Evaluation of the Effects of HMA Density on Mixture Fatigue and Rutting Performance

NEAUPG

North East Asphalt User/Producer Group

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HSRC
Highway Sustainability Research Center

Objectives

- Determine if the available laboratory tests for HMA rutting and fatigue cracking are sensitive to HMA density. Important to understand relationship for specification development.
- Evaluate the effect of density on HMA stiffness.
- Evaluate the impact of density on HMA fatigue cracking.
- Evaluate the impact of density on HMA rutting potential.

Objectives (cont'd)

- Utilize the MEPDG distress prediction equations to predict bottom up cracking and rutting.
- Compare MEPDG distress predictions to laboratory test results. Determine if laboratory tests provide the same cracking and rutting trends as MEPDG predictions.

Experimental Plan

Plant Produced HMA Mixtures

9.5mm Superpave

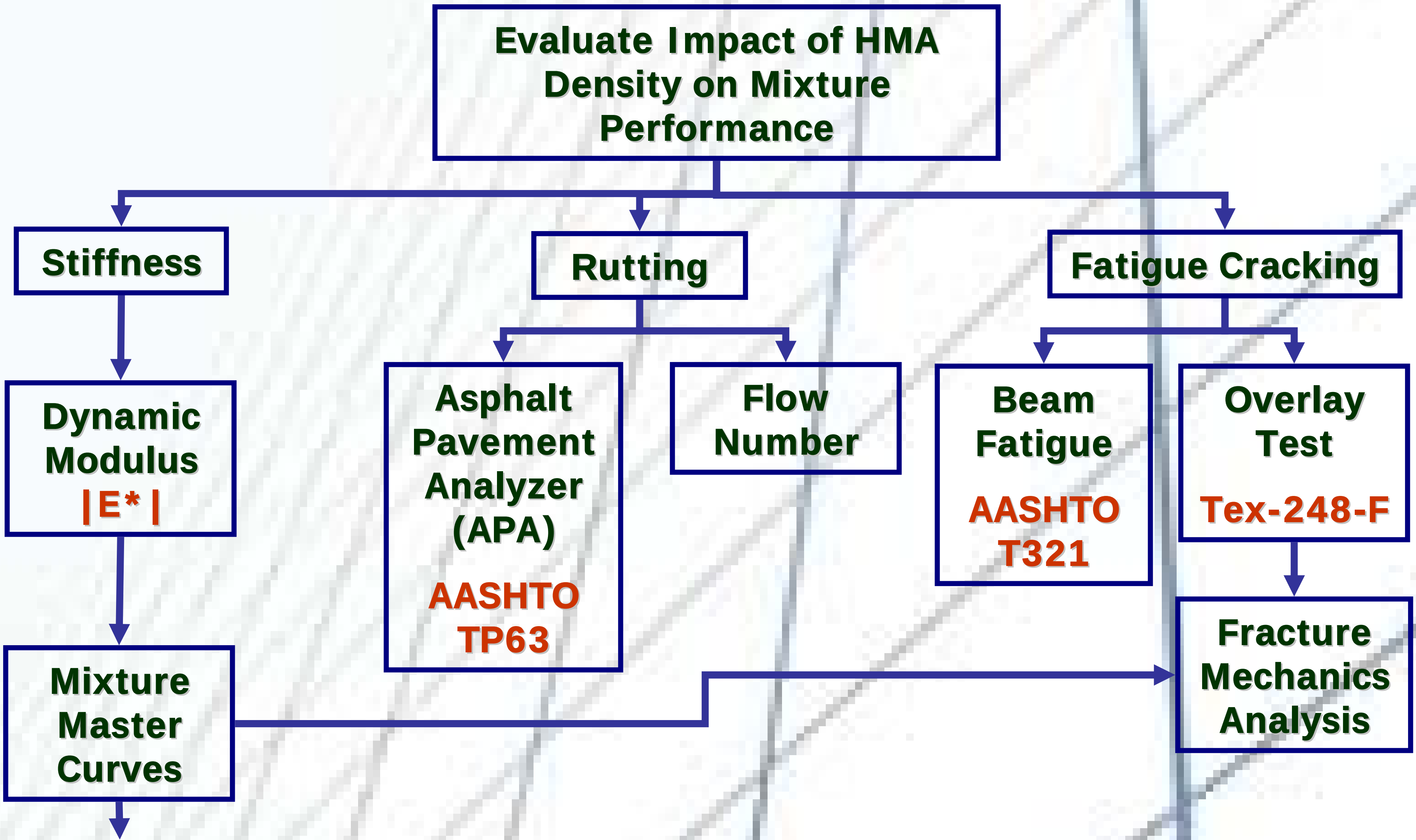
12.5mm Superpave

<u>Vary HMA Mixture Density</u>
(% of G_{mm})

88% 91% 94% 97%

Evaluate Impact of HMA Density on Mixture Performance

Experimental Plan (cont'd)



Experimental Plan (cont'd)

Mixture Master Curves

Mechanistic Empirical Pavement Design Guide (MEPDG) Software

Rutting Prediction Equation

Cracking Prediction Equation

Definitions

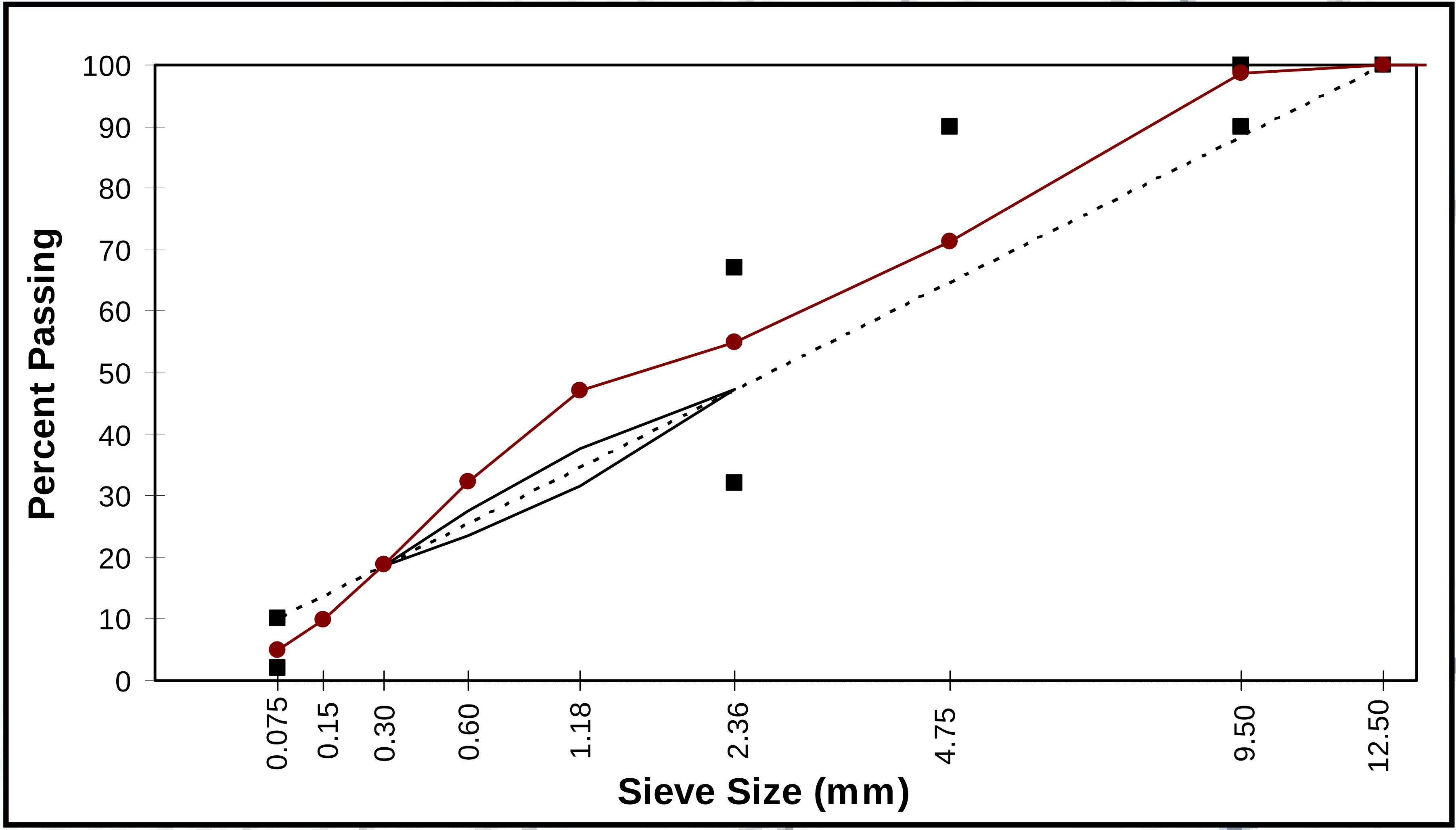
$$\text{Density, \%} = 100 \times \left(\frac{G_{mb}}{G_{mm}} \right)$$

$$\text{Air\_Voids, \%} = 100 \times \left(1 - \frac{G_{mb}}{G_{mm}} \right)$$

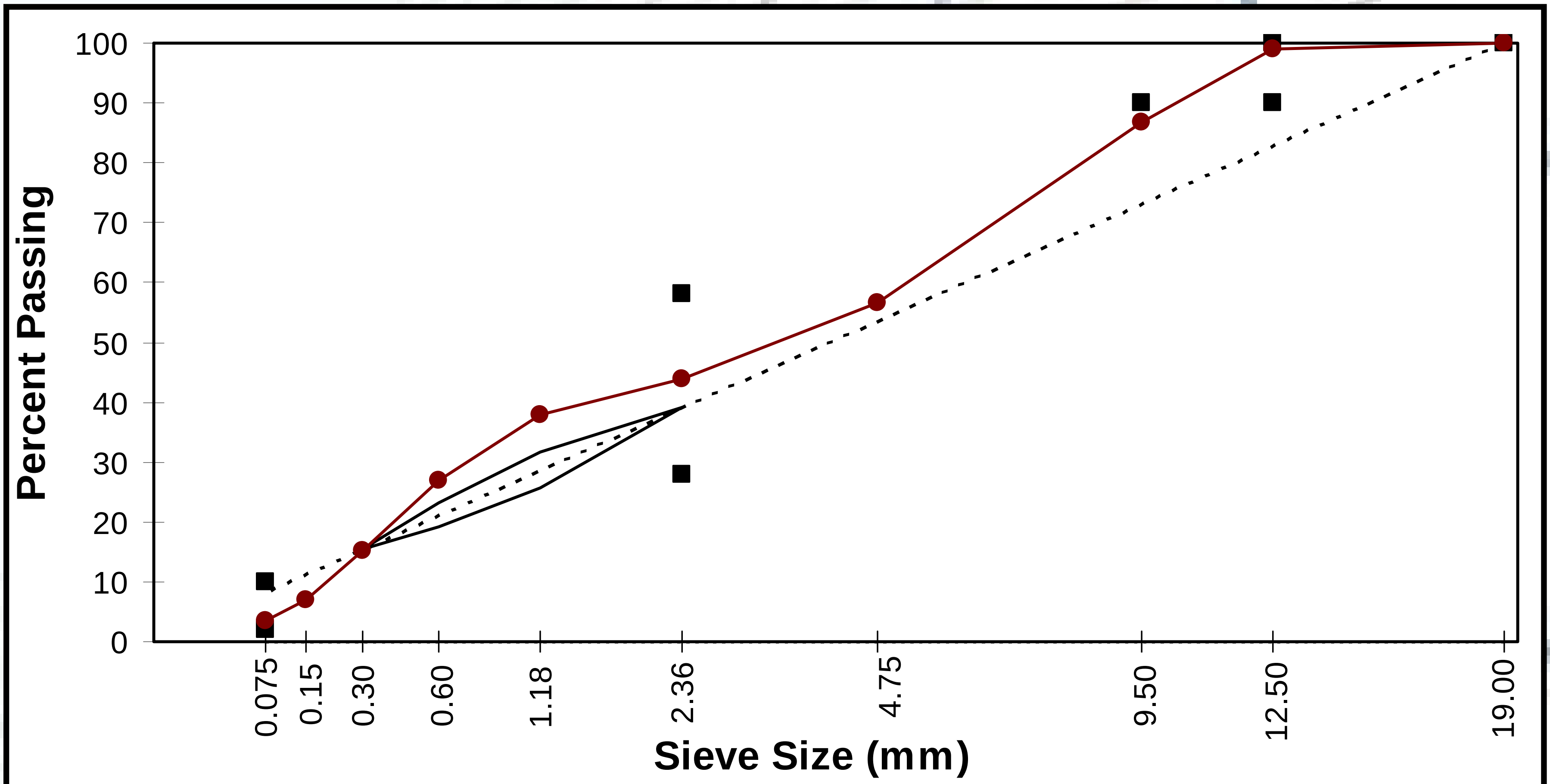
Mixture Designs - General

- Two Superpave plant produced mixtures (9.5mm and 12.5mm NMAS).
- Design ESALs level 0.3 to < 3 million.
- N_{des} = 75 gyrations.
- PG64-28 binder utilized for both mixture designs.

9.5mm Mixture Gradation



12.5mm Mixture Gradation



Mixture Designs

	9.5 mm Mixture	9.5 mm Superpave Specification Range	12.5 mm Mixture	12.5 mm Superpave Specification Range
Binder Content, %	5.8	-	4.8	-
Air Voids at N_{des}, %	4.0	-	4.8	-
VMA at N_{des}, %	15.3	15% min	15.1	14% min.
VFA at N_{des}, %	77.8	65-78	67.4	65-78
Dust to Binder Ratio	1.0	0.6 -1.2	0.8	0.6 -1.2

Specimen Fabrication

Superpave Gyratory Compactor

- AMPT |E*| Specimens
- AMPT Flow Number Specimens
- APA Specimens
- OT Specimens

Asphalt Vibratory Compactor (AVC)

- Flexural Beam Fatigue Specimens

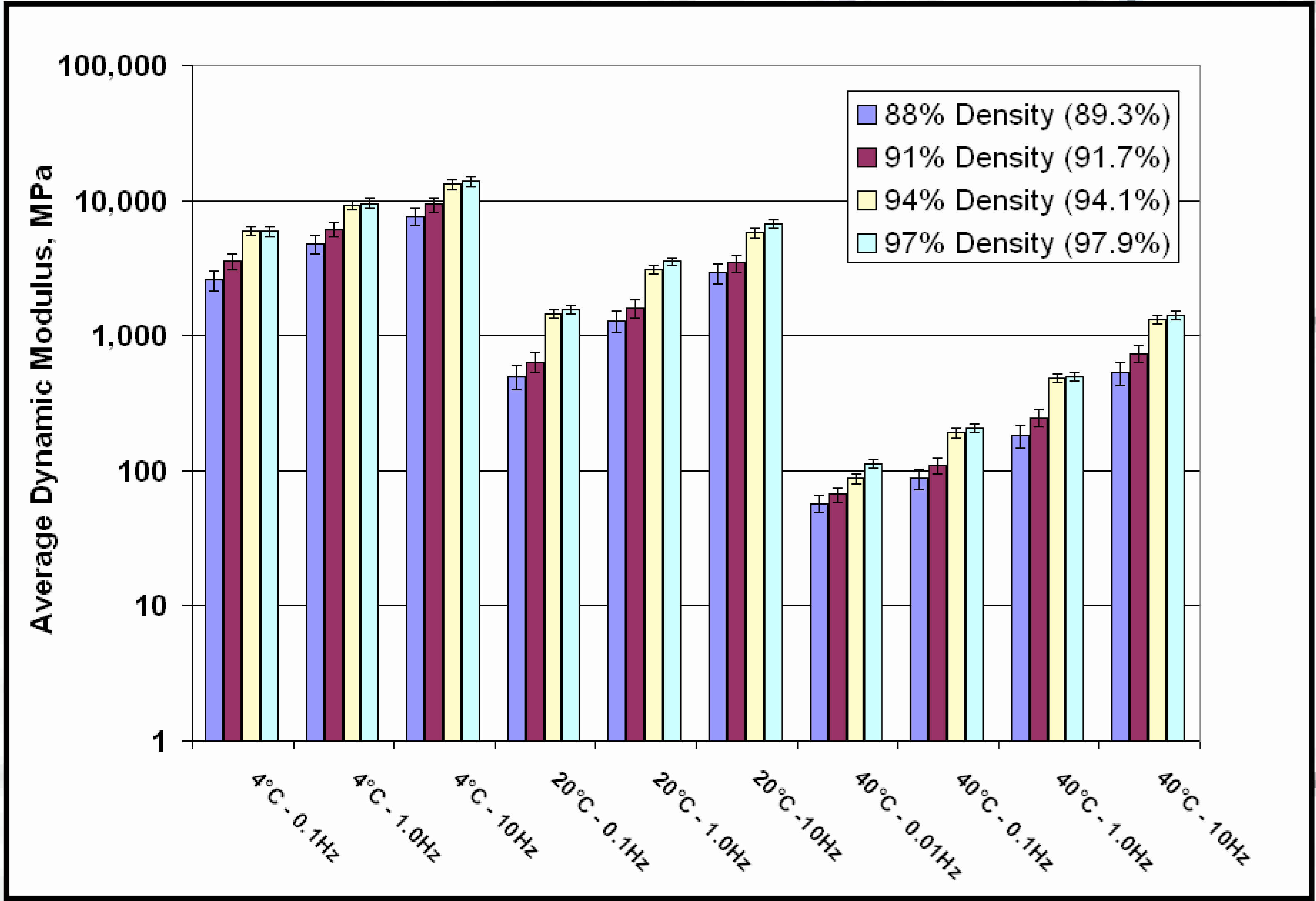
Pictures courtesy of Pine Instrument Company & Pavement Technology Inc.

Mixture Stiffness

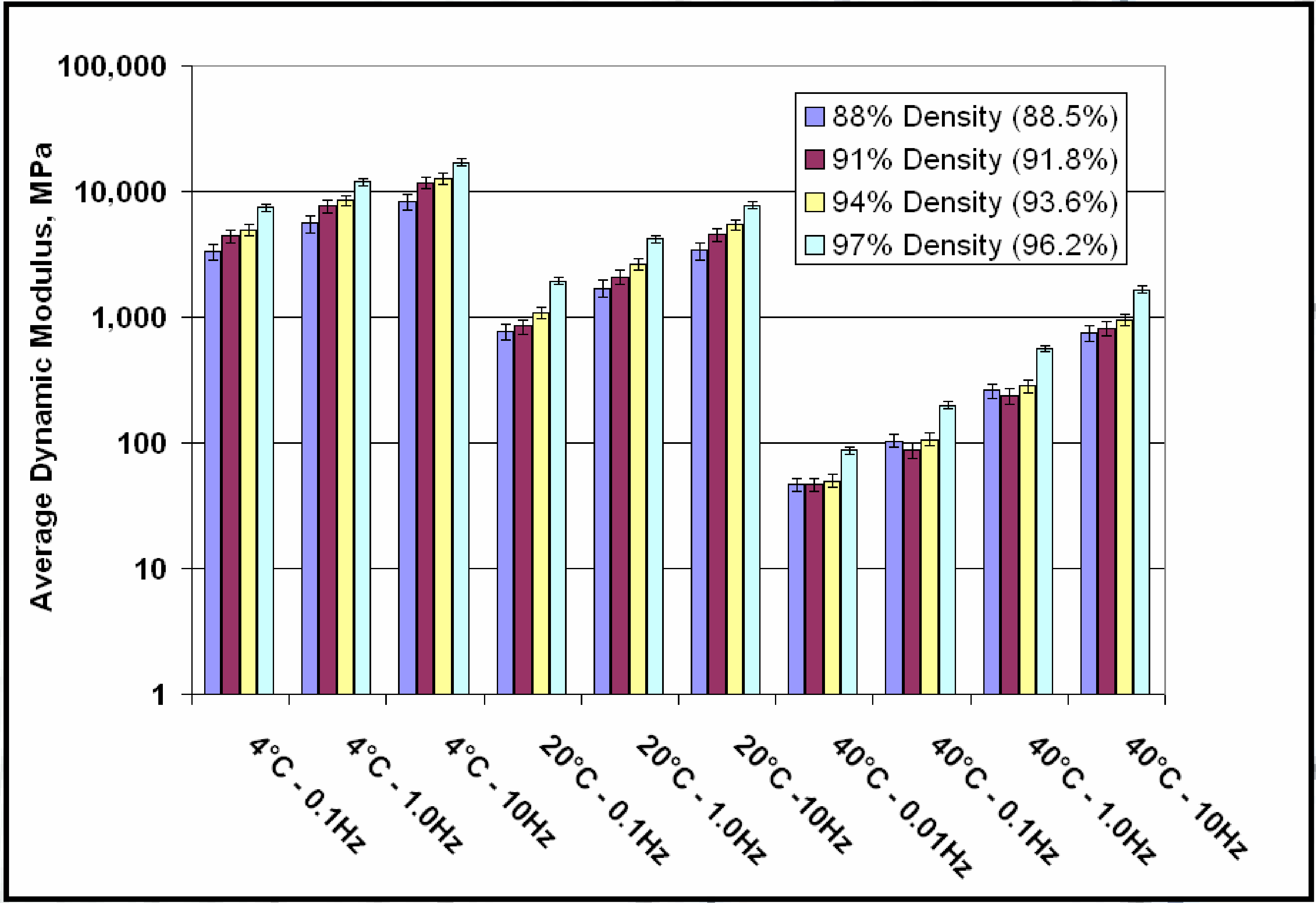
Dynamic Modulus |E*| Testing

Temperature	Frequency
4°C	10 Hz, 1Hz, 0.1Hz
20°C	10 Hz, 1Hz, 0.1Hz
40°C	10 Hz, 1Hz, 0.1Hz, 0.01Hz

|E*| Results - 9.5mm



|E*| Results - 12.5mm



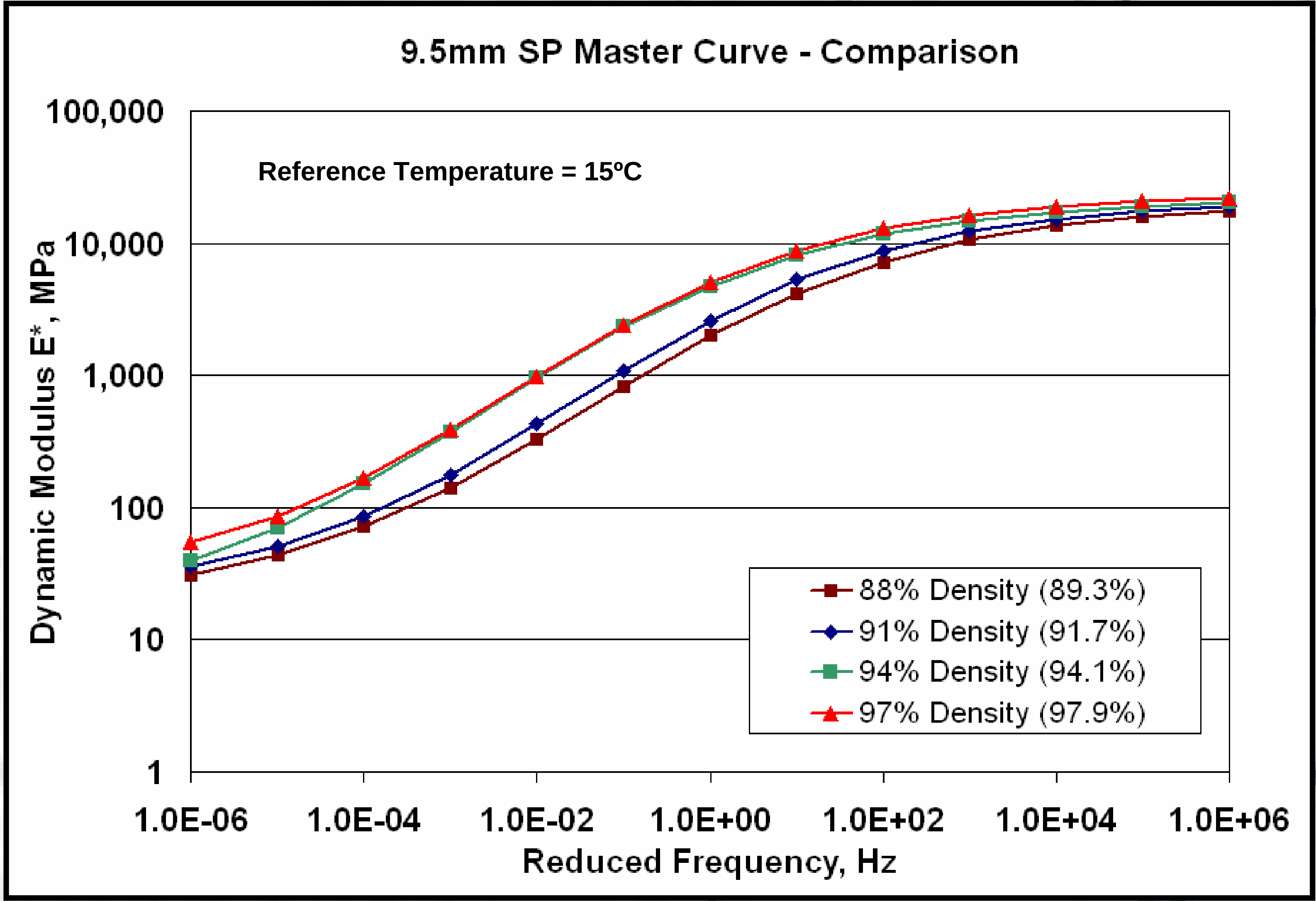
Raw |E*| Results - 9.5mm

Conditions		Target Density Levels			
Temp. (°C)	Frequency (Hz)	88%	91%	94%	97%
		Average Modulus (MPa)			
4	0.1	2,579	3,543	5,919	5,882
4	1	4,743	6,113	9,274	9,547
4	10	7,581	9,329	13,258	13,883
20	0.1	502	638	1,448	1,565
20	1	1,296	1,591	3,069	3,527
20	10	2,898	3,438	5,784	6,739
40	0.01	57	67	88	114
40	0.1	88	109	190	207
40	1	182	247	484	500
40	10	534	739	1,317	1,430

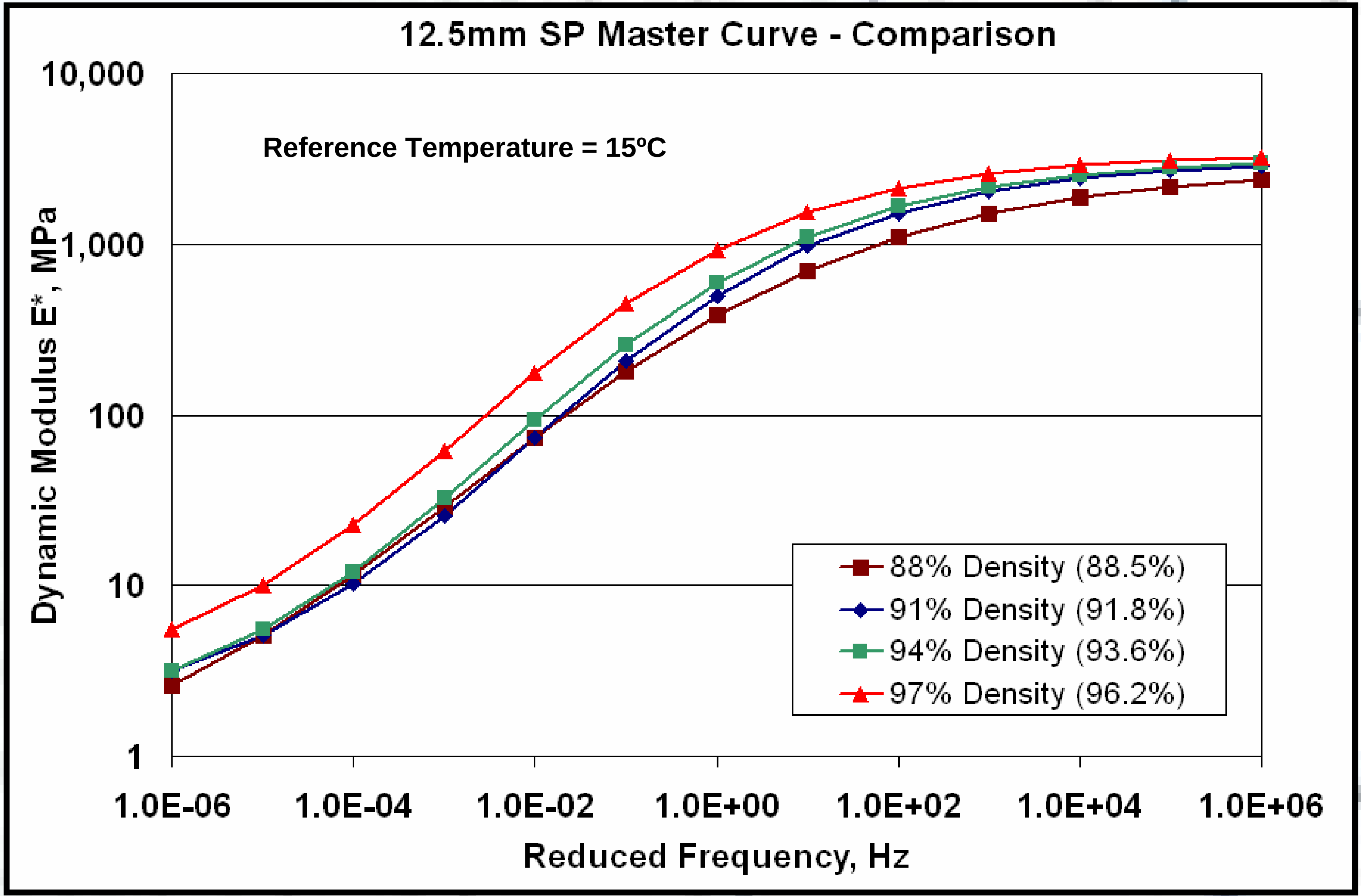
Raw |E*| Results - 12.5mm

Conditions		Target Density Levels			
Temp. (°C)	Frequency (Hz)	88%	91%	94%	97%
		Average Modulus (MPa)			
4	0.1	3,331	4,441	4,942	7,468
4	1	5,551	7,683	8,462	11,917
4	10	8,346	11,647	12,743	17,098
20	0.1	768	846	1,083	1,940
20	1	1,706	2,102	2,647	4,191
20	10	3,398	4,510	5,470	7,762
40	0.01	47	47	50	87
40	0.1	104	88	106	199
40	1	261	239	285	564
40	10	743	815	954	1,660

Master Curves - 9.5mm



Master Curves - 12.5mm



Mixture Stiffness - Conclusions

- The dynamic modulus of the mixture increased as density increased at the different test temperatures and frequencies tested.
- Data indicated that the magnitude of the increase in dynamic modulus was a function of the mixture type tested.
- The 9.5 mm Superpave mixture data showed no significant difference in dynamic modulus between the 88% and 91% density levels. This was also true between the 94% and 97% density levels.

Mixture Stiffness - Conclusions

- The 12.5mm mixture data showed significantly higher stiffness at the 97% target density level as compared to all other density levels tested.

Fatigue Cracking

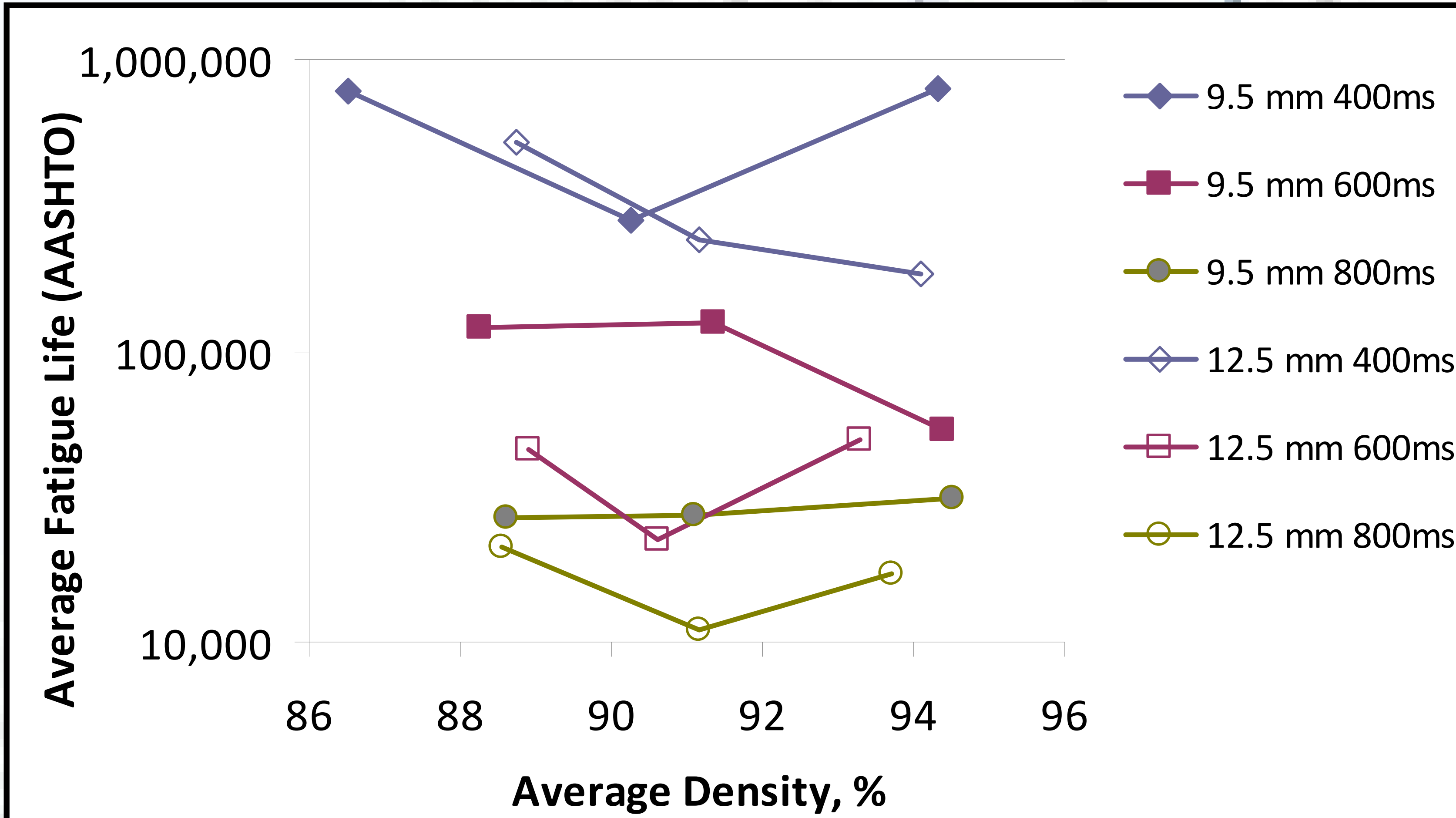
Flexural Beam Fatigue

- Testing in accordance with AASHTO T321 "Determining the Fatigue Life of Compacted HMA Subjected to Repeated Flexural Bending."
- Test temperature of 15ºC (59ºF).
- Strain levels of 400 ms, 600 ms & 800 ms.
- High density (97%) specimens were unable to be made with asphalt vibratory compactor.

Beam Fatigue Device

Picture courtesy of IPC Global (www.ipcglobal.com.au)

Beam Fatigue Results - AASHTO

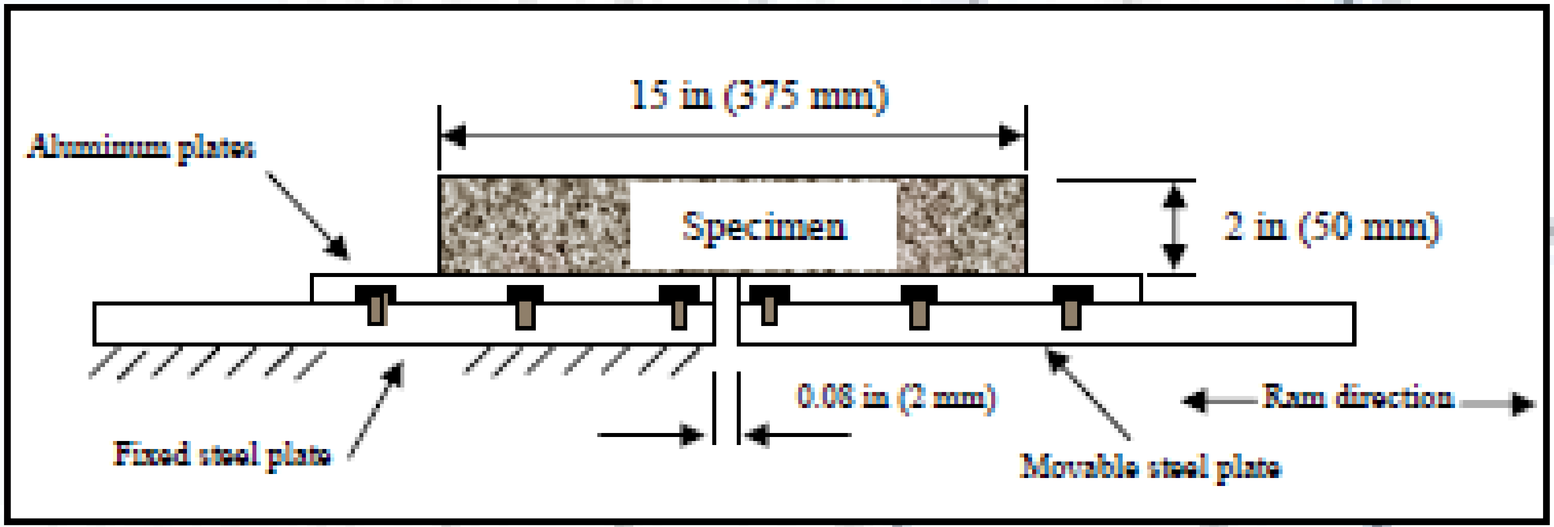


Beam Fatigue Conclusions

- The fatigue life of the 9.5 mm mixture was generally greater than that of the 12.5 mm mixture. This was expected as the design asphalt content of the 9.5 mm mixture was 1.0% higher than the 12.5 mm mixture (5.8% and 4.8%, respectively).
- The general trend of fatigue life with respect to density for each mixture was scattered and in certain cases highly variable.
- No definitive conclusions could be made from beam fatigue data.

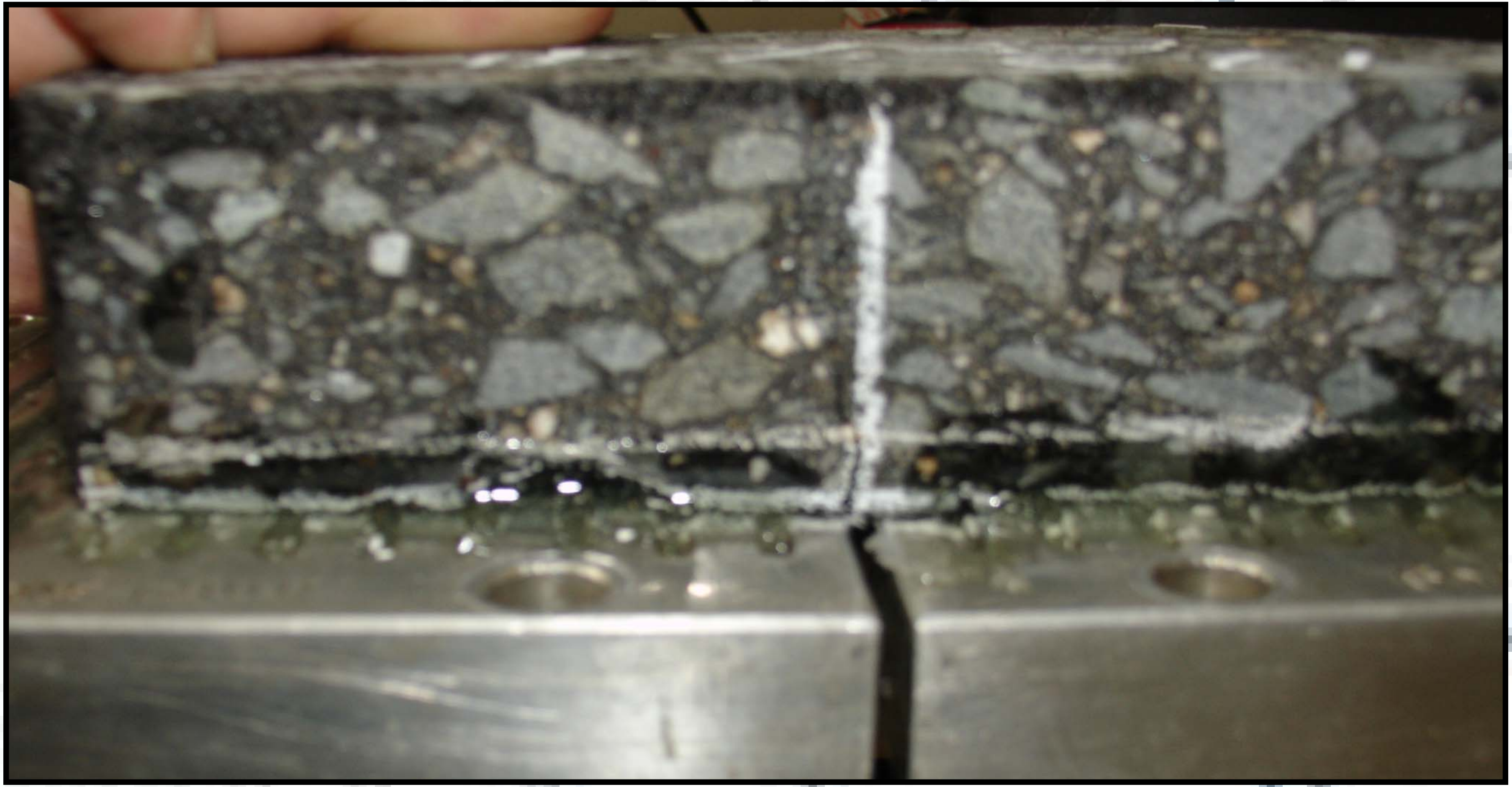
Overlay test (OT)

Overlay Test (OT)



<u>Diagram from:</u>
Zhou and Scullion "Overlay Tester: A Rapid Performance Related Crack Resistance Test" Report No. FHWA/TX-05/0-4467-2 (2005).

Overlay test (OT)



Overlay test (OT)

- Testing conducted in accordance with Texas Department of Transportation Specification Tex-248-F “Overlay Test.”
- Test temperature of 15ºC (59ºF).
- Tests terminated after 93% load reduction required to open/close Maximum Opening Displacement (MOD) = 0.025 inch. One cycle to open and close the MOD takes 10 seconds.
- Fracture mechanics analysis conducted on OT data.
- High density specimens (97%) for either mix did not yield enough OT data to perform fracture mechanics analysis.

Fracture Mechanics Analysis

- Fracture mechanics analysis conducted using procedure developed by Zhou et al in:

  "Development and Verification of the Overlay Tester Based Fatigue Cracking Prediction Approach" Journal of the Association of Asphalt Paving Technologists (AAPT) Vol. 76 (2007)

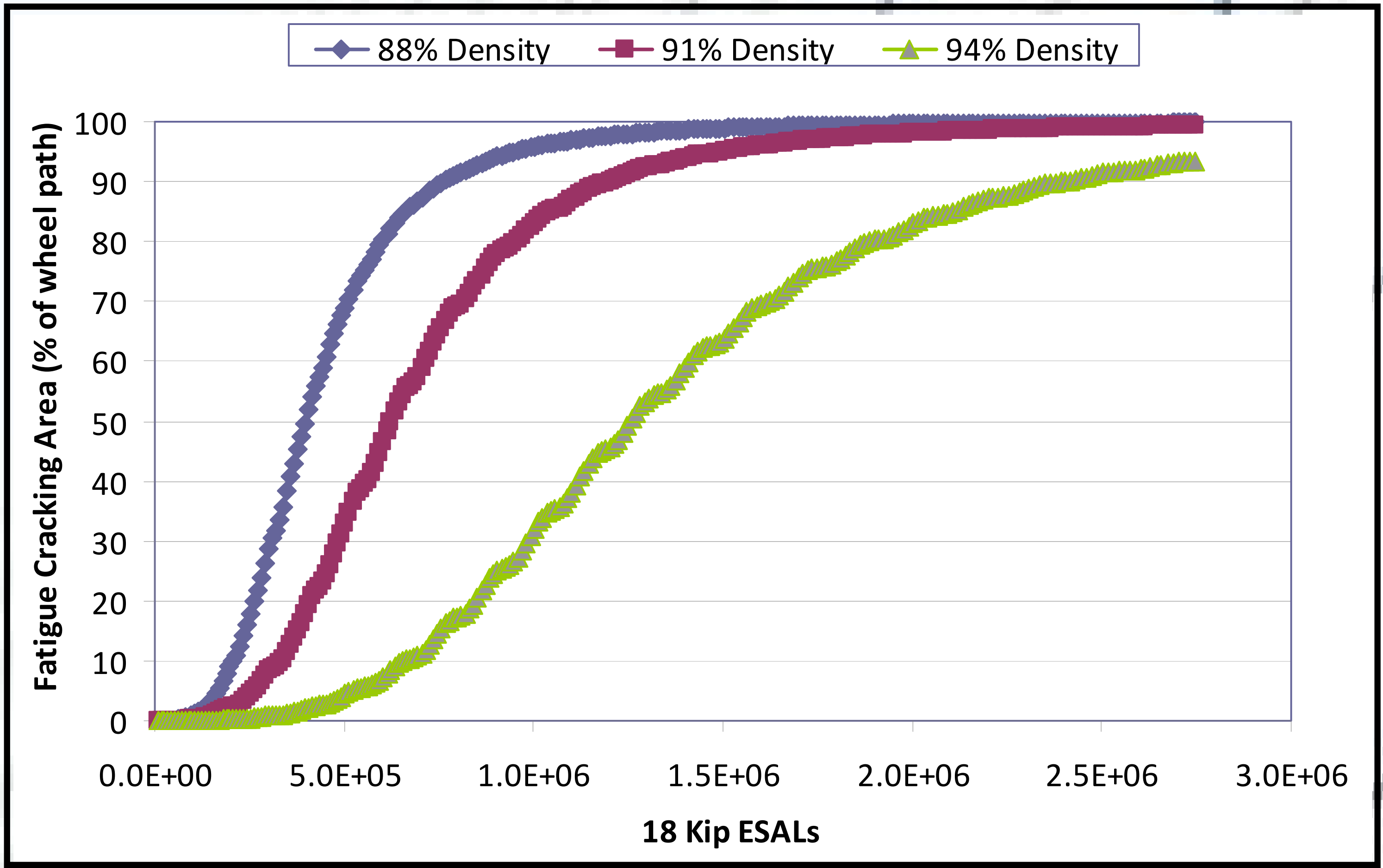
- Input Parameters:
  - OT Test Data
  - E* Master Curves
  - Traffic level (2.7 million ESALs in 20 years)
  - Annual Traffic Growth (2.4%)
  - Weather Station Data (Boston, MA)
  - Traffic Vehicle Speed (v=72 km/h or 45 mph)

Fracture Mechanics Analysis

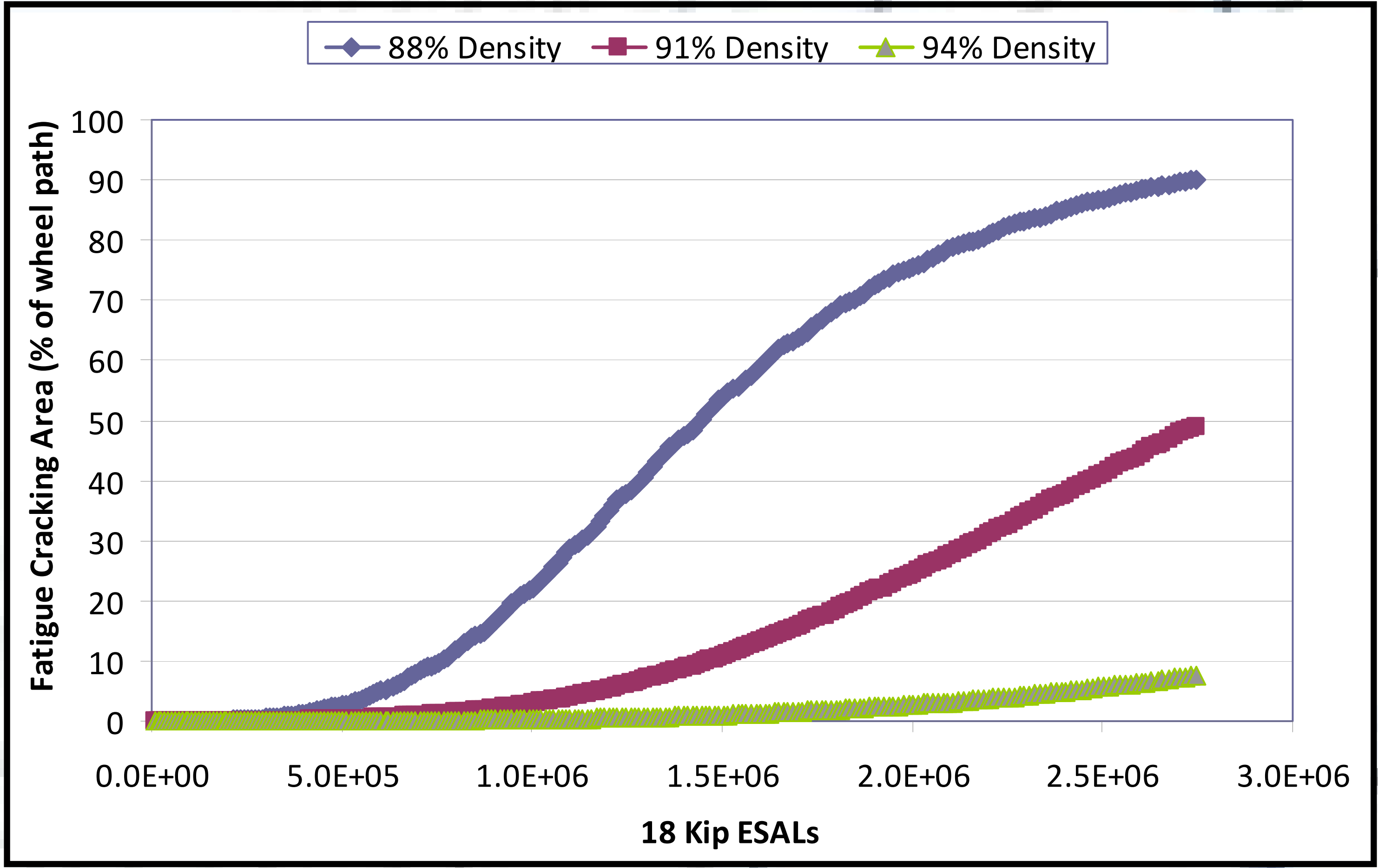
- **The area exhibiting fatigue cracking was predicted for two pavement cross sections using the fracture mechanics analysis.**

Pavement Structure #1	Pavement Structure #2
50 mm Asphalt Layer	**100 mm** Asphalt Layer
200 mm Base E = 345 MPa	200 mm Base E = 345 MPa
150 mm Subbase E = 240 MPa	150 mm Subbase E = 240 MPa
Subgrade 55 MPa	Subgrade 55 MPa

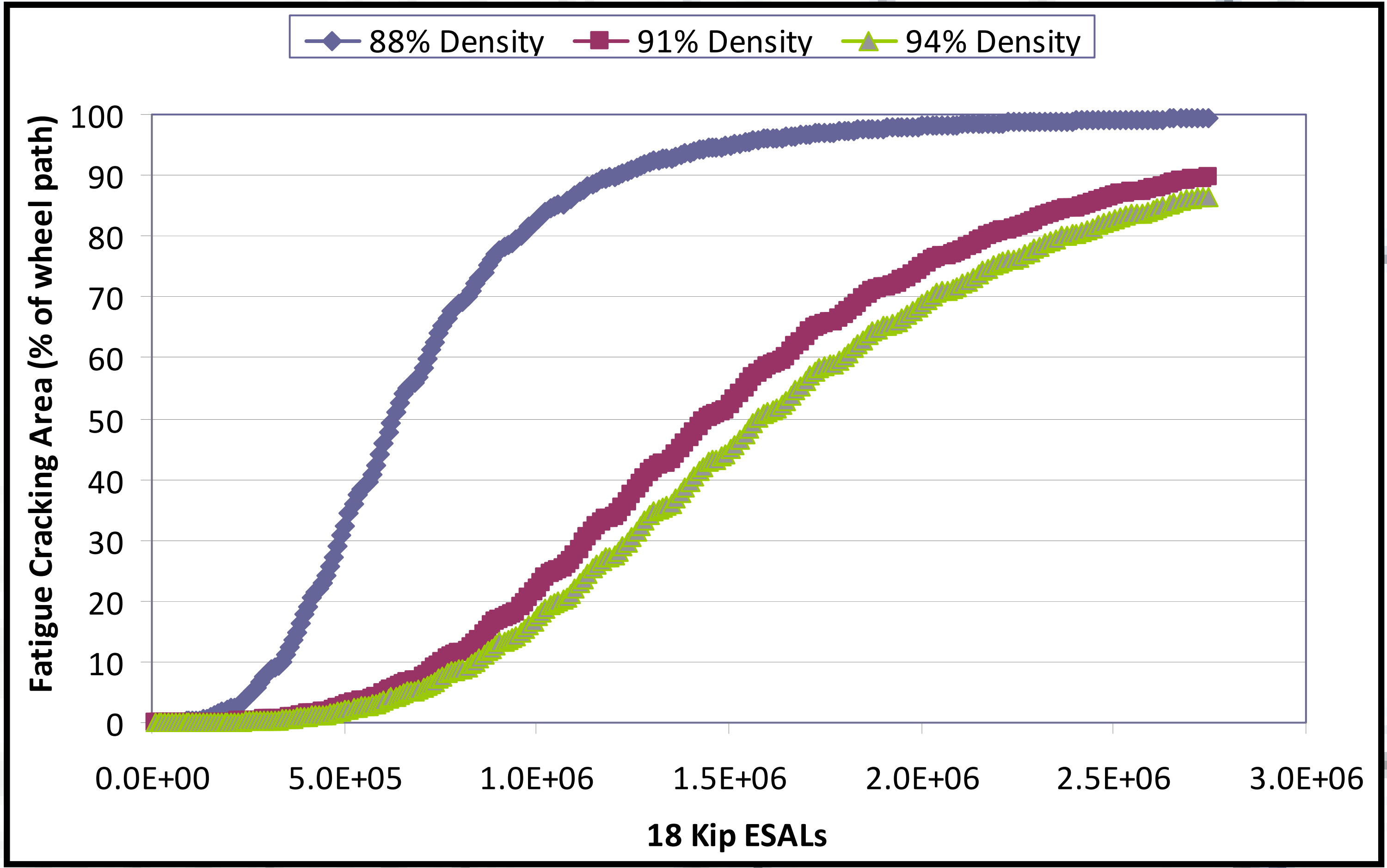
Fracture Mechanics Results
9.5mm – 50mm HMA Layer



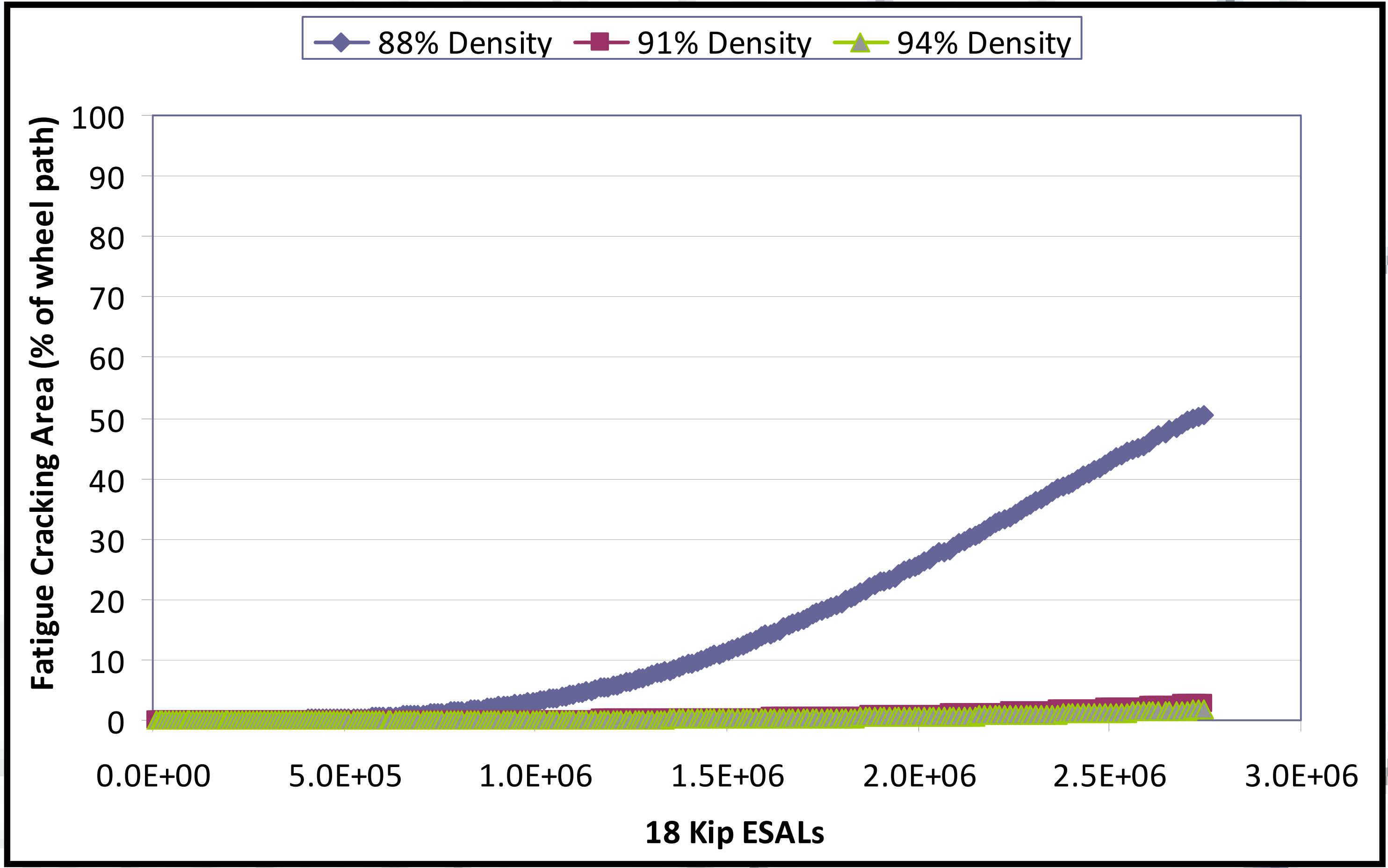
Fracture Mechanics Results 9.5mm – 100mm HMA Layer



Fracture Mechanics Results 12.5mm – 50mm HMA Layer



Fracture Mechanics Results 12.5mm – 100mm HMA Layer



Fracture Mechanics Results Comparison - 9.5mm

		Fracture Mechanics Prediction of ESALs Resulting in 50% Area Cracked	
Density Level Target	Average Specimen Density, %	50 mm Thickness	100 mm Thickness
88%	89.3	398,127	1,443,208
91%	91.7	624,143	>2,700,000*
94%	94.5	1,254,946	>2,700,000*

* Design ESALs for the analysis were 2.7 million.

Fracture Mechanics Results Comparison - 12.5mm

		Fracture Mechanics Prediction of ESALs Resulting in 50% Area Cracked	
Density Level Target	Average Specimen Density, %	50 mm Thickness	100 mm Thickness
88%	89.1	627,161	2,723,445
91%	92.2	1,440,350	>2,700,000*
94%	94.0	1,576,154	>2,700,000*

* Design ESALs for the analysis were 2.7 million.

OT/Fracture Mechanics Conclusions

- **Increasing density improved the fatigue performance of both HMA mixtures tested.**

- **Example - In case of 50 mm thick 9.5mm asphalt layer, if the density were increased from 88% to 94%, the fatigue life corresponding to 50% fatigue area of the wheel path would increase from approximately 398,000 to 1,250,000 ESALs.**

- **Density has a significant influence on mixture performance in terms of fatigue cracking.**

Rutting

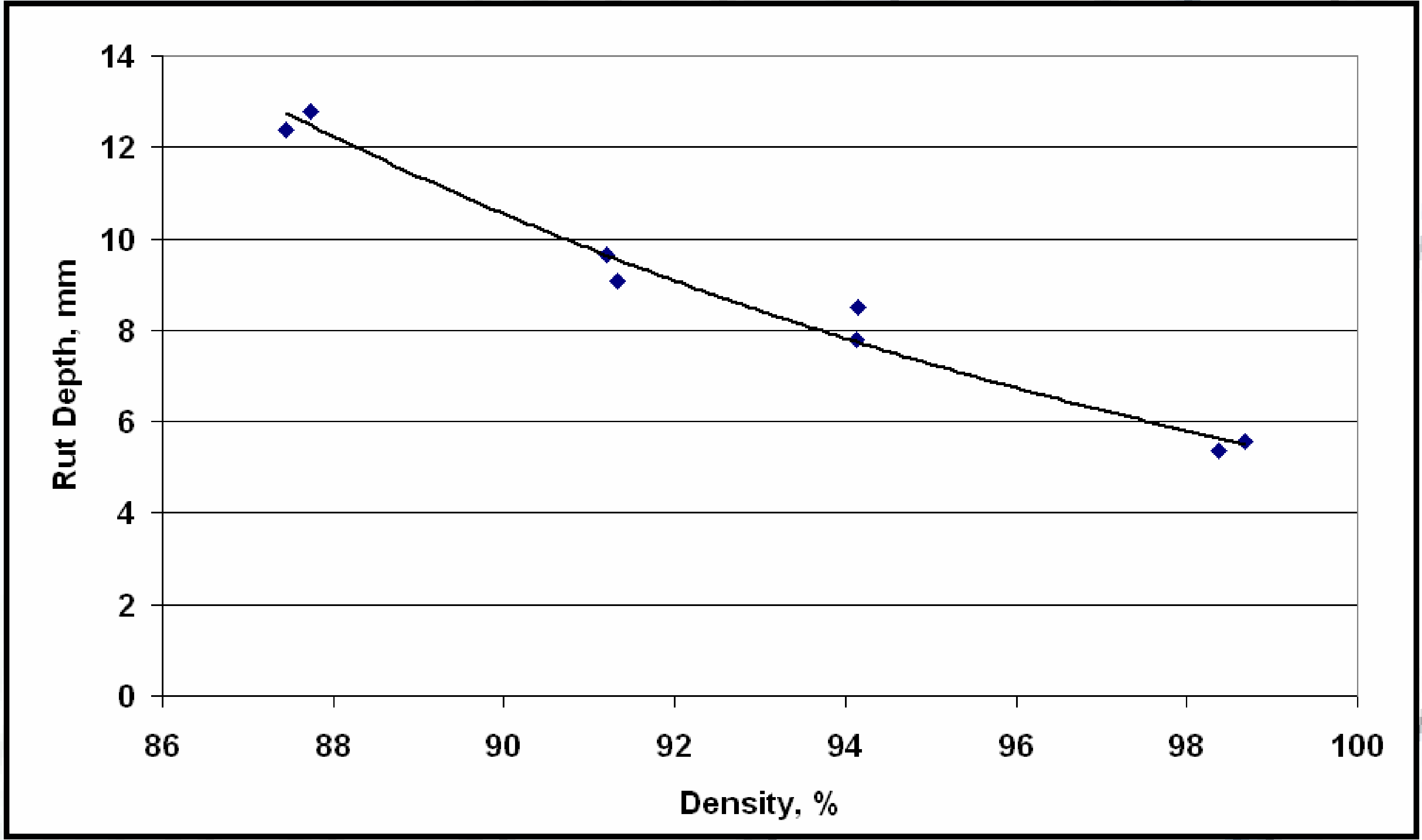
APA Rutting

- Testing conducted in accordance with AASHTO TP63 "Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer."

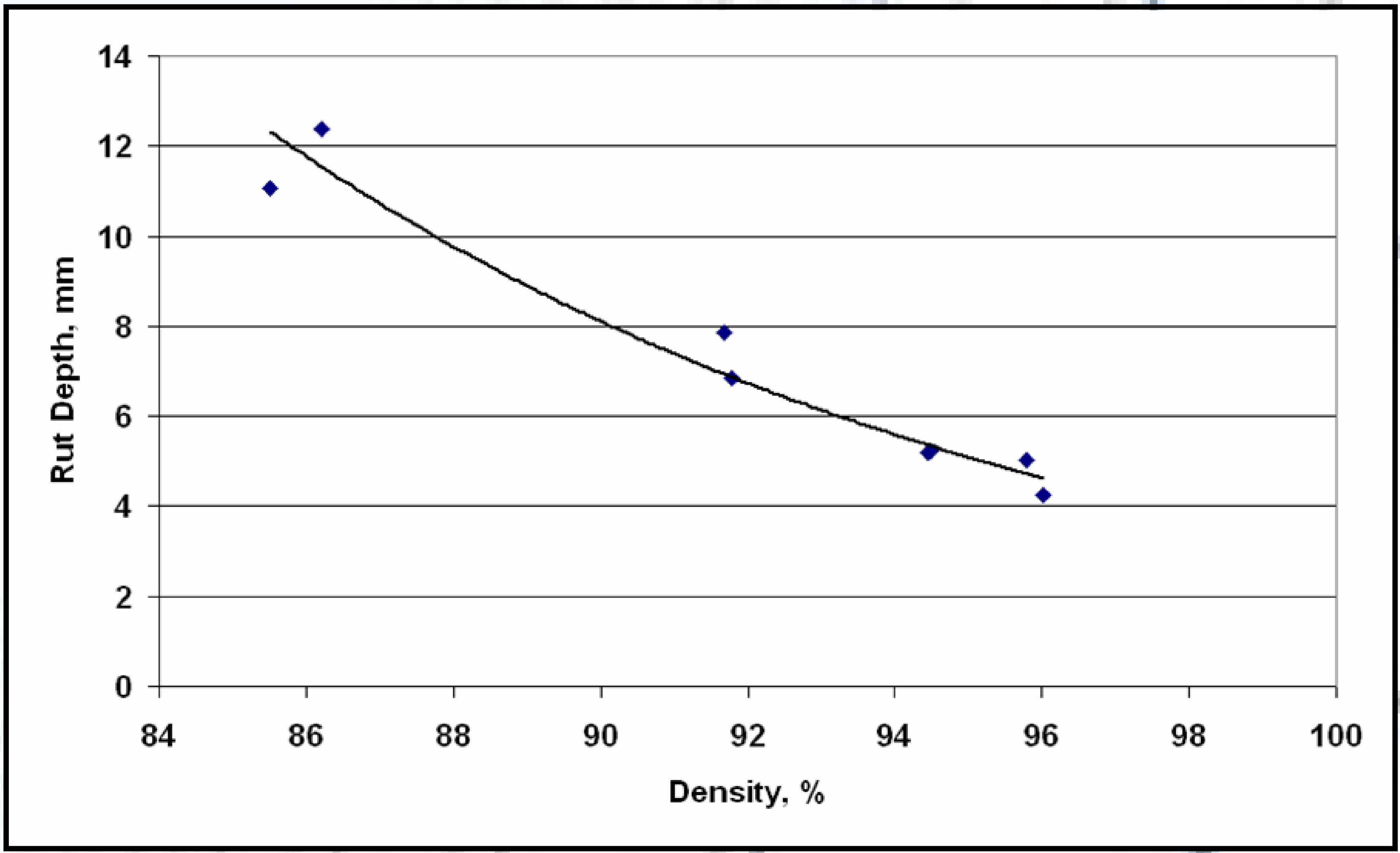
- Test temperature of 64ºC (147ºF) corresponding to high PG grade of binder.

- Tests conducted for a total of 8,000 load application cycles.

APA Results – 9.5mm



APA Results – 12.5mm



Flow Number Test

- AMPT specimen is subjected to a repeated compressive axial load for 0.1 sec followed by a rest period of 0.9 seconds.

- Flow number is defined as the number of load applications corresponds to the onset of tertiary flow of the mixtures.

- Flow number value provides an indication of the mixtures' relative resistance to permanent deformation.

Flow Number

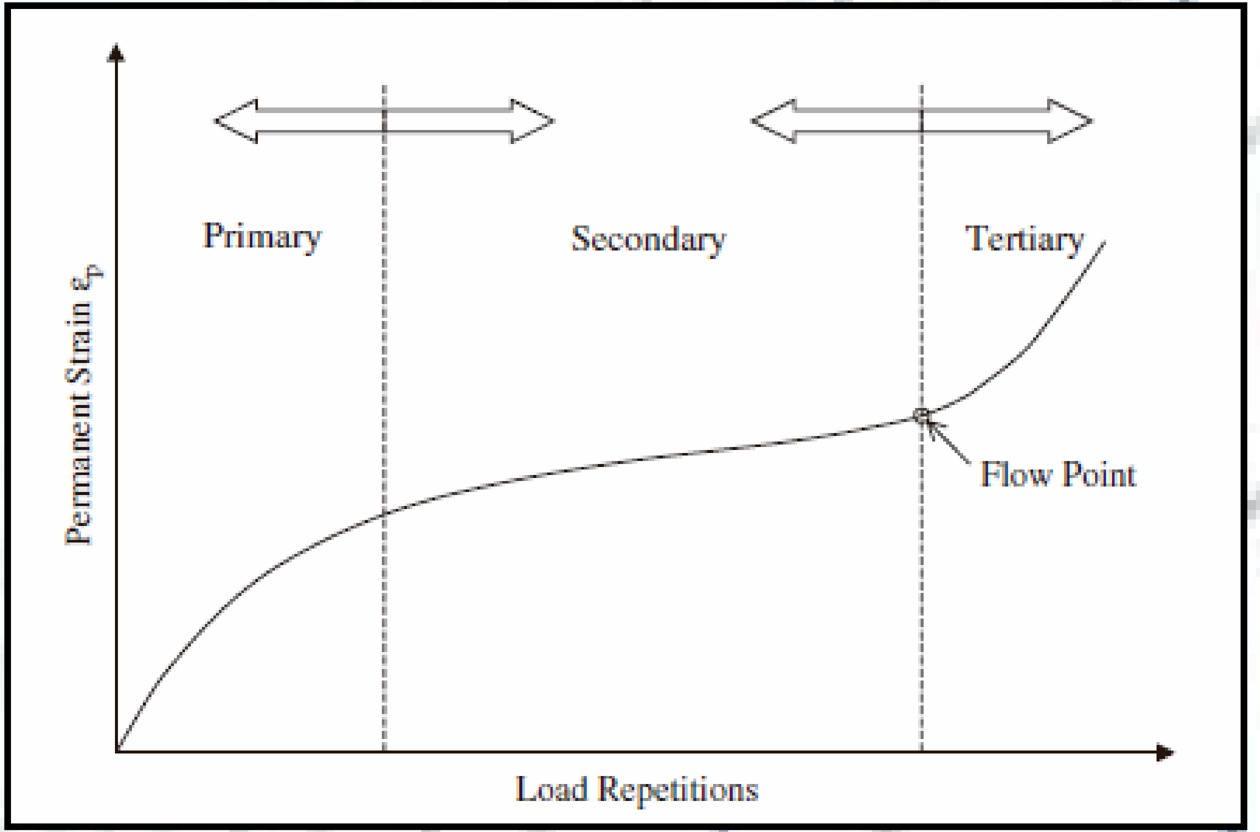


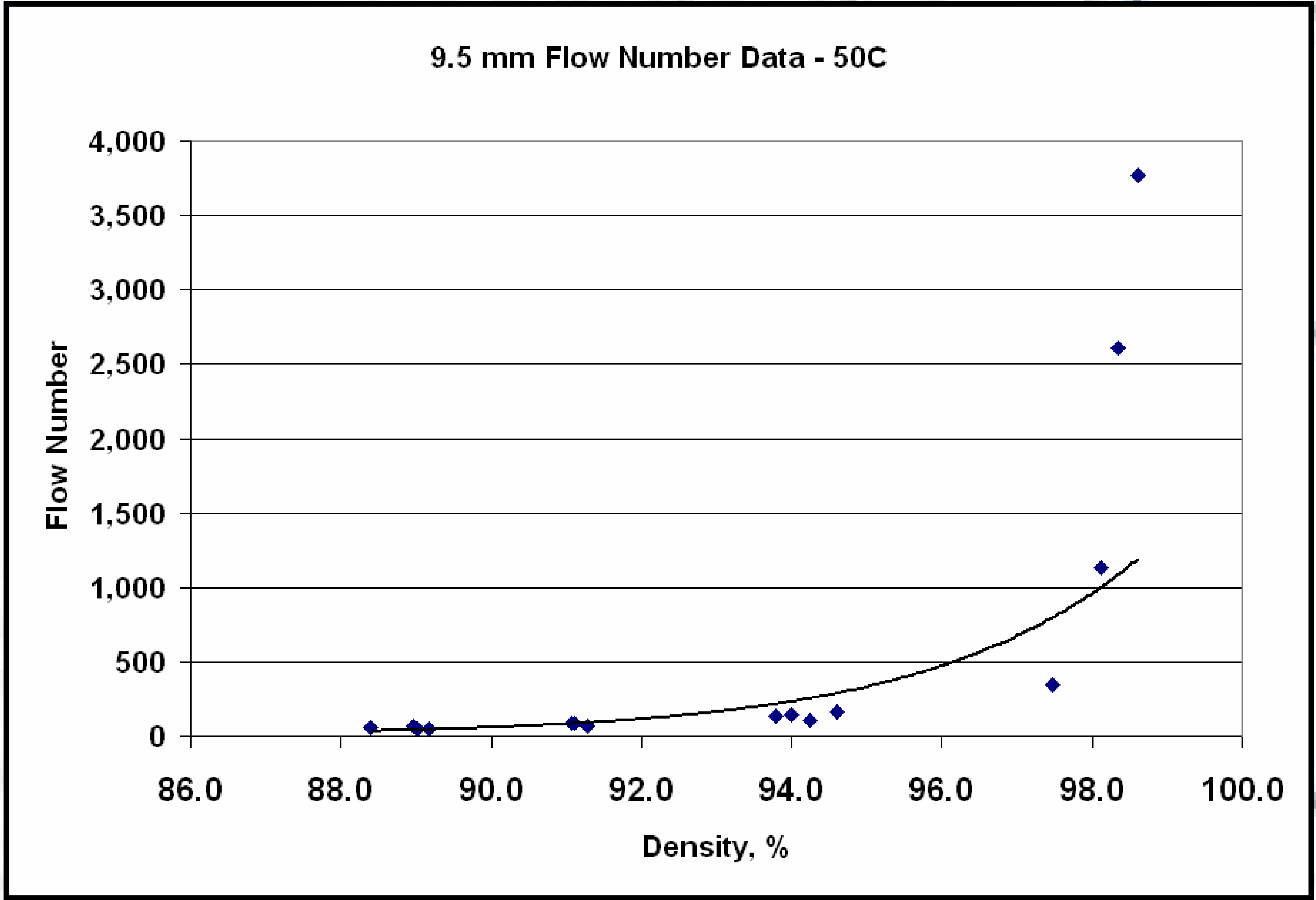
Figure from:

M.W. Witczak "Specification Criteria for Simple Performance Tests for Rutting" National Cooperative Highway Research Program (NCHRP), Report 580, 2007.

Flow Number

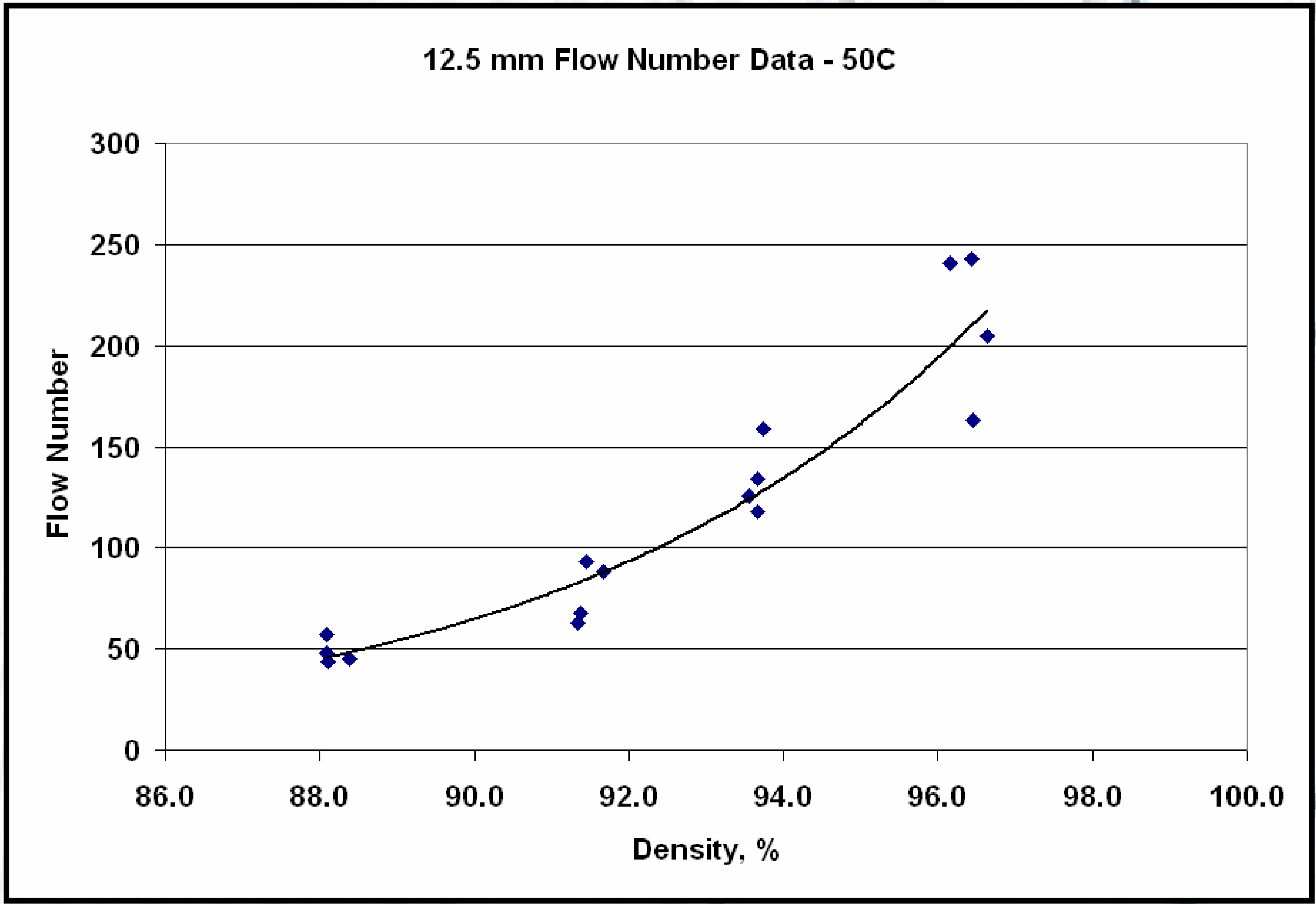
- Flow number test was conducted in accordance with NCHRP Report 629 “Ruggedness Testing of the Dynamic Modulus and Flow Number Tests with the Simple Performance Tester” and the DRAFT final report for NCHRP 9-33 “A Mix Design Manual for Hot Mix Asphalt.”
- Test temperature of 50ºC (122ºF) corresponding to the LTPPBind software seven day average maximum temperature located 20 mm from the pavement surface with 50% reliability.
- Specimens tested in the AMPT unconfined with a 600 kPa deviator stress.

Flow Number



9.5 mm Flow Number Data - 50C
Flow Number
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
86.0
88.0
90.0
92.0
94.0
96.0
98.0
100.0
Density, %

Flow Number



12.5 mm Flow Number Data - 50C
Flow Number
300
250
200
150
100
50
0
86.0
88.0
90.0
92.0
94.0
96.0
98.0
100.0
Density, %

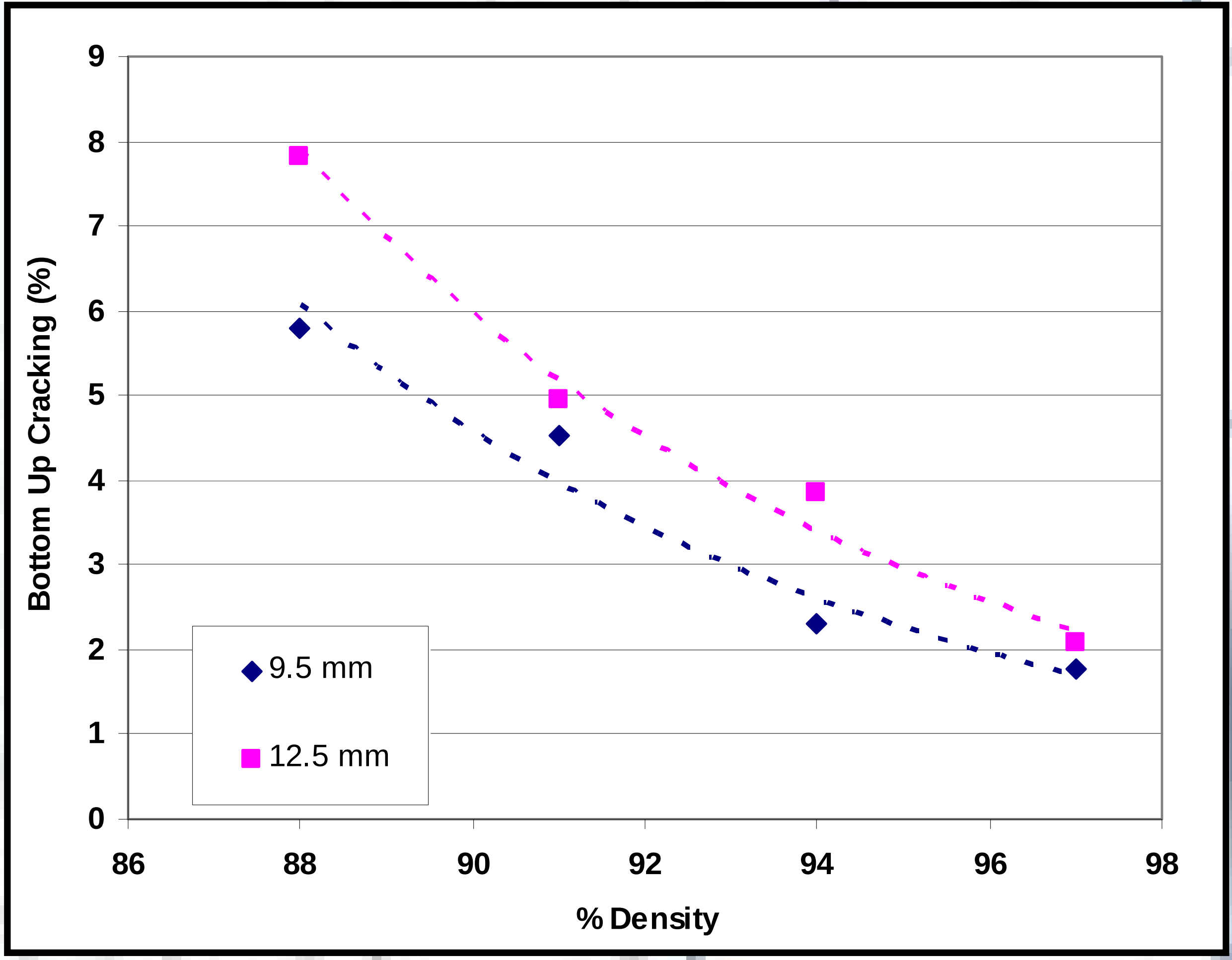
Rut Testing Conclusions

- The APA and flow number data showed the same relationship between density and rutting.
- This relationship indicated that HMA rutting susceptibility decreased as mixture density increased.

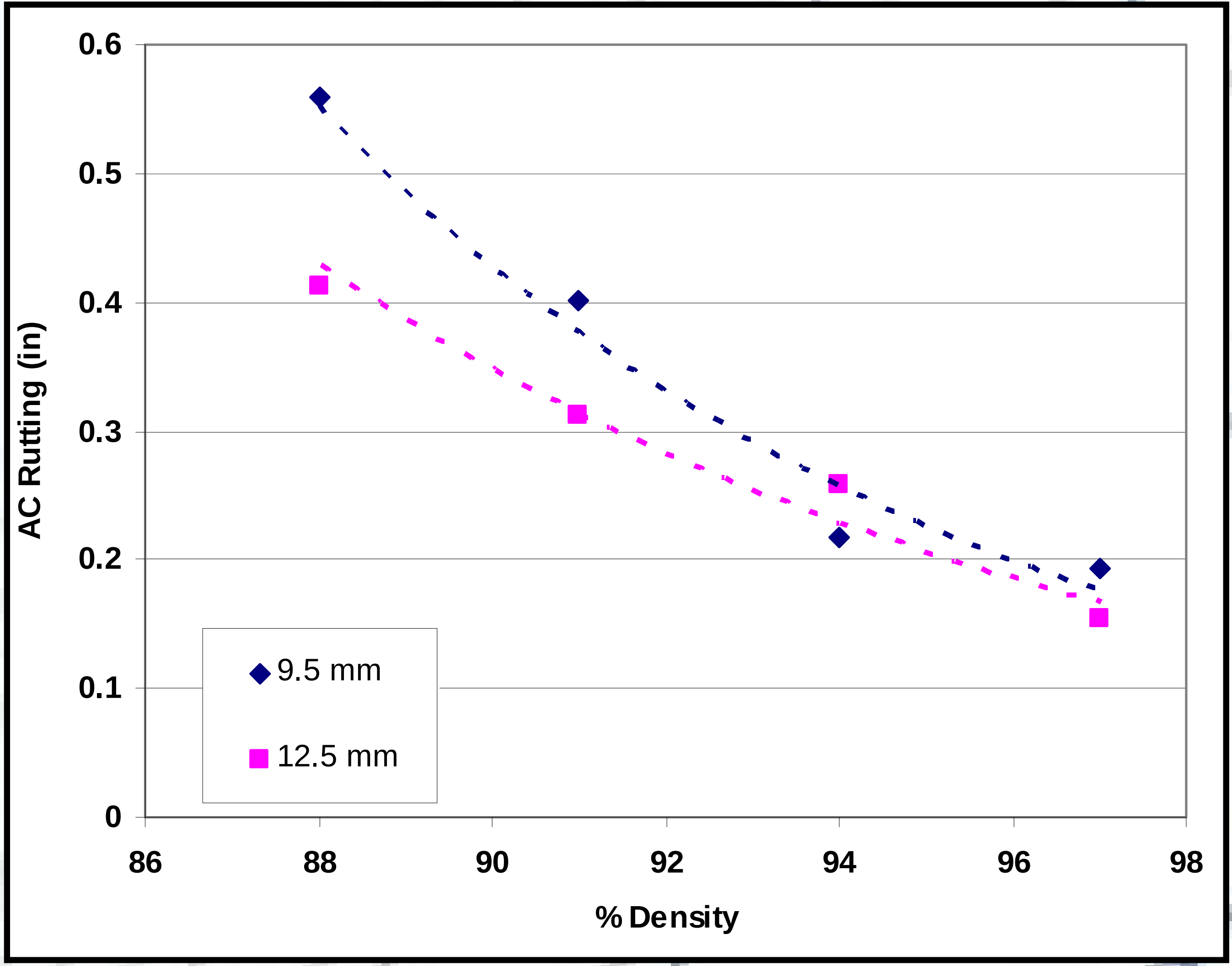
MEPDG Software Analysis

- The MEPDG Version 1.0 Software analysis was utilized to establish if trends obtained from the software were similar to those from the laboratory testing.
- Dynamic modulus master curves generated from the laboratory testing were used in Level 1 analysis runs.
- All analysis inputs remained constant except for dynamic modulus |E*| values, effective binder content of the mixture, and unit weight of the mixture.

MEPDG Analysis – Bottom Up Cracking



MEPDG Analysis – Rutting



MEPDG Conclusions

- The MEPDG Version 1.0 Software showed the trend that as density increased, the amount of fatigue cracking decreased. This was the same general trend obtained from the OT based fracture mechanics analysis of each mixture.
- The rutting prediction showed the same trend obtained from the APA and flow number testing. The trend indicated that as mixture density increased, the rutting susceptibility of the mixture decreased.
- Overall, the MEPDG provided the same trends as the majority of the laboratory test (OT based fracture mechanics, APA, and flow number).

Study Conclusions

- Complex dynamic modulus |E*| data indicated that the test was sensitive to each mixture's density. The trend was as density increased stiffness increased. This trend was consistent for both mixtures tested.

- Flexural beam fatigue testing provided inconclusive trends relating HMA density to fatigue cracking potential.

- OT based fracture mechanics analysis showed that the number of ESALs to reach the fatigue cracking failure criteria (50% area cracked) increased as mixture density increased.

Study Conclusions (cont'd)

- APA rut tests and flow number testing showed that as density increased, the rutting potential decreased. This trend was consistent for both mixtures tested.

- The MEPDG prediction equations indicated similar trends to those obtained by the OT based fracture mechanics approach (cracking) and the APA rut test and the flow number test (rutting).

- Overall, the test and analysis approaches used in this study were sensitive to mixture density.

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Thank you!