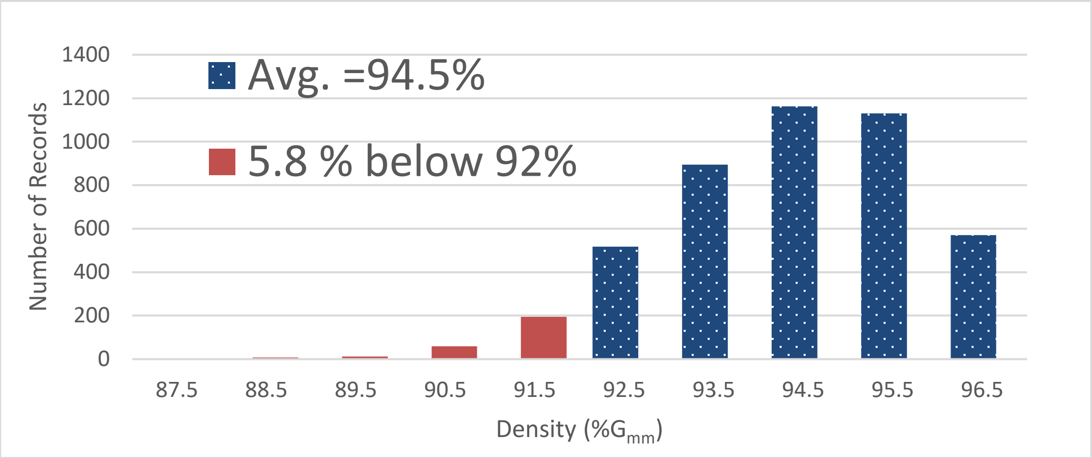


Figure 1. Histogram of Percent Density Results from Maine DOT

In-place density specifications from the twelve SHAs were examined to determine the actual field outcomes yielded from each specification. The density specifications for each SHA and a summary of the project results analyzed for the selected period of the data (Table 1) are shown in Table 2. Based on the information shown in Table 2, the following observations are offered.

- Nine SHAs (AKDOT&PF, INDOT, Maine DOT, MDOT, MoDOT, NJDOT, NYSDOT, PennDOT, and PRHTA) used a percent within limits (PWL) or percent defective (PD) specification with a lower limit ranging from 92.0 to 93.0 percent. Only 3.1 to 8.4 percent of the density test results were below the 92.0 percent threshold.
- Three SHAs (MDOT SHA, MDT, and TDOT) used a minimum lot average specification with a minimum requirement of 92.0 percent. Each of these SHAs also included an incentive. The density test results below the 92.0 percent threshold ranged from 5.3 to 11.0 percent.
- Two of the SHAs that used a minimum lot average specification had an additional requirement. MDOT SHA included a minimum individual sublot requirement of 92.0 percent. MDT included a range requirement. These additional requirements helped minimize the density test results that were below the 92.0 percent threshold. Their results were similar to those from the nine states using the PWL/PD specifications as discussed above.
- All of the twelve SHAs use incentives for the density quality characteristic alone ranging from 1.25 to 8.0 percent.
- For the nine SHAs with less than 6.0 percent of their density test results below the 92.0 percent threshold, their average percent density ranged from 93.7 to 94.9.

Information for Example State is also provided in Table 2 for comparison. Example State had a minimum lot average specification with a lower limit 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. Because of the lower specification limit, 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.

Table 2. Percent Density Specifications and Results from Projects

SHA	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	25.3%
MDOT SHA	Lot Avg. & Ind. Sublot	92.0 to 97.0	5.00%	94.0	94.0	1.03	5.3%
MDT	Lot Avg. & Range	93.0 to 100.0	8.00%	94.0 to 95.0	94.3	N/A	6.6%
TDOT	Lot Avg.	92.0 to 97.0	2.00%	94.0	93.9	N/A	11.0%
ADOT&PF	PWL	93.0 to 100.0	5.00%	Approx. 96.0	94.9	1.76	5.6%

SHA	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}
INDOT	PWL	93.0 to 100.0	1.75%	N/A	93.9	N/A	8.4%
Maine DOT	PWL	92.5 to 97.5	2.50%	Approx. 93.5	94.5	1.20	5.8%
MDOT	PWL	92.5 to 100.0	2.00%	Approx. 94.5	94.4	1.03	5.5%
MoDOT	PWL	92.0 to 97.0	1.25%	Approx. 94.5	93.7	N/A	5.0%
NJDOT	PD	92.0 to 98.0	4.0%	N/A	94.9	N/A	5.4%
NYSDOT	PWL	92.0 to 97.0	5.00%	Approx. 94.0	94.2	1.01	5.0%
PennDOT	PWL	92.0 to 98.0	2.00%	Approx. 94.0	94.4	1.46	3.1%
PRHTA	PWL	92.0 to 99.0	2.50%	Approx. 94.0	94.6	N/A	3.6%

N/A: Not Available

In order to serve as a guide to SHAs that are interested in making improvements to their density requirements, additional information on the density specifications is shown in Table 3. A minimum of seven sublots per lot is encouraged to balance the buyer's and seller's risk. 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 used cores, and they all used G_{mm} values from plant-produced material obtained within the lot. These are all considered best practices.

Table 3. Additional Percent Density Specification Information

SHA	Lot Size (tons)	Sublots per Lot	Frequency (tons)	Measuring G_{mb}	Measuring G_{mm}
Example State	2,000	8	250	6-in. cores: 1 per sublot	Avg. of 5 tests: Every 500 tons
MDOT SHA	Day's production	5 min.	500 max.	4 or 6-in. cores	2 per sublot
MDT	3,000	5	600	4 or 6-in cores	2 per sublot
TDOT	1,000	5	200	4 or 6-in. cores: 1 per sublot	Daily Avg.: 2 tests per day
ADOT&PF	5,000	10	500	6-in. cores: 1 per sublot	Ind. test: 1 per lot
INDOT	3000/5,000	5	600/1000	6-in. cores	1 per sublot
Maine DOT	4,500	6	750	6-in. cores: 1 per sublot	Ind. test: 1 per sublot
MDOT	5,000	5	1000	6-in. cores: 1 per sublot	Ind. test: 1 per sublot
MoDOT	4,000 min.	4	1000 min.	4-in. cores	Ind. test: 1 per sublot
NJDOT	Day's production	5	Varies	6-in. cores	5 per lot
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
PRHTA	1,600	4	400	6-in cores: 2 per sublot	Individual test: 1 per sublot

5.3 Acceptance Practices by Participating SHAs for Longitudinal Joint Density

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 4. 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. INDOT has tried a method specification by requiring the application of a void reducing asphalt membrane (VRAM), which is a longitudinal joint sealant.

Table 4. Longitudinal Joint Density Specification Information

SHA	**Quality Measure**	**Limits (% G_{mm})**	**Incentive for Only Joint Density**
Example State	None	N/A	N/A
MDOT SHA	None	N/A	N/A
MDT	Lot Avg.	Greater than 91.0 Greater than 92.0 for incentive	$4.50 per L.F.
TDOT	Lot Avg.	Greater than 91.0	1.25%
ADOT&PF	Lot Avg.	Greater than 91.0	$1.50 per L.F. (approx. 6.25%)
INDOT	Method	Joint treatment (VRAM) and fog seal	N/A
Maine DOT	PWL	Greater than 91.0	2.00%
MDOT	Lot Avg.	Greater than 90.5	$1.00 per L.F. (approx..4.0%)
MoDOT	Lot Avg.	Greater than 90.0	N/A
NJDOT	None	N/A	N/A
NYSDOT	Under development	N/A	N/A
PennDOT	PWL	Greater than 90	$5000 per Lot (approx. 2.5%)
PRHTA	None	N/A	N/A

N/A: Not Available

5.4 Case Study – Impact of Changing Lower Specification Limit

State 1, as identified in the Phase 2 (P2-S1) demonstration project, had a percent density specification that used 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 2. The statewide average percent density was 93.2 with 20.0 percent of the results below the threshold of 92.0.

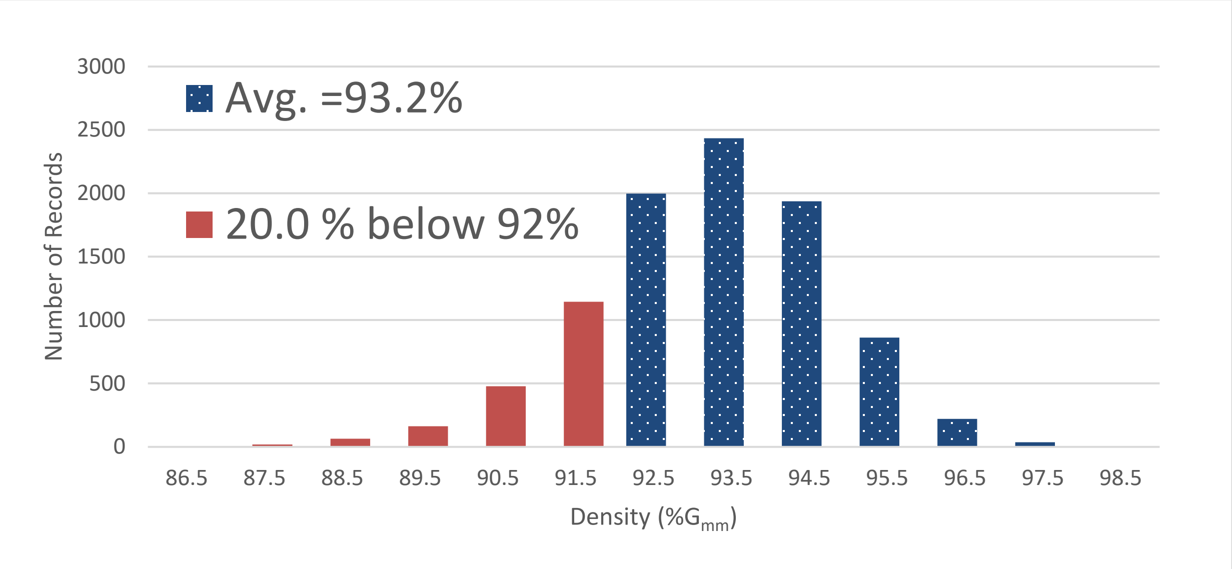


Figure 2. Histogram of Percent Density Results from P2-S1 During 2017 Construction Season

For the density demonstration project, P2-S1 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 3. 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.

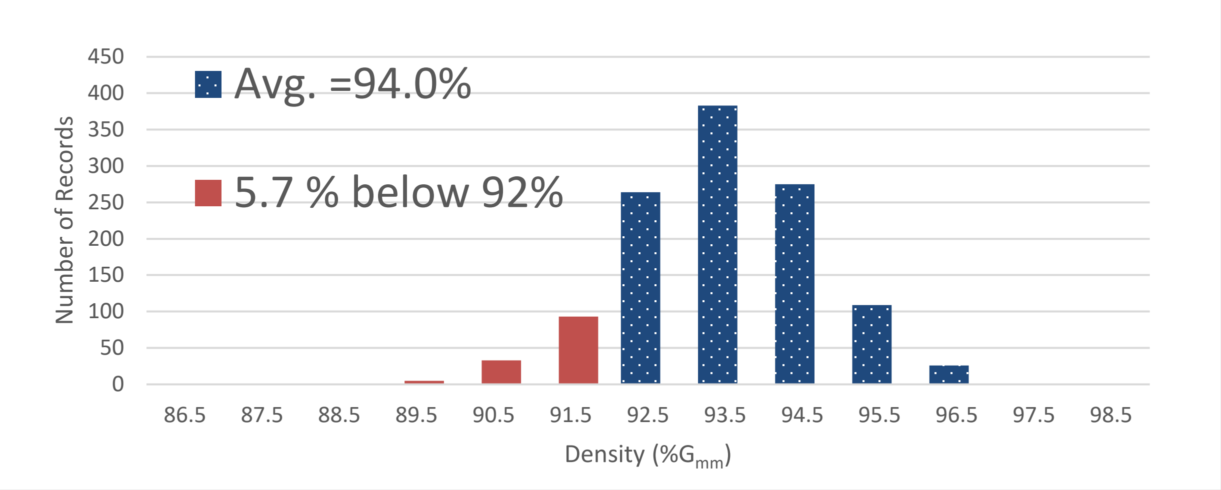


Figure 3. Percent Density Results from P2-S1 During FHWA Density Demonstration Project

5.5 Summary

As determined from the literature review, in-place density should be greater than 92.0 percent and perhaps even 93.0 percent at the time of construction. Considering the variability of materials and construction practices, several SHAs have been successful at averaging just over 94.0 to minimize the number of percent density results below 92.0 percent. Most of these SHAs used the PWL or PD specification. Two of the SHAs successfully used the minimum lot average specification in addition to either a minimum individual sublot or a range requirement. Incentives were included in all of the specifications. Longitudinal joint density is important to pavement performance and should also be included.

Chapter 6: Field Demonstration Projects

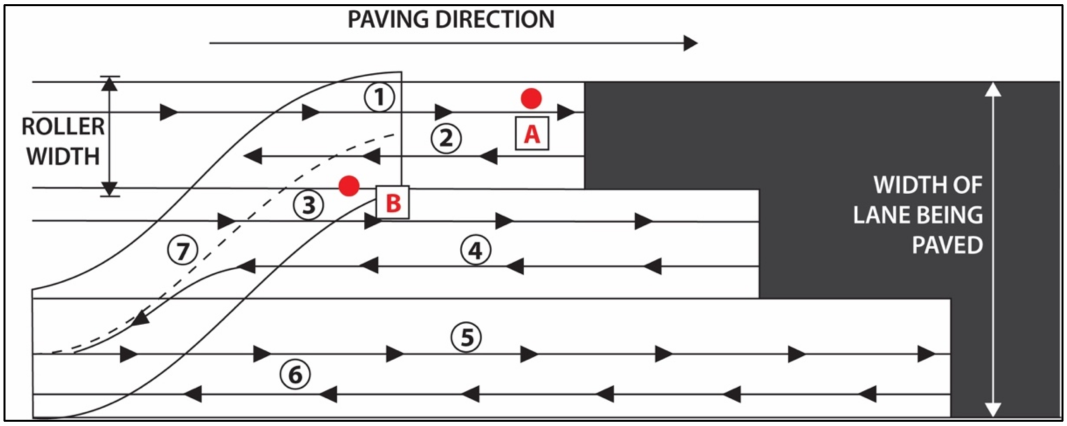
This chapter summarizes information collected from demonstration projects in eleven states. They were selected through an application process for the FHWA Demonstration Project for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. Ten of the states were selected in Phase 3 and one was selected in Phase 2. 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 higher density with enhanced compaction to improve pavement durability.

For each project, the contractor built a control section following their standard compaction techniques and then built a test section with improved compaction techniques utilizing the same equipment and mixture used for constructing 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 used routinely throughout the 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 in Figure 4, 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. In Figure 4, the roller made seven passes.
- **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 as it was often a smaller roller operating in static mode used to remove roller marks. This was done such that the number of passes to obtain density was not skewed.

In this chapter, the results from each of the eleven demonstration projects are discussed. As part of the FHWA Demonstration Project, each SHA agreed to prepare a report to document their findings. A summary of each SHA report is provided here.



Note: This is a 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. To simplify the illustration of roller passes, roller stops made at an angle to avoid stop marks are not shown in this figure.

Figure 4. Definition of Roller Passes

6.1 Phase 3 – State 1 (P3-S1)

6.1.1 Project Description

State 1 constructed their approximately 26 mile long demonstration project on a four-lane interstate highway in a rural area. The existing pavement was milled and inlaid with a new surface of 1.8 inches. The paving occurred in August 2018.

The main objective of the SHA was to assess the impacts of an increase in the lower specification limit (LSL) for compaction in their new specification. The LSL for in-place density was increased from 91.0 percent to 91.5 percent in 2018 and would be increased again to 92.0 percent in 2019. The secondary objective of this project was to evaluate the impacts of the spacing between the breakdown and intermediate rollers. For the demonstration project, the strategy to achieve higher density involved changing the field compactive effort. Two experimental sections placed for this study are as follows.

1. Control Section. This section was constructed based on the state's standard mix design and density specification.
2. Test Section 1 - Changing the rolling pattern. The same mix design as the Control Section was used but with reduced spacing between the breakdown and intermediate rollers.

The two experimental sections were placed in a 2.7-mile section of the northbound lane. Each section was approximately 0.2 miles long.

6.1.2 Asphalt Mixture Design

The gradation was a 9.5-mm NMAS blend that was on the fine side of the primary control sieve. The mixture contained 15 percent RAP. The blended aggregate gradation is shown in Table 5. The t/NMAS for this project was 4.7. A performance grade (PG) binder of PG 58V-22 was used. The asphalt mixture design was performed using 100 gyrations with the Superpave gyratory compactor. The mixture was designed with 4.0 percent air voids (AV) and had a voids in the mineral aggregate (VMA) result of 15.1 percent. The optimum AC was 6.3 percent. Table 6 summarizes the mixture design information. The mixture had passing results for the Hamburg wheel-tracking test's stripping inflection point and tensile strength ratio.

Table 5. Design Gradation Information

Sieve Size	Percent Passing	Specification Limits (%)		Production Tolerance (%)	
		Min	Max	Min	Max
¾ inch (19.0 mm)	100	100			
½ inch (12.5 mm)	99	100		99	100
⅜ inch (9.5 mm)	99			90	100
No. 4 (4.75 mm)	67	48	58	62	72
No. 8 (2.36 mm)	42	32	67	38	46
No. 16 (1.18 mm)	26				
No. 30 (0.60 mm)	17				
No. 50 (0.30 mm)	13				
No. 100 (0.15 mm)	8				
No. 200 (0.075 mm)	4.7	2.0	7.0	2.7	6.7

Table 6. Mixture Design Information

Mixture Design Property	Mixture Design	Specification
Opt. AC (%)	6.3	
AV (%)	4.0	Approx. 4.0
VMA (%)	15.1	≥ 15.0
VFA (%)	74	73 - 76

6.1.3 Field Verification of the Asphalt Mixture Design

Mixture acceptance data for the entire project was provided by the SHA and is shown in Table 7. Only a single sublot had failing AV and VMA results, but most sublots fell outside specification limits for voids filled with asphalt (VFA). Two thirds of the failing VFA results came from sublots with passing air voids and VMA. For example, a test with 4.0 percent air voids would need a VMA of at least 14.9 percent to pass the VFA requirement. However, VFA was not a pay item and does not factor into remove and replace decisions.

Table 7. Acceptance Data Summary

Property	N	Mean	Std. Dev.	Specification		Percent Out of Spec
				Min	Max	
AC (%)	29	6.5	0.2	5.9	6.8	3.4%
AV (%)		4.3	1.2	2.5	5.5	13.8%
VMA (%)		14.8	1.1	13.5	N/A	13.8%
VFA (%)		71.6	6.2	73	76	72.4%
D/A Ratio		1.3	0.2	0.6	1.6	0.0%
Pbe		4.6	0.2	N/A		

6.1.4 Density Measurement and Specifications

The state used a PWL specification for this project. The LSL for the control and test section were 91.0 to 91.5 percent, respectively. Ten nuclear density gauge readings were taken by the SHA using a Troxler 3540 gauge on the nights of August 21 (Control Section) and 22 (Test Section 1). Cores were taken at the beginning of the project and the nuclear gauge was correlated to these cores. The same gauge correction factor was used for the duration of the project.

6.1.5 Experimental Section Construction and Results

The mixture was delivered to the site using end dump trucks and deposited into a Weiler E2850A material transfer vehicle (MTV), which transferred it into a CAT AP1055F paver. Three rollers were used to compact the mix on this project. The breakdown roller was a 15-ton double drum Sakai SW990-1 roller. A 12-ton CAT CB54B roller was used as the intermediate roller and a 10-ton Dynapac CC224HF roller was used as the finishing roller.

The paver was operating at 27 to 35 feet/minute during the nights that were observed. There were only 12 trucks available and the distance from the plant to the site was about 30 minutes roundtrip. The mix was approximately 330^o F when delivered to the site in trucks and 310^o F behind the paver.

A CSS-1 tack was applied at a bar rate of 0.04 gal/yd^2 from the tack truck. The applied tack showed some streaks on the milled surface. The breakdown and intermediate rollers applied 7 to 13 vibratory passes each at various times during observation on the nights of August 21 and 22. The rollers would apply 7 to 11 passes and then the gauge operator would come behind them and check the mat density. If the results were desirable, the rollers would move up, and if they were not, they would continue rolling until they achieved their targeted density. The finishing roller applied seven passes in static mode on those two nights.

The original plan for the Control Section was to allow the contractor to pave under normal operations on the first night (August 21) and then have them focus on reducing roller spacing for only 1000 feet for the test section while data was being recorded. A random section on a straightaway was selected for the Control Section on the first night. Normal paving operations were used in every case except the intermediate roller. The intermediate roller performed 21 passes while data was being recorded. The time between the first pass of the breakdown roller and the final pass of the intermediate roller was 33 minutes.

The plan for the test section was to slow the paver down and have the breakdown and intermediate rollers operate significantly closer together than normal. However, the paving foreman who helped formulate the plan was not present on this night and another foreman was managing the paving crew. During the paving of the test section, the paver increased in speed to 33 feet/minute while the breakdown roller had to stop to refill water. The roller spacing time was 39 minutes in this test section. The paver was moving much too quickly for the breakdown roller to be able to slow down and the intermediate roller was struggling to keep up with the breakdown. Furthermore, the intermediate roller did not operate as the plan intended. For example, at the point in the test section where operations were being observed, the intermediate roller made eight passes between the center and on the left side of the mat before applying a pass to the right side of the mat. A total of 15 minutes passed between the breakdown roller's final pass and the intermediate roller's first pass on the right side of the mat.

The nuclear density gauge readings taken as a part of that experiment on the nights of August 21 (Control Section) and 22 (Test Section 1) are shown in Table 8. A summary of the density measurements for acceptance for the entire project is also shown in Table 9. Cores were taken at the beginning of the project and the nuclear gauge was correlated to these cores. The same gauge correction factor was used for the duration of the project. The gauge measurements were taken by the SHA using a Troxler 3540 gauge.

The minimum density from August 21 (90.4 percent) caused the standard deviation of that dataset to be higher than those from August 22. If this point were removed, the standard deviation of the remaining data from August 21 would be 1.0 percent. All results but one were above the new LSL of 91.5 percent of G_{mm}. Only one test from the entire project resulted in a failing density, but 10 percent were below the LSL of 92.0 percent anticipated to be implemented in 2019. The densities in the experimental sections were greater than the entire project, and the test section actually had a significantly lower standard deviation compared to the whole project.

The averages from the two observed nights were both 2 percent greater than the new LSL of 91.5 percent. The standard deviations of the first night were double that of the second night, but this is almost entirely due to the single failing density result that was measured on the first night. Both the average and the standard deviation of the densities on the second night were excellent.

Table 8. Nuclear Density Results for Control and Test Sections

Reading	8/21/2018 (Control)	8/22/2018 (TS1)
1	92.1%	93.4%
2	93.3%	94.7%
3	95.5%	94.3%
4	94.6%	95.4%
5	94.0%	94.3%
6	92.8%	93.2%
7	93.7%	93.0%
8	90.4%	94.5%
9	93.7%	94.6%
10	94.4%	94.4%
Mean	93.5%	94.2%
Std. Dev.	1.4%	0.7%
Min.	90.4%	93.0%
Max.	95.5%	95.4%

Table 9. Nuclear Density Results for the Entire Project

Statistic	Value
Mean	93.4%
Std. Dev.	1.1%
Min.	91.4%
Max.	96.8%
Percentage Below 91.5	0.3%
Percentage Below 92.0	10.0%

The dielectric values were correlated to the nuclear gauge densities from the same night [During the review of this report, one of the comments was that the DPS measurements should have been correlated to those obtained from the field cores instead of the nuclear density gauge]. The correlations between dielectric values and nuclear densities for both experimental sections are shown in Figure 5. Note that the goodness-of-fit for the Control Section is significantly better than that from the test section. The range of dielectric values from the Control Section is almost three times larger than those from the test section while the range of nuclear densities of the Control Section is twice as large as the range from the test section. This could have an effect on the poor goodness-of-fit for the test section.

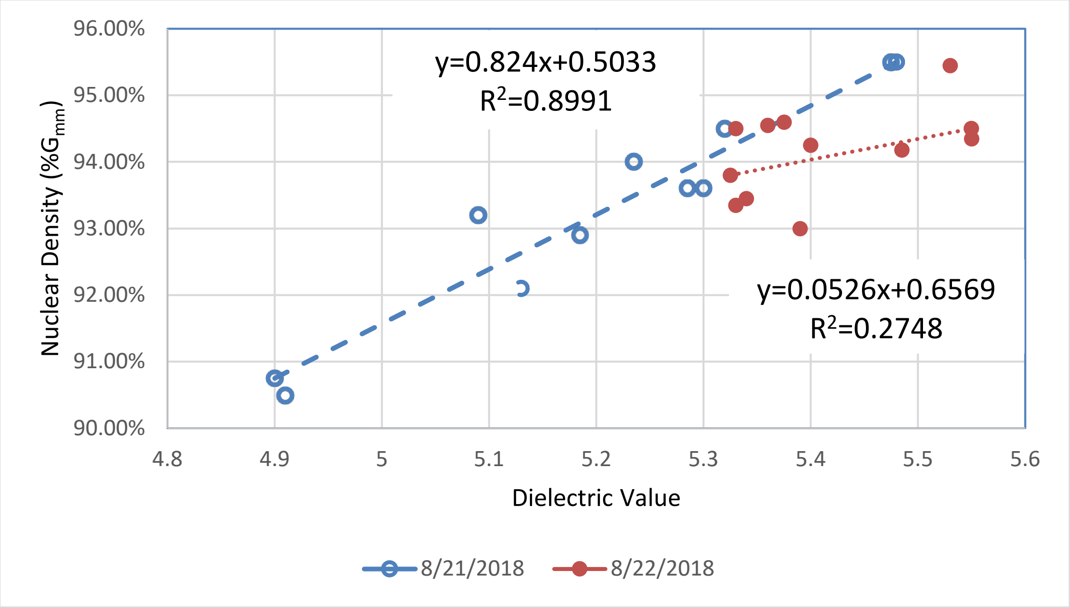


Figure 5. Dielectric Values vs. Nuclear Density

6.1.6 Utilization of New Technologies

A ground penetrating radar density profiling system (GPR DPS) was used to measure density in the two 1000-foot sections. It measured the dielectric value of the pavement continuously and the nuclear gauge was used in 100-foot intervals at a 2-foot offset. The dielectric values come from the ground penetrating radar (GPR) attachments on the density profiling system (DPS). The sensors are spaced at 2 feet apart from each other on the GPR DPS and the equipment can measure an entire 12-foot lane in two passes. No other new technologies such as the paver-mounted thermal profiler (PMTP), WMA, or intelligent compaction were used as part of this project.

6.1.7 Summary of State Findings

For State 1, the percent density increased 0.7 percent due to the increase in the lower limit from 91.0 percent to 91.5 percent. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - The normal breakdown roller pattern included five passes in vibratory mode and the intermediate roller pattern included seven passes in vibratory mode.
    - The standard deviations of density results were significantly improved.
- Observations for specification development (agencies):
    - The field density acceptance quality measure was PWL. The lower specification limit for this project was 91.5 percent.
    - The specification had incentives and disincentives.

6.2 Phase 3 – State 2 (P3-S2)

6.2.1 Project Description

The demonstration project was planned on a rural four-lane state highway. It was approximately 3.0 miles long, and the project scope included paving 1.75 inches of new surface mixture. The demonstration sections were placed in the eastbound lane of the state highway in late August 2018 and early October 2018.

The strategies to achieve higher density considered in this project included reducing the design gyration level (N_{des}), designing at lower air voids, and increasing compaction effort. The sections also included those paved with conventional and spray pavers for comparison. These strategies were evaluated in eight experimental sections as described below. Their paving dates and mat thicknesses are given in Table 10.

1. Group 1 – Paving with a spray paver. Four sections were planned in this group.
    a. Control Section 1. The state's standard mixture design (80 gyrations and 4.0 percent air voids) was used.
    b. Test Section 1: The state's standard mixture was re-designed using 60 gyrations and at 3.5 percent design air voids.
    c. Test Section 2: The same mix was re-designed using 60 gyrations and at 3.0 percent design air voids.
    d. Test Section 3: This section was constructed with the mix used in Test Section 1 but with increased field compaction effort (two additional rollers were added to the paving train).
2. Group 2 – Paving with a conventional paver. Four sections were planned to compare with those in Group 1.
    a. Control Section 2. This section used the same mix design as Control Section 1.
    b. Test Section 4: This section used the same mix design as Test Section 1.
    c. Test Section 5: This section used the same mix design as Test Section 2.

d. Test Section 6: This section used the same mix design and increased field compaction effort as Test Section 3.

Table 10. Section Paving Dates

Section	Date	Thickness (in.)
Spray Paver: Control	8/17/2018	1.75
Spray Paver: 3.5% AV Mixture	8/23/2018	1.75
Spray Paver: 3.0% AV Mixture	8/27/2018	1.75
Spray Paver: 3.5% AV Mixture and Increased Effort	8/28/2018	1.75
Conventional Paver: 3.5% AV and Increased Effort	10/3/2018	1.75
Conventional Paver: Control	10/4/2018	1.75
Conventional Paver: 3.0% AV	10/5/2018	1.75
Conventional Paver: 3.5% AV	10/6/2018	1.75

6.2.2 Asphalt Mixture Design

The eight sections were constructed using three mixture designs. The 12.5-mm NMAS gradations used in these designs (Table 11) were on the coarse side of the primary control sieve. The t/NMAS for this project was 3.5. The control mixture was designed with a N_{des} of 80 gyrations and design air voids of 4.0 percent. This mixture was then redesigned to have design air voids of 4.0 percent with a N_{des} of 60 gyrations. The binder contents were then increased so that the mix design would achieve 3.5 and 3.0 percent air voids. This technique is often referred to as the air void regression approach. The volumetric properties of the three mix designs are summarized in Table 12.

Table 11. Mixture Design Gradations

Gradation	Control Mixture (N_{des} = 80) (Percent Passing)	3.5% AV Mixture (N_{des} = 60) (Percent Passing)	3.0% AV Mixture (N_{des} = 60) (Percent Passing)
¾ inch (19.0 mm)	100	100	100
½ inch (12.5 mm)	96	96	96
⅜ inch (9.5 mm)	85	86	87
No. 4 (4.75 mm)	53	55	59
No. 8 (2.36 mm)	33	35	38
No. 16 (1.18 mm)	21	23	25
No. 30 (0.60 mm)	15	17	17
No. 50 (0.30 mm)	10	11	11
No. 100 (0.150 mm)	6	7	7
No. 200 (0.075 mm)	4.8	5.6	5.6

Table 12. Mixture Design Volumetric Properties

Property	Control Mixture	3.5% AV Mixture	3.0% AV Mixture
AV (%)	4.0	3.5	3.0
AC (%)	4.8	5.0	5.4
VMA (%)	14.3	14.0	14.3
VFA (%)	72	75	80

6.2.3 Field Verification of the Asphalt Mixture Design

Table 13 summarizes the contractor’s quality control test results. Three samples were tested to obtain volumetric properties for the four sections paved with the spray paver, and only two samples were tested for the other sections.

Table 13. Plant Quality Control Average Results

Mixture Section	Asphalt Content (%)	Laboratory Compacted Air Voids (%)	VMA (%)	VFA (%)
Spray Paver: Control	4.8	3.8	14.1	73.3
Spray Paver: 3.5% AV Mixture	4.9	3.8	14.0	72.6
Spray Paver: 3.0% AV Mixture	5.3	3.4	14.5	76.5
Spray Paver: Increased Effort	4.8	4.1	14.0	71.1
Conventional: Paver Control	4.8	4.2	14.6	71.0
Conventional Paver: 3.5% AV Mixture	5.1	3.6	14.3	74.8
Conventional Paver: 3.0% AV Mixture	5.3	3.5	14.5	76.1
Conventional Paver: Increased Effort	4.9	3.8	14.3	73.8

6.2.4 Density Measurement and Specifications

This SHA has a PWL specification with an LSL of 92.0 percent and a USL of 97.0 percent for mat density. Cores were removed from the test sections by the contractor.

6.2.5 Experimental Section Construction and Results

For the sections paved with the spray paver, the mixtures were delivered to the site in dump trailers and loaded directly into a Roadtec SB2500D MTV and then transferred into a Vogele spray jet paver. The asphalt plant was approximately fifteen miles away, which was a 20-minute haul time to the paving site. Compaction for the first three sections was performed by two vibratory steel drum rollers and a static steel drum roller. The breakdown and intermediate rollers were 12-ton steel drum CAT CB 54 vibratory rollers. A 14-ton static steel drum CAT CB 64 was used as the finishing roller. For the increased field compaction effort section, a 12-ton Volvo DD118 and a CAT 14-ton CB 13 were added to the paving train (four rollers total). The conventional paver used for the other sections in this project was a CAT 1055F. Otherwise, the same paving train configuration was used for the conventional-paver sections. Nine vibratory passes were used for the breakdown roller, three vibratory passes were used for the intermediate roller, and three static passes were necessary for the finishing roller to remove the roller marks from the mat. Densities of the sections were monitored by the contractor with a Trans Tech PQI 380 non-nuclear density gauge. The core densities for the spray paver sections are shown in Table 14, and those for the conventional paver sections are included in Table 15.

Table 14. Spray Paver Average Core Densities (Percent G_{mm})

Test Section	Spray Paver Control	Spray Paver 3.5% AV Mixture	Spray Paver 3.0% AV Mixture	Spray Paver Increased Effort
Average	93.23	94.50	94.65	94.55
Standard Deviation	0.59	0.70	NA	NA
Number of Tests	3	3	2	2
Minimum	92.8	93.7	94.3	94.3
Maximum	93.9	95.0	95.0	94.8
Date Constructed	August 17	August 23	August 27	August 28

Table 15. Conventional Paver Average Core Densities (Percent G_{mm})

Test Section	Conventional Paver Control	Conventional Paver 3.5% AV Mixture	Conventional Paver 3.0% AV Mixture	Conventional Paver Increased Effort
Average	92.60	94.93	95.80	95.20
Standard Deviation	0.10	0.38	NA	NA
Number of Tests	3	3	2	2
Minimum	92.5	94.5	95.6	94.2
Maximum	92.7	95.2	96.0	96.2
Date Constructed	October 4	October 6	October 5	October 3

Figure 6 shows the average relative densities from the core densities. On average, all the sections met the LSL of 92.0 percent. The first four columns are for the sections paved with the spray paver, and the others are for the conventional paver sections. The following observations can be drawn from the density results:

- Lowering the design air voids in conjunction with lowering the N_{des} could result in a change in the aggregate gradation and a higher binder content. These, in turn, resulted in a higher in-place density. However, lowering the design compaction effort appeared to have a higher impact on the in-place density than lowering the design air voids.
- Increasing the field compaction effort yielded a similar or higher in-place density, but these sections already had high in-place densities (94.5 percent and above).

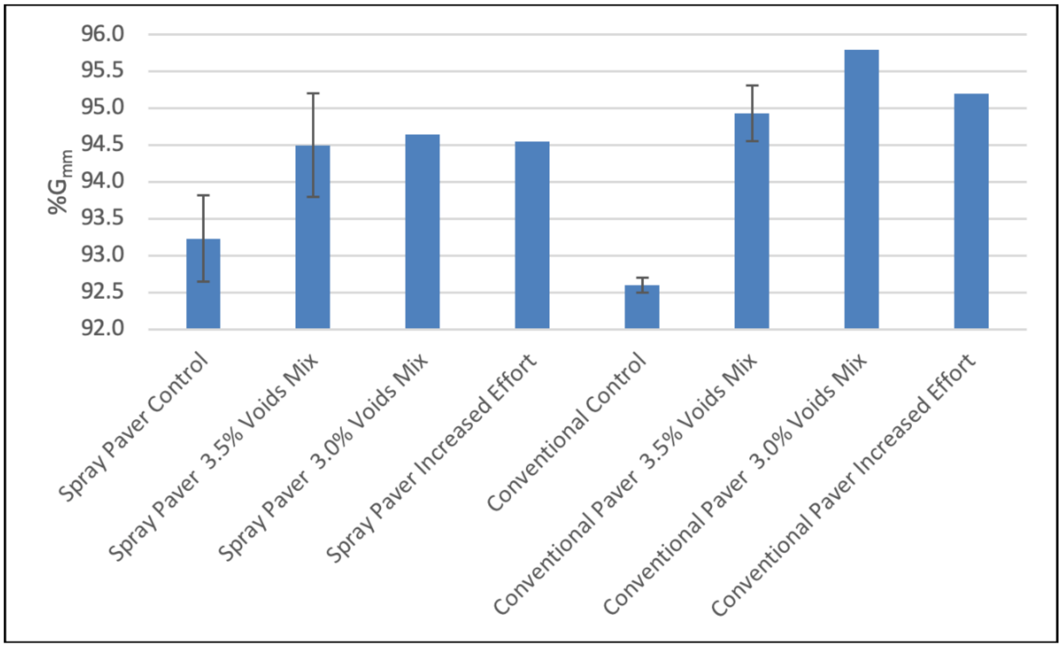


Figure 6. Average Core Density

6.2.6 Utilization of New Technologies

No new technologies such as the PMTP, WMA, intelligent compaction, or GPR DPS were used as part of this project.

6.2.7 Summary of State Findings

For State 2, the percent density increased 1.3 to 3.2 percent due to changes in N_{des}, lower design air voids, and increased field compaction effort. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - The normal breakdown roller pattern included nine passes in vibratory mode and the intermediate roller pattern included three passes in vibratory mode.
    - The standard deviations of density results were not improved but these values were already excellent (below 1.0 percent).
- Observations for specification development (agencies):
    - The field density acceptance specification was PWL. The lower specification limit for this project was 92.0 percent, and the upper specification limit was 97.0 percent.
    - The specification had incentives and disincentives.

6.3 Phase 3 – State 3 (P3-S3)

6.3.1 Project Description

The paving site selected for this demonstration project was a 20-mile section of a rural two-lane state highway. The project scope included paving 1.5 inches of new asphalt mixture. The project was constructed in early October 2018. The demonstration project included 13 sections constructed in four days to evaluate various factors. A control section was planned for each day of construction to make it easier to compare the factors evaluated in that day.

1. Day one included two sections, each approximately one mile in length, to compare the effect of delivery methods. The state's standard mix design and compaction method were used in both sections.
    a. Day 1 Control Section 1: A windrow elevator was used in this section.
    b. Day 1 Test Section 1: The same standard mix design was used, but it was paved using an MTV instead of the windrow elevator.
2. Day two included five sections, each approximately 1000 feet in length, to evaluate a variety of compaction rollers.
    a. Day 2 Control Section 2: The state's standard mixture design and MTV were used.
    b. Day 2 Test Section 2: A pneumatic roller was added for intermediate compaction.
    c. Day 2 Test Section 3: A vibratory pneumatic roller was added for intermediate compaction.
    d. Day 2 Test Section 4: A pneumatic roller and a combination roller were added for intermediate compaction.
    e. Day 2 Test Section 5: A combination roller was added for intermediate compaction.
3. Day three included three sections to evaluate high RAP content and additional asphalt content.
4. Day four also included three experimental sections to evaluate high RAP content with adjusted PG grade and a section with finer gradation.

For the demonstration project, the variables evaluated included (a) using an MTV, (b) changing the rolling pattern, (c) using mixtures with higher RAP contents, and (d) finer gradations. There were four control sections (i.e., four sets of comparisons). Each comparison was conducted as part of an entire day's paving. The experimental sections placed for this study follow.

1. Day 3 Test Section 6: Standard mixture with softer binder.
2. Day 3 Test Section 7: Standard mixture with extra 0.5 percent binder.
3. Day 3 Control Section 3: The state's standard mixture.
4. Day 4 Test Section 8: Standard mixture with high RAP content.
5. Day 4 Test Section 9: Standard mixture with finer gradation.
6. Day 4 Control Section 4: The state's standard mixture.

6.3.2 Asphalt Mixture Design

The gradation was a 9.5-mm NMAS blend that was on the coarse side of the primary control sieve. The standard mixture contained 35 percent RAP and 5 percent RAS. The blended aggregate gradation is shown in Table 16. The t/NMAS was 4.0. A PG 58V-34 binder with a WMA additive was used. The asphalt mixture design was performed using 50 gyrations with the Superpave gyratory compactor. The optimum binder content of the standard mixture was 5.4 percent. Mixture design information is shown in Table 17. Table 18 shows a list of modifications performed to the standard mixture.

Table 16. Design Gradation Information

Particle Size	Gradation		
	Percent Passing	Specification Limit (%)	
		Min	Max
¾ inch (19.0 mm)	100	100	
½ inch (12.5 mm)	98	98	100
⅜ inch (9.5 mm)	95	93	100
No. 4 (4.75 mm)	70	70	87
No. 8 (2.36 mm)	45	45	65
No. 16 (1.18 mm)	28	25	41
No. 30 (0.60 mm)	19	15	31
No. 50 (0.30 mm)	12	10	21
No. 200 (0.075 mm)	5.7	4.0	10

Table 17. Mixture Design Information

Mixture Design Property	Mixture Design	Criteria
Opt. AC (%)	5.4	
AV (%)	3.9	3.0 – 5.0
VMA (%)	15.1	15.0
VFA (%)	74.1	65 - 75
D/A Ratio	1.21	0.7 – 1.7

Table 18. Asphalt Mixtures Used in this Study

Mixture ID	Type	Mixture Composition
SLX_S	Standard SLX	PG 58V-34, 35% RAP, 5% RAS
SLX_M_40-40_R50%	Modified SLX	PG 40-40, 50% RAP, 5% RAS
SLX_S_58V-34_0.5	Standard SLX	PG 58V-34 with 0.5% higher AC, 35% RAP, 5% RAS
SLX_M_52-40_R50%	Modified SLX	PG 52-40, 50% RAP, 5% RAS
SLX_M_58V-34_LCR10%	Modified SLX	PG 58V-34 with 10% less crushed rock (LCR) (10% more washed sand), 35% RAP, 5% RAS

6.3.3 Field Verification of the Asphalt Mixture Design

Acceptance testing was conducted during the construction of these test sections. The results of mixture volumetric properties of several sections are shown in Table 19.

Table 19. Acceptance Mixture Properties

Section	Lab. AV (%)	AV Tolerance (%)	AC (%)
Day 1 Section 1 (Control)	1.5	3.0 – 5.0	6.3
Day 1 Section 2 (MTV)	3.4		5.5
Day 2 Section 2	2.7*		6.1*
Day 2 Section 5	3.9		5.4

*Results provided by the contractor

6.3.4 Density Measurement and Specifications

The state used a minimum lot average specification based on the in-place density. The LSL was 92.5 percent. Density was checked on-site by the agency using a pavement quality indicator (PQI). Six-inch cores were used to measure density for acceptance purposes.

6.3.5 Experimental Section Construction and Results

The asphalt mixture was delivered to the site using belly dump trucks and deposited in a windrow. The mixture was transferred from the windrow to the paver using a Barber Greene BG650 windrow elevator. A CAT AP 1055F paver with SE60V screed was used to lay the mixture. A Weiler E2850A MTV was utilized in part of this demonstration project.

Two 14-ton CAT CB15 rollers operating in high frequency vibratory mode were used as the breakdown rollers and both were used to cover the lane in echelon. A 14-ton CAT CB64B roller was used in static mode as finishing roller. This rolling pattern was kept constant throughout the entire project. On Day 2, two more rollers were added as intermediate rollers utilizing different combinations. Table 20 shows the rollers used for each test section on Day 2.

Table 20. Rollers Used for Each Experimental Section on Day 2

Section	Intermediate
Day 2 Test Section 2	7-Tire Pneumatic Static Mode, SAKAI GW750-2, (10-ton)
Day 2 Test Section 3	7-Tire Pneumatic Vibratory Mode, SAKAI GW750-2
Day 2 Test Section 4	7-Tire Pneumatic Static Mode, SAKAI GW750-2, Combination Roller Vibratory Mode, Ingersoll Rand SD-77DA (8-ton)
Day 2 test Section 5	Combination Roller Vibratory Mode, Ingersoll Rand SD-77DA

The asphalt plant was located about 14 miles from the paving site and the hauling time was estimated to be about 16 minutes. The plant is a drum plant and contains separate cold bins for the fractionated RAP. The receiving surface was to be overlaid with 1.5 inches of asphalt mixture. The paver speed ranged from 15 feet/minute to 20 feet/minute. A CFS-1 diluted (1:1) emulsion was applied at a bar rate of 0.1 gal/yd^2 to the freshly laid asphaltic concrete. The seal application appeared to be uniform throughout all the experimental sections.

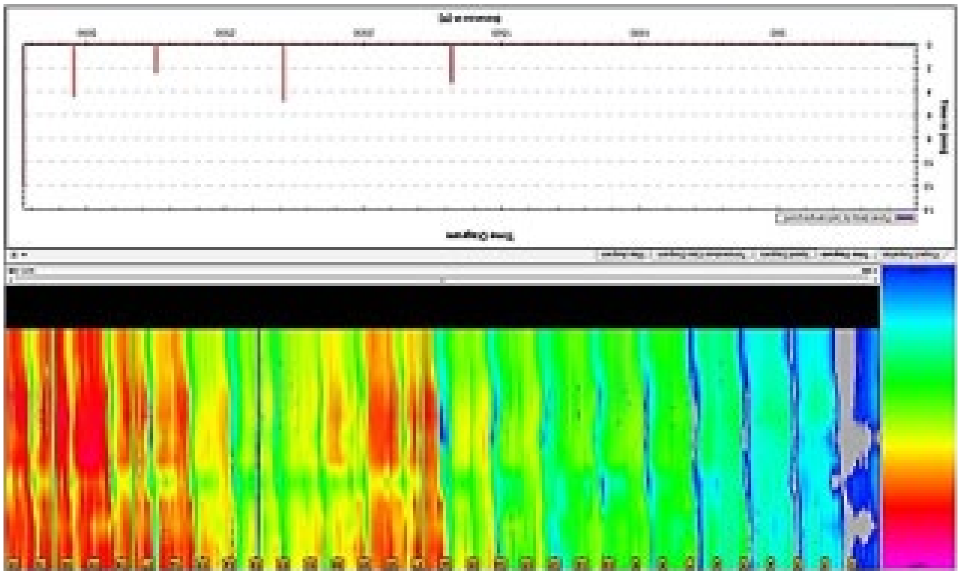
Table 21 shows a summary of the rolling patterns applied on the experimental sections of the first two days of this demonstration project. On the first day, the ambient temperature at the beginning of paving was 40^o F, and it was cloudy and windy. The first section involved the normal paving operation used throughout the entire project. At the beginning of Day 1, temperatures behind the paver ranged from 240 to 245^o F, after a while temperatures ranged from 265 to 270^o F. Two 14-ton CAT CB15 rollers operating in echelon worked in high frequency vibratory mode. The normal paving pattern included one static pass and four vibratory passes of each breakdown roller plus five static passes of the finishing roller. At the beginning of the Control Section, more compactive effort was applied to try to compensate for the lower mixture temperature.

Table 21. Rolling Pattern Summary

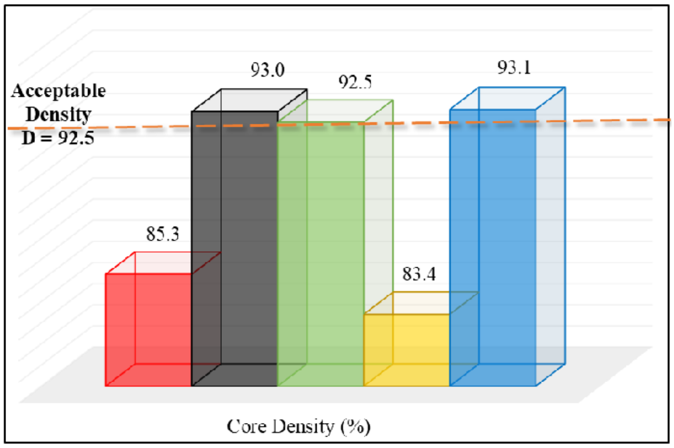
Section	Number of Passes by Roller			Temperature Behind Paver (°F)
	Breakdown	Intermediate	Finishing	
Day 1 Control Section 1	2 Static Mode 14 Vibratory	N/A	5 - 7	240 - 245
	2 Static Mode 10 Vibratory	N/A	5 - 7	265 - 270
Day 1 Test Section 1 (MTV)	2 Static Mode 10 Vibratory	N/A	5	275 - 280
Day 2 Control Section 2	2 Static Mode 8 Vibratory	N/A	5	260 - 275
Day 2 Test Section 2	2 Static Mode 8 Vibratory	3 Static Mode	5	270 - 280
Day 2 Test Section 3	2 Static Mode 8 Vibratory	3 Vibratory Mode	5	270 - 280
Day 2 Test Section 4	2 Static Mode 8 Vibratory	3 Static Mode 3 Combination Roller Vibratory	5	270 - 285
Day 2 Test Section 5	2 Static Mode 8 Vibratory	3 Combination Roller Vibratory	5	270 - 280

PMTP was utilized in this project. Collected temperatures allowed the paving operators to identify zones of low pavement temperatures that may require extra compaction efforts or may affect the uniformity of the mat. After about a mile, the mixture elevator was removed from the paver and an MTV was placed in front of the paver on the same lane.

Figure 7 and Figure 8 show examples of the obtained thermal profile for the mixtures delivered by either windrow elevator or MTV and the density of cores. The largest color variation would be from blue (coldest) to pink (hottest) as shown in the color legend at the top of each page of the scan. The images clearly show that the windrow elevator had the largest thermal segregation and also yielded the largest variance in density, as shown in the bar graph to the right of the scan. Both bar graphs show the line of minimum average density of 92.5. For a 'single point' density, generally a density of 90 or above would be considered acceptable; conversely, the two tests showing 83.4 and 85.3% would be considered not acceptable by all industry standards.

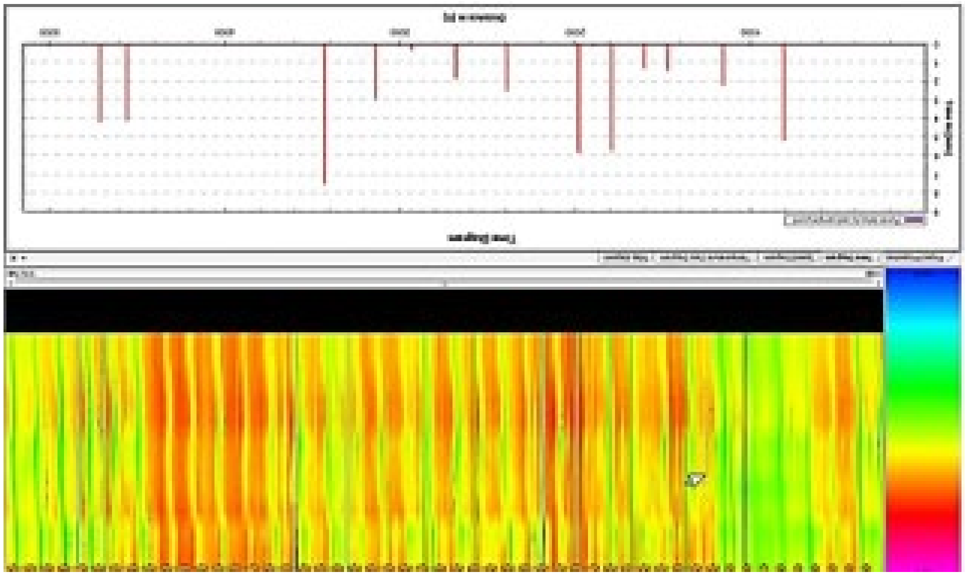


(a) Windrow Elevator ICTS Profile

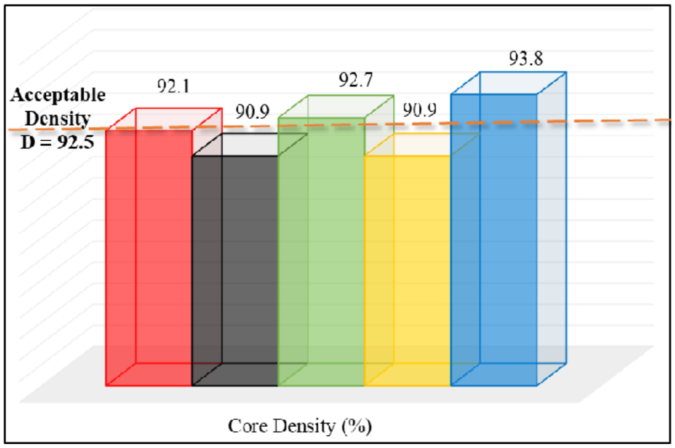


(b) Windrow Elevator In-Place Core Density

Figure 7. ICTS Profile and Single Core Density for Mixtures Delivered by Windrow Elevator



(a) MTV ICTS Profile



(b) MTV In-Place Core Density

Figure 8. ICTS Profile and Single Core Density for Mixtures Delivered by MTV

On the second day, the ambient temperature at the beginning of paving was 40º F and it was sunny. The MTV equipment was used throughout the day on five different experimental sections that were about 1000 feet long with approximately 200 feet of transition zones. The differences among sections were the rolling pattern and incorporation of a pneumatic roller working in either static or vibratory mode and a combination roller (steel drum in the front with rubber rear tires). The same breakdown rolling pattern was maintained throughout (two rollers operating in echelon). The pneumatic roller did not have a skirt to help maintain the tire warmth, and the tires picked up mixture at different locations. Density checked on-site by the agency using a PQI was uniform throughout all of the sections; however, they did not have lab results ready to compute density (percent G_{mm}). Based on PQI readings, density after breakdown roller operation was approximately 95 to 96 percent of G_{mm}. In addition, density after the use of pneumatic intermediate rollers increased between 0.5 to 1.0 percent.

Similar to the first two days of paving, Day 3 began after waiting for temperatures to rise above 32^{o} F. In this section, the ‘standard’ paving operations were used, which included a paver, MTV, and three steel double drum rollers. The normal compaction pattern of one static pass and four vibratory passes of each breakdown roller plus five static passes of the finishing roller was applied on each section of Day 3. In the first section, the SLX mixture was modified by using a PG 40-40 binder and 50 percent RAP (SLX_M_40-40_R50%). These modifications exhibited a change in visual appearance of the mixture that added a very glassy black shiny look to the mix. In addition, there was a noticeable change to the fumes from the windrow. However, after compaction, this section appeared visually similar to the control sections. Increasing the RAP content to 50 percent in the mixture seemed to have reduced the softer binder effects to the combined mix. Therefore, the first section did not really experience a significant improvement to compaction. The decision to increase the RAP content to 50 percent was based on preliminary laboratory testing that yielded similar indirect tensile strength results when compared to the standard/control mix and resulted in very similar field workability and compaction. The standard SLX mixture with 0.5 percent increased binder above the design target was used in the second section; this change did not provide significant changes to laydown or compaction.

Day 4 began with no delay for temperatures. This section again used the ‘standard’ paver, MTV, and three steel double drum rollers. The normal paving pattern of one static pass and four vibratory passes of each breakdown roller plus five static passes of the finishing roller was applied on each section of Day 3. The SLX mixture was modified by using a PG 52-40 and 50 percent RAP (SLX_M_52-40_R50%). In the second section, the coarse crushed rock was reduced by 10 percent and 10 percent fine natural sand was added (SLX_M_58V-34_LCR10%). Similar to Day 3, the following observations were reported by field engineers.

- A visual appearance producing a glassy black shiny look to the mix.
- A noticeable change to the fumes from the windrow seemed less petroleum-based.
- Similar appearance compared to the control sections after compaction.

Table 22 shows density measurements obtained from cores that were extracted by the SHA for Days 1 and 2. During Day 1, five cores were obtained from each section. The specification for this project was 92.5 percent minimum lot average density. On average, Day 1 Section 1 (control) failed to meet this criterion. In addition, laboratory compacted AVs were significantly low (1.5 percent) with high AC (6.3 percent). On average, Day 1 Section 2 (MTV) also failed the specification, however, a significant increase in density and reduction in variability (standard deviation) was obtained as results of the use of the MTV. Laboratory AVs and binder content were closer to the design values in this case.

Day 2 included five experimental sections approximately 1000 feet in length to evaluate the addition of a pneumatic roller with vibratory capabilities and a combination roller. On Day 2, the addition of a pneumatic roller in static mode did not affect the average density of Day 2 Section 2 compared to the Control Section. On the other hand, a combination of several rollers significantly increased the overall density of the remaining sections with lower variability (standard deviation results below 2.0). The addition of the combination roller on Day 2 Section

5 yielded the highest overall density (94.2 percent) with low variability (a standard deviation of 1.3 percent).

Table 22. Days 1 and 2 Acceptance Field Density (Percent G_{mm})

Section	Average	Std. Dev
Day 1 Control Section (windrow elevator)	89.5	4.7
Day 1 Test Section 1 (MTV)	92.1	1.2
Day 2 Control Section 2 (MTV)	92.8	3.3
Day 2 Test Section 2 (Pneumatic Static)	91.1	3.4
Day 2 Test Section 3 (Pneumatic Vibratory)	93.5	1.7
Day 2 Test Section 4 (Pneumatic Static + Combination Roller)	93.5	0.7
Day 2 Test Section 5 (Combination Roller)	94.2	1.3

Table 23 shows density measurements obtained from cores that were extracted by the SHA for Days 3 and 4. On Day 3, increasing the RAP content to 50 percent in the mixture seemed to have reduced the softer binder effects to the combined mix. Therefore, the first section did not really experience a significant compaction improvement. The decision to increase the RAP to 50 percent was based on preliminary laboratory testing that yielded similar indirect tensile strength results when compared to the standard/control mix and resulted in very similar field workability and compaction. The standard SLX mixture with 0.5 percent increased binder above the design target was used in the second section; this variation did not provide significant changes to placement or compaction.

On Day 4, there was a slight reduction in density with the slightly stiffer 52-40 and 50 percent RAP. In the second section, the coarse crushed rock was reduced by 10 percent and 10 percent fine natural sand was added (SLX_M_58V-34_LCR10%). The obtained in-place density results were in good agreement with field observations, indicating that the laydown and compaction of SLX_M_58V-34_LCR10% mixtures were fairly similar to the control mixture (SLX_S).

Table 23. Days 3 and 4 Acceptance Field Density (Percent G_{mm})

Section	Average	Std. Dev
Day 3 Test Section 6 (SLX_M_40-40_R50%)	91.4	2.7
Day 3 Test Section 7 (SLX_S_58V-34_0.5)	90.7	3.9
Day 3 Control Section 3	91.3	0.6
Day 4 Test Section 8 (SLX_M_52-40_R50%)	91.4	1.7
Day 4 Test Section 9 (SLX_M_58V-34_LCR10%)	93.7	0.5
Day 4 Control Section 4	93.5	3.0

A thermal visualization of the construction process provides important insights into the temperature consistency of the material and can open up new optimization potentials. Figure 9 shows temperature versus density measured using the standard/conventional coring technique. Figure 9 displays a linear correlation with R^2 equal to 0.76 between density and temperature. It suggests that, under these paving and temperature conditions, a minimum material temperature of 250 °F (critical minimum) during compaction may promote densities of 90% or greater.

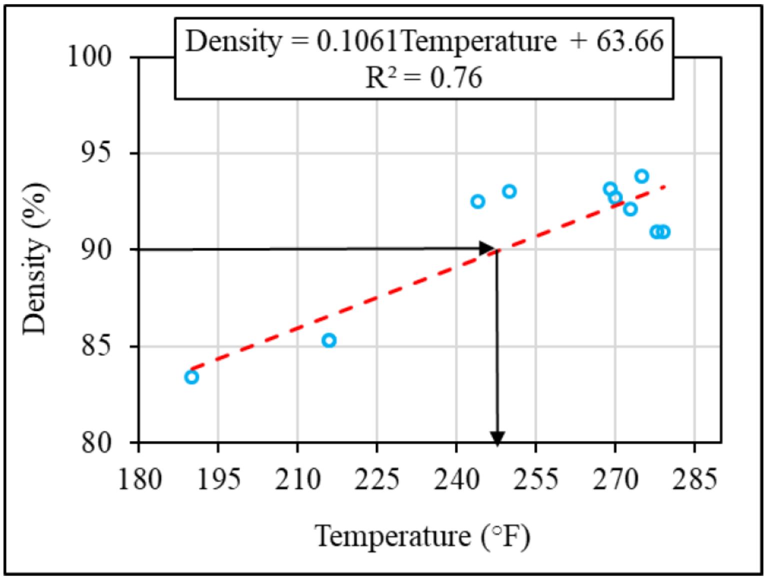


Figure 9. Correlation Between Temperature and In-Place Density of Core Samples

The average densities for each section measured by different techniques are shown in Figure 10. The results indicate a linear correlation between density measured using core samples with the other two techniques (i.e., GPR DPS and PQI); however, the PQI technique shows better correlation compared to the GPR DPS based on R^2 value. Although the PQI and GPR DPS techniques showed good correlation with averaged densities, an evaluation of individual core densities revealed that further testing and evaluation will be required.

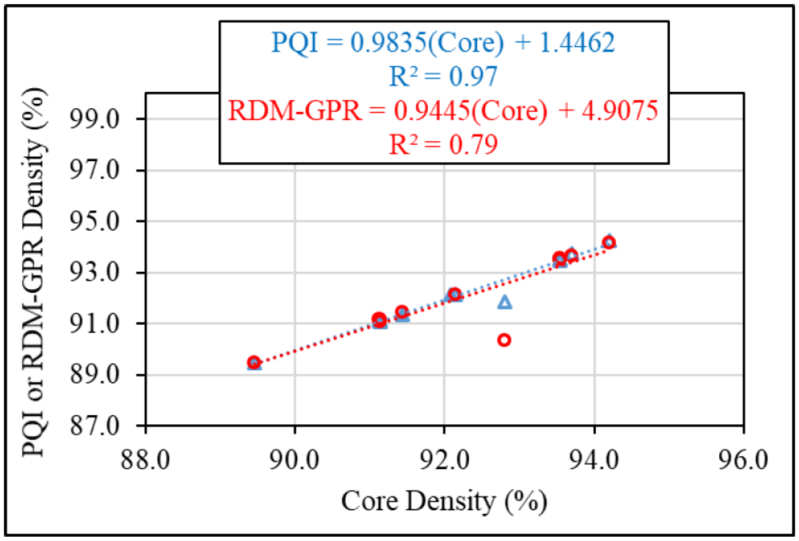


Figure 10. Comparison Between Core Density and Measured Density Using PQI, and GPR DPS

6.3.6 Utilization of New Technologies

A variety of devices were used to measure the density and temperature of the asphalt layer. These devices included the PMTP, Pavement Quality Indicator (PQI), and GPR DPS. The PMTP was used to monitor real-time thermal profile of the road during the construction paving. The

PQI and GPR DPS were employed to measure the in-place density of the layers. The recorded densities were then compared to traditional coring and density measurement methods. In addition, a WMA additive was used in the asphalt mixtures produced with the PG 58—34 binder.

6.3.7 Summary of State Findings

For State 3, the percent density increased between 2.4 to 3.1 percent when the compaction pattern was modified. Modification of the control (standard) mixture with changes in binder content, binder grade, and gradation changes did not provide an increase in density. MTVs provide an effective method to minimize thermal segregation, and therefore, provide improved temperature and density consistency. PMTP is an effective measuring technique that provides real-time information to the producer for improving temperature consistency that will result in more uniform densities.

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

- Observations for field operations (contractors):
    - The normal breakdown roller pattern includes one pass in static mode and four passes in vibratory mode utilizing two rollers in echelon. The intermediate roller pattern changed throughout the entire project.
    - Pneumatic rollers provided an improved mode of compaction. More specifically, the combination roller (CR) provided a consistent improvement compared to the 'Standard' three double drum steel roller compaction method.
    - The standard deviations of density results were significantly improved when the compaction pattern was modified
- Observations for specification development (agencies):
    - The field density acceptance specification was lot average. The minimum specified density for this project was 92.5.
    - Random sample cores with averaging of five tests per lot dampens density variability compared to single test results. The use of non-destructive testing equipment could provide opportunities for a more rigorous acceptance procedure.
    - The specification had incentives and disincentives.

6.4 Phase 3 – State 4 (P3-S4)

6.4.1 Project Description

The construction project was located on a high-volume, four-lane interstate highway. The project scope included milling approximately 3 inches of the existing asphalt mixture and paving 3 inches of new asphalt mixture. The project was constructed in late September 2018. For the demonstration project, the strategy to achieve higher density involved examining the benefits of the oscillatory roller, pneumatic roller, and additional AC. The experimental sections placed for this study follow.

1. Control Section 1: The state's standard mixture design was used.

2. Test Section 1: Oscillating roller as finishing roller.
3. Test Section 2a: Oscillating roller as intermediate roller.
4. Test Section 2b: Oscillating roller as intermediate roller (one day after TS2a).
5. Test Section 3: Pneumatic roller as intermediate roller.
6. Control Section 2: The state's standard mixture design.
7. Test Section 4: Mixture design adjusted using air void regression approach.

The sections being evaluated were placed on top of 9 inches of a new 25-mm NMAS mixture. The oscillating test section was placed in the outside lanes of the project in the southbound direction and the pneumatic and control sections were placed in the outside lane in the northbound direction.

6.4.2 Asphalt Mixture Design

The gradation was a 19.0-mm NMAS blend that was on the fine side of the primary control sieve. The blended aggregate gradation is shown in Table 24. The t/NMAS was 4.0. A PG 70-22 binder was used. The asphalt mixture design was performed using 80 gyrations with the Superpave gyratory compactor. The control mixture was designed with 4.0 percent AV and had a VMA of 14.0 percent. The optimum AC was 4.8 percent. Air void regression was performed to reach 3.2 percent air voids, resulting in an optimum AC of 5.1 percent. Mixture design information is shown in Table 25.

Table 24. Control Mixture Gradation

Gradation	Percent Passing		Specification Limit (%)	
	Control Mixture 1	Control Mixture 2	Min.	Max.
1 inch (25.0 mm)	100	100	100	
¾ inch (19.0 mm)	96	96	90	100
½ inch (12.5 mm)	80	80		90
⅜ inch (9.5 mm)	73	73		
No. 4 (4.75 mm)	48	50		
No. 8 (2.36 mm)	31	34	23	49
No. 30 (0.60 mm)	20	22		
No. 50 (0.30 mm)	14	14		
No. 100 (0.15 mm)	9	9		
No. 200 (0.075 mm)	4.6	4.8	2.0	8.0

Table 25. Control Mixture Design

Property	Control Mixture	Air Void Regressed	Criteria
Op. AC (%)	4.8	5.1	
AV (%)	4.0	3.2	4.0
VMA (%)	14.0	14.0	Min 13.5
VFA (%)	72	72	70 - 78

6.4.3 Field Verification of the Asphalt Mixture Design

No verification results were reported by the SHA on this project.

6.4.4 Density Measurement and Specifications

The state used a PWL specification based on the in-place density. The target density was 95 percent and the LSL and USL were 91.5 and 97.0 percent, respectively. Six-inch cores were used to measure density. Densities of the sections were monitored with a Troxler 3440 nuclear gauge.

6.4.5 Experimental Section Construction and Results

The mixtures were delivered to the site in dump trailers and loaded directly into a CAT AP1055E asphalt paver. The paving site was approximately a 45-minute haul time from the asphalt plant. Compaction for the oscillating test section was performed using two vibratory steel drum rollers and an oscillating steel drum roller. The breakdown roller was a 14-ton Hamm HD+120i High Frequency roller with the vibratory and frequency settings set to high, followed by another Hamm HD+120i High Frequency roller with the vibratory and frequency settings set to high. A 14-ton Hamm Oscillation HD 110+i was used as the finishing roller with the vibratory set to 30 and the oscillation set to 23. For the Control Section, a CAT 12-ton CB 54 vibratory steel drum roller was used as the finishing roller. The mixture was compacted to 3 inches but averaged 3.6 inches in the test sections because of cross slope adjustments. Even though this was an intermediate layer, it would be open to traffic during the winter months. An undiluted SS1-H tack coat was applied at a spray rate of 0.06 gal/yd2.

Test Section 1 was placed in the southbound outside lane on September 20, 2018. In this section, the oscillating roller was used as the finishing roller. This test section was 3,208 feet in length and contained 706 tons of mix. Two static and seven vibratory passes were used for the breakdown roller, two static and eleven vibratory passes were used for the intermediate roller, and five static and six oscillating passes were used for the finishing (oscillating) roller.

Test Section 2 was divided into two sections: one paved on September 20, 2018 and the second on September 21, 2018. The oscillating roller was used as the intermediate roller. This test section was 3,190 feet in length and contained 702 tons. Two static and nine vibratory passes were used for the breakdown roller, two static and nine oscillating passes were used for the intermediate (oscillating) roller, and four static and five vibratory passes were used for the finishing roller.

Test Section 3 (pneumatic section) was placed on September 21, 2018 in the northbound outside lane. This section was 1,550 feet in length and contained 341 tons of mix. This section used a Dynapac pneumatic roller as the intermediate roller. Two static and seventeen vibratory passes were used for the breakdown roller, nineteen static passes were used for the intermediate (pneumatic) roller, and three static and eight vibratory passes were used for the finishing roller. This section was shorter than the other test sections because damage to the mat was caused by asphalt mixture being picked up on the pneumatic roller's tires. The pneumatic roller was not in the best condition and the contractor stated that it was rarely used.

Control Section 1 was placed on September 28, 2018 in the northbound right lane. This section was 5,032 feet in length and contained 1,107 tons of mix. Two static and nine vibratory passes were used for the breakdown roller, two static and nine vibratory passes were used for the intermediate roller, and three static and eight vibratory passes were used for the finishing roller.

Table 26 shows the average density and descriptive statistics of Control Section 1 and Test Sections 1 to 3. Figure 11 shows the average core densities. The core density test results in Figure 11 show little difference in density between the sections; all sections were over 94.0 percent, and most reached the target 95.0 percent. While most sections achieved the established target density, none of the techniques utilized to compact the asphalt mixture had a large reduction in the required number of passes.

Table 26. Average Core Densities (Percent G_{mm})

Test Section	TS1 Oscillating Finish	TS2a Oscillating Intermediate	TS2b Oscillating Intermediate	TS3 Pneumatic	Control 1
Average	95.5	95.2	94.3	94.9	95.2
Standard Deviation	0.39	1.27	1.33	NA	0.34
Number of Tests	3	3	3	2	4
Minimum	95.09	95.69	92.86	93.14	94.93
Maximum	95.85	96.25	95.45	96.65	95.65

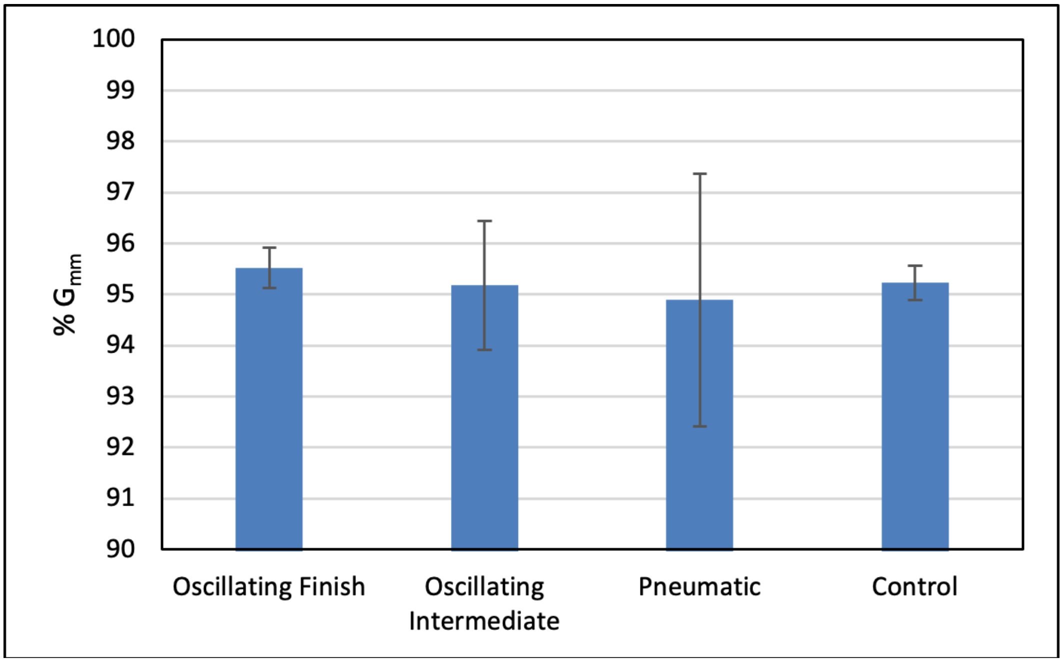


Figure 11. Average Core Densities

Test Section 4 was built on October 16, 2018 and was placed using the air void regression mixture design in the northbound outside 10-foot shoulder. This section was 9,965 feet long and contained 1,873 tons of asphalt mixture. To achieve density, seven vibratory passes and two static passes of the breakdown roller were applied, followed by five vibratory passes and two static passes of the intermediate roller and two static passes of the finishing roller.

Control Section 2 was built on October 12, 2018 and was placed in the northbound outside 10-foot shoulder. This section was 7,850 feet long and contained 1,582 tons of asphalt mixture. To achieve density, seven vibratory passes and two static passes of the breakdown roller were applied, followed by seven vibratory passes and two static passes of the intermediate roller, and two static passes of the finishing roller.

Table 27 shows the average density and descriptive statistics of Control Section 2 and Test Section 4. These two sections are unable to be compared to the other sections due to changing conditions of the roadway and the weather. None of these sections reached the target 95.0 percent and no significant increase in density was obtained when using the regressed air voids mixture.

Table 27. Average Core Densities (Percent G_{mm}) – Regressed Air Voids

Test Section	TS4 Regressed Air Voids	Control 2
Average	93.3	93.1
Standard Deviation	0.84	1.14
Number of Tests	4	3
Minimum	92.4	91.8
Maximum	94.2	94.0

6.4.6 Utilization of New Technologies

The use of oscillatory compaction was considered as new technology in this project. No other new technologies such as the PMTP, WMA, intelligent compaction, or GPR DPS were used as part of this project.

6.4.7 Summary of State Findings

For State 4, the percent density increased by 0.3 from the control to Test Section 1 (with the use of an oscillating steel drum roller). Since densities were already above 95.0 percent and the USL was 97.0 percent, it would likely be difficult to increase density any further. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - Two static and seven to nine vibratory passes were used for the breakdown roller; two static and five to eleven vibratory passes were used for the intermediate roller.
    - The standard deviations of density results did not improve with respect to Control Section 1. However, Control Section 1 had a standard deviation below 1.0 percent.
    - The standard deviation of density of TS4 was improved with the use of the regressed air voids mixture with a standard deviation below 1.0 percent.
- Observations for specification development (agencies):
    - The field density acceptance specification was PWL. The LSL for this project was 91.5 percent, and the maximum was 97.0 percent.
    - The specification had incentives and disincentives.

6.5 Phase 3 – State 5 (P3-S5)

6.5.1 Project Description

The construction project was located on a moderately heavy-volume, four-lane state highway. This asphalt overlay project included 5822 tons and was 4.67 miles in length. It was a single lift overlay with no milling and a target thickness of 2.0 inches. This project was built between October 29, 2018 and November 10, 2018.

The focus for this SHA's in-place density demonstration effort was on longitudinal joint construction. Four different methods or techniques were employed to promote an improved longitudinal joint. The experimental sections placed for this study follow. The state's standard mixture design was used for all experimental sections.

1. Control Section: The state's standard longitudinal joint construction (butt joint).
2. Test Section 1: Joint-bond spray.
3. Test Section 2: Notched wedge.
4. Test Section 3: Joint heater.
5. Test Section 4: Joint adhesive.

6.5.2 Asphalt Mixture Design

The gradation was a 12.5-mm NMAS blend that was on the fine side of the primary control sieve. The blended aggregate gradation is shown in Table 28. The mixture contained 25 percent RAP. The t/NMAS ratio was 4.0. A PG 64S-22 binder was used. The asphalt mixture design was performed using 50 gyrations with the Superpave gyratory compactor. The mixture was designed with 4.0 percent AV and had a VMA of 16.0 percent. The optimum AC was 5.8 percent. Mixture design information is shown in Table 29.

Table 28. Design Gradation

Particle Size	Gradation		
	Percent Passing	Specification Limit (%)	
		Min	Max
¾ inch (19.0 mm)	100	100	
½ inch (12.5 mm)	97	95	100
⅜ inch (9.5 mm)	88		90
No. 4 (4.75 mm)	61	58	80
No. 8 (2.36 mm)	40	34	50
No. 30 (0.60 mm)	22		23
No. 200 (0.075 mm)	6.0	2	10

Table 29. Mixture Design Properties

Mixture Design Property	Mixture Design	Criteria
Opt. AC (%)	5.8	
AV (%)	3.0	
VMA (%)	16.0	14.0
VFA (%)	80.0	65 – 83
D/A Ratio	1.1	0.6 – 1.2

6.5.3 Field Verification of the Asphalt Mixture Design

Acceptance testing was conducted during the construction of these test sections. Descriptive statistics from 15 samples for aggregate gradation and asphalt content are shown in Table 30. The results indicated that binder content was very similar to that from the job mix formula (JMF).

Table 30. Acceptance Asphalt Mixture Properties

Description	Target	Average	Std. Dev.	Max	Min
%passing ¾ inch (19.0 mm)	100	100			
%passing ½ inch (12.5 mm)	97	97	1.1	99	95
%passing ⅜ inch (9.5 mm)	88	88	1.6	91	85
%passing No. 4 (4.75 mm)	61	63	1.8	65	59
%passing No. 8 (2.36 mm)	40	40	1.6	42	37
%passing No. 30 (0.60 mm)	22	22	0.8	23	21
%passing No. 200 (0.075 mm)	6.0	6.1	0.2	6.4	5.7
AC (%)	5.8	5.8	0.15	5.99	5.54

6.5.4 Density Measurement and Specifications

The state used a minimum lot average specification of 92.5 percent based on the in-place mat density. There would be an incentive if 80 percent of the results were greater than 92.5 percent. The density acceptance for this project was by cores. The mat density was measured through 4-inch cores cut out of the mainline every 1500 feet that were bulked in the field and matched to the G_{mm} value from that day's production. The joint density was to be 95 percent of the mat density measure four inches off the joint.

6.5.5 Experimental Section Construction and Results

Table 31 shows the construction layout of each experimental section and Table 32 shows a summary of the field placement conditions and equipment used. As stated above, the only change that was made during construction was the use of four different joint construction technologies.

Table 31. Research Section Layout

Section	Control	TS1	TS2	TS3	TS4
Longitudinal Joint Method	Butt Joint	JointBond Spray	Notched Wedge	Joint Heater	Joint Adhesive
Length	3404 FT	3321 FT	7988 FT	5066 FT	4783 FT
Paving Date	10/30/18 and 10/31/18	10/30/18 and 10/31/18	11/1/18 and 11/7/18	11/8/18 and 11/10/18	11/8/18 and 11/10/18

Table 32. Field Placement

Weather	Average temperature was about 55° F most days; however, last day of paving on 11/10/18 average temperature was 38° F. Multiple days of paving were canceled due to rain.
Preparation	No Milling/No Leveling
Tack Coat	CRS-1H Tack; Application rate of 0.08 gal/SY
Haul truck type	End Dump
Material Transfer Device	Roadtec SB-1500
Paver type	CAT AP1055F
Temperature (behind screed)	285° F
Roller types	1) 14-ton CAT CB66 2) 12-ton CAT CB54
Roller Pattern	Roller 1: 4 Vibratory Passes and 1 Static Pass Roller 2: 5 Static Passes

The JointBond emulsion was sprayed on a pavement joint that had been constructed a week prior for about 0.6 miles. A 2-foot application centered over the joint (1 foot on either side of the joint) was used. Spray application started at 0.08 gal/SY then was upped to 0.11 gal/SY in test sections; a 0.13 gal/SY application rate was selected as the optimum rate for rest of the section. The spray went down as yellow emulsion and blended into the pavement within about an hour.

The notched wedge incorporated a paver attachment to pave a slope extending about a foot from the longitudinal joint with a 1” vertical face at the joint when paving the unconfined side. A plate tamper helped compact the sloped wedge portion. The second lane (confined longitudinal joint) was paved with the end gate extending beyond the 1” vertical face; tack was placed with an increased application rate over the sloped notched wedge joint prior to paving the next lane.

A joint heater was used in paving back the second lane on Saturday, November 10. Surface temperatures were approximately 50° F on a cold and windy day. The heater was 14 feet long, attached to the paver, and applied 350° F heat to the cold side of the asphalt joint. The paving speed was around 25 feet/minute, which was similar to the paving speed for all days on the route. The existing pavement showed 170° F after the heater and did not allow for significant penetration into the cold mat.

The joint adhesive was placed by a Slurry Pavers crack sealing crew for the last mile of paving on November 10. The material was similar to a crack sealant in that it was applied using an electric melter (heating the material up to 400° F) by wand with an angled shoe attachment on the top of the vertical face of the cold side of the longitudinal joint. A squeegee was used to push any extra joint adhesive against the vertical face. The placement was done behind tack application so the crew occasionally stopped to wait on the tack distributor. Only half of the melter tank was needed for the mile of joint placement.

Table 33 shows acceptance density results. These results represent the overall density of the mat, which can also affect density at the longitudinal joint.

Table 33. Average Acceptance Core Density (Percent G_{mm})

Section	Mat Right Lane	Mat Left Lane	Joint
Control Section	94.1%	93.2%	91.1
Test Section 1	92.7%	93.2%	89.8
Test Section 2	94.6%	94.5%	90.8
Test Section 3	93.3%	94.2%	90.1
Test Section 4	92.6%	94.4%	89.5

Joint density was tested in the field using a nuclear gauge placed 4 inches offset from the longitudinal joint. SHA specifications require these joint nuclear gauge density readings to be within 95.0 percent of the control strip nuclear gauge target value. The control strip on this route had an average density of 145.9 pounds per cubic foot; the control strip showed a core density of 92.8 percent of the five-day average G_{mm}. Table 34 shows nuclear gauge readings in ponds per cubic foot and their respective relative field density (relative to the control strip average density).

Table 34. Gauge Readings and Relative Density

Section	Joint (Unconfined)	Joint (Confined)	Joint (% Control Strip)	Joint (% Control Strip)
Control Section	143.2	143.2	98.1%	98.1%
Test Section 1	141.0	141.5	96.6%	97.0%
Test Section 2	144.0	141.3	98.7%	96.8%
Test Section 3	142.6	140.7	97.7%	96.4%
Test Section 4	141.2	140.2	96.8%	96.1%

The cores and nuclear density measurements did not show an improvement from the four test sections when compared to the Control Section. The longitudinal joint nuclear density measurements showed more compaction in the Control Section than any of the experimental sections.

6.5.6 Utilization of New Technologies

No new technologies such as the PMTP, WMA, intelligent compaction, or GPR DPS were used as part of this project.

6.5.7 Summary of State Findings

For State 5, the use of four joint construction techniques did not show an improvement in density when compared to the Control Section. However, there is a possibility that the materials used may result in improved pavement performance. The SHA will monitor the pavement performance of these sections into the future. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - One static and four vibratory passes were used for the breakdown roller, and five static passes were used for the intermediate roller.
- Observations for specification development (agencies):

- The field density acceptance specification was minimum lot average. The minimum specified joint density for this project was 95.0 percent of the control strip.
- The minimum specified density for this project at the joint was 95.0 percent of the average control strip density.
- The specification had incentives and disincentives.

6.6 Phase 3 – State 6 (P3-S6)

6.6.1 Project Description

The construction project was located on a medium-volume, two-lane state highway. The project was approximately 8 miles long in a rural area connecting two smaller towns. The project scope included milling approximately 2 inches of the existing asphalt mixture and inlaying 2 inches of new asphalt mixture. The project was constructed in early June 2018. The strategy to achieve higher density involved using a mixture with additional AC and using additional field compactive effort. The three experimental sections were placed in a 7,300-foot (1.4-mile) section of the northbound lane. The Control Section was 0.4-miles, while Test Sections 1 and 2 were 0.4-miles and 0.6-miles, respectively. The experimental sections placed for this study are as follows.

1. Control Section: The state's standard mixture design and density specification were used.
2. Test Section 1: The same mixture design as in the Control Section was used, but there was 0.2 percent additional AC based on engineering experience.
3. Test Section 2: The same mixture design as in Test Section 1 was used, but there was additional field compactive effort with seven additional static passes.

6.6.2 Asphalt Mixture Design

The gradation was a 12.5-mm NMAS blend that was on the coarse side of the primary control sieve. There was 12.5 percent natural sand. The mixture contained 15 percent RAP. The blended aggregate gradation is shown in Table 35. The t/NMAS was 4.0. A PG 64-22 binder was used. The asphalt mixture design was performed using 75 gyrations with the Superpave gyratory compactor. The mixture was designed with 4.0 percent AV and had a VMA of 15.9 percent. The optimum AC was 5.0 percent. Mixture design information is shown in Table 36. For the test sections, an additional 0.2 percent AC was used based on engineering experience. The optimum AC for the test sections was 5.2 percent.

Table 35. Mixture Design Gradation

Sieve Size	Mixture Design	Criteria
	Percent Passing	
19.0 mm (3/4”)	100	100 max
12.5 mm (1/2”)	94.3	90 – 100
9.5 mm (3/8”)	80.7	90 max
4.75 mm (#4)	49.2	--
2.36 mm (#8)	34.6	28 – 58
1.18 mm (#16)	24.6	--
0.60 mm (#30)	17.7	--
0.30 mm (#50)	11.0	--
0.15 mm (#100)	7.1	--
0.075 mm (#200)	5.8	2 – 10

Table 36. Mixture Design Properties

Mixture Design Property	Mixture Design	Criteria
N_{des}	75	--
Air Voids (%)	4.0	3.0 - 5.0
AC (%)	5.0	--
VMA (%)	15.9	>14.0
VFA (%)	72.0	65 – 78
D/A Ratio	1.2	0.6 – 1.2

6.6.3 Field Verification of the Asphalt Mixture Design

Contractor’s quality control (QC) samples are reported in Table 37 for verification of the mixture design. Asphalt content and volumetric properties were tested every 750 tons. These are average results from three sublots for each mixture.

Table 37. Asphalt Content and Volumetric Results

Sieve Size	Mixture Design	Control	Test Section 1	Test Section 2
	Percent Passing			
19.0 mm (3/4”)	100	100	100	100
12.5 mm (1/2”)	94	94	93	94
9.5 mm (3/8”)	80	84	84	83
4.75 mm (#4)	49	52	50	53
*2.36 mm (#8)	34	33	34	35
1.18 mm (#16)	24	27	28	29
0.60 mm (#30)	17	22	23	24
0.30 mm (#50)	11	15	15	16
0.15 mm (#100)	7	6	6	7
0.075 mm (#200)	5.8	3.7	4.5	4.6
AV (%)	4.0	3.8	1.7	2.7
AC (%)	5.0	5.02	5.19	5.23

6.6.4 Density Measurement and Specifications

The state used a percent defective (PD) specification based on the in-place air voids. The LSL and USL were 2.0 and 8.0 percent, respectively. Six-inch cores were used to measure density, and there were five cores (sublots) per lot. A lot was based on the day's production so the size of the lot varied. The G_{mm} was tested for every sublot. The incentive for density alone was 4.0 percent. The statewide historical average in-place density for the 2018 construction season was 94.9 percent.

6.6.5 Experimental Section Construction and Results

The mixture was delivered to the site using end-dump trucks. The trucks loaded the mixture into a Blaw-Knox MC30 MTV, which transferred it into the CAT AP1055F track paver. Two rollers were used for the compaction. A 14-ton Hamm HD+140 was used as the breakdown roller and a 14-ton CAT CB54XW was used as the finish roller. The experimental sections were placed in one night with an ambient temperature of 70^o F. An RS-1 tack coat was applied to the milled surface at a target rate of 0.05 gal/yd2. The tack coverage was well distributed and did not track significantly. The temperature behind the screed was measured periodically by SHA personnel using a temperature probe. The laydown temperature behind the paver was 285 to 290^o F.

For the Control Section, the breakdown roller made 16 vibratory passes and one static pass. The finish roller operated in static mode and had no consistent roller pattern; it simply smoothed out roller marks. The same roller pattern was used for Test Section 1. The compactive effort was increased in Test Section 2 by having the finish roller apply seven additional static passes and move much closer to the breakdown roller.

For in-place density, five field cores were taken per night by the contractor and were delivered to the SHA for testing. The in-place density results from these cores are shown in Table 38. The average density was increased by 0.6 and 1.5 percent from the Control Section to Test Sections 1 and 2, respectively.

Table 38. SHA In-Place Density Results

Section	Number of Cores	Average Density (%)	Std. Dev of Density (%)
Control Section	5	94.5	0.7
Test Section 1	5	95.1	0.8
Test Section 2	5	96.0	0.6

Figure 12 provides a visual representation for each experimental section. The error bars represent one standard deviation from the mean. The average density for all three experimental sections was very good with all of them averaging greater than 94.0 percent G_{mm}. These density results are equivalent to those obtained by SHAs with the most stringent density specifications discussed in Chapter 5. The standard deviations associated with these densities were also very good, with the highest being only 0.8 percent. Standard deviations at or below 1.0 are also among the best in the country.

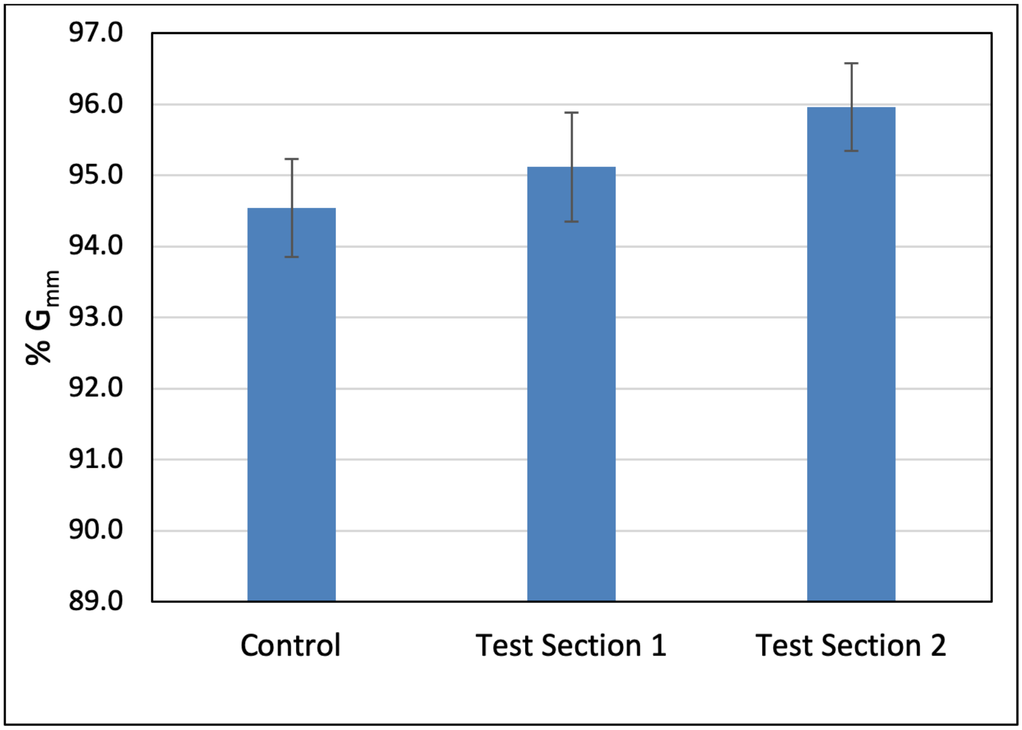


Figure 12. In-Place Density Comparison Between Test Sections

6.6.6 Utilization of New Technologies

No new technologies such as the PMTP, WMA, intelligent compaction, or GPR DPS were used as part of this project.

6.6.7 Summary of State Findings

For State 6, the density increased by 0.6 percent G_{mm} with additional AC of 0.2 percent, and the density increased by 1.5 percent G_{mm} with the additional AC of 0.2 percent and more field compactive effort. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
  - There were 16 vibratory passes and one static pass from the breakdown roller in the Control Section. Additional AC and an additional seven static passes of the finish roller resulted in increased density.
  - Results from the control and test sections were all excellent. The average density was greater than 94.0 percent G_{mm}, and the standard deviations were below 1.0.
- Observations for specification development (agencies):
  - The control asphalt mixture design was adjusted to include 0.2 percent more asphalt binder based on engineering experience.
  - The field density acceptance specification was PD. The LSL and USL were 2.0 and 8.0 percent AV, respectively. With an incentive of 4.0 percent for density alone, the statewide results were excellent.
  - Performance testing for rutting and cracking are being implemented for dense-graded mixtures.

6.7 Phase 3 – State 7 (P3-S7)

6.7.1 Project Description

This construction project was a four-lane state highway with turn lanes in a town with a smaller population. There was moderately heavy traffic as the route provided access to businesses and other facilities. The AADT was 22,500 with 8.5 percent trucks. The project was approximately 1.8-lane miles and 0.35-centerline miles (about 1800 feet) long. The highway was originally a two-lane road that was being widened to accommodate four lanes. The widening included the new construction of 9 inches of cement treated base, while the inside lanes had the original 8 inches of cement treated base with an asphalt leveling course. It was constructed in late October 2018.

For the demonstration project, the strategy to achieve higher density involved using a mixture with additional AC. The experimental sections placed for this study follow.

1. Control Section: The state's standard mixture design and density specification were used.
2. Test Section 1: The same mixture design and compactive effort as the Control Section was used but there was 0.2 percent additional AC as calculated to account for the "black rock" of the RAP.

The experimental sections were the first lift on top of the base. The Control Section was constructed in the outside lanes on the new base, and the test section was constructed in the inside lanes on the old base with a leveling course. The control and test sections were paved on consecutive days.

6.7.2 Asphalt Mixture Design

The gradation was a 12.5-mm NMAS blend that was on the coarse side of the primary control sieve. The aggregates used were #67, #789 crushed granite aggregates, screenings and hydrated lime. The mixture contained 20 percent RAP. The blended aggregate gradation is shown in Table 39. The t/NMAS was 4.0. A PG 64-22 binder was used. The asphalt mixture design was performed using 75 gyrations with the Superpave gyratory compactor. The mixture was designed with 3.9 percent AV and had a VMA of 15.1 percent. The optimum AC was 4.8 percent. Mixture design information is shown in Table 40. For the test section, an additional 0.2 percent AC was used based on a calculation to account for the "black rock" in the RAP. The optimum AC for the test section was 5.0 percent.

Table 39. Mixture Design Gradation

Gradation	Percent Passing	Specification Limit (%)	
		Min.	Max.
1 inch (25.0 mm)	100	98	100
¾ inch (19.0 mm)	99	98	100
½ inch (12.5 mm)	93	90	100
⅜ inch (9.5 mm)	83	76	90
No. 4 (4.75 mm)	56	50	62
No. 8 (2.36 mm)	39	33	43
No. 30 (0.60 mm)	20	15	25
No. 100 (0.15 mm)	8	4	12
No. 200 (0.075 mm)	4	2	6

Table 40. Mixture Design Information

Mixture Design Property	Mixture Design	Criteria
Opt AC (%)	4.8	
Air voids (%)	3.86	3.2 - 4.0
VMA (%)	15.08	14.5
VFA (%)	74.4	70 - 78

6.7.3 Field Verification of the Asphalt Mixture Design

The agency's test results are reported in Table 41 for verification of the mixture design. AC, AV, and VMA properties are reported per the agency's standard requirements. The results indicated that AC and AVs were very similar to those from the mixture design. A slight decrease in VMA was obtained for both mixtures; however, these results were within specified tolerances.

Table 41. Production Mixture Properties

Item	AC (%)	Air Voids (%)	VMA (%)
Control Section	4.54	3.54	14.22
Target	4.80	3.86	15.08
Tolerance	4.37 – 5.23	2.71 – 5.01	13.93 – 16.23
Test Section	5.06	2.71	14.63
Target	5.00	3.34	15.05
Tolerance	4.57 – 5.43	2.19 – 4.49	13.90 – 16.20

6.7.4 Density Measurement and Specifications

The state used a PWL specification for this project. The LSL and USL were 92.2 to 96.0 percent for interstate and U.S. primary routes or 91.2 to 96.0 percent for all other paving. This particular project was considered to be other paving with the 91.2 to 96.0 criteria. It should be noted that the specification was changed as of January 2018 to be an average absolute deviation (AAD) specification. The new criteria for in place density with the AAD specification was 93.0 to 93.9 percent in order to obtain 100 percent pay and a minimum of 94.0 percent to obtain a bonus.

The AAD specification was applied to all paving projects. Six-inch cores were used to measure density every 1,500 feet. A lot was based on the day's production so the size of the lot varied. The G_{mm} was tested every sublot. There was a 5 percent incentive based on equal weighting of three quality characteristics: density, AC and gradation.

6.7.5 Experimental Section Construction and Results

The mixture was delivered to the site in dump trailers and into a Weiler E1250A MTV. The mixture was then placed into CAT AP1055F asphalt paver. The paving site was approximately 25 miles from the asphalt plant, which resulted in a haul time of about 40 minutes. Compaction was performed using two vibratory steel drum rollers. The breakdown roller was a 14-ton Sakai SW 880, followed by a 12-ton CAT CB54XW. Paving was done during the day and weather during construction was clear and sunny. The temperature at the start of paving was 50^{o} F and increased to 70^{o} F, very good conditions for paving. When the test sections were placed on a leveling course, a CRS tack coat was applied at an application rate of 0.06 – 0.08 gal/yd^2. The paver operated at 13 to 15 feet per minute. Paving slowed on several occasions due to trucks being held up in traffic. The control and test sections were paved on consecutive days. The rolling pattern was the same for both sections. There were seven vibratory passes with the breakdown roller and five static passes with the intermediate roller.

The contractor monitored density with a PQI 380 nonnuclear gauge as part of QC. The agency's acceptance testing was with cores and results are shown in Table 42. One of the density results for the test section was deemed a statistical outlier (90 percent confidence level) using the ASTM E178-16a procedure. Table 43 and Figure 13 show the average relative densities of the cores with the outlier removed from the data set.

Table 42. Core Densities (Percent G_{mm})

Core	Control Section	Test Section
Core #1	92.90	93.18
Core #2	91.02	91.42
Core #3	90.82	91.94
Core #4	91.94	87.57
Core #5	92.06	91.22
Core #6	92.66	92.54
Average	91.90	91.93

Table 43. Average Core Densities (Percent G_{mm}) with the Outlier Excluded

Test Sections	Control Section	Test Section
Average	91.90	92.06
Standard Deviation	0.87	1.97
Number of Tests	6	5
Minimum	90.82	91.22
Maximum	92.90	93.18
Tolerance	91.2 – 96.0	

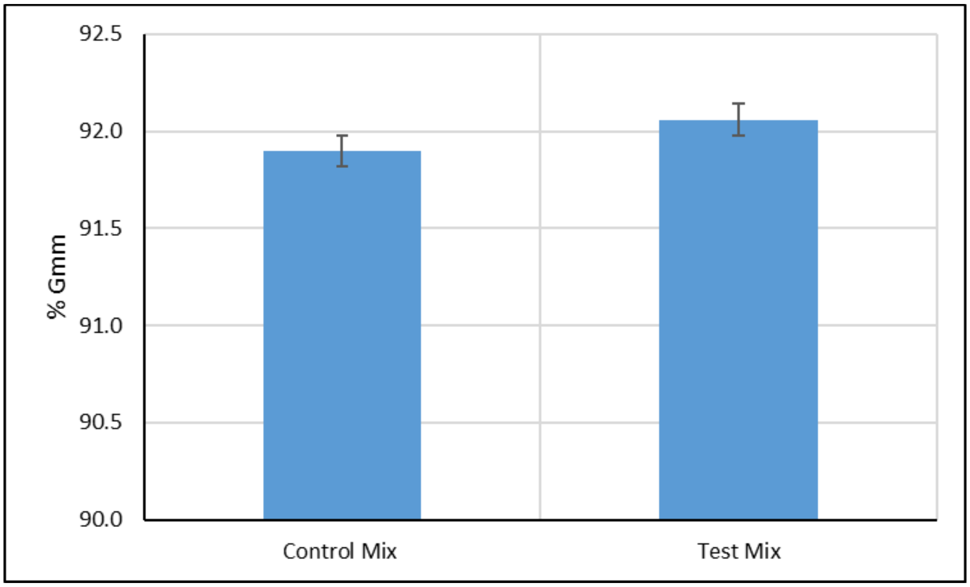


Figure 13. Average Core Densities

The core density test results in Figure 9 show that there was a small difference in density between the control and test sections. A t-test showed there was no statistical difference when the outlier was not included (p-value = 0.76 > alpha = 0.05). It should be noted that there were different bases: the Control Section was on a new base and the test section was on an old base with a leveling course.

6.7.6 Utilization of New Technologies

No new technologies such as the PMTP, WMA, intelligent compaction, or GPR DPS were used as part of this project.

6.7.7 Summary of State Findings

For State 7, there was no change in the density with the increase in 0.2 percent AC. The Control Section was on a new base and the test section was on an old base with a leveling course. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - There were seven vibratory passes from the breakdown roller and five static passes from the intermediate roller applied to both the control and test sections.
    - Density results were marginally acceptable for the specification used on the project, but would have been unacceptable for the newly implemented specification.
- Observations for specification development (agencies):
    - The asphalt mixture used in the test section was adjusted to include an additional 0.2 percent AC.
    - The field density acceptance specification was PWL. The LSL and USL were 91.2 and 96.0 percent, respectively.

- The requirement for in place density with the AAD specification was 93.0 to 93.9 percent in order to obtain 100 percent pay and a minimum of 94.0 percent to obtain a bonus. The AAD specification was applied to all paving projects. The increased LSL should result in higher densities on future projects.
- The new specification did not have lower requirements for other types of projects. Eliminating the lower tier of requirements for other projects should also result in higher densities on future projects.
- The specification had incentives and disincentives.

6.8 Phase 3 – State 8 (P3-S8)

6.8.1 Project Description

This construction project was a section of three westbound lanes (including a truck climbing lane) of interstate highway in a rural area. Due to the ruggedness of the area, the eastbound and westbound had separate alignments and were paved independently. The ADT was 17,360 with an average daily loading of 5,259 equivalent single-axle loads (ESALs). The project was approximately 7.3 miles long. It consisted of 32,000 tons of binder mixture and 11,000 tons of surface mixture. It was paved from June to September 2018. The existing pavement surface was a dense mixture last paved in 2006. The dominant distresses identified were fatigue, block and transverse cracking. The plans called for milling of the existing 1.25-inch surface layer and replacement with both a 2-inch binder and 1.25-inch surface lift. The overall cross section included 8 to 9 inches of cement treated base and an asphalt levelling course.

For the demonstration project, the strategy to achieve higher density involved using intelligent compaction and various t/NMAS sections. The experimental sections placed for this study follow and are also summarized in Table 44.

1. Control Section: The state's standard mixture design and density specification were used. This did not include intelligent compaction (IC) and the t/NMAS was 2.5.
2. Test Section 1: The roller mapping functions were used as part of the intelligent compaction (IC) and the t/NMAS was 2.5.
3. Test Section 2A: The roller mapping functions were used as part of the IC. The overlay thickness was increased for a t/NMAS of 3.0.
4. Test Section 2B: The roller mapping functions were used as part of the IC. The overlay thickness was increased for a t/NMAS of 4.0.

Table 44. Test Sections

Section	Mixture Depth (t/NMAS)	Intelligent Compaction	Experiment
Control	1.25" (2.5 t/NMAS)	Display Screens Covered	Control for IC Experiment
1	1.25" (2.5 t/NMAS)	Display Screen Viewable	Test Case for IC Experiment Control for t/NMAS Experiment
2A	1.5" (3 t/NMAS)	Display Screen Viewable	Test Case A for t/NMAS Experiment
2B	2.0" (4 t/NMAS)	Display Screen Viewable	Test Case B for t/NMAS Experiment

The experimental sections were constructed from mid to late August. The Control Section involved one night of paving. Test Section 1 was done for a majority of the construction project. Test sections 2A and 2B were each done for 1 mile.

6.8.2 Asphalt Mixture Design

The gradation was a 12.5-mm NMAS blend that was on the fine side of the primary control sieve. The aggregates used included limestone meeting polishing requirements and 25 percent natural sand. The mixture contained 7.0 percent RAP and 3.0 percent RAS. The blended aggregate gradation is shown in Table 45. The t/NMAS ranged from 2.5 to 4.0 based on the different overlay thicknesses. A PG 76-22 binder was used. The asphalt mixture design was performed using 75 blows with the Marshall design method. The mixture was designed with 4.0 percent AVs and had a VMA of 16.9 percent. The optimum AC was 5.7 percent and the reclaimed binder ratio was 0.15. Mixture design information is shown in Table 46.

Table 45. Mixture Design Gradation

Particle Size	Gradation		
	Percent Passing	Specification Limit (%)	
		Min	Max
5/8 inch (15.8 mm)	100	100	
½ inch (12.5 mm)	98	95	100
⅜ inch (9.5 mm)	87	80	93
No. 4 (4.75 mm)	61	54	76
No. 8 (2.36 mm)	45	35	57
No. 30 (0.60 mm)	29	17	29
No. 50 (0.30 mm)	18	10	18
No. 100 (0.15 mm)	8.8	3	10
No. 200 (0.075 mm)	5.6	0	6.5

Table 46. Mixture Design Information

Mixture Design Property	Mixture Design	Criteria
Opt. AC (%)	5.7	
Air voids (%)	4.0	3.8 – 5.2
VMA (%)	16.9	14.0
Stability (lb-ft)	3527	2000
D/A Ratio	0.98	0.6 – 1.2
VFA (%)	76.1	

6.8.3 Field Verification of the Asphalt Mixture Design

The agency's test results are reported in Table 47 for verification of the mixture design with aggregate gradation and AC. The results indicated that binder content was very similar to that from the mixture design. A slight increase in dust to asphalt (D/A) ratio was reported; however, most of these results were within specified tolerances and this item is not included in the calculation of the pay factor.

Table 47. Acceptance Asphalt Mixture Properties

Particle Size	Target	Average	Std. Dev.	Max	Min
%passing 5/8 inch (15.8 mm)	100	100			
%passing ½ inch (12.5 mm)	98	97.7	0.8	99.6	96.6
%passing ⅜ inch (9.5 mm)	87	87.2	1.6	91.5	83.5
%passing No. 4 (4.75 mm)	61	59.2	2.2	64.5	56.4
%passing No. 8 (2.36 mm)	45	43.1	1.7	47.3	41.2
%passing No. 30 (0.60 mm)	29	31.2	1.4	32.8	27.6
%passing No. 50 (0.30 mm)	18	20.0	1.0	21.5	17.7
%passing No. 100 (0.15 mm)	8.8	9.2	0.5	10.6	8.3
%passing No. 200 (0.075 mm)	5.6	6.8	0.3	7.3	5.9
Asphalt Content (%)	5.70	5.77	0.13	5.94	5.49
D/A Ratio	0.98	1.18	0.05	1.26	1.03

6.8.4 Density Measurement and Specifications

The state used a lot average specification, and the LSL and USL were 92.0 and 97.0 percent, respectively. Four or six-inch cores were used to measure density, and there were five cores (sublots) per lot. A lot was 1,000 tons, so cores were taken every 200 tons. The G_{mm} was tested twice each day and the average was used. The incentive for density alone was 2.0 percent. The statewide historical average in-place density from the 2015 to 2017 construction seasons was 93.9 percent.

6.8.5 Experimental Section Construction and Results

The paving train for the project consisted of a Roadtec Shuttle Buggy (SB-2500) MTV and a Roadtec rubber-tire asphalt paver (RP-190e). Compaction was performed with a 14-ton CAT steel-wheel vibratory roller (CB 64) in the breakdown position, a 12-ton CAT steel-wheel vibratory roller (CB 54B) in the intermediate position, and a 12-ton Ingersoll Rand static steel-wheel roller (DD 112) as the finish roller. Both CAT rollers were retrofitted with GPS positioning and infrared temperature sensor meeting the state's "Intelligent Compaction Lite" requirements. Paving was done at night. The average high for this period was 81° F and the average low was 65° F. A rain event interrupted paving for three days but otherwise there was little to no measurable rainfall during this period. The control and test sections were paved consecutively.

The rolling pattern was the same for both sections. There were four vibratory passes and one static pass with the breakdown roller and three vibratory passes and four static passes with the intermediate roller. The finish roller was considerably behind the paving train and was there to roll out any noticeable marks in the mat. There was no discernable pattern utilized and estimating how far behind the paver the roller was operating, it was unlikely to be accomplishing much additional compaction. These patterns were utilized for all the experimental sections except Test Section 2B. Near the end of Test Section 2A, the contractor believed that density was lower than expected based on a QC check. For Test Section 2B, the roller pattern was changed to add two extra static passes by the breakdown roller.

Cores were cut by the contractor at the random locations marked by the SHA field inspector; cores were then delivered to the SHA plant technician to determine the bulk density. Specific research testing was conducted on this project using a nuclear gauge and cores for correlation on the specific test sections. For these tests, two longitudinal locations were randomly chosen and five nuclear gauge tests were taken at each across the mat at the same transverse locations mentioned above. Two cores were cut per test section to calculate a correlation factor for each. Generally, these were cut at the center and one foot from the right edge of the first set of tests per test section.

The results of the study appear to show that in-place density was increased and variability of the in-place density was decreased with the use of intelligent compaction and with increased t/NMAS ratios. Tabulated results of the measured in-place density are presented in Table 48. The values in the tables are averaged for all tests, both acceptance and research for each section. In total, 79 individual density tests were taken throughout the demonstration project; 23 in the Control Section, 33 in Test Section 1, 12 in Test Section 2A, and 11 in Test Section 2B.

Table 48 Density Test Results (Percent G_{mm})

Section	1' from Left Edge	Left Wheel Path	Center of Mat	Right Wheel Path	1' from Right Edge	Average Across Mat	Standard Deviation
Control	91.7	93.1	93.7	94.1	92.3	93.0	1.94
TS 1	93.7	93.6	94.4	93.4	94.0	93.8	1.53
TS 2A	94.6	94.4	94.4	92.3	92.6	93.7	1.35
TS 2B	94.9	95.1	95.5	93.5	94.9	94.8	0.98

The increased in-place density and reduced variability in the test sections seemed to demonstrate that both the IC and t/NMAS were effective. Increasing the lift thickness from the typical mixture depth of 1.25 inches to 1.5 inches seemed to have had little effect on density but did reduce variability. However, when increased to 2.0 inches, it did show a significant increase in the in-place density. It also had the lowest amount of variability of all the test sections.

6.8.6 Utilization of New Technologies

Intelligent compaction technology was utilized as part of the experimental plan of this project. No other new technologies such as the PMTP, WMA, or GPR DPS were used as part of this project.

6.8.7 Summary of State Findings

For State 8, the density increased 0.8 percent when intelligent compaction was incorporated on one test section. In addition, the percent density increased 0.0 and 1.0 percent when the t/NMAS was increased from 2.5 to 3.0 and 4.0, respectively. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - The normal breakdown roller pattern included four vibratory passes and one static pass. The intermediate roller pattern included three vibratory passes and four static passes.

  - The standard deviations of density results were significantly improved with the use of IC and the increase in the t/NMAS.
- Observations for specification development (agencies):
  - There were benefits to using intelligent compaction.
  - A slight increase in t/NMAS from 2.5 to 3.0 did not result in increased density. However, an increase in t/NMAS from 2.5 to 4.0 resulted in a 1.0 percent increase in density.
  - The lot average specification from this project required densities between 92.0 and 97.0 percent.
  - The specification had incentives and disincentives.

6.9 Phase 3 – State 9 (P3-S9)

6.9.1 Project Description

The construction project was located on a two-lane state highway. The pavement section was a complete reconstruction consisting of 8 inches of roadbed modification on an existing subgrade covered with 6 inches of plantmix bituminous surface (placed in two 3-inch lifts) topped with ¾-inch of plantmix open-grade surface. The project included 505,855 yd^3 of roadbed modification, 269,911 tons of Type 2C plantmix bituminous surface, and 30,134 tons of plantmix open-grade surface. One control section and two experimental sections were built in June 2019.

The primary objective of the demonstration project was to determine if a 1 or 2 percent increase in the current SHA lower in-place density specifications could be reasonably achieved by means within a typical SHA contractor's control. Table 49 shows the planned adjustments to be performed in order to achieve higher density.

Table 49. Techniques Planned for Test Section Construction

Test Section	Staff Changes	Material Changes	Equipment Changes	Operational Changes
1 (plus 1% density)	Increase QC density technicians from 1 to 2	None	All new Caterpillar breakdown, intermediate, and finish roller equipped with Intelligent Compaction technology	None
2 (plus 2% density)	Increase QC density technicians from 1 to 2	Increase asphalt binder 0.1%	All new Caterpillar breakdown, intermediate, and finish rollers equipped with Intelligent Compaction technology	Increase roller passes

6.9.2 Asphalt Mixture Design

The gradation was a 19.0-mm NMAS blend that was on the fine side of the primary control sieve. The mixture contained 15 percent RAP. The blended aggregate gradation is shown in Table 50. The t/NMAS was 4.0. A PG 76-22 binder was used. The optimum asphalt content was 4.2 percent with an added virgin asphalt content of 3.6 percent. No details on volumetric properties were disclosed by either the SHA or the contractor.

Table 50. Mixture Design Gradation

Particle Size	Gradation		
	Percent Passing	Specification Limit (%)	
		Min	Max
1 inch (25.4 mm)	100	100	
¾ inch (19.0 mm)	93	88	95
½ inch (12.5 mm)	81	70	85
⅜ inch (9.5 mm)	72	60	78
No. 4 (4.75 mm)	53	43	60
No. 10 (2.00 mm)	31	30	44
No. 40 (0.42 mm)	14	12	22
No. 200 (0.075 mm)	7	3	8

6.9.3 Field Verification of the Asphalt Mixture Design

The SHA quality assurance plantmix test reports include AC, gradation, and theoretical maximum specific gravity. For each test section (day of paving one lift), three plantmix samples were obtained. Table 51 is a summary of plantmix test results. Note that theoretical maximum specific gravities were measured on the first two sublot samples each day of paving and were the basis for reported percent relative density. Individual gradation test results for each sample are presented in Table 52. All asphalt and gradation test results were within specification tolerances.

One of the actions the contractor planned to improve density was to increase asphalt content by 0.1 percent on Test Section 2. The JMF target was 4.2 percent. The average asphalt content observed on both test sections was 4.5 percent, so the actual increase was greater than planned and the same for both test sections.

Table 51. SHA Acceptance Plantmix Test Result Summary

Test Section	Sublot	Asphalt Content (%)	Theoretical Maximum Specific Gravity (pcf)
1	1	4.4	160.9
1	2	4.4	160.9
1	3	4.6	-
1	Average	4.5	160.9
2	1	4.4	160.7
2	2	4.6	160.6
2	3	4.6	-
2	Average	4.5	160.7

Table 52. SHA Acceptance Gradation Test Results

Particle Size	Gradation							
	Percent Passing						Criteria (%)	
	TS1-1	TS1-2	TS1-3	TS2-1	TS2-2	TS2-3	Min	Max
1 inch (25.4 mm)	100	100	100	100	100	100	100	
¾ inch (19.0 mm)	93	90	93	93	90	91	88	95
½ inch (12.5 mm)	77	73	77	79	76	75	70	85
⅜ inch (9.5 mm)	73	69	72	74	72	71	60	78
No. 4 (4.75 mm)	57	54	56	58	56	55	43	60
No. 10 (2.00 mm)	32	31	31	34	31	30	30	44
No. 40 (0.42 mm)	15	16	15	17	16	15	12	22
No. 200 (0.075 mm)	7	7	8	8	8	8	3	8

6.9.4 Density Measurement and Specifications

For each lot, five mat density tests were performed using a calibrated nuclear density gauge. Density is reported in percent relative to theoretical maximum specific gravity of the plantmix. Each test section was a plantmix lot that included three sublots. Theoretical maximum specific gravity tests were performed on two of the sublot samples per test section. Both the SHA and contractor personnel used Troxler 4640B nuclear density gauges. The standard percent within limits (PWL) specification has a lower density limit of 92 percent and a maximum of 96 percent. Only the lower limit was increased 1 percent for Test Section 1 and 2 percent for Test Section 2.

6.9.5 Experimental Section Construction and Results

Test Section 1 was constructed on June 26, 2019 and Test Section 2 was constructed on June 28, 2019. The hot plant on site is an Astec Double Barrel Drum plant with six storage silos. Production at the plant started each day at 1:30 a.m. with the first truck loading out at 3:00 a.m. This allowed adequate haul time for paving to begin at 5:00 a.m. each day. The target mix production temperature was 330°F and was typically within 10°F. Only bottom dump haul trucks were used, with most having two trailers carrying approximately 38 tons per truck. All 27 trucks were covered to help retain mix temperature during the haul. The haul distance from the hot plant to the test section location was approximately 50 miles. There is a significant grade between the plant and test section location, which resulted in an average haul time of about 90 minutes.

The equipment used for the test section construction is presented in Table 53. All of the same equipment was used for both test sections. The Caterpillar compactors were all brand new and equipped with intelligent compaction (IC) technology.

Table 53. Placement and Compaction Equipment

Equipment	Model	Units	Use/Notes
BearCat Distributor		1	Prime and tack coat
Roadtec Material Transfer Vehicle	SB2500	1	With windrow pickup
Caterpillar Paver	AP1055F	1	With automated grade controls and hopper extension
Caterpillar Steel Drum Roller	CB66B (14.5 ton)	1	Breakdown rolling with IC
Pneumatic Tire Roller with IC	CW34 (11 ton)	2	Intermediate rolling with IC, No additional ballast
Caterpillar Steel Drum Roller	CB66B (14.5 ton)	1	Finish rolling with IC
Volvo Steel Drum Roller	DD25B (2.8 ton)	1	Transverse joint construction only
Blaw Knox Kick Broom	CB-90	1	Sweeping prior to prime and tack coats

Prior to placement of the 3-inch bottom lift Type 2C plantmix, a prime coat was uniformly applied with the BearCat asphalt distributor. Paving was initiated at 5:00 a.m. and completed by 3:30 p.m. each day. Weather conditions during test section construction are summarized in Table 54. Trucks dumped plantmix in a windrow and the Roadtec MTV was used to pick up and mix it prior to discharging it into the hopper on the Caterpillar AP1055F paver. Breakdown rolling initiated immediately behind the paver with the Caterpillar CB66B roller using both vibratory and static compaction modes. A pair of tandem Caterpillar CW34 intermediate rollers followed the breakdown roller. Finish rolling was accomplished with a second Caterpillar CB66B roller. Longitudinal joints were compacted from the cold side first. Roller passes and plantmix temperatures during compaction are summarized in Table 55.

Table 54. Weather Conditions During Test Section Construction

Test Section	Date Constructed	Ambient Temperature Range (°F)	Relative Humidity Range (%)	Wind Speed (mph)	Cloud Cover
1	06/26/19	73-102	Low	5-18	None
2	06/28/19	71-101	Low	5-10	None

Table 55. Plantmix temperatures, roller passes and modes

Operation	Location	Temperature Range (°F)	Roller Passes and Mode (Test Section 1)	Roller Passes and Mode (Test Section 2)
Asphalt Plant	Discharge	325-355	n/a	n/a
Dumping	Windrow	300-320	n/a	n/a
Breakdown rolling	Behind Paver	290-300	5 Vibratory, 2 Static	6 Vibratory, 3 Static
Intermediate rolling	Multiple	200-290	9	9
Finish rolling	Multiple	175-195	4 Vibratory, 5 Static	4 Vibratory, 7 Static

Table 56 is a summary of mat density results for both test sections showing individual sublot and the lot average values. The sublot values ranged from 93 to 95 percent relative density and all lot averages were above 94 percent, with the exception of Test Section 1 lot 1. This is positive since the standard specification lower density limit is 92 percent. The average density of Test Section 1 is 93.9 percent with a standard deviation of 0.95, and the average density of Test Section 2 is 93.8 percent with a standard deviation of 0.56. The density being achieved under normal operations is referred to as a “control” section. The Control Section consisted of 28 density lots obtained on the same project using the same paving crew, asphalt plant and mixture prior to construction of the density demonstration test section. Individual sublot values of the Control Section range from 92 to 96 percent and the lot averages are 93 to 94 percent. The average for all control lots is 93.3 percent with a standard deviation of 0.76.

Table 56. Test Section Acceptance Density Test Results Summary (Percent G_{mm})

Test Section	Lot	Sublot 1 Relative Density	Sublot 2 Relative Density	Sublot 3 Relative Density	Sublot 4 Relative Density	Sublot 5 Relative Density	Lot Average Relative Density	Standard Deviation
1	1	93.2	93.2	93.5	94.4	93.0	93.5	0.57
1	2	94.3	93.1	95.2	93.8	94.3	94.1	0.75
1	3	94.8	96.0	92.8	94.2	92.7	94.1	1.41
1	Avg	94.1	94.1	93.8	94.1	93.3	93.9	0.91
2	1	94.4	93.1	93.1	93.9	94.8	93.9	0.78
2	2	93.3	93.5	94.3	93.0	93.7	93.6	0.49
2	3	93.7	94.6	93.8	93.8	94.3	94.1	0.41
2	Avg	93.8	93.8	93.7	93.6	94.3	93.8	0.56

Table 57 shows the percent within limits (PWL) and pay factors calculated for each lot with the standard specification and test section special provision mat density requirements applied. Note that the values in bold and italic are the actual values for the two test sections. The other data is simply presented for those curious what the PWL and pay factors would be with each of the different specifications applied. It is important to recognize that when the standard specification is applied, the pay factors for five of the six lots are 100 percent and the corresponding pay factors are all 105 percent with the exception of one lot, which is 99 percent. This illustrates that what the contractor did on both test sections to increase density resulted in a very good quality per the current SHA standard specifications.

Table 57. Test Section Percent Within Limits and Pay Factor Summary by Specification Type

Test Section	Lot	Standard Spec. PWL 92-96%	Standard Spec. Pay Factor 92-96%	Special Provision 1 PWL 93-96%	Special Provision 1 Pay Factor 93-96%	Special Provision 2 PWL 94-96%	Special Provision 2 Pay Factor 94-96%
1	1	100	105	***77***	***94***	19	64
1	2	100	105	***95***	***103***	55	82
1	3	89	99	***69***	***90***	45	78
1	Average	96	103	***80***	***97***	40	75
2	1	100	105	87	98	***44***	***77***
2	2	100	105	87	99	***19***	***64***
2	3	100	105	100	105	***60***	***85***
2	Average	100	105	91	101	***41***	***75***

Table 58 shows a summary of the PWL and pay factors calculated for the control and both test sections with the standard specification and special provision mat density requirements applied. Under the standard specification, the PWL and pay factor for the control are slightly higher than Test Section 1 and slightly lower than Test Section 2. Under special provision 1 (+1 percent), the techniques used by the contractor resulted in both Test Section 1 and Test Section 2 having higher PWL and pay factor values than the Control Section. The same observation is made under special provision 2. The PWL increases from 77 to 91 and the corresponding pay factor increases from 94 to 101 percent under special provision 1. The PWL increases from 27 to 41 percent and the pay factor increases from 69 to 75 percent under special provision 2.

Table 58. Comparison of Control and Test Section Percent Within Limits and Pay Factors

Test Section	Standard Spec. PWL 92-96%	Standard Spec. Pay Factor 92-96%	Special Provision 1 PWL 93-96%	Special Provision 1 Pay Factor 93-96%	Special Provision 2 PWL 94-96%	Special Provision 2 Pay Factor 94-96%
Control	98	104	77	94	27	*69*
Test Section 1	96	103	80	97	40	*75*
Test Section 2	100	105	91	101	41	*75*

6.9.6 Utilization of New Technologies

An intelligent compactor is a compactor equipped with the addition of the following capabilities:

- GPS based location mapping,
- Compaction surface temperature measurement,
- Compaction measurement value determination if a vibratory compactor, and
- On-board monitor/controller/data collection system.

No other new technologies such as the PMTP or WMA were used as part of this project.

6.9.7 Summary of State Findings

When the standard specification was applied, the PWL values for five of the six lots were 100 percent and the corresponding pay factors were all 105 percent with the exception of one lot, which was 99 percent. This illustrates that what the contractor did on both test sections to increase density led to good quality per the current SHA's standard specifications. When the lower density specification limit was raised by 1.0% (Test Section 1), the observed PWL values were 69 to 95 percent and averaged 80 percent. The corresponding pay factors were 90 to 103 percent and averaged 97 percent. When the lower density specification limit was raised by 2.0% (Test Section 2), the observed PWL values were 19 to 60 percent and averaged 41 percent. The corresponding pay factors were 64 to 85 percent and averaged 75 percent. Even though it is a limited data set, the Test Section 2 data suggests that an increase in mat density specification limit of 2 percent would be unreasonable, especially with the extra effort placed on Test Section 2 by this contractor.

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

- Observations for field operations (contractors):
    - The breakdown roller pattern included five vibratory passes and two static passes for TS1 and six vibratory passes and three static passes for TS2. The intermediate roller pattern included nine static passes.
    - The standard deviations of density results were significantly improved with the increase in the lower density limit by 2 percent.
- Observations for specification development (agencies):
    - On average, a 1 percent increase in the specified density resulted in a 0.6 percent increase in density (compared to the Control Section). In addition, a PWL analysis indicated a significant increase in the number of results within limits.
    - On average, a 2 percent increase in the specified density resulted in a 0.5 percent increase in density (compared to the Control Section). Also, a PWL analysis indicated a significant increase in the number of results within limits.
    - The lot average specification from this project required percent densities between 92.0 and 96.0 percent.
    - The specification had incentives and disincentives.

6.10 Phase 3 – State 10 (P3-S10

6.10.1 Project Description

The construction project was located on a two-lane road with no traffic (location A) and on a two-lane low-volume road (location B), both at the SHA's main office. The project was paved on October 10 and October 30, 2018 at locations A and B, respectively. The target thickness of this project was 2.0 inches.

The strategy to achieve higher density in this demonstration project involved modifying the acceptance density limit and increased field compaction effort. The experimental sections placed for this study follow.

1. Test Section 1: The state's standard mixture design was used to achieve a maximum density ("break" the density of the mat) with 14 passes.
2. Test Sections 2 to 4: The same mixture design as Test Section 1 was used with an increased compaction effort (20 passes).
3. Test Section 5: The same mixture design as Test Section 1 was used, and a minimum in place density of 93.0 percent with normal paving operations was established.

This SHA recently made changes to the production portion of the specification to improve mixture characteristics. In 2010, the VMA requirement was increased; in 2017, all mix designs were migrated to 75 design gyrations. These two changes have allowed for increased asphalt in the mixes used in the state.

6.10.2 Asphalt Mixture Design

The gradation was a 9.5-mm NMAS blend that was on the coarse side of the primary control sieve. The mixture contained 25 percent RAP, 4 percent RAS and Evotherm as WMA technology. The blended aggregate gradation is shown in Table 59. The t/NMAS for this project was 5.3. A PG 58-28 binder was used. The asphalt mixture design was performed using 75 gyrations with the Superpave gyratory compactor. The mixture was designed with 4.0 percent AV and had a VMA of 15.5 percent. The optimum binder content was 5.5 percent. Mixture design information is shown in Table 60.

Table 59. Mixture Design Gradation

Particle Size	Gradation		
	Percent Passing	Specification Limit (%)	
		Min	Max
½ inch (12.5 mm)	100	100	
⅜ inch (9.5 mm)	97	90	100
No. 4 (4.75 mm)	72	65	79
No. 8 (2.36 mm)	42	37	47
No. 16 (1.18 mm)	28	24	32
No. 30 (0.60 mm)	19	15	23
No. 50 (0.30 mm)	13	9	17
No. 100 (0.15 mm)	9	5	13
No. 200 (0.075 mm)	6.9	4.9	8.1

Table 60. Mixture Design Properties

Mixture Design Property	Mixture Design	Criteria
Opt. AC (%)	5.5	
Air Voids (%)	4.0	3.0 – 5.0
VMA (%)	15.5	Min 15.0

6.10.3 Field Verification of the Asphalt Mixture Design

Agency AC samples are reported on Table 61 for verification of the mixture design of locations A and B. Binder content from all samples were slightly below the target of 5.5 percent and VMA results were within the specified range.

Table 61. Mixture Acceptance Results

Design Requirement	Test Result 10/9/18 Loc. A		Test Result 10/30/18 Loc. B	
Sample #	1	2	1	2
AC% 5.5	5.2	5.3	5.4	5.3
Air Voids% 4.0	4.1	3.2	2.5	4.3
VMA% 15.5 +/- 1.5	15.6	16.0	15.0	16.4

Design Requirement			Test Result 10/9/18 Loc. A		Test Result 10/30/18 Loc. B	
Gradations	Min (%)	Max (%)	Percent Passing			
12.5mm	100	100	100	100	100	100
9.5mm	90	100	97	96	96	98
4.75mm	-	90	72	72	74	73
2.36mm	32	67	43	42	43	43
1.16mm			28	27	28	29
.60mm			19	18	20	20
.30mm			13	13	14	14
.15mm			10	9	10	10
.075mm	2	10	6.9	6.8	7.3	7.4
Dust/Effective Asphalt			1.3	1.4	1.4	1.5

6.10.4 Density Measurement and Specifications

The density specification is based on lot average. It provides 100 percent pay for an average density of 91.26 percent and the maximum incentive is achieved at a density of 92.75 percent. The incentive starts decreasing at a density of 93.26 percent, and disincentives start at a lot average density of 95.26 percent. The statewide historical average in-place density for the 2018 construction season ranged from 92.5 to 94.5 percent.

The initial plan for Location A was to have three experimental sections. The purpose of these sections was to achieve a maximum density ("break" the density of the mat) and compare it to normal paving operations. However, a fourth section was added due to the compaction issues experienced with the first section. The plan for Location B was to achieve a minimum in place density of 93.0 percent with normal paving operations.

6.10.5 Experimental Section Construction and Results

Asphalt was delivered to the site in tandem axle dump trucks and deposited directly into the paver. A Caterpillar AP600D paver was used to lay the mix. A 15-ton Caterpillar CB64 roller operating in high frequency high amplitude vibratory mode was used as the breakdown roller at both locations. A 12-ton Volvo DD118HFA operating in high frequency vibratory mode was used as the intermediate roller at Location A, and the intermediate roller at Location B was another 14-ton Caterpillar CB64, operating with high frequency low amplitude vibratory settings. The asphalt plant is located five miles from the paving site and the hauling time was estimated to be about five minutes. The asphalt plant is a drum plant and contains separate cold bins for the fractionated RAP.

The receiving surface was a milled asphalt layer and was to be overlaid with 2.0 inches of new asphalt mixture. The paver speed ranged from 15 ft/min to 20 ft/min. A seal application was applied manually resulting in a non-uniform distribution in all the experimental sections.

The initial plan for Location A was to have three experimental sections: (1) the mat density was “broken” (SHA’s definition means to increase the density with the application of compactive effort until a maximum density level is achieved after that point with more compactive effort density starts decreasing, as shown in Figure 14, (2) one pass before “breaking” the mat, and (3) normal paving. Unfortunately, it was determined when paving the southbound lane that the contractor could not “break” the mat so the plan was modified for the northbound lane and a fourth section was added to the experiment.

For the southbound lane, the breakdown roller was operating in vibratory mode in high amplitude low frequency mode and applied a total of nine passes. After the breakdown compaction had been finalized for 10 to 15 minutes, the intermediate roller started compacting in vibratory mode and in high amplitude low frequency mode for a total of five passes.

Location B was paved at night with clear sky. Temperature at the beginning of paving was 59° F. The mixture temperature behind the paver was at 225° F, which is considered very low, even for WMA. Location B included one test section (test section 5) about 200 ft long and the lane was divided into two sub-sections (left and right) for testing purposes.

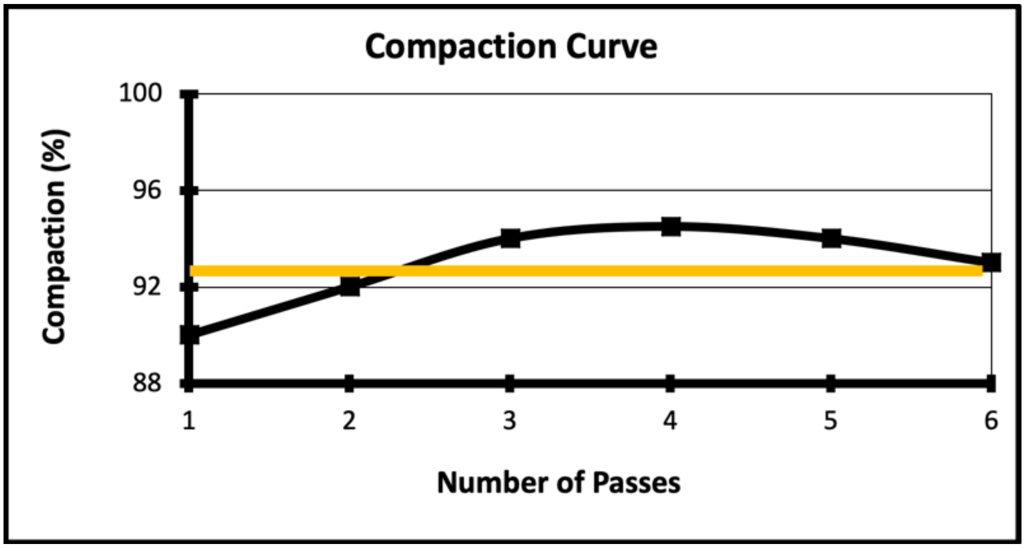


Figure 14. Theoretical Compaction Curve

The number of rolling passes, density gauge readings, and mat temperatures are provided in Table 62 for Location A. The average density from cores was 93.7 percent with a standard deviation of 0.6 percent.

Table 62. Location A, Test Section 1 Field Measurements (QC Results)

Equipment	Passes	*Gauge Reading (%)	Mat Temperature (°F)
Paver, at Screed	-	84.9	298
Breakdown Roller (9 Passes)	3	89.0	-
	5	-	-
	6	90.1	224
	8	90.1	226
Intermediate Roller (5 Passes)	10	91.4	180
	**11	92.1	-
	12	92.1	-
	13	92.1	-
	14	***93.0	-

*Non-nuclear gauge; **Increased amplitude on roller after pass number 10; ***Maximum density achieved

Based on the results of Section 1 in the southbound lane, a field discussion was held before paving the northbound lane at Location A. The decision was made to concentrate all roller efforts down the center of the lane to try to “break” the mat. Three more sections were selected and the number of passes and gauge measurements are shown in Table 63 and Figure 15. A similar compaction pattern was utilized in all three test sections. Both rollers were operating in vibratory mode and it was also decided to apply the same number of passes in the three sections.

Section 2 showed a decrease in density after 16 passes while Sections 3 and 4 showed a decrease after 18 passes. There was an obvious degradation in the mat when the gauge shows a decrease in in-place density measurement in all sections. The overall look of the mat after compaction provided evidence of broken aggregate in the field.

Table 63. Location A, Field Measurements (QC Results) for Test Sections 2 to 4

Roller	Passes	Gauge Reading* (%) Test Section 2	Gauge Reading* (%) Test Section 3	Gauge Reading* (%) Test Section 4
Breakdown (11 Passes)	6	92.1	-	-
	8	93.0	92.0	92.7
	10	92.9	92.8	92.9
Intermediate (9 Passes)	12	93.7	92.8	93.3
	14	93.6	94.0	94.8
	16	94.6**	93.6	94.9
	18	93.9	94.5**	95.2**
	20	94.2	93.8	93.9

*Non-nuclear gauge; **Maximum density achieved

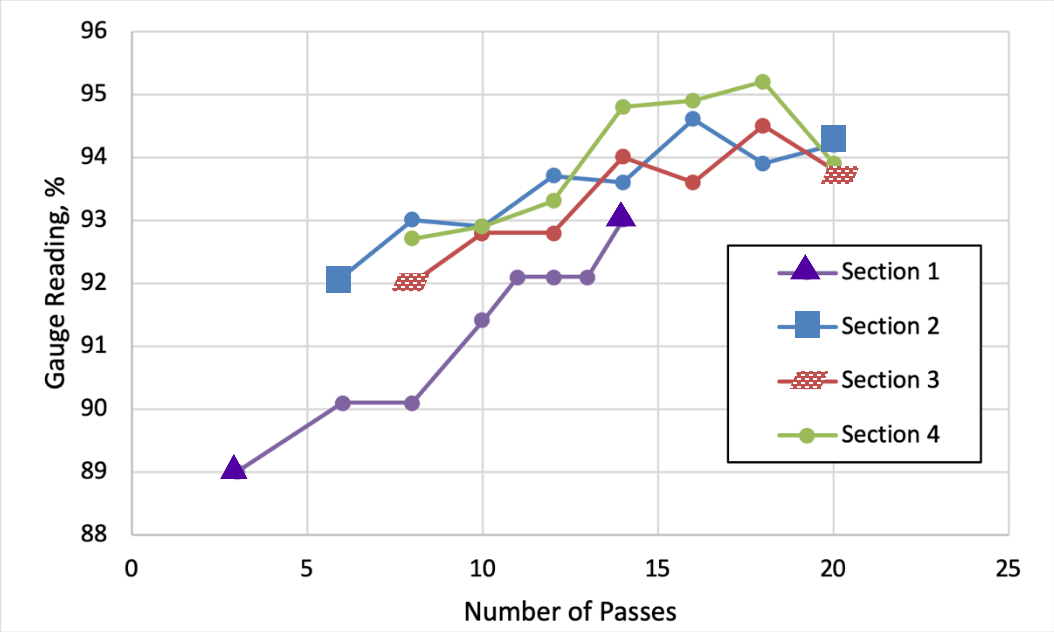


Figure 15. Density Gauge Readings at Location A

As shown in Figure 15, a density of 93 percent was achieved with about 10 passes on sections 2 to 4 at Location A. In addition, a maximum density was achieved; however; the extra compactive effort resulted in degradation in the mat. Therefore, the "normal" paving operation applied by the contractor was slightly adjusted for Location B and monitored to achieve a density of at least 93 percent without going beyond the "breaking" point of the mat.

The number of passes, density gauge readings, and mat temperatures of both sub-sections are shown in Table 64. The intermediate roller also started compacting the mat 10 to 15 minutes after the breakdown compaction was completed. Two different non-nuclear devices were utilized to obtain density readings. The overall look of the mat after compaction was uniform and no signs of broken aggregate were observed in the field. The average density from cores was 94.0 percent with a standard deviation of 1.4 percent.

Table 64. Location B, Test Section 5, Field Measurements (QC Results)

Subsection		Left Side of Paving Pass			Right Side of Paving Pass		
Roller	**Coverages****	**Gauge 1* (%)**	**Gauge 2* (%)**	**Temp. (°F)**	**Gauge 1* (%)**	**Gauge 2* (%)**	**Temp. (°F)**
Breakdown (9 passes)	1	90.7	91.5	232	90.0	91.5	225
	2	91.8	92.5	228	91.1	91.8	237
	3	92.5	93.0	215	91.8	92.4	228
	4	93.1	93.8	214	92.8	93.0	216
Intermediate (7 passes)	5	94.6	94.0	164	93.2	93.0	147
	6	94.4	94.5	151	93.3	93.4	143
	7	94.5	94.8	145	93.2	93.2	140
	8	93.6	94.8	132	93.1	93.2	133

*Non-nuclear gauge; **One coverage = 2 passes

6.10.6 Utilization of New Technologies

WMA technology was used in this project. No other new technologies such as the PMTP or intelligent compaction were used as part of this project.

6.10.7 Summary of State Findings

For State 10, the percent density increased due to changes in the number of gyrations, lower design air voids, and increased field compaction effort. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - The normal breakdown roller pattern included nine passes in vibratory mode and the intermediate roller pattern included three passes in vibratory mode.
    - The standard deviations of density results were not improved but these values were already excellent (below 1.0 percent).
- Observations for specification development (agencies):
    - The field density acceptance specification was PWL. The minimum specified density for this project was 92.0 percent and the maximum was 97.0 percent.
    - The specification had incentives and disincentives.

6.11 Phase 3 – State 11 (P3-S11)

6.11.1 Project Description

The demonstration project was located on a high volume, two-lane state highway. This SHA selected three sections; for each of the three projects, there were no predefined test sections where different methods or materials were used to improve compaction. Instead, the SHA was assessing the effects of the implementation of a “new” specification. This project would be analyzed as a whole compared to previous projects constructed under the “old” specification. The results of the three demonstrations would be compared with historical data to assess the effectiveness of a recently implemented increased density initiative. The specification change required each density gauge reading in the sublots to have equal weight in the SHA’s PWL payment system. This was an improvement over the previous specification, which allowed for an average density to be calculated from all the sublot results in a single lot and that single average value to be included in the PWL analysis. The old method allowed the effect of poor density in sublots to be dwarfed by higher readings throughout the remainder of the lot, thus reducing the penalty assessed to the contractor for failing to achieve the density required in the specification. This project was constructed on three different locations on three different dates using the same asphalt mixture:

- Test Section 1 on July 2018 (two days of testing)
- Test Section 2 on September 11, 2018
- Test Section 3 on September 12, 2018 (screed vibration sub-study)

6.11.2 Asphalt Mixture Design

The gradation was a 12.5-mm NMAS blend that was on the coarse side of the primary control sieve. The blended aggregate gradation is shown in Table 65. For this project, the t/NMAS ratio was 4.0 (TS2-3) and 5.0. A PG 64-22 binder was used in Test Section 1 and Test Section 3; a PG 70-28 was used in Test Section 2. The asphalt mixture design was performed using 80 gyrations with the Superpave gyratory compactor. The mixture was designed with 4.0 percent AV. Table 66 shows the summary information for the mixture design of each test section.

Table 65. Mixture Design Gradation

Gradation	Mixture Design				
	Percent Passing			Specification Limit (%)	
	Section 1	Section 2	Section 3	Min	Max
¾ inch (19.0 mm)	100	100	100	95	100
½ inch (12.5 mm)	98	95	97	90	100
⅜ inch (9.5 mm)	88	89	82		
No. 4 (4.75 mm)	58	53	53	53	63
No. 8 (2.36 mm)	38	34	33	34	42
No. 16 (1.18 mm)	23	25	23		
No. 30 (0.60 mm)	18	17	17	14	22
No. 50 (0.30 mm)	12	13	13		
No. 100 (0.15 mm)	9	10	10		
No. 200 (0.075 mm)	6.9	7.0	6.9	4.9	8.9

Table 66. Mixture Design Properties

Mixture Design Property	Section 1	Section 2	Section 3	Production Tolerance
Opt. AC (%)	5.6	6.6	5.8	5.1 – 6.1
Air Voids (%)	4.0	4.0	4.0	
VMA (%)	15.7	16.7	14.5	
VFA (%)	75	75	72	

6.11.3 Field Verification of the Asphalt Mixture Design

Quality control (QC) and acceptance results were recorded by the SHA during production. The results of the QC testing are shown below in Table 67. The air voids and VMA were slightly low during the first night of paving but the issues were corrected for the following night.

Table 67. Mixture QC results

Mixture Property	Section 1	Section 2	Section 3
Va (%)	3.6	4.8	N/A
VMA (%)	14.7	17.3	N/A
VFA (%)	75.3	72	N/A
AC (%)	5.8	6.6	N/A
DP	1.6	1.3	N/A

6.11.4 Density Measurement and Specifications

The density requirement in the “old” percent within limits (PWL) specification was based on a lower specification limit (LSL) of 92 percent G_{mm} using the average of the average of the sublots. The “new” PWL specification set the LSL of the density requirement at 91.5 percent G_{mm} but required that every sublot result be analyzed individually. The SHA’s goal is to increase the minimum requirement to 92 percent G_{mm} under the new method after reviewing the results of the demonstration projects. Nuclear gauge readings were recorded using a Troxler 3440 nuclear gauge.

6.11.5 Experimental Section Construction and Results

In July 2018, the mixture was delivered to the site in belly dump trucks and deposited in windrows. The mixes were transferred from the windrows to the paver using a Barber Greene BG-650 windrow elevator. A CAT AP 1055D paver was used to lay the mix. The existing surface was a milled surface with an unknown in situ pavement depth. A Trackless HRT tack was applied at a bar rate of 0.07 gal/yd2 from the tack truck. The milled surface appeared inconsistent and the tack application was streaky and uneven. Many of the nozzles appeared to be clogged. The target lift thickness was 2.5 inches. The paver was operating at 12 – 15 ft/min. The slow paver speed was due to a truck shortage, as there were only 15 or 16 trucks available and the distance from and to the plant was 1.5 hours roundtrip. The mixture was about 300^{o} F when delivered to the site in windrows.

Three rollers were used for compacting the mat in this project. The breakdown roller was a 14-ton CAT CB-64B vibratory steel-drum roller. A 12-ton CAT CB-534D XW vibratory steel-drum roller was used as the intermediate roller and a 10-ton CAT CB-534C static steel-drum roller was used as the finishing roller. The breakdown roller applied about 15 vibratory passes on average on high amplitude. The mat was rolled in three lanes and each lane received five passes. The intermediate roller applied four passes per lane operating in vibratory mode on high amplitude and the return fifth pass was static. This was done for all three lanes on the mat for a total of 15 more passes. The finishing roller did not have a set number of passes but would roll until the mat visually looked good.

The density measurements for the two nights that were observed passed the SHA’s “new” specification. The standard deviations were reasonably low, and the averages were well above the LSL of 91.5 percent of G_{mm}. In fact, these results would have received an incentive if the LSL were 92.0 percent of G_{mm}. There were no major issues regarding density. Volumetric adjustments were made after the first night of paving and the following results were within specification. This project demonstrates that the SHA’s specification change does not provide a significant burden on the contractor and that contractors should be able to continue to produce good quality mixes while having every density shot analyzed individually.

On September 11, 2018 the mixture was delivered to the site in belly dump trucks and deposited in windrows. The mix was transferred to the paver using a Bomag windrow elevator. A Terex Cedar Rapids paver was used to lay the mix. Three rollers were used to compact the mix on this project. The breakdown and intermediate rollers were a Volvo DD138 HF vibratory steel-drum roller. An Ingersoll Rand DD16 vibratory steel-drum roller was used as the finishing roller. Intelligent compaction and PMTP infrared technologies were used to monitor rolling and mat temperature for the duration of this project. The breakdown and intermediate rollers applied about 13 vibratory passes on average when observed. The target lift thickness was 2.0 inches.

On September 12, 2018 the mixture was delivered to the site in belly dump trucks and deposited in windrows. The mixes were transferred from the windrows to the paver using a Roadtec SB-2500e material transfer vehicle. A Wirtgen Vögele Vision 5203-2i paver was used to lay the mix. Three rollers were used in the compactive effort on this project. The breakdown and intermediate rollers were both Hamm HD+120 vibratory steel-drum rollers. A Volvo DD90H static steel-drum roller was used as the finishing roller. The breakdown roller applied nine vibratory passes such that each point on the mat had at least three passes. The intermediate roller applied three vibratory passes and six oscillatory passes for a total of nine passes. The finishing roller applied nine static passes. The target lift thickness was 2.0 inches.

The contractor agreed to use the paver screed vibrator for a 1000-ft test section. The screed vibration was set to 80%. The mat with the screed vibrator turned on had higher compaction after the first four passes of the breakdown roller. However, there was no initial compaction benefit directly behind the paver. After the fifth pass, when the mat temperature dropped to below 200°F, the compaction in the test with no screed vibration exceeded the test with screed vibration.

Table 68 shows average density and standard deviation for all the test sections. The density measurements for all test sections passed the SHA's "new" specification. The standard deviations were reasonably low, and the averages were well above the LSL of 91.5 percent of G_{mm}. In fact, these results would have received an incentive if the LSL were 92.0 percent of G_{mm}. There were no major issues regarding density. Volumetric adjustments were made after the first night of paving and the following results were within specification. This project demonstrates that the SHA's specification change does not provide a significant burden on the contractor and that contractors can continue to produce good quality mixes while having every density shot analyzed individually.

Table 68. Nuclear Density Results

Date	Avg.	Std. Dev.
7/18/2018	94.1%	1.3%
7/19/2018	94.4%	1.0%
9/11/2018	94.1%	1.8%
9/12/2018*	93.2%	0.9%
9/12/2018	92.9%	1.1%

**Screed Vibration*

Several other large paving projects around the state were constructed using current standard specifications (control projects) and compared to the new proposed specification. According to this SHA, similar average densities were seen between the test sections and the control projects. The test sections achieved a significantly lower standard deviation of density based on each individual test.

6.11.6 Utilization of New Technologies

Intelligent compaction and the PMTP were used in this project. No other new technologies such as the WMA or rolling density meter were used as part of this project.

6.11.7 Summary of State Findings

For State 11, the percent density met the old and new specifications. No significant increase in density was observed with the addition of screen vibration. Below is a summary of observations from this demonstration project that fits with the common themes.

- Observations for field operations (contractors):
    - The breakdown roller applied between 9 to 15 vibratory passes. The intermediate roller applied between 5 to 9 passes per lane operating in vibratory mode on high amplitude and the return pass was static.
    - Only one test section showed a standard deviation of density results below 1.0 percent.
- Observations for specification development (agencies):
    - The field density acceptance specification was PWL. The minimum specified density for this project was 91.5.
    - The specification had incentives and disincentives.

Chapter 7: Observations for Demonstration Projects Constructed in Phase 3

Density can be improved through focused efforts on field compaction. Seven of the eleven states improved in-place density by at least 0.5 percent on their demonstration projects and eight of the eleven states averaged greater than or equal to 94.0 percent in at least one section. For three SHAs, their goal was to raise the lower specification limit by at least half percent and to provide evidence of improvement in the standard deviation and higher in-place density due to that change. In another state, the SHA focus in the demonstration effort was on longitudinal joint construction. Based on the observations from these demonstration projects, techniques were identified to improve density, which would be of interest to agencies and contractors. They are presented below in no particular order.

7.1 Overview

Many of the SHAs participating in Phase 3 of FHWA's Demonstration Project for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density* constructed more than one test section for a total of 56 test sections built. 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. Thus, 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 69. The primary control sieves and control points defined in AASHTO M 323 were used to make this determination. A 9.5-mm mixture was listed as coarse-graded when less than 47 percent of the gradation was passing the 2.36-mm sieve. A 12.5-mm mixture with less than 39 percent passing 2.36-mm sieve was shown as coarse-graded. The effect of each variable is discussed below.

Table 69 Summary of Mixture Properties on In-Place Density

State-Section Number	NMAS (mm)	Fine- or Coarse-Graded	Thick to NMAS	Num of Gyr	Mixture Design AC (%)	Mixture Design Air Voids (%)	Prod Air Voids (%)	Mixture Design VMA (%)	Prod VMA (%)	Density (%G_{mm})
1-C	9.5	Fine	4.7	100	6.3	4.0	4.3	15.1	14.8	93.5
1TS1	9.5	Fine	4.7	100	6.3	4.0	4.3	15.1	14.8	94.2
2-C1	12.5	Coarse	3.5	80	4.8	4.0	3.8	14.3	14.1	93.2
2-TS1	12.5	Coarse	3.5	60	5.0	3.5	3.8	14.0	14.0	94.5
2-TS2	12.5	Coarse	3.5	60	5.4	3.0	3.4	14.3	14.5	94.6
2-TS3	12.5	Coarse	3.5	80	4.8	4.0	4.1	14.3	14.0	94.6

State-Section Number	NMAS (mm)	Fine- or Coarse-Graded	Thick to NMAS	Num of Gyr	Mixture Design AC (%)	Mixture Design Air Voids (%)	Prod Air Voids (%)	Mixture Design VMA (%)	Prod VMA (%)	Density (%G_{mm})
2-C2	12.5	Coarse	3.5	80	4.8	4.0	4.2	14.3	14.6	92.6
2-TS4	12.5	Coarse	3.5	60	5.0	3.5	3.6	14.0	14.3	94.9
2-TS5	12.5	Coarse	3.5	60	5.4	3.0	3.5	14.3	14.5	95.8
2-TS6	12.5	Coarse	3.5	80	4.8	4.0	3.8	14.3	14.3	95.2
3-C	9.5	Coarse	4.0	50	5.4	3.9	1.5	15.1	NA	89.5
3-TS1	9.5	Coarse	4.0	50	5.4	3.9	3.4	15.1	NA	92.1
3-C2	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	92.8
3-TS2	9.5	Coarse	4.0	50	5.4	3.9	2.7	15.1	NA	91.1
3-TS3	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	93.5
3-TS4	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	93.5
3-TS5	9.5	Coarse	4.0	50	5.4	3.9	3.9	15.1	NA	94.2
3-TS6	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	91.4
3-TS7	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	90.7
3-C3	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	91.3
3-TS8	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	91.4
3-TS9	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	93.7
3-C4	9.5	Coarse	4.0	50	5.4	3.9	NA	15.1	NA	93.5
4-C1	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	95.2
4-TS1	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	95.5
4-TS2a	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	95.2
4-TS2b	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	94.3
4-TS3	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	94.9
4-TS4	19.0	Fine	4.0	80	5.1	3.2	NA	14.0	NA	93.3
4-C2	19.0	Fine	4.0	80	4.8	4.0	NA	14.0	NA	93.1
5-C Joint	12.5	Fine	4.0	50	5.8	3.0	NA	16.0	NA	91.0
5-TS1	12.5	Fine	4.0	50	5.8	3.0	NA	16.0	NA	89.8
5-TS2	12.5	Fine	4.0	50	5.8	3.0	NA	16.0	NA	90.7
5-TS3	12.5	Fine	4.0	50	5.8	3.0	NA	16.0	NA	90.1
5-TS4	12.5	Fine	4.0	50	5.8	3.0	NA	16.0	NA	89.5
6-C	12.5	Coarse	4.0	75	5.0	4.0	3.8	15.9	NA	94.5
6-TS1	12.5	Coarse	4.0	75	5.0	4.0	1.7	15.9	NA	95.1
6-TS2	12.5	Coarse	4.0	75	5.0	4.0	2.7	15.9	NA	96.0
7-C	12.5	Coarse	4.0	75	4.8	3.8	3.5	15.1	14.2	91.9
7-TS1	12.5	Coarse	4.0	75	4.8	3.8	2.7	15.1	14.6	92.1
8-C	12.5	Fine	2.5	NSP	5.7	4.0	NA	16.9	NA	93.0
8-TS1	12.5	Fine	2.5	NSP	5.7	4.0	NA	16.9	NA	93.8
8-TS2	12.5	Fine	2.5	NSP	5.7	4.0	NA	16.9	NA	93.7
8-TS3	12.5	Fine	2.5	NSP	5.7	4.0	NA	16.9	NA	94.8
9-C	19.0	Fine	4.0	NA	4.2	NA	NA	NA	NA	93.3
9-TS1	19.0	Fine	4.0	NA	4.2	NA	NA	NA	NA	93.9
9-TS2	19.0	Fine	4.0	NA	4.2	NA	NA	NA	NA	93.8
10-C	9.5	Coarse	5.3		5.5	4.0	NA	NA	NA	93.0

State-Section Number	NMAS (mm)	Fine- or Coarse-Graded	Thick to NMAS	Num of Gyr	Mixture Design AC (%)	Mixture Design Air Voids (%)	Prod Air Voids (%)	Mixture Design VMA (%)	Prod VMA (%)	Density (%G_{mm})
10-TS1	9.5	Coarse	5.3	NA	5.5	4.0	NA	NA	NA	93.7
10-TS2	9.5	Coarse	5.3	NA	5.5	4.0	NA	NA	NA	94.5
10-TS3	9.5	Coarse	5.3	NA	5.5	4.0	NA	NA	NA	95.2
10-TS4	9.5	Coarse	5.3	NA	5.5	4.0	NA	NA	NA	94.0
11-TS1A	12.5	Coarse	5.0	80	5.6	4.0	3.2	15.7	14.4	94.1
11-TS1B	12.5	Coarse	5.0	80	5.6	4.0	4.3	15.7	15.4	94.4
11-TS2	12.5	Coarse	4.0	80	6.6	4.0	4.8	16.7	17.3	94.1
11-TS3A	12.5	Coarse	4.0	80	5.8	4.0	NA	14.5	NA	93.2
11-TS3B	12.5	Coarse	4.0	80	5.8	4.0	NA	14.5	NA	91.7

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.

- Five states used fine gradations (States 1, 4, 5, 8, and 9), and
- Six states used coarse gradations (States 2, 3, 6, 7, 10, and 11).

Experience has shown that fine-graded mixtures are generally more workable and easier to compact than coarse-graded mixtures. It is clear from the data in Table 69 that good or poor density could be obtained with either fine-graded or coarse-graded mixtures. Based on this data, 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.

- Three states used 9.5-mm NMAS (States 1, 3, and 10),
- Six states used 12.5-mm NMAS (States 2, 5, 6, 7, 8, and 11), and
- Two states used 19.0-mm NMAS (States 4 and 9).

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 NMAS values. 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 in the demonstration projects generally followed the best practice guidelines, as follows.

- One state with t/NMAS < 3.0 (State 8)
- One state with t/NMAS ≥ 3.0 (State 2)
- Seven states with t/NMAS ≥ 4.0 (States 1, 3, 4, 5, 6, 7, and 9), and
- Two states with t/NMAS ≥ 5.0 (States 10 and 11).

7.4 Asphalt Mixture Design

Superpave asphalt mixture design requirements are defined in AASHTO M323 and R35. 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 gyration level is reduced, the amount of asphalt needed to fill the voids to the desired level is increased for the same gradation. However, if the design VMA requirement is unchanged, lowering the design gyration level in the mix design specification may not result in a higher design binder content as the gradation can be changed to meet the VMA requirement at the lower design gyration level.

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, as 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.

One state made engineering adjustments to the AASHTO Superpave mixture design to obtain higher optimum AC (State 2). This state increased the asphalt binder content by 0.2 to 0.6 percent. Engineering adjustments to obtain a slightly higher optimum asphalt content included adjusting gyrations (from 80 to 60 gyrations) and lowering design air voids (from 4.0 to 3.5 and 3.0). The resulting increase in density ranged from 1.3 to 3.2 percent. In addition to State 2, States 5 and 7 looked at designing an asphalt mixture with lower laboratory air voids. However, these states did not have another mixture at higher air voids to evaluate the effect on field density.

When adjusting the mixture design criteria, it is important to adjust the field density requirement. For instance, if an agency makes engineering adjustments to increase the optimum asphalt content, then the agency should also adjust the percent density requirement. State 1 increased the minimum specified field density from 91.0 percent to 91.5 percent in 2018 (during the execution of this project) and it will be increased to 92.0 percent in 2019. State 11 has a minimum density requirement of 91.5 percent but requires that each sublot result be analyzed individually. Their goal is to increase the minimum requirement to 92 percent after reviewing the results of the demonstration projects.

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 from that shown in the design. The laboratory properties of the asphalt mixture during production should correlate better with in-place density than the design properties. The asphalt mixture design was adequately verified by each SHA, and adjustments were made as needed to ensure that the production gradations and mixture volumetric properties met the specification requirements.

Six states reported laboratory compacted air voids during production (States 1, 2, 3, 6, 7, and 11). Compared to the design air voids, a decrease in production air voids was observed for these six states. Four states reported laboratory compacted VMA values during production (States 1, 2, 7, and 11). Compared to the design VMA, a decrease in VMA during production was also observed for these states.

7.6 Placement and Compaction

The placement and compaction data along with in-place density results are provided in Table 70. MTVs have been shown to provide improved smoothness and reduced segregation and were used in the demonstration projects in seven states (States 2, 3, 5, 6, 7, 9, and 11). The number of compaction rollers varied from as few as two rollers on one demonstration project (State 6) and up to six compaction rollers on another demonstration project (State 3). A summary of some key observations follows. Since State 5 focused on joint density, the number of passes was not included here.

- The total number of passes on the test section with the highest density was as follows:
    - Five states used < 15 passes (States 1, 2, 3, 7, and 8),
    - Two states used 15 to 20 passes (States 9 and 10), and
    - Three states used > 20 passes (States 4, 6, and 11).
- When vibratory or oscillatory rollers were used, all of the passes generally used the vibratory or oscillatory mode. In some cases, there were one or two final passes that were static. Four states used the vibratory mode of the roller with less than 10 passes in the Control Section (States 3, 5, 7, and 8).
- State 3 used breakdown rollers in echelon.
- Three states used pneumatic rollers (States 3, 4, and 11).
- One state used vibratory pneumatic rollers (State 3).

Overall, the results showed that the amount of rolling significantly affected the in-place density. An additional roller was helpful in increasing density. Three SHAs used an additional roller to successfully obtain higher in-place density (States 3, 4, and 6).

Table 70. Summary of Effect of Placement, Compaction, and New Technologies

State–Section	MTV	Compaction Rollers*	Passes (Total)	New Tech.	Density (%G_{mm})	Lot Std. Dev.
1-C	Yes	2 steel wheel	12 vibratory	GPR DPS	93.5	1.4
1TS1	Yes	2 steel wheel	12 vibratory	GPR DPS	94.2	0.7
2-C1	Yes	2 steel wheel	12 vibratory	Spray paver	93.2	0.59
2-TS1	Yes	2 steel wheel	12 vibratory	Spray paver	94.5	0.7
2-TS2	Yes	2 steel wheel	12 vibratory	Spray paver	94.6	NA
2-TS3	Yes	3 steel wheel	15 vibratory	Spray paver	94.6	NA
2-C2	Yes	2 steel wheel	12 vibratory	None	92.6	0.1
2-TS4	Yes	2 steel wheel	12 vibratory	None	94.9	0.38
2-TS5	Yes	2 steel wheel	12 vibratory	None	95.8	NA
2-TS6	Yes	3 steel wheel	15 vibratory	None	95.2	NA
3-C	No	2 steel wheel	24 vibratory, 2 static	WMA, IR, GPR DPS	89.5	4.7
3-TS1	Yes	2 steel wheel	24 vibratory, 2 static	WMA, IR, GPR DPS	92.1	1.2
3-C2	Yes	2 steel wheel	8 vibratory, 2 static	WMA, IR, GPR DPS	92.8	3.3
3-TS2	Yes	2 steel wheel, 1 pneum.	8 vibratory, 2 static, 3 pneum. (S)	WMA, IR, GPR DPS	91.1	3.4
3-TS3	Yes	2 steel wheel, 1 pneum.	8 vibratory, 2 static, 3 pneum. (V)	WMA, IR, GPR DPS	93.5	1.7
3-TS4	Yes	2 steel wheel, 1 pneum., 1 CR	8 vibratory, 2 static, 3 pneum. (S), 3 CR (V)	WMA, IR, GPR DPS	93.5	0.7
3-TS5	Yes	2 steel wheel, 1 CR	8 vibratory, 2 static, 3 CR (V)	WMA, IR, GPR DPS	94.2	1.3
3-TS6	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	91.4	2.7
3-TS7	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	90.7	3.9
3-C3	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	91.3	0.6
3-TS8	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	91.4	1.7
3-TS9	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	93.7	0.5
3-C4	Yes	2 steel wheel	8 vibratory, 2 static	WMA, GPR DPS	93.5	3.0
4-C1	No	3 steel wheel	18 vibratory, 4 static	None	95.2	0.34
4-TS1	No	3 steel wheel	18 vibratory, 4 static	Oscillating Roller (F)	95.5	0.39
4-TS2a	No	3 steel wheel	9 vibratory, 9 Oscillatory, 4 static	Oscillating Roller (I)	95.2	1.27
4-TS2b	No	3 steel wheel	9 vibratory, 9 Oscillatory, 4 static	Oscillating Roller (I)	94.3	1.33
4-TS3	No	2 steel wheel, 1 pneum.	17 vibratory, 2 static, 19 pneum.	None	94.9	NA
4-TS4	No	2 steel wheel	12 vibratory, 4 static	None	93.3	1.14
4-C2	No	2 steel wheel	14 vibratory, 4 static	None	93.1	0.84
5-C Joint	Yes	2 steel wheel	4 vibratory, 6 static	None	91.1	NA
5-TS1	Yes	2 steel wheel	4 vibratory, 6 static	Joint bond	89.8	NA

State–Section	MTV	Compaction Rollers*	Passes (Total)	New Tech.	Density (%G_{mm})	Lot Std. Dev.
5-TS2	Yes	2 steel wheel	4 vibratory, 6 static	Notched edge	90.8	NA
5-TS3	Yes	2 steel wheel	4 vibratory, 6 static	Joint heater	90.1	NA
5-TS4	Yes	2 steel wheel	4 vibratory, 6 static	Joint emulsion spray	89.5	NA
6-C	Yes	1 steel	16 vibratory, 1 static	None	94.5	0.7
6-TS1	Yes	1 steel	16 vibratory, 1 static	None	95.1	0.8
6-TS2	Yes	2 steel	22 vibratory, 2 static	None	96.0	0.6
7-C	Yes	1 steel	3 vibratory	None	91.9	0.87
7-TS1	Yes	1 steel	3 vibratory	None	92.1	1.97
8-C	Yes	2 steel	7 vibratory, 5 static	IC	93.0	1.94
8-TS1	Yes	2 steel	7 vibratory, 5 static	IC	93.8	1.53
8-TS2	Yes	2 steel	7 vibratory, 5 static	IC	93.7	1.35
8-TS3	Yes	2 steel	7 vibratory, 8 static	IC	94.8	0.98
9-TS1	Yes	1 steel, 1 pneum.	5 vibratory, 11 static	IC	93.9	0.76
9-TS2	Yes	1 steel, 1 pneum.	6 vibratory, 15 static	IC	93.8	0.56
10-C	No	2 steel	14 vibratory	WMA	93.0	NA
10-TS1	No	2 steel	16 vibratory	WMA	93.7	0.6
10-TS2	No	2 steel	18 vibratory	WMA	94.5	NA
10-TS3	No	2 steel	18 vibratory	WMA	95.2	NA
10-TS4	No	2 steel	16 vibratory	WMA	94.0	1.4
11-TS1A	No	2 steel	27 vibratory, 3 static	None	94.1	1.3
11-TS1B	No	2 steel	27 vibratory, 3 static	None	94.4	1.0
11-TS2	No	2 steel	13 vibratory, 3 static	None	94.1	1.7
11-TS3A	Yes	2 steel	13 vibratory, 3 static	IC, PMTP	93.2	0.9
11-TS3B	Yes	2 steel	13 vibratory, 3 static	IC, PMTP	91.7	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 Longitudinal Joints

While longitudinal joints were not a specific part of this study, good compaction in the joints is very important for good performance. Some of the demonstration projects had a roller focusing on the density at the joint, and some included the application of a sealant. The sealant was applied as a thin strip that is provided in a roll and can be unrolled and placed on the free edge of a previously placed lane before the adjacent lane is placed. No testing was performed to determine its effectiveness, but this is something that has been done in the past to improve joint performance. Joint heaters were used on one of the demonstration projects. The effectiveness of any of these efforts on the longitudinal joint was not evaluated as part of this study.

The focus of State 5's in-place density demonstration effort was on longitudinal joint construction. Four different techniques were employed to promote an improved longitudinal joint, mostly through increasing the asphalt density at the joint. However, the use of four joint construction techniques did not show an improvement in density when compared to the Control Section.

7.8 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 G_{mm} 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 states reported density as a percent of G_{mm} or the air voids in the compacted mix.

7.9 Field Acceptance Specification

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

- The contractors' job is to be the low bidder and to meet the specifications. Simply asking for higher density, four states (States 1, 9, 10, and 11) 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. Eight states (States 1, 2, 3, 4, 6, 8, 9, and 11) 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. Nine states (States 1, 2, 3, 4, 6, 7, 8, 9, and 11) used incentives. Several states noted the importance of the incentive to the success of their improvement in density.

7.10 New Technologies

Several states evaluated new technologies to help ensure good compaction. The technologies used included warm mix asphalt, GPR DPS, oscillating roller, PMTP, joint construction equipment, spray paver, and intelligent compaction. The number of states using each of the technologies was as follows:

- WMA was used by two states (States 3 and 10);
- GPR DPS was used by two states (States 1 and 3);
- Oscillating roller was used by two states (States 4 and 11);
- PMTP was used by two states (States 3 and 11);
- Joint construction equipment was used by one state (State 5);
- Spray paver was used by one state (State 2); and
- IC was used by three states (States 8, 9 and 11).

Chapter 8: Summary of Observations for All Three Phases of the Demonstration Project

This summary of Phases 1, 2, and 3 includes:

- Techniques used to increase density, and
- Changes made by SHAs and their other observations.

Twenty-nine demonstration projects were constructed in Phases 1, 2, and 3 of FHWA's Demonstration Project for *Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density*. As shown in Table 71, three SHAs participated in two phases for a total of 26 unique SHAs. The demonstration projects included 119 experimental sections, which included 34 control sections and 85 test sections. Control sections were intended to represent what the SHA normally did. The test sections were intended for the SHA and contractor to try other methods to increase density. On some demonstration projects, SHAs constructed more than one control section in order to examine different techniques. One example was using a conventional paver on the control section and then on the test sections to evaluate different compaction techniques, and then using a spray paver as a second control section and on additional test sections. On average, there were 4.2 experimental sections constructed per demonstration project.

Table 71. Summary of the Number of Projects and Experimental Sections

Statistics	Number
SHAs	26
Demonstration Projects	29
Control Sections	35
Test Sections	86
Experimental Sections	121

For this summary, SHAs will be identified by Px-Sy. The "P" is the abbreviation for the phase and the "x" can be 1, 2, or 3. The "S" is the abbreviation for state and is the anonymous, randomly-assigned number which can be 1, 2, 3, etc. So, P2-S7 is the state that was randomly assigned number "7" in the second phase of this effort.

In Phases 1, 2 and 3, some metrics were compiled related to the increase in density (at least 1.0 percent) from the control section and the average density (at least 94.0 percent) in at least one test section. The metrics are summarized in Table 72.

The number of demonstration projects with at least 1.0 percent increase in density from the control section to a test section was 17 of 29 as follows.

- Phase 1: P1-S1, P1-S2, P1-S3, P1-S4, P1-S5, P1-S6, P1-S7, and P1-S8 (7 of 10 states),
- Phase 2: P2-S2, P2-S3, P2-S4, P2-S5, and P2-S7 (5 of 8 states), and
- Phase 3: P3-S2, P3-S3, P3-S6, P3-S8, P3-S9, and P3-S10 (5 of 11 states).

The number of demonstration projects able to average at least 94.0 percent in at least one test section was 23 of 29 follows.

- Phase 1: P1-S1, P1-S2, P1-S3, P1-S4, P1-S5, P1-S6, P1-S7, and P1-S10 (7 of 10 states),
- Phase 2: P2-S1, P2-S2, P2-S3, P2-S4, P2-S5, P2-S7, and P2-S8 (7 of 8 states),
- Phase 3: P3-S1, P3-S2, P3-S3, P3-S4, P3-S6, P3-S8, P3-S9, P3-S10, and P3-S11 (9 of 11 states).

The number of demonstration projects with either at least 1.0 percent increase in density or able to average at least 94.0 percent in at least one test section was 24 of 29.

These projects were constructed between 2016 and 2018 in 26 unique states. As time has passed, 24 of the 26 SHAs have made changes or are in the process of making changes to their density specifications.

Table 72. Metrics from the 29 Demonstration Projects

Description	Demonstration Projects
Increased Density ≥ 1.0% from the Control Section	17 of 29
Test Section Achieved ≥94.0%	23 of 29
Increased Density ≥ 1% from the Control Section OR Test Section Achieved ≥ 94.0%	24 of 29
SHAs making specification changes	24 of 26

8.1 Techniques Used to Increase Density

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.

8.1.1 More Effort: Additional Passes and/or Roller

The summary of passes used by each state on the test section with the highest density follows. P3-S5 examined joint density using different joint construction methods. Passes were not part of that particular demonstration project, so it is not included.

- Nine of the 27 states used < 15 passes (States P1-S2, P1-S6, P1-S9, P2-S2 P3-S1, P3-S2, P3-S3, P3-S7, and P3-S8),
- Nine of the 27 states used 15 to 20 passes (States P1-S5, P1-S7, P1-S10, P2-S4, P2-S5, P2-S6, P2-S7, P2-S8, and P3-S10), and
- Ten of the 27 states used > 20 passes (States P1-S1, P1-S3, P1-S4, P1-S8, P2-S1, P2-S3, P3-S4, P3-S6, P3-S9, and P3-S11).

The number of rollers on the demonstration projects ranges from 1 to 6. The number of passes ranged from 9 to 33. There was a wide range of compactive efforts observed around the country.

Thirteen states added passes as shown in Table 73. Ten of the 13 did this by adding at least one roller, and three of the states added two rollers. Five states added a double-drum vibratory roller which was the most common. Other types of rollers added included oscillation, pneumatic, pneumatic in the vibratory mode, and a combination roller. The increase in passes ranged from 2 to 12. The most common increase in passes was 5 with an average of 6. The average increase in density ranged from 0 to 2.5 percent and averaged 1.2 percent. In cases where there was no increase, it could have been that the: 1) density was already at or above 94.0 percent or 2) mixture was low in asphalt content and already reached a "refusal" density.

Table 73. Summary of States Adding Passes and/or Rollers and the Results

State	Control Section Density (%G_{mm})	Passes Added	Roller Type Added	Test Section Density (%G_{mm})	Change in Density (%G_{mm})
P1-S1	93.5	9	Pneumatic	95.4	+1.9
P1-S2	91.0	2	---	91.8	+0.8
P1-S3	94.0	5	DDV	93.7	-0.3
P1-S4	93.5	5	DDV	95.0	+1.5
P1-S4*	93.5	5	DDV	95.4	+1.9
P2-S1	93.2	6	---	94.0	+0.8
P2-S3	92.9	9	DDV	94.0	+1.1
P2-S3	92.9	11	DDV (2 added)	94.7	+1.8
P2-S4	95.8	5	DDV	95.7	-0.1
P2-S4*	95.8	5	DDV	97.1	+1.3
P2-S5	92.0	12	DDV Vib. Pneumatic	94.5	+2.5
P2-S7	92.8	7	Pneumatic	93.5	+0.7
P3-S2	94.9	10	DDV (2 added)	95.2	+0.3
P3-S3	91.7	3	Pneumatic	91.1	-0.6
P3-S3	91.7	3	Vib Pneumatic	93.5	+1.8
P3-S3	91.7	6	Pneumatic Combination Roller	93.5	+1.8
P3-S3	91.7	3	Combination Roller	94.2	+2.5
P3-S6	94.5	7	DDV	96.1	+1.6
P3-S10	92.8	Not Known	---	94.0	+1.6
Average		6.4			+1.2

DDV – Double Drum Vibratory *Added asphalt content

8.1.2 Roller Type and Position

Ten states used breakdown rollers in echelon (States P1-S1, P1-S3, P1-S4, P1-S5, P1-S6, P1-S7, P2-S3, P2-S5, P2-S7, and P3-S3). Nine of these 10 had densities of at least 94.0 percent and 5 of these 10 had densities of at least 95.0 percent. Two states used a pneumatic roller in the intermediate position in echelon (P1-S3 and P1-S4).

Eleven states used pneumatic rollers (States P1-S1, P1-S3, P1-S4, P1-S5, P1-S8, P2-S3, P2-S5, P2-S7, P2-S8, P3-S3, and P3-S4). When a comparison could be made between using and not using a pneumatic roller, the associated density increase was inconsistent. In one case, it was significant, and in two cases it was negligible as shown in Table 74.

Table 74. Summary of States Adding a Pneumatic Roller and the Results

State	Density (%G_{mm}) w/o Pneumatic	Passes Added w/ Pneumatic	Density (%G_{mm}) w/ Pneumatic	Change in Density (%G_{mm})
P1-S1	93.5	9	95.4	+1.9
P3-S3	91.7	3	91.1	-0.6
P3-S4	95.2	0	94.9	-0.3

Two states used vibratory pneumatic rollers (States P2-S5 and P3-S3), and the associated density increase was approximately 2.0 percent as shown in Table 75.

Table 75. Summary of States Adding a Vibratory Pneumatic Roller and the Results

State	Density (%G_{mm}) w/o Vib. Pneumatic	Passes Added w/ Vib. Pneumatic	Density (%G_{mm}) w/ Vib. Pneumatic	Change in Density (%G_{mm})
P2-S5	92.0	7 and 5 DDV	94.5	+2.5
P3-S3	91.7	3	93.5	+1.8

Seven states used oscillation (States P1-S5, P1-S9, P2-S4, P2-S8, P3-S4, P3-S6, and P3-S11). Table 76 compares the results of oscillation and vibratory rollers. For P1-S5, there was a focus on using the oscillation and there were very positive results: fewer passes and greater density. For P1-S9, the oscillatory roller was primarily used in static mode, and there was not a significant difference.

Table 76. Summary of States Adding Oscillation and the Results

State	Density (%G_{mm}) w/o Oscillation	Change in Passes w/ Oscillation	Density (%G_{mm}) w/ Oscillation	Change in Density (%G_{mm})
P1-S5	92.5	-5	93.2	+0.7
P1-S9	92.2	-6	92.0	-0.2

One state used a combination roller (State P3-S3), and the associated density increase was just over 2.0 percent in two different test sections, as shown in Table 77.

Table 77. Summary of States Adding a Combination Roller and the Results

State	Density (%G_{mm}) w/o Comb. Roller	Passes Added	Density (%G_{mm}) w/ Comb. Roller	Change in Density (%G_{mm})
P3-S3	91.1	3	93.5	+2.4
P3-S3	91.7	3	94.2	+2.5

Two states used the same rollers in the control and test sections, and they focused on a tighter and more consistent roller pattern (States P1-S8 and P3-S1). In one case, there was no change in density and in the other case the density achieved was slightly higher, 0.7 percent. In both cases the standard deviation of the density results was improved significantly, approximately half.

8.1.3 Material Transfer Vehicle (MTV) vs. Windrow Elevator

MTVs have been shown to provide improved smoothness and reduced segregation and were used on 18 of the 28 demonstration projects (States P1-S1, P1-S4, P1-S5, P1-S6, P1-S7, P1-S8, P1-S9, P1-S10, P2-S2, P2-S3, P2-S5, P2-S6, P2-S7, P3-S2, P3-S3, P3-S5, P3-S6, and P3-S7). One state compared the density obtained when the MTV was used vs. the windrow elevator (State P3-S3). When using the MTV there was an increase of 2.6 percent density.

8.1.4 Conventional Paver vs. Spray Paver

One state (P3-S2) compared the density obtained using a conventional paver with that using a spray paver. Four experimental sections were constructed with each type of paver. Based upon the comparison, the conventional paver was about 0.5% higher density in three of the four experimental sections.

8.1.5 Thickness to Nominal Maximum Aggregate Size (t/NMAS)

There was a trend noticed regarding the use of asphalt mixtures with smaller NMAS aggregates. The breakdown of NMAS used within the demonstration projects is shown below. Some demonstration projects used multiple NMAS mixtures.

- 8 states used 9.5-mm NMAS (P1-S3, P1-S4, P1-S6, P1-S7, P2-S4, P3-S1, P3-S3, and P3-S10),
- 20 states used 12.5-mm NMAS (P1-S1, P1-S2, P1-S3, P1-S4, P1-S5, P1-S8, P1-S9, P2-S2, P2-S3, P2-S5, P2-S6, P2-S7, P3-S2, P3-S5, P3-S6, P3-S7, P3-S8, and P3-S11), and
- 6 states used 19.0-mm NMAS (P1-S10, P2-S1, P2-S2, P2-S8, P3-S4, and P3-S9).

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 in the demonstration projects generally followed the best practice guidelines. The summary of t/NMAS used on each demonstration project follows. Multiple t/NMAS were used on demonstration projects in P1-S3, P1-S4, P2-S2, and P3-S8.

- Two states with t/NMAS < 3.0 (States P1-S10 and P3-S8),
- Six states with t/NMAS≥ 3.0 and < 4.0 (States P1-S3, P1-S4, P1-S8, P2-S5, P3-S2, and P3-S8),
- Twenty states with t/NMAS ≥ 4.0 and <5.0 (States P1-S1, P1-S2, P1-S3, P1-S4, P1-S5, P1-S6, P1-S7, P1-S9, P2-S1, P2-S2, P2-S5, P2-S7, P2-S8, P3-S1, P3-S3, P3-S4, P3-S5, P3-S6, P3-S7, and P3-S8), and
- Five states with t/NMAS ≥ 5.0 (States P2-S3, P2-S4, P2-S6, P3-S10, and P3-S11).

Four states compared the density obtained when the t/NMAS was adjusted (States P1-S3, P1-S4, P2-S5, P3-S8) as shown in Table 78. State P1-S3 adjusted the NMAS from 12.5 mm to 9.5 mm keeping the lift thickness the same. The t/NMAS changed from 3.0 to 4.0 and there was a 0.5 percent increase in density. State P1-S4 adjusted the NMAS from 12.5 mm to 9.5 mm keeping the 1.75-inch lift thickness the same. The t/NMAS changed from 3.5 to 4.7 and there was a 1.7 percent increase in density. State P2-S5 adjusted the lift thickness from 2 to 1.75 inches keeping the NMAS at 12.5 mm the same. The t/NMAS changed from 4.0 to 3.5. With thinner lifts, the densities remained greater than 94.0 percent. State P3-S8 adjusted the lift thickness from 1.25 to 2.0 inches keeping the NMAS at 12.5 mm the same. The t/NMAS changed from 2.5 to 4.0. The increase in t/NMAS as a result of thicker lifts, there was a 1.8 percent increase in density. When the t/NMAS was changed by more than 1.0, there was a significant increase in density. When the t/NMAS was changed less than 1.0, the density change was negligible.

Table 78. Summary of States Changing the t/NMAS and the Results

State	t (in.)	NMAS (mm)	t/NMAS	Density (%G_{mm})	t (in.)	NMAS (mm)	t/NMAS	Density (%G_{mm})	Change
P1-S3	1.5	12.5	3.0	93.8	1.5	9.5	4.0	93.7	-0.1
P1-S4	1.75	12.5	3.5	94.0	1.75	9.5	4.7	95.2	+1.2
P2-S5	2.0	12.5	4.0	>94.0	1.75	12.5	3.5	>94.0	---
P3-S8	1.25	12.5	2.5	93.8	1.5	12.5	3.0	93.7	-0.1
P3-S8	1.25	12.5	2.5	93.8	2.0	12.5	4.0	94.8	+1.0

The t/NMAS ratios recommended by various researchers differ somewhat, especially in older references. To help ensure that adequate density can be achieved, a great deal of recent literature recommends that the t/NMAS ratio be at least 3:1 for fine graded mixes and at least 4:1 for coarse graded mixes. Some researchers recommend even higher ratios, especially for coarse mixtures. Thin lifts make it more difficult to achieve adequate compaction, especially at longitudinal joints (McDaniel, 2019).

8.1.6 Mixture Design: Gradation

The number of states using fine and coarse gradations is shown as follows.

- Eleven states used fine gradations (States P1-S1, P1-S4, P1-S5, P1-S10, P2-S1, P2-S6, P2-S8, P3-S1, P3-S4, P3-S5, and P3-S8), and
- Eighteen states used coarse gradations (States P1-S2, P1-S6, P1-S7, P1-S8, P1-S9, P1-S10, P2-S2, P2-S3, P2-S4, P2-S5, P2-S6, P2-S7, P3-S2, P3-S3, P3-S6, P3-S7, P3-S10, and P3-S11).

Changes in density based on changes in gradation were examined by two states (P1-S6 and P2-S6). The changes in density were examined when using the same aggregates with a coarse versus fine gradation (P2-S6). There was no difference in density. It should be noted that the density values were at 94.0 percent. Another state (P1-S6) changed the gradation to account for higher VMA and higher air voids. This state could obtain 2.1 percent higher density.

8.1.7 Mixture Design: Increased Asphalt Content

There are various methods to adjust the optimum asphalt content. Twelve different states made adjustments to their mixture design method in order to increase the optimum asphalt content, and six of them used multiple techniques. There were 12 demonstration projects with 16 different test sections constructed. A summary of techniques and those used by each state as part of this study follows.

- Three states used engineering judgement to adjust the optimum asphalt content (States P2-S2, P2-S4, and P3-S3),

- Six states selected optimum asphalt content at lower air voids (States P1-S4, P1-S5, P2-S5, P2-S7, P3-S2, and P3-S4),
- Three states selected optimum asphalt content by using a lower number of gyrations (States P1-S3, P2-S5, and P3-S2),
- Seven states selected optimum asphalt content with the support of performance testing, similar to a balanced mix design approach (States P1-S4, P2-S2, P2-S4, P2-S5, P2-S7, P3-S2, and P3-S6), and
- One state adjusted the optimum asphalt content based on the aged binder in the RAP (State P3-S7).

Changes in density were measured based on the increased asphalt content on the 12 different demonstration projects shown in Table 79. Generally, these adjustments to the mixture design process resulted in an additional 0.2 to 0.3 percent asphalt and an increase in density of 1.4 percent. In two cases, the state adjusted both the design air voids and gyrations, the increase in asphalt was 0.6 percent (P3-S2) and 0.7 percent (P2-S5). Changes in density can be summarized as follows.

- Seven of 11 had density increase ≥1.0 percent (States P1-S4, P1-S5, P2-S2, P2-S4, P2-S5, P2-S7, and P3-S2).
- Eight of 11 had density ≥94.0 percent (States P1-S4, P1-S5, P2-S2, P2-S4, P2-S5, P2-S7, P3-S2, and P3-S6).
- Eight of 11 either had density increase ≥1.0 percent or density ≥94.0 percent (States P1-S4, P1-S5, P2-S2, P2-S4, P2-S5, P2-S7, P3-S2, and P3-S6).

In these comparisons, the only change was the optimum asphalt content, and the roller pattern stayed the same.

In one state (P3-S2), the mixture design, performance testing and density requirement are all related. They all go together. Changes to one impact the other two, so a comprehensive change needs to be coordinated between these factors. It is important to note when making changes to the asphalt mixture design to obtain higher asphalt contents, be sure to coordinate the change with the density specification.

Table 79. Summary of States Adjusting the Optimum Asphalt Content and the Results

State	Control Section Density (%G_{mm})	Asphalt Added	Test Section Density (%G_{mm})	Change in Density (%G_{mm})
P1-S3	92.9	0.3	93.5	+0.6
P1-S4	93.5	0.3	94.6	+1.1
P1-S5	92.5	0.3	95.2	+2.7
P2-S2	92.2	0.2	94.5	+2.3
	95.6	0.2	95.9	+0.3
P2-S4	95.8	0.2	96.5	+0.7
	95.7	0.2	97.1	+1.4
P2-S5	92.0	0.7	95.0	+3.0
	92.0	0.1	93.7	+1.7
P2-S7	92.8	0.2	94.5	+1.7
P3-S2	92.6	0.2	94.9	+2.3
	92.6	0.6	95.8	+3.2
P3-S3	91.3	0.5	90.7	-0.6
P3-S4	TBD			
P3-S6	94.5	0.2	95.1	+0.6
P3-S7	91.9	0.2	91.9	0.0
Average		0.29		+1.4

8.1.8 Mixture Design: Warm Mix Asphalt

Five different states used WMA as part of their experiment. They are as follows.

- Two states used WMA at lower temperatures (States P1-S4 and P2-S1), and
- Five states used WMA at normal production temperatures (States P1-S3, P1-S4, P2-S1, P2-S2, and P2-S8).

In each of these cases, a chemical WMA additive was used. Changes in density were examined based on the use of WMA. When WMA was used at a lower temperature, there was no change in density: either higher or lower. The rollers had the same number of passes. When WMA was used at normal production temperatures, an increase in density of 3.0 percent was obtained by one state. Density increased from 92.2 percent to 95.2 percent. On another project at normal production temperatures, there were 2 fewer passes per roller to achieve the same density. Although no change in density was observed in the other three states, the densities were already at or above 94.0 percent.

8.1.9 Use of New Technology

Nine different states used new technologies like intelligent compaction (IC), paver-mounted thermal profiling (PMTP), or ground penetrating radar density profiling system (GPR DPS). These states included:

- Six states used IC (States P1-S10, P2-S1, P2-S6, P2-S8, P3-S8, and P3-S9),
- Two states used PMTP (States P1-S3 and P1-S10), and
- Four states used GPR DPS (States P1-S3, P1-S10, P3-S1, and P3-S3).

Changes in density were examined based on the use of new technology. Generally, the use of these new technologies did not result in an increase in density. Two states tried covering the IC screens as the control section and utilizing the IC screens as a test section. Two of the states (P2-S8 and P3-S9) did not see an increase in density, but density results were already at 94 percent. The other state (P3-S8) saw an increase in density of nearly 1.0 percent: from 93.0 percent to 94.0 percent. Both states reported that the roller mapping feature was very effective at increasing uniformity and lowering standard deviations. The lower standard deviations were approximately 50 percent lower (P2-S8) and 30 percent lower (P3-S8) with IC.

8.2 Summary of Changes Made by SHAs and Their Other Observations

These 29 demonstration projects were constructed between 2016 and 2018 in 26 unique states. As time has passed, 24 of the 26 SHAs have made changes or are in the process of making changes to their density specifications. These changes were tracked and are summarized below.

8.2.1 Increasing Use of Primary Density Specification (3 States Changing)

States often have different density specifications for different types of projects. Their specifications are often in tiers. Lower trafficked roads often have lower density requirements or use roller pattern studies. Three states (P2-S7, P3-S4, and P3-S7) are changing the tiering criteria for their different density specifications. As a result, the primary density specification will be used more often, and the secondary density specification will be used less often. One state (P3-S4) made improvements to their secondary density specification.

8.2.2 Quality Measure (e.g. PWL, AAD, Minimum Lot Average) (5 States Changing)

A quality measure is any one of several mathematical tools that are used to quantify the level of quality of an individual quality characteristic, e.g. average, percent within limits, percent defective, etc. Five states are making changes to their quality measure. Three states (P1-S7, P1-S9, and P2-S8) have implemented PWL for density instead of an average. One state (P3-S3) uses minimum and maximum lot averages for density and is adding a minimum individual sublot requirement. One state (P3-S7) is implementing the average absolute deviation (AAD) quality measure, as well as increasing their minimum criteria.

8.2.3 Specification Limit (Upper and Lower) (14 States Changing)

A specification limit is the limiting value(s) placed on a quality characteristic, established preferably by statistical analysis, for evaluating material or construction within the specification requirements.

- **Summary of states increasing upper limit (5 states changing)**. Five states are increasing their upper limit to a value between 97 to 100 percent to allow the contractor to achieve higher in-place densities (P1-S1, P1-S7, P2-S3, P3-S7, and P3-S9). Decker (2017) found about 77 percent of the respondents indicated that they use an upper specification limit between 97 and 98 percent density, with 58 percent of the respondents indicating an upper specification limit of 97 percent. It is interesting to note that 21 percent of the respondents indicated an upper limit of 100 percent density and approximately 35 percent indicated no upper limit for percent density in the upper specification limit.

- **Summary of states increasing lower limit (10 states changing)**. Ten states are increasing their lower specification limit (States P1-S6, P1-S7, P1-S8, P1-S9, P2-S1, P2-S8, P3-S1, P3-S2, P3-S4, and P3-S7). Specification limits are typically being increased to a lower specification limit of 92.0 percent when using PWL or 93.0 percent when using AAD.

8.2.4 Acceptance Plan

An acceptance plan (i.e., standard deviation, lot, incentive/disincentive, quality characteristic) is also called acceptance sampling plan or statistical acceptance plan. This agreed upon process for evaluating the acceptability of a lot of material includes: lot size and sample size (i.e., number of samples), quality measure, acceptance limit(s), evaluation of risks, and pay adjustment provisions. Several states took the opportunity to adjust their acceptance plan.

- **Summary of observations with standard deviation (7 states observing)**. Standard deviations of the density within each lot was improved by more consistent roller patterns or more consistent materials. This was observed by seven states (States P1-S7, P1-S8, P2-S1, P2-S4, P2-S8, P3-S1, and P3-S6). Although consistently achieving a standard deviation below 1.0 was not commonly observed, these states were able to do so.
- **Summary of states adjusting lot/sublot size (2 states changing)**. The number of tests per sublot and sublots per lot is an important part of the acceptance plan that impacts acceptance. Two states are making changes along these lines (State P3-S3 and P3-S11). In order to balance the buyer's and seller's risk, it is encouraged to have a minimum of 5 sublots per lot to make sure the material is appropriately represented and can be statistically evaluated.
- **Summary of states adjusting incentives / disincentive (7 states changing)**. Seven states adjusted incentives for the density quality characteristic by either increasing the incentive or adding an incentive for density (States P1-S1, P1-S8, P1-S9, P1-S10, P3-S1, P3-S3, and P3-S7). State P3-S1 increased the incentive for density alone by 150 percent. Nationally, for those states using an incentive, the level of incentive ranged from 1 percent to 10 percent for the density quality characteristic with an average of 2.9 percent bonus (Phase 1 Report, 2017).
- **Summary of states adjusting quality characteristics (1 state changing)**. One state added a quality characteristic for acceptance. VMA was added as part of the composite pay factor (State P3-S1). As VMA is a method to control the minimum asphalt content, having VMA as a quality characteristic will assist in obtaining density by keeping asphalt in the mixture during production.

8.2.5 Inspection and Validation (Aggregates and Validation Process) (2 States Changing)

Two states identified a need to strengthen their QA program through inspection or validation. Inspection is the act of examining, measuring, or testing to determine the degree of compliance with requirements. Through inspection, P3-S6 identified that the aggregates used for the approved mixture design were different than the aggregates being used for field production. This state will take additional steps to verify the aggregates used for production. Validation is the mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data and contractor data.) State P2-S7 used contractor's test results as part of the acceptance decision. With only 5 passes from one roller, the contractor's results indicated densities greater than 92.0 percent. When cores were tested by an independent third party as part of this study, the density results were less than 89.0 percent. This state is strengthening their validation process.

8.2.6 Quality Control (1 State's Observation)

Quality control is the process specified by the agency for a contractor to monitor, assess, and adjust their production or placement processes to ensure that the final product will meet the specified level of quality. One state identified the value of the contractor's improved quality control on their aggregate stockpiling process in which the gradations were more consistent (P2-S1). The contractor attributed the improved aggregate crushing and loading of the cold feed bins to the improved standard deviation of in-place density results. The standard deviation of the lots from density improved from approximately 1.4 to 1.0.

8.2.7 Adjusting t / NMAS (3 States Changing)

Two states are making changes related to the t/NMAS (State P3-S3 and P3-S8). State P3-S8 saw benefits from an increased t/NMAS. They have a desire to keep their 1.25-inch overlay program for budgetary reasons. They are now examining the change from 12.5 to 9.5 mm NMAS. State P3-S3 does a lot of late-season paving that is in the cold weather. They are exploring a minimum 2.0-inch overlay program.

8.2.8 Longitudinal Joint Density (4 States Changing)

Four states are either adding a longitudinal joint density specification or increasing the lower limit (States P2-S3, P2-S4, P2-S7, and P3-S5).

8.2.9 Testing Methodologies (Correlate Gauges / G_{mm} as Reference) (2 States Changing)

Two states are making changes to follow national best practices for testing and calculation of density (P1-S4 and P1-S9). One state measured in-place density using the nuclear density gauge and will now start correlating the nuclear readings to cores. Another state will calculate the percent density using the theoretical maximum specific gravity as the reference.

8.2.10 Mix Design Changes: Increasing Asphalt Content (14 States Changing)

Several states were concerned with the low asphalt contents from the Superpave asphalt mixture design procedure. Asphalt content in a mixture design was increased by designing at lower air voids, using lower gyrations, or accounting for the aged binder on RAP. States that tried this as part of their demonstration project included P1-S3, P1-S4, P1-S5, P1-S6, P1-S9, P2-S1, P2-S2, P2-S4, P2-S5, P2-S7, P3-S2, P3-S3, P3-S6, and P3-S7. These states are also making changes to their current specifications. It should be noted that several other states involved in the demonstration had already made changes to the Superpave mixture design process but considered those changes to be their standard practice.

8.2.11 Mix Design Changes: Performance Test (10 States Changing)

Several states were concerned about using Superpave volumetric properties alone, particularly if they were making changes to the mixture design method. As part of the demonstration project, several states used rutting and/or cracking performance tests to supplement the volumetric properties.

- States including rutting tests as part of their demonstration projects included P1-S4, P1-S5, P1-S7, P1-S9, P2-S2, P2-S5, P2-S7, P3-S2, P3-S6, and P3-S9.
- States using rutting and cracking tests included P1-S4, P1-S5, P1-S7, P1-S9, P2-S2, P2-S5, P3-S2, P3-S6.

It should be noted that several other states involved in the demonstration had already started using performance tests but had already made those changes to be part of their standard practice. Although the performance tests were used, they were not a change that was part of the demonstration project.

8.2.12 New Technology: IC / PMTP / GPR DPS (5 States Changing)

Several states are taking advantage of implementing new technology to obtain higher and/or more consistent density results. Intelligent compaction (IC) is being implemented by four states (States P1-S3, P2-S8, P3-S4, and P3-S8). Paver-mounted thermal profiler (PMTP) is being implemented by three states (States P1-S3, P1-S10 and P3-S3). The GPR DPS is being implemented by two states (States P1-S3 and P1-S10). It should be noted that one state is implementing all three: IC, PMTP, and GPR DPS (State P1-S3). One state is implementing PMTP and GPR DPS (State P1-S10).

8.3 Key General Observations

Generally speaking, there were several observations related to the ability to achieve higher density. With a sound asphalt mixture design that had appropriate asphalt content, higher density was possible with no extraordinary effort generally needed. There was a trend for states to use smaller NMAS aggregates as there were few 19.0-mm NMAS mixtures and many more 12.5-mm mixes. Many states were using or experimenting with 9.5-mm NMAS mixtures.

As noted by P3-S2, the asphalt mixture design, performance testing, and density requirements are all related. They all go together. Changes to any of these should be considered as a system and coordinated.

8.4 Obstacles to Achieving Higher In-place Density

While constructing the experimental sections throughout the three phases of the demonstration project, there were situations that presented obstacles for increasing in-place density. In most cases, these obstacles were overcome. This section is intended to highlight several of those obstacles and strategies used to overcome them.

There are several best practices documented in the literature (Brown et al., 2009; AI, 2007; USACE, 2000). A summary of these include:

- Understanding factors affecting compaction such as material properties (aggregates, asphalt cement and mix properties), environmental variables (layer thickness,

temperature, wind velocity, solar flux, and time available for compaction), and types of rollers,
- Determining a roller pattern such as calculation of the roller pattern, measuring density, compaction of stiff and tender mixtures, and the tender zone, and
- Addressing mat problems such as surface waves, tearing, nonuniform texture, screed marks, screed responsiveness, surface shadows, poor compaction, joint problems, checking, shoving, bleeding, roller marks, and segregation.

The information presented here is intended to document some of the practices encountered on FHWA's density demonstration project and to supplement and expand upon the published literature.

8.4.1 Stiff Mixtures

Some asphalt mixtures are very stiff and pose challenges to obtaining higher density. One of the most important strategies with stiff mixtures is to compact them while they are hottest, as this is the time that they will be the least stiff. As mentioned previously, ten demonstration projects used breakdown rollers in echelon. This strategy allows for twice the passes in the same time compared to a conventional roller pattern with one breakdown roller. With breakdown rollers in echelon, more passes are applied while the asphalt mixture is hottest. This is also an important benefit when compacting thin lifts and late season compaction when the mat cools very quickly. Several demonstration projects also used intermediate rollers in echelon (States P1-S3, P1-S4, and P3-S9). Note: P1-S3 means that this was in State 3 in Phase 1 of the FHWA Demonstration Project. Applying the most compactive effort while the asphalt mixture was hot was a very effective strategy. A few suggestions to obtaining density on a stiff mixture include:

- Tight roller patterns were effective (P1-S8 and P3-S1). Keeping rollers at consistent spacing and the breakdown roller near the paver helped achieve density more quickly. It also reduced the standard deviation of the density results. Conversely, it is particularly important to avoid the "lazy" roller pattern in which the rollers have large spaces between them and are far behind the paver.
- Balancing the paver speed with the rollers is important. If a paver speed is too fast, it can "outrun" the rollers and make density harder to achieve. Often a consistent paver speed that is balanced with the rollers can have the same production as using a fast paver speed and a lot of stopping and starting. Of course, this also improves ride quality.
- As a rule of thumb, it is desirable to obtain all but approximately 2 percent of the target density needed by completion of the breakdown rolling. If this is not being achieved, then this would be a time to review the best practices such as temperature, speed, using breakdown rollers in the echelon position, etc.

8.4.2 Tender Mixtures

Some asphalt mixtures have a lot of movement under the rollers. They may have a large bow wave in front of the roller and/or move laterally. This was experienced in P3-S11. These asphalt mixtures are difficult to compact and often referred to as "*tender mixtures*." Tender mixtures may be created by properties of the mixture design or additional fluids. In this demonstration project, it was believed to be primarily from additional fluids. The fluids could be from moisture within the aggregates or reclaimed materials that were not removed by the asphalt plant. The additional fluids could also be from additives (e.g., anti-stripping additives, warm mix asphalt additives, etc.) Tender mixtures may also be a result of a soft binder. Some binders have very low, low-temperature grades or other modifiers that were used in order for the binder to meet the performance grading requirements.

The "*tender zone*" occurs through a specific temperature range for any given mix. Tender behavior (pushing and shoving under the roller) occurs in the "*tender zone*" and behaves normally (more stable) above and below the tender zone. The upper and lower temperature limits of the tender zone are best identified by observation in the field and measuring temperature of the mat while observing mixture behavior under the action of steel drum rollers. A typical example of a tender zone may be from 230°F down to 190°F. Echelon rolling can achieve density before the mix cools to 230°F (in this example). Alternatively, where density is not achieved before the mix temperature reaches the upper limit of the tender zone, further compaction is carried out after the mixture cools below the lower limit (190°F in this example). Depending on job site conditions, this approach may be nearly impossible to achieve, and echelon rolling may be necessary. It has also been found that the diameter of the roller's drum can have an impact. The larger the diameter drum, the less impact the roller will have on creating the bow wave.

In any case, the best solution is to address the cause of a tender mixture and resolve it. When dealing with tender mixtures from additional fluids, it is important to make adjustments at the plant. The moisture needs to be removed in the drying process and/or the additives need to be accounted for as part of the mixture design.

Time typically heals these issues, and the pavement can experience normal performance once the asphalt mat "sets," "cures," or "dries." If the mat does not do this in a reasonable time, then the mat should be removed with a skid steer or front-end loader. A question often arises when tender mixtures are encountered, which is to ask about the appropriateness of rolling to obtain additional density tomorrow. Although it is possible, it is not desirable. It is best to identify the cause of the tenderness and make the appropriate adjustments at the plant (e.g., removing the moisture during the drying process).

8.4.3 Aggregate Degradation and/or Soft Aggregate

State P1-S1 had soft aggregates; therefore, two double drum vibratory rollers were used in echelon in the static mode. The density in these sections were lower than what many of the "gold medal specifications" could obtain. As part of the test section, a pneumatic roller was added. The density was increased such that the density in the test section averaged over 94.0 percent. Pneumatic rollers can be very effective when compacting asphalt mixtures with soft aggregates. Further, states P1-S3, P1-S4 and P3-S9 used pneumatic rollers in the intermediate position in echelon. Not only could this strategy assist with preventing degradation of aggregate, it was also observed that there was a lower standard deviation of density results. Pneumatic rollers have also been known to provide more uniform compaction through the depth of the asphalt layer.

State P3-S10 had some lessons learned from their demonstration project. The maximum in-place density of the mat achieved for Section 1 at Location A was only 93 percent after 20 passes applied by the breakdown and intermediate rollers. The compaction process stopped when some aggregate degradation was observed in the mat. The roller's amplitude, frequency, and speed were not coordinated, and it was apparent that something was wrong. Section 1 was considered a "failed" experiment as the contractor was not able to "break" the density (i.e., a peak density was not realized) of the mat. However, several lessons can be learned from this "failed" experiment, and they are discussed below with suggestions for future improvement.

1. Mix design. The mixture design used in Section 1 may need to be examined. A mix design with a high recycled content from RAP and RAS such as the one used in Section 1 may require more virgin asphalt than the optimum binder content determined based on the volumetric requirements (i.e., AASHTO M323). The high recycled content made the mix very stiff and more difficult to achieve a higher in-place density.
2. Compacting when it is hot. The best way to achieve a higher density and prevent aggregate degradation is to compact the mat when it is hot. Higher mat temperatures behind the paver could have been used, especially for asphalt mixtures with high recycled contents. One of the best methods for compacting the mixture when it is hot is to have two breakdown rollers in echelon. Twice the number of passes can be made in a given amount of time.
3. Importance of vibration amplitude. The high amplitude used for compaction was probably too high. A lower amplitude would have been better in reducing aggregate degradation. However, with the stiff mixture (low temperatures and high recycled content), the high amplitude may have been the only option to achieve higher density. To reduce aggregate degradation, a combination of lower amplitude with higher frequency, along with higher temperatures, would have been better.
4. Use of pneumatic roller. A pneumatic roller has been used as an intermediate roller with great success in other demonstration projects to increase in-place density without breaking aggregates in the mat.
5. Use of WMA at lower temperatures made the mat more challenging to compact. Although WMA can allow for lowered temperatures, this rule-of-thumb for WMA applies to virgin mixtures. This particular mixture in Section 1 had a high recycled content. The combination of lower temperatures (even with WMA) and higher recycled material contents still resulted in the mixture being very stiff and difficult to compact. This scenario could result in a lower maximum in-place density and aggregate degradation.

8.4.4 Weak Subgrade and/or Base

Asphalt pavement is often paved directly on soil subgrade or aggregate base course. In many of these cases, the subgrade and base are weak or soft (particularly when compared to the stiffness of the asphalt mat) and make it challenging to obtain density in the asphalt mixture being placed. P1-S4 uses a lower density requirement in lowest lift for these cases recognizing in advance that there will be an obstacle to achieving density. In high traffic applications, the lower limit of density is decreased by 1.0, and in low traffic applications, the lower limit is decreased by 2.0.

Prior to lowering the density requirement, there are a couple of options. One option is to make sure the subgrade or base is properly compacted by using an appropriate density specification. Historically, proof rolling is also another good tool. More recently, intelligent compaction has shown to be another effective tool to identify areas of weak base support by pre-mapping prior to paving. A second option is to determine the cause of the weak subgrade or base and correct it.

Another strategy can be employed as part of the mixture design. Since the lowest lift is almost always a fatigue resistant layer, it could be designed at a higher asphalt content. A higher asphalt content will help the fatigue resistant layer meet its intended function and also make it more compactible against a soft or weak subgrade or base. In these cases, an agency could create special mixture design requirements for the purpose of increasing the asphalt content. A fatigue resistant pavement layer will be more effective with a higher asphalt content and higher in-place density.

8.4.5 Density Curve and Break Point

It was particularly observed that three SHAs (P1-S9, P3-S7, and P3-S10) put a strict emphasis on the roller pattern study. They documented the number of passes and density after each pass until the density of the mat “broke” or dropped to set the number of passes. The density curve and break point provide valuable information, but there needs to be flexibility. It was noted that two of these (P1-S9 and P3-S7) had the second and third lowest densities in the control sections of the entire demonstration project. P3-S10 had the lowest historical average.

On one hand, strict adherence to the density curve and break point can be misleading in identification of the number of roller passes. There are many factors that change with time: temperature, moisture, type of roller, etc. Sometimes a pause may be necessary to start increasing density again. Sometimes aggregates re-orientate and decrease density prior to increasing density again. This could be considered a density that could be a “false summit.” This has also been observed with many asphalt mixtures, including some polymer modified mixtures. The density curves do not account for rollers in echelon and could even encourage “lazy” roller patterns. The density curve and break point are a very good tool, but they should not be used so strictly as to hinder gaining additional density.

On the other hand, a contractor’s best effort is often provided during the construction of the test strip. When actual production for the project begins, things can change. Contractors may speed up their paving operation and go faster than what they did on the test strip which can negatively impact the ability to obtain density. The results of the roller pattern study are then no longer applicable. This further emphasizes the need for flexibility.

8.4.6 Smoothness

In some cases, it has been reported that excessive rolling of the asphalt mat creates issues with smoothness. Throughout the course of this demonstration project, that issue did not occur but was raised as a concern. It should be pointed out that the biggest influence on smoothness under the contractor’s control is related to the paver operation and mixture delivery. The biggest influence to obtain smoothness under the agency’s control is the number of lifts and thickness of each lift.

Rollers play a minor role in impacting smoothness. If for some reason the roller is creating an issue with smoothness, it can easily be fixed by matching the amplitude, frequency and speed. This is often best accomplished by slowing down the roller and making sure there are 10 to 12 (sometimes even up to 16) impacts per foot. However, it is recognized that slowing down the roller can be challenging if the paver speed is fast. As another consideration, by going slower with the roller there may need to be fewer passes by the roller making it easier to keep up with the paver.

The type of roller can also impact smoothness. Oscillation was a great tool for creating a smoother finish. P1-S5 had great success with the use of oscillatory rollers. The oscillatory roller can be used when the mix gets below the temperature in which vibration can’t be used and create a much smoother finish.

Throughout the demonstration project, it was observed that roller pattern techniques are a key to smooth pavements as well. Operators stopped at the end of their passes on an angle and not straight. They also did not be stop in the same spot but rolled through their last stopped location at the end of their pass. Further, operators neither shut off vibratory mode too soon nor start them back up too late. The roller only went as far as a length and a half of the machine or as long as the rear drum goes past where the front drum stopped vibrating.

8.4.7 “Roll Until Meets” Philosophy

As described previously, no extraordinary compactive effort was needed to commonly obtain increased density. States and contractors worked together to identify numerous methodologies to do this. When a SHA writes a specification, the contractor’s goal is to meet the specification in an efficient manner in order to be the lowest bidder. The contractor strives to provide the SHA what is required in the specification as efficiently as possible. This often leads to a philosophy towards the compaction process of “rolling it until it meets.” There is nothing wrong with this philosophy. However, when a SHA has low density specification requirements, the contractor will bid the project with fewer rollers and fewer passes. This was observed most notably on a project with P1-S2. The specification was a lot average with a lower limit of 91.0 percent. The contractor met the specification with only one, double-drum vibratory roller making 7 passes. This was the fewest number of rollers and fewest number of passes in this entire demonstration project. SHAs need to set reasonable limits, and contractors can respond with innovative approaches to obtain the higher density.

8.4.8 Summary

There are often challenges when trying to increase in-place density. When agencies embrace the idea to increase the density requirements in their specifications, contractors and agencies commonly go through a learning curve. There are strategies to overcome the challenges of obtaining increased in-place density, and it often takes time and education.

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