DEVELOPMENT OF A SIMPLE METHOD FOR DETERMINING MIXING AND COMPACTION TEMPERATURES FOR HOT-MIX ASPHALT

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Malvern Instruments

Recommendations from NCHRP 9-39
Outline

- Background
  - Problem statement
  - Project objectives
- Research plan
  - Binder tests: Candidate methods
  - Mixture tests
  - Materials
Outline

- The Steady Shear Flow Method
- The Phase Angle Method (AKA the Casola Method)
- Correlations with Mixture Test Results
- Correlation of SSF and Casola Results
- Recommendations
- Limitations of the methods
The Asphalt Institute Equi-Viscous Method

![Graph showing temperature and viscosity relationship with compaction and mixing ranges highlighted.](image)

**Viscosity, Pa·s**
- 10
- 5
- 1
- 0.5
- 0.3
- 0.2
- 0.1

**Temperature, °C**
- 100
- 110
- 120
- 130
- 140
- 150
- 160
- 170
- 180
- 190
- 200

- **Compaction Range**
- **Mixing Range**
Modified binders have significantly different temperature susceptibility.
Viscosity

Shear Stress

μ

μ

Shear Rate

μ

μ

Pseudoplastic Fluid

Newtonian Fluid
Viscosity

- Newtonian Fluid
- Power Law Region
- Shear Thinning Fluid
- 1st Newtonian Region
- 2nd Newtonian Region
Background

- The Asphalt Institute equiviscous concept works well for unmodified, unfilled binders.
- For most modified binders, the equiviscous concept results in excessive mixing and compaction temperatures:
  - Emission concerns
  - Binder degradation concerns
- Most specifying agencies have relied on binder suppliers to recommend appropriate temperatures. However, no consensus exists on how that should be done.
Does Compaction Temperature matter?

- The SGC compaction process is insensitive to binder stiffness because the compactor operates in a constant strain mode.
  - Temperature has almost negligible effect on volumetric properties.
  - However, mechanical tests on HMA are affected by mixing and compaction temperatures.
Candidate Methods for Determining Mixing & Compaction Temperatures

- Keep it Simple (binder test)
- Use Existing Equipment
- Work for Modified and Unmodified Binders
  - High Shear Rate Viscosity (Yildirim)
  - Steady Shear Flow (Reinke)
  - Dynamic Shear Rheology (Casola)
High Shear Rate Viscosity Method
High Shear Viscosity

Binder Viscosity

Shear rate during compaction

unmodified

modified

Shear Rate
High Shear Viscosity

Rotational Viscosity
180°C

Viscosity, PaS

Shear Rate, 1/sec

Viscosity, PaS

Rotational Viscosity
180°C

Viscosity, PaS

Shear Rate, 1/sec

High Shear Viscosity

76-22

76-22+Sasobit

67-22

0 10 20 30 40 50 60 70 80 90 100

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

0 10 20 30 40 50 60 70 80 90 100

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

0 10 20 30 40 50 60 70 80 90 100
Steady Shear Flow Method
Steady Shear Flow Test

PG 76-22 Steady Shear Flow #2
Extrapolation of SSF Viscosity

Temperature, C
Viscosity, Pa-s

Mixing Range
Compaction Range

52 58 64 70 76 88 82 88 100 120 135 150 165 180 200
Steady Shear Flow Method

- **Mixing Temperature (°F)**
  \[ T_m \rightarrow 0.17 \pm 0.02 \text{ Pa} \cdot \text{s} \]

- **Compaction Temperature (°F)**
  \[ T_c \rightarrow 0.35 \pm 0.03 \text{ Pa} \cdot \text{s} \]
Steady Shear Flow (Viscosity) Method

- Use standard DSR (meets requirements of AASHTO T 315)
- Most DSRs have routine for Steady Shear Flow test (application of a steady torsional shear stress)
- Sample preparation is same as T 315, unaged sample
- 0.5 mm gap
- Stress levels: 0.3, 0.5, 0.8, 1.3, 2, 3, 5, 8, 13, 20, 30, 50, 80, 130, 200, 300, and 500 Pa
- 76, 82, and 88°C (higher temperatures cause trouble with water baths)
- Binders that give trouble: heavily modified, no problem with rubber
Casola (Phase Angle) Method
Background on the Casola Method

- Mixing stresses & shear rates are extremely complex

- The ability to coat & compact differ from ‘Neat’ to ‘Modified’ binders

- The transition from Newtonian to non-Newtonian behavior makes for an easily identifiable threshold to rank these binders
Superpave Grade Temp $G^*$ at 10 rad/sec

Legend:
- HUSKY C, FREQUENCY 60°C
- HUSKY C, FREQUENCY 70°C
- HUSKY C, FREQUENCY 80°C
- HUSKY C, FREQUENCY 90°C
- HUSKY C, FREQUENCY 100°C
- HUSKY C, FREQUENCY 110°C
- HUSKY O, FREQUENCY 50°C
- HUSKY O, FREQUENCY 60°C
- HUSKY O, FREQUENCY 70°C
- SUPERPOSITION
- SUPERPOSITION: 1
Superpave Grade Temp Phase Angle at 10 rad/sec
Phase Angle Identifies the Amount of Modification

- O unmodified
- C modified

The graph shows the relationship between the phase angle and the amount of modification. The x-axis represents different frequencies, while the y-axis shows the amount of modification. Points 'O' and 'C' indicate unmodified and modified states, respectively.

Legend:
- HUSKY C, FREQUENCY 60C
- HUSKY C, FREQUENCY 70C
- HUSKY C, FREQUENCY 80C
- HUSKY C, FREQUENCY 90C
- HUSKY C, FREQUENCY 100C
- HUSKY O, FREQUENCY 110C
- HUSKY O, FREQUENCY 50C
- HUSKY O, FREQUENCY 60C
- HUSKY O, FREQUENCY 70C
- SUPERPOSITION
- SUPERPOSITION:1
Flow Behavior of Asphalt; Time - Temperature Dependence

From the Asphalt Institute
Superpave
Binder Testing Manual
Background on the Casola Method

- Phase angle of 86° is an easily identifiable transition point of the material exhibiting Visco-Elastic behavior for comparison.

- To see this transition over a reasonable range of frequency, the procedure investigates these samples at a reference temperature of 80°C.

- The procedure uses higher temps for modified & lower temps for unmodified asphalt binders.
Low freq relates to high temps & High freq low temps

Frequency inversely relates to Temperature:

- High Temperatures
  - C modified

- Low Temperatures
  - O unmodified
The Casola Method; 86° Phase Angle Data at 80°C
Concept of the Mixing Temperature Chart

![Graph showing estimated mixing temperature with frequency and temperature axes.](image-url)
Casola Method Equations

- *Mixing Temperature (°F) = 325ω^{-0.0135}*

- *Compaction Temperature (°F) = 300ω^{-0.012}*
### Calculations

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Modification Type</th>
<th>DSR Data Collected temp (°C)</th>
<th>DSR Data Collected phase (°)</th>
<th>DSR Data Collected freq (rad/sec)</th>
<th>Temperature (°F) mix</th>
<th>Temperature (°C) compaction</th>
<th>Temperature (°F) mix</th>
<th>Temperature (°C) compaction</th>
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<td>62.6</td>
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<td>285</td>
<td>153</td>
<td>141</td>
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</table>

*Equation 1: 325(freq)^{-0.0135}*

*Equation 2: 300(freq)^{-0.012}*

Using the CASOLA Method to determine the asphalt binder mix & compaction temperature.
The Procedure...

- Test asphalt binders using existing DSRs
4.4 The required temperatures to test the sample will depend on the Performance Grade (PG) of the binder. Lower PG binders will be tested at lower temperatures while higher PG binders will be tested at higher temperatures. All grades will be tested at 80°C. The chart in Table 1, below provides a guide to temperature selection.

**Table 1**—Temperature testing schedule

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>46</th>
<th>52</th>
<th>58</th>
<th>64</th>
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<th>75</th>
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<td>xx</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>xx</th>
<th>May be required to achieve a phase angle of 75 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxx</td>
<td>May be required to achieve a phase angle of 88 degrees</td>
</tr>
</tbody>
</table>

4.5 Test specimens 1 mm thick by 25 mm in diameter are formed between parallel metal plates. During testing, one of the parallel plates is oscillated with respect to the other at pre-selected frequencies and rotational deformation amplitudes (strain control) (or torque amplitudes (stress control)). The required stress or strain amplitude depends upon the value of the complex shear modulus of the asphalt binder being tested. The required amplitudes have been selected to ensure that the measurements are within the region of linear behavior.
Test set up

- Freq sweep
- 0.1 to 100 rad/sec
- 12% strain
- At defined temperatures
Analysis requires the creation of a master curve
Superposition helps in the analysis
Superposition Variables

Superposition (New Analysis) : Step 3 of 6 - Select Variables

Tag: Superposition

- **X Variable:** Angular Frequency
  - Use Log X

- **Y Variable:** Phase Angle
  - Use Log Y

- **Iso Variable:** Temperature
Reference Temperature at 80°C
Master Curve Results
Shift Factors are used to check data quality
X15. VERIFICATION OF MASTER CURVE WORKING DATA BY USING BLACK SPACE DIAGRAM

X15.1. A good example of a Black Space diagram where there is shown a continuous curve exhibited in the results (Figure X15.1). This is where there are not obvious discontinuities.

FIGURE X15.1- Good example of Black Space diagram
Discontinuities are an example of poor data

X15.2. A poor example of a Black Space diagram, where there are obvious discontinuities in the results (Figure X15.2). In the case of a poor Black Space, the data should be retested with particular attention to ensuring all the data are collected in the linear visco-elastic region by ensuring the correct strains are applied properly to all frequencies and that the temperatures are correct for each frequency tested. (Figure X15.2)
Summary Review

- Collect family of Freq Sweep at various temps as needed to collect phase angle data crossing 86°.
- Perform WLF time-temp superposition master curve for results shifted to 80°C.
- Check shift factors and/or Blacks curves to verify data quality.
- Identify the Frequency where the phase angle equals 86° within +/-0.1° phase angle.
- Calculate mixing temp using 325(freq)\(^{-0.0135}\).
- Calculate compaction temp using 300(freq)\(^{-0.012}\).
RESEARCH PLAN
Research Approach

- Use candidate methods to predict mixing and compaction temperatures
- Check reasonableness
- Use mix tests to validate mixing and compaction temperatures
- Use correlation analyses between predicted mix and compaction temps with mix test results
- Determine temperature limits that cause binder degradation and emissions problems
14 Asphalt Binders

Part 1: Binder Testing
- Steady Shear Flow Tests
- Rotational Viscosity Tests
- Dynamic Shear Rheology
- Smoke & Emissions Potential Test
- Grade Binders Before & After SEP

Part 2: Mix Testing
- Mix Coating Tests
- Mix Workability Tests
- Mix Compaction Tests
- IDT Creep & Strength Test

Predict Mix & Compaction Temps
- Correlations & Reasonableness
- Check for Excessive Temps
- Determine Minimum Mixing Temps
- Determine Intermediate Mix Handling Temps
- Determine Compaction Temps Range
- Determine Effect of Temps on Mix Props

Establish Max Temp to Avoid Emissions
- Establish Max Temp to Avoid Degradation

Select Best Method
- 4 Asphalt Binders
- Validation of Method

Draft New Test Method for Establishing Mixing & Compaction Temperatures
## High Shear Viscosity method results

<table>
<thead>
<tr>
<th>Binder ID</th>
<th>True Grade</th>
<th>Mixing Temperature</th>
<th></th>
<th></th>
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<tbody>
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<td></td>
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<td>Equiviscous Method</td>
<td>High Shear Viscosity</td>
<td>Equiviscous Method</td>
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<tr>
<td>M</td>
<td>85.5 -19.5</td>
<td>372 (189)</td>
<td>363 (184)</td>
<td>343 (173)</td>
</tr>
<tr>
<td>N</td>
<td>84.3 -25.5</td>
<td>433 (223)</td>
<td>433 (223)</td>
<td>401 (205)</td>
</tr>
<tr>
<td>G</td>
<td>82.5 -24.2</td>
<td>379 (193)</td>
<td>372 (189)</td>
<td>352 (178)</td>
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<td>H</td>
<td>78.3 -26.1</td>
<td>365 (185)</td>
<td>363 (184)</td>
<td>338 (170)</td>
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<tr>
<td>C</td>
<td>75.1 -38.7</td>
<td>388 (198)</td>
<td>385 (196)</td>
<td>355 (179)</td>
</tr>
<tr>
<td>I</td>
<td>71.8 -29.2</td>
<td>333 (167)</td>
<td>333 (167)</td>
<td>311 (155)</td>
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<td>352 (178)</td>
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<tr>
<td>F</td>
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<td>318 (159)</td>
<td>298 (148)</td>
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SSF method results

<table>
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## Casola method results

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<th>Binder ID</th>
<th>True Grade</th>
<th>Freq. at $\delta=86$ $T=80 , ^{\circ}C$</th>
<th>Mixing Temp. $F , (^{\circ}C)$</th>
<th>Compaction Temp. $F , (^{\circ}C)$</th>
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</table>
Mix Coating Tests

- Lab Pugmill Mixer and Bucket Mixer to simulate Batch Plant and Drum Plant Mixing
- Mix binders with a standard aggregate blend at four temperatures for a set time
- Rate aggregate coating percentage using Ross count

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<thead>
<tr>
<th>Mixing Temperature (C)</th>
<th>Percent Coated (decimal)</th>
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<td>186.0</td>
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\[ S = 0.02273991 \]
\[ r = 0.99150818 \]
Mix Compactability

- Four compaction temperatures
- Used 25 gyrations to amplify effect of binder stiffness

<table>
<thead>
<tr>
<th>Temperature, C</th>
<th>% Gmm</th>
<th>Granite Base Mix</th>
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<td></td>
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<td>y = 0.0182x + 90.26, R^2 = 0.589</td>
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<tr>
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<td></td>
<td>y = 0.0193x + 89.51, R^2 = 0.8498</td>
</tr>
<tr>
<td></td>
<td></td>
<td>y = 0.0228x + 89.085, R^2 = 0.7794</td>
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</table>
Mix Workability

Binder H-1

\[ y = 0.002x^2 - 0.834x + 95.567 \]

\[ R^2 = 0.8922 \]
CORRELATION ANALYSES: REGRESSIONS BETWEEN RESULTS OF CANDIDATE METHODS TO MIXTURE TESTS
## Statistical Comparison of Results

<table>
<thead>
<tr>
<th>Mix Test</th>
<th>Steady Shear Flow</th>
<th>Casola</th>
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<tr>
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<td>Coating: Bucket</td>
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<td>Coating: Pugmill</td>
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<td>Compaction</td>
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Comparison of SSF and Casola Results

SSF Mix T = -79.22 + 1.228 Phase Angle Mix T

Regression
95% CI
95% PI

S 6.40025
R-Sq 91.0%
R-Sq(adj) 90.1%
Smoke & Emissions Potential

- Stroup-Gardiner and Lange
- Oven with Opacity Meter and Internal Balance
- Tests conducted at 130, 150, 170, and 190°C
- Use to evaluate maximum temperature binder can be used without degrading the binder or causing emission problems.
Opacity Results

Modified Binders

Unmodified Binders
Opacity at Producers’ Recommended Mixing Temp.
Evaluation of Degradation of SEP Conditioned Binders

1. changes in the true grade critical high temperature of the binders
2. changes in the true grade critical low temperature of the binders
3. changes in the phase angle of the binders at their respective grade temperatures
4. changes in the MSCR non-recoverable creep compliance
# Change in High Temp Grade

<table>
<thead>
<tr>
<th>Binder ID</th>
<th>True Grade</th>
<th>SEP Temperature (°C)</th>
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<th></th>
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<td>G</td>
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## Change in Low Temp Grade

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## Change in Phase Angle

<table>
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<th>SEP Temperature (°C)</th>
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<tbody>
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<tr>
<td>Avg. of Unmodified Binders</td>
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<td>-0.5</td>
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</tbody>
</table>
MSCR Non Recoverable Compliance (Jnr)

Unmodified Binders

Modified Binders
Observations on Binder Degradation from SEP test

- Opacity increases with temperature
- Opacity does not appear to be related to grade, or modification
- Four binders had mass losses > 1.0% which has been linked to high odor potential
- 8 of 13 binders increased high PG grade one level (e.g. PG 70- to a PG 76)
- 7 of 13 binders increased low PG grade level (e.g. -28 to a -22)
Creep Compliance and Strength

- Specimens compacted at 110, 130, 150, and 170°C
- AASHTO T 322
  - Compliance at -20, -10, 0°C
  - Strength at -10 or 0
Creep Compliance – PG Low Temp. Relationships

\[ y = 0.0493e^{-0.0855x} \quad R^2 = 0.8206 \]

\[ y = 0.0456e^{-0.078x} \quad R^2 = 0.8710 \]

\[ y = 0.0615e^{-0.0882x} \quad R^2 = 0.8207 \]

\[ y = 0.0517e^{-0.081x} \quad R^2 = 0.8108 \]
Creep Compliance – PG Low Temp Relationships

![Graph showing creep compliance at different temperatures and load factors.]

Creep Compliance at 0°C x 10^-6 1/kPa

Low PG Temperature

110
130
150
170

CC = 20.9x0.93^PGxTcomp^-1.131
Recommendations

- Steady Shear Flow or Phase Angle (Casola) Method are options for determining mixing and compaction temperatures.
- Both methods can be easily included in routine PG binder testing.
- These methods should be further evaluated by users to compare the results to their current recommendations and assess the validity of results.
Limitations

- The recommended procedures are based only on binder characteristics. Other factors that effect coating and compactability include:
  - Aggregate & mineral filler characteristics
  - RAP & other recycled materials
  - Warm mix additives/processes

- The methods are not suitable for binders containing:
  - Some WMA technologies
  - Rubber
Different Views on Lab and Field Use of Mixing and Compaction Temperatures

- Some agencies set strict tolerances on discharge temperatures for plant mix using equiviscous temperatures.
- Some agencies consider equiviscous mixing and compaction temperatures applicable to the lab and use global temperature ranges in the field.
Any Questions?