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DEMONSTRATION PROJECT FOR ENHANCED DURABILITY OF ASPHALT PAVEMENTS THROUGH INCREASED IN-PLACE PAVEMENT DENSITY

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16. Abstract
Recognizing the importance of in-place density in building cost effective asphalt pavements, a Federal Highway Administration (FHWA) Demonstration Project was created for "Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density." Based on prior studies, a one-percent decrease in air voids achieved through improved compaction was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent. A one-percent decrease in air voids through improved compaction was estimated to extend the service life by 10 percent, conservatively. The objective of this demonstration project was to determine the benefit of additional compaction and show that additional density could be obtained through improved techniques. Many states also added additional compaction equipment and showed that this allowed for obtaining additional density. This project effort included two major components: 1) a literature search to serve as an educational component regarding the best practices for increasing density, and 2) the construction of 10 field demonstration projects.

The literature search identified best practices and new technologies that can help achieve higher densities. These included mixture design factors, field compaction techniques, best practices such as longitudinal joints and tack coats, measurement and payment, and the use of warm-mix asphalt. Two success stories of the many identified were highlighted.

Eight of the ten states improved densities by at least one percent compared to a control section on their demonstration projects. There were at least two pavement sections constructed within each of the 10 states that participated in this demonstration project. Many of the states constructed more than two pavement sections for a total of 38 sections. There were many variables including mixture type, construction equipment, and procedures between states and within states. A summary of the methods that states used to obtain increased density generally fell into one of five categories: (1) improving the agency's specification by including or increasing incentives and increasing the minimum percent density requirements; (2) making engineering adjustments to the asphalt mixture design to obtain slightly higher optimum asphalt content (although not part of the original goal of the demonstration project); (3) improving consistency as measured by the standard deviation; (4) following best practices; and (5) using new technologies.

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1 INTRODUCTION

The American Society of Civil Engineers (ASCE) reports that an annual investment of approximately $35 billion is needed for preserving the existing conditions of United States highways and bridges through 2040 (*Economic Development Research Group, 2011*). Based on this estimate, an improvement of 5 to 25 percent in pavement performance could potentially yield an annual savings of $1.75 to $8.75 billion, which could then be reinvested in the highway system to improve overall condition, safety, and congestion.

Although several factors can influence the performance of an asphalt pavement, one of the most important factors is in-place density (*Asphalt Institute, 2007*). A small increase in in-place density can potentially lead to a significant increase in the service life of asphalt pavements. Based on studies reviewed in a previous report, a one-percent decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent (*Tran et al., 2016*). In addition, based on field data, a one-percent decrease in air voids would extend the service life by 10 percent, conservatively.

To illustrate the effect of in-place density on the life cycle cost analysis (LCCA) of asphalt pavements, an LCCA was conducted on two alternatives in which the same asphalt overlay would be constructed to 93 percent and 92 percent (densities) of the maximum theoretical gravity (G_{mm}). Using the conservative 10 percent increase in service life, the LCCA results revealed that the state highway agency (SHA) would see a net present value (NPV) cost savings of $88,000 on a $1,000,000 paving project (8.8 percent) by increasing the minimum required density by 1 percent of G_{mm} (*Tran et al., 2016*). This savings does not consider other costs such as operation, maintenance, and road user costs.

An increase in in-place density can begin with improved field compaction. As Chuck Hughes stated at the 1977 Association of Asphalt Paving Technologists (AAPT) Annual Meeting, "The single most important construction control that will provide for long-term serviceability is compaction" (*Hughes, 1989*).

Other technology advancements and improved construction techniques can also yield the potential to increase asphalt pavement density while improving cost effectiveness. Some of these advancements include warm-mix asphalt, intelligent compaction, infrared thermal imaging, and rolling density meter (for continuous density measurement). Improved construction techniques include best practices for compaction, construction joints, tack coats, agency specifications to incentivize achieving higher in-place densities, and others. Many of these advancements are already being employed; however, in many instances, standards for in-place density have remained unchanged. It is anticipated that by using these technology advancements and improved techniques, in-place density can be increased. Thus, increased density targets lead to improved asphalt mixture durability and longer pavement service life.

Recognizing the importance of in-place density in building cost effective asphalt pavements, a Federal Highway Administration (FHWA) Demonstration Project was created for "Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density." A key aspect of the demonstration project was the partnership with the National Asphalt Pavement Association, each SHA, and the contractors that built the control and test sections.

2 OBJECTIVE AND SCOPE

Overall, the objective of this demonstration project was to achieve increased in-place asphalt pavement density that resulted in improved asphalt pavement performance. There were two major components of this study: 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.

Several recent advancements in technology and techniques have made increased in-place asphalt pavement density achievable. Tran et al. (2016) identified the importance of in-place density in building cost effective asphalt pavements. This field demonstration project was 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 worked 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.

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

The FHWA identified ten SHAs for participation in this demonstration project through an application process. Successful applicants received a workshop and field assistance for construction. Consideration for applications was given to those SHAs that could benefit most from increased compaction requirements as well as a distribution of SHAs in varied geographic and climatic regions.

Each SHA selected for the demonstration project hosted an "Enhanced Durability through Increased In-Place Pavement Density Workshop" developed and delivered jointly by the Asphalt Institute and FHWA. The target audience was the SHA, contractors, equipment suppliers, and academia. The workshop included the use of currently recognized best practices as well as new materials and technologies.

Part of the demonstration project was for each SHA and contractor to construct a field demonstration project with a control and one or more test sections. The control section was built by the contractor to achieve field density in their normal manner. The first test section was required 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 goal was to obtain increased density without having to add additional rollers or do anything else that would significantly result in increased cost. For the additional test sections, it was left to the SHAs to determine what they wanted to try. They generally added additional rollers to improve density or applied other ideas of interest. It was important that the SHAs try what they believed would work best in their local state. During the field construction, on-site technical advice was provided to the participating SHAs by staff from the National Center for Asphalt Technology (NCAT).

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, the density was 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 breakdown roller is the first compactor to roll the freshly laid asphalt mixture.
- **Intermediate rolling**. Intermediate (or secondary) rolling should closely follow breakdown rolling while the asphalt mixture is still hot and compactable. Intermediate

rolling is used to increase the density from that provided during breakdown rolling up to the required minimum density.

- **Finish rolling**. Finish rolling is conducted primarily to remove roller marks and provide aesthetic improvement of the surface, although in some instances it is still possible to increase density.
- **Echelon rolling**. In echelon rolling, two rollers are operating with one being slightly behind the other. The two rollers are staggered and offset from each other. With echelon rolling, the two rollers may complete one full lane-width of coverage as they each complete one pass.

4 BACKGROUND AND LITERATURE SEARCH

The long-term performance and life cycle cost of asphalt pavements can be improved if higher in-place density is achieved in a cost-effective manner. This chapter summarizes key findings of a literature search conducted to document the best practices and new technologies that can help achieve density. Some of this information was presented to the SHAs by the FHWA and Asphalt Institute as part of the "Enhanced Durability through Increased In-Place Pavement Density Workshop" prior to field demonstration project construction.

4.1 Mix Design and Field Verification

4.1.1 Gradation Type

Aggregates are required to meet the specifications for hardness, soundness, durability, angularity, and gradation for use in asphalt mixtures. Among these properties, the gradation plays an important role in the compactability of an asphalt mixture. While some state agencies may still use coarse-graded Superpave (i.e., Superior Performing Asphalt Pavements) mixtures for improving rutting resistance, research results at the Westrack experiment (*Epps et al., 2002*) and at the NCAT Test Track (*Timm et al., 2006*) showed that fine-graded Superpave mixtures are easier to compact, less prone to segregation, and less permeable while performing as well as coarse-graded Superpave mixtures under heavy traffic. Based on these findings, many state agencies have allowed the use of more fine-graded mix designs.

4.1.2 Nominal Maximum Aggregate Size (NMAS)

In addition to the selected gradation type (i.e. fine-graded versus coarse-graded gradations), the relationship between NMAS and lift thickness is also important for compactability of asphalt mixtures. Based on studies by Moutier (1982) and further analysis by Zeinali et al. (2014), compaction effectiveness for asphalt mixtures could be improved by increasing lift thickness. Brown et al. (2004) recommended that the minimum lift thickness be a minimum of three and four times the NMAS for fine and coarse dense-graded mixes, respectively, to provide sufficient thickness for the aggregate particles to re-orient and pack together during the compaction process. This is commonly referred to as the minimum lift thickness to NMAS (t/NMAS).

4.1.3 Asphalt Mixture Design

Most SHAs currently use the Superpave mixture design method as documented in American Association of State Highway and Transportation Officials (AASHTO) R 35, “Superpave Volumetric Design for Asphalt Mixtures,” and AASHTO M 323, “Superpave Volumetric Mix Design.” When the Superpave mixture design method was implemented, one of the major changes from the prior mix design methods is the use of the Superpave gyratory compactor for densifying mixes in the laboratory. In the volumetric mixture design, the optimum asphalt content is selected for desired air voids. The quality of asphalt mixtures in situ is controlled by verifying the quality of constituent materials, volumetric properties, and in-place density. SHAs have asphalt mixture design specification requirements to ensure that satisfactory quality materials are used and properly combined to meet specific volumetric requirements.

After implementing the original Superpave volumetric mix design, some SHAs have expressed concerns that the Superpave system produces asphalt mixtures that are too dry (low asphalt binder content), potentially resulting in durability issues. The Superpave method specifies that the optimum asphalt content for a given gradation be selected at 4 percent air voids. In many instances, requirements in the Superpave volumetric mixture design described in the AASHTO standards have been refined by SHAs based on their experience, including the design air voids, minimum voids in the mineral aggregate (VMA), and/or the design gyrations.

To provide guidance in making changes to the AASHTO standards, the FHWA Asphalt Mixture Expert Task Group (ETG) recommended agencies perform an independent evaluation prior to making any adjustments to gyratory compaction levels from the AASHTO R 35 standard. The evaluation would include the effect of the proposed changes in gyration level on performance for typical aggregates, binder, and mixture designs (*FHWA Tech Brief FHWA-HIF-11-031, 2010*).

One example of a change in mixture design criteria was Superpave 5 (*Hekmatfar et al., 2013*). A Superpave mixture is typically designed at 4 percent air voids, but it is compacted to 7 to 8 percent air voids in the field. In Superpave 5, mixtures are designed to have the same density in the lab and in the field, and optimum binder content is chosen at 5 percent air voids rather than the currently specified 4 percent. This would increase pavement durability by decreasing the in-place air voids from 7 to 8 percent to 5 percent. To maintain the same effective asphalt content, the minimum VMA is increased by 1 percent compared to the Superpave mixture. The Superpave 5 asphalt mixture uses 50 design gyrations. To evaluate the Superpave 5 mixture design approach, two asphalt mixtures were designed at 5 percent air voids. The results suggested that it was possible to compact the asphalt mixtures to 5 percent air voids in the field. Laboratory results indicated that the asphalt mixtures should have acceptable permanent deformation performance.

Superpave level 1 mix design was an improved material selection and volumetric mix design process. Level 2 mix design procedures use the volumetric mix design as a starting point and included a battery of tests to arrive at a series of performance predictions. These tests were to be empirical or surrogate performance tests. Level 3 mixture design included a more comprehensive array of tests and results to achieve a more reliable level of performance prediction. These tests were to be more mechanistic or fundamental (Asphalt Institute SP-2). Performance testing (levels 2 and 3) was not implemented as part of the Strategic Highway Research Program (SHRP) due to the cost and complexity of the testing technologies at that time. As a result, Superpave mixture design was implemented based solely on volumetric properties. Performance engineered mixture design adds performance testing to the volumetric properties to ensure the proper combination of quality constituent materials to resist premature deterioration from pavement distresses such as rutting, cracking, and moisture damage. A mixture designed using this approach is required to pass established performance tests criteria for permanent deformation and cracking for a given level of traffic, climate, and pavement structure. This approach has the potential to fulfill the intent of the Superpave mixture design system to include performance testing. Examples of SHAs using a level 2 approach include Texas (*Zhou et al., 2014*), New Jersey (*Bennert et al., 2014*), California (*Harvey et al., 2014*), Louisiana (*Cooper III et al., 2014*) and Illinois (*Al-Qadi et al., 2017*).

4.1.4 Field Verification

A complete asphalt mixture design is a good starting point for the asphalt mixture design and optimum asphalt content at the start of the project, but it is likely adjusted during production due to the following reasons:

- Field-produced materials are often different than laboratory-mixed materials,
- Field-produced materials may be more variable than those used in the laboratory, and
- Field-acceptance criteria may be different than the criteria used for the asphalt mixture design.

First, the asphalt mixture often has different properties than the mixture design prepared in the laboratory. For example, the materials in the field may have more moisture and mixing in the field is a very different process than mixing in the laboratory. Thus, some adjustments may be needed during production. Care should be taken when making these adjustments as they can have a significant impact on the compactability and performance of the mixture. Also, breakdown of the aggregate typically occurs increasing the amount of fines (material passing the No. 200 sieve) and lowering the air voids and VMA. Adjustments are often needed to the mix to bring the volumetric properties back within specification requirements.

Second, during construction, typical quality control (QC) and acceptance specifications rely on acceptance testing, comparison testing between SHA and contractor, quality level analysis, and pay factor determinations. It is essential that the gradation, asphalt binder content, and volumetric properties (such as air voids and voids in mineral aggregate) be closely controlled so that the variability is low. Most SHAs have construction tolerance requirements and pay factors related to these properties. For example, laboratory air voids are generally controlled within ± 1 percent from the target for dense-graded mixtures. If the laboratory air voids are a little high, long term durability of the mix may be reduced. If the air voids are a little low, bleeding (and possibly rutting) in the asphalt mixture may occur. Thus, the gradation, binder content, and volumetric properties must be consistent during construction for best field performance. These properties can also influence the field compactability of the asphalt mixture.

Third, the acceptance criteria used for the asphalt mixture design should be used for field acceptance. For example, the asphalt mixture design has target air voids with a minimum and maximum, minimum VMA, and others. During production, some SHAs keep the same target air voids and minimum VMA design requirement and other SHAs allow a wider tolerance for field-produced materials in terms of air voids and VMA. The acceptance criteria and resulting range of as-produced material properties can influence the field compactability of the asphalt mixture.

4.2 Field Compaction

The desired level of density in asphalt layers in the field is achieved by the means of roller compaction. The aggregates in an asphalt layer interlock as the result of the compaction process. As an asphalt layer is compacted, it becomes denser and the air voids are reduced. An asphalt surface should have a smooth, uniform surface and a homogenous appearance. The achieved in-place density of an asphalt pavement results from a combination of different activities that include proper design, production, placement, compaction, and quality control of the mixture (*Asphalt Institute, 2007*). An asphalt mixture behind a paver typically has a density of 80 to 85 percent of its G_{mm}. Generally, the goal of compaction in many SHAs is often an in-place average density level of 92 to 93 percent of G_{mm} (i.e., the equivalent of 7 to 8 percent air voids).

4.2.1 Project Selection and Scoping Regarding Weak Base and Rutting

The structure of the pavement base must be considered as a primary criterion for implementing increased in-place density requirements. The use of increased in-place density is most applicable to structural overlays rather than functional overlays. Structural overlays have a designed pavement thickness to address the anticipated traffic for a given design life. Functional overlays are often maintenance projects to address existing distresses: a Band-Aid. If functional overlays are placed on weak bases, it may be very difficult to obtain even minimal in-place density requirements. Appropriate project selection must be considered. In addition, to avoid the potential for roller bridging leading to uneven compaction, existing asphalt surfaces with rut depths greater than one-half inch should be milled before overlays are placed.

4.2.2 Compaction Equipment and Operation

Asphalt pavement density does not increase linearly with additional compaction; rather, it changes randomly “due to continuous reorientation of aggregates and the randomness of aggregate shapes and textures” (*Beainy et al., 2014*). Two of the most important factors in obtaining density are the temperature of the asphalt mixture and lift thickness. In general, compaction consistency and overall compaction are increased through additional roller passes.

The rolling pattern is critical to achieve proper compaction without causing aggregate damage to the asphalt pavement structure. Rolling patterns should be optimized based on the drum-to-pavement width relationship. The traditional rolling train typically consists of a breakdown, double-drum vibratory roller followed by an intermediate vibratory or pneumatic roller followed by a finish roller (typically a static steel-wheeled roller).

When it is difficult to obtain compaction, the contractor may elect to use two or more vibratory breakdown rollers in echelon (staggered, adjacent, and offset) to apply one coverage with one pass from each roller. The full width of the mat can be best compacted when it is at the optimum temperature. The optimum temperature is determined based on the equi-viscous temperature and past experience. For asphalt mixtures that are hard to compact, there can also be intermediate vibratory or pneumatic rollers in echelon (*Scherocman, 2006*).

The speed, frequency, and amplitude of vibratory rollers are also important. There is a relationship between the speed and frequency of the vibratory roller. It is desired to apply at least 10 to 14 impacts with a vibratory roller per foot; otherwise, corrugations may occur. Hence, the speed and frequency need to be synchronized. When using vibratory rollers, "the depth of penetration of the compaction energy imparted depends on the weight of the roller as well as the amplitude and frequency of the vibrations. For a given setting of amplitude and frequency, the density achieved depends on the thickness of the mat and the underlying pavement layers" (*Beainy et al., 2014*).

Whether asphalt mixtures are stiff or tender, breakdown or initial rollers should be used immediately following the paver to ensure that the mixture is compacted while hot (*Scherocman, 2006*). Breakdown rolling is typically completed before the mat cools to 240^{o}F and finish rolling is completed when the surface temperature is above 175^{o}F. By optimizing and automating these variables, the effectiveness of achieving higher in-place densities with vibratory rollers can be greatly improved. Monitoring the surface asphalt pavement temperature zones through the use of real-time infrared sensors can allow operators to monitor ideal compaction times (*Starry, 2006*).

There have been many recent advances in compaction equipment, and construction practices regarding compaction have been analyzed much more closely. The use of vibratory rollers, oscillatory rollers, or vibratory pneumatic tire rollers can achieve optimized in-place density when properly employed (*Nose, 2006*). Intelligent compaction techniques have also been used, which will be discussed in more detail in a later section. Advances in vibratory roller manufacturing have led to the advent of high frequency rollers to enable faster rolling speeds where a vibratory roller can complete breakdown rolling and keep up with the paver, while maintaining the consistent impact spacing needed for compaction. Vibratory drum spacing should be based on drum diameter to ensure the smoothness of pavement surfaces.

4.2.3 Balancing Paving Operations

Balancing paving operations relates to the consistency and impacts the ability to obtain density. Best practices are documented by NAPA (1996). Balancing includes the tons per hour at the plant, number of trucks, paver speed, number of rollers, and roller speed calculations. A case history example is provided by Schmitt et al. (1977). One of the more common occurrences of paving operation imbalance relates to the rate of plant production. If the plant production rate is too high, the loaded trucks line up at the paver waiting to be unloaded. This allows the mixture in the trucks to cool and encourages the paver operator to go faster. In turn, the rollers may not be able to keep up with the paver, so the roller speeds increase and/or reduce the number of passes. The production rate, number of trucks, paver speed, number of rollers, and roller speed are all important and interrelated factors.

4.2.4 Asphalt Mixture Temperature and Weather Conditions

As the lift thickness increases, the time available for compaction increases due to the thicker lift cooling more slowly. Two of the most important factors are lift thickness and temperature of the asphalt mixture. The base temperature, air temperature, and wind speed are also important. These factors can be input into PaveCool (*Minnesota Department of Transportation, 2015*) or MultiCool (*National Center for Asphalt Technology at Auburn University*), which were developed to estimate the available time for compaction. They also provide a cooling curve. PaveCool was developed initially and then MultiCool was developed to simulate multiple lifts that were cooling. Both are available for the desktop personal computer or smart phone applications.

4.2.5 Permeability

In-place air void content of dense-graded asphalt mixtures has a significant effect on in-place permeability of pavements (*Mallick, 2003*). There is a relationship to the in-place density, NMAS, and permeability. To ensure that permeability is not an issue, the in-place air voids should be between 6 and 7 percent or lower. This appears to be true for a wide range of mixtures regardless of NMAS, gradation, or air void level (*Brown et al., 2004*). Work by the Florida DOT indicated that coarse-graded Superpave mixes can be excessively permeable to water at air void levels around 6 percent (*Choubane et al., 1998*). The Arkansas State Highway Transportation Department (AHTD) found that in-place air void levels below 6 percent were acceptable, although it could be expected that the life of a permeable pavement would be shorter than that of a “less permeable” pavement (*Westerman, 1998*). Infiltration of water or air into a pavement can affect the durability of that pavement. Probably the most harmful effect takes place through the invasion of water into the pavement that results in stripping.

4.3 Other Best Practices

4.3.1 Longitudinal Joints

Many asphalt pavement failures can be attributed to insufficient compaction of longitudinal joints. These failures are primarily affected by the density of the free edge of a lane, the compaction of the material in the joint, and how well the hot side of the joint is compacted. The construction of longitudinal joints requires precise workmanship to achieve optimal compaction. One sequence of methods to achieve required compaction is to compact the first lane (cold side) with the roller overhanging the edge by six inches, followed by placing the second lane (hot side) with a one to one-and-a-half-inch overlap of the first layer dictated by the edger plate on the paver screed. Finally, the second lane should be compacted from the hot side with the outside tire of a rubber tire roller directly on the joint or by a steel drum roller with the drum extending six inches over the top of the joint (*Brown, 2006; Benson and Scherocman, 2006*). More information about best practices for construction and specifying asphalt pavement longitudinal joints is available on the Asphalt Institute's website (2016).

Based on experience from the Port Authority of New York and New Jersey (PANYNJ), even with method specifications for specific types of longitudinal joint configurations, many projects had low density in these joints. PANYNJ has implemented an end-result density specification along with a specific joint configuration mandate to incentivize achievement of compaction criteria regardless of construction method (*Bognacki, 2006*). Some state DOTs have also adopted a longitudinal joint density specification.

4.3.2 Tack Coat

Bonding of pavement layers is vital to the creation of long life asphalt pavements (*FHWA, 2016*). The tack coat also assists with improving compaction. While sometimes listed as "incidental" in SHA specifications, tack coat is vital to pavement layer bonding. With proper bonding of the layers, a monolithic structure is formed, greatly improving a pavement's resistance to stress and fatigue. This is consistent with the assumptions common to all pavement thickness design methods.

Selection of an appropriate tack coat material, applied in the recommended residual ranges, provides the glue necessary to bond the pavement layers. Surface preparation, creating a clean and dry surface, is required for bonding. Milling of existing surface materials will further improve bonding capabilities, thus, typically improving pavement performance. Maintaining and calibrating the distributor truck is also needed to provide the desired uniform application. It is important to select the appropriate nozzles and sizes to match both the material and the target residual application rate. Truck speed and pump capacity are also important in nozzle selection. Additionally, the spray bar should be set to achieve either a double or triple overlap to ensure uniform coverage. Poor uniformity can be due to many factors including blocked nozzles, improper angle, improper nozzle size, improper distributor truck speed, or inadequate pump pressure.

A key to developing a successful bond between pavement layers for peak long-term performance is a uniform application of a high-quality tack coat at the appropriate residual asphalt rate to a clean and dry surface. This also enhances the compactability of the asphalt pavement.

4.4 Measurement and Payment

As part of the FHWA demonstration project, the Asphalt Institute conducted an SHA "specification mining" effort. With assistance from Asphalt Institute engineers, all SHA specifications were gathered and reviewed for density requirements. All states and the District of Columbia were included for 51 total specifications. SHAs often had more than one requirement for in-place density such as an "Option A" (cores required with density measured) and “B” (roller pattern only no cores required), for example. The specifications for the SHAs’ highest level of density requirement were gathered, which are naturally on the highest traveled pavements (interstate/primary routes) in that state. The data summarized in this section came from the Asphalt Institute’s specification mining effort.

The goal of specification mining was to understand how SHAs specify mat density. The following data was collected:

- Methods of measure
    - Cores
    - Gauge
    - Roller pattern
- Baseline measure
    - Maximum theoretical specific gravity (G_{mm})
    - Laboratory bulk sample (G_{mb})
    - Control strip
- Specification type
    - Percent within limits (PWL)
    - Other advanced statistics
    - Simple average
- Specification limits
    - Most focus on lowest limit (how low before pay is reduced below 100 percent?)
- Compaction incentives
    - Amount in percentage or $/ton

The data and specifications from each SHA were then compiled and reviewed. The data was reviewed with specifications as much as possible to quality check the information. Since some SHA’s specifications leave some area for interpretation, there may be some mistakes. Difficulty of interpretation was common in several standards. Some specifications had critical information of G_{mm}, lot size, density, etc. spread over many pages or books (i.e. construction materials manuals or inspector manuals) that can be difficult to obtain instead of being in the specification. Some specifications did not address when the G_{mm} is measured, while it is assumed to be daily. Lack of clear language and ease of understanding can lead to misinterpretation of specifications and measures. This is an example of clear language stating the most critical information about density in a paragraph.

> *“Five randomly selected cores (4” min./ 6” max. diameter), from the travel lane, will be tested to determine density compliance and acceptance. One core shall be taken from each sublot. The Bulk Specific Gravity (Gmb) of the cores shall be determined as stated above and the average calculated. The maximum theoretical gravity (Gmm) from acceptance testing for that shift’s production will be averaged and the percent density will be determined for compliance by dividing the Gmb average by the Gmm average.”*

Naturally from an effort this size, there were a few broad observations that are worth noting.

- Neighboring states tend to match specifications and incentives.
- Usually there were two to three levels of specification for compaction including roller pattern and non-inspection. Two levels of compaction were most common.
- Several specifications allow for greater than 4 percent air voids design (4.3 to 4.5%) or field adjustments up to 5% air voids, making density even more difficult to achieve. Superpave NMAS lift thickness recommendations (four times the NMAS for coarse graded mixes) were based on a 4 percent air void design.
- PWL specifications may "frighten" some with their more complex calculations.

Although specifications change annually, the specification mining effort represents the best and most current information. This is what we believe that SHAs are actually doing per their standards and practices. A few examples are:

- Caltrans has used PWL acceptance, but practice in the past two years is simple average.
- Several SHAs have reported moving or attempting to move to PWL, such as PennDOT.
- Other SHAs have recently or are considering increasing the minimum accepted density.

4.4.1 Measuring Density

Density is measured in the pavement after field compaction. This is often referred to as the bulk specific gravity of the asphalt mixture (G_{mb}). The method most commonly used (38 SHAs) was with cores, as shown in Figure 1. Some SHAs also use the nuclear density gauge or a combination of the gauge and cores.

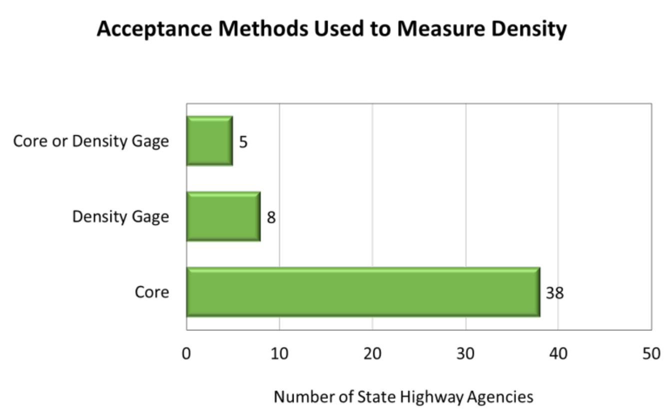

Figure 1. Method Used to Measure Field Density

Some useful information about the G_{mb} and G_{mm} determination is presented in the FHWA Tech Brief (2010). It includes a review of the G_{mb} measured by AASHTO T 166, "Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens," and the theoretical maximum specific gravity G_{mm} as measured by AASHTO T 209, "Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Hot-Mix Asphalt (HMA)." Each specific gravity determination was reviewed in terms of: (1) problems and issues with current standard test methods; (2) modifications and/or alternate methods; and (3) areas that need further research and development. In addition, the impacts of specific gravity measurements on mixture design properties and mixture acceptance were also investigated.

4.4.2 Calculating Percent Density

A baseline is used to calculate the percent density. It can be G_{mm}, laboratory compacted G_{mb}, or percent of the control strip. In the past, SHAs commonly used the density, G_{mb}, of laboratory samples for target density, but this had the potential for greater variation in field compaction (*Santucci, 1998*). Methods other than G_{mm} only provide an indirect measure of the air voids and can be misleading in some cases. Reporting density as percent of theoretical maximum density (TMD) directly provides the air voids in the compacted mix. More recently, most SHAs have compared the in-place field density with G_{mm} from field-produced samples (49 SHAs), as shown in Figure 2.

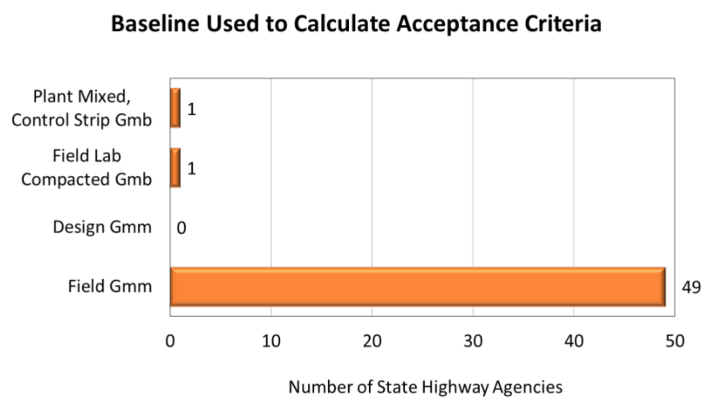

Figure 2. Baseline Used to Calculate Percent Density

4.4.3 Specifying Percent Density

Many SHAs have used statistically based acceptance specifications for asphalt pavement construction. The basic objective was to specify and measure quality characteristics (asphalt mixture properties such as asphalt content, gradation, VMA, and in-place density) that were related to pavement performance, and then to pay the contractor for the quality provided.

Agency specifications must use appropriate measures for setting requirements for in-place pavement performance. As early as 1989, Hughes recommended a realistic target average value of 93 percent of G_{mm} with a standard deviation of 1.5 percent. While some states have adopted higher target values for in-place density, additional improvements in roadway service life could be realized if specifications required minor increases in the in-place densities. A lack of universal in-place density guidance has made implementation of standards difficult, as changes in construction practices, test protocols, and materials have resulted in changes to pavement structures (*Seeds et al., 2002*).

The two most common methods of specifying density for acceptance were the minimum lot average and percent within limits (PWL). Approximately the same number of SHAs used the minimum lot average as those that used the PWL, as shown in Figure 3. While more SHAs have tried PWL, the chart represents current practice on SHAs top-level/trafficked pavements.

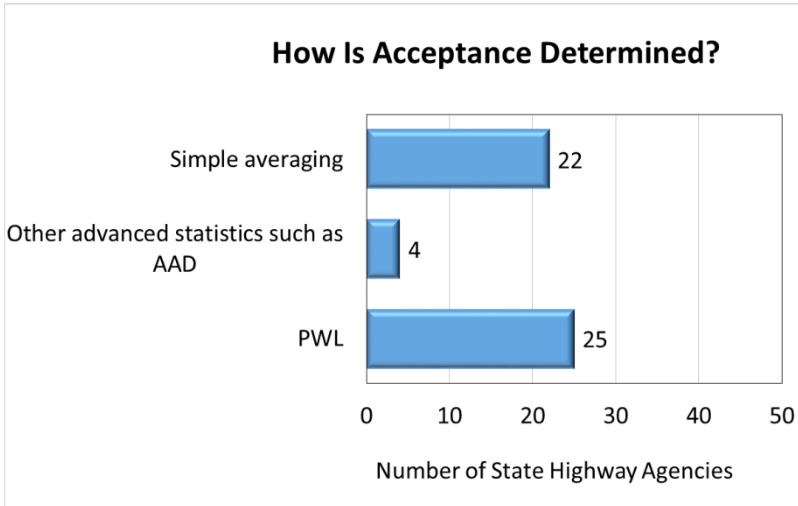

Figure 3. Type of Acceptance Specification for Percent Density

For SHAs using the minimum lot average, the distribution of these minimum values is shown in Figure 4. The most common minimum lot average is 92.0 percent (13 out of 22 SHAs using a simple average). When the minimum lot average was used, some SHAs also had a minimum requirement for each individual sublot or test.

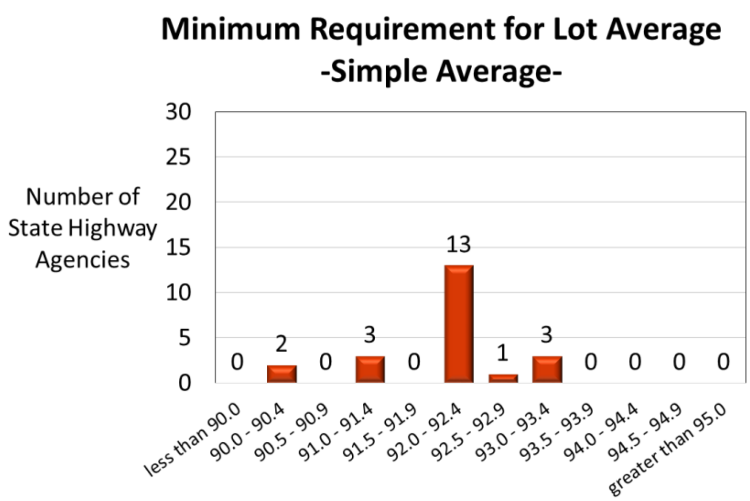

Figure 4. Distribution of Minimum Requirement for Lot Average Specifications

For SHAs using the PWL, the distribution of the lower specification limits is shown in Figure 5. The most common lower specification limit for PWL is 92.0 percent (12 out of 29 SHAs using a PWL or advanced statistics).

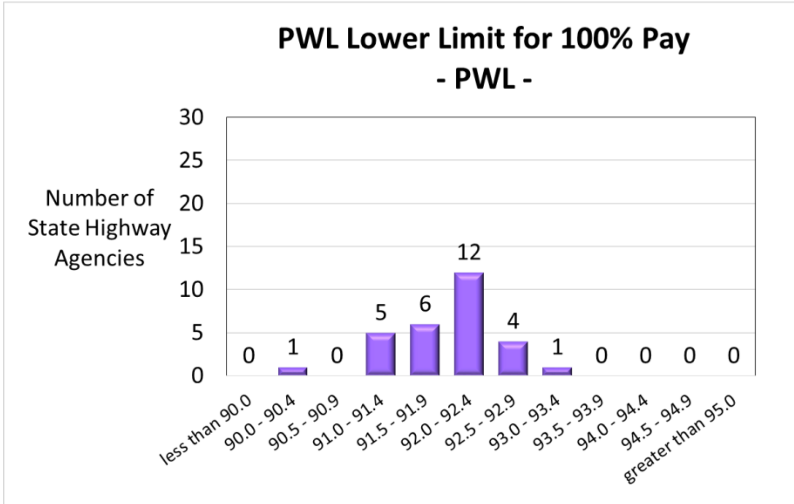

Figure 5. Distribution of the Lower Specification Limit for PWL Specifications

It should be noted that the lower specification limit for PWL specifications is not equivalent to the same value if it were used in a minimum lot average specification. The PWL lower specification limit typically represents a value where 90 percent of the results are acceptable and 10 percent of the test results are defective for 100 percent payment. So, 90 PWL is where there will be 100 percent payment. The minimum lot average allows approximately 50 percent of the test results to be defective. When comparing a minimum lot average and lower specification limit of 92 percent, the minimum lot average would allow 50 percent defective, and the lower specification limit would allow 10 percent defective. When using a lower specification limit, it essentially requires a density target approximately 1.0 to 1.5 percent higher than the minimum lot average to have the same percent defective. So, a 92 percent lower limit on a PWL specification will probably produce field densities of 93 percent or higher.

The PWL is then used to determine payment through pay factors (PF) giving consideration to agency and contractor risk. These factors, which include incentives (bonuses) and disincentives (penalties), are assigned for different PWL values and serve as a basis for payment. Typical specifications include composite PFs with in-place density or plant-produced, laboratory compacted air voids normally being the most heavily weighted component.

4.4.4 Use of Incentives and Disincentives

Finally, to fully implement a requirement for increased in-place density, test methods for measuring in-place field density must be standardized and acceptance criteria and performance incentives must be established to properly motivate and reward construction contractor performance. Many SHAs have developed performance incentives based on various asphalt acceptance properties (*Santucci, 1998*). Many SHAs include volumetric properties of the plant-produced, laboratory-compacted asphalt mixtures. Construction performance incentives should be established based on the economic impact to the SHA. In general, inferior performance penalties and superior performance bonuses should be based on the cost to the SHA due to more frequent or less frequent anticipated rehabilitation requirements (*Santucci, 1998*).

A majority of SHAs use an incentive for the density quality characteristic, as shown in Figure 6. For those SHAs not using an incentive, most of them were using the minimum lot average. For those 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.

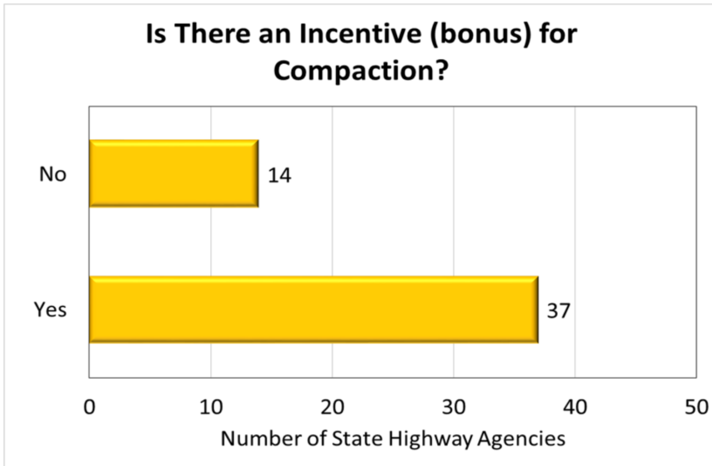

Figure 6. Number of SHAs Using an Incentive for Density

When the Arizona DOT implemented a true incentive specification in 1990, average in-place air voids decreased from 8.5 to 7.5 percent. The ideal Arizona DOT specification would yield an in-place air void target of 7 percent. The 1 percent increase in in-place density was a direct result of implementation of the compaction incentive (*Nodes, 2006*). Further implementation of specific construction performance incentives should encourage attainment of enhanced compaction.

A contractor performing work for multiple SHAs was interviewed regarding their company's philosophy regarding incentives. The contractor changed their level of effort in achieving density based on the way the SHAs' specifications were written and the contractor's ability and effort needed to achieve it.

- In one state, the contractor only attempts to earn 40 percent of the available incentive. The asphalt mixture is very stiff, so the contractor does not find it cost effective to go beyond that.
- In another state, the contractor attempts to earn 60 percent of the available incentive. The asphalt mixture and in-place density specification was reasonable and motivated the contractor to make additional efforts.
- In a third state, the contractor targets achieving around 80 percent of the available incentive. The SHA has reasonably incentivized the density at the longitudinal joint so the contractor makes a significant effort.

A well written and prepared SHA specification can be used to produce superior results. It includes an asphalt mixture design specification that can result in workable and compactable mixtures with an incentive that is obtainable for in-place density.

4.5 Success Stories

4.5.1 Pennsylvania Department of Transportation

The Pennsylvania Department of Transportation (PennDOT) was identified as a success story for using the minimum lot average specification. In fact, PennDOT was using a minimum individual sublot specification. With one test per sublot, they required the minimum of each test to be greater than or equal to 92.0 percent with their Restricted Performance Specification. The density is measured with cores. Results from their 2015 statewide average density for wearing and binder asphalt mixtures are shown in Figure 7. For the non-PWL projects constructed in 2016, the statewide average percent density was 94.3 percent and the standard deviation was 1.53.

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

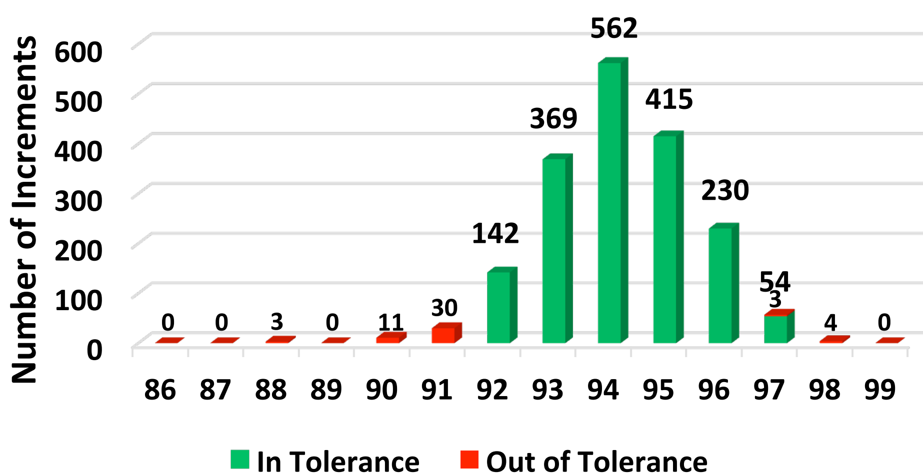

Figure 7. Results of PennDOT's Minimum Sublot Specification in 2015

4.5.2 New York State Department of Transportation

The New York State Department of Transportation (NYSDOT) was identified as a success story for using the PWL specification. The NYSDOT 50 Series is used on Interstates and principal arterials with full or partial control of access. The density is measured with cores. The lower specification limit and upper specification limits were set at 92.0 and 97.0 percent, respectively. There is a 5 percent incentive available on density alone. For 2015, the statewide average density was 94.1 percent, as shown in Figure 8. There was not a significant improvement from

2002-2014 to 2015. As observed by NYSDOT, contractors understand that PWL specifications require a focus on consistency in addition to the average density and are focusing on being more consistent. The standard deviation of projects statewide was 0.83.

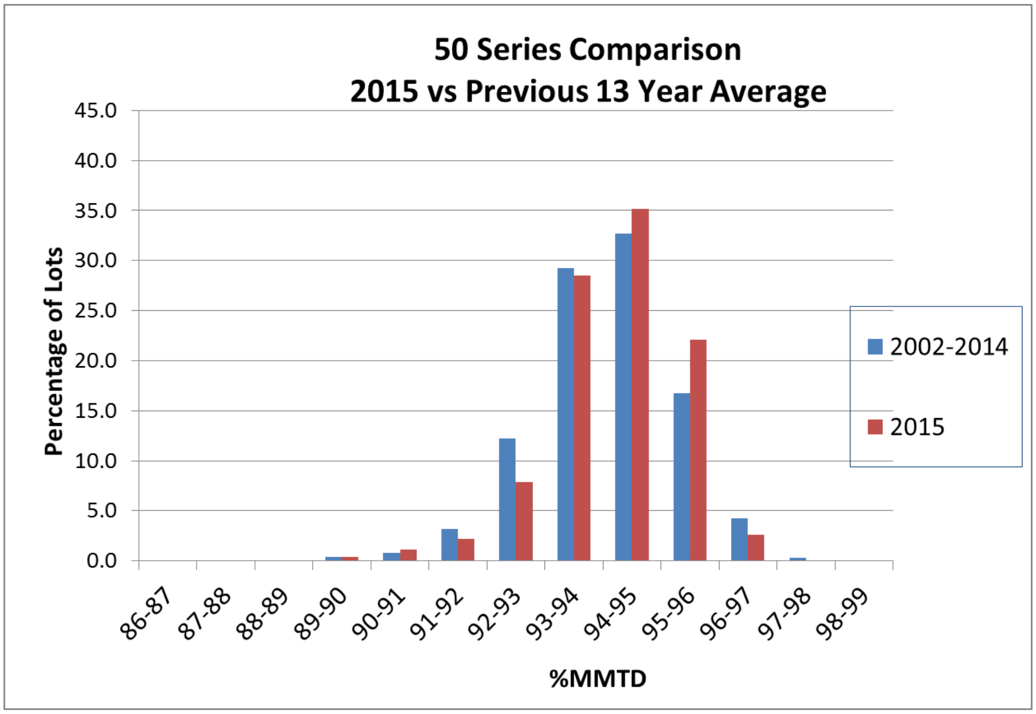

Figure 8. Results of NYSDOT's PWL Specification

4.6 New Technologies

Agencies may consider implementing a higher in-place density requirement, which can be achievable by following best practices and adopting new asphalt pavement technologies and knowledge gained from recent research. These technologies and knowledge are briefly discussed in the following sections and include warm-mix asphalt, intelligent compaction, and infrared imaging.

4.6.1 Warm-mix Asphalt

The term warm-mix asphalt (WMA) refers to asphalt mixtures that can be produced at temperatures that are typically 25^{o}F to 90^{o}F lower than standard asphalt mixture production temperatures. The WMA technologies can be considered compaction aids when produced at standard temperatures. They can be used to improve the workability of an asphalt binder, increase time for mixture compaction during normal paving operations, and enhance compaction during cold weather paving (*Bonaquist, 2011*). More information about WMA is included in NAPA's Quality Improvement Publication 125, *Warm-Mix Asphalt: Best Practices* (2012).

Based on a review of studies comparing the compaction of WMA to the compaction of traditional asphalt mixtures, it appears that WMA can be compacted to similar in-place densities at much lower compaction temperatures (*Prowell et al., 2012; Estakhri et al., 2009; Hurley, 2010; Aschenbrener, 2011; Zinke, 2014; Anderson, 2014*). The benefits of this include improved in-place densities for projects requiring longer haul times, which have increased temperature loss during transit, and improved in-place densities during cold weather construction.

4.6.2 Intelligent Compaction

The asphalt paving industry has also seen the introduction of new vibratory rollers equipped with an integrated intelligent compaction (IC) system. This system may include an onboard computer, Global Positioning System (GPS) based mapping, and optional feedback controls. It allows real-time monitoring of compaction and adjustments as needed to achieve optimum density and consistent coverage. In addition, color-coded mapping provides a continuous record showing the location of the roller, number of roller passes, and material stiffness measurements. During compaction, the location of the roller, its speed, number of passes, and coverage can be monitored using the GPS. Compaction meters or accelerometers mounted in the drum monitor the applied compaction effort, frequency, and material response. Some rollers also have instrumentation to monitor the surface temperature of asphalt paving materials.

The results of prior studies show that the relationship between IC measurements and in-place density is inconsistent (*Minchin et al., 2001; Maupin, 2007; Chang et al., 2011; Chang et al., 2014*). It appears that IC measurements are currently not a good candidate for replacing cores for density measurement as an acceptance test. The use of IC does, however, show some potential as a real-time measure of compaction and may be useful for QC and for identifying locations on the asphalt mat that may not have achieved the desired compaction level.

This new technology makes it easier to optimize and automate compaction parameters to achieve higher in-place densities such as rolling pattern, frequency, drum spacing, amplitude, and temperature control. In addition, the use of GPS-based mapping provides real-time monitoring of compaction and a continuous record that shows the location of the roller, the number of roller passes, and material stiffness measurements to achieve consistent coverage. While the IC system helps improve the compaction process, it is not currently used in place of traditional cores for density measurement as an acceptance test for the asphalt mixture.

4.6.3 Infrared Imaging

Infrared (IR) imaging technology can be used for real-time temperature testing of potentially 100 percent of the pavement surface as it is placed, providing much more inspection coverage than existing QC methods. This new technology has improved the state of the practice for obtaining QC data in asphalt pavement construction.

The IR imaging technology can measure thermal consistency of the full paving lane width, which enables inspectors and paving crews to measure the real-time mat temperature. Real-time temperature QC allows for prompt adjustments by the paving crew, thereby minimizing segregation problems that can occur when the range in temperature is too high. In addition to savings resulting from these innovations, near-term benefits include more consistently constructed asphalt layers and better in-place field density. The information obtained from this technology can be part of QC data in asphalt pavement construction. The following guidelines were established to help improve the consistency of in-place density (*Willoughby et al., 2001*). They also found that end-dump trucks showed a greater temperature spread.

- ≤ 25°F – generally consistent air voids
- ≥ 25°F – greater air void spread

4.7 Summary

This chapter documents key findings of a literature search and review of SHA specifications to identify best practices and new technologies that can help achieve density. Higher in-place density can be obtained to improve the long-term performance of asphalt pavements in a cost-effective manner by adopting some of the following practices and technologies.

- Mixture 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.
    - During pavement design, the lift thickness should be designed to be a minimum of three and four times the intended 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.
    - For some SHAs, mix design requirements have been refined to encourage increasing effective binder volume. Examples of changes to the Superpave volumetric mix design include Superpave 5 and performance engineered mix design. These concepts are new and should be used only after local experience. These changes can improve field compactability 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. Paving operations should be balanced to improve the ability to obtain density and consistency.

    - 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.
- Other best practices
    - Best practices should be followed to achieve optimal compaction for longitudinal joints. 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.
- Measurement and payment
    - The in-place field density should be compared with G_{mm} from field-produced samples.
    - Incentive specifications can be adopted to yield higher in-place density. A good SHA specification should include an asphalt mixture design procedure that can result in workable and compactable mixtures with an incentive that is obtainable for in-place density.
    - Utilizing good specifications, the PennDOT and NYSDOT were able to obtain good in-place density results using the minimum lot average specification and the PWL specification, respectively.
- New technologies
    - WMA can be utilized to improve compaction, especially for projects requiring longer haul times and/or constructed in cold weather conditions.
    - 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 coverage in order to achieve higher in-place density and consistency.
    - IR imaging can be deployed to measure the real-time mat temperature and make adjustments to improve temperature consistency and in-place density.

5 FIELD DEMONSTRATION PROJECTS

Ten SHAs were selected for the demonstration projects through an application process. Each demonstration project was required to have a preconstruction meeting to discuss proposed procedures to build the test sections. The SHAs and contractors generally partnered for planning control and test sections to evaluate the ability to obtain increased density with enhanced compaction to improve pavement durability.

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

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

5.1 State 1

5.1.1 Project Description

The demonstration project was located on a high-volume, six-lane divided interstate highway. The project included a control section and two test sections; each section was 1000 feet long. A total of approximately 337 tons of asphalt mixture was used in construction of the control section and the test sections. All three sections were constructed on June 1, 2016.

The project consisted of milling 2.75-inches deep followed by a 2-inch overlay covered with a ¾-inch friction course. The test and control sections were on the 2-inch overlay. However, based on spread rates, it appeared that the average thickness of the lower layer was closer to 1.5 inches than to the desired 2.0 inches.

5.1.2 Asphalt Mixture Design

The gradation used was a ½-inch NMAS blend that was on the fine side of the primary control sieve. The primary control sieve and control point are defined in AASHTO M 323. The gradation shall be classified as coarse-graded when it passes below the primary control sieve's control point. All other gradations shall be classified as fine-graded. There is a different primary control sieve and control point for each NMAS. The gradations for the asphalt mixture design and for production of the control and test sections are provided in Table 1. The aggregates met all the agency specification requirements. The asphalt mixture contained 20 percent RAP. The target t/NMAS was 4.0 for the surface layer but was closer to 3.0 based on actual thickness. The asphalt binder used for this project was a polymer modified PG 76-22.

The asphalt mixture was designed with 100 gyrations using a Superpave gyratory compactor. The optimum asphalt content was 5.0 percent, which was selected to achieve 4.0 percent air voids for the control section and test sections 1 and 2. The VMA was required to be at least 14.0 percent for the asphalt mixture design and at least 13.0 percent during construction. The VMA for the design was 14.1 percent.

Performance testing was conducted on field-produced samples. The tests on loose mix sampled in the field and compacted in the lab included the Hamburg wheel-track test and the Texas overlay test. The tests on pavement cores included the Illinois Flexibility Index Test and the Nflex. Nflex is a test under development at NCAT to determine mixture fracture resistance. This testing is beyond the scope of this study; thus, results are not included in the report.

5.1.3 Field Verification of the Asphalt Mixture Design

The asphalt mixture design was verified during field production based on asphalt content, gradation, and volumetric properties per the agency's standard requirements. The results indicated that the gradations for each section were very similar to those from the asphalt mixture design (Table 1). The volumetric properties for the asphalt mixture design and production of the mixture for the control and test sections are provided in Table 2. The air voids and VMA appeared to be a little lower for the two test sections than for the asphalt mixture design and control section.

Table 1. Design and Production Aggregate Gradations

Gradation	Mix Design Percent Passing	Control Section Percent Passing	Test Section 1 Percent Passing	Test Section 2 Percent Passing
¾ inch	100	100	100	100
½ inch	100	99	100	100
3/8 inch	88	94	97	95
No. 4	65	69	70	70
No. 8	47	47	48	48
No. 16	34	33	33	34
No. 30	25	24	25	25
No. 50	17	15	16	16
No. 100	10	8	9	9
No. 200	5.0	4.9	5.2	5.1

Table 2. Asphalt Content and Volumetric Test Results for Mix Design and Each Section

Section	Asphalt Content	Air Voids	VMA	TMD	Dust to Asphalt Ratio
Mix Design	5.0	4.0	14.1	---	---
Control	5.1	3.7	13.7	2.565	1.2
TS1	5.0	3.3	13.3	2.561	1.3
TS2	5.2	3.3	13.4	2.561	1.2

5.1.4 Density Measurement and Specifications

The agency uses a PWL specification with a lower specification limit of 91.8 percent and an upper specification limit of 95.0 percent of the theoretical maximum density of field-produced mix. For acceptance, the percent density was determined by comparing the in-place density measured by cores to the theoretical maximum density. There are five cores per sublot and the agency also has a specification for a minimum sublot average of 89.5 percent. The statewide historical results have averaged 92.6 percent.

For the demonstration project, field density testing was measured using a non-nuclear density gauge for quality control, but cores were used for acceptance. The target density for the control section was set at 93.0 percent of the theoretical maximum density. For the test sections and future work, it was anticipated to raise the target density along with the lower and upper limits by 1.0 or 2.0 percent.

5.1.5 Control and Test Section Construction and Results

A Roadtec SB-2500 MTV was used on this project to transfer the asphalt mixture from the trucks to the asphalt paver. The asphalt mixture was hauled to the project and dumped directly into the MTV, which then fed into the paver (CAT AP 1000D). It took approximately one hour to place 1000 feet of asphalt mixture in the control section, resulting in an average paver speed of approximately 17 feet per minute. This is a slow speed compared to most paving projects, and this slower speed typically results in improved density. A TransTech PQI 380 non-nuclear density gauge was used to quickly measure density for quality control during construction of the section. Acceptance was based on density results measured from cores.

The weather during paving was clear with little wind, and air temperatures ranged from 85 to 90^{o}F.

During compaction of the control section, two vibratory rollers (both CAT CB54) rolled almost continuously but without vibration. Typically, approximately nine passes (one trip forward plus one trip back is two passes) of each roller was applied to the asphalt mixture. The rollers generally stayed close behind the paver with one of the rollers operating on one side of the mat and the other roller operating on the opposite side of the mat. The breakdown rollers operated in echelon.

There was no buffer between the sections so the buffer would have to be the first part of each constructed section. The control section followed normal placement and compaction procedures. The plan for test section 1 was to improve rolling procedures while using the same rollers used for the control section. The plan for test section 2 was to add a pneumatic roller to the rolling operation.

Test section 1 was constructed with the same equipment as for the control section. It took one hour to place this test section resulting in an average paver speed of approximately 17 feet per minute. There was some stopping and starting of the paver in all three sections since the delivery of asphalt mixture was at a slow rate. Generally, approximately nine passes of the two vibratory rollers (operating statically) were used for compaction. One or two passes with vibration were used, believing that this would improve density in comparison to the control section, which was all static compaction. Several adjustments in the rolling pattern were made in an attempt to improve the density.

The plan for test section 2 was to compact the mix by adding a pneumatic roller (CAT CW34) in addition to the existing vibratory rollers. However, personnel discovered that the watering system was not working properly. Placement of this section began at 13:05 but the pneumatic roller was delayed until 13:50 while attempting to solve the problem. The pneumatic roller was eventually used, but the watering system was not able to apply an even spray of water on the tires.

The density results measured from cores are provided in Table 3. The density results averaged 93.5 percent in the control section, 93.2 percent in test section 1, and 95.4 percent in test section 2. The contractor earned the maximum incentive.

Table 3. Density Test Results

Control Section		Test Section 1		Test Section 2	
Core No.	**Bulk Density**	**Core No.**	**Bulk Density**	**Core No.**	**Bulk Density**
CS-1	2.405	TS1-1	2.388	TS2-1	2.452
CS-2	2.429	TS1-2	2.255	TS2-2	2.486
CS-3	2.439	TS1-3	2.376	TS2-3	2.389
CS-4	2.384	TS1-4	2.425	TS2-4	2.442
CS-5	2.405	TS1-5	2.435	TS2-5	2.469
CS-6	2.374	TS1-6	2.381	TS2-6	2.421
CS-7	2.420	TS1-7	2.384	TS2-7	2.450
CS-8	2.383	TS1-8	2.406	TS2-8	2.455
CS-9	2.352	TS1-9	2.424	TS2-9	2.443
CS-10	2.393	TS1-10	2.396	TS2-10	2.424
Average	2.398		2.387		2.443
Standard Deviation	0.026		0.051		0.027
TMD	2.565		2.561		2.561
Percent TMD	93.5		93.2		95.4

5.1.6 Utilization of New Technologies

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

5.1.7 Summary of State Findings

For State 1, the percent density increased by 1.9 percent with the addition of a pneumatic roller. There were several common themes from the ten demonstration projects that will be discussed later. Below is a summary of observations from this particular demonstration project that fits with the common themes.

- Observations for field operations (contractors)
  - Two breakdown rollers were used in echelon although they were in the static mode for the control section.
  - There were approximately 18 static passes from the breakdown rollers in echelon and 9 passes from the pneumatic roller for a total of 27 passes in test section 2.
  - The pneumatic roller water system was not working properly.
- Observations for specification development (agencies)
  - The field acceptance specification was PWL with a lower specification limit of 91.8 percent.
  - The specification had incentives and disincentives.

5.2 State 2

5.2.1 Project Description

The demonstration project was located on a six-lane divided interstate highway. It was located in a highly populated urban area and subjected to significant traffic that primarily consisted of cars but also included a significant amount of truck traffic. For the control section, test sections, and buffer sections, the total length of pavement was 1450 feet. The total amount of asphalt mixture placed in the area with the control and test sections was 234 tons. The milling was performed during the night of August 30, 2016 and the overlay was placed during the daytime on August 31.

The surface condition of the pavement at the time of repair was relatively good with few cracks, little raveling, and little rutting. The pavement section consisted of a surface layer, an asphalt intermediate course, and other underlying layers. The total pavement section is not known, but it is estimated that the design was sufficient for 10 to 15 years of traffic. The project consisted of removing 2 inches by milling followed by the application of a 2-inch overlay.

5.2.2 Asphalt Mixture Design

The gradation was a ½-inch NMAS blend that was slightly on the coarse side of the primary control sieve. The JMF developed during the asphalt mixture design and the production test results are provided in Table 4 along with specifications for minimum and maximum passing each sieve size. The aggregates were provided by a local supplier and met all of the agency specification requirements. The aggregates were all crushed since no natural sand was used in the mixture except for the amount of natural sand that was possibly available in the RAP. This asphalt mixture included 14 percent RAP. The t/NMAS was 4.0. The asphalt binder was a PG 70-22 and included an antistrip additive.

The asphalt mixture design was performed with 100 gyrations using a Superpave gyratory compactor. The optimum asphalt binder content was 5.0 percent corresponding to 4.1 percent air voids. The VMA was 15.9 percent and met the requirements of at least 14.0 percent but no more than 16.0 percent. The agency requirements for gyrations, design air voids, and VMA matched the AASHTO Superpave requirements. No performance testing was conducted on any of the asphalt mixtures.

5.2.3 Field Verification of the Asphalt Mixture Design

Field verification of the asphalt mixture design was conducted based on asphalt content, gradation, and volumetric properties per the agency's standard requirements. Results of the field verification are shown on Tables 4 and 5. These tables include the aggregate gradations, volumetric properties, and specification requirements.

Table 4. Aggregate Gradation Test Results

Sieve Size	Mix Design	Average Production	Lower Limit	Upper Limit
3/4 inch	100	100	100	100
1/2 inch	94	96	90	100
3/8 inch	84	83	77	90
No. 4	53	49	46	60
No. 8	34	30	28	40
No. 16	23	21	17	29
No. 30	16	16	10	22
No. 50	11	11	5	17
No. 100	8	8	4	12
No. 200	4.9	5.3	2.9	6.9

Table 5. Mixture Volumetric Test Results and Specifications

	Binder (%)	Va	VMA	VFA	Gmb	Gmm	Gsb
JMF Percent	5.0	4.1	15.9	74.3	2.503	2.609	2.826
Production	4.9	4.3	15.1	71.7	2.523	2.636	2.826
Specifications		3.5-5.6	14.0-16.0	65-78			

5.2.4 Density Measurement and Specification

The agency used a specification based on the minimum of each individual test result to be greater than 96.0 percent of a field-produced, laboratory-compacted sample (G_{mb}). Percent density was determined by comparing the in-place density measured by cores to the G_{mb} of laboratory samples. The field density was measured with three cores every 500 feet per lane. There were no incentives, only disincentives. The statewide historical results have averaged 98.5 percent based on the G_{mb}.

For the demonstration project, field density testing was measured using a Troxler 4640-B nuclear gauge operating in backscatter mode. Nuclear density results were correlated to cores. The cores were taken at the same location as nuclear gauge readings to allow for comparison. Percent density was determined by comparing the in-place density of the nuclear gauge or cores to the density of laboratory compacted samples (G_{mb}). A total of 14 cores were taken and tested to determine the in-place density.

5.2.5 Control and Test Section Construction and Results

End dump trucks hauled the asphalt mixture to a CAT AP1055F paver and dumped the material directly into the paver hopper. An attempt was made to monitor paver speed but this was difficult due to the short length of construction and delays. Approximately 234 tons of asphalt mixture were placed in approximately four hours, so the production rate and average paver speed were very slow. A Bomag (BW 161 AD-5) was used for compaction of the mixture and a smaller roller, a Bomag (BW 138 AD-5), was used as a finish roller. The larger roller weighed approximately 10 to 11 tons and the smaller roller weighed approximately 4 to 5 tons.

Generally, seven passes in the vibration mode were used to compact the control section and nine passes in the vibration mode were used to compact the test section.

The weather was sunny with air temperatures ranging from approximately mid-80s to low 90s. The mixture temperature at production was 305°F.

The contractor's plan to achieve increased density in the test section involved increasing the number of passes with the large vibratory roller to obtain one percent higher density. In fact, early testing indicated that seven passes could achieve approximately 96 percent of laboratory compacted density (G_{mb}) and nine passes could achieve approximately 98 percent of laboratory compacted density (G_{mb}).

Percent density results are shown on Table 6. The field density was measured with cores. The average percent density for the control section was 95.7 percent of the laboratory compacted density (G_{mb}). The average percent density of the test section was 96.5 percent of the laboratory density. It was desired to reach 96.0 percent in the control section and 97.0 percent in the test section. While the density was a little less than the goal, rounding the results caused the data to meet the goal for the test section with only two additional passes.

Table 6. Density Results from Control and Test Sections

Section	Average Lab Density	Average Core Density	Average Density % of Lab (G_{mb})	Goal Density % of Lab
Control	159.4	152.6	95.7	96.0
Test	159.4	153.8	96.5	97.0

5.2.6 Utilization of New Technologies

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

5.2.7 Summary of State Findings

For State 2, the percent density increased by nearly 1 percent with the addition of two passes from the vibratory breakdown roller. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
  - There were nine vibratory passes from the breakdown roller, which was the total number of passes in the test section.
- Observations for specification development (agencies)
  - The field acceptance specification required that each sublot have a density of at least 96 percent of the lab compacted density.
  - There were only disincentives.

5.3 State 3

5.3.1 Project Description

Two different demonstration projects were constructed on two different highways. These two highways were both located in rural areas. The first highway (Highway A) had two lanes in each direction that were separated by a median. The project length was 7.7 miles. A total of 24,317 tons of asphalt mixture were placed on the mainline and 4,072 tons were placed on the shoulders. Work consisted of paving over a 2.5-week period in May 2016.

For Highway A, the overlay was expected to last 17 years at an expected traffic level of 10 million ESALs. The project consisted of removing 2 inches of asphalt mixture by milling and then overlaying with 3 inches of asphalt mixture placed in two, 1.5-inch layers. The existing pavement consisted of 4.5 inches of asphalt mixture placed over 9 inches of concrete pavement over a 6-inch aggregate base course. Two primary variables were evaluated in these tests. These variables included using two asphalt contents (5.2 percent for two sections and 5.5 percent for two sections) and using varying numbers of rollers (four rollers for two sections and five rollers for two sections). These two levels of asphalt content were established using two gyration levels as discussed in Section 5.3.2.

The second highway (Highway B) had two lanes and the project was 13.6 miles long. A total of 50,182 tons of asphalt mixture were placed on the mainline and 5,242 tons of asphalt mixture were placed on the shoulder. Work consisted of paving over a five-week period primarily in September 2016. The design life for this pavement was 8 to 10 years at an expected traffic level of 1 million ESALs. The project consisted of removing 2 inches of the existing surface by milling followed by adding a 3.5-inch overlay (2-inch for the underlying layer and 1.5 inch for the surface). The existing pavement consisted of 6 to 7 inches of asphalt mixture over 7 to 9 inches of concrete pavement.

The biggest difference in the two demonstration projects was the traffic levels. Highway A had 10 million ESALs and Highway B had 1 million ESALs.

5.3.2 Asphalt Mixture Design

For Highway A, the gradation was a ½-inch NMAS blend. The mixture design was proprietary information; hence, much of the information was not available. The t/NMAS was 3.0. The grade of asphalt binder used was PG 58-28.

The design was performed using 90 gyrations and 60 gyrations with a Superpave gyratory compactor. The purpose of the two compaction levels was to provide differing asphalt contents between the same mixture compacted at the two gyration levels. The agency required an asphalt mixture design with 90 gyrations as required for the traffic level. An asphalt mixture design meeting the requirements at 90 gyrations was submitted by the contractor and optimum asphalt content was selected at 4.0 percent air voids. The agency then compacted this same aggregate structure at various asphalt contents with 60 gyrations. Optimum asphalt content was then selected at 4.0 percent air voids. This was called the gyratory regression approach. (Be aware that simply lowering the number of gyrations would not necessarily result in increased asphalt content, as a contractor would likely change the aggregate structure to keep the asphalt content relatively low). It was determined that the difference in optimum asphalt content was 0.3 percent between mixes using the two gyration levels. There was no performance testing conducted as part of the mix design.

For Highway B, the gradation was a ½-inch NMAS blend for the control section and test sections 1 and 5. The gradation was 3/8-inch NMAS blend for test sections 2, 3 and 4. The mix design for this project was also proprietary information. The t/NMAS for the ½-inch NMAS was 4.0 for the underlying layer and 3.0 for the surface course. The t/NMAS for the 3/8-inch NMAS aggregate was 4.0 for the surface course. The grade of asphalt binder was PG 64-28 for the mainline and PG 58-28 for the shoulder.

The design was performed using 60 gyrations with a Superpave gyratory compactor. No performance testing was conducted on either of the asphalt mixtures.

5.3.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content, gradation, and volumetric properties. Although this was performed on the project, no results were provided by the agency. Based on discussions with the agency, the asphalt mixture design was successfully verified in the field.

5.3.4 Density Measurement and Specification

The agency used a minimum lot average specification. For wearing surfaces, the minimum lot average was 92.0 percent of the field-produced, theoretical maximum density, and it was 93.0 percent for non-wearing surfaces. Percent density was determined by comparing the in-place density measured by 4-inch diameter cores to the theoretical maximum density. Only disincentives were applied; there were no incentives.

For the demonstration project, field density testing was measured using cores and also with a rolling density meter (RDM), which had been recommended as promising technology by SHRP2 research. More than 20 density cores were taken on Highway A and a total of 32 cores were taken on Highway B.

5.3.5 Control and Test Section Construction and Results

This agency constructed two demonstration projects on two different highways. One control section was constructed on Highway A along with three test sections. One control section was constructed on Highway B along with five test sections.

For both demonstration projects, asphalt mixture was hauled to the paving site with bottom dump trucks and placed in a windrow to be picked up and fed into the paver hopper of the Bomag paver. An MTV was not used. The paver moved at a rate of 30 feet per minute. The tack coat material was CSS-1H. A MOBA Pave-IR System scanner was attached to the paver to evaluate thermal segregation.

A summary of the rolling effort and mix properties for the control and test sections and their differences is shown in Tables 7 and 8 for Highways A and B, respectively. The percent density values (average air voids) shown in these tables are from the RDM. As shown in Table 7, Highway A used four rollers for the control section, five rollers for test section A, four rollers for test section B, and five rollers for test section C. One of the rollers was an intelligent compactor, which collected the data related to the asphalt mixture density, stiffness, and passes. Rollers used included two Dynapac CC624 steel-wheel rollers, a Hamm HD130 oscillatory roller, a CAT CW35 pneumatic roller, and a Hamm GRW18 pneumatic roller. The standard rolling pattern was five passes each with two breakdown rollers used in echelon, seven passes each with two pneumatic rollers used in echelon, and seven passes by the trailing steel wheel roller in vibratory mode. During compaction, some minor breaking of the aggregate was observed on the pavement surface. It was not clear if this breaking was due to excessive rolling with steel wheel rollers, soft limestone aggregate, thickness of the asphalt mixture, or some combination of these factors.

In addition to the changes in the number of rollers, asphalt content, and NMAS, a WMA additive, Evotherm, was also evaluated as a compaction aid. When a WMA additive is used as a compaction aid, the asphalt mixture production temperatures are not lowered.

On Highway A, the weather and asphalt mixture temperatures were not recorded. On Highway B, the weather was 50°F, mostly sunny, and breezy. The asphalt mixture temperatures were not recorded.

The average density for all of the sections was approximately 94.0 percent of theoretical maximum density using the RDM. However, when using cores to compare the control to the test section, one of the test sections was notably different. The percent density increased 1.2 percent when the asphalt mixture design had 0.3 percent additional asphalt and an additional roller.

Test section 1 for Highway B was the only density from the RDM that appeared to be significantly different from the other results, and even this one was not much different. The density of this section was 94.9 percent of theoretical maximum density while all of the other sections were closer to 94.0 percent density. Even though a number of test sections were constructed, the density of each test section was very similar to all other test sections and to the control section. The density of all sections was very good (93.5 to 94.9 percent of TMD) so it was likely that sufficient compaction effort was applied to adequately compact all of the different sections, even though some of them were likely significantly more difficult to compact. Hence, increasing rolling or any other approach evaluated did not significantly increase the density based on test results with the RDM. The RDM data was provided here for information.

Table 7. Test Plan for Highway A

Section	Number of Rollers	Target Asphalt Content	Average In-place Air Voids	In-place Air Voids Standard Deviation
Control Section	4	5.2	6.0	0.95
Test Section A	5	5.2	6.3	1.07
Test Section B	4	5.5	6.5	0.98
Test Section C	5	5.5	5.8	1.69

Table 8. Test Plan for Highway B

Section	NMAS (in.)	Number of Rollers	Use of Evotherm	Average In-place Air Voids
Control Section	½	3	No	6.3
Test Section 1	½	4	No	5.1
Test Section 2	3/8	3	No	6.4
Test Section 3	3/8	4	No	5.8
Test Section 4	3/8	3	Yes	6.3
Test Section 5	½	3	Yes	6.2

5.3.6 Utilization of New Technologies

Several new technologies were used on this project.

- The MOBA Pave-IR System using the thermal temperature scanner was attached to the paver to evaluate thermal segregation during the project.
- One of the rollers used intelligent compaction technology to help evaluate density of the asphalt mixture.
- A RDM (that was recommended during SHRP2) was used to non-destructively measure the density during construction.
- A WMA additive was used as a compaction aid.

While all of these technologies were used on this project, there was not enough work to fully evaluate the acceptability of each of these technologies. However, an example of the benefit of integrating these technologies was demonstrated. As shown in Figure 9, there are results from three of the technologies as mapped in the same location: [A] RDM dielectric constants, [B] paver speed, and [C] MOBA Pave-IR thermal temperature scanner.

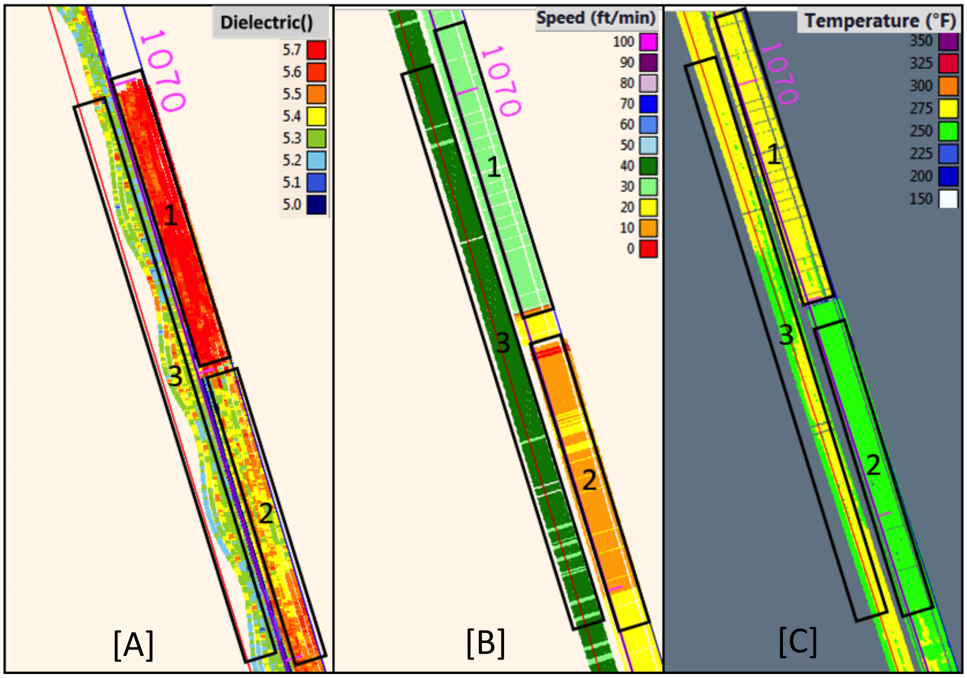

Figure 9. Maps of Results from Three of the New Technologies from the Same Location: [A] RDM Dielectric Constants, [B] Paver Speed, [C] MOBA Pave-IR Thermal Temperature Scanner

The following trends were observed in the maps.

1. Region 1 can serve as the baseline with the highest density [A in red]. There was a paver speed of 30 feet per minute [B in light green] with a mat temperature of 275 to 300°F [C in yellow].
2. Region 2 had a lower density [A in yellow and orange] than region 1. Although there was a slower paver speed of 10 to 20 feet per minute [B in orange and yellow], the mat temperature was much cooler at 250°F [C in green].
3. Region 3 had the lowest density of all [A in yellow, green and light blue]. The paver speed approached 50 feet per minute [B in dark green and blue] and the mat temperature was in the 250 to 275°F range [C in yellow and green].

Real-time density, paver speed, and temperature data were demonstrated to be invaluable quality control tools for the contractor when troubleshooting and analyzing results.

5.3.7 Summary of State Findings

For Highway A in State 3, the percent density increased by 1.2 percent as measured by cores. The test section included an additional roller and an engineering adjustment to the asphalt mixture design resulting in an increased asphalt content of 0.3 percent. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
    - Two breakdown rollers were used in echelon.
    - Two pneumatic rollers were used in echelon.

    - There were 10 vibratory passes from the two breakdown rollers and 14 passes from the two pneumatic rollers for a total of 24 passes in the control section.
- Observations for specification development (agencies)
    - An engineering adjustment to the asphalt mixture design resulted in an increase of 0.3 percent asphalt content.
    - The field acceptance specification was a minimum lot average of 92 percent.
    - The specification had incentives and disincentives.
- Observations from new technologies (both agencies and contractors)
    - The use of the MOBA Pave-IR scanner and rolling density meter were valuable quality control tools.

5.4 State 4

5.4.1 Project Description

The demonstration project was located on a rural, two-lane state highway with 12-foot wide lanes and 5-foot shoulders. The traffic volume used for design was 2 to 8 million ESALs. The total length of pavement containing the control and test sections was approximately 11.9 miles. Just over 20,000 total tons were placed for this project with approximately 2500 tons placed for each of the eight sections. These sections were constructed between July 25 and August 16, 2016.

For over 95 percent of the project, the pavement section consisted of milling 2 inches below the surface and removing the material. An additional 6 inches of material were removed by milling and replaced as cold mix. After completing placement of the cold mix, a 4-inch overlay of asphalt mixture was placed. The bottom lift was 2.25-inches thick and the top lift was 1.75 inches. For the remainder of the project (less than 5 percent), two inches of asphalt mixture were removed by milling and replaced with a 2-inch overlay. The existing pavement contained 8 to 9 inches of asphalt mixture, some of which was placed over an asphalt stabilized base course, while the remainder of the overlay was placed over a crushed aggregate base course.

5.4.2 Asphalt Mixture Design

The gradations were ½-inch and 3/8-inch NMAS blends and both were slightly on the fine side of the primary control sieve. The design aggregate gradations for the ½-inch and 3/8-inch NMAS asphalt mixtures are shown on Tables 9 and 10, respectively. The aggregates were provided by a local supplier and met all of the agency specification requirements. This was all crushed material since no natural sand was used in the mixture except for a small amount of natural sand that may have been included as a portion of the RAP. The ½-inch mixture contained 19 percent RAP while the 3/8-inch mixture contained 8 percent RAP. The t/NMAS was 4.5 for the base lift and 3.5 for the surface lift. The grade of asphalt binder used was PG 58-28.

The asphalt mixture was designed using 75 gyrations with the Superpave gyratory compactor. The volumetric properties of the JMF are provided in Table 11. The minimum VMA requirement was 0.5 percent higher than the AASHTO Superpave requirements. The design air void content for the control section was 4.0 percent but was adjusted to 3.0 percent using the air void regression technique as mentioned previously for test sections 2, 3, and 6. This resulted in 0.3 percent higher asphalt content for those test sections.

5.4.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content, gradation, and volumetric properties. The asphalt mixture design was verified during field production. The asphalt mixture design and field verification volumetric properties along with the specifications are provided in Table 11.

Table 9. Design Aggregate Gradation for 12.5-mm NMAS with Upper and Lower Limits

Sieve Size	Mix Design	Lower Limit	Upper Limit
3/4 inch	100	---	100
1/2 inch	98	90	100
3/8 inch	89	---	90
No. 4	66	---	---
No. 8	48	28	58
No. 16	35	---	---
No. 30	25	---	---
No. 50	13	---	---
No. 100	6	---	---
No. 200	3.1	2	10

Table 10. Design Aggregate Gradation for 9.5-mm NMAS with Upper and Lower Limits

Sieve Size	Mix Design	Lower Limit	Upper Limit
3/4 inch	100	---	100
1/2 inch	100	100	100
3/8 inch	95	90	100
No. 4	75	---	90
No. 8	54	20	65
No. 16	39	---	---
No. 30	27	---	---
No. 50	15	---	---
No. 100	6	---	---
No. 200	3.7	2	10

Table 11. Asphalt Mixture Design and Field Verification Results for Volumetric Properties and Specifications

	Binder Content (%)	Va	VMA	VFA	Dust to Asphalt	Gmb	Gmm	Gsb	TSR	Nuclear Density (% of TMD)
JMF (3/8 inch NMAS)	5.7	4.0	15.7	74.6	0.7	2.389	2.489	2.694	82.8	--
Specifications (3/8 inch NMAS)	--	4.0	15.5 min	70-76	0.6-1.2	--	--	--	75 min	--
JMF (1/2 inch NMAS)	5.5	4.0	15.8	74.7	0.6	2.401	2.501	2.694	84.4	--
Specifications (1/2 inch NMAS)	--	4.0	14.5 min	70-76	0.6-1.2	--	--	--	75 min	--
Control Section	5.3	4.6	15.9	--	--	2.390	2.499	--	--	93.5
Test Section 1 (1/2 inch NMAS)	5.3	4.4	15.7	--	--	2.398	2.510	--	--	95.0
Test Section 2 (1/2 inch NMAS)	5.5	3.4	15.3	--	--	2.409	2.495	--	--	94.6
Test Section 3 (1/2 inch NMAS)	5.6	2.6	14.7	--	--	2.433	2.490	--	--	95.4
Test Section 4 (1/2 inch NMAS)	5.3	4.4	16.0	--	--	2.393	2.498	--	--	92.5
Test Section 5 (1/2 inch NMAS)	5.4	3.8	15.6	--	--	2.404	2.500	--	--	93.4
Test Section 6 (1/2 inch NMAS)	5.5	3.2	15.5	--	--	2.409	2.489	--	--	94.0
Test Section 7 (3/8 inch NMAS)	5.5	3.8	16.0	--	--	2.377	2.473	--	--	95.2

5.4.4 Density Measurement and Specification

The agency used a minimum lot average specification of 91.5 percent of the field-produced, theoretical maximum density. Percent density was determined by comparing the in-place density measured by nuclear gauge results to the theoretical maximum density. The nuclear gauge results were not correlated to cores. Only disincentives were applied; there were no incentives.

For the demonstration project the agency measured in-place density of the sections by taking cores while the contractor measured the in-place density with a nuclear density gauge. The contractor's nuclear gauge results were correlated to core density testing. The agency's testing was not very extensive so the agency elected to report the contractor's nuclear gauge density results. The cores were taken at the same location as nuclear gauge readings to allow for comparison. All field density results were compared to the theoretical maximum density to determine percent density, and this is reported in Table 11.

5.4.5 Control and Test Section Construction and Results

The 12-mile section of roadway asphalt pavement was divided into approximately eight equal sections including a control section and seven test sections. The control section was placed using normal compaction procedures and had a minimum density requirement of 91.5 percent of theoretical maximum density. The plan for each test section is described below.

- The first test section was to increase the density by 1.0 to 2.0 percent by increasing compactive effort.
- The second test section adjusted the optimum asphalt content in the mixture design. Optimum asphalt was selected at 3.0 percent air voids instead of 4.0 percent air voids to increase the amount of asphalt binder in the mixture. This was called a design air void regression technique.
- The third test section strived to achieve 1 to 2 percent higher density by increasing the asphalt binder with the air void regression technique and by adding additional compactive effort.
- The fourth test section was constructed using WMA additive and lower temperatures to hopefully achieve density similar to that in the control section.
- The fifth test section was constructed using the same mixture as in the control section and adding WMA additive but using the same mix production temperature as for the control section.
- The sixth test section looked at the use of a WMA additive using reduced temperatures with the asphalt mixture designed with the air void regression technique.
- The seventh test section adjusted the mix to have a 3/8-inch NMAS blend instead of a ½-inch NMAS blend to increase the t/NMAS.

Asphalt mixture was hauled to the project and fed into the paver hopper with an MTV. The control section used a Terex CR662M MTV to feed the asphalt mixture into a RoadTec RP190 paver that utilized a joint heater. For test section 1, a Weiler E2850 MTV was used. For test sections 2 and 3, a Cedar Rapids 18118 MTV was used to feed the material into the asphalt paver. For test sections 4 through 7, the Weiler E2850 MTV was again used. The paver operated at a slow walking speed. Several rollers were available for compaction and there was some switching of rollers for some of the sections. Generally, four rollers were used for compaction of the sections. There were two breakdown vibratory rollers used in echelon. Generally, five to seven passes were used with each vibratory roller, 11 to 13 passes with the pneumatic roller, and seven to nine passes with the finish roller. However, test sections 1 and 3 used an additional vibratory roller in an attempt to improve compaction. The rollers available included a Dynapac CC624HF vibratory roller, Volvo DV 140B vibratory roller, Hamm GRW280 pneumatic roller, and Case DV210 steel wheel roller.

The asphalt mixture temperature at the paver was generally approximately 260^{o}F for the hot-mix asphalt sections and 220^{o}F for the WMA sections. The sections were placed during warm weather. The high temperature for each day of production ranged from 79 to 89^{o}F and it was sunny on most days. Some rain did occur during the day when test section 6 was placed.

The control section was compacted to an average density of 93.5 percent of theoretical maximum specific gravity, which exceeded the specification requirements of at least 91.5 percent of theoretical maximum density. Efforts to increase the density in test sections 1 through 7 were successful in some cases. Test sections 4, 5, and 6 were compacted to a density approximately equal to that achieved in the control section. Test sections 1, 2, 3, and 7 were compacted to densities between 1 and 2 percent higher than the control section. Test sections 4, 5, and 6 all used a form of WMA additive, and for this project, this did not result in improved density. Increasing the optimum asphalt content and increasing compactive effort did result in improved density. Test sections 1 and 3 used an additional roller for a total of five rollers.

5.4.6 Utilization of New Technologies

A WMA additive was used on several of the test sections. The use of the WMA additive did not result in improved density. None of the other new technologies such as the MOBA Pave-IR System, intelligent compaction, or rolling density meter were used as part of this project.

A joint heater was used on this project. This was not new technology but this approach had not been used very often and there was not a lot of data on its use. It was not clear if this joint heater improved density in the joints.

5.4.7 Summary of State Findings

For State 4, the percent density increased by 1.9 percent with an additional roller and an engineering adjustment to the asphalt mixture design resulting in an increased asphalt content of 0.3 percent. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
    - Two breakdown rollers were used in echelon.
    - There were 10 vibratory passes from the two breakdown rollers and 11 passes from the pneumatic roller for a total of 21 passes in test sections 2 and 4.
    - There was switching of MTVs and rollers due to equipment not working properly.
- Observations for specification development (agencies)
    - An engineering adjustment to the asphalt mixture design resulted in an increase of 0.3 percent asphalt content.
    - The field acceptance specification was a minimum lot average with a lower specification limit of 91.5 percent.
    - There were only disincentives.

5.5 State 5

5.5.1 Project Description

The demonstration project was on a rural, two-lane state highway. The total length of the project was four miles. The total length of the control section and all of the test sections was approximately one mile. Just over 9,000 total tons were placed for this project with approximately 1,200 tons placed in the control section plus all of the test sections. The leveling course for all sections was placed on October 19 and 20, 2016 and the surface course for all sections was placed on October 25.

The pavement section consisted of a 1.5-inch level course followed by a 2-inch surface course. The existing pavement had some thermal cracking, longitudinal cracking, delamination, and raveling.

5.5.2 Asphalt Mixture Design

The gradation used was a ½-inch NMAS blend that was slightly on the fine side of the primary control sieve. The JMF developed for the asphalt mixture design is provided in Table 12 along with the average production gradations. The aggregates were provided by a local aggregate supplier and met all of the agency specification requirements. The aggregate blend contained 30 percent natural sand and the remainder of the aggregate was crushed. No RAP was used in the mixes. The t/NMAS was 4.0 for the surface layer. The asphalt binder used for this project was a PG 64-22.

The asphalt mixture design was performed using 50 gyrations with a Superpave gyratory compactor. Two asphalt mixture designs were developed using the same aggregate gradation. The first design was performed to provide 4.0 percent air voids and was used for the control section and test section 1. For the second asphalt mixture design, the optimum asphalt content was determined at 3.0 percent air voids using air void regression. The volumetrics for the two designs along with in-place density results are provided in Table 13. The optimum asphalt binder content for the first mixture was 5.3 percent designed at 4.0 percent air voids. The optimum asphalt binder content for the second mixture was 5.6 percent, which was designed to provide 3.0 percent air voids. The VMA was required to be at least 14.5 percent during mix design and at least 14.0 percent during construction. The VMA for the first asphalt mixture design was 14.8 percent and for the second was 14.7 percent. The TSR was 0.90 for both designs (it appeared that the TSR testing was conducted for one of the designs and the results were used for both designs). The minimum TSR was required to be at least 0.80 during mix design and at least 0.75 during construction. The results met these requirements. Hamburg wheel-track testing was conducted on samples compacted to 94 percent theoretical maximum specific gravity and showed no potential rutting problems for the mixtures. The Hamburg results on the two mixtures were approximately the same even though one mixture had more asphalt binder.

5.5.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content, gradation, and volumetric properties. The asphalt mixture design was verified during field production and results are shown in Tables 12 and 13. The verification included the JMF, production test results, and in-place density. Results during production were acceptable.

Table 12. Aggregate Gradations for the Two Mix Designs and Production

Sieve Size	Mix Design	Average Production	Lower Limit	Upper Limit
3/4 inch	100	100	100	100
1/2 inch	94	92	87	100
3/8 inch	87	84	80	94
No. 4	64	65	57	71
No. 8	44	44	39	49
No. 16	29	30	25	33
No. 30	19	20	15	23
No. 50	11	14	7	15
No. 100	6	8	3	9
No. 200	5.3	6.4	3.3	7.3

Table 13. Mixture Volumetric Test Results and Specifications

	Binder (%)	Va	VMA	VFA	Gmb Lab	Gmb In-place	Gmm	Gsb	In-place Density % of TMD
JMF (4.0% air voids mix)	5.3	4.0	14.8	73.0	2.323		2.420	2.581	---
JMF (3.0% air voids mix)	5.6	3.1	14.7	78.9	2.346		2.421	2.596	---
Specifications	Plus or minus 0.4	3.5-5.6	14.5 min mix design 14.0 min production	65-78 for 4% air void design	---		---	---	92 to 97
Control Section (4.0% air voids mix)	---	3.6	14.4	---	2.346	2.250	2.432	---	92.5
Test Section 1 (4.0% air voids mix)	---	3.6	14.4	---	2.346	2.267	2.432	---	93.2
Test Section 2 (3.0% air voids mix)	---	2.8	15.0	---	2.350	2.303	2.419	---	95.2

5.5.4 Density Measurement and Specifications

The agency used a PWL specification with a lower specification limit of 92.0 percent and an upper specification limit of 97.0 percent of the field-produced, theoretical maximum density. Percent density was determined by comparing the in-place density measured by cores to the theoretical maximum density. Incentives and disincentives were applied. The statewide historical results had averaged 93.3 percent.

For the demonstration project, field density testing was measured using a nuclear density gauge for quality control but cores were used for acceptance.

5.5.5 Control and Test Section Construction and Results

A Terex CR662RM MTV was used on this project to transfer the asphalt mixture from the trucks to the asphalt paver. The asphalt mixture was hauled to the project and dumped directly into the MTV, which then fed the paver. For the control section, four rollers were used applying five passes each with two 15-ton vibratory rollers in echelon, five passes with a 12-ton pneumatic roller, and three passes with a 12-ton static steel wheel roller. For test section number 1, three rollers were used applying five passes each with two 15-ton oscillatory rollers in echelon and five passes with a 15-ton static steel wheel roller. The oscillatory roller was using both vibration and oscillation. For test section 2, four rollers were used applying five passes each with two 15-ton vibratory rollers, five passes with a 12-ton pneumatic roller, and seven passes with a 12-ton static steel wheel roller.

The contractor's plan was to compact the control section using normal compaction procedures. The plan for test section 1 was to use oscillatory rollers in place of the vibratory rollers. The plan for test section 2 was to increase the asphalt content approximately 0.3 percent to allow for easier compaction. In test section 3, some work was performed with a WMA additive but very little results were provided to document this section.

Each of the sections (control and test sections) were 1000 feet long with 500 foot buffers between the sections. There was no buffer between test section 2 and test section 3 and the length of test section 3 was 805 feet. Approximately 350 tons were placed in the control section, 300 tons in test section 1, 250 tons in test section 2, and 161 tons in the abbreviated test section 3.

The average compaction in the control section was 92.5 percent, which met the minimum specified density requirements. The density result for test section 1 was 93.2 percent, which was a slight increase over the density obtained in the control section. The density result in test section 2 was 95.2 percent, which was approximately a 2.7 percent increase over the control section.

5.5.6 Utilization of New Technologies

A WMA additive was used in test section 3 but very little testing was conducted to determine the change in density results in this test section. No other new technologies such as the MOBA Pave-IR System, intelligent compaction, or rolling density meter were used as part of this project.

5.5.7 Summary of State Findings

For State 5, the percent density increased by 2.7 percent with an engineering adjustment to the asphalt mixture design resulting in an increased asphalt content of 0.3 percent. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
    - Two breakdown rollers were used in echelon.

  - There were 10 vibratory passes from the breakdown rollers and five passes from the pneumatic roller for a total of 15 passes in test section 2.
- Observations for specification development (agencies)
  - There was an engineering adjustment to the asphalt mixture design resulting in an increased asphalt content of 0.3 percent.
  - The field acceptance specification was PWL with a lower specification limit of 92.0 percent.
  - The specification had incentives and disincentives.

5.6 State 6

5.6.1 Project Description

The demonstration project was located on a US highway. It was an urban arterial in a city with a small population. There were several businesses, and hence, there was a relatively high amount of car traffic with a small percentage of trucks. The AADT was estimated at 17,790 with 5 percent trucks. The total length of pavement used for the control and test section was approximately nine lane miles (approximately 1.8 centerline miles). Approximately 5,400 tons of asphalt mixture were placed. The entire project was finished in seven working days in early to mid-November 2016.

The existing pavement had moderate deterioration with some raveling, weathering, cracking, and rutting. This pavement had 5 inches of asphalt pavement over an old concrete pavement. The structure was considered adequate with no need for improvement, hence, milling and overlay was selected for the repair. The project consisted of removing 1.5 inches by milling followed by the application of a 1.5-inch overlay.

5.6.2 Asphalt Mixture Design

The gradation was a 3/8-inch NMAS blend on the coarse side of the primary control sieve. The JMF and the production test results are provided in Table 14 along with specifications for minimum and maximum percent passing each sieve size. The aggregates were provided by a local supplier and met agency specification requirements. The control mixture had 22 percent natural sand and the test section used all crushed material except for the uncrushed material that might have been included in the RAP. The asphalt mixture for the control section included 14.5 percent RAP and 3.0 percent RAS. The mix for the test section included 14.1 percent RAP and 2.9 percent RAS. The t/NMAS for both sections was 4.0. The asphalt binder was a PG 70-22 and it was not polymer modified.

The asphalt mixture design was performed using 100 gyrations with the Superpave gyratory compactor for the control section and 50 gyrations for the test section. The mixture for the control section was designed to have 4.0 percent voids and the mixture for the test section was designed to have 5.0 percent voids. The specifications required that the VMA be at least 15 percent in the asphalt mixture design for the control section and at least 16 percent for the test section. The volumetric properties for the asphalt mixture design and construction are provided in Table 15. The amount of total asphalt binder in the JMF was 6.7 percent for the control mix and 6.8 percent for the test section. No performance testing was conducted on any of the asphalt mixtures.

5.6.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content and volumetric properties. The asphalt mixture design was verified during field production, and JMF and production test results are shown in Tables 14 and 15. Test results were acceptable.

Table 14. Aggregate Gradation Job Mix Formula and Production Results

Sieve Size	Control Section Job Mix Formula	Control Section Average Production	Test Section Job Mix Formula	Test Section Average Production
3/4 inch	100	100	100	100
1/2 inch	100	100	100	100
3/8 inch	94	95	94	93
No. 4	59	64	63	60
No. 8	34	33	37	35
No. 16	22	21	22	21
No. 30	13	13	14	14
No. 50	8	8	9	9
No. 100	6	6	6	6
No. 200	4.9	4.8	5.1	4.9

Table 15. Mixture Volumetric Test Results and Specifications

	Binder (%)	Air Voids (Lab Compacted)	VMA	VFA	Gmb	Gmm	Gsb	In-Place Density (%)
Control Section JMF	6.7	4.0	15.2	73.7	2.357	2.455	2.593	---
Test Section JMF	6.8	5.0	16.5	69.7	2.322	2.445	2.594	---
Production Test Results Control Section	6.5	4.7	15.3	69.3	2.300	2.466	---	93.3
Production Test Results Test Section	6.7	5.6	16.5	66.1	2.343	2.457	---	95.4
Specifications	---	2.6-5.4 for control section 3.6-6.4 for test section	LSL = greatest of spec - .5 or JMF - 1.2 USL = lesser of spec + 2.0 or JMF + 1.20	---	---	---	---	93% target for control section 95% target for test section

5.6.4 Density Measurement and Specification

The agency used a PWL specification with a lower specification limit of 91.0 percent of the field-produced, theoretical maximum density. Percent density was determined by comparing the in-place density measured by cores to the theoretical maximum density. Incentives and disincentives were applied. To avoid disincentives, it was generally required to obtain at least 93.0 percent density in the control section and at least 95.0 percent density in the test section. Statewide historical results have averaged at 93.0 percent.

For the demonstration project, field density test results were determined from cores tested by the agency and by the contractor. Density testing was conducted by two labs (contractor and agency) and for two sections (control and test sections). Each set of tests used 10 cores to determine the average density. Hence, a total of 40 cores were used to determine the density. All 20 cores from the control section were averaged and results are provided in Table 15. The same method was used for determining the average density of the test section.

5.6.5 Control and Test Section Construction and Results

End dump trucks hauled the asphalt mixture to the paver and dumped the material into a Roadtec SB 2500 MTV, which fed the material into the paver hopper. A joint adhesive was applied to the pavement edge where an adjacent lane was to be placed. This adhesive did not improve compaction but the goal was to seal the joint. Compaction was provided with two, 10-ton vibratory rollers (CAT CB 534) in echelon. Each roller provided five vibratory passes and two static passes. The same type of steel wheel roller was used for finish rolling and applied five static passes.

The temperature during the days of work varied from a low of 37^{o}F to a high of 59^{o}F, as shown in Table 16.

Table 16. Temperatures during Construction

Date	Ambient Temperature, ^{o}F
Nov 9	43 to 52
Nov 10	41 to 59
Nov 11	43 to 54
Nov 12	37 to 48
Nov 14	39 to 57

The contractor's plan was to use standard procedures to place and compact the asphalt mixture for the control section. The plan was to then modify the asphalt mixture design as discussed under "Asphalt Mixture Design" to provide an asphalt mixture that was more compactible for the test section. The difference in asphalt content between the two mixtures was only 0.1 to 0.2 percent but the resulting difference in density was significant. There was also some difference in the aggregates used and gradation of the blend. There were no significant differences in rolling procedures between the control and the test sections.

A total of 40 cores were taken for density testing for the two sections. The average density (based on cores) for the control section was 93.3 percent of theoretical maximum density. The average density of the test section was 95.4 percent of theoretical maximum density. It was desired to reach a density of 93.0 percent of theoretical maximum density for the control section and at least 95.0 percent of theoretical maximum density for the test section. The specified density requirements were met.

5.6.6 Utilization of New Technologies

A joint adhesive was added at the longitudinal joints to attempt to provide a more waterproof joint. No new technologies such as the MOBA Pave-IR System, intelligent compaction, WMA, or rolling density meter were used as part of this project.

5.6.7 Summary of State Findings

For State 6, the percent density increased by 2.1 percent with an engineering adjustment to the asphalt mixture design. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
  - Two breakdown rollers were used in echelon.
  - There was a total of 14 passes from the two breakdown rollers of which 10 were vibratory in the control and test sections.
- Observations for specification development (agencies)
  - There was an engineering adjustment to the asphalt mixture design resulting in slightly increased asphalt content. Adjustments were made to the design gyrations, air voids, and VMA.
  - The field acceptance specification was PWL with a lower specification limit of 91.0 percent.
  - The specification had incentives and disincentives.

5.7 State 7

5.7.1 Project Description

The demonstration project was located on a major arterial state highway having a design speed of 45 miles per hour. The volume of traffic was estimated to be 14,500 average daily traffic and 6 percent trucks. The project was approximately 3.5 miles long and had several turning locations along the route. Approximately 9,500 tons of asphalt mixture were placed and defined by four lots. The first three lots were completed between June 6 and June 14, 2016. Lot 4 was completed between July 19 and July 21.

The existing pavement was milled down approximately 2 inches, patching was performed in some localized areas, and a scratch coarse approximately ½-inch thick was placed followed by a 1.5-inch overlay placed on top.

5.7.2 Asphalt Mixture Design

The same asphalt mixture design was used for all four lots. The gradation was a 3/8-inch NMAS blend that was slightly on the coarse side of the primary control sieve. The JMF developed during the asphalt mixture design and the range of production test results are provided in Table 17. The aggregates met the agency specification requirements. The mixture included 15 percent RAP. The t/NMAS for all four lots was 4.0. The virgin asphalt binder was a PG 76-22. It was polymer modified and included a WMA additive.

The asphalt mixture was designed for 0.3 to 3 million ESALs. The asphalt mixture design was performed using 75 gyrations with the Superpave gyratory compactor. The mixture for all four lots was designed to have 3.5 percent air voids. The VMA requirement was also a minimum of 15.5 percent, which is 0.5 percent higher than the AASHTO Superpave standard. The amount of total asphalt binder in the JMF was 6.2 percent. The volumetric properties for the asphalt mixture design and the range of test results during construction are provided in Table 18. No performance testing was conducted on any of the asphalt mixtures.

5.7.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content gradation and volumetric properties. The asphalt mixture design was verified during field production and results are shown on Tables 17 and 18. These tables include the JMF, production test results, and specification requirements. Results were acceptable.

Table 17. Aggregate Gradation Job Mix Formula and Production Results

Sieve Size	Control Section Job Mix Formula	Average Production
3/4 inch	100	---
1/2 inch	100	---
3/8 inch	96	---
No. 4	67	---
No. 8	46	44-47
No. 16	29	---
No. 30	18	---
No. 50	11	---
No. 100	7	---
No. 200	4.7	4.7-5.5

Table 18. Mixture Volumetric Test Results and Specifications

	% Binder	Air Voids	VMA	VFA	Gmb	Gmm	Gsb
Job Mix Formula	6.2% total 5.4% PG 76-22 0.8% from RAP	3.5	16.2	78.0	2.377	2.463	2.672
Production Test Results	6.1-6.4	3.4-3.5	16.1-16.9	---	---	2.455-2.461	---
Specifications	6.0-6.4	2-5	15.5	---	---	2.443-2.483	---

5.7.4 Density Measurement and Specification

For the control sections, the agency used their standard specification based on the minimum and maximum of each individual sublot where the density test result must be between 92.0 and 97.0 percent theoretical maximum density. One core was taken from each sublot in all four lots. Most commonly, there were five sublots per lot. Only disincentives are applied; there were no incentives. This specification was also used for the control section. The statewide historical results have averaged 93.6 percent.

For the test sections, the agency used their pilot PWL specification with lower and upper specification limits of 92.0 and 98.0 percent theoretical maximum density. At least 90 percent of the test results were required to be within these limits to achieve 100 percent pay. Incentives and disincentives were applied. The density results are provided in Table 19.

Table 19. Density Test Results for each Sublot

	Sublot 1	Sublot 2	Sublot 3	Sublot 4	Sublot 5	Sublot 6	Sublot 7	Average	Standard Deviation
Lot 1	91	92	96	97	96	---	---	94.4	2.7
Lot 2	95.4	95.8	96.4	95.9	96.9	---	---	96.1	0.6
Lot 3	97.0	96.3	95.4	---	---	---	---	96.2	0.8
Lot 4	97.1	95.8	96.7	96.5	97.0	95.4	94.2	96.1	1.0

5.7.5 Control and Test Section Construction and Results

End dump trucks hauled the asphalt mixture to the paver and dumped the material into an MTV (Roadtec SB 1500), which fed the material into the paver (CAT AP 1055F) hopper. The paver operated at a slow walking speed. A notched wedge joint was used to facilitate construction of the longitudinal joint. Compaction was provided with three vibratory rollers (two Cat CB 54B rollers and one Sakai WS800) in echelon. Each vibratory roller applied four vibratory passes and one static pass. Another roller following a similar roller pattern was used to provide continuous compaction of the longitudinal joint.

The air temperatures varied from a low of 45 to a high of 88°F during construction of the project as shown in Table 20. Low temperature varied from 45 to 64°F and the high temperature varied from 62 to 79°F for the first three lots. The low temperature varied from 59 to 67°F and the high temperature varied from 77 to 88°F for lot 4. The mix temperature when added to the MTV generally ranged from 285 to 300°F.

Table 20. Temperatures during Construction

Date	Ambient Temperature, °F
Jun 6	64 to 79
Jun 7	63 to 64
Jun 9	45 to 62
Jun 10	47 to 75
Jun 13	58 to 62
Jun 14	52 to 67
Jul 19	67 to 77
Jul 20	59 to 88
Jul 21	59 to 87

The four lots had varying numbers of sublots with each sublot representing 400 to 500 tons of asphalt mixture. Lot numbers 1 and 2 each had five sublots, lot 3 had three sublots, and lot 4 had seven sublots. A total of 20 density tests were conducted for the four lots (five for lot 1, five for lot 2, three for lot 3, and seven for lot 4). The average of density tests for lot 1 was 94.4 with a standard deviation of 2.7. The average for lot 2 was 96.1 with a standard deviation of 0.6. The average density from lot 3 was 96.2 with a standard deviation of 0.8. The average density for lot 4 was 96.1 with a standard deviation of 1.0. This would seem to indicate that lot 1, constructed to meet the existing minimum individual sublot specification, reached a lower density than lots 2-4, which were constructed to meet the specification being considered for adoption. All of these samples were randomly selected and there were no outliers.

A closer look shows that the first two tests in lot 1 were significantly lower than the last three tests in the lot, which were closer to the density in lots 2 to 4. Also, the pavement in the area where the first two sublots were placed was placed with pavers in echelon without additional rolling; it is believed that this is the reason that the density for these two test results was lower. Also, there was no apparent change in compaction procedures between lot 1 and lots 2 to 4, so even though the specification was different between lot 1 and the other lots, there was no difference in compaction equipment or procedures used, so there was no reason to believe that the density in lot 1 would be different from the other lots.

There was a significant difference in the standard deviation. For the minimum individual sublot specification with five sublots per lot, the statewide average standard deviation was 1.55. For the pilot PWL specification with five sublots per lot, the statewide average standard deviation was 0.95. The use of the new pilot PWL specification demonstrated an increased consistency.

5.7.6 Utilization of New Technologies

A WMA additive was used on this project. No other new technologies such as the MOBA Pave-IR System, intelligent compaction, or rolling density meter were used.

5.7.7 Summary of State Findings

For State 7, the percent density increased only slightly with the new PWL specification, but there was a significant improvement in consistency as measured by the standard deviation. The standard deviation was lowered from 1.55 to 0.95 for statewide averages. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
    - Three breakdown rollers were used in echelon.
    - There were 15 passes from the breakdown rollers, of which 12 were vibratory, and there was a total of 15 passes in the test section.
- Observations for specification development (agencies)
    - The field acceptance specification for the test section was PWL with a lower specification limit of 92.0 percent.
    - On projects using the pilot PWL specification, the standard deviation was significantly lower.
    - The specification had incentives and disincentives.

5.8 State 8

5.8.1 Project Description

The demonstration project was located on a four-lane principal arterial that was part of an urban area with a larger population. The 2015 AADT for the test section was 30,746 with 6 percent trucks. The project was over six miles long and the control and test sections were 1.5 miles long. The total quantity of asphalt mixture produced for this project was approximately 8,440 tons. It was paved at night between July 13 and August 10 of 2016.

The existing asphalt pavement contained a 1.8-inch asphalt surface paved in 2001. It was placed over 4.8 to 6 inches of asphalt pavement, over 4.2 inches of asphalt treated base, over 3.6 inches of untreated base. The pavement was in fair condition with low to medium severity alligator cracking, low and medium severity longitudinal cracking, low severity transverse cracking, and low severity patching. The plans generally called for milling with a 1.8-inch overlay.

5.8.2 Asphalt Mixture Design

The gradation was a ½-inch NMAS blend that was slightly on the coarse side of the primary control sieve. The aggregates were provided by a local supplier and met all of the agency specification requirements including sand equivalent (54 percent), uncompacted voids for fine aggregate (46 percent), and percent fracture for coarse aggregate (100 percent). There were no recycled materials in the asphalt mixture. The t/NMAS was 3.6. The asphalt binder was a PG 64-22.

The mix design used 100 gyrations with the Superpave gyratory compactor. The optimum asphalt binder content was 5.7 percent and was selected at 4.0 percent air voids. The VMA of

16.4 percent exceeded the minimum of 14.0. The gyrations, design air voids, and minimum VMA matched the AASHTO Superpave requirements. The Hamburg wheel-track testing was used as a performance requirement.

5.8.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements were to use asphalt content, gradation, and volumetric properties. The asphalt mixture design was verified during field production and results are shown in Table 21. This table includes the asphalt content and volumetric properties along with their upper and lower acceptance criteria, standard deviation, and mean results.

Table 21. Field Verification Results of the Asphalt Mixture Designs

	Binder (%)	Va	VMA	VFA	D/A	Pbe	Gmb	Gmm	Gsb	Gb
JMF Percent	5.7	5.5	16.4	67	1.4	4.8	2.338	2.475	2.637	1.028
Upper Acceptance	6.2	5.5		75	1.6					
Lower Acceptance	5.2	2.5		65	0.6					
Mean	5.6	3.5	14.6	76	1.3	4.7	2.387	2.474	2.637	1.028
Std. Deviation	0.1	0.8	0.6	5	0.1	0.1	0.017	0.006	0	0

5.8.4 Density Measurement and Specification

The agency uses a PWL specification with the lower specification limit of 91.0 percent and an upper specification limit of 100.0 percent of the field-produced, theoretical maximum density. Percent density was determined by comparing the in-place density measured by the nuclear gauge to the theoretical maximum density. The nuclear gauge was correlated to cores. The field-produced theoretical maximum density was determined using a moving average. The frequency of testing is generally every 100 tons. Incentives and disincentives are applied. The statewide historical results have averaged approximately 93.0 percent with a standard deviation of 1.39.

For the demonstration project, field density testing was measured using a Troxler 3450 nuclear gauge operating in direct transmission mode at a depth of 2 inches. More than 75 nuclear density measurements were taken on the control section, and a total of 11 were taken on the test section.

5.8.5 Control and Test Section Construction and Results

The demonstration project involved night paving. End dump trucks hauled asphalt mixture to a Weiler E2850 MTV, which remixed the asphalt mixture before transferring into the CAT AP1055E paver. A traditional rolling train was used. The breakdown roller was a CAT CB68B vibratory, steel-wheel roller. The intermediate roller was a Dynapac CP30 pneumatic roller with a CAT CB54B steel-wheel finish roller operating in a non-vibratory mode.

The basic roller pattern consisted of eight passes of the breakdown roller, all in vibratory mode. The breakdown roller made one additional pass to pinch the inside joint from the cold side, with a total of nine passes. The vibratory roller width was 84 inches so it easily covered the mat in two passes. The pneumatic roller followed a somewhat erratic pattern but generally consisted of 13 to 17 passes. The effort of the pneumatic roller was skewed to the middle of the mat although several passes were normally made on the edge of the mat as well. The finish roller operated in static mode and was used to remove roller marks.

The weather was slightly overcast with ambient air temperature of 70°F and surface temperatures of 68°F. The temperature of the asphalt mixture as it was loaded into the delivery trucks was 310°F. The temperature of the asphalt mixture at the screed was 285°F at the start of paving but soon increased to 295°F shortly after production paving was underway.

The contractor’s plan to achieve increased density in the test section included an increase in the weight of the intermediate pneumatic roller form 13.4 tons to 16.5 tons by adding 800 gallons of water. Primarily, there was attention to better control the roller pattern with closer spacing during compaction.

A total of 77 density samples were obtained for the 7,415 tons of asphalt mixture placed on the control section. The average result was 93.1 percent with a standard deviation of 1.58. These results provided a pay factor of 1.04. A total of 11 density results were obtained from the 1,025 tons of HMA placed for the test section. The average density result was 93.0 percent with a standard deviation of 0.67. Table 22 lists the data for both the control and test sections.

Table 22. Results from the Control and Test Sections

Section	Total Tonnage	Number of Tests	Average (%)	Std. Dev	High (%)	Low (%)
Control	7415	77	93.1	1.58	96.4	89.9
Test	1025	11	93.0	0.67	94.0	91.6

The decrease in variability of the two sections was demonstrated by the reduction of the standard deviation from the control section, which was 1.58, to the test section, which was 0.67. For the same PWL, a lower standard deviation equated to a different lower specification limit. Effectively, this was an increase in 1.0 of the lower specification limit. This is shown graphically in Figure 10.

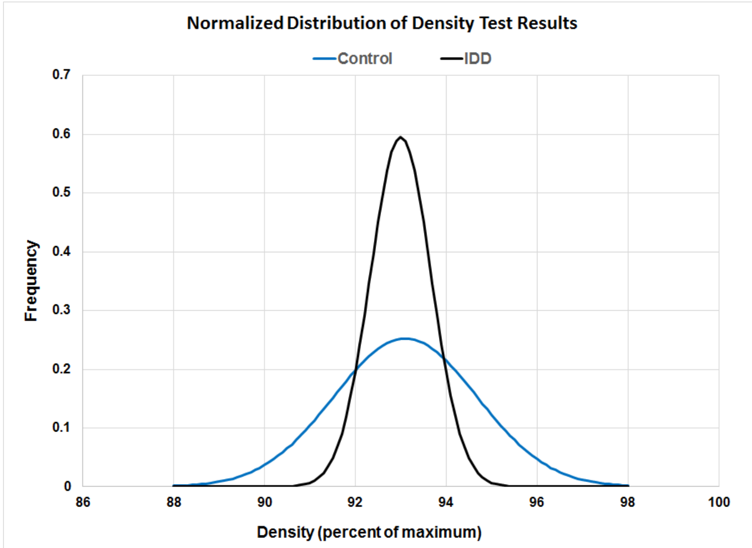

Figure 10. Normalized Distribution of Density Test Results from Control and Test Sections

5.8.6 Utilization of New Technologies

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

5.8.7 Summary of State Findings

For State 8, the percent density did not change by implementing better practices with the roller pattern but there was a significant improvement in consistency as the standard deviation was lowered from 1.58 to 0.67. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
  - There were eight vibratory passes and one static pass from the breakdown roller and 15 passes from the pneumatic roller for a total of 24 passes in the control and test sections.
  - Although it was desired to utilize additional compaction equipment, it was not available.
- Observations for specification development (agencies)
  - The field acceptance specification was PWL with a lower specification limit of 92.0 percent.
  - For the test section the standard deviation was significantly lower.
  - The specification had incentives and disincentives.

5.9 State 9

5.9.1 Project Description

The demonstration project was located on a two-lane rural primary US highway. The AADT was 3900 with approximately 6 percent trucks. The entire length of the project was approximately 2-1/4 miles. The project included a control section and two test sections. The control section utilized 1103 tons, test section 1 utilized 1057 tons, and test section 2 utilized 862 tons. The control section was constructed on September 14, 2016. Test section 1 was constructed on September 15 and test section 2 was constructed on September 16.

The pavement section consisted of approximately 8 inches of asphalt mixture with the latest overlay being placed in 2007. The existing pavement had some low to moderate fatigue cracking with some areas of high severity cracking. The plans called for a 2-inch overlay to be placed. No milling or level course was required on this project.

5.9.2 Asphalt Mixture Design

The gradation was a ½-inch NMAS blend that was slightly on the coarse side of the primary control sieve. The gradation for the asphalt mixture design is provided in Table 23 along with the average production gradations. The aggregates met all of the agency specification requirements. The aggregate blend used all crushed material except for some uncrushed material that may have been contained in the RAP. No natural sand was added to the mixture. The mixture contained 16 percent RAP. The t/NMAS was 4.0 for the surface layer. The asphalt binder used for this project was a PG 64S-22, which is typically used by the agency for mixtures designed for 0 to 3 million ESALs. The mix also used a WMA additive to improve adhesion and compactability.

The same asphalt mixture design was used in all sections. The asphalt mixture design was performed with 50 gyrations with a Superpave gyratory compactor. The volumetric properties for the asphalt mixture design along with in-place density results are provided in Table 24. The optimum virgin asphalt binder content for the mixture was selected to be 5.6 percent and this resulted in an air void content of 3.1 percent. The VMA of the designed mix was 15.6 percent and the voids filled with asphalt were 80.5 percent. The minimum requirement for VMA was 15.0 percent, which is 1.0 percent higher than the requirement in the AASHTO Superpave standard. The requirements for voids filled with asphalt were 73 to 79 percent. The minimum TSR was required to be at least 0.80 but no results were reported in the mix design information.

5.9.3 Field Verification of the Asphalt Mixture Design

For field verification of the asphalt mixture design, the agency's standard requirements are to use asphalt content, gradation, and volumetric properties. The asphalt mixture design was verified during field production and results are shown in Tables 23 and 24. These tables include the JMF, production test results, and in-place density.

Table 23. Aggregate Gradations for Mix Design and Production

Sieve Size	Mix Design Percent Passing	Average Production Percent Passing	Production Standard Deviation Percent
3/4 inch	100	100	0
1/2 inch	95	94	1
3/8 inch	85	84	2
No. 4	58	56	2
No. 8	38	36	2
No. 16	---	---	---
No. 30	19	18	1
No. 50	---	---	---
No. 100	---	---	---
No. 200	6.0	4.7	0.24

Table 24. Mixture Volumetric Test Results and Specifications

	Percent Binder	Air Voids	VMA	VFA	Gmb Lab	Gmm	Gsb	In-place Density % of TMD	In-Place Density Standard Deviation
JMF	5.6	3.1	15.6	80.5	2.441	2.520	2.742	---	---
Specifications	---	---	Min 15	73 to 79	---	---	---	---	---
Control Section	5.6	3.6	15.8	77	---	2.543	---	92.2	1.3
Test Section 1	5.6	2.7	15.3	82	---	2.554	---	92.0	2.1
Test Section 2	5.7	3.4	16.0	79	---	2.552	---	92.0	1.3

5.9.4 Density Measurement and Specifications

The agency used a specification based on the percent density from the control strip. The minimum required percent density was 98.0 percent and the maximum was 102.0 percent. Percent density was determined by comparing the in-place density measured by cores. The statewide historical results had averaged approximately 91 percent of the theoretical maximum density.

For the demonstration project, the percent density was expressed as a percentage of the theoretical maximum density. A total of 10 cores were taken from each of the three sections. As shown in Table 24, the average density was 92.2 percent for the control section, 92.0 percent for test section 1, and 92.0 percent for test section 2. The target for the control section was 92.5 percent and the target for the test sections was 94.0 percent. The measured density did not meet the target density requirements.

5.9.5 Control and Test Section Construction and Results

A Blaw-Knox MC 330 MTV was used to transfer the asphalt mixture from the truck to the paver (CAT AP1055D). The MTV equipment had a mechanical problem at the beginning of the project and was not used during placement of the control section but was used for test sections 1 and 2. Even though an MTV was used for the two test sections, it did not remix materials due to an issue with its mixing component. The material was simply transferred by the MTV from the truck to the paver. The tack coat used on this project was a reduced tracking emulsified tack coat applied at 0.05 gallons per square yard. Three rollers were available for compaction. Roller 1 was a CAT CB64B eleven-ton roller with intelligent compaction. Roller 2 consisted of a HAMM HD+90 nine-ton roller with oscillator vibration. The Hamm roller used vibration and oscillation. Roller 3 was an Ingersoll Rand DD-90HF nine-ton finish roller. For the control section, roller 1 applied three vibratory and six static passes, followed by seven static passes with roller 2. For test section 1, roller 1 applied five vibratory and two static passes, followed by two oscillatory passes and one static pass with roller 2. For test section 2, roller 1 applied five vibratory passes, followed by two oscillatory passes and three static passes with roller 2.

The air temperature during placement of the control section ranged from 69 to 93^{o}F; for test section 1 it ranged from 69 to 77^{o}F, and for test section 2 it ranged from 69 to 78^{o}F.

The contractor's plan was to compact the control section using normal compaction procedures. The target minimum density for the control section was 92.2 to 92.5 percent of theoretical maximum density. The goal was to achieve 1.5 percent higher density in the test sections. As shown in Table 24, the density changed very little between the control section and the test sections. Hence, the goal of increasing the density by 1.5 percent was not achieved. It should also be noted that there was not a significant difference in the field compactive effort applied to the asphalt pavement for the various sections.

5.9.6 Utilization of New Technologies

A WMA additive was used in all sections to improve compactability and to improve adhesion. The MOBA Pave-IR System was used to monitor temperatures at the paver. These readings showed a significant degree of temperature segregation. Intelligent compaction technology was used. Even though several new technologies were used, they were likely not optimized or used for feedback since each section was relatively small. They were simply used to provide information, and hence, did not lead to improved density.

5.9.7 Summary of State Findings

For State 9, there was no change in the percent density in the test sections. This demonstration project used the least amount of compactive effort in the field of all the demonstration projects. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
    - There were nine passes from the breakdown rollers, three of which were in the vibratory mode, and a total of 16 passes in the control section.
    - The MTV had mechanical problems and was not used for all of the sections.
- Observations for specification development (agencies)

- The field acceptance specification was based on the percent of the control strip with a minimum of 98.0 percent.
- There were disincentives on the project.

5.10 State 10

5.10.1 Project Description

The demonstration project was located on a four-lane divided primary highway with 50,000 ADT. The length of the project was 15.2 miles. The test strip was constructed prior to start of work on the control section and test sections and contained 615 tons of asphalt mixture. The purpose of the test strip was to develop a rolling pattern and validate other techniques to be used for the control section and test sections. The control section contained 1670 tons and the test section contained 3570 tons. A total of approximately 50,000 tons were to be placed in the test section, but only 3570 tons were placed in 2016 with the remainder to be placed in 2017. This report only includes results from the 3570 tons placed in the test section in 2016. The test strip was placed on September 10 and the control section was placed on September 13. The test section was placed on September 18 and 19. The mix produced on September 10, 13, and 18 was produced in the first plant and the mix produced on September 19 was produced in a second plant due to a breakdown of the first asphalt plant. This was a night paving project.

The paving project consisted of a 2.0-inch mill and fill. Due to the use of studded tires, this road had been generally overlaid every six to seven years. The existing pavement (before the mill and fill project) had experienced rutting in some places exceeding 1.75 inches and in some places delamination had occurred.

5.10.2 Asphalt Mixture Design

There were two asphalt mixture designs developed for this project. Two plants were used for the project and each plant had its own mix design. The gradations for the two designs were 3/4-inch NMAS blends. The first asphalt mixture design was slightly on the fine side of the primary control sieve and the second was slightly on the coarse side. The gradations for the two asphalt mixture designs are provided in Tables 25 and 26. The aggregates met all of the agency specification requirements. No RAP was used in the mixture. The t/NMAS was 2.7 for the surface layer. The asphalt binder used for this project was a PG 64-40 that was highly polymer modified. Both mix designs used a WMA technology to improve adhesion and workability.

The asphalt mixture designs were performed using 75 gyrations with a Superpave gyratory compactor. The first asphalt mixture design had an optimum asphalt content of 5.6 percent and provided 4.0 percent air voids. The second asphalt mixture design had an optimum asphalt content of 5.5 percent and provided an air void level of 3.7 percent. The asphalt binder content for the second asphalt mixture design, required to provide 4.0 percent air voids, was 5.2 percent. However, the optimum asphalt content was increased to 5.5 percent so that the mix would have a little more asphalt binder and improved durability.

The volumetric properties for the asphalt mixture designs along with in-place density results are provided in Table 27. The VMA was required to be at least 13.0 percent. The VMA was 16.6 percent for the first asphalt mixture design and 15.1 percent for the second mixture design.

5.10.3 Field Verification of the Asphalt Mixture Design

The agency's standard requirements for field verification of the asphalt mixture design were to use asphalt content, gradation, and volumetrics for control. The asphalt mixture designs were verified during field production and test results are shown on Tables 25 through 27. These tables include the aggregate gradations, volumetric properties, and specification requirements.

Table 25. Aggregate Gradations for Mix Design 1

Sieve Size	Mix Design	Production Average	Production Standard Deviation	Lower Spec Limit	Upper Spec Limit
3/4 inch	100	100	0.0	100	100
1/2 inch	90	91	1.4	84	96
3/8 inch	73	75	1.7	67	79
No. 4	48	47	1.2	42	54
No. 8	32	31	0.7	26	38
No. 16	21	21	0.5	16	26
No. 30	15	16	0.5	11	19
No. 50	10	11	0.5	6	14
No. 100	7	8	0.5	4	10
No. 200	5.2	5.8	0.3	3.2	7.2

Table 26. Aggregate Gradation for Mix Design 2

Sieve Size	Mix Design	Production Average	Production Standard Deviation	Lower Spec Limit	Upper Spec Limit
3/4 inch	100	100	0.0	100	100
1/2 inch	85	87	2.1	79	91
3/8 inch	70	72	1.0	64	76
No. 4	45	45	1.0	39	51
No. 8	31	31	1.0	25	37
No. 16	20	21	0.5	15	25
No. 30	14	16	0.5	10	18
No. 50	9	11	0.5	5	13
No. 100	7	8	0.5	4	10
No. 200	5.0	5.3	0.3	3.0	7.0

Table 27. Mixture Volumetric Test Results

	Binder (%)	Va	VMA	VFA	Gmb Lab	Gmb In-place	Gmm	Gsb	In-place Density % of TMD
Job Mix Formula (Mix 1)	5.6	4.0	16.6	76	2.453	---	2.568	2.784	---
Specifications (Mix 1)	5.2 to 6.0	4.0	13.0 minimum	65-78	---	---	---	---	92.0 min
Test Strip (Mix 1)	5.5	---	---	---	2.459	---	---	---	95.8
Control Section (Mix 1)	5.4	---	---	---	2.455	---	---	---	95.6
Job Mix Formula (Mix 2)	5.5	3.7	15.1	76	2.409	---	2.509	2.703	---
Specifications (Mix 2)	5.1 to 5.9	---	13.0 minimum	65-78	---	---	---	---	96.0 min
Test Section (Mix 1)	5.3	---	---	---	2.456	---	2.585	---	95.0
Test Section (Mix 2)	5.2	---	---	---	2.412	---	2.521	---	95.7

5.10.4 Density Measurement and Specifications

The agency used a PWL specification with a lower specification limit of 92.0 percent and an upper specification limit of 100.0 percent of the theoretical maximum density. Essentially, there was not an upper specification limit. Percent density was determined by comparing the in-place density measured by cores to the theoretical maximum density for acceptance. Field density was measured using a nuclear density gauge for quality control. The specification had incentives and disincentives. The statewide historical results had averaged 95.1 percent.

The specification requirements for the control section were set at a minimum of 92.0 percent for the mat and a minimum of 91.0 percent for the joint. The specification requirements for the test section were set at a minimum of 96.0 percent for the mat and a minimum of 94.0 percent for the joints. No joint density results were provided. The density results for the mat are shown in Table 27.

5.10.5 Control and Test Section Construction and Results

This was a night paving project. Two asphalt plants provided the mix for the project. Each plant had its own asphalt mixture design. The haul distance was typically 30 to 45 minutes. The last night of paving (September 19) required a longer haul distance, resulting in more temperature segregation.

A Roadtec MTV was used to transfer the asphalt mixture from the truck to the asphalt paver for the test section but the MTV was not used for the control section. A CAT 1055 model F paver was equipped with a MOBA Pave-IR scanner to monitor temperature segregation. Two Dynapac

CC72 rollers, equipped with intelligent compaction technology, were used for breakdown and intermediate rolling. Both sections received nine vibratory passes from the breakdown and intermediate rollers for a total of 18 passes. The MOBA Pave-IR System and intelligent compaction were used for the test section but not for the control section. The finish roller was a CAT CB 64. A rolling density meter was used to measure the density during the last two nights of paving for the test section.

The contractor's plan was to compact the control section using normal compaction procedures. The plan for the test section was to use an MTV, intelligent compaction technology, a rolling density meter, and WMA technology. The average compaction in the control section was 95.6 percent, which exceeded the minimum specified density requirements. The density results for the test section averaged 95.0 percent for the first mixture and 95.7 percent for the second mixture. While these density results are slightly lower than the 96 percent target, they are very close to the desired results. Further, there was no significant difference in the density of the control section and the test section. The method of rolling these two sections was very similar, so it was not surprising that there was no significant difference between the results.

Very good density was achieved for all paving performed on this project. It was concluded that the technology utilized in the test section did not result in increased mean densities. This was likely due to the contractor using very good compaction equipment and providing a good roller pattern on a relatively narrow mat. The 75 gyration mix was relatively easy to compact for the site conditions and equipment present, and the use of Evotherm WMA additive likely resulted in a mix that was compactable well below the recommended compaction temperature of 305 to 315^{o}F, resulting in little impact from mat temperature differentials. Further, the density was very good in both sections so it is likely that the maximum achievable density was reached or nearly reached in both sections.

5.10.6 Utilization of New Technologies

Several new technologies were investigated in this project, including intelligent compaction, the MOBA Pave-IR System, WMA, and a rolling density meter.

The agency's goal was to identify cold spots in the mat behind the paver and record their locations. in order to perform a density profile after compaction. The agency specifications for this project required the contractor to apply infrared heat to low density areas in the mat and re-compact until the minimum acceptable density was obtained. Due to insufficient telecommunications between local cellular service providers and the MOBA Pave-IR System, the agency was unable to process data in real time and the locations of cold spots were not available until the following night. Since the roadway had been re-opened to traffic, it was not possible to perform density profiling at these cold spots. Upgrades to the Pave-IR communications module are expected to allow real-time location of cold spots when paving resumes in the spring of 2017.

An example of the use of the new technology is shown in Figure 11. The top portion of the figure shows an aerial view of the highway with two lanes in each direction separated by a median. The middle portion shows the MOBA Pave-IR scan data. The red is the hottest temperature and the blue is the coolest temperature. The bottom portion shows the RDM data. The red represents the lowest density and the blue represents the highest density.

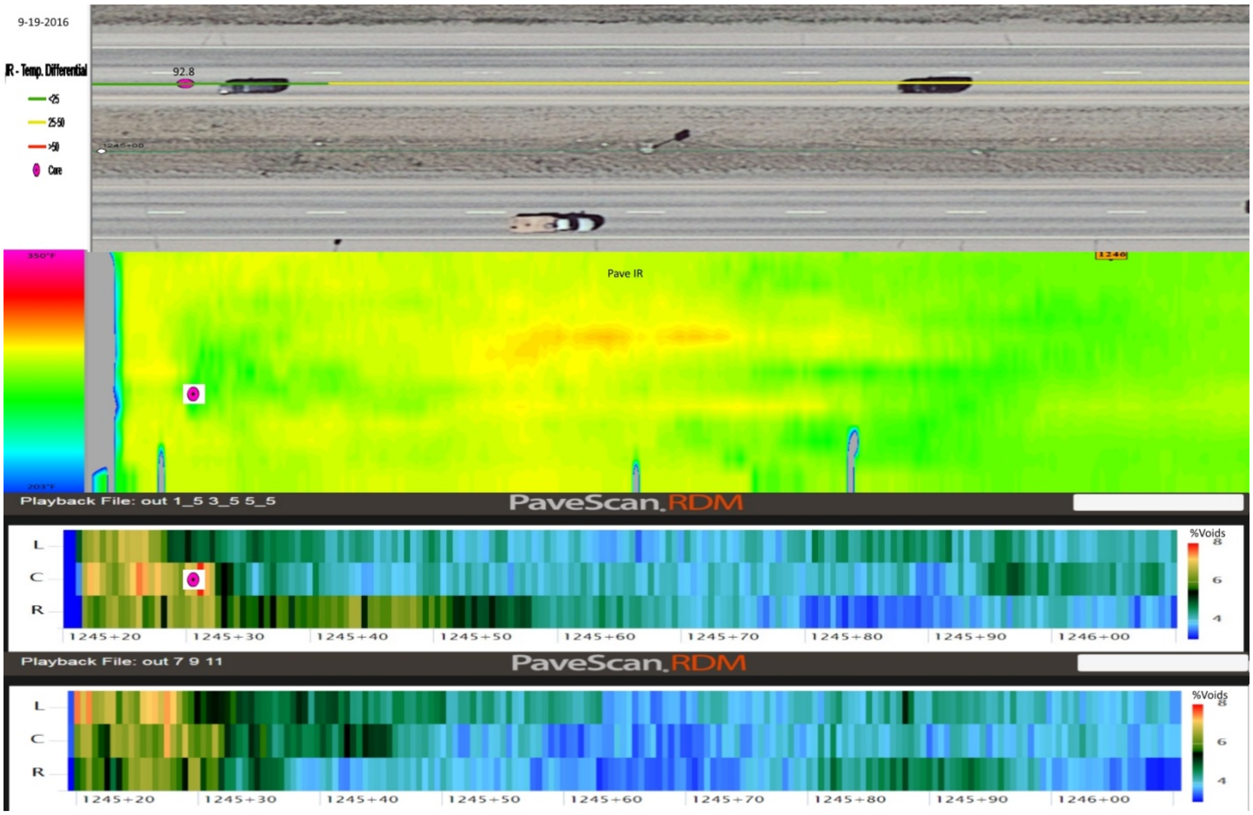

Figure 11. Schematic of Highway (Top Third), Pave IR Plot (Middle Third), and RDM (Bottom Third)

The lowest density, 92.8 percent from drilled cores, was at Station 1245+30 as located by the pink circle. That location was identified by the MOBA Pave-IR scan during an 1100 feet calibration scan at the start of paving on September 19, 2016. The Pave-IR scan at this same location shows a cold spot. A Pave-IR scan was performed in calibration mode and selected 15 points for coring to establish the best correlation between dielectric value and core void content. Once the core data was entered, the percent density was displayed instead of dielectric value. The agency was only able to drill two of the 15 core locations, so they selected the highest and lowest locations.

5.10.7 Summary of State Findings

For State 10, very good density was achieved for all paving performed on this project. It was concluded that the technology utilized in the test section did not result in increased mean densities. This was likely due to the contractor using very good compaction equipment and a good roller pattern in the control section, and it was difficult to improve on this for the test section. Below is a summary of observations from this particular demonstration project that fits with the common themes from the ten demonstration projects.

- Observations for field operations (contractors)
  - There were a total of 18 vibratory passes from the breakdown and intermediate rollers.
  - Two plants were used for paving the project, as one of them broke down.
- Observations for specification development (agencies)
  - The field acceptance specification was PWL with a lower specification limit of 92.0 percent.
  - Incentives and disincentives were applied.
- Observations from new technologies (both agencies and contractors)
  - The MOBA Pave IR scanner, intelligent compaction, and rolling density meter have the potential to be valuable quality control tools.

6 OBSERVATIONS

Density can be improved through focused efforts on field compaction. Eight of ten states improved densities by at least one percent on their demonstration projects. One of the states that did not improve the density did improve the consistency or standard deviation. There was enough improvement in the standard deviation to effectively raise the lower specification limit by one percent. In the other state that did not see an improvement in density, there was not much compactive effort for the control section and very little additional compaction effort for the test section. Based on the observations from these ten demonstration projects, techniques were identified to improve density that will be of interest to agencies and contractors. They will be presented here in no particular order.

6.1 Overview

There were at least two pavement sections constructed within each of the 10 states that participated in this demonstration project to enhance durability through increased density. Many of the states constructed more than two pavement sections. A total of 38 sections were constructed. There were many variables including mixture types, construction equipment, and procedures between states and within states, making it very difficult to compare the density results between various pavement sections. The number of variables that were intentionally changed within a state was much less than the number of changes between states. This was expected, as it was a demonstration project and not a formal experiment. As a demonstration project, each state (the contractor and agency) was empowered to focus on changes to improve density that they thought would be most beneficial for their situation. So, it was much easier to compare the changes made within a state to show the effect of these changes on performance.

A summary of the asphalt mixture data along with in-place density is provided in Table 28. The observed effect of each of these variables is provided in the following paragraphs. Note: 9.5-mm mixtures below 47 percent passing the 2.36-mm sieve were coarse-graded and 12.5-mm mixtures below 39 percent passing 2.36-mm sieve were coarse-graded. The primary control sieve and control point as defined in AASHTO M 323 were used to make this determination.

Table 28. Summary of Mixture Properties on In-Place Density

State – Section Number	NMAS (mm)	Fine-graded or Coarse-graded	Thick to NMAS	Num of gyr	Mix Design AC (%)	Mix Design Air Voids (%)	Prod Air Voids (%)	Mix Design VMA (%)	Prod VMA (%)	Density (% of TMD)
1-C	12.5	Fine	4.0	100	5.0	4.0	3.7	14.1	13.7	93.5
1-TS1	12.5	Fine	4.0	100	5.0	4.0	3.3	14.1	13.3	93.2
1-TS2	12.5	Fine	4.0	100	5.0	4.0	3.3	14.1	13.4	95.4
2-C	12.5	Coarse	4.0	100	5.0	4.1	4.3	15.9	15.1	91.0
2-TS1	12.5	Coarse	4.0	100	5.0	4.1	4.3	15.9	15.1	91.8
3A-C	12.5	---	3.0	90	5.2	---	---	---	---	92.9
3A-TS1	12.5	---	3.0	90	5.2	---	---	---	---	92.9
3A-TS2	12.5	---	3.0	60	5.5	---	---	---	---	93.5
3A-TS3	12.5	---	3.0	60	5.5	---	---	---	---	94.1
3B-C	12.5	---	3.0	60	---	---	---	---	---	93.7
3B-TS1	12.5	---	3.0	60	---	---	---	---	---	94.9
3B-TS2	9.5	---	4.0	60	---	---	---	---	---	93.6
3B-TS3	9.5	---	4.0	60	---	---	---	---	---	94.2
3B-TS4	9.5	---	4.0	60	---	---	---	---	---	93.7
3B-TS5	12.5	---	3.0	60	---	---	---	---	---	93.8
4-C	12.5	Fine	3.5	75	5.5	4.0	4.6	15.8	15.9	93.5
4-TS1	12.5	Fine	3.5	75	5.5	4.0	4.4	15.8	15.7	95.0
4-TS2	12.5	Fine	3.5	75	5.8	3.0	3.4	15.8	15.3	94.6
4-TS3	12.5	Fine	3.5	75	5.8	3.0	2.6	15.8	14.7	95.4
4-TS4	12.5	Fine	3.5	75	5.5	4.0	4.4	15.8	16.0	92.5
4-TS5	12.5	Fine	3.5	75	5.8	3.0	3.8	15.8	15.6	93.4
4-TS6	12.5	Fine	3.5	75	5.5	4.0	3.2	15.8	15.5	94.0
4-TS7	9.5	Fine	4.7	75	5.7	4.0	3.8	15.7	16.0	95.2
5-C1	12.5	Fine	4.0	50	5.3	4.0	3.6	14.8	14.4	92.5
5-TS1	12.5	Fine	4.0	50	5.3	4.0	3.6	14.8	14.4	93.2
5-TS2	12.5	Fine	4.0	50	5.6	3.0	2.8	14.7	15.0	95.2
6-C	9.5	Coarse	4.0	100	6.7	4.0	4.7	15.2	15.3	93.3
6-TS1	9.5	Coarse	4.0	50	6.8	5.0	5.6	16.5	16.5	95.4
7-C1	9.5	Coarse	4.0	75	6.2	3.5	3.4	16.2	16.5	94.4
7-TS1	9.5	Coarse	4.0	75	6.2	3.5	3.4	16.2	16.5	96.1
8-C1	12.5	Coarse	3.6	100	5.7	5.5	3.5	16.4	14.6	93.1
8-T1	12.5	Coarse	3.6	100	5.7	5.5	3.5	16.4	14.6	93.0
9-C	12.5	Coarse	4.0	50	5.6	3.1	3.6	15.6	15.8	92.2
9-TS1	12.5	Coarse	4.0	50	5.6	3.1	2.7	15.6	15.3	92.0
9-TS2	12.5	Coarse	4.0	50	5.6	3.1	3.4	15.6	16.0	92.0
10-C	19.0	Fine	2.7	75	5.6	4.0	---	16.6	---	95.6
10-TS1	19.0	Coarse	2.7	75	5.6	4.0	---	16.6	---	95.0
10-TS2	19.0	Coarse	2.7	75	5.5	3.7	---	15.1	---	95.7

6.2 Gradation Type

As discussed previously, density relates to permeability. Permeability is also impacted by the type of gradation (coarse vs. fine) and the NMAS. A one 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.

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

For the most part, the test sections within each state did not attempt to evaluate the effect of changing the aggregate gradation. One reason for this may be that it is very difficult to quantify a change in gradation. A few states did make some changes in the mixture but it was not possible to determine the effect of changes in gradation on the measured density.

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

6.3 Nominal Maximum Aggregate Size

The breakdown of the NMAS used by each state is shown below.

- Four states used 9.5-mm NMAS (States 3, 4, 6 and 7),
- Seven states used 12.5-mm NMAS (States 1, 2, 3, 4, 5, 8 and 9), and
- One state used 19-mm NMAS (State 10).

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

- One of ten states < 3.0 (State 10),
- Nine of ten states ≥ 3.0 (States 1, 2, 3, 4, 5, 6, 7, 8 and 9), and
- Eight of ten states ≥ 4.0 (States 1, 2, 3, 4, 5, 6, 7 and 9).

States 3 and 4 both evaluated the effect of two different NMASs with the same lift thickness. Each state produced at least one section with a 12.5-mm mixture and at least one section with 9.5-mm mixture. State 3 showed that a 94.1 percent average density was obtained with 12.5-mm mixture and 93.8 average density was obtained with 9.5-mm mixtures. These density results were not significantly different. State 4 showed 94.1 percent average density for the 12.5-mm mixture and 95.2 percent density for the 9.5-mm mixture. This difference of 1.1 percent density is probably significant. The purpose of changing the NMAS was to examine the effect of the t/NMAS.

6.4 Asphalt Mixture Design

Superpave requirements for asphalt mixture design are defined in AASHTO standards. There are several factors in an asphalt mixture that might affect the compacted density. The two biggest factors are likely gyration level during laboratory compaction and the level of air voids used for selecting the optimum asphalt content. Engineering adjustments to these standards can be made, but it is recommended to follow the guidelines in the FHWA Tech Brief (2010). If the gyration level is reduced, the amount of asphalt needed to fill the voids to the desired level is increased for the same gradation. Hence, if the only variable is the gyration level, an increase in the gyration level will result in lower optimum asphalt content.

Some states obtain higher density by adding additional asphalt binder to the mix and others obtain higher density by increasing compaction with rollers. These two approaches of reducing the in-place air voids don't have the same effect on performance. It is important that a satisfactory mix be designed and produced to ensure good performance and that this mix be compacted to the adequate density in the field. As a word of caution, adding additional asphalt solely for compaction changes the mixture properties, and this adjusted mix should only be used if laboratory test results have shown that this adjusted mix is satisfactory.

Four of ten states made engineering adjustments to the AASHTO Superpave mix design to obtain higher optimum AC: States 3, 4, 5 and 6. These states had an increase of 0.1 to 0.3 percent asphalt. Engineering adjustments to obtain a slightly higher optimum asphalt content included adjusting gyrations (States 3 and 6) and air void regression (States 4 and 5).

The gyration level for State 3 was varied and in this case the increase in density was 1.2 percent. State 6 reduced the gyration level from 100 to 50 and the in-place density increased by approximately 2.1 percent. State 6 simultaneously decreased the air void content at design from 4 to 3 percent and increased the VMA requirement from 15 to 16 percent. Hence, as expected, States 3 and 6 showed that lower gyrations during laboratory compaction ultimately resulted in a higher in-place density (lower air voids).

Another factor in mix design that has an effect on density is the design air void level. A pavement section designed with lower design air voids will be easier to compact than one with higher design air voids for the same gradation. Two states that looked at varying the laboratory air voids without significantly changing other mixture properties or compaction procedures were States 4 and 5. The results from State 5 showed that lowering the design air voids from 4.0 to 3.0 percent resulted in an approximate 2.5 percent increase in in-place density. The results from State 4 showed that lowering the design air voids from 4.0 to 3.0 percent without changing the gradation resulted in an approximate 1.9 percent increase in in-place density.

When the starting point for the optimum asphalt content is determined from the AASHTO Superpave standards, then engineering adjustments to the asphalt mixture design to add up to 0.3 percent asphalt content are appropriate. For those agencies starting with higher optimum asphalt contents than would be provided from the AASHTO Superpave standards, then it is recommended to conduct performance testing on the asphalt mixture, including rutting, cracking and moisture damage testing. If an agency does make engineering adjustments to increase the optimum asphalt content, then the agency should also adjust the percent density requirement.

6.5 Field-Produced Mixture Properties

The asphalt mixture design properties will 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 will make the mixture properties different than that shown in the design. These laboratory properties of the asphalt mixture during production should correlate better with in-place density than the design properties. The asphalt mixture design was adequately verified by each of the states and adjustments were made as needed to ensure the production gradations and mixture volumetrics met the specification requirements.

6.6 Placement and Compaction

The placement and compaction data along with in-place density results are provided in Table 29.

MTVs have been shown to provide improved smoothness and reduced segregation and were used on eight of the ten projects. A summary of the states that used MTVs on at least one of the sections were: States 1, 4, 5, 6, 7, 8, 9, and 10.

Table 29. Summary of Effect of Placement, Compaction, and New Technologies on In-Place Density

State – Section Num.	MTV	Compaction Rollers	Passes (Total)	New Tech.	Density (% of TMD)
1-C	Yes	2 steel wheel	9 static passes each in echelon (18)	None	93.5
1-TS1	Yes	2 steel wheel	2 vibratory and 7 static each in echelon (18)	None	93.2
1-TS2	Yes	2 steel wheel, 1 pneum.	9 vibratory each in echelon and 9 pneum. (27)	None	95.4
2-C	No	1 steel wheel	7 vibratory passes (7)	None	91.0
2-TS1	No	1 steel wheel	9 vibratory passes (9)	None	91.8
3A-C	No	2 steel wheel, 2 pneum.	5 vibratory passes in echelon, 7 pneum. passes in echelon (24)	MOBA Pave-IR, IC, rolling density meter	94.0
3A-TS1	No	3 steel wheel, 2 pneum.	5 vibratory passes in echelon, 7 pneum. passes in echelon, plus 5 vibratory passes (29)	MOBA Pave-IR, IC, rolling density meter	93.7
3A-TS2	No	2 steel wheel, 2 pneum.	5 vibratory passes in echelon, 7 pneum. passes in echelon (24)	MOBA Pave-IR, IC, rolling density meter	93.5
3A-TS3	No	3 steel wheel, 2 pneum.	5 vibratory passes in echelon, 7 pneum. passes in echelon, plus 5 vibratory passes (29)	MOBA Pave-IR, IC, rolling density meter	94.2
3B-C	No	3 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter	93.7
3B-TS1	No	4 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter	94.9
3B-TS2	No	3 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter	93.6
3B-TS3	No	4 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter	94.2
3B-TS4	No	3 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter, use of WMA	93.7
3B-TS5	No	3 rollers	Not clear which rollers used	MOBA Pave-IR, IC, rolling density meter, use of WMA	93.8
4-C	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	None	93.5
4-TS1	Yes	3 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes, 5 vibratory passes (26)	None	95.0
4-TS2	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	None	94.6
4-TS3	Yes	3 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes, plus 5 vibratory passes (26)	None	95.4
4-TS4	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	Use of WMA	92.5
4-TS5	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	Use of WMA	93.4

4-TS6	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	Use of WMA	94.0
4-TS7	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 11 pneum. passes (21)	None	95.2
5-C1	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 5 pneum. passes (15)	None	92.5
5-TS1	Yes	2 steel wheel	5 oscillatory passes in echelon (10)	None	93.2
5-TS2	Yes	2 steel wheel, 1 pneum.	5 vibratory passes in echelon, 5 pneum. passes (15)	None	95.2
6-C	Yes	2 steel wheel	5 vibratory passes and 2 static passes in echelon (14)	Longitudinal joint adhesive	93.3
6-TS1	Yes	2 steel wheel	5 vibratory passes and 2 static passes in echelon (14)	Longitudinal joint adhesive	95.4
7-C1	Yes	3 steel wheel	4 vibratory passes and 1 static pass in echelon (15)	WMA	94.4
7-TS1	Yes	3 steel wheel	4 vibratory passes and 1 static pass in echelon (15)	WMA	96.1
8-C1	Yes	1 steel wheel, 1 pneum.	8 vibratory and 1 static pass, 15 pneum. passes (24)	None	93.1
8-T1	Yes	1 steel wheel, 1 pneum. w/increased wt.	8 vibratory and 1 static pass, 15 pneum. passes (24)	None	93.0
9-C	Yes, but not effective due to mechanical problems	2 steel wheel	3 vibratory passes and 6 static, 7 static passes (16)	WMA, MOBA Pave-IR, IC	92.2
9-TS1	Yes, but not effective due to mechanical problems	2 steel wheel	5 vibratory and 2 static pass, 2 oscillatory and 1 static pass (10)	WMA, MOBA Pave-IR, IC	92.0
9-TS2	Yes, but not effective due to mechanical problems	2 steel wheel	5 vibratory passes, 2 oscillatory and 3 static pass (10)	WMA, MOBA Pave-IR, IC	92.0
10-C	No	2 steel wheel	9 vibratory passes, 9 vibratory passes (18)	None	95.6
10-TS1	Yes	2 steel wheel	9 vibratory passes, 9 vibratory passes (18)	MOBA Pave-IR, IC, rolling density meter	95.0
10-TS2	Yes	2 steel wheel	9 vibratory passes, 9 vibratory passes (18)	MOBA Pave-IR, IC, rolling density meter	95.7

The number of compaction rollers varied from as few as one roller on one of the demonstration projects (State 2) and up to five compaction rollers on another demonstration project (State 3). This is a tremendous difference in compaction effort. A summary of some key observations included:

- A summary of the total number of passes on the test section were:
  - Two of ten states used < 10 passes (States 2 and 9),
  - Four of ten states used 10 to 20 passes (States 5, 6, 7 and 10), and
  - Four of ten states used > 20 passes (States 1, 3, 4 and 8).

- When vibratory or oscillatory rollers were used, generally all of the passes used the vibratory or oscillatory mode. In some cases there may have been a final one of two passes that were static. However, one state did not use the vibratory mode as much.
  - Two of ten states used the vibratory mode of the roller on only two or less of 10 passes in the control section (States 1 and 9).
- A summary of states where rollers were used in echelon included:
  - Six of ten states used breakdown rollers echelon (States 1, 3, 4, 5, 6, and 7), and
  - One of ten states used intermediate pneumatic rollers in echelon (State 3).
- A summary of states which used pneumatic rollers included:
  - Five of ten states used pneumatic rollers (States 1, 3, 4, 5, and 8).

  It should be noted that none of these particular projects that used pneumatic rollers used polymer modified asphalt.

States 2, 8, and 9 clearly had the lowest density values compared to the other states. State 2 used one roller for compaction but was still able to make an improvement in density by using just two more passes. State 8 used two rollers for compaction. State 8 focused on consistency and lowered the standard deviation sufficiently to effectively raise the lower specification limit by 1.0 percent. Finally, State 9 used one vibratory roller and one oscillating roller but with very few passes. State 9 was the only state not able to make an improvement in density in their test section. In fact, they used fewer passes in their test section than the control section. As expected, this showed that the amount of rolling significantly affected the density.

An additional roller was helpful in increasing density. Three of ten states used an additional roller: States 1, 3, and 4. These states were all successful at obtaining higher density. State 1 obtained higher density with the addition of a pneumatic roller. Additional density could not be achieved with only the use of the steel-wheeled rollers.

State 4 conducted a cost-benefit analysis for using an additional roller. A summary is shown in Table 30. An estimate of the improved benefit from a life-cycle cost analysis is 10 percent, conservatively. For an asphalt mixture that costs $60 per ton, a 10 percent improvement was the equivalent of “six dollar signs” as shown in Table 30. State 4 evaluated the costs (one “$” is relative to the $60 per ton mixture) of the other factors to increase density as part of the demonstration project. These factors are also shown in the table. State 4 believes these adjustments were cost effective.

Table 30. State 4 Cost-Benefit Analysis of Adjustments to Increase In-place Density

<table>
<tr><th>Item</th><th>Benefit</th><th>Cost</th><th>Increase in Percent Density</th></tr>
<tr><td>LCCA performance</td><td>$$$$$$</td><td></td><td></td></tr>
<tr><td>Additional roller</td><td></td><td>≤ $</td><td rowspan="2">+ 1.9</td></tr>
<tr><td>Engineered mix design adjustment</td><td></td><td>≤ $$</td></tr>
<tr><td>WMA additive</td><td></td><td>≤ $</td><td>----</td></tr>
<tr><td>Smaller NMAS</td><td></td><td>≈ $$</td><td>+ 1.7</td></tr>
</table>

It should be noted that there are many best practices to achieve higher density other than adding a roller, which could include: roller settings, vibration vs. speed, mat temperature, vibrating screed, paver speed, etc. These best practices may even be less costly than an additional roller. Many of these were outside the scope of each of the SHA's demonstration project.

During placement and compaction, there were a surprising number of issues with equipment operation. Five of the ten states had equipment-related issues (States 1, 4, 8, 9 and 10). In each of these demonstrations, the equipment issue was an impediment to achieving higher density. An agency may need to require a QC plan to make sure compaction equipment is working properly prior to paving.

6.7 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. Some of the demonstration projects included application of a sealant. The sealant was applied as a thin strip of asphalt sealant 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 done to determine the effectiveness, but this is something that has been done in the past to improve joint performance. Joint heaters were used on some of the demonstration projects. The effectiveness of any of these efforts on the longitudinal joint was not evaluated as part of this study.

6.8 Measuring and Reporting Density

Some states specified and controlled density using a method other than percent of TMD. For Tables 28 and 29, the density is reported for all states as percent of TMD. Two of the ten states that used a method other than TMD included: States 2 and 9.

The primary property that is important during compaction is the percent air voids in the in-place mixture. Reporting density as percent of TMD 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.

6.9 Field Acceptance Specification

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

- The contractors' job is to be the low bidder and meet the specifications. Simply by asking for higher density, two of ten states (States 1 and 2) achieved higher density. Although this would not work in all of the states, some states could simply raise the minimum density requirements and the contractors could easily make adjustments to their compaction methods to meet specifications.
- An advantage of a PWL specification over the minimum lot average specification is that the consistency, as measured by the standard deviation, is included as part of the

specification. The consistency in an important factor. Two of ten states (States 7 and 8) demonstrated improvements in the standard deviation, and showed that standard deviations below 1.00 were possible.

- Incentives can be a valuable part of the specification to gain improvements in density. Seven of ten states (States 1, 3, 5, 6, 7, 8 and 10) used incentives. Several states noted the importance of the incentive to the success of their improvements in density.
- Only four of ten states (States 1, 5, 7 and 9) had a maximum or upper specification limit on density.

6.10 New Technologies

Several states evaluated new technologies to help ensure good compaction. The technologies used included warm-mix asphalt, MOBA Pave-IR System, rolling density meter and intelligent compaction. The number of states using each of the technologies was:

- WMA was used by six of the ten states (States 3, 4, 5, 7, 9 and 10),
- MOBA Pave-IR System was used by three of the ten states (States 3, 9 and 10),
- IC was used by three of the ten states (States 3, 9 and 10) and
- RDM was used by two of the ten states (States 3 and 10).

All of these new technologies showed some promise. However, although these new technologies were used and data was collected, very little analysis of data was made in most cases, particularly in real time. Most of these technologies have the potential to improve the quality of large projects but were not very effective when used in small sections as used on this project. These technologies generally provided information that would have been useful in making adjustments as work progresses so would be most useful for larger projects. The application of these new technologies was evaluated but they had little benefit in placement and compaction of these small sections.

A potential benefit of some of these new technologies is that there will be more test results and better quantification of in-place materials. There can be challenges with the new technologies, such as issues getting real-time data in order to make project adjustments. Also, the use of some of the results for acceptance purposes has not been fully demonstrated to be accurate. Although these new technologies may be a good quality control tool, care should be exercised for acceptance.

7 SUMMARY OF OBSERVATIONS

The demonstration projects show that density can be improved. Eight of the ten states improved densities by at least one percent on their demonstration projects. A summary of the methods used to obtain increased density seemed to fall into one of the following five categories.

1. Improving the agency's specification by including or increasing incentives and examining the minimum percent density requirements. There was a significant difference in the number of rollers used for compaction between states. Some states used as little as one

compaction roller while others used as many as four or five compaction rollers. The number of passes for each roller used varied considerably among states. There is a strong association between the rolling effort and the agency's requirements. Some states were able to obtain high density in the range of 95.0 to 96.0 percent of TMD while other states only obtained density in the range of 90 to 91 percent. As expected, using fewer rollers and fewer vibratory passes generally resulted in lower in-place density, and using more rollers resulted in higher in-place density.

2. Making engineering adjustments to the asphalt mixture design to obtain slightly higher optimum asphalt content was successful at achieving higher in-place densities. Also, reducing the number of gyrations during mix design resulted in increased density in the field. Some states obtain higher density by increasing the optimum asphalt binder content with engineering adjustments. It is important that a satisfactory mix be designed and produced to ensure good performance and that this mix be compacted to adequate density in the field. As a word of caution, adding additional asphalt solely for compaction changes the mixture properties and this adjusted mix should only be used if laboratory test results have shown that this adjusted mix is satisfactory.

3. Consistency is one of the most important factors in improving in-place density. Consistency can be generally defined as consistency in temperatures, paver speeds, roller patterns, and all of the other factors that impact density and standard deviation of density measurements. Improving consistency as measured by the standard deviation was accomplished by two of the states. Information from states 7 and 8 demonstrated that a standard deviation below 1.00 was possible and could be achieved routinely.

4. Following best practices is important. There was a lot of attention on the construction of the control and test sections. Since this was part of an experiment, there was more attention to best practices than there would normally have been. In many states, the results in the control section were greater than that of the statewide average results that would normally be expected. When examining the improvement in density from the control to the test section, the increases could have been even greater. Improvement in density reported from each of the demonstration projects was likely even better than documented in this report.

   Many of the pavement sections constructed in this project were very small and some states reduced the speed of the paver and rollers due to the lower production rate. This slower rate of placement likely aided good compaction for these states. Hence, it is likely that the in-place density may decrease for some when full scale production occurs.

   Finally, it should be noted that there are many best practices other than those used for these demonstration projects. Although the states tried many things, there were likely many other best practices that could have made a difference. Best practices other than adding another roller could include: roller settings, vibration vs. speed, mat temperature, vibrating screed, paver speed, etc. These best practices may even be less costly than using an additional roller.

5. Using new technologies was helpful. These technologies used included warm-mix asphalt, MOBA Pave-IR System, rolling density meter and intelligent compaction. All of these new technologies showed some promise.

Not all of these methods may work for every state. However, the list can serve as a toolbox or checklist of considerations to identify areas for improvement.

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