# Limitations of Foamed Warm Mix Asphalt Produced by Water Injection

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# Research Team

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# Acknowledgements


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- Mr. Craig Landefeld (Construction Administration)
- Mr. Eric Biehl (Materials Management)

# Outline

- Background
- Study Objectives
- Research Methodology
- Material Information
- Results and Discussion
- Conclusions
- Questions

# Background

# Background

- Traditional asphalt mixtures are produced at temperatures ranging between 300$^{o}$F to 325$^{o}$F (150$^{o}$C to 165$^{o}$C). These mixtures are commonly referred to as hot mix asphalt (HMA).
- In recent years, there has been an increased interest in using a new type of asphalt mixtures called warm mix asphalt (WMA).

# Background (Cont.)

- Several WMA technologies are available:
  - Chemical and organic additives
  - Foamed asphalt binders
- Foamed WMA produced by water injection has received increased interest and use in Ohio since it requires a one-time plant modification and does not require the use of costly additives.

# Background (Cont.)

- Over the last five years, the amount of foamed WMA used in Ohio has increased to more than 50% of the total amount of asphalt mixtures used in the state.
- Key benefits of foamed WMA include:
  - Reduced emissions during production
  - Improved field compaction
  - Improved working conditions
  - Ability to use higher RAP contents

# Background (Cont.)

- Despite the previous advantages, there are several concerns regarding the long-term performance of foamed WMA
- Main concerns:
  - Increased rutting due to reduced binder aging
  - Increased moisture-damage due to insufficient aggregate drying
  - Insufficient aggregate coating
  - Applicability of HMA mix design to foamed WMA

# Background (Cont.)

- Therefore, research is needed to evaluate the performance of foamed WMA and determine the factors that affect its long-term durability.
- In addition, current mix design methods and specifications used by ODOT for foamed WMA mixtures shall be validated or revised to ensure satisfactory long-term performance.

# Study Objectives

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- Evaluate the factors that affect the volumetric properties, performance, and durability of foamed WMA mixtures.
- Determine the limitations of foamed WMA mixtures.
- Identify changes to current mix design and evaluation procedures, if any, that will be required for foamed WMA mixtures.

# Study Objectives (Cont.)

- Evaluate current ODOT quality control and placement procedures to determine applicability to foamed WMA mixtures.
- Identify changes to current ODOT specifications for foamed WMA mixtures to ensure satisfactory long-term performance.

# Research Methodology

# Research Methodology

Part 1: Performance Evaluation of Foamed WMA and HMA in the Laboratory

Part 2: Workability and Compactability of Foamed WMA and HMA

Part 3: Effect of Mix Preparation Procedure on Foamed WMA

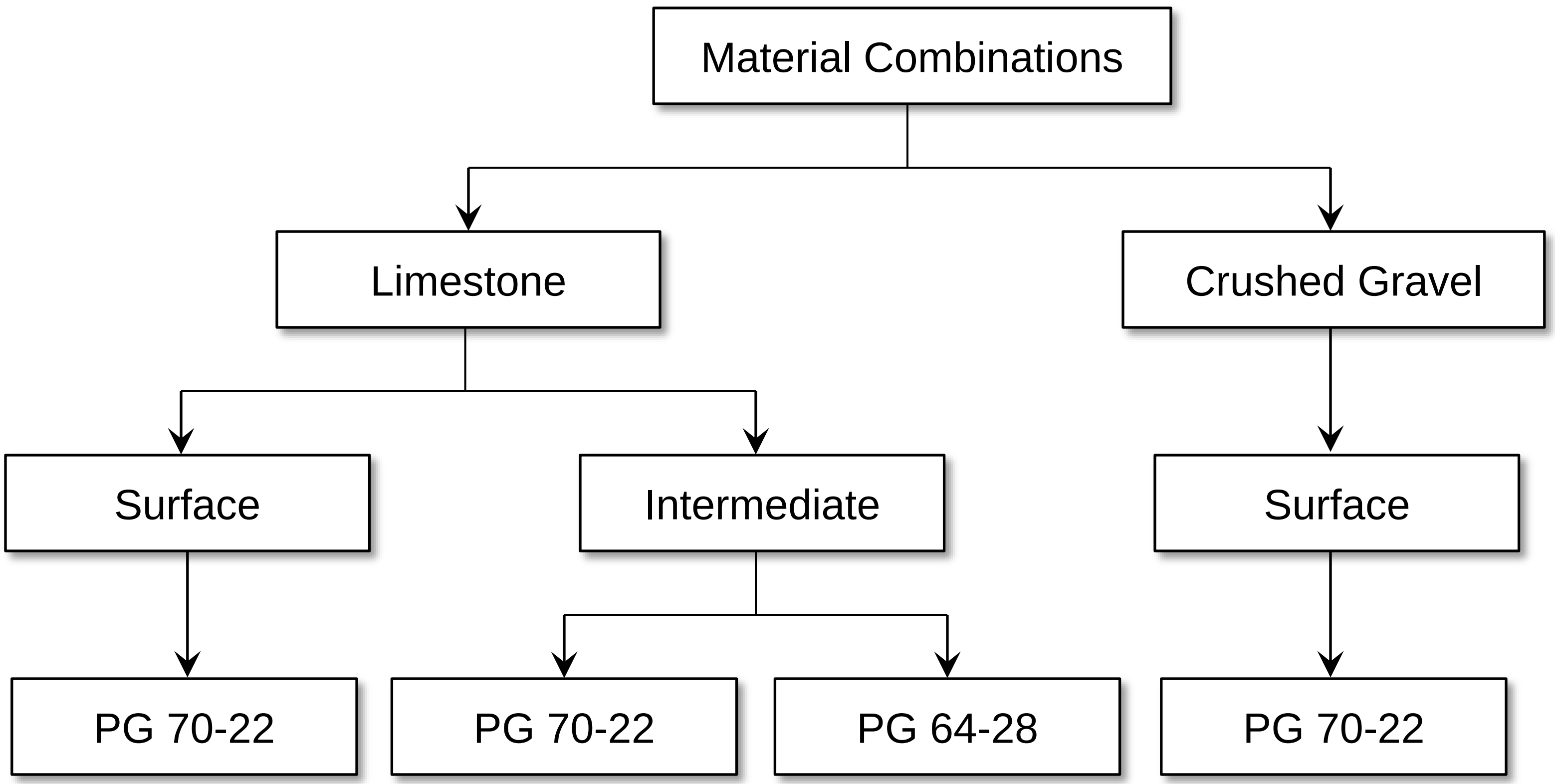
Part 4: Performance Evaluation of Foamed WMA and HMA in the APLF

Part 5: Performance Evaluation of Foamed WMA and HMA using the MEPDG

# Part 1:
# Laboratory Performance of Foamed WMA and HMA

# Material Information

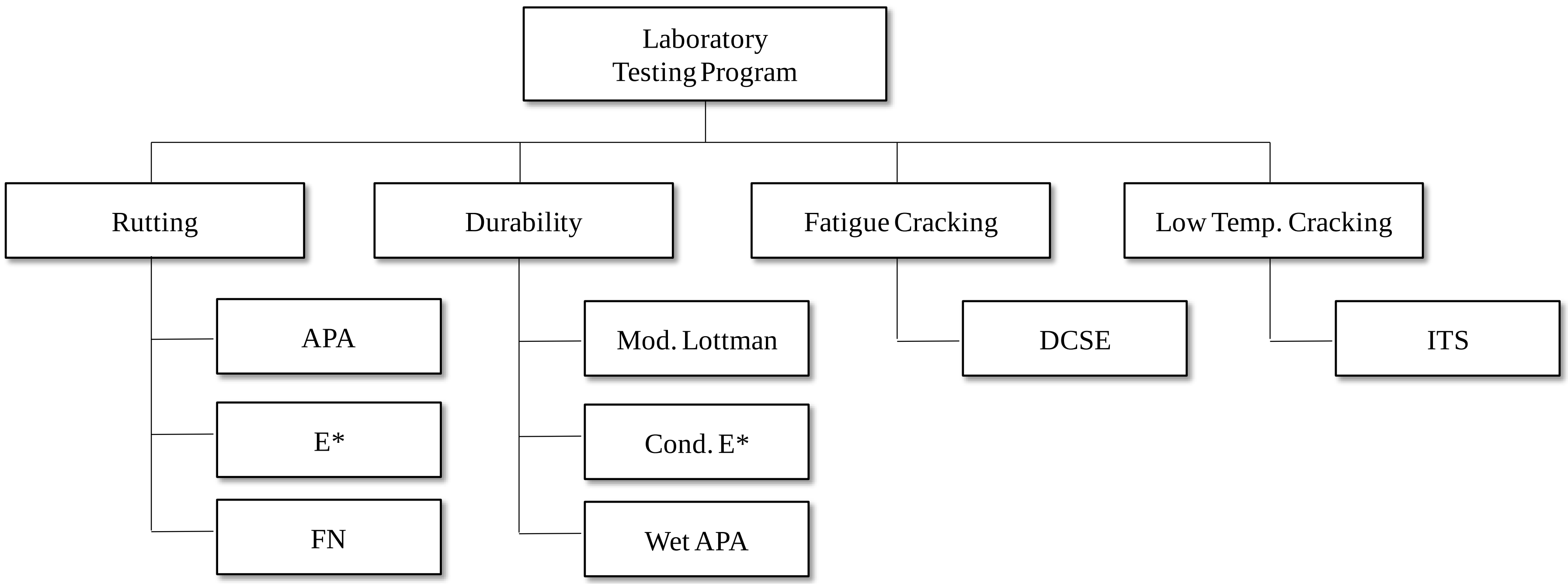
# Material Information



# Production of Foamed WMA

# Laboratory Testing Plan

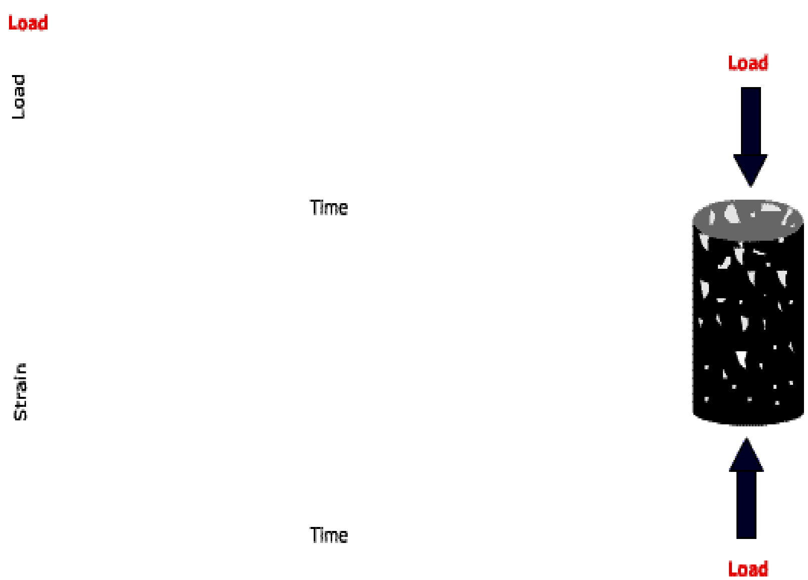
# Laboratory Testing Plan

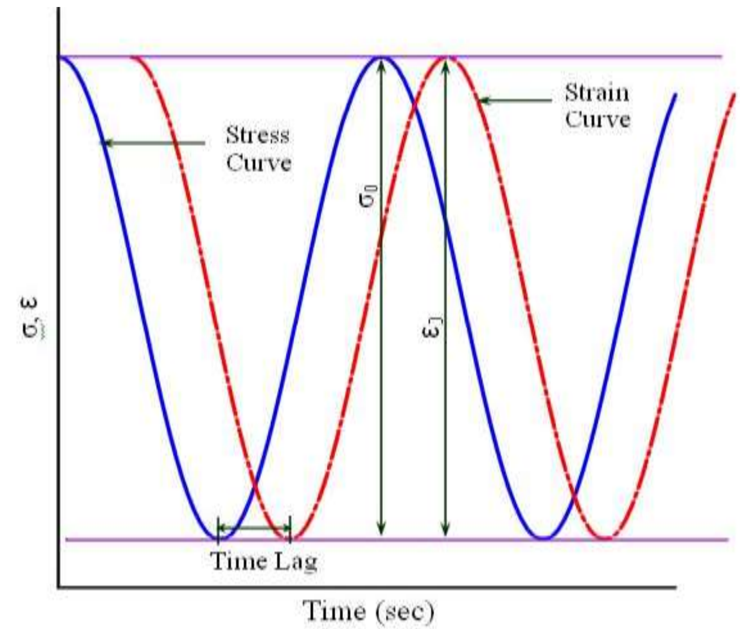


# Asphalt Pavement Analyzer (APA)

- Test method: AASHTO TP 63-07 and ODOT Supplement 1057
- Specimen dimensions: 2.95” height x 6” diameter
- Air voids: 7 ± 1%
- Testing temperature: 120°F
- Hose pressure: 100 psi
- Wheel load: 115 lbf
- Rut depth: 5, 500, 1000, and 8000 passes

# Dynamic Modulus |E*| (Cont.)




Dynamic Modulus

$$|E^*| = \frac{\sigma_o}{\varepsilon_o}$$

Phase Angle

$$\phi = \frac{T_i}{T_p} \times 360^o$$

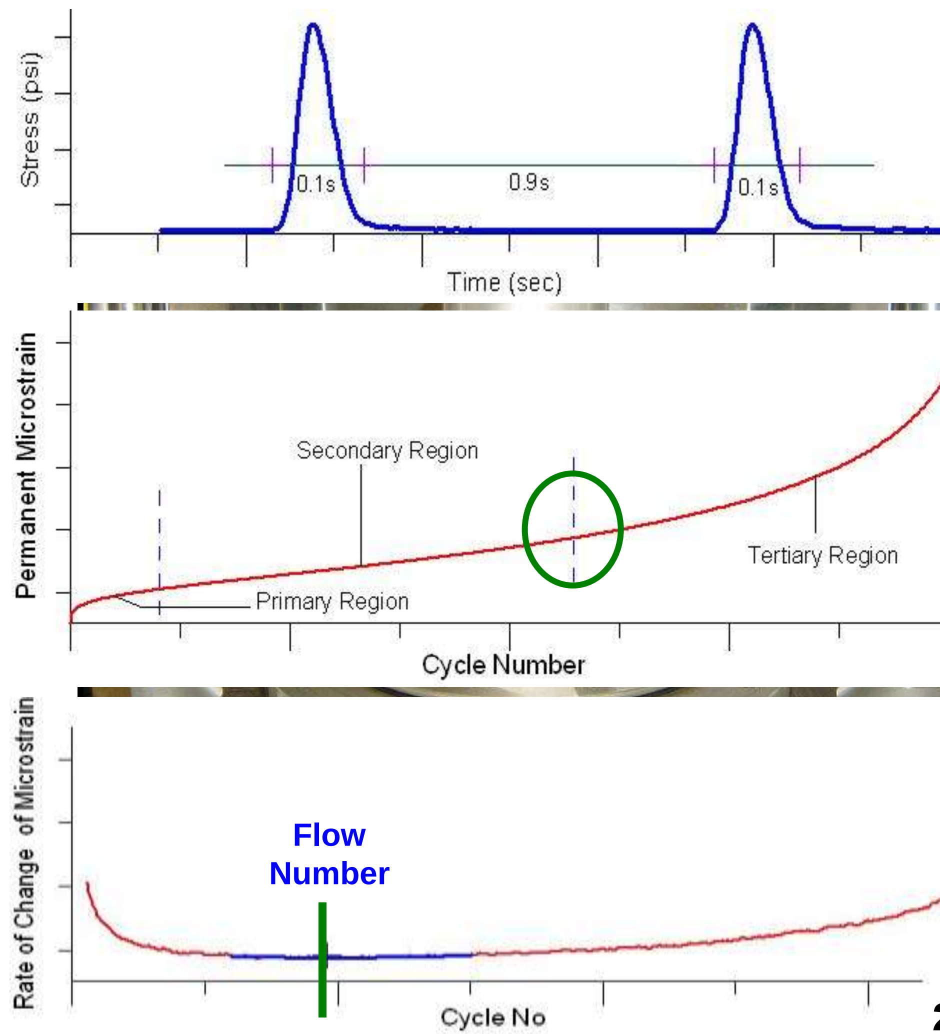
# Dynamic Modulus |E*| (Cont.)

# Dynamic Modulus |E*|

- Test method: AASHTO TP 62-03 and NCHRP 513
- Specimen dimensions: 6” height x 4” diameter
- Air voids: 7 ± 0.5%
- Conditioning:
  - Age loose mixture for 4 hours at 275$^{o}$F (short-term AASHTO R30)
- Loading magnitude: 75 to 125 micro-strain
- Loading frequencies: 25, 10, 5, 1, 0.5, and 0.1 Hz
- Testing temperature: 40, 70, 100, and 130$^{o}$F

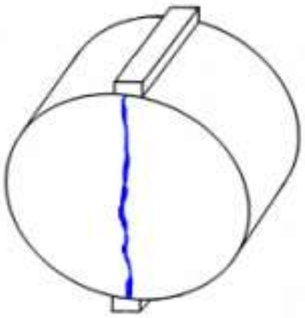
# Flow Number ($F_N$)

- NCHRP 513 {Annex B}
- Temperature: 54.4°C
- Haversine compressive stress
  - Stress level: 30 psi
  - Loading: 0.1 sec
  - Rest period: 0.9 sec
- $F_N$
  - Tertiary failure
  - 10,000 cycles



# Modified Lottman (AASHTO T 283)

- Test method: AASHTO T 283 and ODOT Supplement 1051
- Specimen dimensions: 3.75” height x 6” diameter
- Air voids: 7 ± 0.5%
- Conditioning:
  - Age loose mixture for 4 hours at 275$^{o}$F
  - Soak compacted samples in water for about 4 hours
  - Partially saturate to 80 to 90%
  - Apply one freeze and thaw cycle
- Loading rate: 2 inch/min
- Testing temperature: 77°F

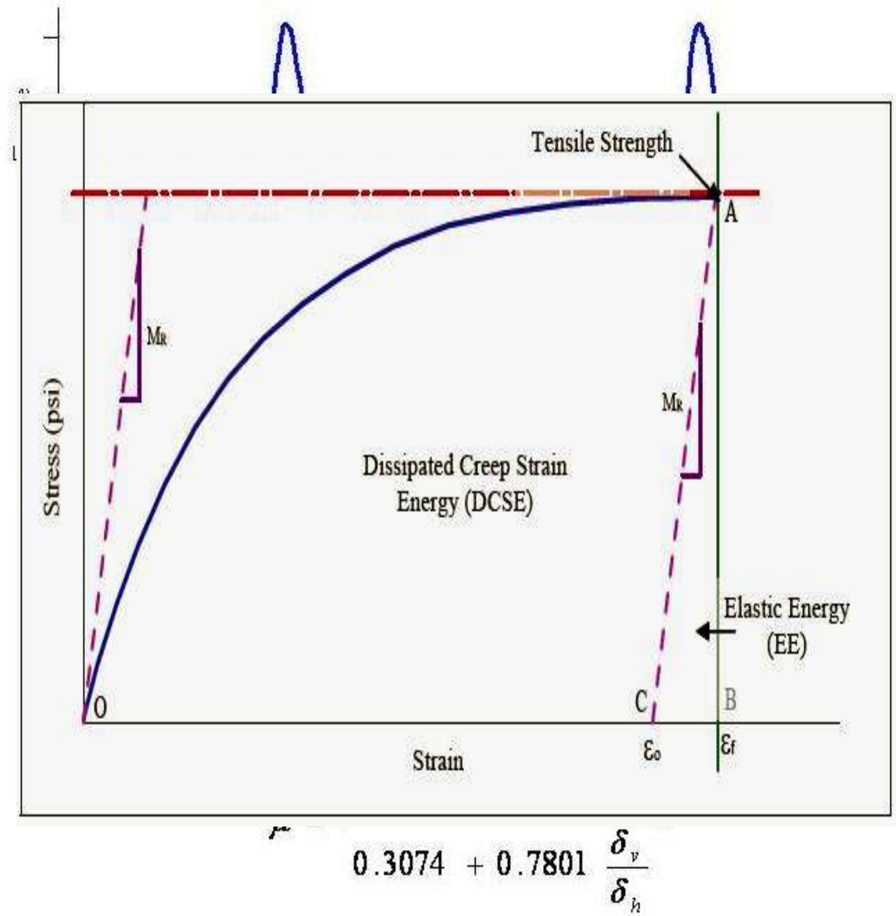


# Dissipated Creep Strain Energy (DCSE)

- Protocol: Roque et al. (2002)
- Temperature: 10°C
- Specimen: 150 mm x 50 mm
- Two tests:
  - Resilient Modulus ($M_R$) [NCHRP-285]
  - ITS [AASHTO T 322-03]

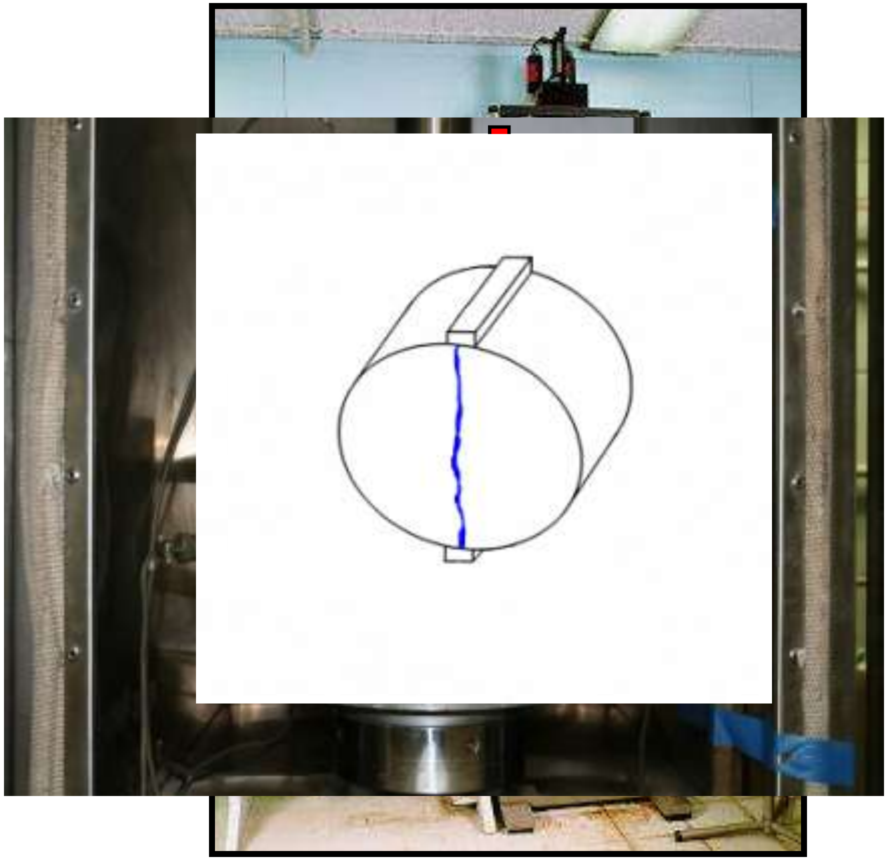
$$DCSE = FE - EE$$

$$DCSE = FE - \frac{1}{2} \times S_t \times (\varepsilon_f - \varepsilon_0)$$



# Indirect Tensile Strength (ITS)

- Test method: AASHTO T 322
- Temperature: -10°C
- MTS 810
- Specimen: 150 mm x 50 mm
- Loading: 12.5 mm/min



# Summary of Results

# Permanent Deformation

- Foamed WMA mixtures exhibited slightly higher rut depth values in the unconditioned and conditioned APA tests, slightly lower dynamic moduli, and slightly lower flow number values than the traditional HMA mixtures.
- However, the difference was found to be statistically insignificant. Therefore, the rutting potential of foamed WMA mixtures is expected to be comparable to that of the HMA mixtures.

# Moisture-Induced Damage

- Foamed WMA mixtures exhibited slightly lower unconditioned and conditioned ITS values and comparable TSR ratios to the HMA mixtures in the AASHTO T 283 test. In addition, foamed WMA mixtures exhibited slightly higher unconditioned and conditioned rut depth values in the APA test.
- However, the effect of the mix type was found to be statistically insignificant on the unconditioned and conditioned ITS values as well as the unconditioned and conditioned APA rut depths.

# Moisture-Induced Damage

- By comparing the unconditioned and conditioned APA rut depths, it was observed that the effect of sample conditioning was more pronounced on the HMA mixtures than the foamed WMA mixtures. This trend was also observed in the unconditioned and conditioned dynamic modulus tests for some of the mixtures.

# Fatigue Cracking

- The foamed WMA mixtures exhibited slightly lower DCSE values than the HMA mixtures. However, the difference was found to be statistically insignificant.
- In addition, the DCSE values for all foamed WMA and HMA mixtures were greater than 0.75 $kJ/m^3$, which has been suggested by Roque et al. (2007) as a minimum DCSE threshold value to ensure satisfactory resistance to fatigue cracking.
- This indicates that both foamed WMA and HMA mixtures are expected to have adequate resistance to fatigue cracking.

# Low-Temperature Cracking

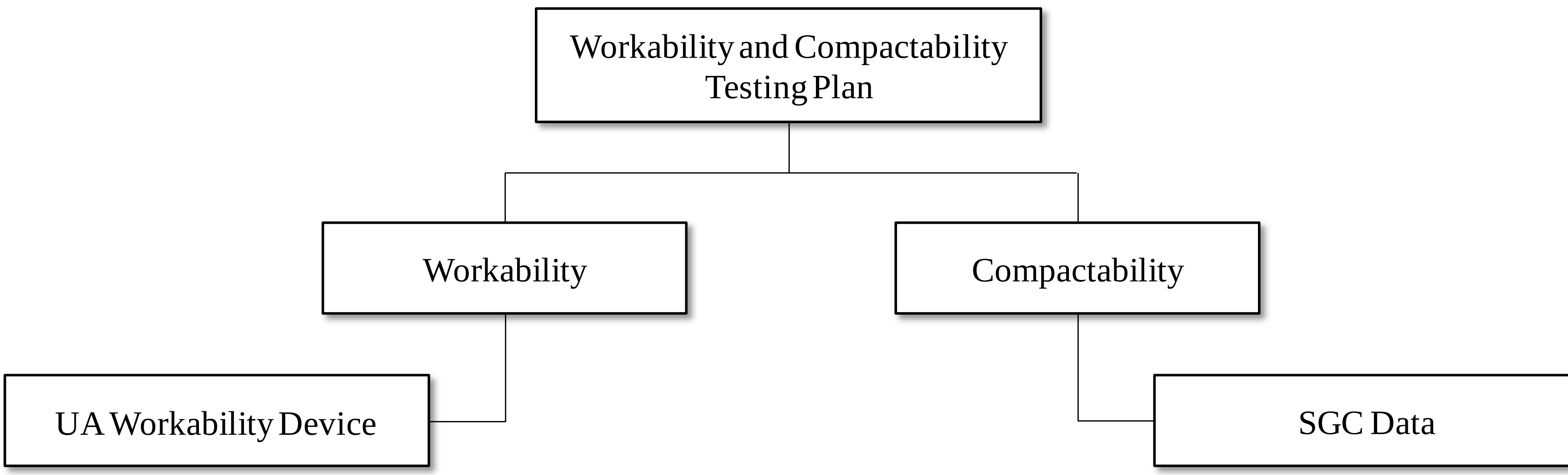
- Foamed WMA mixtures exhibited slightly lower ITS values at 14°F (-10°C) and comparable or slightly higher failure strain values than the corresponding HMA mixtures. The effect of the mix type was found to be statistically significant on the low temperature ITS values, but not on the failure strains.
- Since the HMA mixtures had higher ITS values and similar failure strain values to the foamed WMA mixtures, the HMA mixtures are expected to have better resistance to thermal cracking.

## Part 2:

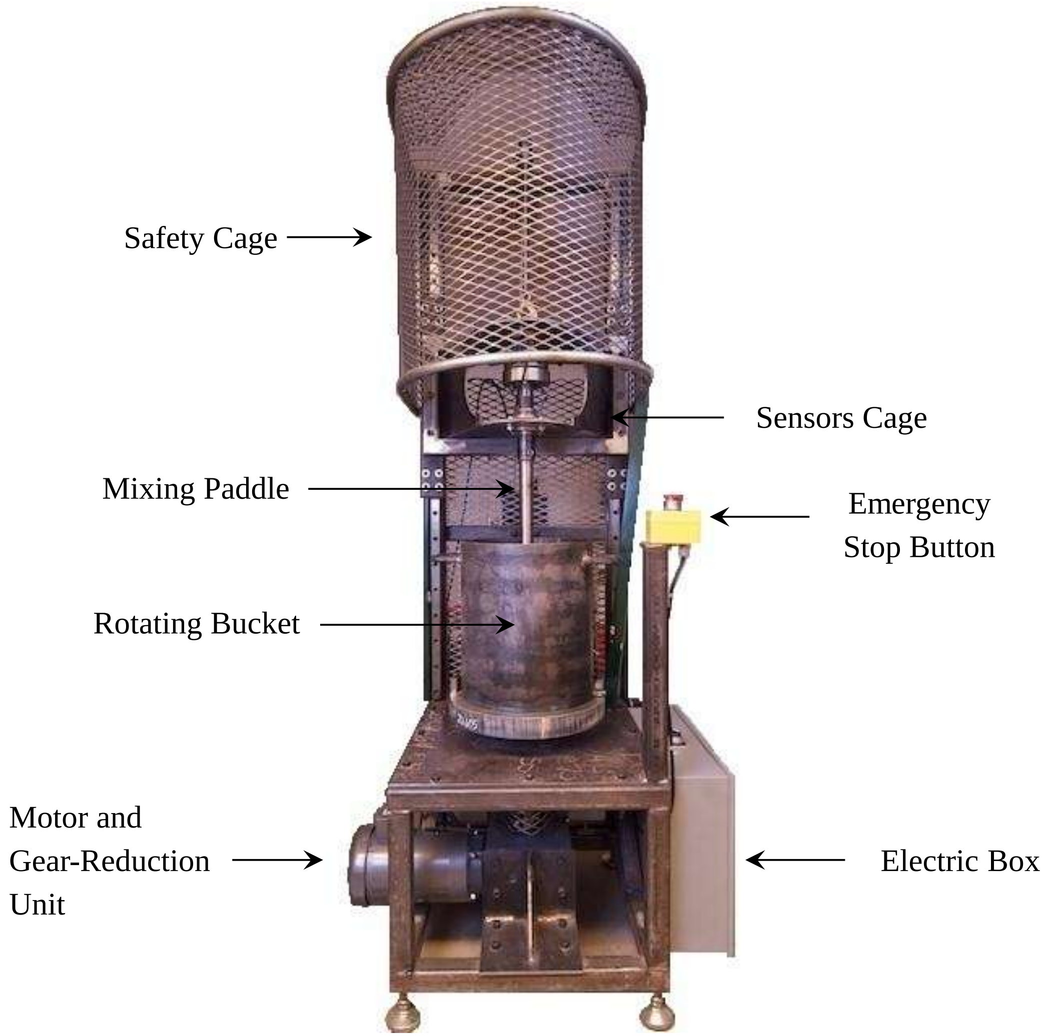
# Workability and Compactability of Foamed WMA & HMA

# Testing Program

# Testing Program



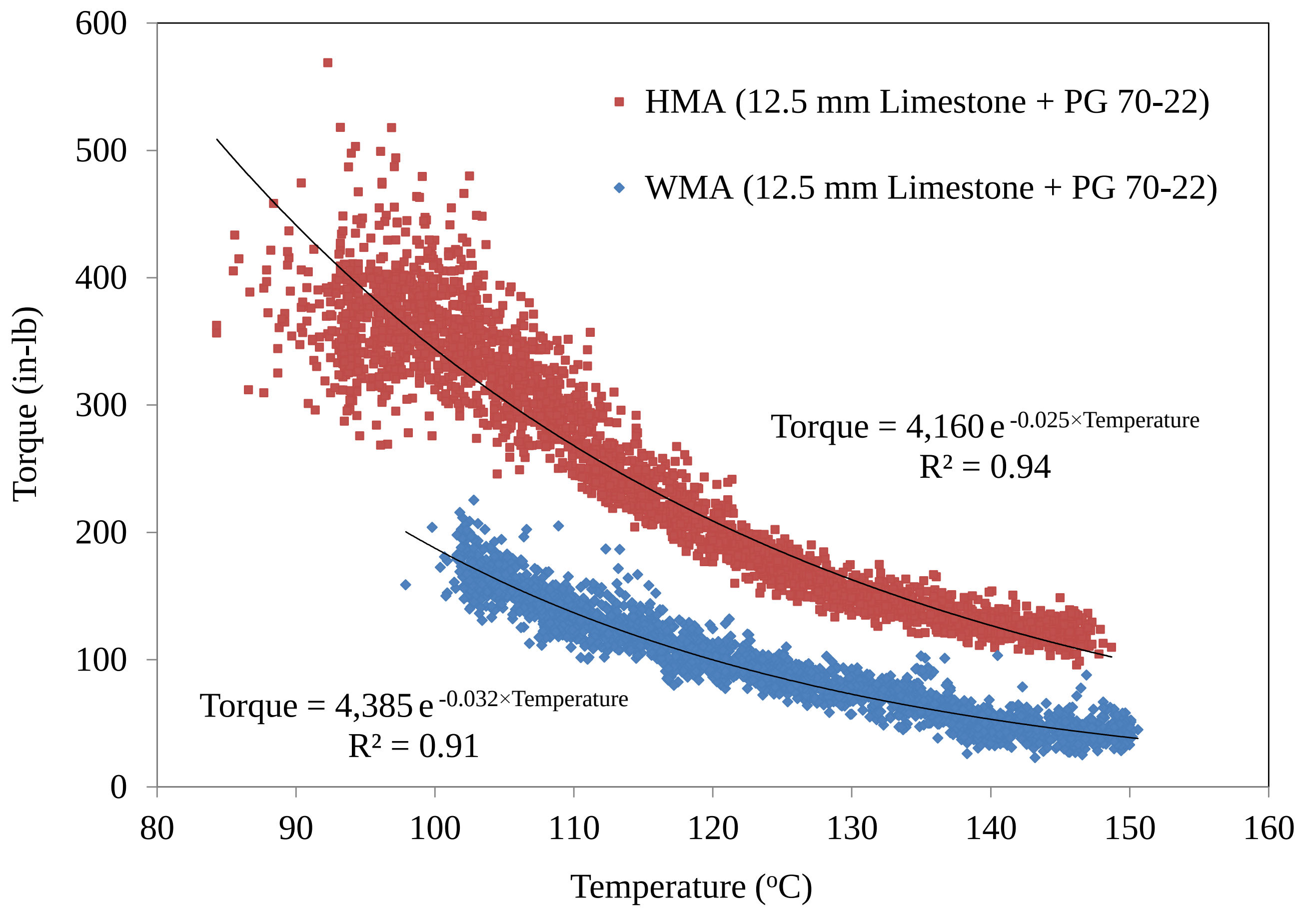
# Workability Device



# Workability Device (Cont.)

# Test Results

# Workability

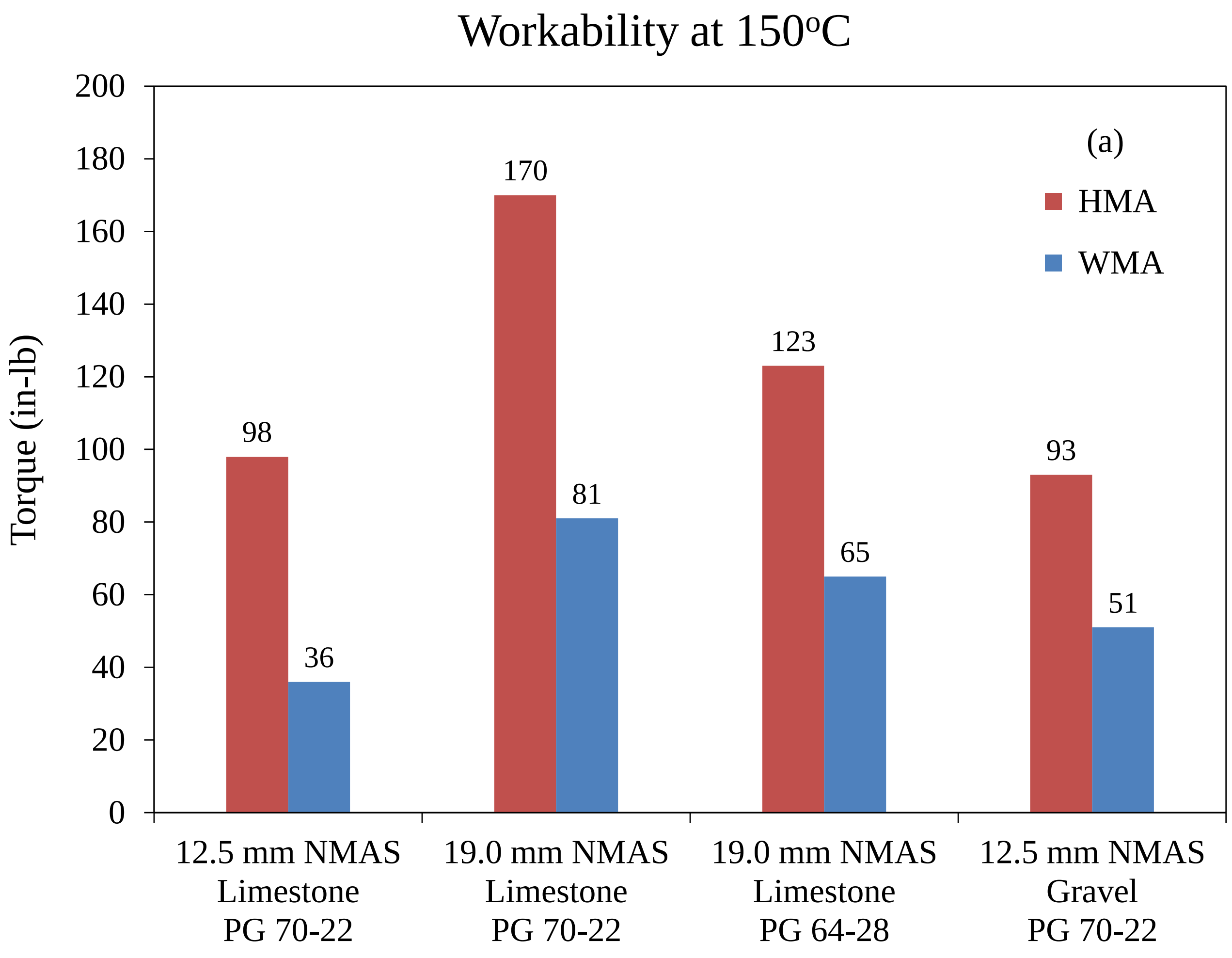


# Workability

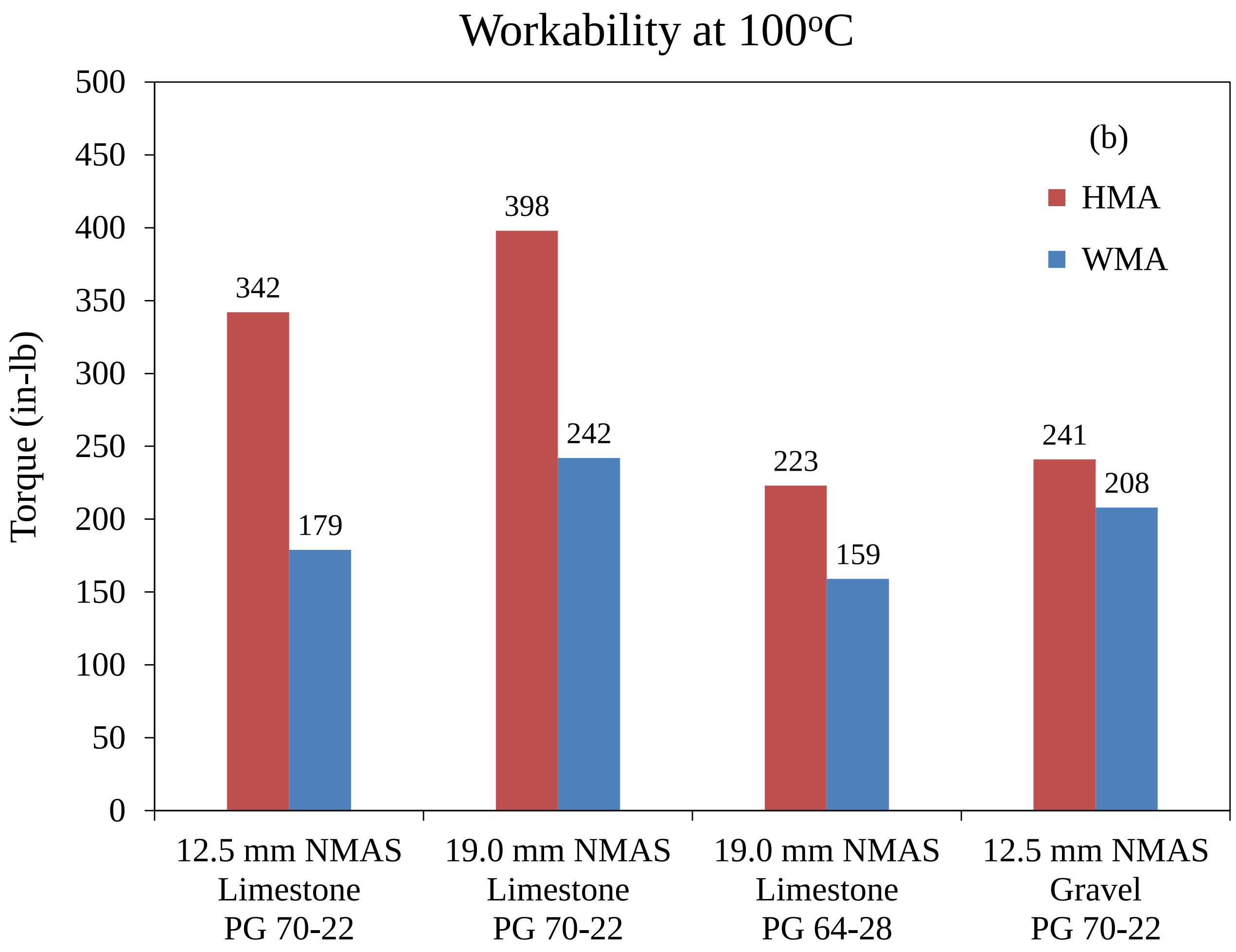
Workability Exponential Models

| Mix Type | Aggregate Type | Aggregate NMAS (mm) | Binder Grade | Workability Model | $R^2$ |
|---|---|---|---|---|---|
| HMA | Limestone | 12.5 | PG 70-22 | $Torque = 4{,}160\ e^{-0.025\ Temp}$ | 0.94 |
| | Limestone | 19.0 | PG 70-22 | $Torque = 2{,}179\ e^{-0.017\ Temp}$ | 0.87 |
| | Limestone | 19.0 | PG 64-28 | $Torque = 742\ e^{-0.012\ Temp}$ | 0.79 |
| | Gravel | 12.5 | PG 70-22 | $Torque = 1{,}611\ e^{-0.019\ Temp}$ | 0.95 |
| WMA | Limestone | 12.5 | PG 70-22 | $Torque = 4{,}385\ e^{-0.032\ Temp}$ | 0.91 |
| | Limestone | 19.0 | PG 70-22 | $Torque = 2{,}183\ e^{-0.022\ Temp}$ | 0.86 |
| | Limestone | 19.0 | PG 64-28 | $Torque = 964\ e^{-0.018\ Temp}$ | 0.75 |
| | Gravel | 12.5 | PG 70-22 | $Torque = 3{,}426\ e^{-0.028\ Temp}$ | 0.94 |

# Workability



# Workability



# Compactability

| | | | | Average No. of Gyrations | | | |
|---|---|---|---|---|---|---|---|
| **Mix** | **Agg. Type** | **Agg. Size** | **Binder Type** | **APA** | **T283** | **E*** | **ITS/DCSE** |
| HMA | Limestone | 12.5 mm | PG 70-22 | 38 | 36 | 29 | 41 |
| HMA | Limestone | 19.0 mm | PG 70-22 | 23 | 23 | 18 | 27 |
| HMA | Limestone | 19.0 mm | PG 64-22 | 29 | 22 | 18 | 24 |
| HMA | Gravel | 12.5 mm | PG 70-22 | 15 | 15 | 12 | 14 |
| WMA | Limestone | 12.5 mm | PG 70-22 | 43 | 28 | 29 | 38 |
| WMA | Limestone | 19.0 mm | PG 70-22 | 27 | 22 | 18 | 24 |
| WMA | Limestone | 19.0 mm | PG 64-22 | 27 | 17 | 17 | 18 |
| WMA | Gravel | 12.5 mm | PG 70-22 | 16 | 12 | 9 | 14 |

# Conclusions

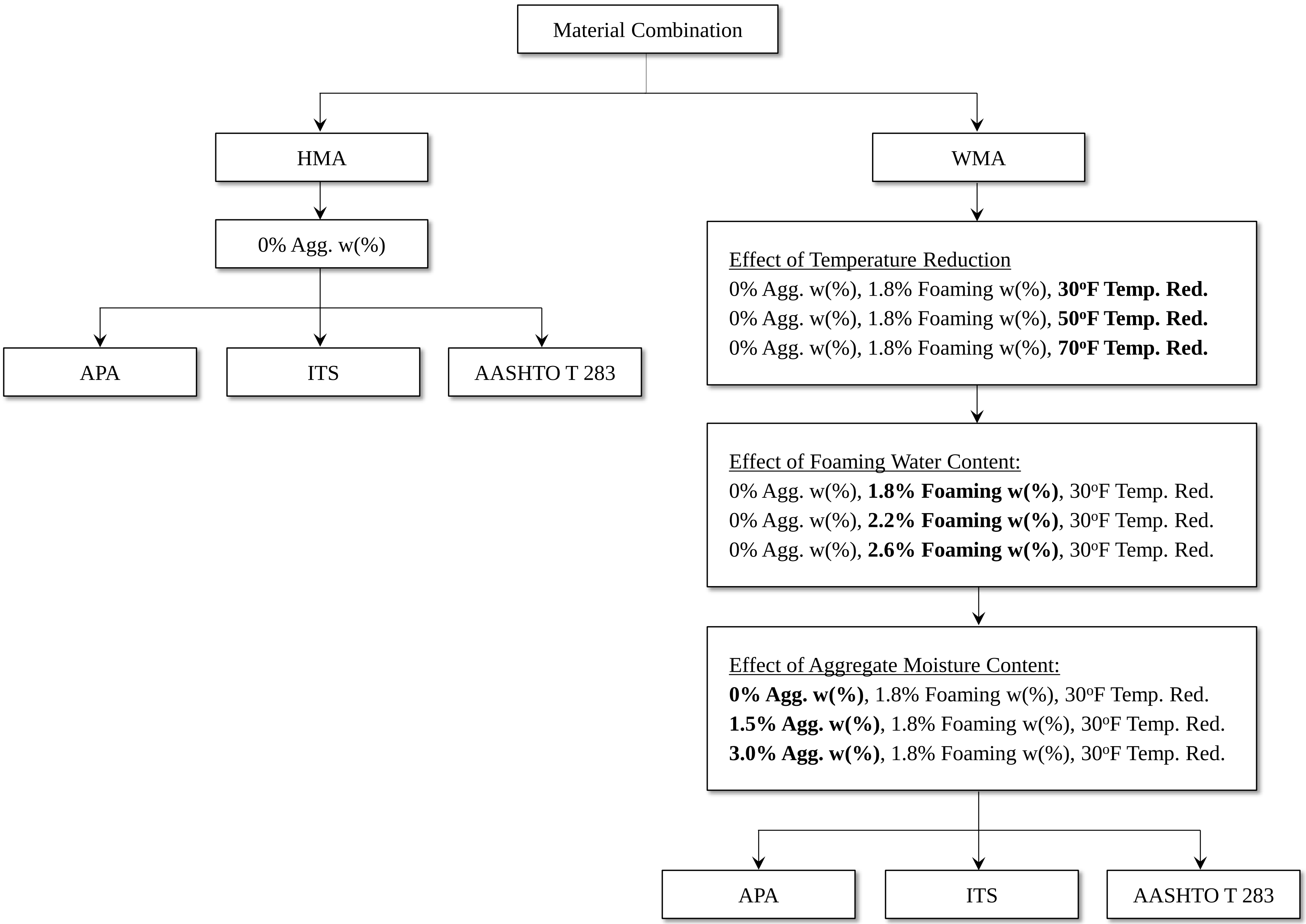
# Workability

- The foamed WMA mixtures exhibited better workability than the traditional HMA mixtures. This was attributed to the lower asphalt binder absorption observed for the foamed WMA mixtures.
- Another factor that might have contributed to the improvement in workability for foamed WMA mixtures is the presence of vapor pockets entrapped within the foamed asphalt binder that serve to keep the binder slightly expanded and reduce its viscosity.

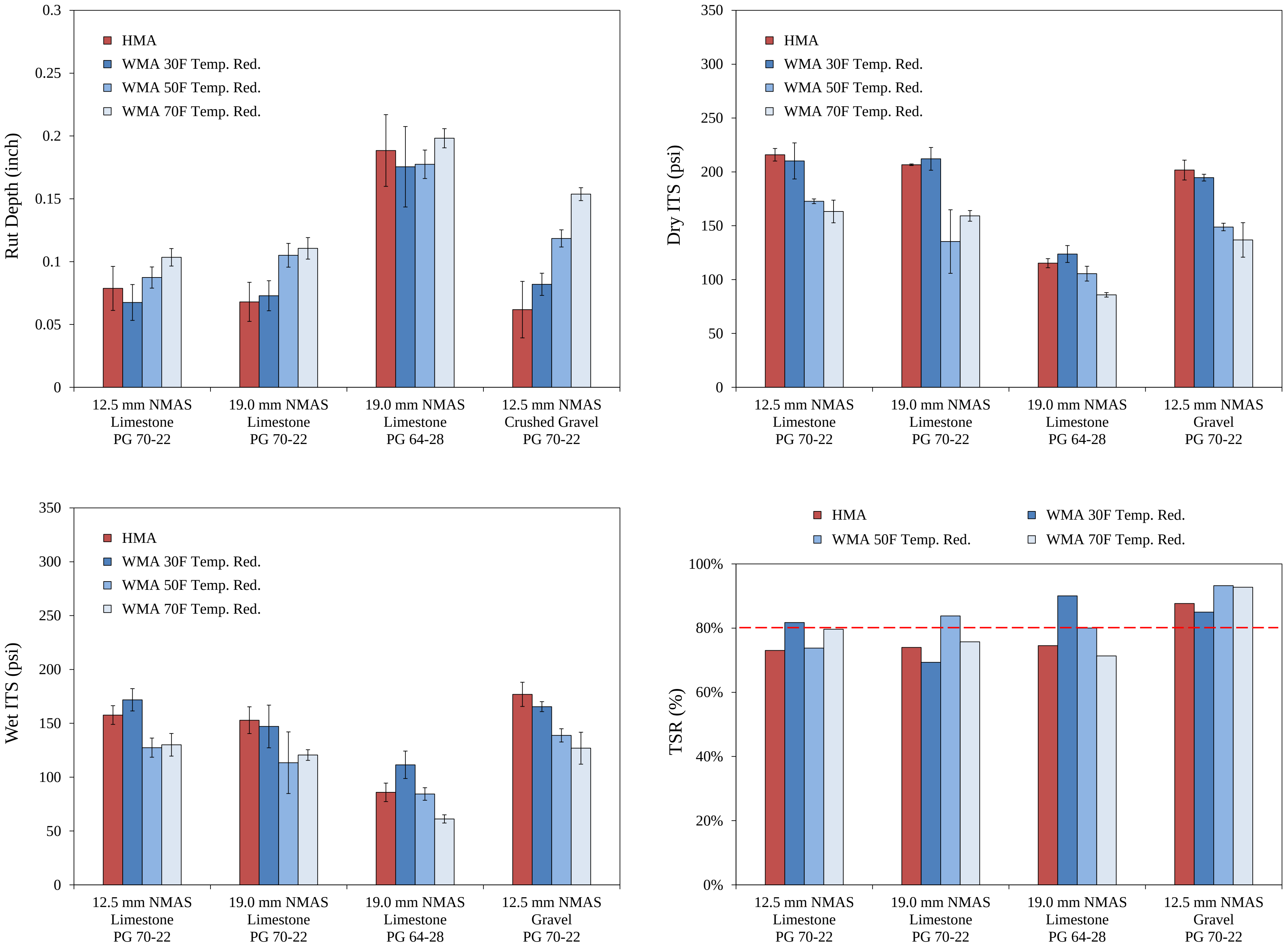
# Compactability

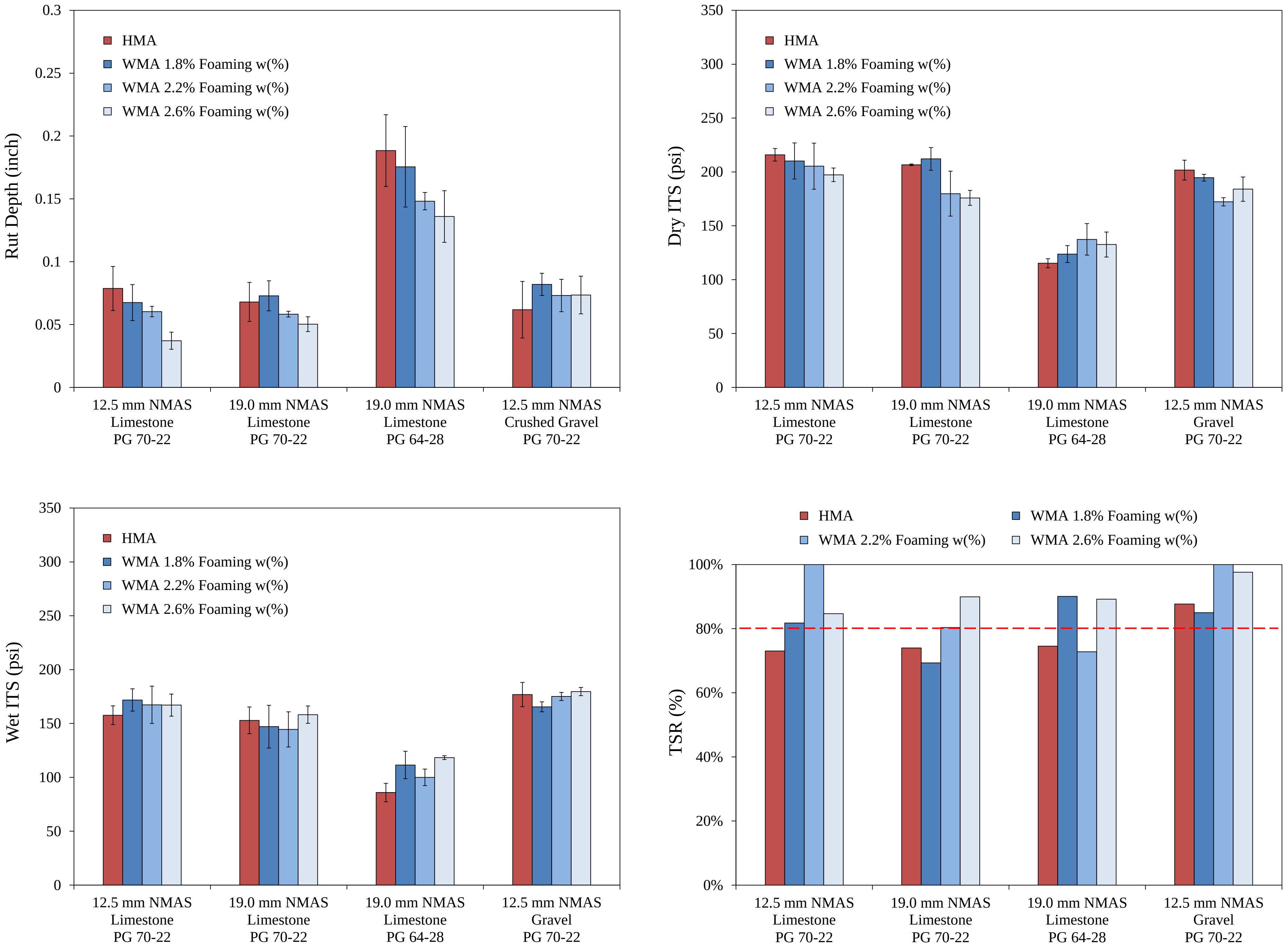
- By comparing the compaction data obtained using the Superpave gyratory compactor during the preparation of the laboratory specimens, it was observed that the number of gyrations needed to achieve the target air void levels for the foamed WMA specimens was relatively close to that of the HMA specimens.
- This indicates that the compactability of the foamed WMA mixtures is comparable to that of the corresponding HMA mixtures.

# Part 3:
# Limitations of Foamed WMA

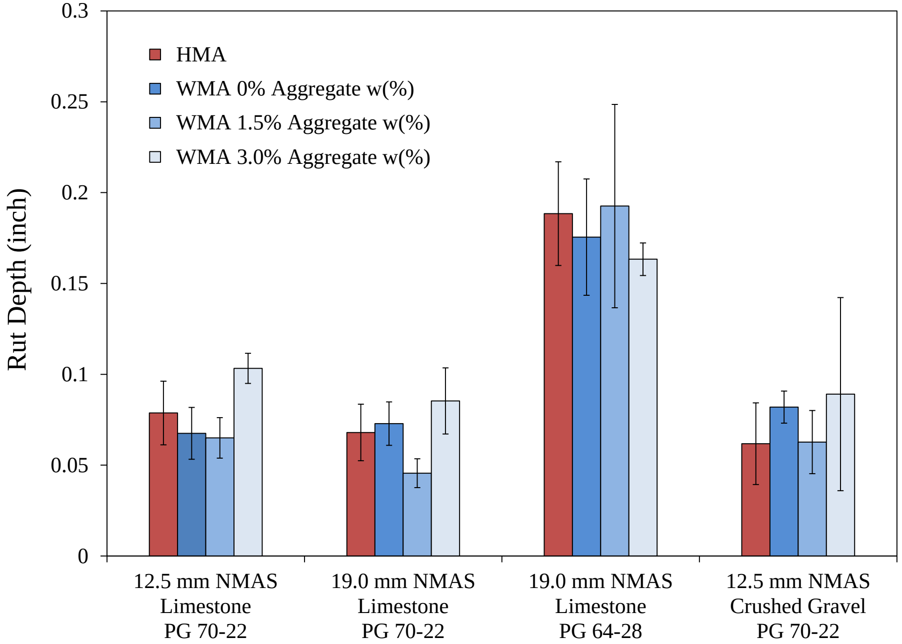

Material Combination
HMA
WMA
0% Agg. w(%)
APA
ITS
AASHTO T 283
Effect of Temperature Reduction
0% Agg. w(%), 1.8% Foaming w(%), 30°F Temp. Red.
0% Agg. w(%), 1.8% Foaming w(%), 50°F Temp. Red.
0% Agg. w(%), 1.8% Foaming w(%), 70°F Temp. Red.
Effect of Foaming Water Content:
0% Agg. w(%), 1.8% Foaming w(%), 30°F Temp. Red.
0% Agg. w(%), 2.2% Foaming w(%), 30°F Temp. Red.
0% Agg. w(%), 2.6% Foaming w(%), 30°F Temp. Red.
Effect of Aggregate Moisture Content:
0% Agg. w(%), 1.8% Foaming w(%), 30°F Temp. Red.
1.5% Agg. w(%), 1.8% Foaming w(%), 30°F Temp. Red.
3.0% Agg. w(%), 1.8% Foaming w(%), 30°F Temp. Red.
APA
ITS
AASHTO T 283

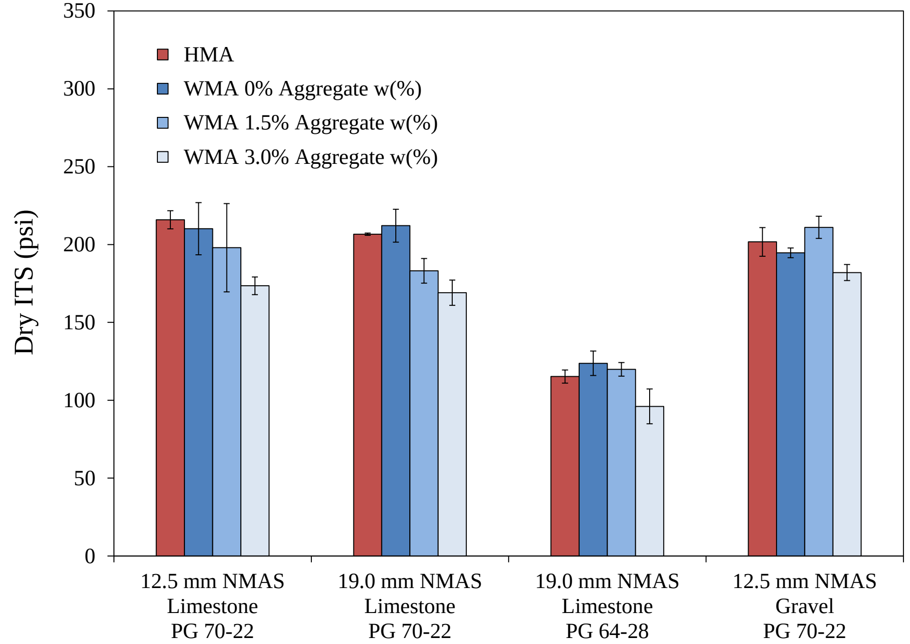
# Test Results

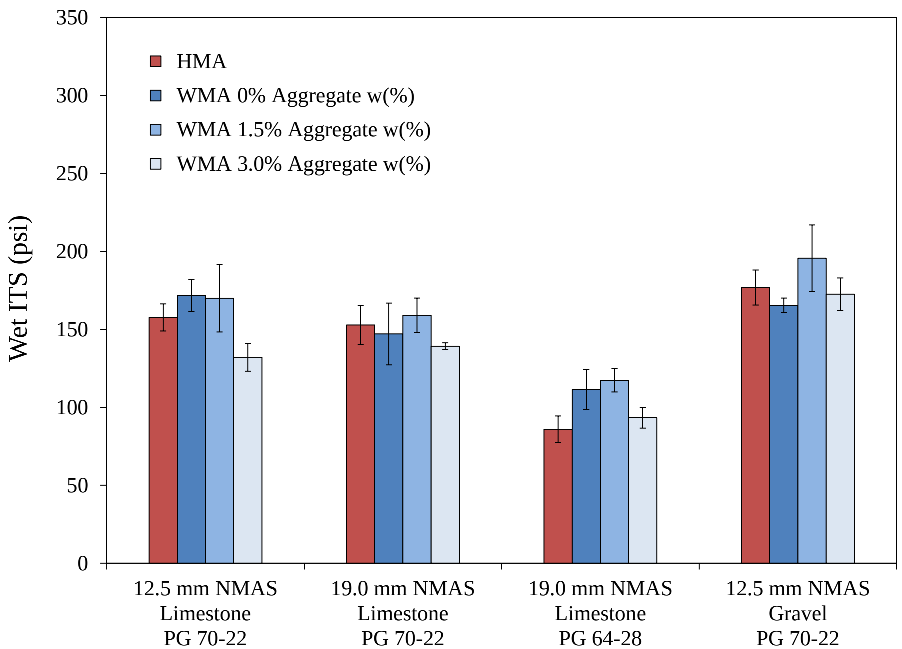

Rut Depth (inch)
0.3
0.25
0.2
0.15
0.1
0.05
0
HMA
WMA 30F Temp. Red.
WMA 50F Temp. Red.
WMA 70F Temp. Red.
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Crushed Gravel PG 70-22
Dry ITS (psi)
350
300
250
200
150
100
50
0
HMA
WMA 30F Temp. Red.
WMA 50F Temp. Red.
WMA 70F Temp. Red.
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22
Wet ITS (psi)
350
300
250
200
150
100
50
0
HMA
WMA 30F Temp. Red.
WMA 50F Temp. Red.
WMA 70F Temp. Red.
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22
TSR (%)
100%
80%
60%
40%
20%
0%
HMA
WMA 30F Temp. Red.
WMA 50F Temp. Red.
WMA 70F Temp. Red.
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22

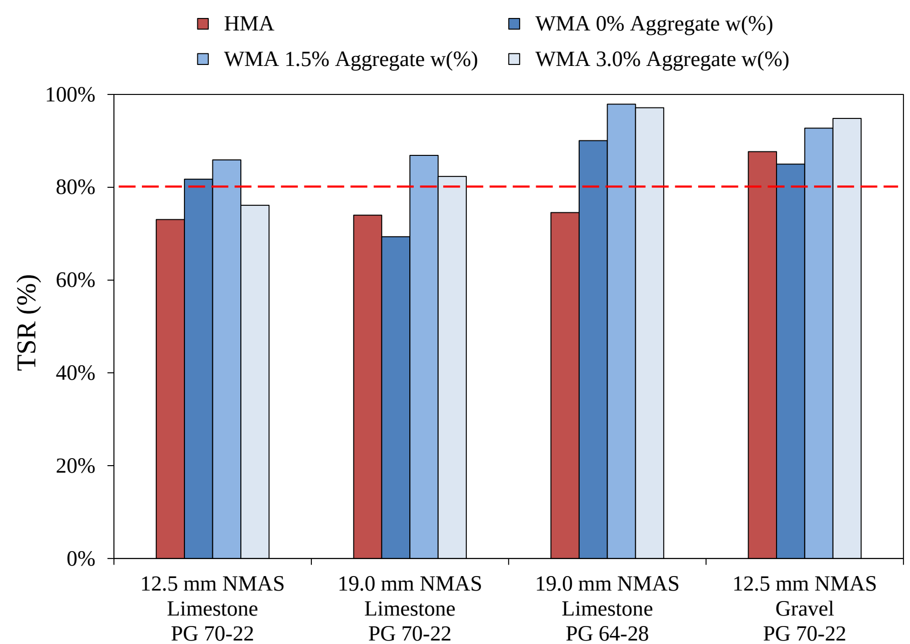


Rut Depth (inch)
0
0.05
0.1
0.15
0.2
0.25
0.3
HMA
WMA 1.8% Foaming w(%)
WMA 2.2% Foaming w(%)
WMA 2.6% Foaming w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Crushed Gravel PG 70-22
Dry ITS (psi)
0
50
100
150
200
250
300
350
HMA
WMA 1.8% Foaming w(%)
WMA 2.2% Foaming w(%)
WMA 2.6% Foaming w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22
Wet ITS (psi)
0
50
100
150
200
250
300
350
HMA
WMA 1.8% Foaming w(%)
WMA 2.2% Foaming w(%)
WMA 2.6% Foaming w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22
TSR (%)
0%
20%
40%
60%
80%
100%
HMA
WMA 1.8% Foaming w(%)
WMA 2.2% Foaming w(%)
WMA 2.6% Foaming w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22


Rut Depth (inch)
0.3
0.25
0.2
0.15
0.1
0.05
0
HMA
WMA 0% Aggregate w(%)
WMA 1.5% Aggregate w(%)
WMA 3.0% Aggregate w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Crushed Gravel PG 70-22


Dry ITS (psi)
350
300
250
200
150
100
50
0
HMA
WMA 0% Aggregate w(%)
WMA 1.5% Aggregate w(%)
WMA 3.0% Aggregate w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22


Wet ITS (psi)
350
300
250
200
150
100
50
0
HMA
WMA 0% Aggregate w(%)
WMA 1.5% Aggregate w(%)
WMA 3.0% Aggregate w(%)
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22


HMA
WMA 0% Aggregate w(%)
WMA 1.5% Aggregate w(%)
WMA 3.0% Aggregate w(%)
TSR (%)
100%
80%
60%
40%
20%
0%
12.5 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 70-22
19.0 mm NMAS Limestone PG 64-28
12.5 mm NMAS Gravel PG 70-22

# Conclusions

# Effect of Temp. Red.

- Reducing the production temperature of foamed WMA led to increased susceptibility to permanent deformation (rutting) and moisture-induced damage.
- Therefore, it is recommended to continue to use a reduction temperature of 30$^{o}$F (16.7$^{o}$C) for the production of foamed WMA.

# Effect of Foaming Wtr. Cont.

- Increasing the foaming water content (up to 2.6% of the weight of the asphalt binder) during production of foamed WMA did not seem to have a negative effect on the rutting performance or moisture sensitivity of foamed WMA.
- Therefore, a higher foaming water content can be specified for the production of foamed WMA in Ohio.

# Effect of Agg. Moist. Cont.

- Producing foamed WMA using moist aggregates resulted in inadequate aggregate coating leading to concerns with regard to moisture-induced damage and long-term durability.
- Therefore, it is critical to use fully dried aggregates in the production of foamed WMA to ensure satisfactory mix performance.

# Compaction and Mix Design

- There is no need to compact the foamed WMA mixtures to a higher density level than commonly used for HMA mixtures.
- Since the performance of the foamed WMA was comparable to that of the HMA, no modifications are needed to the current mix design process used by ODOT for foamed WMA mixtures.

# Questions?