ARC Project Update

Asphalt Binder Lubricity, Impacts of WMA on Energy and Emissions

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Warm Mix Technical Working Group Meeting

May 18, 2010
Auburn, AL

Outline of Talk

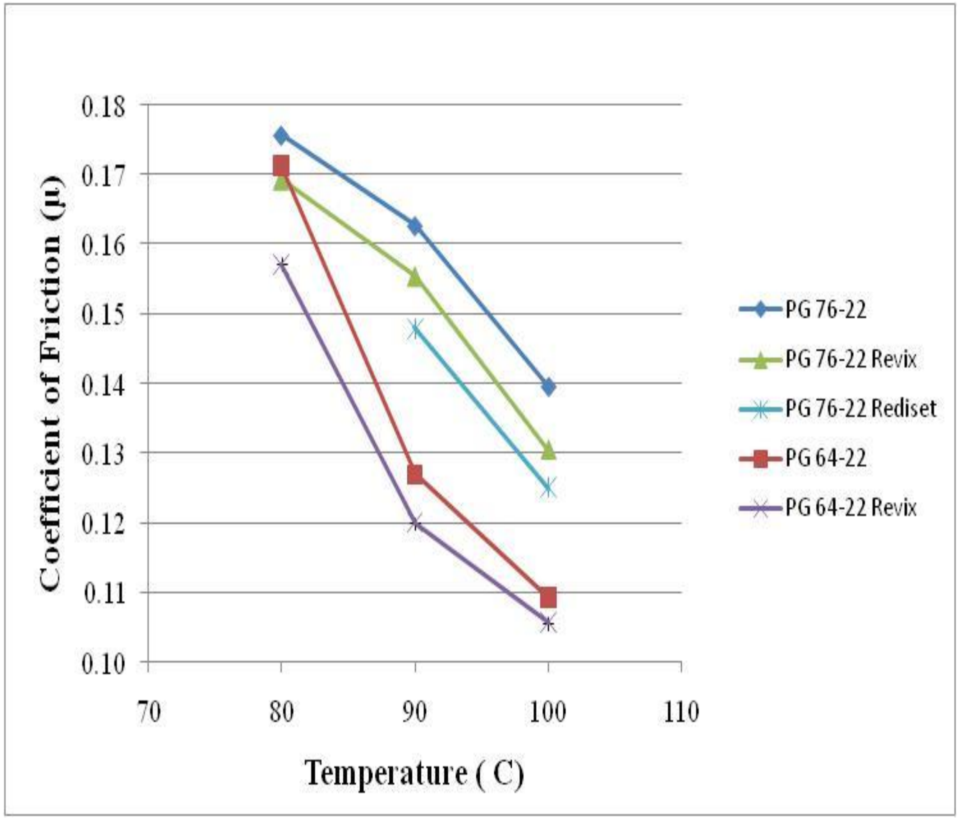
- Asphalt Binder Lubricity
  - New Procedure for Higher Temperatures
  - Preliminary Results
  - Relationship with Mixture Workability Parameters
- Impact of Reduced Production Temperatures
  - Energy Consumption
  - Emissions: Laboratory Measurements and Field

Study Main Objectives

- Verfify Warm Mix Additives (WMA) Effects
  - Reducing viscosity
  - Lubrication
- Determine how much is needed.
  - WMA content versus temperature reduction
  - Cost is based on content, justify use by saving heat energy and recuing emissions

Asphalt Binder Lubricity – Previous Results

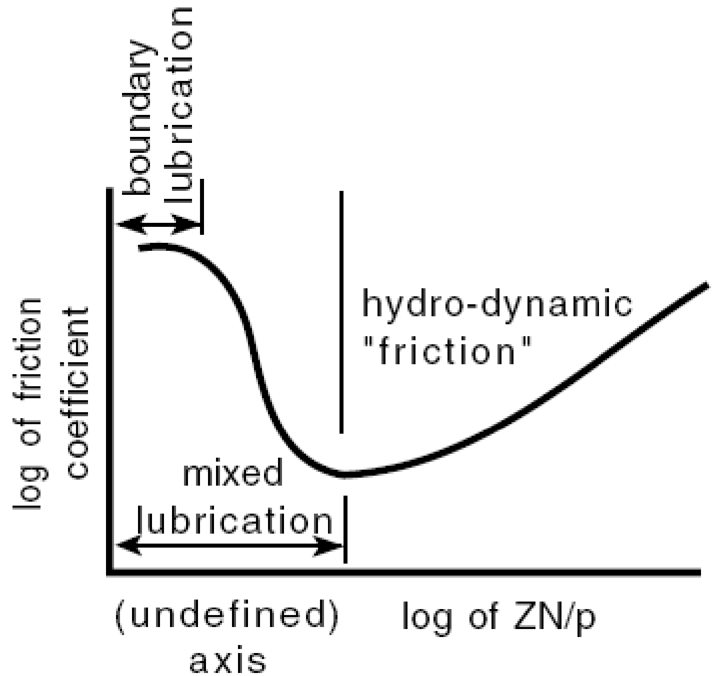
- Presented procedure to measure Coefficient of Friction for Asphalt Binders.
- Results showed potential to differentiate between binder grades and WMA Additives
- Due to machine limitations testing was limited to <100ºC

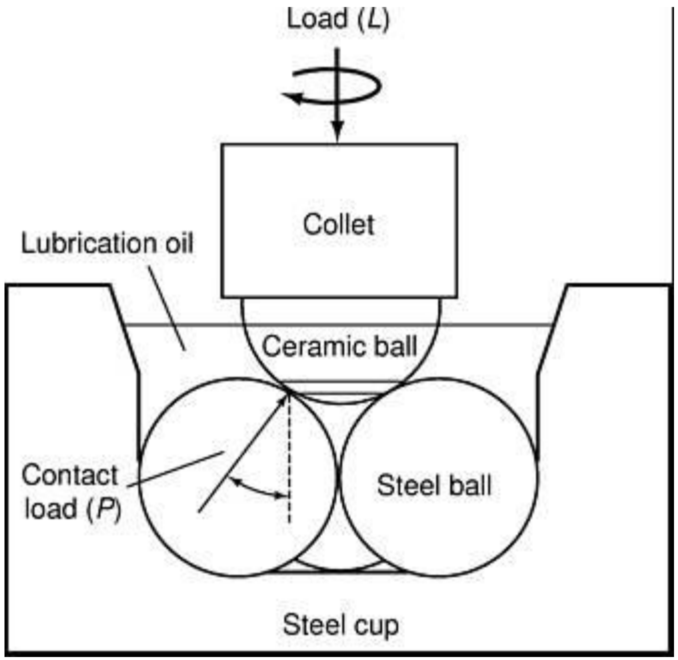


Asphalt Binder Lubricity – New Efforts

- Modify Testing Fixture
  - Allow for testing at higher temperatures.
  - Requires use of different DSR in UW Madison Laboratories
- Modify Test Procedure
  - Control Gap, Speed, and Temperature During Testing.
  - Increase thermal equilibration time.
  - Monitor Normal Force and Torque.
- Test at temperatures consistent with lab mixture compaction
  - 90, 110, and 135ºC

Asphalt Lubricity Test – Based on ASTM Standards for oils





Measurement Tool

Stribeck : Friction a function of viscosity (Z), pressure (P), and speed (N).

Asphalt Binder Lubricity – New Fixture

Cup machined for torsion bar geometry in TA DSR.

Balls are fixed by lid that screws into cup.

Asphalt Binder Lubricity – New Fixture

Torque and normal force applied by chuck from top of machine.

Before testing zero gap is established using cup and chuck.

Asphalt Binder Lubricity – Test Procedure

- After gap is zeroed, a sample of asphalt (4 gm) is placed in the cup and melted at 90ºC.
- Chuck is lowered until a normal force of ~15N is established.
- Thermal equilibration for 45 minutes – 1 hour.
- Test is conducted at speeds of 10, 20, and 40 RPM.
- Procedure is repeated for 110ºC and 135ºC

Asphalt Lubricity Test - Calculations

- **Torque** and **normal force** are monitored under constant **speed and gap**.
- The **coefficient of friction (μ)** is obtained from the normal force and torque measured

$$\mu = C \times \frac{T}{P \times d}$$

  – Where:
  – C = 2.842 – Value of constant for the four ball testing fixture geometry, T = Torque (N), P = Normal Force (N), d = diameter (m)

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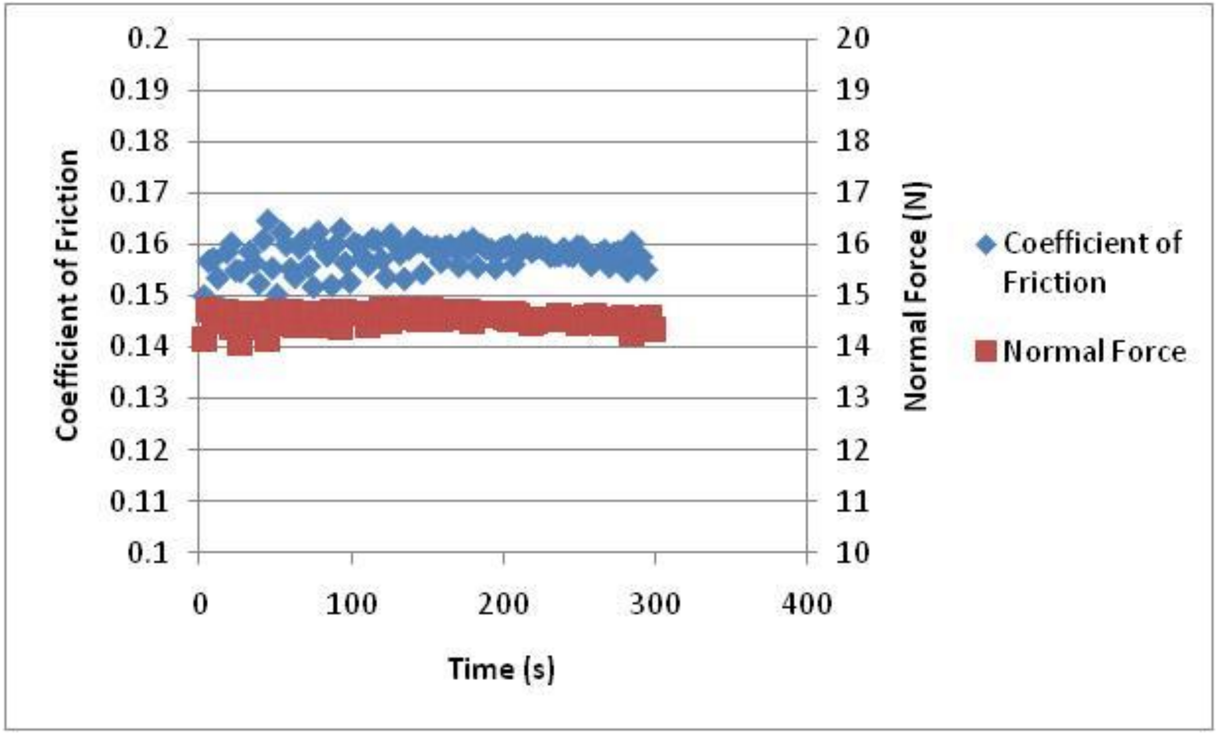
Asphalt Lubricity Test – Example Data



Statistics

Avg	Stdev	COV
0.16	0.003	2.0%
14.56	0.125	0.9%

Controlling the gap allows for consistent values of torque and normal force.

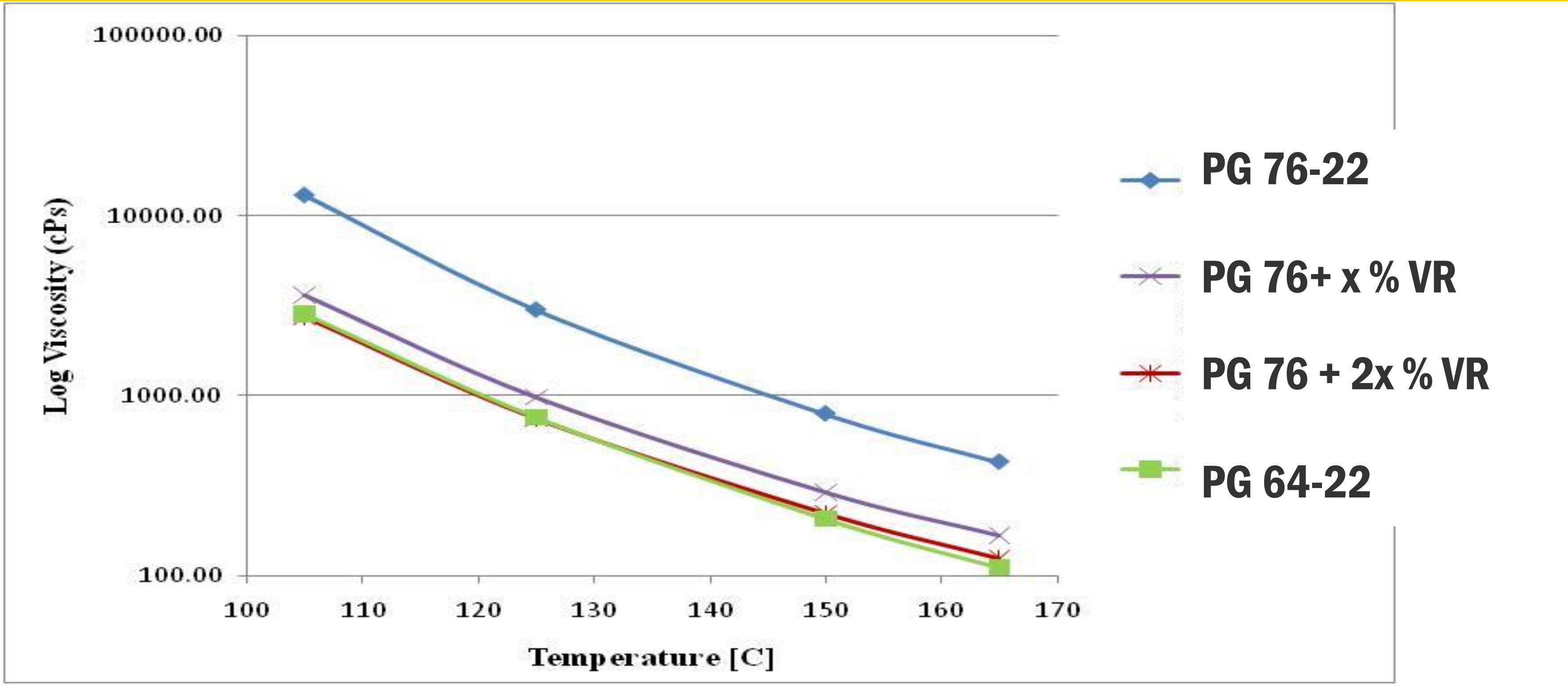
Experimental Design – Example Data to Date

- One Warm Mix Additive:
  - Viscosity Reducer (RV).
  - Two concentrations: X% and 2x%
- Two base binders:
  - Unmodified PG64-22 and
  - SBS modified PG 76-22
- Two Mixture Gradations: Fine and Coarse

Experimental Plan - Testing

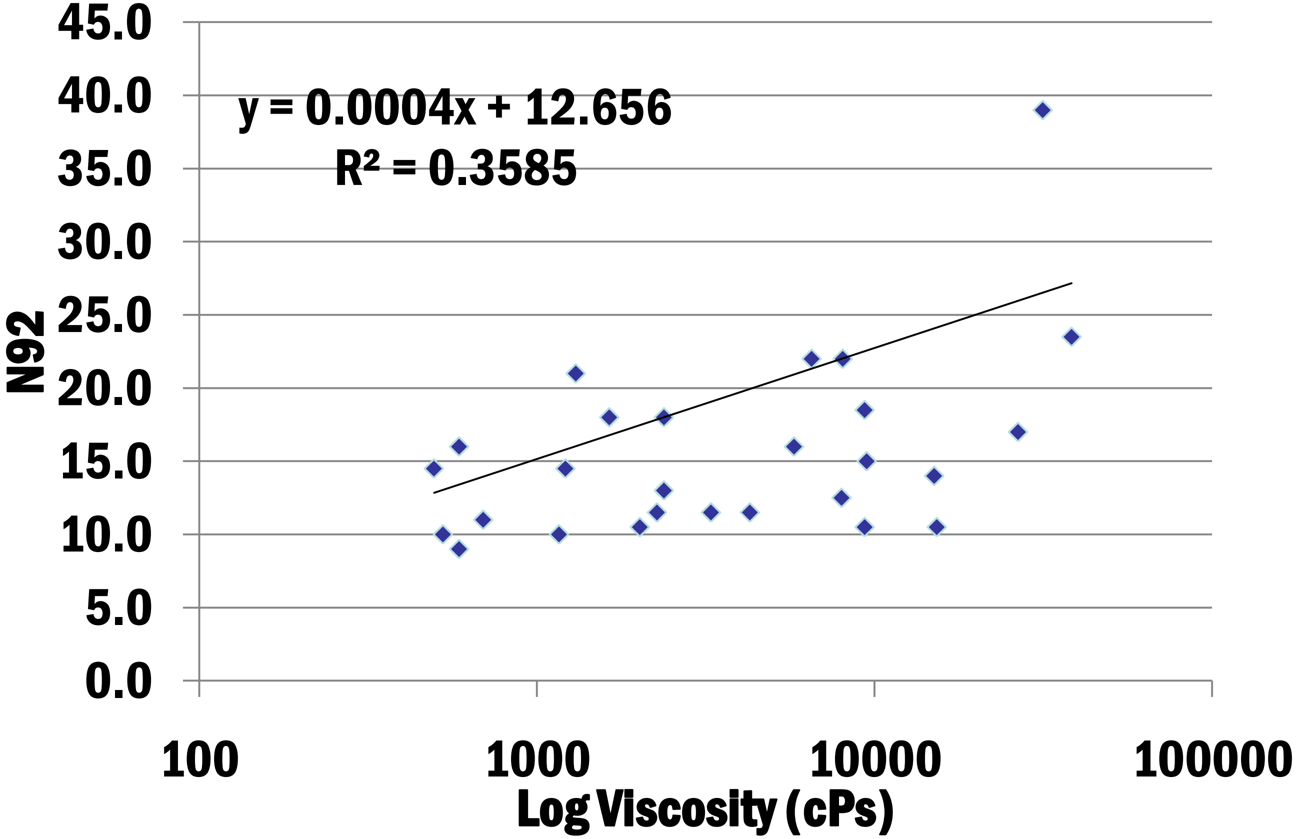
- Binder Workability:
  - Asphalt Binder Viscosity – Rotational Viscometer
  - Asphalt Binder Lubricity – New DSR test
- Mixture Workability:
  - Gyratory Compaction Indices:
    - > Construction Force Index using the GPDA - (CFI)
    - > Number of Gyrations to 92 % Gmm- N92

Effect of WMA Additive on Viscosity



VR-2 results in a PG 76-22, with similar viscosity to unmodified PG 64-22.

Viscosity and Compaction Effort



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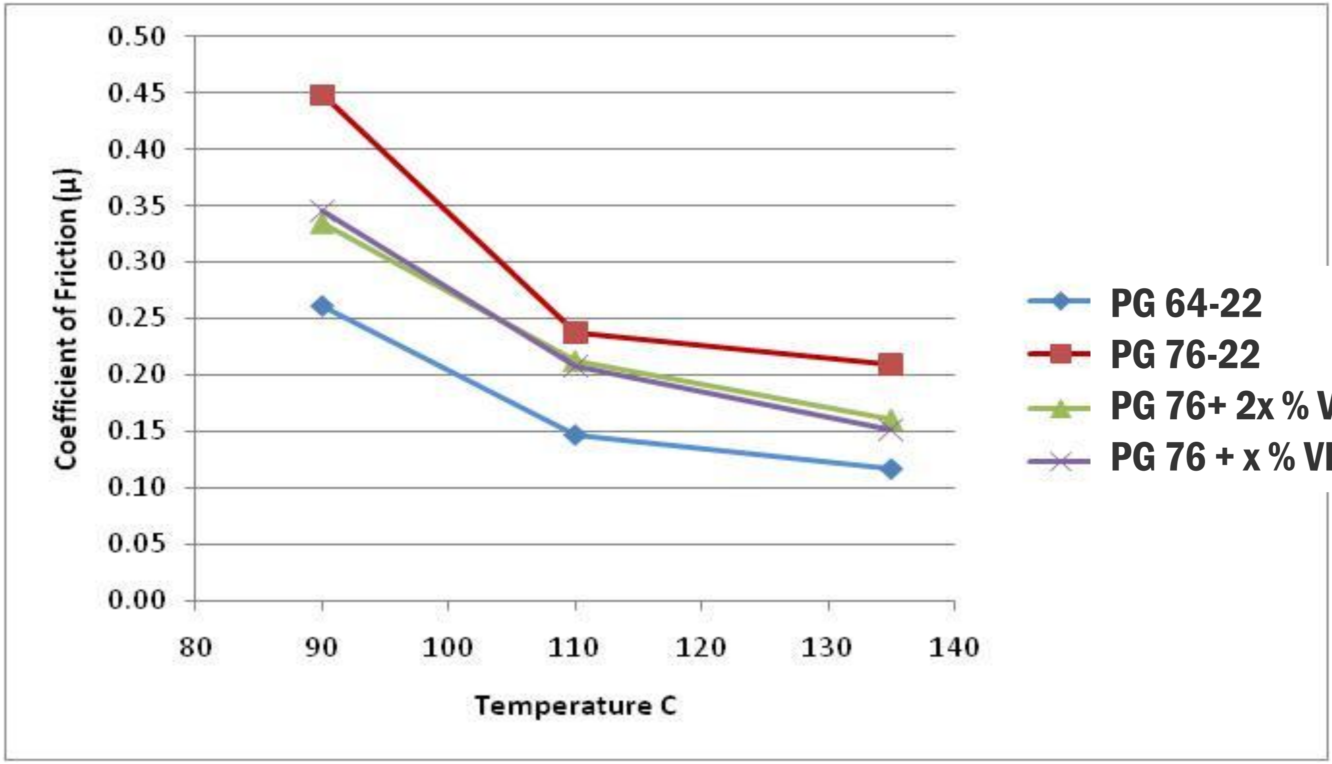
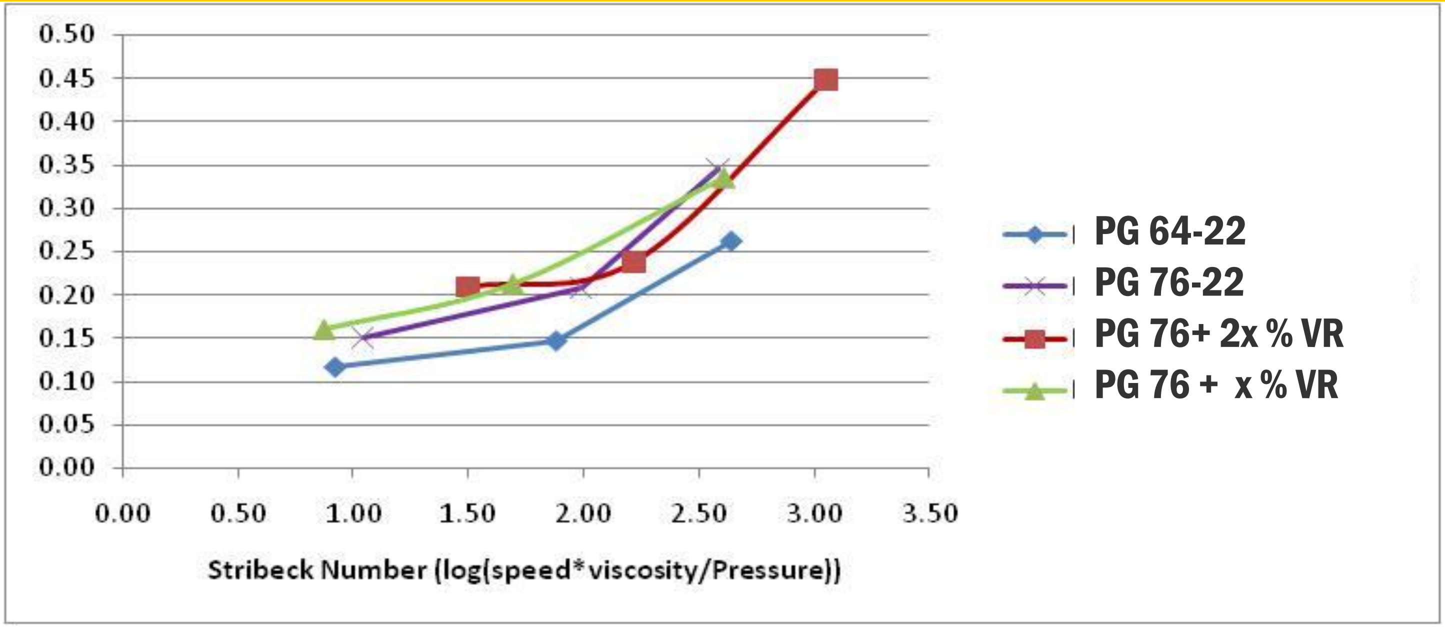
New Test Method "Asphalt Lubricity Test" – Initial Results – Temperature Dependence



- Effect of Additive and temperature most significant at 90C.
- Effect of binder: Clear reduction in friction due to PG 64.

Results: Coefficient of Friction vs. Stribeck Number

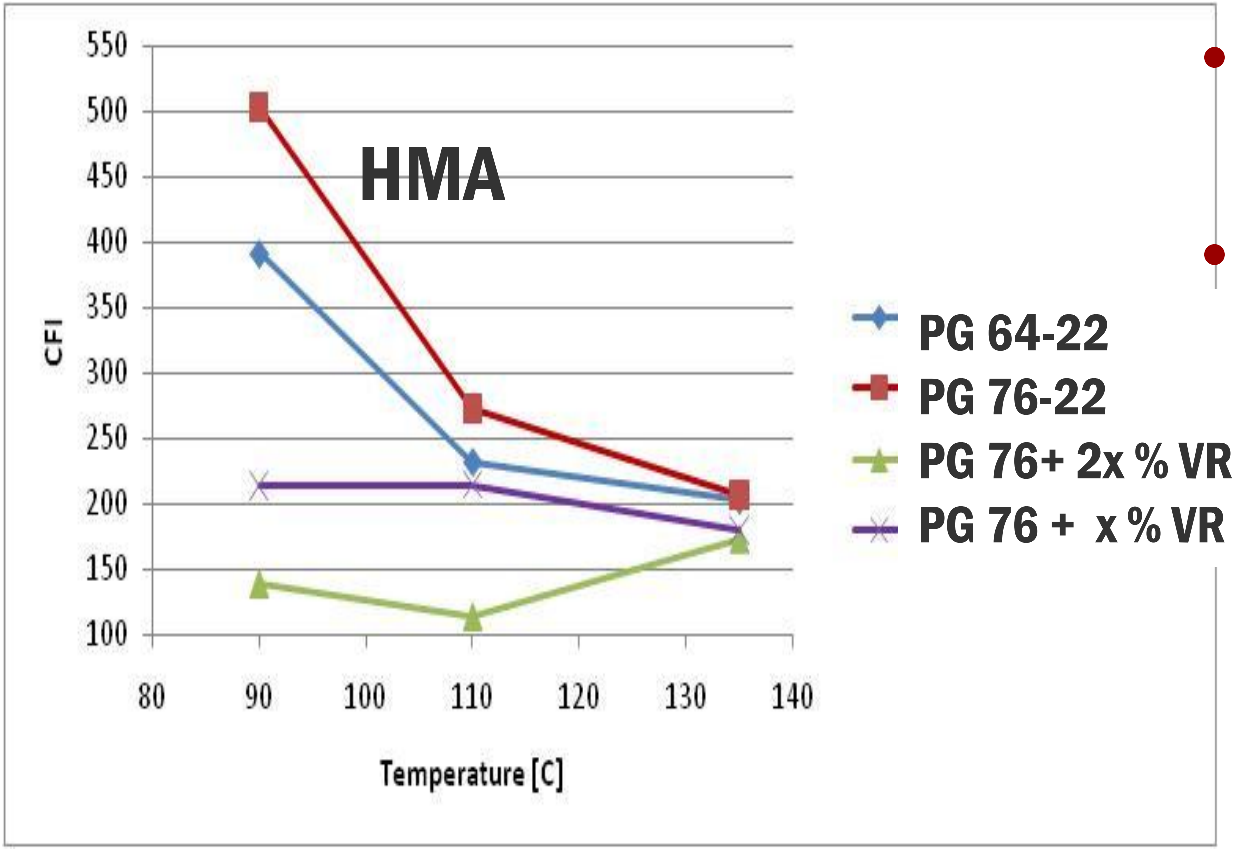


- VR-2 behaves similarly to PG 64.
- Due to differing viscosities, Stribeck number is much higher for PG 76. Temperature reduction of ~15C needed for other materials to demonstrate μ similar to PG 76.

Mixture Workability

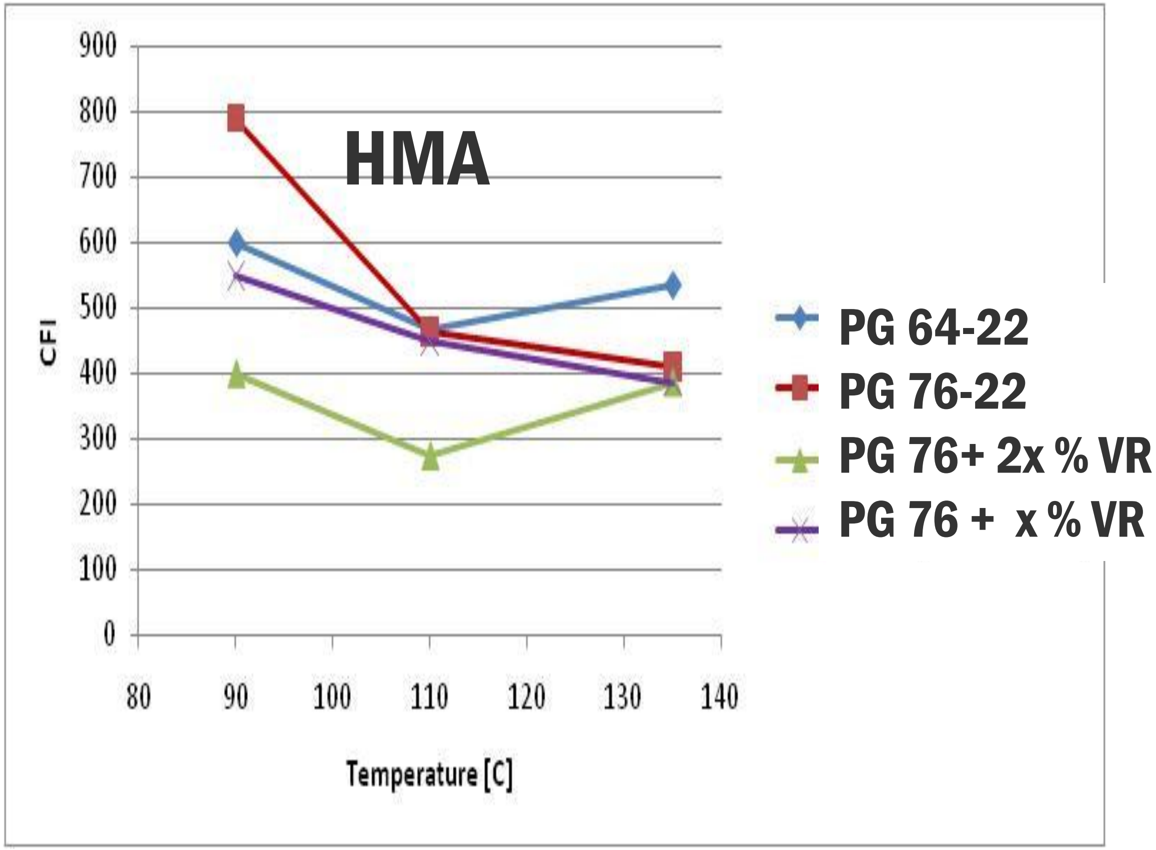
- Evaluation Criteria
  - Gyratory Compaction indices
    - Gyrations to 92% Gmm
    - Construction Force Index (CFI) using the GPDA

Effects of WMAs on CFI (Mixture Workability) – Fine Gradation



- Major WMA effects at 90ºC.
- VR-2 at 2x% show more effects at all temperatures.

Effect of WMA on CFI – Coarse Gradation



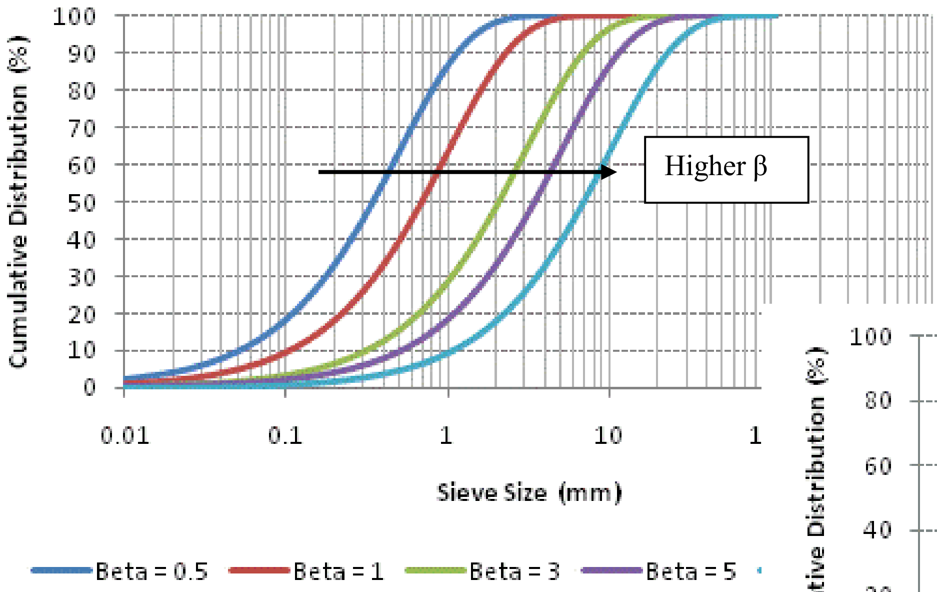
- WMA Effects – similar to fine gradation.
- Effect of gradation on workability.
  - CFI (FINE)Range: 150-500
  - CFI (COARSE) Range: 300-800

Regression Analysis

- **Model Parameters**
  - Asphalt Binder Workability
    - Viscosity: Estimated at 90C, tested at 110C and 135C
    - Lubricity: Tested at 90, 110, and 135C. Avg of three speeds.
  - Gradation
    - Quantified using Beta
      - Fine: 4.29
      - Coarse: 6.34

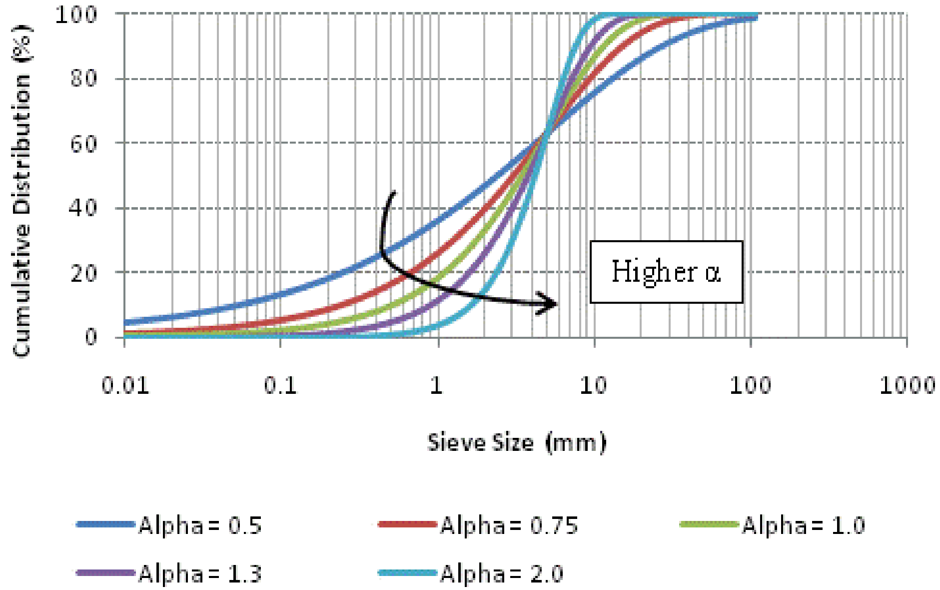
- **Response**
  - Mixture Workability – CFI and N92

Gradation Analysis and Modeling



$$F(x, \alpha, \beta) = 1 - e^{-\left(x/\beta\right)^{\alpha}}$$

Weibull distribution

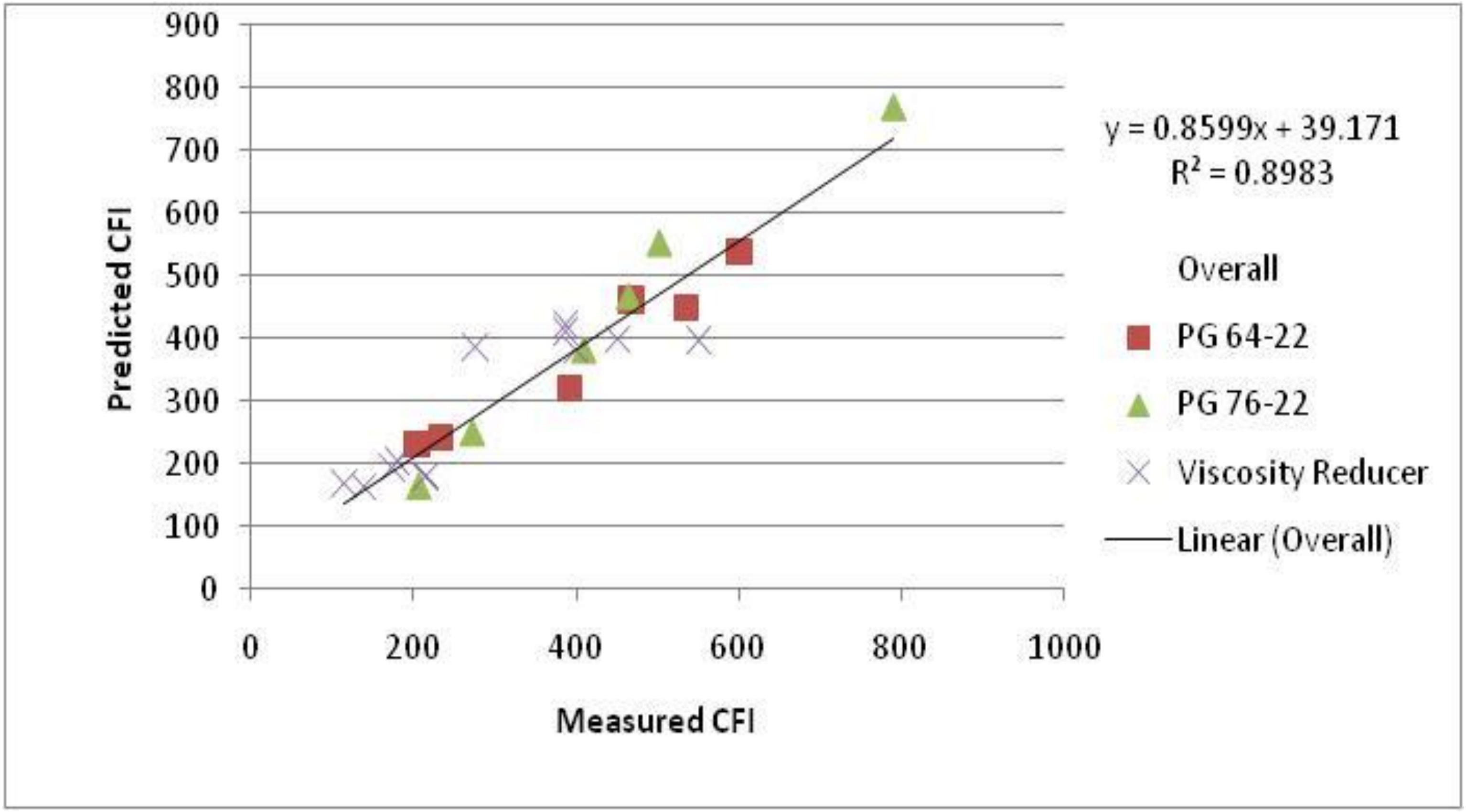


Regression Results (Compaction Force Index)

- **Regression Analysis: CFI = F(Coef Fric, Visc, Bet a)**
- **CFI = - 108+ 106 Beta -1036 Coef Fric. + 0.0202 Visc**

Predictor	Coef	SE Coef	T	P
Constant	-108	89.66	-1.2	0.224
Beta	**106**	**13.24**	**8.03**	**0.000**
Coef. Friction	**-1036**	**302.2**	**-3.43**	**0.003**
Visc	**0.02**	**0.004**	**6.34**	**0.000**

Regression Results (CFI)

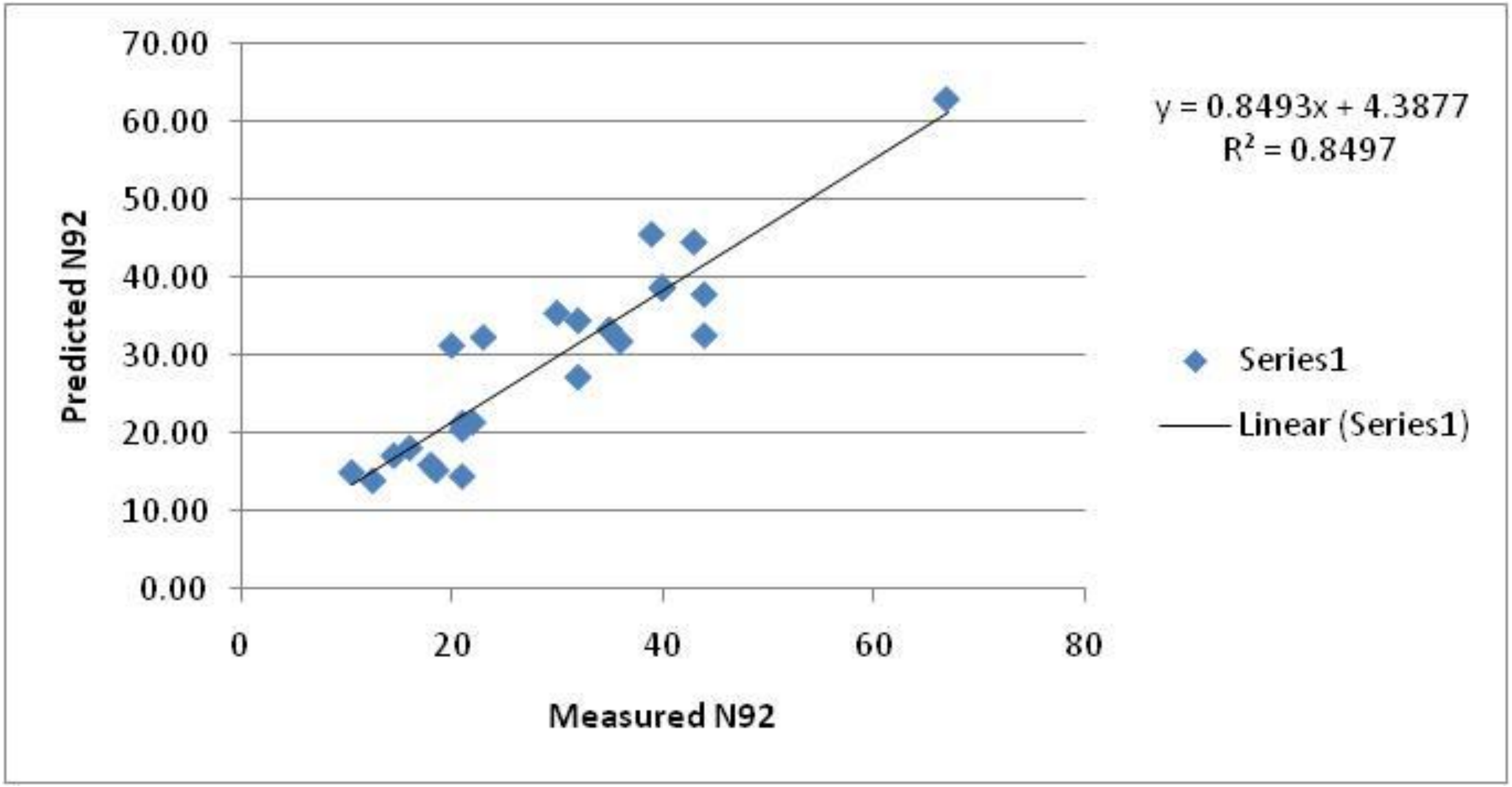


Regression Results (N92)

- N92 = - 5.55 + 8.455 Beta – 89.8 Coef. Friction - 0.00167 Visc

Predictor	Coef	SE Coef	T	P
Constant	-5.55	7.504	-0.74	0.468
Beta	**8.455**	**1.108**	**7.63**	**0.000**
Coef. Friction	**-89.81**	**25.3**	**-3.55**	**0.002**
Visc	**0.00163**	**0.00026**	**6.24**	**0.000**

Regression Results (N92)



Summary of Interim Findings

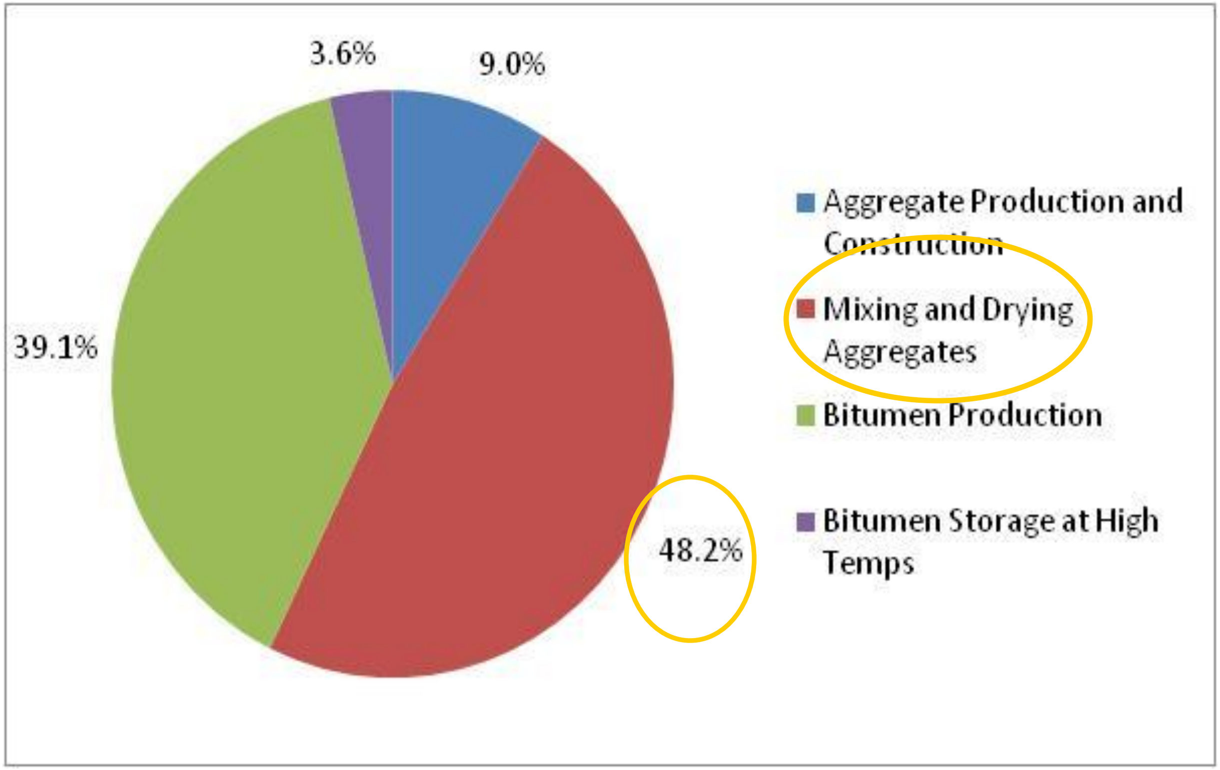
- Warm Mix Additive affect laboratory compaction.
  - Main affect at lower temperatures (<100 C).
  - Reduction in viscosity and coefficient of friction both identified as significant.
- Results were consistent with classification of WMA additive as a viscosity reducer.
- Cost need to be justified by energy savings & environmental impact.

Next Steps

- More Lubricity Testing is needed
  - Establish repeatability of procedure.
  - More WMA additives.
  - Wider range of temperatures?
- Potential to use lubricity and viscosity to classify WMA additives
  - Confirm findings with other viscosity reducers (Sasobit)
  - Establish similar relationship for other WMA mechanisms

Impacts of WMA Additives on Energy Consumption

Energy Consumption in Production of HMA

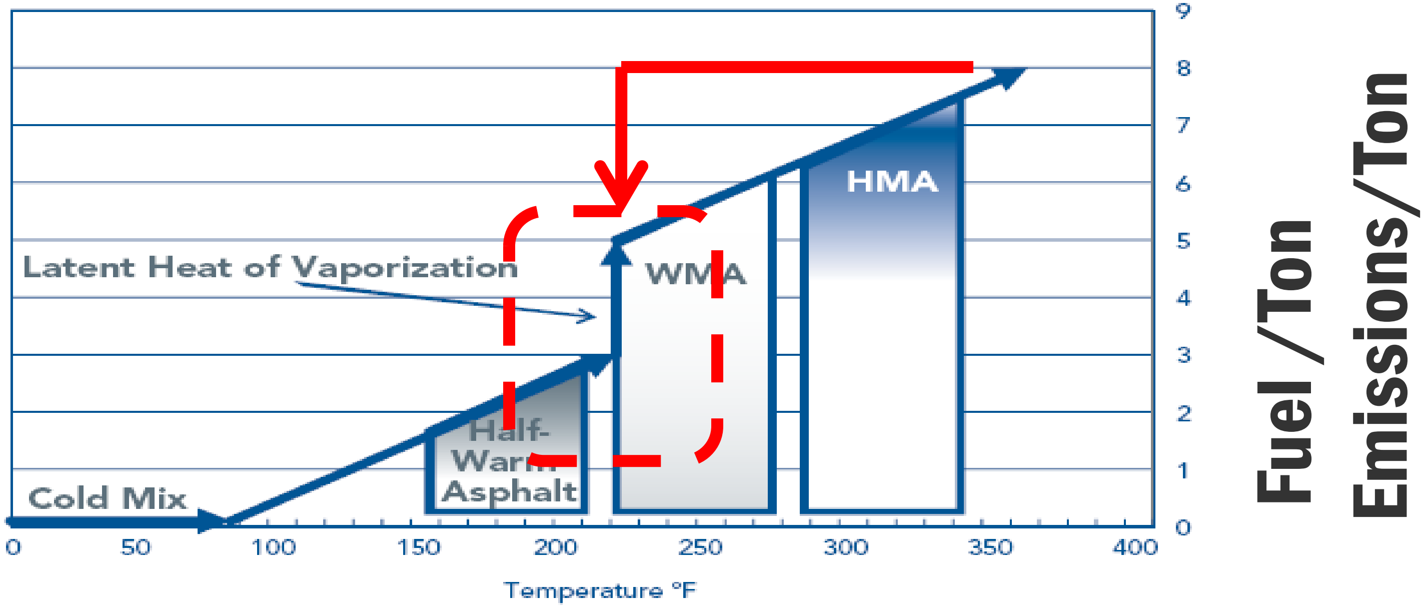


Opportunities for Energy Reduction

- Reduce production temperature: Warm Mix, Half Warm Mix, Cold Mix.
- Reduce/control moisture content of aggregates prior to production.

Benefits of Warm Mix Asphalt : Conceptual Reduction in Energy

Source: FHWA



Energy Reduction Relative to HMA

WMA: ~25%- 40%

HWMA: ~60% - 80%

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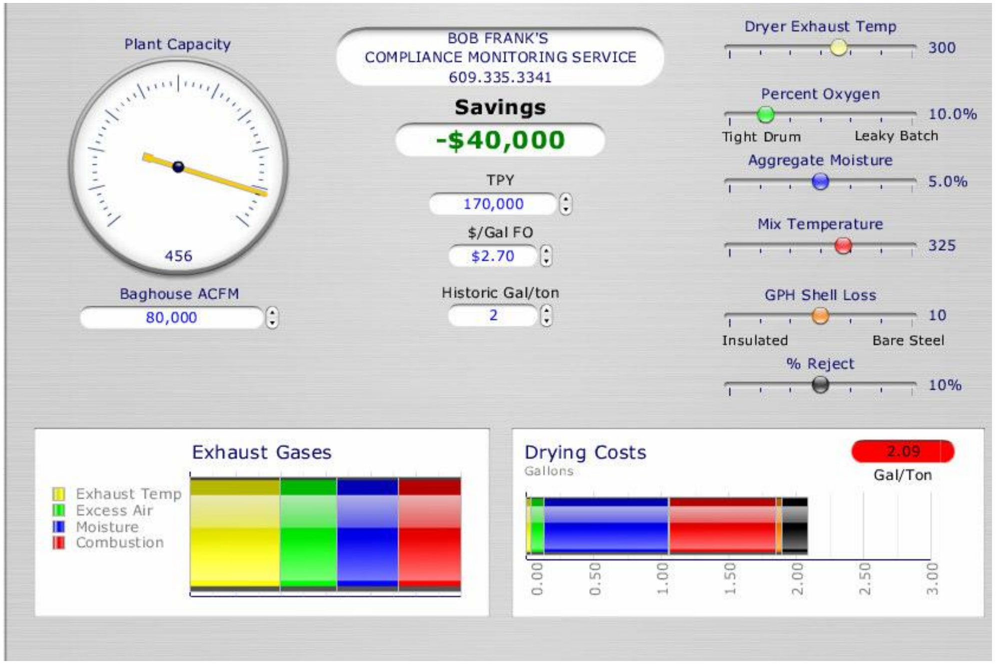
Tools Available to Quantify Environmental Impacts of WMA

- Plant Diagnostic Tool
  - Pennsylvania Asphalt Pavement Association (PAPA)
- Estimation Tool
  - Models Developed by the World Bank

PAPA Plant Diagnostic Tool

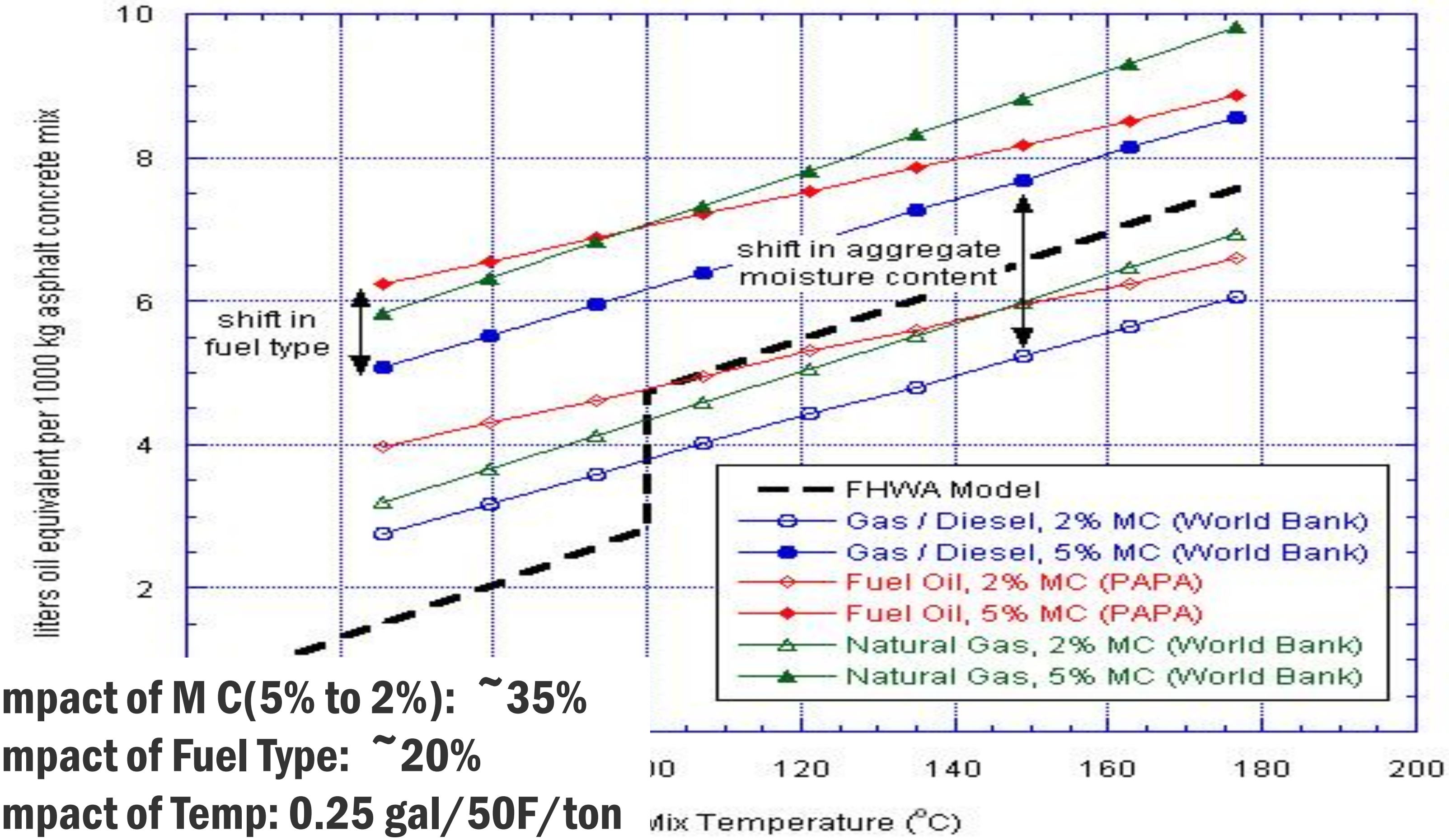


- **Generalize plant operations: Focused on drying costs and exhaust gases in a web-based interface.**

World Bank Estimation Tools

- Estimate Emissions and Energy Consumption as a function of:
  - Aggregate Moisture Content
  - Fuel Type
  - Production Temperature
- Tool to quantify importance and relative impacts of production related factors.

Impacts of Moisture Content and Fuel Type on Energy Consumption – 3 models

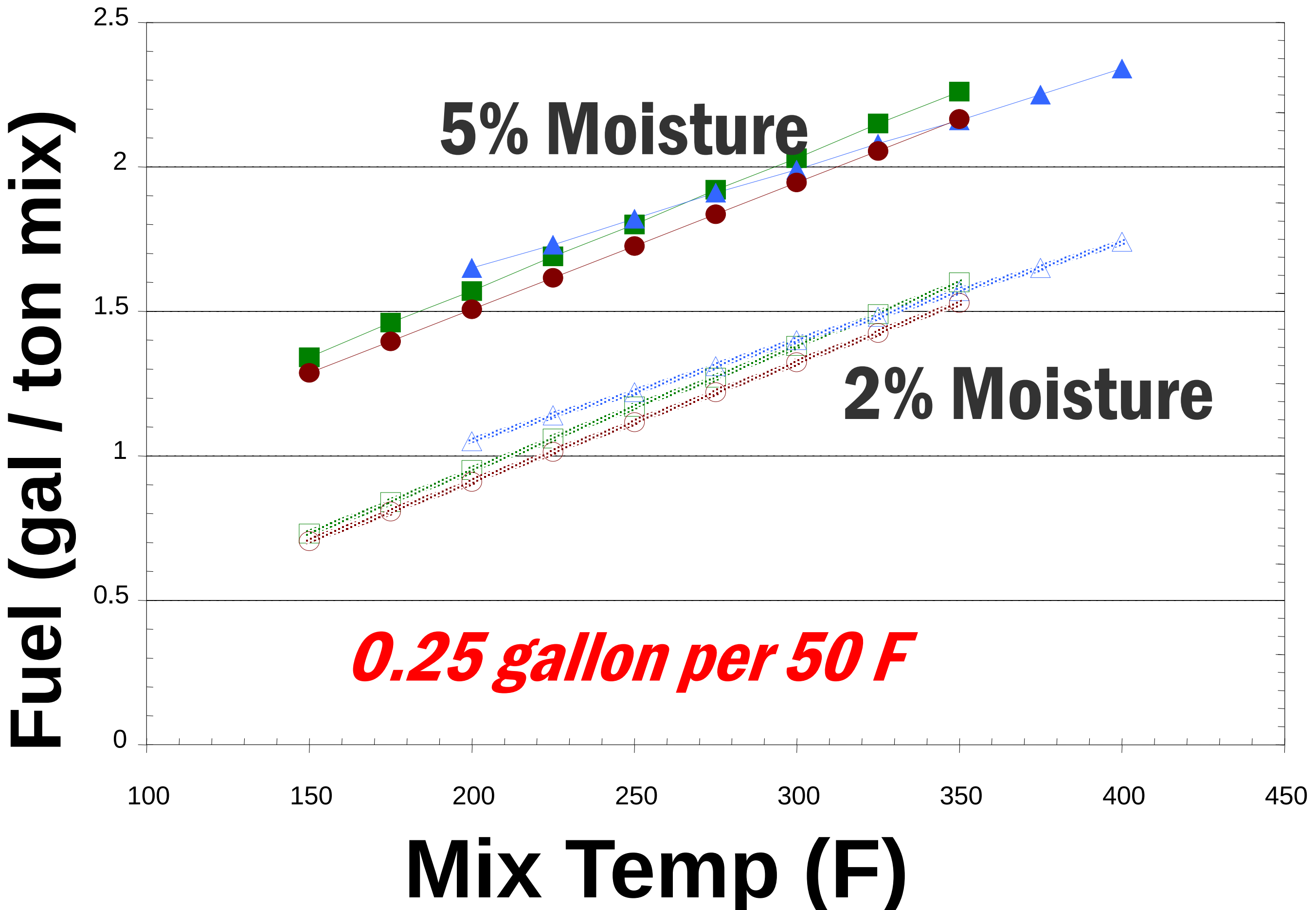


Impact of M C(5% to 2%): ~35%

Impact of Fuel Type: ~20%

Impact of Temp: 0.25 gal/50F/ton

Reduction in Fuel Consumption Based on Three Existing Models



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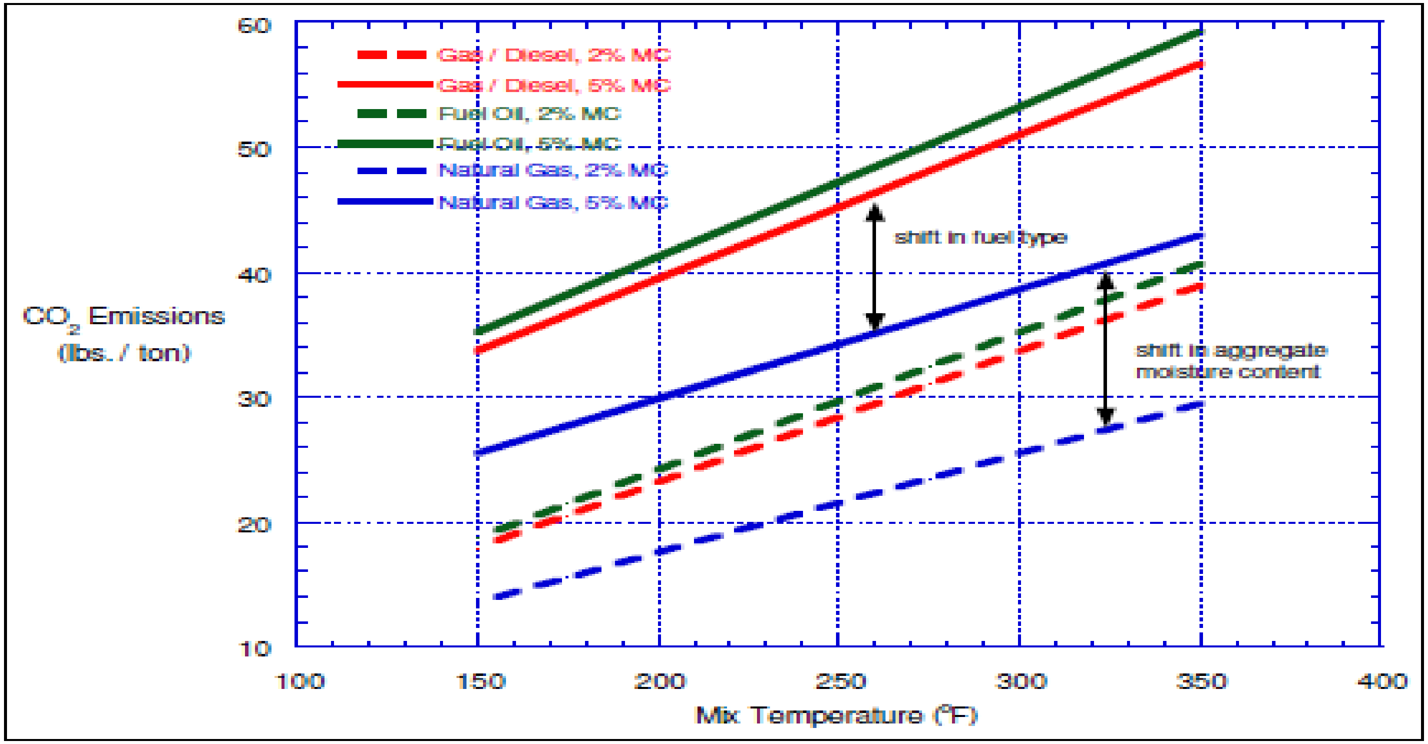
Impacts of Moisture Content and Fuel Type on Emissions– 3 Models



Impact of Moisture Content (5% to 2%): ~40%

Impact of Fuel Type: ~20%

Impact of Temp: 5 lbs/50F/ton

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Conclusions –Opportunities to Reduce Emissions and Energy Consumption

- Energy Consumption
  - Use of WMA alone can result in 40% reduction.
  - Super heating of aggregates reduced or eliminated.
  - Control of aggregate moisture content.
- Emissions
  - Cleaner fuel types.
  - Lower production temperatures.

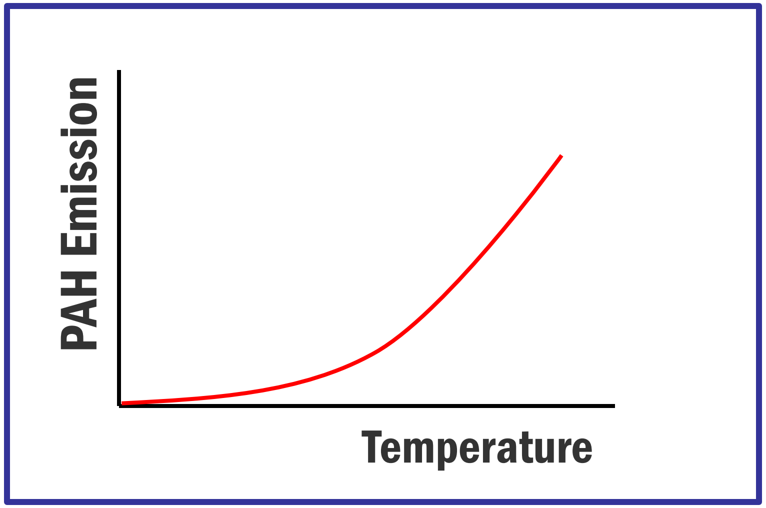
Next Steps

- Life-cycle perspective.
  - Performance of WMA must be similar to HMA for environmental benefits to be realized.
- Field Projects with WisDOT (4-6 this summer)
  - Laboratory Performance: Binder and Mixture
  - Fuel Consumption
  - Estimate of Emissions
  - Monitoring of Pavement Performance

Laboratory Measurement of Emissions and Impacts of Reduced Temperatures

Study Objective / Scope

- Laboratory Testing
  - Model asphalt fume PAH emission vs. temperature



- Laboratory & Field (asphalt plant stack) Testing
  - Corroborate WMA usage benefits regarding emissions
  - Corroborate Jullien (LCPC) results
  - Corroborate EPA emission factors
  - Quantify asphalt and burner fuel emission fractions

Study Objective / Scope

Emissions of Interest

- Asphalt Plant Emissions
  - CO
  - CO_2
  - SO_2
  - NO_x
  - CH_4
- Occupational Health Emissions
  - Polycyclic Aromatic Hydrocarbons (PAH)
    - Anthracene
    - Benzo(a)anthracene
    - Benzo(a)Pyrene
    - Chrysene
    - Coronene*
    - Fluoranthene*
    - Methyl Cholanthrene (3-)
    - Naphthalene
    - Perylene
    - Phenanthrene
    - Pyrene

*Testing resulted in no measurable quantity

Experimental Design (Laboratory)

- Testing
  - 40 *Extended OSHA 58 Method* tests by Wisconsin Occupational Health Laboratory (WOHL)
- Two Phase Analysis (20 tests each)
  - Phase I: Design of Experiment (DOE)
    - Factorial Design: 2^4 (2 Level, 4 Factors)
      - $2^4 = 16$
      - 4 "Blanks" (contamination check)
  - Phase II: PAH/Temperature Modeling
    - 4 sample types @ 5 temperatures

Experimental Design (Laboratory)

• Experimental Factors

Factors	Level -1	Level 1
Asphalt Source	Flint Hills	Citgo
Flask Rotation (ω/min)	40	90
Test Duration (min)	15	45
Test Temperature (C)	130	180

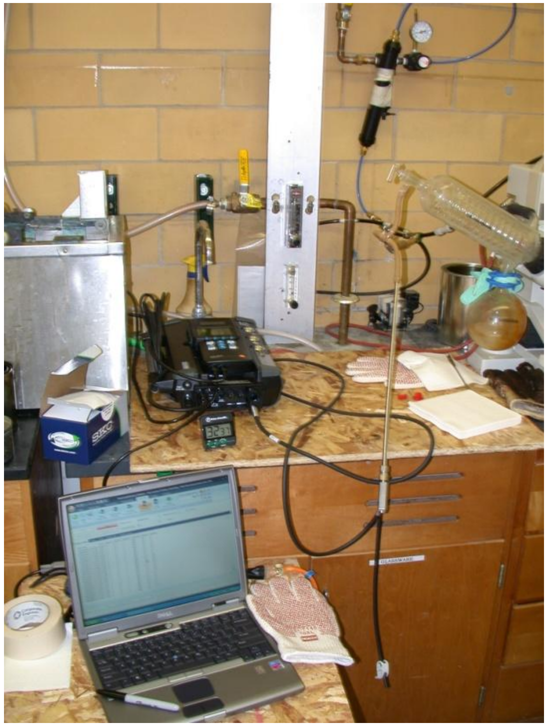
• Experimental Design

StdOrder	RunOrder	AC Source	Rotation	Test Duration	Test Temp
1	13	-1	-1	-1	-1
2	7	1	-1	-1	-1
3	14	-1	1	-1	-1
4	3	1	1	-1	-1
5	12	-1	-1	1	-1
6	16	1	-1	1	-1
7	1	-1	1	1	-1
8	11	1	1	1	-1
9	15	-1	-1	-1	1
10	5	1	-1	-1	1
11	6	-1	1	-1	1
12	10	1	1	-1	1
13	8	-1	-1	1	1
14	4	1	-1	1	1
15	2	-1	1	1	1
16	9	1	1	1	1

Blank samples were run prior to runs: 1, 5, 9, 13

Laboratory Testing

- UW-Madison Test Setup



Overall Setup

Laboratory Testing

- UW-Madison Test Setup

Laboratory Testing

- UW-Madison Test Setup

Laboratory Testing

- **Testo 350**

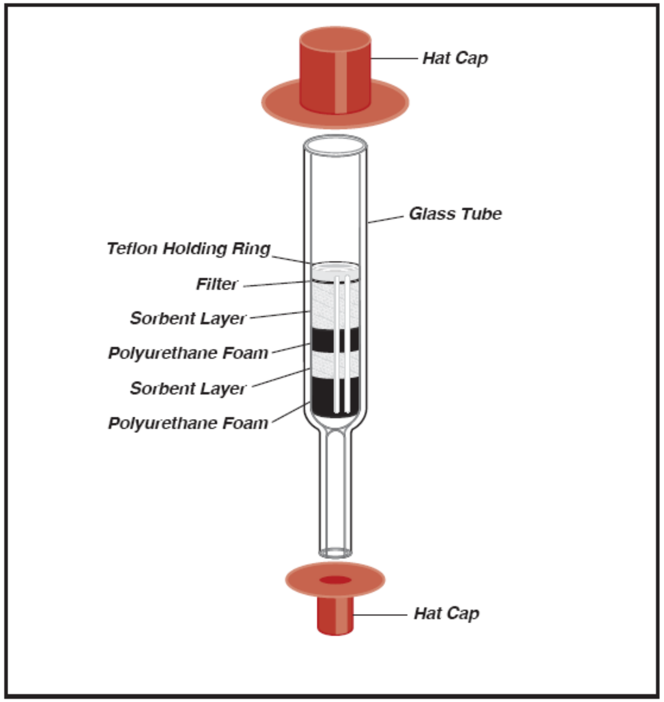
The total solution for emission testing and combustion analysis

www.testo350.com

	Range	Accuracy	Resolution	Response Time		
O_2	0 to 25% vol.	< 0.2% of m.v.	0.1 vol. %	20 s (t_{95})		
CO	0 to 10,000 ppm H_2 comp.	< 5 ppm (0 to 99 ppm) < 5% of m.v. (100 to 2,000 ppm) < 10% of m.v. (2,001 to 10,000 ppm)	1 ppm	40 s (t_{90})		
CO LOW	0 to 500 ppm H_2 comp.	< 2 ppm (0 to 39.9 ppm) < 5% of m.v. (40 to 500 ppm)	0.1 ppm	40 s (t_{90})		
NO	0 to 3,000 ppm	< 5 ppm (0 to 99 ppm) < 5% of m.v. (100 to 2,000 ppm) < 10% of m.v. (2,001 to 3,000 ppm)	1 ppm	30 s (t_{90})		
NO LOW	0 to 300 ppm	< 2 ppm (0 to 39.9 ppm) < 5% of m.v. (300 ppm)	0.1 ppm	30 s (t_{90})		
NO_2	0 to 500 ppm	< 5 ppm (0 to 99 ppm) < 5% of m.v. (500 ppm)	0.1 ppm	40 s (t_{90})		
SO_2	0 to 5,000 ppm	< 5 ppm (0 to 99 ppm) < 5% of m.v. (100 to 2,000 ppm) < 10% of m.v. (2,001 to 5,000 ppm)	1 ppm	30 s (t_{90})		
H_2S	0 to 300 ppm	< 2 ppm (0 to 39.9 ppm) < 5% of m.v. (40 to 300 ppm)	0.1 ppm	35 s (t_{90})		
C_xH_y	0.01 to 4%	< 400 ppm (100 to 4,000 ppm) < 10% of m.v. (> 4,000 ppm)	0.001 vol. % = 10 ppm	40 s (t_{90})		
CO_2	0 to 50% vol.	± 0.3% vol. +1% of m.v. (0 to 25% vol.) ± 0.5% vol. +1.5% of m.v (> 25 to 50% vol.)	0.01% vol. (0 to 25% vol.) 0.01% vol. (> 25% vol.)	10 s (t_{90})		
CO_2 (Calculated)	0 to CO_2 max vol. %	Calculated from O_2	0.1 vol. %			
Differ. Press. 1	± 80" H_2O	< 1% m.v. (-20" to 80" H_2O) < 1% m.v. (+20" to +80" H_2O) < 0.5% m.v. (-19" to +19" H_2O)	0.01" H_2O			
Differ. Press. 2	± 16" H_2O	< 1% m.v. (16" to 1.2" H_2O) < 1% m.v. (+16" to +1.2" H_2O) < 0.5% m.v. (-1.2" to +1.2" H_2O)	0.01" H_2O			
Efficiency	0 to 100%		0.1%			
Flow Velocity	0 to 7900 ft/min		10 ft/min			
Current Voltage	0 to 20 mA	± 0.04 mA	± 0.01 mA			
Current Voltage	0 to 10 V	± 0.01 V	± 0.01 V			
rpm	20 to 20,000 rpm		1 rpm			
Temp	-40 to 2192°F	± 0.9° F (-40 to +212° F) ± 0.5% m.v. (+212 to +2,192° F)				

Laboratory Testing

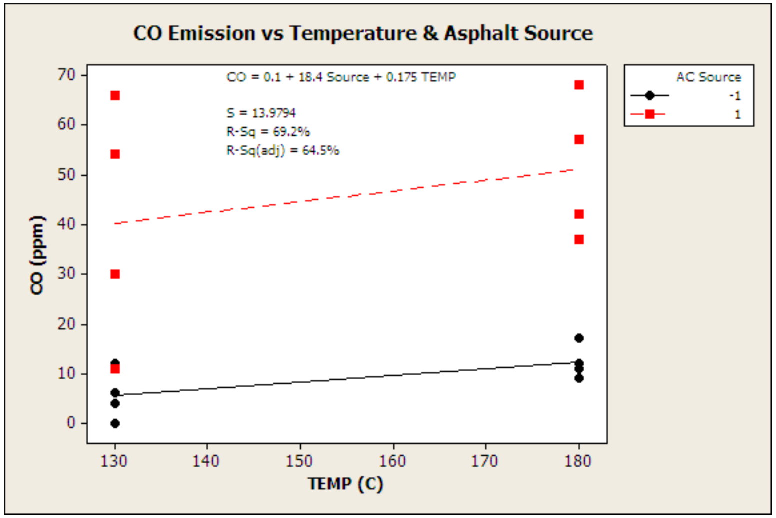
- OSHA Versatile Sampler Tubes (OVS Tube)
  - Designed to trap aerosols and adsorb vapors
  - Typical Flow Rate of 1.0 L/min
  - Tubes analyzed for PAHs by high performance liquid chromatography (HPLC)* with a fluorescene (FL) detector

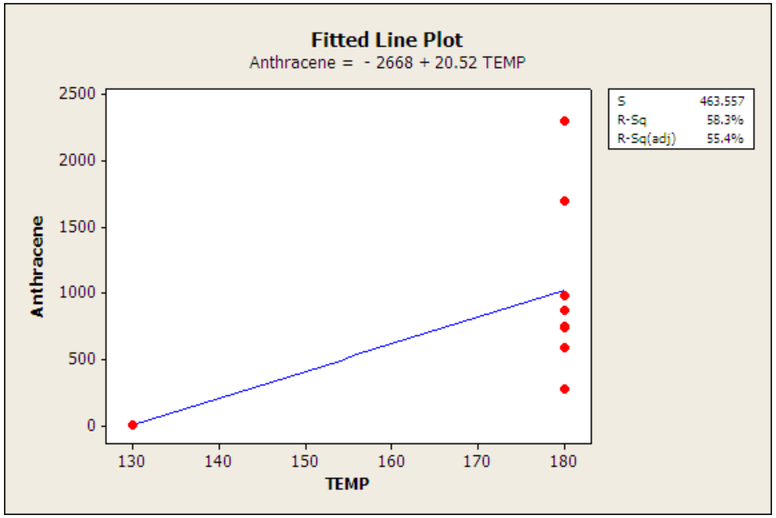


*Performed by WOHL

Data Analysis DOE Results

- **Preliminary Models developed**
  - Emission Gas = Constant + a[Source] + d[Temperature]
  - PAH = Constant + d[Temperature]





Conclusions

- Laboratory process evaluation
  - "Blank" sample analysis
    - Possible residual contamination from previous test
      - Affected measurements: NO, SO_2, NO_x, Naphthalene
    - Incorporate a "cleaning cycle" between tests
  - Lab setup components
    - System air flow control
    - Heated rotating flask
    - Testo 350 collection/measurement
    - OVS Tube collection / analysis
    - All worked well

Conclusions

- DOE Results
  - Significant Factors: Asphalt Source, Test Temperature
  - Future Testing: use slow flask rotation speed and 15 min test duration
- Phase I of the study complete

Study Continuation

- Begin Phase II
  - Create Asphalt emission development vs temperature models
  - Conduct field stack testing
    - Corroborate WMA benefits
    - Corroborate Jullien results
    - Corroborate EPA emission factors
    - Quantify asphalt/burner fuel emission fractions