TechBrief

The Asphalt Pavement Technology Program is an integrated national effort to improve the long-term performance and cost effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry and academia, the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement suggestions, methods, procedures and other tools for use in asphalt pavement materials selection, mixture design, testing, construction and quality control.

U.S. Department of Transportation
Federal Highway Administration

Office of Preconstruction, Construction, and Pavements

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# Techniques and Tools for Improving Density

*This Technical Brief summarizes contractor and agency changes made leading to increased density on projects associated with the FHWA Enhancing Durability of Asphalt Pavements Through Increased In-Place Density Demonstration Project.*



## Introduction

This is the second of four Technical Briefs on ***Enhancing Durability of Asphalt Pavements Through Increased In-Place Density*** associated with the Federal Highway Administration (FHWA) Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) program. The AID-PT program advances practices and technologies for constructing and maintaining high-quality, long-lasting pavements in accordance with six goals established by Congress (1). The overall objective of the demonstration project was to show that additional density could be obtained through improved techniques. This set of Tech Briefs focuses on the importance of mat and joint density, techniques and tools that have been demonstrated to help improve density, examples of specifications, and overcoming obstacles to achieving density. The information used to develop them was obtained through the literature, a series of workshops and support of 29 field demonstration projects performed by State Departments of Transportation (DOTs). This is the second in a series of four planned Technical Briefs meant to complement each other that are organized as follows:

1. Density Demonstration Projects and Related Specifications
2. Techniques and Tools for Improving Density
3. Overcoming Obstacles to Achieving Density
4. Improving Longitudinal Joint Performance

Although several factors can influence the performance of an asphalt pavement, one of the most important factors is in-place density (2). A small in-place density increase can potentially lead to a significant increase in the service life of asphalt pavements. Based on studies reviewed in a literature search, a 1 percent increase in density (percent of $G_{mm}$) was estimated to improve the fatigue performance of asphalt pavements between 8 and 44 percent and improve rutting resistance by 7 to 66 percent (3, 4). In addition, based on field data, a 1 percent increase in density would conservatively extend the asphalt pavement service life by 10 percent.

Recognizing the importance of in-place density in building cost effective asphalt pavements, FHWA initiated the Demonstration Project for "Enhanced Durability of Asphalt Pavements through Increased In-place Pavement Density" (4, 5, 6, 7). The objective of this demonstration project was to support DOTs in their evaluation of their current density requirements for acceptance. Twenty-six DOTs participated with 121 experimental sections constructed, comprised of 35 control sections and 86 test sections.

There were many variables including mixture type, construction equipment, and procedures between States and within States, making it challenging 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 the State thought would be most beneficial for the situation. So, it was much easier to compare the changes made within a State to show the effect on performance. This Tech Brief highlights what contractors changed to obtain higher density and what changes agencies made. Additional details on the demonstration projects can be found in References 4 through 9.

## Changes Contractors Made in Demonstration Projects

The changes contractors made to obtain higher density included operational changes and equipment changes that are summarized in the following four categories:

- More Effort: Additional Passes and/or Rollers.
- Roller Type and Position.
- Windrow Elevator versus Material Transfer Vehicle (MTV).
- Conventional Paver versus Spray Paver

### More Effort: Additional Passes and/or Rollers

The summary of passes used by each State on the test section with the highest density follows. A pass is when the roller passes over one point in the mat one time. When observing a rolling pattern, the number of passes recorded might vary depending on where the point is selected on a mat; on these projects, the number of passes was reported as those that a roller made as part of the rolling pattern. One of the States focused on longitudinal joints in which the number of passes were not part of that study, so only 28 demonstration projects are reported.

- Nine of the 28 States used less than 15 passes,
- Nine of the 28 States used 15 to 20 passes, and
- Ten of the 28 States used more than 20 passes.

The number of rollers on the demonstration projects ranged from 1 to 5. The number of passes ranged from 9 to 33. There was a wide range of compactive efforts observed around the country based on the number of rollers and number of passes.

Roller passes were added on 13 of the demonstration projects. Ten did this by adding at least one roller, and three of the States added two rollers. Five States added a double-drum vibratory roller. Other types of rollers added included oscillation, pneumatic, pneumatic in the vibratory mode, and a combination roller. The increase in passes ranged from 2 to 12. The most common increase in passes was 5, with an average of 6. The increase in density on each project ranged from less than zero up to 2.5 percent and averaged 1.2 percent for all the projects as shown in Figure 1. The figure illustrates that in most cases density did increase. It is important to note that in cases where there was no increase, it could have been that the: 1) density was already at or above 94.0 percent; 2) mixture was low in asphalt content and already reached a "refusal" density; or 3) time needed to achieve compaction increased and temperature decreased, so temperature was too low to increase density.

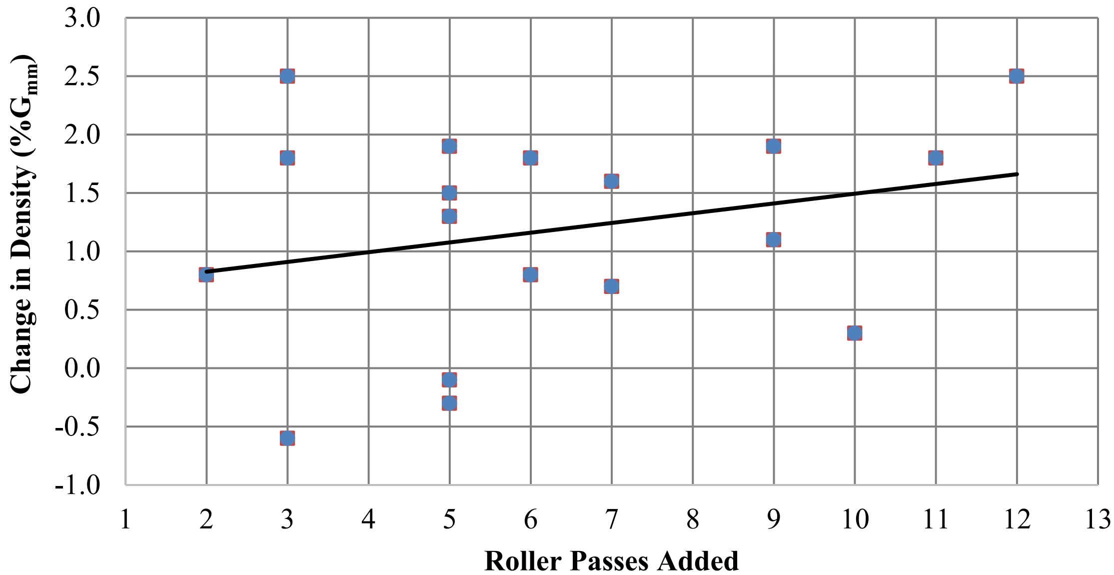


**Figure 1. Change in Density with Added Passes.**

## Roller Type and Position

A summary of the impact roller type and position had on density in presented in Table 1. Ten demonstration projects used breakdown rollers in echelon. Nine of the 10 had densities of at least 94.0 percent and 5 of the 10 had densities of at least 95.0 percent. Two States used a pneumatic roller in the intermediate position in echelon. Using rollers in echelon was highly effective.

Eleven demonstration projects used pneumatic rollers. When a comparison could be made between using and not using a pneumatic roller, the associated density increase was inconsistent. In one case, the density was significantly higher, and in two cases the increase was negligible. Two demonstration projects used vibratory pneumatic rollers, and the associated density increases were 1.8 and 2.5 percent. Vibratory pneumatic rollers had a particular impact on increasing density.

Seven demonstration projects used oscillation. A comparison could often not be made between oscillatory and vibratory rollers. When there was a focus on using the oscillation, there were positive results: fewer passes and greater density.

**Table 1. Influence of Roller Type, Position and Process on Density.**

| Roller Type/Position/Process | Number of Projects | Outcome |
|---|---|---|
| Breakdown in Echelon | 10 | 9 of 10 projects had density ≥ 94%<br>5 of 10 project had density ≥ 95% |
| Pneumatic Intermediate in Echelon | 2 | Highly effective |
| Pneumatic | 11 | Inconsistent |
| Vibratory Pneumatic | 2 | 1.8 to 2.5% density increase |
| Oscillatory | 7 | Comparison to vibratory not possible<br>Fewer passes and greater density |
| Combination | 1 | 2.0% density increase |
| Same in Tighter Rolling Pattern | 2 | Density standard deviation decreased 50% |

One demonstration project used a combination roller, and the associated density increase was just over 2.0 percent in two different test sections. The combination roller thus had a relatively big impact on increasing density.

Two demonstration projects used the same rollers in the control and test sections, and focused on a tighter, more consistent roller pattern. In one case, there was no change in density and in the other case the density achieved was slightly higher, 0.7 percent. In both cases the standard deviation of the density results was improved significantly, reduced by approximately one half. Consistency of the roller pattern can have an impact on consistency of the density results.

### Windrow Elevator versus Material Transfer Vehicle (MTV)

The use of MTVs has been shown to provide improved smoothness and reduced segregation when compared with conventional paving operations. They were used on 19 of the 29 demonstration projects. One demonstration project compared the density obtained when the MTV was used versus the windrow elevator. When using the MTV there was an increase of 2.6 percent density as opposed to using the windrow elevator.

### Conventional Paver versus Spray Paver

One demonstration project compared the density obtained using a conventional paver versus that obtained when using a spray paver. Four experimental sections were constructed with each type of paver. Based upon the comparison, the density was about 0.5 percent higher when placed with the conventional paver in each of the four experimental sections than with the spray paver.

## Changes Agencies Made in Demonstration Projects

The changes agencies made to obtain higher density included three materials/design changes that are summarized in the following categories:

- Thickness to Nominal Maximum Aggregate Size (t/NMAS).
- Mixture Design with Increased Asphalt Content.
- Warm-mix Asphalt (WMA) Technologies.

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

Based upon the literature search, 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 (. There was a noticeable trend regarding the use of asphalt mixtures with smaller NMAS aggregates. Demonstration projects in four States had test sections with 9.5-mm NMAS. The breakdown of NMAS used within the demonstration projects is shown below. Some demonstration projects used multiple NMAS mixtures.

- Eight States used 9.5-mm NMAS.
- Twenty States used 12.5-mm NMAS.
- Six States used 19.0-mm NMAS.

The summary of t/NMAS used on each demonstration project follows. Multiple t/NMAS were used on several demonstration projects.

- Two States with t/NMAS less than 3.0.
- Six States with t/NMAS greater than or equal to 3.0 and less than 4.0.
- Twenty States with t/NMAS greater than or equal to 4.0 and less than 5.0.
- Five States with t/NMAS greater than 5.0.

Four demonstration projects compared the density obtained when the t/NMAS was adjusted as shown in Table 2 and Figure 2.

**Table 2. Impacts of Changing t/NMAS.**

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

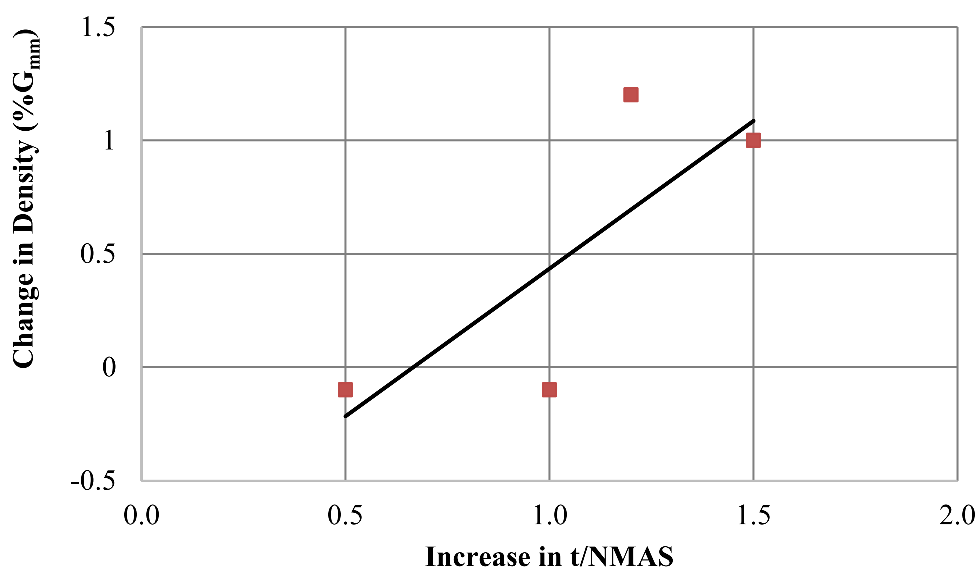


**Figure 2. Change in Density with t/NMAS Increase**

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

## Mixture Design with Increased Asphalt Content

Optimum asphalt content is often obtained per the Superpave methodology found in AASHTO M 332, *Standard Specification for Superpave Volumetric Mix Design* and AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures* (9, 10). Various methods to adjust these procedures to increase optimum asphalt content exist. On 12 different demonstration projects adjustments were made to mixture designs to increase optimum asphalt content, and six used multiple techniques, resulting in 16 different test sections constructed on 12 demonstration projects. A summary of techniques and those used by each demonstration project as part of this study follows.

- Three used engineering judgment to adjust the optimum asphalt content,
- Six selected optimum asphalt content at lower air voids,
- Three selected optimum asphalt content by lower number of gyrations,
- Seven selected optimum asphalt content with the support of performance testing, similar to a balanced mix design approach, and
- One adjusted the optimum asphalt content based on the aged binder in the recycled asphalt pavement (RAP).

Changes in density were measured based on the increased asphalt content on the 12 demonstration projects shown in Table 3 and Figure 3.

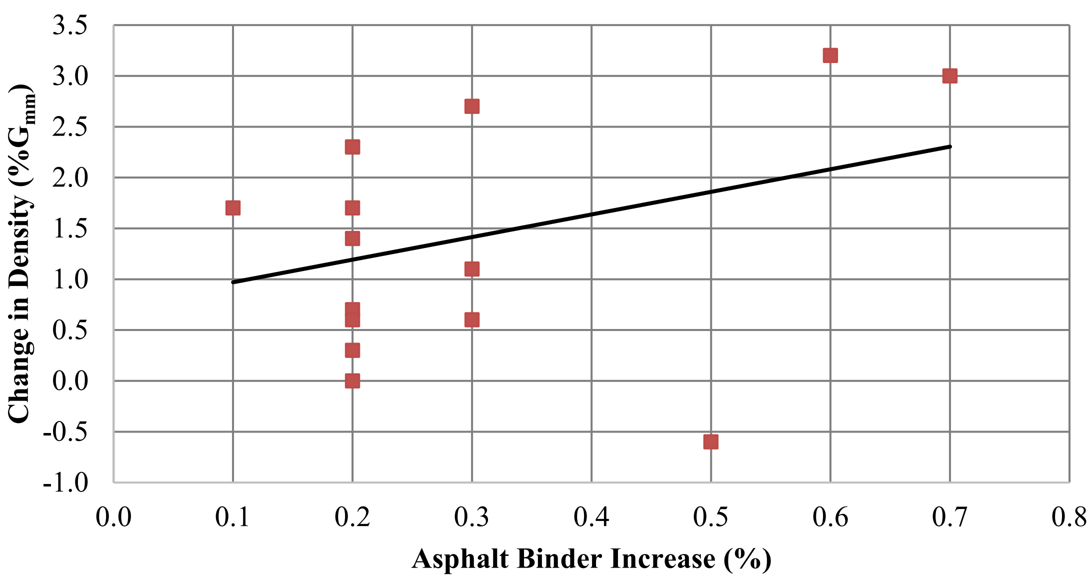


**Figure 3. Change in Density with Increase in Asphalt Binder.**

**Table 3. Impacts of Optimum Asphalt Content.**

| State | Control Section Density (%$G_{mm}$) | Asphalt Added (%) | Test Section Density (%$G_{mm}$) | Change in Density (%$G_{mm}$) |
|---|---|---|---|---|
| P1-S3 | 92.9 | 0.3 | 93.5 | 0.6 |
| P1-S4 | 93.5 | 0.3 | 94.6 | 1.1 |
| P1-S5 | 92.5 | 0.3 | 95.2 | 2.7 |
| P2-S2 | 92.2 | 0.2 | 94.5 | 2.3 |
| | 95.6 | 0.2 | 95.9 | 0.3 |
| P2-S4 | 95.8 | 0.2 | 96.5 | 0.7 |
| | 95.7 | 0.2 | 97.1 | 1.4 |
| P2-S5 | 92.0 | 0.7 | 95.0 | 3 |
| | 92.0 | 0.1 | 93.7 | 1.7 |
| P2-S7 | 92.8 | 0.2 | 94.5 | 1.7 |
| P3-S2 | 92.6 | 0.2 | 94.9 | 2.3 |
| | 92.6 | 0.6 | 95.8 | 3.2 |
| P3-S3 | 91.3 | 0.5 | 90.7 | -0.6 |
| P3-S6 | 94.5 | 0.2 | 95.1 | 0.6 |
| P3-S7 | 91.9 | 0.2 | 91.9 | 0 |
| Average | | 0.29 | | 1.4 |

Generally, these adjustments resulted in an additional 0.2 to 0.3 percent asphalt and an increase in density of 1.4 percent. In two cases, the State adjusted both the design air voids and gyrations, the increase in asphalt was 0.6 percent and 0.7 percent. Changes in density can be summarized as follows:

- Seven of 11 had density increase greater than or equal to 1.0 percent.
- Eight of 11 had density greater than or equal to 94.0 percent.
- Eight of 11 either had density increase greater than or equal to 1.0 percent or density greater than or equal to 94.0 percent.
- In these comparisons, the only change was the optimum asphalt content, and the roller pattern stayed the same.

On one demonstration project, the State reported that the mixture design, performance testing, and density requirement are all related, so a comprehensive change needs to be coordinated between these factors. Changes to the asphalt mixture design in an effort to obtain higher asphalt contents should be coordinated with change with the density specification.

## Warm-mix Asphalt (WMA) Technologies

Five different demonstration projects used WMA technologies. Two used WMA at lower production temperature. Five used WMA at normal production temperatures. A chemical WMA additive was used in each project. Changes in density were examined based on the use of WMA. When a WMA additive was used at a lower temperature and the number of roller passes were held constant, there was no change in density: either higher or lower. When WMA additives were used at normal production temperatures, an increase in density of 3.0 percent (from 92.2 percent to 95.2 percent) was obtained by one State. On another project at normal production temperatures, there were 2 fewer passes per roller to achieve the same density. Although no change in density was observed in the other three States, the densities in the control section were already at or above 94.0 percent.

# Specification Changes Made to Improve Specifications

Since construction of the demonstration projects, 24 of the 26 SHAs have made changes, or are in the process of making changes, to their density specifications. These changes were tracked over time and are available to be used by other agencies when reviewing their own density specifications. The changes are summarized in the following categories:

- Primary Density Specification Used More Often
- Quality Measure (e.g., PWL, AAD, Minimum Lot Average)
- Specification Limit (Upper and Lower)
- Acceptance Plan (e.g., Lot size, sublot size)
- Inspection and Validation (aggregates and validation process)
- Quality Control
- Adjusting t/NMAS
- Longitudinal Joint Density
- Testing Methodologies (Correlate Gauges/$G_{mm}$ as reference)
- Mix Design Changes: Increasing Asphalt Content
- Mix Design Changes: Performance Test
- New Technology

## Primary Density Specification Used More Often (3 States Changing)

States often have different density specifications for different types of projects. State specifications are often in tiers. Lower-trafficked roads often have lower density requirements or use roller pattern studies. Three States are changing the tiering criteria for their different density specifications. The primary density specification will be used more often, and the secondary density specification will be used less often. One State made improvements to its secondary density specification.

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

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

## Specification Limit (Upper and Lower)

### (14 States Changing)

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

- ***Summary of States increasing upper limit (5 States Changing)*** Five States are increasing their upper limit to a value between 97 to 100 percent to allow the contractor to achieve higher in-place densities. Decker found about 77 percent of the respondents indicated that they use an upper specification limit between 97 and 98 percent density, with 58 percent of the respondents indicating an upper specification limit of 97 percent (12). Twenty-one percent of the respondents indicated an upper limit of 100 percent density and approximately 35 percent indicated no upper limit for percent density in the upper specification limit.

- ***Summary of States increasing lower limit (10 States Changing)*** Ten States are increasing their lower specification limit. Specification limits are typically being increased to a lower specification limit of 92.0 percent when using PWL or 93.0 percent when using minimum lot average or AAD.

## Acceptance Plan

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

- ***Summary of observations with standard deviation (7 States Observing)*** Standard deviations of the density within each lot were improved by more consistent roller patterns or more consistent materials. This was observed by seven States. Although consistently achieving a standard deviation below 1.0 was not commonly observed, these States were able to do so.

- ***Summary of States adjusting lot/sublot size (2 States Changing)*** The number of tests per sublot and sublots per lot is an important part of a DOT acceptance plan. Two States are making changes along these lines. To balance the buyer's and seller's risk, a minimum of 10 sublots per lot of the material may be appropriately represented for statistical evaluation (13). However, many agencies use more frequent smaller lots with 5 to 7 sublots per lot.

- ***Summary of States adjusting incentives/disincentive (7 States Changing)*** Seven States adjusted potential incentives to the contractor for the density quality characteristic. This was either increasing the incentive or adding an incentive for density. One State increased the incentive for density alone by 150 percent. Nationally, for those States using an incentive, the level of incentive ranged from 1 percent to 10 percent for the density quality characteristic with an average of 2.9 percent bonus (5).

- ***Summary of States adjusting quality characteristics (1 State Changing)*** One State added a quality characteristic for acceptance. VMA was added as part of the composite pay factor. As VMA is a method to control the minimum asphalt content, having VMA as a quality characteristic should assist in obtaining density by keeping asphalt in the mixture during production.

## Inspection and Validation (aggregates and validation process) (2 States Changing)

Inspection is the act of examining, measuring, or testing to determine the degree of compliance with requirements. Two States identified a need to strengthen their QA program through inspection or validation. Through inspection, one State identified that the aggregates used for the approved mixture design were different than the aggregates being used for field production. This State will take additional steps to verify the aggregates used for production.

Validation is the mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data and contractor data.) One State used contractor's test results as part of the acceptance decision. With only 5 passes from one roller, the contractor's results indicated densities greater than 92.0 percent. When cores were tested by an independent third party as part of this study, the density results were less than 89.0 percent. This State is strengthening its validation process.

## Quality Control (1 State's Observation)

Quality control is the process specified by the agency for a contractor to monitor, assess and adjust production or placement processes to ensure that the final product will meet the specified level of quality.

One State identified the value of the contractor's improved quality control on its aggregate stockpiling process in which the gradations were more consistent. The contractor attributed the improved aggregate crushing and loading of the cold feed bins to the improved standard deviation of in-place density results. The standard deviation of the lots from density improved from approximately 1.4 to 1.0.

## Adjusting t/NMAS (3 States Changing)

Two States are making changes related to the t/NMAS. One State saw benefits from an increased t/NMAS. The State kept its 1.25-inch overlay program for budgetary reasons and is now examining the change from 12.5 to 9.5 mm NMAS. Another State does a lot of late-season paving that is in the cold weather. During that demonstration project, the State was able to obtain 50 percent more minutes to obtain compaction by increasing its lift thickness from 1.5 to 2.0 inches. The State is exploring a minimum 2.0-inch overlay program.

## Longitudinal Joint Density (4 States Changing)

Four States are either adding a longitudinal joint density specification or increasing the lower limit.

## Testing Methodologies (Correlate Gauges/$G_{mm}$ as reference) (2 States Changing)

Two States are making changes to follow typical practices for testing and calculation of density. One State measured the in-place density using the nuclear density gauge and will now start correlating the nuclear readings to cores. The other State will calculate the percent density using the theoretical maximum specific gravity as the reference

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

Several States were concerned with the low asphalt contents from the Superpave asphalt mixture design procedure (11). Asphalt content in a mixture design was increased by designing at lower air voids, using lower gyrations, or accounting for the aged binder on RAP. Several States that tried this as part of their demonstration project. These States are also making changes to their current specifications. It should be noted that several other States involved in the demonstration had already made changes to the Superpave mixture design process but considered those changes to be their standard practice.

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

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

- Ten States include rutting tests.
- Eight States used rutting and cracking tests.

Several other States involved in the demonstration had started using performance tests prior to the demonstration project and had made those changes to their standard practices.

## New Technology (5 States Changing)

Several States are implementing new technology to obtain higher and/or more consistent density results. Intelligent compaction (IC) is being implemented by four States. Paver-mounted thermal profiler (PMTP) is being implemented by three States. The ground penetrating radar density profiling system (GPR DPS) is being implemented by two States. One State is implementing all three: IC, PMTP, and GPR DPS. Another State is implementing PMTP and GPR DPS.

## Summary

Several observations were made during the demonstration projects related to the ability to achieve higher density. With a sound asphalt mixture design that had appropriate asphalt content, achieving higher density was possible without much additional effort. Some States used different methods of increasing mixture asphalt content. Many States used different roller types, positions, and operations. Using echelon breakdown and intermediate pneumatic rollers was shown to be effective. In general, though not always, density increased with compactive effort. Similarly, with an increase of at least 1.0 in t/NMAS, density increased. There was a trend for States to use smaller NMAS aggregates as there were few 19.0-mm NMAS mixtures and many more 12.5-mm mixtures. Many States were using or experimenting with 9.5-mm mixtures. Many States made or planned density specification changes. They included quality measures used, specification limits, acceptance plans, inspection and validation, adjusting t/NMAS, longitudinal joint density changes, testing methodologies, mix design changes to increase asphalt content, and use of mixture performance tests. As noted by one of the States, the asphalt mixture design, performance testing, and density requirements are all related; as a result, changes to any of these should generally be considered as a system and coordinated.

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# Techniques and Tools for Improving Density

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