Introduction

- RP 175 developed a mathematical algorithm for determining a Gyratory Stability (GS) index for asphalt mixtures based on the Servopac gyratory compactor.
- The GS index describes the ability of asphalt mixtures to resist rutting.
- The GS index is determined during the mix design stage without additional required testing.
- The GS index was found to have good correlation with the Flow number and APA rutting tests.
Introduction

- The current GS index algorithm was developed for the Servopac gyratory compactor.
- ITD has adopted the use of Pine gyratory compactor in all districts as well as at headquarter labs. Therefore, it is essential to develop a modified mathematical algorithm for Pine Gyratory Compactor.
- Furthermore, there is a need to examine the sensitivity of GS index to the binder and RAP contents in asphalt mixtures.

Study Goal

- Investigate the Gyratory Stability and or other gyratory compaction indicators to detect the variability of RAP content and binder content in HMA mixes.
- Evaluate the effect of mix composition (binder and RAP content) on mix performance.
Compaction Curves

Part A
• represents densification of loose mixes (steep change in slope)
• aggregates do not experience significant amount of shear forces

Part B
• height does not change significantly and air voids relatively constant.
• aggregates experience more particle contacts and shear stresses.
• Most of the energy is dissipated through aggregate sliding. Consequently, it increases sample shear strength.
• Therefore, Part B is of interest to calculate the mix stability at ambient temperature

Compaction Indices

○ Various compaction indices were investigated including:
  • Gyratory Stability (GS)
  • Construction Densification Index (CDI)
  • Laboratory Compaction index (LCI)
  • Compaction Force Index (CFI)
  • Locking Point (LP)
  • Compactability Energy Index (CEI)
  • Workability Energy Index (WEI)

○ Different studies showed that some indices are more sensitive to the change in mix composition than others.
### Development of Testing Matrix

**Laboratory-Mixed Laboratory-Compacted (LMLC) Test Specimens**

<table>
<thead>
<tr>
<th>Mix type</th>
<th>SP5</th>
<th>RAP</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
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<tbody>
<tr>
<td>RAP Sources</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AV%</td>
<td>4%</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate Type</td>
<td>Basalt</td>
<td>River Gravel</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Binder Grade</td>
<td>PG 76-22</td>
<td>PG 64-28</td>
<td>PG 58-34</td>
<td></td>
<td></td>
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<tr>
<td>Binder Content</td>
<td>OBC</td>
<td>OBC+0.75%</td>
<td>OBC-0.75%</td>
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<td></td>
</tr>
<tr>
<td>Anti-Stripping agent</td>
<td>0%</td>
<td>1.50%</td>
<td></td>
<td></td>
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</tbody>
</table>

### Development of Testing Matrix

**Plant-Mixed Laboratory-Compacted (PMLC) Test Specimens**

<table>
<thead>
<tr>
<th>Mix #</th>
<th>District</th>
<th>Project ID</th>
<th>Construction Year</th>
<th>Project Key No.</th>
<th>Location</th>
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<tr>
<td>1</td>
<td>D1</td>
<td>P1-b1</td>
<td>2020</td>
<td>20794</td>
<td>US-95, I-84/86 Interchange System</td>
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<tr>
<td>2</td>
<td>D1</td>
<td>P1-b1</td>
<td>2020</td>
<td>20795 &amp; 19794</td>
<td>Sh-81, Declo to Burley</td>
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<tr>
<td>3</td>
<td></td>
<td>P1-b2</td>
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<td>18881</td>
<td>US-95, Garwood Rd &amp; H-57, Priest River Boat Access</td>
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<tr>
<td>4</td>
<td>D3</td>
<td>P5-b1</td>
<td>2020</td>
<td>19711</td>
<td>US-Ashton Bridge to Dumpground Road</td>
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<tr>
<td>5</td>
<td>D3</td>
<td>P5-b2</td>
<td>2020</td>
<td>19711</td>
<td>US-Ashton Bridge to Dumpground Road</td>
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<tr>
<td>6</td>
<td>D3</td>
<td>P5-b3</td>
<td>2019</td>
<td>19711</td>
<td>US-Ashton Bridge to Dumpground Road</td>
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<tr>
<td>7</td>
<td>D6</td>
<td>P1-b1</td>
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<td>20794</td>
<td>US-95, I-84/86 Interchange System</td>
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<tr>
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<td>P1-b2</td>
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<td>18881</td>
<td>US-95, I-84/86 Interchange System</td>
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<td>9</td>
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<td>US-95, I-84/86 Interchange System</td>
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<td>D1</td>
<td>P2-b1</td>
<td>2019</td>
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<td>US-95, I-84/86 Interchange System</td>
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<td>P2-b2</td>
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<td>US-95, I-84/86 Interchange System</td>
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<td>12</td>
<td>D1</td>
<td>P2-b3</td>
<td>2019</td>
<td></td>
<td>US-95, I-84/86 Interchange System</td>
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<tr>
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<td>D4</td>
<td>P1-b1</td>
<td>2020</td>
<td>20170</td>
<td>Sh-81, Declo to Burley</td>
</tr>
<tr>
<td>14</td>
<td>D4</td>
<td>P1-b2</td>
<td>2020</td>
<td>20170</td>
<td>Sh-81, Declo to Burley</td>
</tr>
<tr>
<td>15</td>
<td>D4</td>
<td>P1-b3</td>
<td>2020</td>
<td>20170</td>
<td>Sh-81, Declo to Burley</td>
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</table>
Task 2: Development of Testing Matrix

Plant-Mixed Laboratory-Compacted (PMLC) Test Specimens

<table>
<thead>
<tr>
<th>Project #</th>
<th>District</th>
<th>Project ID</th>
<th>Mix Type</th>
<th>Specified Binder PG</th>
<th>Virgin Binder PG</th>
<th>Binder Content Pb (%)</th>
<th>RAP (%)</th>
<th>NMAS</th>
<th>Theoretical Specific Gravity (Gmm)</th>
<th>Bulk Specific Gravity (Gsb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D1</td>
<td>D1-P1</td>
<td>SP3</td>
<td>PG64-28</td>
<td>PG 58-34</td>
<td>5.2</td>
<td>30</td>
<td>1/2”</td>
<td>2.473</td>
<td>2.646</td>
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<tr>
<td>2</td>
<td>D3</td>
<td>D3-P5</td>
<td>SP3</td>
<td>PG64-34</td>
<td>N/A</td>
<td>5.4</td>
<td>0</td>
<td>1/2”</td>
<td>2.430</td>
<td>2.571</td>
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<tr>
<td>3</td>
<td>D6</td>
<td>D6-P1</td>
<td>SP5</td>
<td>PG64-34</td>
<td>PG64-34</td>
<td>5.9</td>
<td>16</td>
<td>3/4”</td>
<td>2.382</td>
<td>2.481</td>
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<td>4</td>
<td>D1</td>
<td>D1-P2</td>
<td>SP3</td>
<td>PG64-28</td>
<td>PG 58-34</td>
<td>5.3</td>
<td>30</td>
<td>1/2”</td>
<td>2.476</td>
<td>2.654</td>
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<tr>
<td>5</td>
<td>D4</td>
<td>D4-P1</td>
<td>SP5</td>
<td>PG70-28</td>
<td>N/A</td>
<td>5.1</td>
<td>17</td>
<td>3/4”</td>
<td>2.414</td>
<td>2.559</td>
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<tr>
<td>6</td>
<td>D4</td>
<td>D4-P2</td>
<td>SP3</td>
<td>PG64-28</td>
<td>N/A</td>
<td>6.2</td>
<td>17</td>
<td>1/2”</td>
<td>2.293</td>
<td>2.417</td>
</tr>
</tbody>
</table>

Develop Mathematical Algorithm for GS

Load cells measure force vector in the actuator arm.

Actuators apply angle of gyration and drives the gyrations.

Generating a Value for Gyratory Shear
Pine's Gyratory Shear Measurement
Develop Mathematical Algorithm for GS

$$\sum_{M_0} = 0$$
$$2R \cdot \cos(\delta) - (F_g \cdot h/2) - (\omega/2 \cdot \sin(\delta)) = 0$$

Since $\delta$ is small angle, we can assume $\sin(\delta) = 0$ and $\cos(\delta) = 1$

$$2R \cdot e - F_g \cdot h/2 = 0$$

$$F_g = \frac{2R \cdot e}{h/2} = \frac{4R \cdot e}{h}$$

at half of the sample

So, the shear force ($F_g$) can be calculated at any gyration number.

$$F_g = \frac{2R \cdot e}{h}$$
$$M = R \cdot e$$
$$F_{gi} = \frac{2M_i}{h_i}$$

The shear stress ($S_{gi}$) can be calculated at any gyration number as:

$$S_{gi} = \frac{2M_i}{Ah_i}$$

Develop Mathematical Algorithm for GS

GS: the summation of shear energy increments between $N_{g2}$ and $N_{g1}$

$$GS = \sum_{N_{g1}}^{N_{g2}} \{(2M_i/h_i)(\Delta h_i)\}$$

where:

$N_{g1}$ = the number of gyrations at which the second derivative of the air voids function with respect to the number of gyrations is zero. It is assumed that particle contacts are developed at $N_{g1}$.

$N_{g2}$ = the gyration number corresponding to 96% Gmm

$M_i$ = the moment at each gyration number, which is readily measured and provided in the Pine Excel spreadsheet.
Laboratory Testing

Gyratory Stability and other compaction Indices
Asphalt Pavement Analyzer (APA-Jr)
Hamburg Wheel Tracking Test (HWTT)
Indirect Tensile Strength (IDT)
Dry and Wet

Compaction Indices

Gyratory Stability (GS) Sensitivity to Different Binder Contents

GS decreased with the increase in binder content; there was statistically significant difference between (dry vs. wet) samples but not between 4.25% and 5% for all cases.
Compaction Indices

**Laboratory Compaction Index (LCI) Sensitivity to Different Binder Contents**

LCI increased with the increase in binder content; there was statistically significant difference between (dry vs. wet) samples but not between 4.25% and 5%

\[
\text{Laboratory Compaction Index} = 100 \times \frac{b^{1.2}}{a}
\]

where,

- \(a\) = The intercept of the compaction curve
- \(b\) = The slope of the compaction curve (absolute value)

- The LCI: A function of the absolute value of the slope \((b)\) and intercept \((a)\), of the laboratory compaction curve
- Asphalt mixtures with higher LCI values are easier to compact compared to those with lower LCI values
Task 4: Laboratory Testing Compaction Indices

Compaction Densification Index (CDI) Sensitivity to Different Binder Contents

CDI decreased with the increase in binder content; there was statistically significant difference between (dry vs. wet) samples but not between 4.25% and 5% for all cases.

Construction Densification Index (CDI)

\[
CDI = \sum_{N_{=8}}^{N_{92}} \%G_{mm}
\]

- \(\%G_{mm}\) = Percent maximum density
- \(N_{=8}\) = Gyration number 8
- \(N_{92}\) = Number of gyrations at 92% \(G_{mm}\)

The CDI: the area measured under the densification curve from the eighth gyration to the number of gyrations at 92% of the theoretical maximum specific gravity (Gmm)
Compaction Indices

Other compaction Indices.....

- Compaction Force Index (CFI)
- Locking Point (LP)
- Compactability Energy Index (CEI)
- Workability Energy Index (WEI)

Gyratory Stability (GS) Sensitivity to Different RAP Contents

No consistent trend for the effect of RAP content on GS;
No significant difference in the results
Compaction Indices

Laboratory Compaction Index (LCI) Sensitivity to Different RAP Contents

No consistent trend for the effect of RAP content on LCI;
No significant difference in the results

Compaction Indices

Compaction Densification Index (CDI) Sensitivity to Different RAP Contents

No consistent trend for the effect of RAP content on CDI;
No significant difference in the results
Compaction Indices

**Gyratory Stability (GS) for RAP1 and RAP2**

No consistent trend for the effect of binder source on GS;
No significant difference in the results

**Laboratory Compaction Index (LCI) for RAP1 and RAP2**

No consistent trend for the effect of binder source on LCI;
No significant difference in the results
Compaction Indices

Compaction Densification Index (CDI) for RAP1 and RAP2

No consistent trend for the effect of binder source on CDI;
No significant difference in the results

Gyratory Stability (GS) of PMLC Mixes

Batch 1
Batch 2
Batch 3
Laboratory Testing Compaction Indices

Laboratory Compaction Index (LCI) of PMLC Mixes

Compaction Densification Index (CDI) of PMLC Mixes
Laboratory Testing Rutting

Rutting Performance Results

APA Rutting Depths at Different Binder Contents (PG58-34)
Laboratory Testing Rutting

Hamburg Rutting Depths at Different Binder Contents (PG58-34)

APA Rutting Depths at Different RAP Contents

APA rut depth is less than 5 mm
Laboratory Testing Rutting

**Hamburg Rutting Depths at Different RAP Contents**

Overall, mixtures with RAP had less HWTT rut depth; HWTT was less than 12.5 mm

**Hamburg Rutting Depths of PMLC Mixes**

HWTT was less than 12.5 mm after 20,000 passes
Laboratory Testing Rutting

**Correlation between GS and APA Rutting Data of LMLC Mixes**

**Correlation between GS and Hamburg Rutting Data of LMLC Mixes**

**Correlation between CDI and APA Rutting Data of LMLC Mixes**

**Correlation between CDI and Hamburg Rutting Data of LMLC Mixes**
Laboratory Testing Rutting

Correlation between LCI and APA Rutting Data of LMLC Mixes

Correlation between LCI and Hamburg Rutting Data of LMLC Mixes

Correlation between GS, CDI, LCI and Hamburg Rutting Data of PMLC Mixes
Laboratory Testing Cracking

- Monotonic IDT Cracking resistance indicators
  - IDEAL-CT\textsubscript{Index}
  - Cracking Resistance Index (CRI)
  - N\textsubscript{flex}
  - Weibull\textsubscript{CRI}
  - Fracture Energy (G\textsubscript{f})
  - IDT\textsubscript{Strength}
  - IDT\textsubscript{Modulus}
  - Flexibility Index (FI)

**Effect of Binder Grade/Content and RAP Content on IDEAL-CTIndex**
Laboratory Testing Cracking

Effect of Binder Grade/Content and RAP Content on WeibullCRI

Effect of Binder Grade/Content and RAP Content on IDT strength
Laboratory Testing Cracking

Effect of Binder Grade/Content and RAP Content on IDT Modulus

- D4-P2: higher binder content (6.2%) and lower RAP content (17%)
- D3-P5: 0% RAP and 5.4% binder content; was dry during compaction
Laboratory Testing Cracking

WeibullCRI of PMLC

Laboratory Testing Cracking

IDT Strength of PMLC
Laboratory Testing Cracking

**IDT Modulus of PMLC**

![Graph showing IDT Modulus of PMLC with different batches and samples](image)

**Coefficient of Variation (COV) in Cracking Performance Indicators of Mixes**

![Graph showing Coefficient of Variation for various test indicators](image)
Evaluation of Compaction and Stability Indices

- Based on the comprehensive evaluation of the results of the compaction indices, the GS, CDI, and LCI were found to be sensitive to binder content; however, all the compaction indices were less sensitive to the change in the RAP content and binder grade.
- The GS decreased with the increase in binder content for all mixes (with and without RAP) for different binder grades. Drier mixtures required more energy needed for compaction than softer mixtures.

Evaluation of Rutting Performance and Moisture Susceptibility

- The rutting performance evaluation using the APA rut test and HWTT showed that all LMLC and PMLC had good resistance to rutting. In addition, there was no sign for moisture damage for all mixtures tested using HWTT.
- The APA and HWTT rut depth increased with the increase in binder content as expected. However, there was a statistically significant difference in the APA rut depth results between mixtures with 5.75% binder content and 4.25% binder content, while the difference in the HWTT results was not statistically significant between 5.75% and 4.25% binder content.
Evaluation of Rutting Performance and Moisture Susceptibility

- Overall, mixtures prepared with RAP tended to have slightly less rutting compared to mixtures without RAP at the corresponding binder contents, but the difference was not statistically significant.
- The LCI showed a better correlation with the APA rut depth ($R^2 = 0.64$).

Evaluation of Cracking Performance

- The results demonstrated that the IDTModulus and IDTStrength were able to capture the change in binder content, binder grade, and RAP content. Other indices including IDEAL-CT Index, WeibullCRI, CRI, and Nflex factor were sensitive to binder content and RAP contents from the second source of RAP. Overall, the cracking resistance improved with the increase in binder content as expected. Also, all mixtures prepared at different RAP contents (up to 50%) from the first source of RAP had good resistance to cracking; however, the mixtures prepared with the second source of RAP did not show this trend.
Evaluation of Cracking Performance

- The results also illustrated that the cracking performance of mixtures prepared with RAP (up to 50%) from the second source of RAP can be improved by increasing the binder content. This indicates the importance of the balanced mix design when incorporating RAP materials in asphalt mixtures.

Implementation

- ITD may consider implementing and applying a balanced (engineered) mix design concept for asphalt mixtures prepared with high RAP content to ensure that such mixtures have adequate resistance to cracking and rutting comparable or superior to the control mix. The results of this study showed that adjusting the binder content improved the cracking performance of mixtures prepared with up to 50% RAP.
Questions.......