Enhanced Durability Through Increased In-Place Pavement Density

FHWA—AI Cooperative Initiative

Introduction
Section 1

Workshop Outline

1. Introduction
2. Mixture Factors Effecting Compaction
3. Compaction Best Practices
4. Other Best Practices
5. Measurement & Payment
6. New Technologies
7. Wrap Up

Learning Objectives / Outcomes

1. Understand the importance of density
2. Understanding definitions
3. Link density to pavement durability
4. Understand mix design factors that affect achieving density
5. Discuss the factors affecting compaction
6. Understanding compactive forces & rollers
7. Discuss roller operations and procedures
8. Discuss how to achieve density on Joints
9. Discuss the importance of Tack Coats
10. Measurement & Payment
11. Improving compaction with technology
12. Summarizing learning outcomes

Part 626.3 Policy.
“Pavement shall be designed to accommodate current and predicted traffic needs in a safe, durable, and cost effective manner.”

Premise:
- Compaction is essential for long-term pavement performance
- There are many compaction enhancements currently in use
- Compaction goals can be improved

Effect of In-Place Air Voids on Life Cycle Cost
- From the past studies, 1% increase in air voids would decrease the service life by an conservative estimate of 10%.
  This means …
- An asphalt overlay constructed to 93% density might be expected to last 20 years while the exact same asphalt overlay constructed to 92% density would only be expected to last 18 years

Today’s Environment
2011 FHWA Division Office Assessment
About ½ of SHA’s are not satisfied with overall performance of longitudinal joints

2013 NAPA Industry Survey
More than 30% of asphalt materials are produced using WMA technology, RAP use has increased to 20+, and there is a significant interest in other recycled materials.

Significant Advancements
Many State Target Density requirements have not changed since the 1980s!

Current Technologies that Influence Compaction…

Asphalt Pavement Compaction
Typical Asphalt Pavement Density requirements are based on what was achievable yesterday.

Today we have made significant advancements in material and construction technology and techniques.
Today we are also placing more and more materials containing higher levels of recycled, reclaimed, and reuse (RRR) products.

Challenge: Can we use today’s technology and techniques to raise-the-bar on in-place density to improve durability and thus extend pavement service-life?
Enhanced Durability through Increased In-Place Pavement Density

- Assumption – Pavement density can be increased with a minimum of additional cost
- Long-Term Objective – States will increase their in-place asphalt pavement density requirements resulting in increased pavement life

A 1% increase in field density (1% less air voids) is claimed to increase asphalt pavement service-life 10+%! (conservatively)

Today’s compaction target is typically 92% of maximum \( G_{mm} \) (8% air voids), with varying requirements for the area near the longitudinal joint

**Increased Density Pavements** target a 2% increase across the entire pavement!

- Just 2% more… makes a huge difference!

Challenges – Many Considerations

**How is Density Measured?**
- Nuclear density device correlated with cores

**How are Results Analyzed?**
- Percent within Limits (PWL)
- Minimum with Maximum
- Running Average
- Target with Tolerances

**Important Considerations:**
- Appropriate lift thickness for NMAS and coarse gradations
- Appropriate mix design requirements
- Appropriate test methods (both \( G_{mm} \) and \( G_{mb} \))
- Density only a surrogate for permeability

Increased Density Initiative

**Next Steps:**
1. State participants have been identified!
2. Fund (FMIS) State Agency trials/reports on feasibility completed
3. On-site training (AI), Information search (NCAT), Conduct Webinars (NAPA)

Increased Density Pavements

**Planned Schedule for Field Demonstration Projects**
- By March 2016, 10 State projects were identified
- By December 2016, 10+ State highway agencies hosted an “Increased Density” Asphalt Construction Workshop
  - SHA, Contractors, Equipment Supplies, and Academia
- By December 2016, 10 State highway agencies placed a “Increased Density” Pavement Section
  - FHWA funding evaluations on existing pavement projects
- 2017, document number of states that modify existing standards
  - Goal 10+ states…….
WHY ARE WE HERE?
To connect the link between density and durability.

“More emphasis must be placed on obtaining adequate density.”

Discussion / Questions
Is there anything specific you want covered?

Importance of Compaction

Learning Objective 1
Understanding the Importance of Density

Importance of Compaction
“Compaction is the single most important factor that affects pavement performance in terms of durability, fatigue life, resistance to deformation, strength and moisture damage.” – C. S. Hughes, NCHRP Synthesis 152, Compaction of Asphalt Pavement, (1989)

“The amount of air voids in an asphalt mixture is probably the single most important factor that affects performance throughout the life of an asphalt pavement. The voids are primarily controlled by asphalt content, compactive effort during construction, and additional compaction under traffic.” – E. R. Brown, NCAT Report No. 90-03, Density of Asphalt Concrete—How Much is Needed? (1990)

Four Million Miles of Roads in US

Federal = 3%
State = 20%
Local = 77%

2/3 are Paved (1/3 Unpaved)
94% of Paved have an Asphalt Surface
+2.5 Million Miles of Asphalt Roads!

Source: FHWA 2011
Budgets vs. Needs

Source: FHWA 2013

Durability Concerns

- SAPA's, AI, and NAPA all concerned with durability
  - Need for more binder in the mix
  - Many DOT’s looking for ways to improve durability
  - Minimum binder contents
  - Optimize mix designs
  - Balance rutting with fatigue

Improved density typically not considered

Evolution of Traffic

- Interstate highways - 1956
- AASHO Road Test - 1958-62
  - still widely used for pavement design
  - legal truck load - 73,280 lbs.
- Legal load limit to 80,000 lbs. - 1982
  - 10% load increase
  - 40-50% greater stress to pavement
- Radial tires, higher contact pressure
- FAST Act raising load limit to 120,000 lbs. (in select locations)

Growth in Traffic Volumes and Loadings on the Rural Interstate System

Source: FHWA Highway Statistics 2014

Led to Rutting in 1980s

Source: pavementinteractive.org

Which led to...Superpave

- Fixed the rutting problem
- Gyratory compaction lowered binder contents
- Add in higher and higher recycled materials?
Understanding the Importance of Density

What is Durability?

The ability to resist wear and decay, or to be long lasting.

Reasons for Compaction

- To minimize prevent further consolidation
- To provide shear strength and resistance to rutting
- To improve fatigue cracking resistance
- To improve thermal cracking resistance
- To ensure the mixture is waterproof (impermeable)
- To minimize oxidation of the asphalt binder

Compaction also provides a smooth, quiet driving surface

All are elements of durability

Terminology Confusion - “Density”

The term “density” is often only properly understood by the context in which it is used

- Definition: mass per unit volume, also known as “unit weight”
  - units of mass/volume, e.g. pcf, g/cm³
- “Roadway density” typically percentage of Theoretical Maximum Density or % TMD
  - no units
- also called percent relative density
  - roadway density relative to TMD
  - be careful: percent relative density can also be relative to laboratory density or control strip density!

Understanding the Context

We also need to understand whether “density” is used in the context of lab-molded density or in-place roadway density

- Lab-molded density gives information about the mix properties
- In-place roadway density gives information about the quality of compactive effort on the roadway
Terminology Confusion - “Density”

Keeping with the industry jargon, this workshop uses the term “density” to mean roadway density as percent theoretical maximum density unless otherwise noted.

Density / Air Voids

The term “air voids” is also used to discuss how well the roadway has been compacted.

\[
\text{% Air Voids} = 100 - \text{Density}
\]

\[
\text{Density} = 100 - \text{% Air Voids}
\]

Reference Densities

![Reference Densities](image)

Discussion / Questions

Definitions

Learning Objective 2

Learning Objective 3

Link Density to Pavement Durability

Improved Compaction = Improved Performance

A BAD mix with GOOD density out-performed a GOOD mix with POOR density for ride and rutting.

WesTrack Experiment
Density vs. Loss of Pavement Service Life

For both thicker and thinner, reduced in-place density at the time of construction results in significant loss of Service Life!

In-Place Voids vs Fatigue Life

Effect of Percentage of Air Voids on Fatigue Life

UK-AI Study
1.5% increase in density leads to 10% increase in fatigue life.

NCAT Report 16-02 (2016)

Literature Review on connecting in-place density to performance

- 5 studies cited for fatigue life
- 7 studies cited for rutting
- “A 1% decrease in air voids was estimated to improve the fatigue performance of asphalt pavements between 8.2 and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to extend the service life by conservatively 10%.”

Average Decrease in Rut Depth for 1% Decrease in Air Voids

Average Increase in Fatigue Life for 1% Decrease in Air Voids
Research from New Jersey

\[ Y(\text{time}) = -1.1 \times \text{(Air Voids)} + 16.6 \]
\[ R^2 = 0.32 \]

\[ \begin{array}{|c|c|}
\hline
\text{Time After Construction (years)} & \text{Average In-Place Air Voids (\%)} \\
\hline
0 & 0 \\
1 & 1 \\
2 & 2 \\
3 & 3 \\
4 & 4 \\
5 & 5 \\
6 & 6 \\
7 & 7 \\
8 & 8 \\
9 & 9 \\
10 & 10 \\
\hline
\end{array} \]

…and then there’s permeability

Permeability can be Catastrophic

NCAT Permeability Study

Finer NMAS mixes generally less permeable at equivalent air void levels!

From NCAT Report 05-02

Research on Critical Air Void Level for Impermeability

<table>
<thead>
<tr>
<th>5.5 mm Mixes</th>
<th>Critical Voids where permeable</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Zube - California Dept. of Highways - 1962</td>
<td>8.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>12.5 mm Mixes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Westerman – Arkansas HTD - 1998</td>
<td>6</td>
</tr>
</tbody>
</table>

“…to ensure that permeability is not a problem, 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 and grading.” – NCHRP 531
**Historical Summary**

- Traffic Loadings Increasing
- Rutting Became a Problem in the 1980s
- Led to Superpave
  - Robust Pavement \( \rightarrow \) Computed Rutting Well
  - Lower Asphalt Contents \( \rightarrow \) Led to Durability Issues
- Increasing Density = Increasing Durability
  - 1% ↑ Density = 10% ↑ Durability
- Balance Mixes to Resist Rutting AND Maintain Durability
- Construct Higher Density Pavements
  - Employ Construction Best Practices
  - Employ Newer Technology

**Cost of Compaction**

- Least expensive part of the paving process
- Aggregates and binders are expensive in comparison
- Compaction adds little to the cost of a ton of asphalt

**Life Cycle Cost Components**

\[
NPV = I.C. + \sum_{k=1}^{N} R.C. \cdot \frac{1}{(1 + i)^{k}}
\]

- Initial Construction
- Rehabilitation
- Maintenance
- Salvage

**Life Cycle Cost Comparison**

The user agency would see an NPV cost savings of $88,000 on a $1,000,000 paving project (or 8.8%) by increasing the minimum required density by 1% (all else equal).

**How does greater durability affects LCCA?**

- First Cost
  - More attention to density likely to increase first cost slightly 😞
- Maintenance Costs
  - Higher density should reduce maintenance 😊
  - Higher density should extend maintenance periods 😊
  - Example: longer time to first overlay
- Rehabilitation
  - Higher density should extend or eliminate rehabilitation cycles 😊

**Mix Design vs. Field Density Incentive**

- Bonus Contractor Tries to Earn
  - State A: 40% of incentive
    - (stiff mix design: contractor doesn’t try hard)
  - State B: 60% of incentive
  - State C: 80% of incentive
    - (generous longitudinal joint specification: contractor tries significantly)
- Agency needs a workable mix design and an incentive that is obtainable
What is Achievable?

Discussion / Questions

Link Density to Pavement Durability

Learning Objective 3

Mix Design Properties that Affect Compatibility and Durability

Learning Objective 4

Understand mix design factors that affect achieving density and durability.

Mixture Factors Affecting Compaction

Choosing a Gradation

- Mix Properties
- Aggregate
  - Gradation
  - Angularity
- Asphalt Cement
  - Grade
  - Quantity
- Volumetrics
  - Air Voids
  - VMA
  - VFA
- Balancing a Mix

Courtesy of NCAT
Choosing a Gradation

- More Compactable
- More Workable
- Less Permeable

Effect of Aggregate on Compaction

- **GRADATION**
  - continuously-graded, gap-graded, etc.
- **SHAPE**
  - flat & elongated, cubical, round
- **SURFACE TEXTURE**
  - smooth, rough
- **STRENGTH**
  - resistance to breaking, abrasion, etc.

Effect of Binder on Compaction

- **PERFORMANCE GRADE**
  - Binder grades that are “stiffer” at paving temperatures can make the mix more difficult to compact
- **MODIFIED BINDERS**
  - In general, the grades with modifier added tend to be stiffer and more difficult to compact.
  - The time available for compaction tends to decrease as the amount of modifier increases.

Mix Design – Balancing Act

Smooth Quiet Ride
Skid Resistance
Durability
Crack Resistance
Raveling
Permeability

Balanced Mix Design

**ETG Definition**: “Asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure.”

A mix design that is balanced for rutting and cracking resistance.
Balanced Mix Design Approach

- General Procedure
  - Design and test mix for Rutting
  - Test mix for Cracking and/or Durability
  - Performance Testing
- States that are using this approach
  - Texas
  - Louisiana
  - New Jersey
  - Illinois
  - California
  - Wisconsin

NJDOT/Rutgers

- Balanced Mixture Design Concept
- Mixes are designed to optimize performance
  - Not around a target air void content
- Take an existing mix design
  - Start at a “dry” binder content
  - Add binder at 0.5% increments – measure rutting and cracking
  - Determine range where rutting and cracking are optimized
  - Conduct volumetric work
- Performance criteria (limits) already determined

New Jersey Balanced Design

![Image of graph showing asphalt content vs. rutting and cracking]

- Most NJ mixes found to be below (dry) of the balanced area
- Plant QC air voids requirements need to be re-evaluated to account for the added binder
- Changes in production volumetrics are likely required to move the mixes in the right direction

Balanced Mix Design Research – New Jersey

- Area of Balanced Performance
  - 5.2 - 5.9%

FHWA Performance Based Mix Design

<table>
<thead>
<tr>
<th></th>
<th>Fatigue Cracking</th>
<th>Rutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Air Voids</td>
<td>For every 1% increase</td>
<td>40% increase 22% decrease</td>
</tr>
<tr>
<td>Design VMA</td>
<td>For every 1% increase</td>
<td>73% decrease 32% increase</td>
</tr>
<tr>
<td>Compaction Density</td>
<td>For every 1% lower in-place Air Voids (Increasing Density Improved Both!)</td>
<td>19% decrease 10% decrease</td>
</tr>
</tbody>
</table>

Superpave 5 – Purdue Research

- Design at 5% air voids and compact to 5% voids in field (95% G_{mm})
- Lower design gyration to increase in-place density
  - No change in rutting resistance
  - No change in stiffness
  - Improve pavement life
  - Reduced aging
- Maintained Volume of Eff. Binder (V_{be})
  - Increased VMA by 1%
Lab-Molded / Roadway Air Voids

Why are the target values for lab-molded air voids and roadway air voids different? Lab-molded air voids simulate the in-place density of HMA after it has endured several years of traffic in the roadway.

In-place Density

Lab-Molded Density

Future Traffic

Air Voids

≈15-25% Before Rolling

6 - 8 % After Rolling

Lab Screening

- Flow Number (rutting evaluation)
  - N100/4/7  840 cycles
  - N30/5/5  1180 cycles ↑

- Stiffness
  - N100/4/7  2,072 MPa
  - N30/5/5  2,645 Mpa ↑

Note: gradations had to be altered to maintain Effective Asphalt Contents

Courtesy of Gerald Huber

Volumetric Results

<table>
<thead>
<tr>
<th>Sublot</th>
<th>Air Voids</th>
<th>VMA</th>
<th>Density (%Gmm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sublot 1</td>
<td>5.1%</td>
<td>17.2%</td>
<td>93.4</td>
</tr>
<tr>
<td>Sublot 2</td>
<td>4.8%</td>
<td>16.6%</td>
<td>94.1</td>
</tr>
<tr>
<td>Sublot 3</td>
<td>4.7%</td>
<td>17.2%</td>
<td>96.5</td>
</tr>
<tr>
<td>Average</td>
<td>4.9%</td>
<td>17.0%</td>
<td>94.7</td>
</tr>
<tr>
<td>Target</td>
<td>5.0%</td>
<td>16.3%</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Question?

Does lowering gyration level - i.e. compactive effort in the lab - always increase percent binder in the mix?

NO!

Why – Because the gradation can be changed to lower the binder content back to where it began.

Question?

Will lowering the gyration levels always increase field densities?

NO!

Why – Because the changed gradation and lower binder content may not lower the compactive effort required in the field

Summary

Mix Design Properties that Affect Compactability and Durability

- Aggregate Properties
  - Gradation
  - Effect on Permeability
  - Effect on Compactability
  - NMAS
  - Shape
  - Surface Texture
- Binder Properties
  - PG Grade
  - Quantity

- Volumetrics
  - Air Voids
  - VMA
  - VFA

- Balancing the Mix
  - Rut Resistance
  - Durability
Learning Objective 5

Factors Affecting Compaction

Factors in Affecting Compaction

- Base Condition
- Lift Thickness vs. NMAS
- Laydown Temperature
- Ambient Conditions
- Cooling Rates
- Balancing Production Through Compaction
- Paver Operations

Subgrade & Base Support

- Good support critical to obtain proper density
- Spongy or unstable support
  - Provides little resistance to the rollers
  - Mixture not confined, energy dissipated
- Mixture moves and cracks rather than compacts

Lift Thickness’ Effect on Compaction

- Aggregates need room to densify
- Too thin vs. NMAS leads to:
  - Roller bridging
  - Aggregate lockup
  - Aggregate breakage
  - Compaction Difficulties

  - Fine Graded Mix—Minimum Thickness = 3 X NMAS
  - Coarse Graded Mix—Minimum Thickness = 4 X NMAS
  - SMA Mix—Minimum Thickness = 4 X NMAS

1” Leveling course – 19 mm (12.5)
Start with the standard load in the gyratory mold and made successive trials with less material and looked at sample height after compaction.

Compaction effort was the same but it was not possible to achieve the same density as the thickness of the sample reduced.

### Asphalt Mixtures

**Superpave Mix Designations**

<table>
<thead>
<tr>
<th>Superpave Mix Designations</th>
<th>Maximum Size</th>
<th>Minimum Compacted Lift Thickness (Fine)</th>
<th>Minimum Compacted Lift Thickness (Coarse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5 mm (1-1/2 inch)</td>
<td>50.0 mm (2 inch)</td>
<td>112.5 mm (4-1/2 inch)</td>
<td>150 mm (6 inch)</td>
</tr>
<tr>
<td>25.0 mm (1 inch)</td>
<td>37.5 mm (1-1/2 inch)</td>
<td>75 mm (3 inch)</td>
<td>100 mm (4 inch)</td>
</tr>
<tr>
<td>19.0 mm (3/4 inch)</td>
<td>25.0 mm (1 inch)</td>
<td>57 mm (2-1/4 inch)</td>
<td>76 mm (3 inch)</td>
</tr>
<tr>
<td>12.5 mm (1/2 inch)</td>
<td>19.0 mm (3/4 inch)</td>
<td>37.5 mm (1-1/2 inch)</td>
<td>50 mm (2 inch)</td>
</tr>
<tr>
<td>9.5 mm (3/8 inch)</td>
<td>12.5 mm (1/2 inch)</td>
<td>28.5 mm (1-1/8 inch)</td>
<td>38 mm (1-1/2 inch)</td>
</tr>
<tr>
<td>4.75 mm (3/16 inch)</td>
<td>9.5 mm (3/8 inch)</td>
<td>14.25 mm (9/16 inch)</td>
<td>19 mm (3/4 inch)</td>
</tr>
</tbody>
</table>

### Effect of Temperature on Compaction

- **Superpave Mix Designations**
- **Temperature Control is Critical**

### Compaction Temp. Vs. Density

- **Charles F. Parker (1959)**
  - 275°F – standard temperature – reference air voids
  - 200°F – doubled the air voids
  - 150°F – quadrupled the air voids
- **Kim A. Willoughby, et.al. (2001)**
  - Mix temperature differentials
  - ≤ 25°F – generally consistent air voids
  - ≥ 25°F – greater air void spread
  - Pneumatic rollers reduced spread
  - End dumps showed a greater spread
  - Most important factor in achieving density

### Mat Temperature

- Compacting asphalt in the correct temperature range is very important
- Temperatures must be neither too hot nor too cold
- Optimum compaction temperatures vary depending on many factors
  - Start compaction: 310 – 280°F
  - Stop compaction: 180 – 175°F
Environmental Factors and Compaction

Several factors come into play regarding how fast the mix cools onsite, affecting time available for compaction:

- Ambient air temperature
- Temperature of the existing surface
- Wind speed
- Lift thickness
- Mix temperature
- Solar Radiation

Material Cooling

- Thicker = More Time for Compaction
- Free tools for estimating compaction time
  - PaveCool—single lift (generation 1)
    - PC
    - iOS App
    - Google App
  - MultiCool—multiple lifts (generation 2)
    - PC
    - Google App
    - Mobile Web

PaveCool Example

- Key Inputs
  - Temperature
  - Air
  - Base
  - Mix Delivery
  - Wind Speed
  - Lift Thickness

- Output
  - Cooling Curve
  - Estimated Compaction Time

PaveCool Example

- 2.5 Inch Lift
  - 50°F Air, Surface Temp
  - Mix Delivery temp - 300°F
  - 39 minutes to complete compaction operations

- 2 Inch Lift
  - 50°F Air, Surface Temp
  - Mix Delivery temp - 300°F
  - 28 minutes to complete compaction operations

Temperature and Weather Limitations

Many agencies specify minimum surface temperatures on which to lay, as shown in the example below:

<table>
<thead>
<tr>
<th>Lift Thickness, inches</th>
<th>Min. Surface Temp., °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3</td>
<td>40</td>
</tr>
<tr>
<td>2 - 3</td>
<td>45</td>
</tr>
<tr>
<td>&lt; 2</td>
<td>50</td>
</tr>
</tbody>
</table>

Balancing the Paving Operation
Paving Goals

- Continuous Operations
  - Hot plant running nonstop
  - Paver running at constant speed nonstop
- Production = Hauling = Paver Processing = Compaction Speed

Paver Speed and Output

Assume:
2-Inch Compacted Mat
12-Foot Pull
140 lbs/ft³ Compacted Unit Weight

Calculating Paver Production

Paving Time Today =
Plant Production Rate =
Tons to be placed today =
DOT Spread Rate =
Length of Paving in feet = (Total Tons / Tons per mile) x 5280

Theoretically perfect paving speed = Length(ft) / Paving Time(min) = fpm

Paving Efficiency Factor (EF) is from 0.70 to 0.85
Actual Paver Speed = Theoretical Speed / Efficiency Factor

Discussion / Questions

Factors Affecting Compaction
Learning Objective 5

Learning Objective 6

Forces of Compaction and Roller Types

Vibratory Screed Should Always be “ON”

Note: screed operator walking along side
Roller Equipment

- Forces of Compaction
- Roller Type
  - Steel Drum
    - Static
    - Vibratory
  - Pneumatic
  - Newer Technology
    - Vibratory Pneumatic
    - Oscillatory Steel Drum

Forces of Compaction

- Compaction forces
  - Low force
  - Static pressure
  - Manipulation
  - Higher forces
    - Impact
    - Vibration

Effect of Roller Type, Size, Passes

Roller type and size affects:
- Magnitude of the load
- Manner the load is imparted to the pavement

Number of passes:
- Increases the density
- To break over point after a # of passes
  - Lowers compaction
  - If continued, damages mat

Roller Types

- Static Steel-Wheeled
- Pneumatic
- Vibratory

Static Steel-Wheeled Rollers

- 8-14 ton rollers normally used for HMA compaction
  - Commonly use vibratory rollers operated in static mode
- Lighter rollers used for finish rolling
- Drums must be smooth and clean
  - Water spray & scraper bars
- For initial compaction, drive wheel must face paver

Pneumatic Rollers

- Reorients particles through kneading action
- Tire pressures:
  - ~80 psi (cold) for compaction
  - ~50 psi (cold) for finish rolling
  - Range of tire pressures not to exceed 10 psi
- Used as Intermediate or as Breakdown Roller
- Tires must be hot to avoid pickup
- Tires must be smooth - no tread
- Not used for PFC mixes or SMA
Many experts believe kneading action helps in providing a tighter surface that is more dense and less permeable compared to drum rollers.

- Research supports this
- But must keep these away from the unsupported edge to avoid excessive lateral movement of mat.
- Use during intermediate rolling of the supported edge.
- Not finish rolling

Commonly used for initial (breakdown) rolling
- 8-18.5 tons, 57-84 in wide ("heavy" rollers)
  - 50-200 lbs/linear inch (PLI)
- Frequency: 2700-4200 impacts/min.
- Amplitude: 0.016-0.032 in.
  - For thin overlays (≤ 2 in.) use low amplitude or static mode
- Operate to attain at least 10 impacts/ft
  - 2-4 mph

Movement of drum initiates particle motion
- When particles are moving
  - Resistance to deformation is reduced
- Force applied by weight of drum plus inertia
  - Produces a greater compactive effect
  - Achieving more compaction per pass than static rollers

Vibratory Rollers - Amplitude

- Spinning eccentric weight causes drum movement
- Falling drum adds to compactive force
- Distance drum moves is called amplitude
- Amplitude determines impact force

Vibratory Rollers - Frequency

- Frequency
  - Drum impacts per minute
  - Match travel speed to frequency
  - Best results when impact spacing is 10-14 per foot
**Recommended Breakdown Rolling Speed = 2-3 mph**

**Effective Roller Speed is 90% using a Reversal Factor of 10%**

Maximum Vibratory Rolling Speed (MVRS) is calculated based on 10-12 Impacts per foot (IPF) and roller frequency (VPM)

\[
MVRS = \frac{VPM}{IPF} = \text{fpm}
\]

\[
MVRS = \frac{3000}{12} = 250 \text{ fpm}
\]

Effective Rolling Speed (ERS) = MVRS x 0.90

\[
ERS = 225 \text{ fpm}
\]

Drum Width = 84 inches

Effective Drum width is 6" less due to overlap.

Effective Width = 78 inches / 12 in/ft = 6.5 ft

Paving Width = 14 ft

Calculate number of passes to cover Mat width.

\[
\text{No. of passes} = \frac{\text{Paving Width}}{\text{Effective Roller Width}}
\]

\[
\text{No. of passes} = \frac{14}{6.5} = 2.15 \text{ passes}
\]

Rounding up to the nearest whole number = 3 passes

**Number of passes to achieve density from Test Strip = 5**

Calculate the Total Number of passes to achieve Density across the full width of the pavement. Density Passes x Width Passes = Total # of Passes

If the Total number of passes is an even number, add 1 make-up pass

Total number of Passes = 

Compaction Production Rate (Comp Rate) = ERS / Total # of Passes

Comp Rate = 

Roller Efficiency Factor is typically from 0.75 to 0.80

Roller Efficiency Factor (REF) = 0.80

Effective Compaction Rate = Comp Rate x REF

\[
15.26 \times 0.80 = 12.21 \text{ fpm (Paver Speed)}
\]

When using 2 Compaction Rollers the Paver Speed may be doubled.

**Drum Impacts per Foot**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>2 MPH</th>
<th>3 MPH</th>
<th>4 MPH</th>
<th>5 MPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 vpm</td>
<td>11.36</td>
<td>7.58</td>
<td>5.68</td>
<td>4.55</td>
</tr>
<tr>
<td>2200 vpm</td>
<td>12.50</td>
<td>8.33</td>
<td>6.25</td>
<td>5.00</td>
</tr>
<tr>
<td>2400 vpm</td>
<td>13.64</td>
<td>9.09</td>
<td>6.82</td>
<td>5.45</td>
</tr>
<tr>
<td>2600 vpm</td>
<td>14.77</td>
<td>9.84</td>
<td>7.39</td>
<td>5.91</td>
</tr>
<tr>
<td>2800 vpm</td>
<td>15.91</td>
<td>10.61</td>
<td>7.95</td>
<td>6.36</td>
</tr>
<tr>
<td>3000 vpm</td>
<td>17.05</td>
<td>11.36</td>
<td>8.52</td>
<td>6.82</td>
</tr>
<tr>
<td>3200 vpm</td>
<td>18.18</td>
<td>12.12</td>
<td>9.09</td>
<td>7.27</td>
</tr>
<tr>
<td>3400 vpm</td>
<td>19.32</td>
<td>12.88</td>
<td>9.66</td>
<td>7.72</td>
</tr>
<tr>
<td>3600 vpm</td>
<td>20.45</td>
<td>13.64</td>
<td>10.22</td>
<td>8.18</td>
</tr>
<tr>
<td>3800 vpm</td>
<td>21.59</td>
<td>14.39</td>
<td>10.80</td>
<td>8.63</td>
</tr>
<tr>
<td>4000 vpm</td>
<td>22.72</td>
<td>15.16</td>
<td>11.36</td>
<td>9.10</td>
</tr>
</tbody>
</table>

**Vibratory Rollers - Amplitude**

- Amplitude too high
- Travel speed too fast
- Vibrating cool mat
  - Roll closer to paver
- Finish rolling too cool
  - Roll closer to intermediate roller
- Finish roller too light

**Newer Roller Technology**

- Technology
  - Intelligent Compaction (Stay tuned)
  - Vibratory Pneumatic
  - Oscillatory Rollers
- Purported Benefits (last two)
  - Aid in compacting difficult mixes
  - Lower cessation temperature
  - Contact suppliers for additional information
Oscillatory Rollers

How Does a Oscillatory Roller Work?

Discussion / Questions

Forces of Compaction & Roller Types
Learning Objective 6

Compaction Variables Under the Roller Operator’s Control

Learning Objective 7

Roller Operations & Roller Procedures

Compaction Variables at the Roller

- Roller Patters
- Sequencing
- Passes—A roller passing over one point in the may one time
- Roller Speed
- Rolling Zone
- General Rolling Operations
- Dealing With Challenging Mixes
Traditional Roller Operations Sequencing

- Breakdown Rolling
- Intermediate Rolling
- Finish Rolling

Pattern Decisions

- How many passes?
- How to be sure mix is rolled at correct temperature?
- How fast to roll?

Rolling Pattern

100 - 170 ft
- Roller width should overlap 6 inches
- Odd number of passes to advance
- Repeat uniformly

Establishing Breakdown Rolling Pattern

Goal: 93.5% G_{mm}

Select: 3 Passes
(Intermediate will get the rest of the density)

Rolling Pattern

- Speed and lap pattern for each roller
- Number of passes for each roller
  - One trip across a point on the mat
  - Set minimum temperature each roller finishes

IMPORTANT:
- Paver speed must not exceed compaction!!!
- Paver makes single pass
- Roller pattern requires 3-7 passes

Roller Operations - Temperature Zones

- Compactive Force
- Pressure Impact Vibration
- Pressure Manipulation
- Pressure

Temperature Ranges

- Breakdown 300° - 260°F
- Intermediate 250° - 220°F
- Finish 200° - 180°F
Roller Speed is Critical

![Graph showing the relationship between density and number of passes at different speeds.](image)

- Slower = More Compaction/Pass

Breakdown Rolling

- First roller behind paver
- Gets most of density
- Begin at highest temperature without huge mat distortion
- May have to work very close to paver for some mixes
- May be performed with two coordinated rollers

Echelon Vibratory Rollers

- Traditionally 3-wheel steel
- D/D vibratory most common
- Vibration most productive during breakdown
- Pneumatics
  - Used on base courses
  - Leveling courses
    - Forces mix into cracks
    - Compacts without bridging minor ruts
  - Can leave marks – may be harder to roll out

Intermediate Rolling

- Final step in getting density and initial smoothness
- Mat hot enough to allow aggregate movement
- Mat already close to final density
- Too much force will fracture aggregate
- Typical roller type:
  - Traditionally pneumatic
  - Vibratory at low amplitude and/or static mode

Pneumatic Roller

- Manipulation
**Finish Rolling**

Main purpose
- Minimal compaction
- Smoothness
- Removal of any marks
- Once smooth, stop rolling

Typical roller types:
- Tandem steel-wheel
- Pneumatic w/lower pressure
- Vibratory static mode only

**General Rolling Procedures**

For best results
- Roll at highest temperature without excessive displacement
- Stay close to paver
- Monitor weather
- Keep up but not too fast
  - Slower paver speed
  - Not faster roller speed

**General Rolling Procedures**

- 6” overlap assures uniform compaction
- Include overlap selecting drum width
- Roller should cover mat in no more than 3 passes

**Compact the Mat While It Is Hot!**

Stay Close to the Paver with Breakdown Rollers.
Always Stop and Reverse Directions at an Angle!

“Birdbath” from roller stopping on hot mat
Why Rollers Need to Turn to Stop

Rollers need to turn to stop because:
- Paver lays thicker lift
- Roller compacts to the design thickness
- Superpave mixes rolldown ~ 25%
- SMA, PFC & other open-graded mixes rolldown ~ 15%

General Rolling Procedures

Rolldown:
- Paver lays thicker lift
- Roller compacts to the design thickness
- Superpave mixes rolldown ~ 25%
- SMA, PFC & other open-graded mixes rolldown ~ 15%

Summary of “Good Practice”

- Compact mat when it is hot!
- Conduct a density control strip at the beginning of the project
  - Determine optimum roller pattern
  - Stick with roller pattern throughout project unless something changes in the conditions
- Reverse directions properly
  - Turn into stops
  - Do not turn while standing
- Do not stop roller on hot mat
- Use proper technique when compacting longitudinal joints

Overcoming Challenges—When Things Aren’t Going Right

- Compaction of stiff mixes
- Compaction of tender mixes
- Tender zone
- Segregation

Compaction of Stiff Mixes

- Verify Mix Matches the Design
- Modify Rolling Pattern
  - Use Two Rollers in Echelon for Breakdown Rolling
  - Consider a Pneumatic for Breakdown Rolling
  - Alter Roller Settings
    - Amplitude
    - Frequency
  - Consider Oscillatory Roller
- Increase Production Temp
  - Do not exceed supplier’s recommendations.
- Use WMA as a compaction aid.

Compaction of Tender Mixes

- Verify Mix Matches the Design
  - Verify Natural Sands not Higher Than Allowed
- Modify Rolling Pattern
  - Alter Breakdown Roller Settings
    - Amplitude
    - Frequency
    - Static
  - Allow Mix to Cool Slightly
    - Verify that density requirements can still be achieved as mix will be stiffer.
- Redesign of Mix May be Needed
  - Consider use of the Bailey Method.
Dealing With the Tender Zone

- Tender Zone = Temperature Range (240 – 190°F typically) where mix becomes tender.
- Complete Breakdown Rolling before reaching upper end of tender zone.
- Only use pneumatic roller (Intermediate Roller) when in tender zone.
- Begin Finish Rolling below tender zone.

Dealing With Segregation

- Identify source of segregation
  - Mix Design
  - Stockpiling
  - Plant operations
  - Truck loading and/or unloading
  - Paver operations
- Change operations to correct
  - Example: Paver operations
    Running paver out of mix while waiting for trucks
    Never let the paver hopper fall below 1/4 to 1/3 full

Segregation = Poor Density

Additional Resources

QIP-110, NAPA
https://store.asphaltpavement.org/index.php?productID=218

MS-22, Al
https://mxo.asphaltinstitute.org/webapps/displayItem.htm?acctitemid=317

Discussion / Questions

Roller Operations & Roller Procedures
Learning Objective 7

Other Best Practices
Section 4

Time for LUNCH?
60 Minute Break
• Best Practices for Specifying and Constructing HMA Longitudinal Joints

• Tack Coat Best Practices
  
  • Both these sub-sections built directly from the two 4-hr workshops developed on each of these critical topics. Those workshops, and related info, can be viewed at: www.asphaltinstitute.org/engineering
  
  • Both topics directly relate to better in-place density

---

**Learning Objective 8**

Achieving Density on HMA Joints

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**Two Goals**

- Best way To Build it.
- Best way To Spec it.

---

**We Know** Unsupported Edge Will Have Lower Density

- Proper Overlap
- Sufficient Material for Roll-Down

---

- Low Density Area

Please note Cold side and Hot side, as they are terms used throughout this Workshop.

---

**Literature Review on Longitudinal Joints**

- Construction
  - Actual in-place densities?
  - What is achievable?

- Permeability/Density
  - Relation to performance?
  - Where is danger zone?
### Joint vs. Mat Density

![Joint Density vs. Mat Density](image1.png)

2006-2007, with 6" cores taken over joint

### Typical Nuclear Density Profile

Texas Transportations Institute Study

![Typical Nuclear Density Profile](image2.png)

### Research a Decade Ago: Recommended Minimum of 90% TMD, or 2% Less than Required Mat Density

- “It is recommended to specify minimum compaction level at the longitudinal joint (generally 2% lower than that specified for the mat away from the joint).” NCAT / PaDOT, 2002
- “Maximum of 2% less than the corresponding mat density and minimum of 90% of TMD at the specific location.” Nevada, 2004
- “The evaluation is considered failing if the joint density is more than 3.0 pcf below the density taken at the core random sample location and the correlated joint density is less than 90%.” TTI, 2006
- “Joint density, 2% less than mat density, is achievable when measured with cores.” NCAT, 2007

### Proposed Acceptance Criteria for an LJ Density Spec

Six-inch Cores located either directly over visible joint for butt joint, or middle of wedge for wedge joint. This gives a 50/50 split, in order to average the $G_{mm}$ of both lots.

- $> 92\%$ of $G_{mm}$: maximum bonus
- Between 92% and 90% of $G_{mm}$: 100% pay, pro-rated bonus, suggest “overband” or “surface seal” joint
- $< 90\%$ of $G_{mm}$: reduced payment, overband or surface seal joint
The Pennsylvania Example

PA Story on Longitudinal Joint Density

• Increasing density was viewed as key
• 2007 - began measuring joint density
• 2008 - method specification of best practices
• 2008 and 2009 - continued gathering data on joints
• 2010 - New joint density specification. Transition year with no bonuses or penalties.
• 2011-2015 – bonuses and penalties on joint density

PA Joint Density Spec Highlights

• Both type of LJs allowed (butt or notch wedge)
• Joint Lot = 12,500’. Core every 2,500’. 5 cores per lot.
• Core location
  • For Butt: directly over visible joint
  • For Notch Wedge: middle of wedge
• Percent Within Limits (PWL)
  • Incentive starts at 80% PWL
  • Disincentive at <50% PWL
• Lower Specification Limit
  • 2010-2013: 89% TMD
  • 2014-2015: 90% TMD
• Corrective action for < 88% TMD

PA: How Did it Work?

<table>
<thead>
<tr>
<th>Year</th>
<th># Lots</th>
<th>Avg. Roadway Density, %TMD</th>
<th>Avg. Joint Density, %TMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>18</td>
<td>93.9</td>
<td>87.8</td>
</tr>
<tr>
<td>2008</td>
<td>43</td>
<td>94.1</td>
<td>88.9</td>
</tr>
<tr>
<td>2009</td>
<td>29</td>
<td>94.1</td>
<td>89.2</td>
</tr>
<tr>
<td>2010</td>
<td>No data, transition to PWL spec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>137</td>
<td>94.1</td>
<td>91.0</td>
</tr>
<tr>
<td>2012</td>
<td>162</td>
<td>94.0</td>
<td>91.6</td>
</tr>
<tr>
<td>2013</td>
<td>167</td>
<td>93.9</td>
<td>91.4</td>
</tr>
<tr>
<td>2014</td>
<td>316</td>
<td>94.1</td>
<td>92.3</td>
</tr>
<tr>
<td>2015</td>
<td>493</td>
<td>92.6</td>
<td>PWL, LSL 90%</td>
</tr>
</tbody>
</table>

PA: Increased Projected Life of Joints Due to Improved Joint Density

Percent Service Life

Compaction Level

93% 92% 91% 90% 89%
PA: Annual Statewide Totals on Incentives/Disincentives for Joint Density

<table>
<thead>
<tr>
<th>Year</th>
<th>Incentive Payments</th>
<th>Disincentive Payments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>$268K</td>
<td>$99K</td>
</tr>
<tr>
<td>2012</td>
<td>$489K</td>
<td>$63K</td>
</tr>
<tr>
<td>2013</td>
<td>$588K</td>
<td>$25K</td>
</tr>
<tr>
<td>2014</td>
<td>$1,002K</td>
<td>$127K</td>
</tr>
</tbody>
</table>

Note: MI and CT have averaged over 91.5%, and AK over 92.0% density at the joint over recent construction seasons.

Next: 2nd Goal

The Best Longitudinal Joint: Echelon Paving

New Jersey

Rolled Hot

Constructing a Quality Longitudinal Joint
- Types of LJs
- Planning for the Joint
- Placement and Rolling

Use best practices for paving previously discussed!

But, the need to maintain traffic limits the opportunities to pave in echelon

Consequently, most longitudinal joints are built with a cold joint.

Preferred Joint Type? Experts Evenly Divided.

Notched Wedge

Butt
Wedge Joints and Compaction

Plan for Longitudinal Joints...
(i.e. Discuss During Pre-Con Meeting)

- Joint Type
- Layout Plan of Final Lift showing joints (DelDOT)
  - Recognize need to offset joints between layers
  - Avoid wheel paths, RPMs, striping (if possible)
- Testing of Joint
  - Type, location, schedule, by whom
- Joint Construction Practices
  - Paving, rolling, materials
- Pave low to high when possible for *shingle effect*
  -Avoids holding rain water at joint by hot side being slightly higher (recommendation later)

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notched Wedge</td>
<td>91.7%</td>
<td>91.7%</td>
<td>“mostly notched wedge joints”</td>
</tr>
<tr>
<td>Butt (vertical)</td>
<td>90.3%</td>
<td>90.7%</td>
<td></td>
</tr>
</tbody>
</table>

Offset joints between layers by at least 6-inches; surface joint should be near centerline (not in wheelpath)

First Pass Must Be Straight!
string-line should be used to assure first pass is straight

Great Results

Stringline for reference, and/or Skip Paint, Guide for following
Tough to get proper overlap (1") with next pass

Best Way to Roll an Asphalt Joint

Rolling Unconfined Side? 50-50 on Where to Put 1st Pass

Option 1
Hang over 4-6"

Option 2
1st Pass 4-6" inside

4-6"

Roller

2nd Pass hang over 4-6"

Roller

4-6"

What To Watch for With Option 2

Rolling Unsupported Edge With First Roller Pass

Vibratory Roller

If edge of drum is located just inside the unsupported edge, a stress crack can occur here.

So Our Recommendation: Option 1
1st Roller Pass Hangs Over 4-6 inches

Compacting Notched Wedge

Vibrating wedge

Wheel compactor
Paint the Side of Joint (Butt or Wedge)

- Emulsion (Good)
- PG Asphalt (Better)
- Or Joint Adhesive (JA) (Best)

When Closing Joint, Set Paver Automation to Never Starve the Joint of Material

- Target final height difference of +0.1” on hot-side versus cold side
  - NH spec requires 1/8” higher
- Joint Matcher (versus Ski) is best option to ensure placing exact amount of material needed
- If hot-side is starved, roller drum will “bridge” onto cold mat and no further densification occurs at joint

Ski Best for Smoothness

- (reference is average over length of ski)

Versus Joint Matcher, which is best for joint

- (reference is exact location just in front of auger)

Note: If underlying pavement already smooth, some contractors feel they can get good joint with ski, but must finish 1/10” high

Destined for Failure

Likely that the hot side of joint was starved of material at these locations and bridging occurred.

Proper Overlap:

- 1.0 ± 0.5 inches
- Exception:
  - Milled or sawed joint should be 0.5 inches

All Photos show Bottom of Lift

(Nota voids in top two from no overlap)
Do NOT Rake Across the Joint

Lute the Longitudinal Joint

Rolling the Supported Edge

Our Recommendation:

1st pass all on hot mat with roller edge off joint approx 6-12 inches

2nd pass overlaps on cold mat 3-6 inches

Versus an Alternate Method of

1st Pass over the Supported Edge

Roller in vibratory mode with edge of drum overhanging 2 to 4-inches on cold side.

Concern with this method is if insufficient HMA laid on hot side at joint, then bridging occurs with first pass (roller supported by cold mat)

Long. Joint Construction Example

Other Options / New Products

• Mill & Pave One Lane at a Time
• Cut Back joint
• Joint Heaters
• Joint Adhesives (hot rubberized asphalt)
• Surface Sealers Over Joint
• Rubber Tire Rollers
• Warm Mix Asphalt
• Intelligent Compaction

Details provided in full workshop
GOAL
14 year old surface

- I-65 in IN: SR252 to US31
- 12 inches HMA over Rubblized JCP
- Warranty Project

Summary LJ Best Practices

- Specify a Joint Density
  - Work with Industry to Implement
  - Mat Density -2% is Typical.
- Utilize Construction Best Practices
- Use Bonding Material at the Joint
  - Tack Coat
  - PG Binder
  - Joint Adhesive

Summary LJ Best Practices

- Layout Longitudinal Joints Before Paving Begins
  - Stagger Joints with Each Lift
  - Keep Joints Out of Wheel Paths
- Get Proper Overlap at the Joint
- Do NOT Rake and/or Starve the Joint

Discussion / Questions

Achieving Density on HMA Joints
Learning Objective 8

Learning Objective 9

Tack Coat’s Important Role in Compaction and Durability

Discuss the Importance of Tack Coats
Tack Coats

- Role in Achieving Compaction
- Importance in Producing Durable Pavements
- Tack Coat Costs
- Tack Coat Challenges
- Tack Coat Best Practices

Tack Coat’s Role in Compaction

Good bond between underlying and the new layer being compacted is critical to “confine” the bottom of the new lift and keep it from sliding during rolling.

Tack Coat’s Role in Compaction

Successful Tack Coat

The Ultimate Goal:
Uniform, complete, and adequate coverage

Poor tack coat applications that do not properly bond the layers can impact the ability to properly compact the mix and affect the long term durability of the pavement.

Full width of mat to minimize movement of unsupported edge during compaction
Importance of Tack Coats

- To promote the bond between pavement layers.
- To prevent slippage between pavement layers.
- Vital for structural performance of the pavement. *(Durability)*
- Resist rutting.
- Achieve optimum density.

Loss of Fatigue Life Examples

- May & King:
  - 10% bond loss = 50% less fatigue life
- Roffe & Chaignon
  - No bond = 60% loss of life
- Brown & Brunton
  - No Bond = 75% loss of life
  - 30% bond loss = 70% loss of life

Loss of Fatigue Life Examples

- 10% bond loss = 50% less fatigue life
- 30% bond loss = 70% less fatigue life
- No bond = 60% loss of life
- No Bond = 75% loss of life

So is it worth it to apply a tack coat?

Cost of Tack Coat

- New or Reconstruction
  - About 0.1-0.2% of Project Total
  - About 1.0-1.5% of Pavement Total Cost
- Mill and Overlay
  - About 1.0-2.0% of Project Total
  - About 1.0-2.5% of Pavement Total Cost

Best Practices

- Surfaces need to be clean and dry
- Uniform application
- Tack all surfaces
  - Horizontal
  - Vertical

Spray Bar/Nozzles

- Single Coverage
- Double Coverage
- Triple Coverage
- Nozzle angle setting: 15 to 30 degrees
- Spray bar axis
Proper Nozzle Sizing

- Consult with distributor truck manufacturer to match the material to the nozzle.
- ONE SIZE DOES NOT FIT ALL

Application Rates?

- **What is the Optimal Application Rate?**
  - Surface Type
  - Surface Condition
- **Recommended Ranges**

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Residual Rate (gpy)</th>
<th>Appx. Bar Rate Undiluted (gpy)</th>
<th>Appx. Bar Rate Diluted 1:1 (gpy)</th>
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</thead>
<tbody>
<tr>
<td>New Asphalt</td>
<td>0.02 – 0.05</td>
<td>0.03 – 0.07</td>
<td>0.06 – 0.14</td>
</tr>
<tr>
<td>Existing Asphalt</td>
<td>0.04 – 0.07</td>
<td>0.06 – 0.11</td>
<td>0.12 – 0.22</td>
</tr>
<tr>
<td>Milled Surface</td>
<td>0.04 – 0.08</td>
<td>0.06 – 0.12</td>
<td>0.12 – 0.24</td>
</tr>
<tr>
<td>Portland Cement Concrete</td>
<td>0.03 – 0.05</td>
<td>0.05 – 0.08</td>
<td>0.10 – 0.16</td>
</tr>
</tbody>
</table>

*Assume emulsion is 33% water and 67% asphalt.

Summary

- Tack Coat plays a significant role in the compaction process.
- Tack coat creates the bond between asphalt layers.
- The bond “confines” the asphalt layer and holds it in place while it is being compacted.
- A poorly bonded pavement will fatigue significantly faster.
- It is good practice to place the tack coat should be 3-6 inches wider than the lane being placed when there is an unsupported edge.
- Tack coat is vital for performance but low in cost.

Additional Resources

- [http://store.asphaltinstitute.org/tack-coat-information/](http://store.asphaltinstitute.org/tack-coat-information/)
- [http://www.asphaltinstitute.org/tack-coat-information/](http://www.asphaltinstitute.org/tack-coat-information/)

Discussion / Questions

Discuss the Importance of Tack Coats
Learning Objective 9

Measurement and Payment of Density
Section 5
Learning Objective 10

Measurement and Payment

Section 5 – Measurement and Payment

- Inspector roles
- Types of specifications
- Measurement of density
- Method of calculation
- Various State specifications

Inspection on HMA Construction

- Sound inspection practices during construction are vital to obtain quality
- Both agency and contractor responsible
- Process control and acceptance procedures alone will not ensure quality
- Key components of inspection are:
  - Enforcement of specifications
  - Ensure good practices are being used
  - Observation of materials and workmanship

HMA Construction Inspection

Each link is critical for success!

What is Quality?

Definition of Quality for HMA?

- How do we define quality?
  - Meets agency mixture specifications
  - Meets agency density specifications
  - Smooth riding surface
  - Uniform texture and appearance
  - Obtains expected service life
  - Long lasting asphalt pavement
HMA Inspection

**Responsibilities**
- Represent the owner’s interests
- Keep daily construction diary
- Monitor ambient air and mat temperatures
- Track tonnage with truck tickets
- Calculate yield
- Monitor compaction with nuclear or non-nuclear gauge
- Observe materials and workmanship
- Make sure that good practices are being used

Density Acceptance/Quality Control

**Measuring Density**

*Using cores...... or a nuclear density gauge*

AASHTO T 166 - Method C (Rapid Test)

- Place both in an oven at 110 ± 5°C (230 ± 9°F) and dry to a constant mass.
- Cool the pan and specimen to 25 ± 5°C (77 ± 9°F).
- Determine the mass of the pan and specimen.
- Subtract the mass of the pan, and record as the dry mass A.

AASHTO T 166 - Method A

- Dry the specimen to a constant mass at 52 ± 3°C (125 ± 5°F).
- Dry saturated samples overnight and then weigh at 2-hour intervals until constant mass.
- Recently compacted lab specimens do not require drying.
- Cool the specimen to 25 ± 5°C (77 ± 9°F).
- Weigh and record the dry mass as A.

AASHTO T 166 - Method C

- Immerse each specimen in water at 25 ± 1°C (77 ± 1.8°F) for 4 ± 1 minutes and record the immersed mass as C.
- Remove the specimen from the water bath, damp-dry the specimen by blotting it with a damp towel as quickly as possible (not to exceed 5 seconds).
- Weigh and record the SSD mass as B. Any water that seeps from the specimen during weighing is considered part of the specimen.
AASHTO T 166 - Method C Calculation

Calculate the bulk specific gravity:

\[
\text{Bulk Specific Gravity} = \frac{A}{B - C}
\]

Where:
- \(A\) = mass of the specimen in air, g
- \(B\) = mass of the SSD specimen in air, g
- \(C\) = mass of the specimen in water, g

Calculate the water absorbed by volume:

\[
\% \text{ Water Absorbed by Volume} = \frac{B - A}{B - C} \times 100
\]

Where:
- \(A\) = mass of the specimen in air, g
- \(B\) = mass of the SSD specimen in air, g
- \(C\) = mass of the specimen in water, g

* If this percentage exceeds 2.0, use either T 275 (Paraffin Coating) or T 331 (Corelok) to determine bulk specific gravity.

Is T 166 always the most accurate?

For mixtures with low density and/or coarse texture, AASHTO T 166 overestimates density because specimen volume is under measured.

Several methods are used to measure true volume, the most common of which is the CoreLok device (AASHTO T 331)

How much is the difference?

Source: FHWA TechBrief
FHWA-HIF-11-033 December 2010
http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=705
When to use CoreLok instead of T 166?

AASHTO T 166 says CoreLok should be used if percent absorption is more than 2.0%.

Based on research, FHWA recommends to use CoreLok on all specimens with absorption more the 1.0%.

Quality Control and Acceptance

On almost every roadway project, the component materials are tested.

Quality Control - testing that helps the producer ensure that they are providing a quality product.

Acceptance - testing that helps the owner ensure that they are receiving a quality product.

The Evolution of Specifications

The Evolution of Specifications

Types of Acceptance Specifications

- Method
  - Extreme agency control
    - Materials
    - Equipment
    - Construction methods
- End-Result
  - Less agency control
  - What does “good quality” look like?

Types of Specifications

- Assurance
  - Statistically based
  - QC by contractor
  - Acceptance (QA) by agency or their representative
- Performance-Type
  - Evaluation of in-place performance
  - Predetermined parameters and timeframes
  - Warranty
- Combinations

Random Sampling

A key component of obtaining a representative sample of any construction material is the concept of random sampling.

Random means that all parts of the lot of material have an equal chance of being included in the sample.
Stratified-Random Sampling

ASTM D 3665 provides the standard practice for random sampling of construction materials. It suggests that the best and most practical method of ensuring that samples include the full range of a construction process is a process called stratified-random sampling.

Note: ASTM D 3665 can be complex so states may develop their own random sampling program using a spreadsheet, calculator, or table.

Statistical Concepts - Average

The average of a group of numbers is something everyone understands: simply add the numbers together and divide by the number of observations.

The mathematical equation looks like this:

$$\bar{X} = \frac{\sum X}{n}$$

Statistical Concepts - Normal Distribution

A Normal Distribution naturally occurs as specific values are targeted, but not always hit.

Quality characteristics in asphalt paving typically follow a normal distribution excluding smoothness.

Statistical Concepts - Standard Deviation

The standard deviation of a group of numbers is a measure of the amount of variability in the data.

The mathematical equation looks like this:

$$s = \sqrt{\frac{\sum (X_i - \bar{X})^2}{n - 1}}$$
**Standard Deviation vs. Area**

- **Mean ± 1 Standard Deviation ≈ 68%**
- **Mean ± 2 Standard Deviations ≈ 95%**
- **Mean ± 3 Standard Deviations ≈ 99.7%**

**Single Specification PWL**

Single Specification PWL:

- PWL_L
- PWL_U
- LSL
- USL

**Double Specification PWL**

Double Specification PWL:

- PWL_L
- PWL_U
- LSL
- USL

or

- PWL
- LSL
- USL
Percent Within Limits (PWL) specifications required that a certain percentage of a lot remain within certain limits.

Uniformity is the key!

A small “s” gives the average a lot of flexibility

Uniformity comes from balancing plant/delivery/paver/compaction!

Percent Within Limits Specification

Percent-Within-Limits is a statistically-based method to estimate the percentage of a “lot” of material that falls within the required specifications.

A basic assumption is that the test values follow a normal distribution. The method then incorporates both the sample mean and standard deviation to estimate PWL.

Pay Factor

Definition

A multiplication factor, often expressed as a percentage, that considers a quality characteristic and is used to determine a contractor’s payment for a unit of work.

Using PWL to Compute Pay Factors

Pay Factors:

- Recoup losses expected from poor quality work
- Reward increased performance from increases in product consistency

Composite Pay Factor

Definition

A multiplication factor, often expressed as a percentage, that considers two or more quality characteristics and is used to determine the contractor’s final payment for a unit of work.
Using Composite Pay Factors

The ultimate performance of most construction items is dependent upon several quality characteristics.

Highway construction specifications usually include multiple Acceptance requirements.

When 2+ pay factor clauses appear in a single specification, they are typically combined into a Composite Pay Factor.

Example: CPFs

- Use the data presented below to determine the Composite Pay Factor.

<table>
<thead>
<tr>
<th>Quality Characteristic</th>
<th>Pay Factor (%)</th>
<th>Pay Adjustment Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder Content</td>
<td>103.2</td>
<td>20</td>
</tr>
<tr>
<td>Laboratory Air Voids</td>
<td>102.5</td>
<td>35</td>
</tr>
<tr>
<td>Voids in the Mineral Aggregate (VMA)</td>
<td>104.0</td>
<td>10</td>
</tr>
<tr>
<td>In-Place Density</td>
<td>99.8</td>
<td>35</td>
</tr>
</tbody>
</table>

\[
CPF = \frac{f_1(PF_1) + f_2(PF_2) + \ldots + f_i(PF_i)}{\sum f_i}
\]

Example: CPFs

\[
CPF = \frac{20(103.2) + 35(102.5) + 10(104.0) + 35(99.8)}{100}
\]

\[
CPF = 10185 / 100
\]

\[
CPF = 101.85 \text{ (rounds to 101.9)}
\]

Measurement of Density

- Cores taken from the field
- Nuclear gauge readings
- Non-nuclear gauge readings
- Gauges correlated to field cores

State Highway Agency (SHA) Density Specification Mining

FHWA Co-op Task 2.15 State Density Maps
Background

Goals of data mining – how to SHA’s specify mat density:

• **Methods of measure**
  - Cores, gage, roller pattern

• **Baseline measure**
  - Max. Theoretical Gravity ($G_{mm}$), lab bulk sample ($G_{mb}$), control strip

• **Sampling**
  - Lot/sublot size and how averaged

• **Spec type**
  - PWL, other advanced statistics, simple average

• Specification limits
  - Is there a compaction incentive?

The Process

- Asphalt Institute Regional Engineers gathered information from latest SHA specifications and direct agency contacts
- Data was sent to Phil Blankenship, AI Sr. Research Engineer to compile and review
- Data was reviewed with specs as much as possible
  - Since some specs allow for interpretation, there may be some mistakes.
- What we looked at:
  - Focus was on a high-level review of specifications to gather density requirements for SHA highest level compaction standard (interstate / primary route pavements)

The Good, Bad and Ugly

• Critical information was usually difficult to interpret or find. Seems to be known or understood locally.
  - Some specs referenced other documents which were sometimes hard to access.
  - Some specs had the critical information of $G_{mm}$ lots, density spread over many pages or books.
  - Some did not address when the $G_{mm}$ is measured.
  - “Specification Creep” has set in.

The Good, Bad and Ugly

• EASY and to the POINT
  - “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 ($G_{mb}$) of the cores shall be determined as stated above and the average calculated. The maximum theoretical gravity ($G_{mm}$) from acceptance testing for that shift’s production will be averaged and the percent density will be determined for compliance by dividing the $G_{mb}$ average by the $G_{mm}$ average.”
  - Most everything you need about density in one paragraph!

Density Acceptance Methods

<table>
<thead>
<tr>
<th>Core or Density Gage</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density Gage</td>
<td>8</td>
</tr>
<tr>
<td>Core</td>
<td>38</td>
</tr>
</tbody>
</table>

Number of State Highway Agencies

Density Acceptance Methods

| Method Used to Measure In-Place Density |

Source: SHA Data Analysis - SHA Asphalt Institute (Asphalt Creep)

Measure Dens. using core or density gage method.
How Is Acceptance Determined?

- Simple averaging: 23
- Other advanced statistics such as AAD: 4
- PWL: 24

Lowest Specification Density
Simple Average

Lowest Specification Density for 100% Pay - Simple Average -

Simple Average Specs

Reference Densities

Reference MS-22, Fig. 7.09
NYSDOT

• “60 series” – end result specification
  • Test strip with 4 G_{mm} samples and 4 cores (G_{mb}) taken to calibrate gauges
  • Project Target Density (PTD) selected as 94.5% of G_{mm}
  • Readings every 200 ft.
  • The minimum acceptable density reading is 96% and no greater than 103% of the PTD at a single test location and 98% of the PTD calculated as a moving average of the last 10 test locations.
  • Additional cores taken based on the number of paving days
  • Lot size not defined for routine paving – defined as the days production with 4 sublots when cores are taken
  • No incentives – just disincentives
  • All roadways not meeting the 50 series requirements, i.e., non-interstate types.

NYSDOT

• “50 series” – quality assurance specification
  • Test strip with 4 G_{mm} samples and 4 cores (G_{mb}) taken to calibrate gauges
  • A paving lot is defined as a day’s production of at least 200 tons
  • Each paving lot will be equally divided into four sublots
  • Acceptable density limits are 92-97% of G_{mm}
  • 4 cores and 4 G_{mm} samples taken each day (lot) – or 1 core and 1 G_{mb} sample per sublot
  • Incentives/disincentives applied to all lots
  • All full or partial controlled access roadways, i.e., interstates and parkways.
NYSDOT - 50 vs. 60 Series

<table>
<thead>
<tr>
<th>Specification Type</th>
<th>PWL</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incentives</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Disincentives</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Acceptance Measurement</td>
<td>Cores</td>
<td>Gauge Readings</td>
</tr>
<tr>
<td>Use</td>
<td>Interstates/Parkways</td>
<td>Non-interstate routes</td>
</tr>
</tbody>
</table>

NYSDOT – 50 vs. 60 series

<table>
<thead>
<tr>
<th>Year</th>
<th>9.5mm - 50 series</th>
<th>9.5mm - 60 series</th>
<th>12.5mm - 50 series</th>
<th>12.5mm - 60 series</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>98</td>
<td>97</td>
<td>95</td>
<td>98</td>
</tr>
<tr>
<td>2013</td>
<td>94</td>
<td>93</td>
<td>92</td>
<td>94</td>
</tr>
<tr>
<td>2014</td>
<td>92</td>
<td>91</td>
<td>90</td>
<td>92</td>
</tr>
<tr>
<td>2015</td>
<td>91</td>
<td>90</td>
<td>89</td>
<td>91</td>
</tr>
</tbody>
</table>

Measurement and Payment

- Inspection roles
- Different types of specifications
  - Method
  - End result
  - QA
- How is density measured
  - Cores
  - Gauges
    - Correlated
    - Non-correlated
- How is density calculated
  - % G_{lab} – lab or test strip
  - % G_{field} – field or lab

Discussion / Questions

Measurement and Payment
Learning Objective 10

Time for a quick Break?

15 Minute Break
Newer Technologies to Enhance Compaction

Section 6

Learning Objective 11

Improving Compaction with Technology

Newer Technologies to Enhance Compaction

- Warm Mix Asphalt (WMA)
- SHRP2 Infrared (IR)
- Intelligent Compaction (IC)
- Safety Edge

Warm Mix Asphalt

WMA - What is it?

- Plant mix asphalt produced at lower temperatures while maintaining the workability required to be successfully placed
- “Warm Mix” may be a misnomer – it’s still quite hot!

Classification by Temperature
WMA General Technology Categories

- Material Processing
  - Ex. LEA (Hot Coated Coarse Agg + Moist Fin Agg + Additives)
- Organic Additives
  - Waxes, Zeolite
- Chemical Additives
  - Surfactants
- Foaming Processing
  - Water Injection, Zeolite
- Hybrid Systems
  - Ex. H₂O + Surfactant

What % of total WMA was produced using...

2015 Survey

- 84.5%
- 15.5%

- WMA Additive
- Plant Foaming

How does it work?

Although there are several different WMA technologies and products, the basic function is to change the binder properties to allow for sufficient coating of the aggregates at lower temperatures, while maintaining good workability and durability.

WMA is an Excellent Compaction Aid!

Extended paving season/night paving/longer hauls

Reduced Aging

WMA Lanes

This Lane: HMA Control

Pavement stays blacker, longer

WMA Summary

- Reduced temperatures = reduced aging of binder
- This leads to greater crack resistance
- WMA act like compaction aides
  - Increasing the amount of time available for compaction when compared to HMA
  - Provides the opportunity for more consistent compaction
- Reduced emissions
- Better workplace
**Warm-Mix Asphalt: Best Practices, 3rd Edition**

- Stockpile Moisture Management
- Burner Adjustments and Efficiency
- Aggregate Drying and Baghouse Temperatures
- Drum Slope and Flighting
- Combustion Air
- RAP usage
- Placement Changes

http://store.asphaltavement.org/index.php?productID=552

**SHRP2 IR**

**Thermal Segregation**

- Cooling of mix during transport is not remixed during the laydown process.
- Paver set-up
- Paver operations
  - Inconsistent mix quantity
  - "Winging" the hopper
- Results in erratic mat temperatures that are not apparent to the laydown crew.

**Damage Mechanism**

- Placement of this cooler HMA creates pavement areas near cessation temperature (about 175°F)
- No significant compaction typically occurs below cessation temperature

**Another Problem**

- Localized "spots" of coarse surface texture
- Premature failure due to fatigue cracking, raveling, and moisture damage
- Increased roughness

**IR – What is it and why use it?**

Application and use of the IR-Bar and Scanner

- Continuous readings to evaluate mat uniformity through temperature uniformity.
- Non-uniform temperatures usually mean, non-uniform densities.

*Courtesy FHWA*
What is Intelligent Compaction?

An Innovation in Compaction Control and Quality Control

• IC consists of a vibratory roller that is equipped with various hardware and software tools that work together to:
  • Improve the pavement material compaction process through consistency and uniformity
  • Provide data that can be processed, viewed and analyzed by contractors/owners for enhanced evaluation of compaction related parameters

Intelligent Compaction for Asphalt

• IC technology is available from multiple suppliers in the United States
• IC offers many advantages over conventional compaction equipment for Quality Control
  • Real-time feed back to operator via color coded display
    • Mixture temperature
    • Pass count
    • Roller speed
    • Mat stiffness
  • Permanent record of compaction process and data
• IC offers a way for owner/agencies to specify innovative technology that can improve pavement life

Standard Features of Intelligent Compaction

• Double drum vibratory rollers that are equipped with:
  • Accelerometer-based IC Measurement Value (ICMV)
  • GPS-Based documentation system
  • On-Board, Color-Coded display
  • Surface temperature measurement system
  • Data produced is compatible with Veta software

Double Drum IC Rollers

BOMAG Hamm-Wirtgen Dynapac-Atlas Copco
Caterpillar Sakai Volvo

Components of an Intelligent Compaction Roller

GPS Components
On-Board, Color-Coded Display
Infrared Temperature
Documentation System

Courtesy: Sakai America
Specifications

- FHWA generic and state specifications are available for download by agencies on www.intelligentcompaction.com
  - Generic IC Specification for Asphalt Materials
  - Generic IC Specifications for Soils
- Specification recommend use of IC for quality control only (not acceptance)
  - ICMV does not correlate well enough with mat density to be used for acceptance
  - ICMV has been shown to relate to density to some degree
  - A target ICMV can be established and used for QC

Intelligent Compaction Capabilities - Asphalt

- FHWA Generic Specifications provide a comprehensive approach using “full” IC
- Agency can specify which capabilities are required:
  - “Coverage”
    - Roller passes and surface temperature only
  - “Full IC”
    - Roller passes and surface temperature
    - Use of ICMV for QC

www.intelligentcompaction.com

IC Usage Across the United States
Summary – Intelligent Compaction

- IC is a valuable tool that improves the compaction process
- IC is readily available from many manufacturers
- [www.intelligentcompaction.com](http://www.intelligentcompaction.com) is a “one stop” resource
  - Generic specs in AASHTO format
  - Information on training and support
- IC provides valuable, real time feedback to the roller operator during compaction
  - Consistent application of the optimum number of roller passes at the correct temperature
- IC can result in better and more consistent density
- IC should be used as a QC tool and not for acceptance

Questions?

The Safety Edge

- Conventional at 43°
- Safety Edge at 30°

Profile View of Safety Edge

Safety Edge and Density

- NCAT Test track construction information
  - Asphalt Base Layer → +1% Density
  - Intermediate Asphalt Layers → +4% Density
  - SMA Surface Layer → +7% Density

Additional Information

https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/safetyedge.cfm
Discussion / Questions

Improving Compaction with Technology
Learning Objective 11

Wrap Up
Section 7

Learning Objective 12

Summarizing Learning Outcomes

Maximizing Our R.O.I.

- Infrastructure loads continue to rise
- Budget availability continues to fall
- Increased pavement life can be economically achieved
- Research conservatively shows that a 10% increase in pavement life can be achieved by increasing compaction by 1%.

What would a 3% increase in compaction do for our industry?

Balance the Mix Design
Smooth Quiet Ride
Skid Resistance

- Strength/Stability
- Rut Resistance
- Shoving
- Flushing
- Resistant

Durability
Crack Resistance
Raveling
Permeability

DON’T ATTACK ONE HALF AT THE EXPENSE OF THE OTHER HALF!!

Reduce Permeability

- Finer aggregate gradations are less permeable
  - May require higher level consensus properties
  - May require higher binder contents

- Design to a **minimum** lift thickness
  - ≥ 3X NMAS on fine graded mixtures
  - ≥ 4X NMAS on coarse graded mixtures

- Do not neglect future pavement preservation
Proper Tack Coat Application

• Specify and monitor adequate tack coat application
  • Allow the use of alternate materials
    • Low Tracking tack
    • Modified materials
    • Paving grade binders

A well compacted pavement section will not perform if it is not properly bonded!!

Specify Increased Compaction

• Shoot for 94% TMD
  • Regularly achieved on airfields throughout the country.
• Use Percent Within Limit specifications
  • A 92% LSL demands 93 – 94% compaction target
  • Use a one sided test – LSL only
  • Consider high side outlier testing
• Assure Density is achieved on the road
  • Consider cores for acceptance
  • Require adequate gauge calibration
  • Regularly determine G_{mm} on plant produced mix
• Pay for increased compaction – 5% Bonus

Use Best Construction Practices

Uniform Paving Train Operation

• Determine plant production rate
• Plan for sufficient, timed mix delivery
• Establish a constant paver speed
• Assure ample rollers are available
  • Keep water trucks up to the rollers

Use Best Construction Practices

Promote Innovation

• Encourage / require Intelligent Compaction
• Use WMA – compaction aid
• SHRP2 – IR
• Consider alternative rollers
  • Pneumatic
  • Vibratory Pneumatic
  • Oscillatory
  • ?

Demo Projects’ Processes and Technologies

• None are Found on All of the Projects
• Processes:
  • Altered Rolling Pattern
    • Additional Roller Passes
    • Altered Roller Spacing
  • Added Rollers to Compaction Process
  • Modified Mix Design
    • Increased Asphalt Content
• Technology
  • Intelligent Compaction
  • Ground Penetrating Radar

Improve Longitudinal Joints

Permeable Longitudinal Joints will:

• Cause safety concerns
• Necessitate premature maintenance
• Contribute to delamination
• Severely impact the life cycle performance
• Joint density no less than 2% mat density requirement

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    • Increased Asphalt Content
• Technology
  • Intelligent Compaction
  • Ground Penetrating Radar
Preliminary Results

- Process Changes
  - Altered Roller Patterns
    - Increased Density
    - 0.3-1.9% ↑
  - Modified Mix Design
    - Increased Density
    - 1.2% ↑
- Technology
  - No Preliminary Results Available

FHWA Demonstration Project Field Project Results

- 8 of 10 projects to date
- Key Lessons:
  1. Follow best practices
     - 4 of 8 had equipment issues
     - 6 of 8 increased density from control
  2. Inter-relationship between:
     - Mix design (2 of 8)
     - Field mix verification
     - Density specification
  3. Higher density is achievable:
     - Optimistically: higher density with best practices only (8 of 8)
     - Pessimistically: higher density with additional roller (4 of 8)

Bottom Line

Increased compaction = Increased Performance
Better “Return on Investment” for the taxpayers

More Successful Pavements = More Tonnage
for the HMA Industry !!!

Thank you for your time!!!

Discussion / Questions

Summarizing Learning Outcomes
Learning Objective 12

Questions/Discussion

What is Achievable?