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Evaluation of Warm Mix Asphalt Technology in Flexible Pavements

by

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16. Abstract

Warm mix asphalt (WMA) describes various technologies that allow asphalt mixtures to be produced at lower temperatures as compared to hot mix asphalt (HMA). WMA technologies also offer improvements in workability, cost, and environmental sustainability such as reduced fuel usage, greenhouse gas emissions, and wear and tear at plants, while enhancing worker health and safety conditions. The primary objective of this study was to evaluate the laboratory performance of plant-produced lab-compacted mixtures utilizing various WMA technologies, including some mixtures with higher percentages of RAP. The secondary objective of this study was to compare WMA energy consumption cost and emission data to conventional HMA mixtures in terms of fuel/energy savings at the plant and in terms of CO and CO_2 emissions. Six projects in Louisiana utilizing four different WMA technologies were considered in this study, yielding 20 mixtures total. Each project included a companion HMA mixture section to allow for direct comparison. Loose mixtures were obtained from trucks at the plant and compacted on-site in a mobile asphalt laboratory. Laboratory tests included dynamic modulus (|E*|), flow number (F_N), loaded wheel tracking (LWT) test, indirect tensile (IDT) test, semi-circular bend (SCB) test, thermal stress restrained specimen test (TSRST), and the Lottman moisture susceptibility test. Results indicated that WMA mixtures exhibit similar high and intermediate temperature performances in the laboratory as compared to HMA. On average, $1.61 of energy savings per ton of produced asphalt mixture was observed, along with a considerable reduction in air pollutants at the plant. However, the cost of additives and royalty fees would reduce the total cost savings from using WMA. These benefits were observed without reduction in the mechanistic performance of the mix.

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ABSTRACT

Warm mix asphalt (WMA) describes various technologies that allow asphalt mixtures to be produced at lower temperatures as compared to hot mix asphalt (HMA). WMA technologies also offer improvements in workability, cost, and environmental sustainability such as reduced fuel usage, greenhouse gas emissions, and wear and tear at production plants, while enhancing worker health and safety conditions. The primary objective of this study was to evaluate the laboratory performance of plant-produced lab-compacted (PL) mixtures utilizing various WMA technologies, including some mixtures with higher percentages of reclaimed asphalt pavement (RAP). The secondary objective of this study was to compare WMA energy consumption cost and emission data to conventional HMA mixtures in terms of fuel/energy savings at the plant and in terms of CO and CO_2 emissions. Six projects in Louisiana utilizing four different WMA technologies were considered in this study, yielding 20 total mixtures. Each project included a companion HMA mixture section to allow for direct comparison. Loose mixtures were obtained from trucks at the plant and compacted on-site in a mobile asphalt laboratory. Laboratory tests included dynamic modulus ($|E^*|$), flow number (F_N), loaded wheel tracking (LWT) test, indirect tensile (IDT) test, semi-circular bend (SCB) test, thermal stress restrained specimen test (TSRST), and the Lottman moisture susceptibility test. Results indicated that WMA mixtures exhibit similar high and intermediate temperature performances in the laboratory as compared to HMA. On average, $1.61 of energy savings per ton of produced asphalt mixture was observed, along with a considerable reduction in air pollutants at the production plant. However, the cost of additives and royalty fees would reduce the total cost savings from using WMA. These benefits were observed without reduction in the mechanistic performance of the mix.

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IMPLEMENTATION STATEMENT

Based on the findings and the results of this project, specification recommendations were developed and communicated to the DOTD Asphalt Specification Committee. Several rehabilitation projects included those specifications as special provisions. DOTD has adopted permissive specifications to be included in the *2016 Standard Specifications for Roads and Bridges* manual. An approved list of WMA additives and processes has also been developed to be maintained by the DOTD Materials section. In addition, a procedure for qualifying new manufacturers of WMA additives and processes for inclusion in the approved list was developed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Concerns about ever-increasing construction costs coupled with the negative impacts to the environment have led the asphalt industry to search for alternatives that can potentially mitigate these problems. One type of technology that addresses both production cost and environmental issues is the warm mix asphalt (WMA). It allows for mixing, production, placing, and compaction of asphalt mixtures at significantly lower temperatures than conventional hot mix asphalt (HMA) practices. This technology was developed in Europe as an effort to reduce greenhouse gas emission associated with asphalt pavement construction.

The benefits associated with WMA are reduced fuel usage and emissions, easier compaction, possible use of higher percentage of RAP, extended paving season, longer haul times and distances, and improved job site conditions for workers. WMA practice can be a potential step towards preserving resources while addressing growing environmental sustainability. Broadly, WMA technologies can be classified into two categories based on the way they achieve lower binder viscosity: use of chemical additives and through a foaming process.

WMA practice can have a significant impact on pavement construction and rehabilitation projects in and around non-attainment zones such as large metropolitan areas. Some of these areas have air quality restrictions that cannot be observed with the use of conventional technologies. The reduction in fuel usage to produce the mix would also have a significant impact on the cost of transportation construction projects. With the availability of several proprietary chemicals and processes, it is now possible to produce warm asphalt without affecting the properties of the mix.

Despite all the potential benefits, the lower mixing temperatures have raised concerns that the aggregates may contain some water and yield a mixture that is susceptible to moisture damage. Another concern is that the asphalt binder may not possess adequate stiffness characteristics at elevated pavement surface temperatures, resulting in rutting susceptibility. This brings up the need to thoroughly test the WMA mixtures to ensure the adequate performance of the mixtures.

Literature Review

Warm-mix technology uses various techniques to reduce the effective viscosity of the binder enabling full coating and subsequent compact-ability at lower temperatures. The WMA technologies can be classified in different ways. Depending on the technology adopted to reduce the temperature, the WMA technologies can be broadly divided into three categories:

foaming techniques, both water-based and water-bearing; organic or wax additives; and chemical additives *[1, 2]*.

Foaming Techniques

A wide range of foaming techniques is available to reduce the viscosity of asphalt binder, by introducing small amounts of water into the binder. The water turns to steam, increases the volume of the binder and reduces its viscosity for a short period until cooled. The foam then collapses and the mixture behaves as a normal binder. The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder *[3]*. Liquid anti-stripping additives can be added to the binder before mixing with the aggregates, to ensure that the moisture susceptibility is minimized *[4, 5]*. The foaming techniques can be further classified into water-based and water-bearing.

Organic or Wax Additives

Different organic additives can be used to lower the viscosity of the asphalt binder. WMA mixtures employing these technologies exhibit lower viscosities during production at temperatures higher than the melting point of the additives. After the crystallization process of the additive, it may enhance the stiffness of the mixture. The type of additive must be selected carefully so that its melting point is higher than the expected in-service temperatures, otherwise, permanent deformation of the pavement structure may result. The organic additives usually are waxes or fatty amides. A commonly used additive is a special paraffin wax produced by treating hot coal with steam in the presence of a catalyst *[6]*.

Chemical Additives

Chemical additives do not reduce the viscosity of the asphalt binder. As surfactants, they work at the microscopic interface of the aggregates and the binder reducing the frictional forces at that interface *[1]*. Chemical additives usually are combination of emulsions, surfactants, and polymers that enhance coating, workability, compaction, and adhesion properties of the mixtures.

Previous Research Studies on Performance of Different WMA Technologies

WMA is a relatively new practice adopted in the United States. A significant amount of research is being done on WMA to evaluate and quantify the performance of these technologies. The use of warm asphalt technologies was initially developed in Europe with the aim of reducing greenhouse gases produced by manufacturing industries *[3]*. Specifically, the European Union agreed to reduce CO_2 emissions by 15% by 2010. With this goal, several field trials were conducted in Europe to evaluate the use of WMA mixtures and their compactability and in-service performance. Those trials were carried out in Norway, the United Kingdom, and the Netherlands *[7]*. Emissions during construction were measured, and visual inspection of the trial roads after placing and after up to three years of trafficking indicated performance similar to control sections constructed using conventional asphalt. Cores from the field trials showed similar stability and adhesion characteristics to those of conventional asphalt.

The United Nations conference on the environment and sustainable development held at Rio de Janeiro in 1992 marked the beginning of universal awareness on increasing global warming *[8]*. In 1997 the Kyoto Protocol by the United Nations formalized this awareness by committing to bring down the greenhouse gas emission rates to 1990 levels. This agreement came into force on February 13, 2005. WMA technology addresses this issue in a rather small but important way.

Some of earlier work on warm asphalt in the United States was conducted by the National Center of Asphalt Technology (NCAT) *[9 - 13]*. NCAT evaluated the use of Zeolite, Sasobit, and Evotherm® as potential additives to produce warm asphalt mixtures at temperatures lower than the conventional asphalt mixtures. An infrared camera was used to monitor the thermal consistency during paving *[14]*. Improved compactability was reported at temperatures as low as 190°F. These additives showed no effect on the resilient modulus of the asphalt mixtures. The resulting mixtures, however, showed poor resistance to moisture damage as measured by the tensile strength ratio (TSR). Stripping was also observed when testing the mixtures in the Hamburg Wheel Tracking Test.

Buss et al. used MEPDG to compare the effects of WMA technologies on pavement performance *[15]*. Dynamic modulus data was used as the input for the MEPDG, and the performance of the WMA mixes was compared to the respective control HMA mixes. Duralife and DureClime were used as additives for the warm mix asphalt mixtures. The results showed that WMA mixtures exhibited similar or better performance to that of the conventional HMA mixtures *[15]*.

Goh et al. evaluated the performance of several WMA mixtures in comparison with a conventional HMA *[16]*. Aspha-min, Sasobit, Evotherm®, and Asphaltan B were used as WMA additives. The effect of WAM-Foam technology was also evaluated. Results showed that, based on a Level 1 analysis, WMA had a lower predicted rut depth than the conventional HMA mixture. Also, the dynamic modulus values were not significantly different between the mixtures. WMA technologies has shown significant reduction in mixing and compaction temperature

Diefenderfer et al. evaluated the long-term performance effects of WMA and found that the performance did not differ significantly from conventional HMA *[17]*. Sasobit and Evotherm® were the additives considered in this study. These studies showed that the use of WMA did not have a significant effect on the results of the MEPDG performance predictions when compared to the predictions of conventional HMA mixtures. The performance grading of the recovered binder indicated reduction in the rate of in-service aging of the binder of WMA produced by Sasobit, when compared to control HMA.

Goh and You performed a field study to evaluate the rutting performance of the WMA mixture with Sasobit additive *[18]*. A companion HMA mixture with a similar mixture design was also constructed in the demonstration. The WMA was produced at 260°F and showed similar rutting performance as compared to the control the HMA mixture.

In 2009, Washington Department of Transportation conducted an experimental field study involving a control HMA mixture and a WMA mixture with Sasobit additive *[19]*. WMA section was compacted at reduced temperatures in the range of 30 to 50 °F. Density testing revealed better compaction of the WMA section. Hamburg Wheel Tracking testing showed identical rut performance between the two pavement sections, and stripping was not evident in either of the sections.

Wasiuddin et al. studied the rutting potential and the rheological properties of the binder *[20]*. WMA mixtures with Aspha-min and Sasobit additives were evaluated in this study. A decrease in the rut potential of the mixtures was observed with the decrease in the production temperatures. A field study in Florida revealed that the addition of Aspha-min additive improved the workability of the mixture, and similar performance in terms of moisture susceptibility *[9]*.

The National Cooperative Highway Research Program (NCHRP) performed various research studies involving the WMA technologies. The research project NCHRP 9-43, *Mix Design Practices for WMA*, was initiated to develop mixture design and analysis procedures for wide range of WMA technologies *[21]*. WMA technologies such as Evotherm®, Sasobit, Advera, LEA, and Gencor foaming, etc. were evaluated in this study. The research indicated similar volumetric properties for the WMA and HMA mixtures. The research showed differences in the moisture sensitivity between HMA and WMA mixtures, but also showed improved resistance to moisture damage with addition of anti-strip additives. The rutting resistance of all the WMA mixtures except Sasobit, as measured by flow number testing, was lower as compared to the control HMA mixture. The fatigue evaluation of the mixtures showed similar performance between the HMA and WMA mixtures.

Research project NCHRP 9-47, *Engineering Properties, Emissions, and Field Performance of WMA Technologies,* was conducted to establish relationships among engineering properties of WMA binders and mixtures and the field performance of various WMA technologies *[22]*. Research showed that WMA mixtures produced with Astec's Double Barrel Green system and 30% RAP exhibited comparable rut performance compared to the

HMA mixtures. Few WMA mixtures showed reduced rut performance and indirect tensile strength values as compared to the control HMA mixtures.

There are several research studies sponsored by the NCHRP to evaluate the performance of the WMA mixtures. The list of those projects that are either recently completed or on-going is shown below.

- *NCHRP Project 9-47A, Properties and Performance of WMA Technologies*
- *NCHRP Project 9-49, Performance of WMA technologies: Stage I – Moisture Susceptibility*
- *NCHRP Project 9-49A, Performance of WMA technologies: Stage II – Long-Term Field Performance*
- *NCHRP Project 9-52, Short-Term Laboratory Conditioning of Asphalt Mixtures*
- *NCHRP Project 9-53, Properties of Foamed Asphalt for Warm Mix Asphalt Applications*
- *NCHRP 9-54, Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction*
- *NCHRP Project 9-55, Recycled Asphalt Shingles in Asphalt Mixtures with WMA Technologies*

Previous Research Studies on Environmental and Economic Benefits

Lower mixing and production temperatures yield lower emissions and reduced energy consumption. This section documents some of the research studies and findings that quantify the potential environmental and economic benefits observed since the introduction of the WMA technologies.

There are approximately 3600 HMA plants in the U.S. producing 500 to 600 million tons of asphalt mixture annually *[23]*. The Federal Clean Air Act requires emission sources like HMA plants to use the "best available control technology" to limit the emissions *[24]*. Previous research studies indicate that the emissions during the production of WMA are lower, than in the production of the conventional HMA *[25-27]*. Emissions in the range of 30 to 98% to that of HMA were observed under varying circumstances. Measurements of energy consumption indicated a reduction during the WMA practice as compared to the conventional HMA practice. WMA production recorded reductions in the range of 20 to 75% compared to that of HMA production *[28-31]*.

Rajib et al. conducted a laboratory study to evaluate the CO_2 emissions through the use of WMA technologies, utilizing Sasobit *[32]*. This research implied that WMA technology is an effective way of lowering the emissions; both directly and by usage of lesser energy for production. The addition of 1.5% of Sasobit to the asphalt binder resulted in a reduction of production temperatures in the range of 10 - 30°C. At the same time, about 40% of savings were observed in energy consumption as compared to HMA practice.

A research study performed by the Ohio Department of Transportation to assess the performance of WMA pavements adopted WMA technologies Aspha-min, Sasobit, and Evotherm®. Emissions at the paving site reported reductions in the range of 67 – 77% compared to HMA. Emissions at the plant revealed a reduction of 50% for volatile organic compounds, 60% for carbon monoxide, 20% for nitrogen oxide, and 83% for sulfur dioxide *[33]*.

OBJECTIVE

The primary goal of this research project was to quantify the performance of field produced and laboratory compacted mixtures that utilize WMA technology and to develop a framework for design, construction, and implementation of this technology in Louisiana. Specific objectives include:

1. Determine the relative measures of laboratory performance between WMA mixtures and conventional HMA mixtures;
2. Compare production and placement practices of WMA mixtures and conventional HMA mixtures; and
3. Recommend specifications for the use of WMA technology to be included in DOTD's standard specifications.

SCOPE

Six field rehabilitation projects across Louisiana were selected for the evaluation of WMA technologies. Several chemical additives and processes were evaluated. A companion conventional asphalt mixture was included in each field project. A total of 20 mixtures were included in this study. The field experiment included two types of WMA technologies, namely, chemical additives (Evotherm®, Rediset, and Sasobit) and foaming processes (Astec Double Barrel Green system and Accu-Shear system), two mixture compaction levels (design traffic levels 1 and 2), two asphalt binder types (PG70-22M and PG76-22M per DOTD specifications), two projects where higher RAP contents were evaluated; and two nominal maximum aggregate sizes (0.50 in. [12.5 mm] and 0.75 in. [19.0 mm]). A suite of laboratory mechanical tests was performed to ascertain the performance and durability of the asphalt mixtures evaluated. The tests conducted include dynamic modulus (E*), flow number (F_N), semi-circular bend (SCB) at intermediate temperature, indirect tensile strength and strain, loaded wheel tracking (LWT), dissipated creep strain energy (DCSE), and modified Lottman.

METHODOLOGY

Field Projects and Materials

Field Projects

Six field projects across Louisiana were selected to provide a total of 20 mixtures for the evaluation of the WMA technologies. Figure 1 shows the locations and routes of these projects. Details of the asphalt mixtures, including the mix code designations used in the remainder of the report, are summarized in Table 1. All project selections were made after consultation with the Louisiana Department of Transportation and Development (DOTD) research and construction personnel.

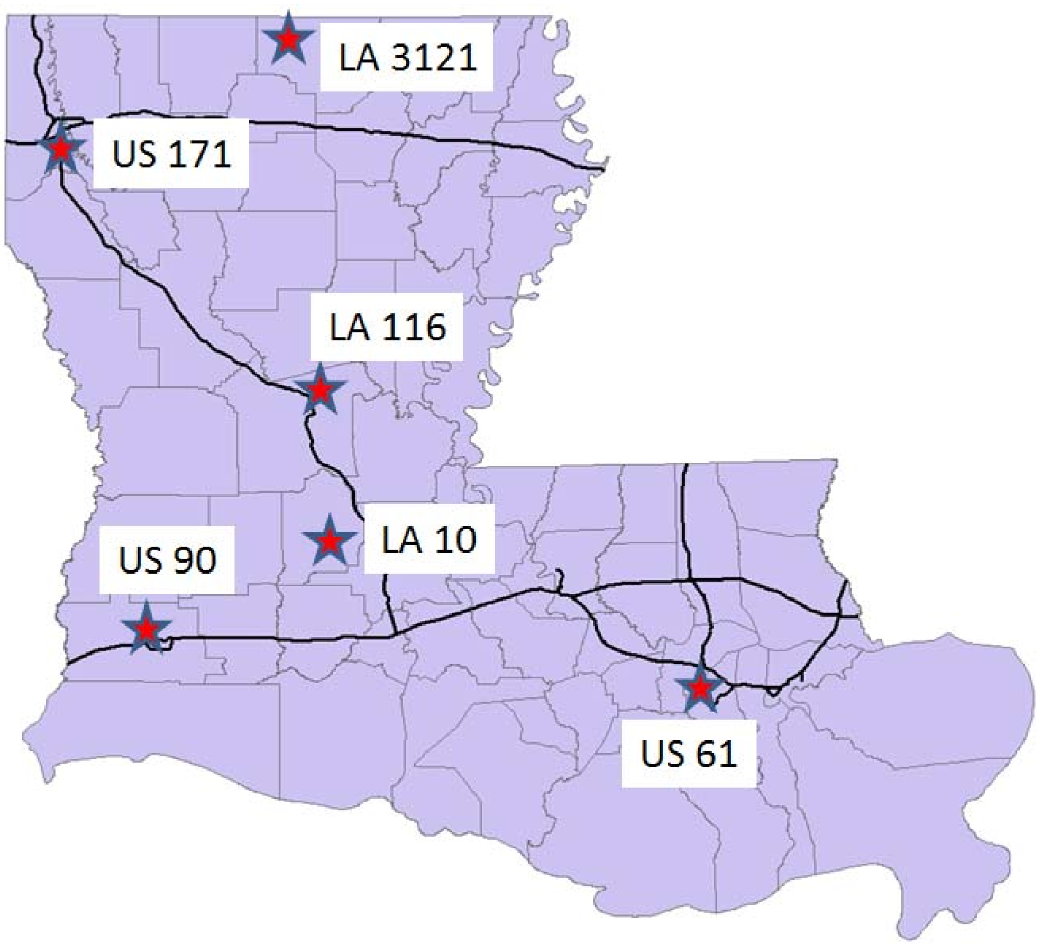


Figure 1
Map showing locations of the field projects

Table 1
Field projects and mixtures

Traffic Level	Route (Parish)	Mix Code	Mix Type	Asphalt Grade	NMAS, mm	RAP, %	Remarks
Level I	LA 3121 (Union)	3121-1	HMA-WC	PG70-22M*	12.5	15	
		3121-2	WMA-WC	PG70-22M	12.5	15	Evotherm®
		3121-3	WMA-WC	PG70-22M	12.5	30	Evotherm®
	US 171 (Caddo)	171-1	HMA-WC	PG70-22M	12.5	15	
		171-2	WMA-WC	PG70-22M	12.5	15	Foamed
		171-3	WMA-WC	PG70-22M	12.5	30	Foamed
		171-4	WMA-WC	PG70-22M	12.5	15	Rediset
	LA 116 (Rapides)	116-1	HMA-WC	PG70-22M	12.5	15	
		116-2	HMA-BC	PG70-22M	19	20	
		116-3	WMA-WC	PG70-22M	12.5	15	Foamed
		116-4	WMA-BC	PG70-22M	19	20	Foamed
	LA 10 (Evangeline)	10-1	HMA-BC	PG70-22M	19	20	
		10-2	WMA-BC	PG70-22M	19	20	Evotherm®
Level II	US 90 (Calcasieu)	90-1	HMA-WC	PG76-22M	19	15	
		90-2	WMA-WC	PG76-22M	19	15	Evotherm®
	US 61 (St. Charles)	61-1	HMA-WC	PG76-22M	12.5	15	
		61-2	WMA-WC	PG76-22M	12.5	15	Evotherm®
		61-3	WMA-WC	PG76-22M	12.5	15	Sasobit
		61-4	WMA-WC	PG76-22M	12.5	15	Foamed
		61-5	WMA-WC	PG76-22M	12.5	15	Sasobit

* The letter M designates polymer modification

Materials

All the mixtures used in this study were designed following Louisiana Superpave Specifications [DOTD 2006 spec]. The Level 1 mixtures contained PG70-22M binder while the Level 2 mixtures contained PG76-22M binder. Both Level 1 and 2 groups included 12.5 and 19 mm Nominal Maximum Aggregate Size (NMAS) mixtures. The mix design details for the Level 1 and 2 mixtures are presented in Tables 2 and 3 respectively.

To avoid re-heating, loose mixture was obtained from trucks at the plant and compacted on-site in the Louisiana Transportation Research Center (LTRC) mobile asphalt laboratory for most of the projects, the exceptions being the LA 10 and US 90 projects.

In each of the projects, a companion conventional hot mix asphalt mixture was included and used as the control mixture. Additionally, in two of the projects (LA 3121 and US 171), a mixture with 30% RAP was included to determine if WMA additives and processes could be used with mixtures containing high RAP content.

Figures 2 and 3 present the gradations for the 12.5 and 19 mm NMAS mixtures, respectively. Gradations for only the control mixtures for each project are shown since their companion WMA mixtures had the same aggregate gradations. The only exception to this is the US 61 project where two gradations were used, the first three mixtures (61-1, 61-2, and 61-3) had one gradation while the last two mixtures (61-4 and 61-5) had a different gradation. The first three mixtures were produced with granite as the main aggregate, however the contractor ran out of the granite material, and the last two mixtures were produced using a different gradation with sandstone as the main aggregate.

Table 2
Job mix formula for Level 1 mixtures

Mixture code		3121-1	3121-2	3121-3	171-1	171-2	171-3	171-4
Mix type		12.5 mm HMA	12.5 mm WMA	12.5 mm WMA	12.5 mm HMA	12.5 mm WMA	12.5 mm WMA	12.5 mm WMA
Aggregate Blend		25.7% #78LS 47.1% #11LS 12.9% sand 14.3% RAP	25.7% #78LS 47.1% #11LS 12.9% sand 14.3% RAP	21.4% #78LS 39.3% #11LS 10.7% sand 28.6% RAP	10% 5/8" Novaculite 52% ½" Novaculite 15% RAP 10% screens 7% C. sand 6% fine sand	11% 5/8" Novaculite 46% ½" Novaculite 15% RAP 15% screens 13% C. sand	10% 5/8" Novaculite 38% ½" Novaculite 30% RAP 15% screens 7% C. sand	11% 5/8" Novaculite 46% ½" Novaculite 15% RAP 15% screens 13% C. sand
Binder type		PG 70-22M						
Design volumetric properties	%Gmm, Ni	84.2	84.2	84.2	88.7	88.2	88.2	88.2
	%Gmm, Nd	95.9	95.9	95.9	96.7	96.6	96.5	96.6
	%Gmm, Nm	97.3	97.3	97.3	98.0	97.5	97.4	97.5
	%AC	4.8	4.8	4.8	5.0	5.0	5.5	5.0
	%Voids	4.1	4.1	4.1	3.3	3.4	3.6	3.4
	%VMA	15	15	15	14.5	14	14	14
	%VFA	73	73	73	78	76	75	76
Gradation, sieve size in mm (US unit) (% passing)	25 (1)	100	100	100	100	100	100	100
	19 (3/4)	100	100	100	100	100	100	100
	12.5 (1/2)	96	96	96	93	94	93	94
	9.5(3/8)	87	87	87	82	81	82	82
	4.75 (#4)	53	53	53	50	55	53	54
	2.36 (#8)	34	34	34	34	40	38	40
	1.18 (#16)	23	23	23	27	30	28	29
	0.6 (#30)	18	18	18	23	25	22	24
	0.3 (#50)	11	11	11	18	20	17	18
	0.15 (#100)	6	6	6	8	10	10	9
	0.075 (#200)	3.8	3.8	3.8	5	5	6	5

* LS: Limestone
* RAP: Reclaimed Asphalt Pavement
* C. sand: coarse sand
* N_i: initial number of gyrations
* N_d: design number of gyrations
* N_m: maximum number of gyrations
*VFA: voids filled with asphalt
*VMA: voids in mineral aggregate

Table 2
Job mix formula for Level 1 mixtures (continued)

Mixture code		116-1	116-2	116-3	116-4	10-1	10-2
Mix type		12.5 mm HMA	19.0 mm HMA	12.5 mm WMA	19.0 mm WMA	19.0 mm HMA	19.0 mm WMA
Aggregate Blend		21.5% #78LS 14.6% #89LS 14.1% RAP 36.9% #11LS 12.9% sand	17.8% #67LS 24.3% #78LS 18.9% RAP 26.8% #11LS 12.2% C. sand	21.5% #78LS 14.6% #89LS 14.1% RAP 36.9% #11LS 12.9% sand	17.8% #67LS 24.3% #78LS 18.9% RAP 26.8% #11LS 12.2% C. sand	20% #57 SS 14% 5/8" SS 8% ½" SS 28% #11SS 10% C. sand 20% RAP	20% #57 SS 14% 5/8" SS 8% ½" SS 28% #11SS 10% C. sand 20% RAP
Binder type		PG 70-22M					
Design volumetric properties	%Gmm, Ni	88.1	88.4	88.1	88.4	90.3	90.3
	%Gmm, Nd	96.4	96.5	96.4	96.5	96.4	96.4
	%Gmm, Nm	97.4	97.3	97.4	97.3	97.3	97.3
	%AC	4.6	4.1	4.6	4.1	4.7	4.7
	%Voids	3.7	3.5	3.7	3.5	3.0	3.0
	%VMA	14	13	14	13	13	13
	%VFA	74	73	74	73	78	78
Gradation, sieve size in mm (US unit) (% passing)	25 (1)	100	100	100	100	100	100
	19 (3/4)	100	96	100	96	96	96
	12.5 (1/2)	90	86	90	86	80	80
	9.5(3/8)	88	73	88	73	70	70
	4.75 (#4)	63	50	63	50	55	55
	2.36 (#8)	44	37	44	37	43	43
	1.18 (#16)	33	29	33	29	32	32
	0.6 (#30)	26	23	26	23	23	23
	0.3 (#50)	15	13	15	13	12	12
	0.15 (#100)	8	8	8	8	8	8
	0.075 (#200)	6	6	6	6	5.9	5.9

*SS: Sandstone

Table 3
Job mix formula for Level 2 mixtures

Mixture code		90-1	90-2	61-1	61-2	61-3	61-4	61-5
Mix type		19.0 mm HMA	19.0 mm WMA	12.5 mm HMA	12.5 mm WMA	12.5 mm WMA	12.5 mm WMA	12.5 mm WMA
Aggregate Blend		19% #67 LS 32% #78Gr. 21% #11LS 13% C. sand 15% RAP	19% #67 LS 32% #78Gr. 21% #11LS 13% C. sand 15% RAP	30.0% #7 Gr. 14.4% #78LS 21.1% -1/2 Grav. 15.5% Man. sand 3.7% C. sand 14.3% RAP 1% BH fines	30.0% #7 Gr. 14.4% #78LS 21.1% -1/2 Grav. 15.5% Man. sand 3.7% C. sand 14.3% RAP 1% BH fines	30.0% #7 Gr. 14.4% #78LS 21.1% -1/2 Grav. 15.5% Man. sand 3.7% C. sand 14.3% RAP 1% BH fines	30.1% #78SS 14.8% -1/2 C. Gr. 29.5% Man. Sand 14.3% RAP 10.3% sand 1% BH fines	30.1% #78SS 14.8% -1/2 C. Gr. 29.5% Man. Sand 14.3% RAP 10.3% sand 1% BH fines
Binder type		PG 76-22M						
Design volumetric properties	%Gmm, Ni	88.8	88.8	87.7	87.7	87.7	89.6	89.6
	%Gmm, Nd	96.8	96.8	96.3	96.3	96.3	96.8	96.8
	%Gmm, Nm	97.5	97.5	97.5	97.5	97.5	96.9	96.9
	%AC	4.0	4.0	4.7	4.7	4.7	4.7	4.7
	%Voids	3.3	3.3	3.7	3.7	3.7	3.3	3.3
	%VMA	13	13	14	14	14	13	13
	%VFA	75	75	73	73	73	75	75
Gradation, sieve size in mm (US unit) (% passing)	25 (1)	100	100	100	100	100	100	100
	19 (3/4)	98	98	100	100	100	100	100
	12.5 (1/2)	81	81	96	96	96	90	90
	9.5(3/8)	66	66	83	83	83	85	85
	4.75 (#4)	45	45	51	51	51	65	65
	2.36 (#8)	36	36	36	36	36	52	52
	1.18 (#16)	28	28	25	25	25	36	36
	0.6 (#30)	22	22	18	18	18	26	26
	0.3 (#50)	11	11	12	12	12	15	15
	0.15 (#100)	8	8	8	8	8	9	9
	0.075 (#200)	5.6	5.6	6.1	6.1	6.1	6.5	6.5

*****BH: Baghouse
*Gr.: Granite

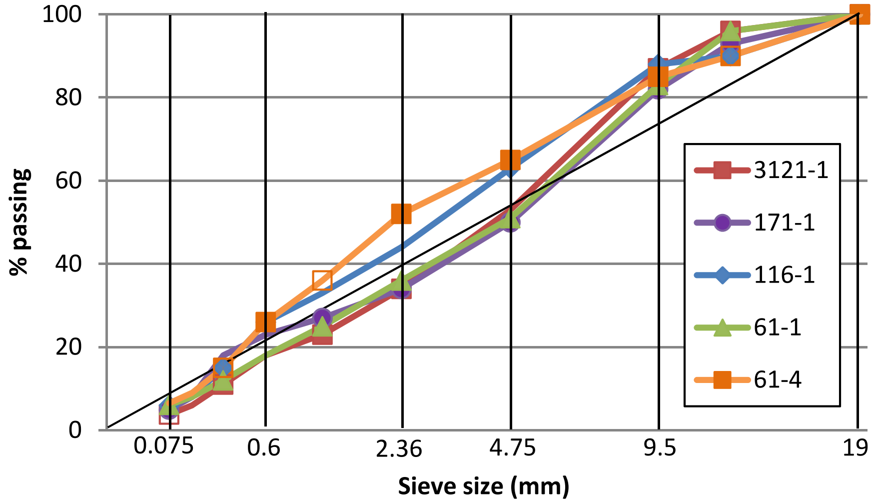


Figure 2
Gradation chart for 0.5-in. (12.5-mm) mixtures

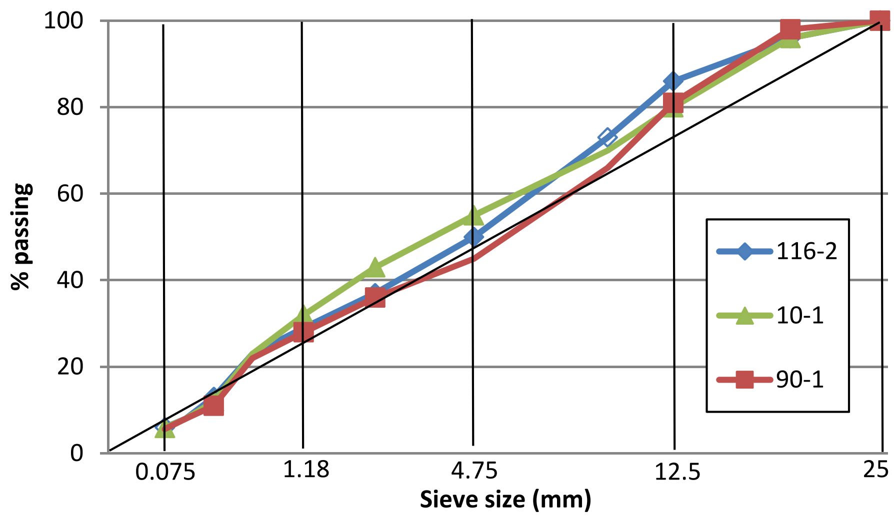


Figure 3
Gradation chart for 0.75-in. (19.0-mm) mixtures

Warm Mix Asphalt Technologies

The WMA in this study was produced by either adding a chemical additive or by strategically adding water to the liquid asphalt through a process termed “foaming.” Both methods lead to a reduction in the viscosity of the asphalt binder. The details of the technologies investigated are given below.

Chemical Additives

Evotherm®. Evotherm® is a chemical additive produced by the MeadWestvaco Corporation. Figure 4 shows the product, which is available as a dark amber liquid, and is added to the asphalt binder either at the terminal or at the plant. Evotherm® includes surfactants to improve asphalt-aggregate adhesion. A surfactant or surface active agent is a compound that reduces the surface tension between a solid and a liquid or between two liquids. Evotherm® was added at the rate of 0.5% by weight of binder for the LA 3121 project and at a rate of 0.6% for the other projects (LA 10, US 90, and US 61). Additionally, it has anti-stripping properties as well, eliminating the need for an anti-strip agent.

Figure 4
Chemical additive Evotherm®

Rediset WMX. The second chemical additive used in this study was a product manufactured by AkzoNobel, called Rediset. Figure 5 presents a picture of the additive pastilles. Rediset was added to the plant at a rate of 2% by weight of the binder. It, too, is a surfactant-based additive and provides anti-strip protection as well.

Figure 5
Pastilles of the chemical additive Rediset

Sasobit. The third additive used in this study was a product from the Sasol company called Sasobit. Figure 6 shows a picture of the Sasobit pellets, which are added to the binder tank at the plant. The dosage rate used was 1.5% by weight of the binder. Sasobit dissolves in the binder and reduces its viscosity, enabling lower mixing and compaction temperatures.

Figure 6
Pellets of the chemical additive Sasobit

Foaming Processes

Astec Double Barrel Green System. The equipment for this foaming process is manufactured by Astec, Inc. The process involves injecting water into the liquid asphalt just prior to entering the mixing chamber, thus creating the foamed binder. Details of the equipment can be found at the manufacturer's website.

Accu-shear System. The second foaming process tried in this study was the Accu-shear system supplied by the Stansteel company. In this process, water is added to the asphalt binder and mechanically blended to ensure through mixing. Figure 7 shows a picture of the equipment used at the plant for the LA 116 project. Additional details of the equipment and process can be found at the manufacturer's website.

Figure 7
Accu-shear blending equipment

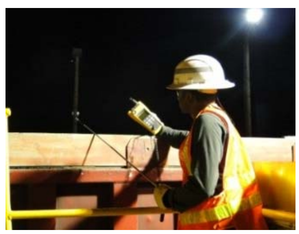
Specimen Preparation and Test Methods

Details of specimen preparation and test methods used are provided in the Appendix.

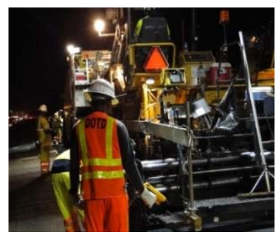
Environmental Evaluation of WMA

Carbon monoxide (CO) is a toxic gas that contributes to ground level ozone and to smog formation. CO_2 is a greenhouse gas, which absorbs and emits infrared radiation, causing global warming. To evaluate the environmental benefits of WMA, CO and CO_2 emissions were monitored and quantified during the production and placement of two additional WMA field projects to the ones reported in Table 1. The first field project utilized mixtures containing two WMA technologies, namely, foaming and Sasobit additive. The second field project consisted of a conventional HMA mixture. A portable Fluke-975V® air quality analyzer device with a CO monitoring range from 0 to 500 ppm and a CO_2 monitoring range from 0 to 5000 ppm was used. As seen in Figure 8, CO and CO_2 emissions were monitored during the following production and placement activities: at exit of the mixture drum, during truck loading at the base of the silo, on the sampling platform, behind paver screed, and behind compaction roller.

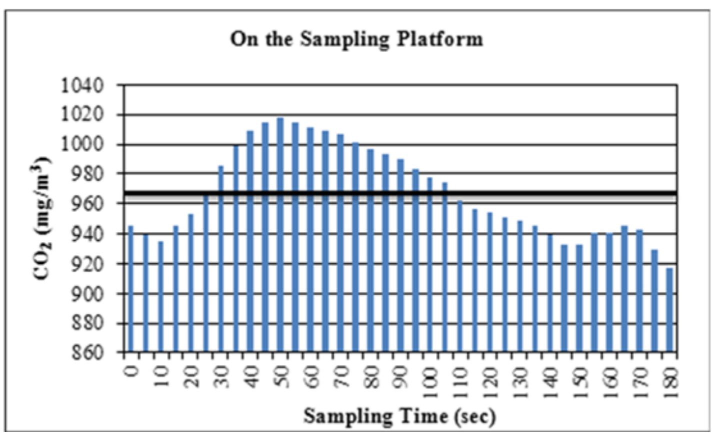
Figure 8(c) presents a typical output from CO_2 measurements at the truck-sampling platform for the WMA field project using foaming technology. As shown in this figure, the amount of CO_2 emitted gradually increased during monitoring, reached a maximum value, and then decreased. To ensure consistency in the analysis, the averages CO and CO_2 emitted during each activity were calculated.



(a) On the Sampling Platform



(b) Behind Paver Screed



(c) Typical CO_2 Variation on the Sampling Platform

Figure 8
Emission measurements

Life-Cycle Assessment

Life-cycle assessment (LCA) was used for environmental-economic analysis of WMA technology as compared to conventional HMA. The Building for Environmental and Economic Sustainability (BEES) version 4.0 model was used in the analysis *[34]*. This model provides a systematic methodology to select sustainable construction alternatives that balance environmental and economic performances. Ten of the 12 environmental impact factors considered in the BEES 4.0 model were included in the analysis: global warming, acidification, eutrophication, fossil fuel depletion, water intake, criteria air pollutants, human health (noncancerous and cancerous), smog formation, ozone depletion, and ecological toxicity.

Since environmental impact factors such as global warming and impacts on human health cannot be assessed using a regular monetary scale, the BEES model computes a single index for each considered factor in order to quantify the impact of a product on the environment. For instance, global warming is expressed in grams of carbon dioxide produced per functional unit of a product. The global warming index is calculated based on the following relation:

$$GlobalWarmingIndex = \sum_i m_i \text{ x } GWP_i \quad (1)$$

where, m_i = mass (in grams) of emission i per functional unit; and GWP_i = conversion factor from one gram of emission i to its equivalent of carbon dioxide.

Equivalency factors are provided by the BEES model based on research conducted by the U.S. Environmental Protection Agency (EPA). A Life-cycle inventory was developed for WMA mixtures to provide a compilation of the energy requirements, material inputs, and the emissions associated with its production and installation. A wide range of published reports and databases were reviewed to collect emission data for each process and activity used in WMA *[35-37]*. The functional unit considered was one ton of WMA placed. The LCI considered energy and emissions associated with the manufacturing of asphalt binder, production of aggregate, plant operations, and mixture placement. However, the in-service use phase was excluded from the analysis. Compilation of the required raw data was conducted manually and a Life Cycle Inventory Assessment (LCIA) was conducted based on the BEES model. The presented LCIA neglected the environmental impacts of the WMA additives, given their small masses compared to the functional unit considered in the analysis. It is recommended that future LCA studies consider the environmental and economic impacts of WMA additives.

DISCUSSION OF RESULTS

Relative Measures of Laboratory Performance Between Conventional and WMA Mixtures

The testing factorial included seven different testing procedures in which the WMA mixtures were compared against a companion control HMA mixture, referred herein as conventional mixture. Permanent deformation (rutting), fatigue/fracture cracking, and moisture susceptibility were the three major distress conditions considered in the evaluation of the mixtures. Results obtained from F_N and LWT tests were used to assess the high temperature performance of the mixtures. Results from ITS (indirect tensile strength), DCSE, SCB were used to evaluate the intermediate temperature performance of the mixtures. Moreover, the |E*| values were used for intermediate (4.4^{o}C and 25^{o}C) and high temperatures performances (37.8^{o}C and 54.4^{o}C). The modified Lottman test results were used to assess the susceptibility to moisture induced damage for the mixtures.

The results are presented in six groups corresponding to each respective project. Within each group, the results are compared quantitatively in respect to the control mixture. The overall comparison among projects was carried out based on normalized values to avoid variability due to differences in mixtures. The HMA mixtures served as the baseline for normalization of the results which were then used for an overall assessment of performance. The experimental results from the six projects are presented as follows.

LA – 3121

LA-3121 project was comprised of three mixtures. The control HMA mixture contains 15% RAP. The two warm mixtures incorporated 15% and 30% RAP, respectively, and used Evotherm® as the warm mix additive.

Flow Number. The $\mathbf{F_N}$ test was conducted on three replicate samples from each mixture to assess the permanent deformation characteristics of asphalt mixtures. The test was conducted at a single test temperature of 54.4°C, and $\mathbf{F_N}$ was calculated. If a sample never showed tertiary flow during the whole loading cycle (10,000 cycles), a $\mathbf{F_N}$ of 10,000 was reported for that specimen. A higher $\mathbf{F_N}$ represents a better resistance to permanent deformation which leads to a better rut performance in the field. Table 4 presents the $\mathbf{F_N}$ results for the three mixtures along with their respective average values and coefficients of variation. Problems occurred during the fabrication and testing of replicates 1 and 3 of the WMA 15% RAP. Those specimens were discarded and only one value of $\mathbf{F_N}$ was obtained.

Table 4
LA – 3121 flow number test results

Conventional	
Replicate #	**Flow Number**
1	2592
2	2136
3	1968
Average	2232
CV [%]	14.5
WMA 15% RAP Evotherm®	
Replicate #	**Flow Number**
1	
2	2536
3	
Average	2536
CV [%]	n/a
WMA 30% RAP Evotherm®	
Replicate #	**Flow Number**
1	1592
2	1920
3	1584
Average	1699
CV [%]	11.3

*CV: Coefficient of Variation

The analysis revealed that the WMA mixture containing 30% RAP had a lower F_N when compared to the conventional HMA mixture. The WMA mixture containing 15% of RAP showed a higher F_N in respect to its HMA counterpart; however, the analysis was affected by the low number of replicates (only one), therefore, no other sound conclusions can be drawn in this case. Figure 9 graphically shows the results from the three mixtures along with the maximum and minimum error limits.

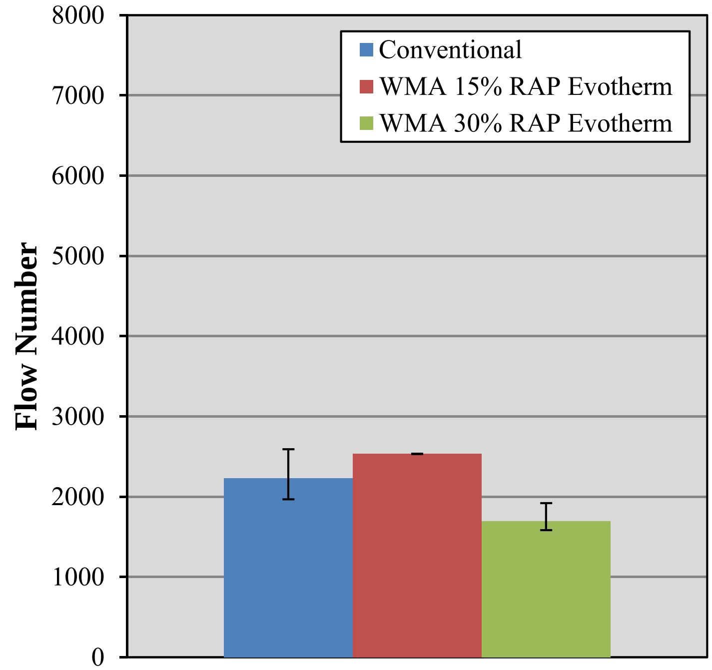


Figure 9
LA – 3121 flow number test results

Loaded Wheel Tracking Test (LWT). The LWT test was conducted to evaluate the moisture susceptibility of each of the mixtures evaluated. A single test temperature of 50°C was employed for the study, and average rut depth obtained from two tests was reported. Rut depth was measured for 20,000 passes or until a rut depth of 20 mm was reported. Mixtures with least rut depth are considered rut resistant and less moisture susceptible. A rut depth less than 6.0 mm at 20,000 passes represents a mixture that is considered rut and moisture induced damage resistant. The results are shown in Figure 10. Both HMA and WMA mixture performed well. The WMA mixtures had slightly higher rut depths when compared to the conventional.

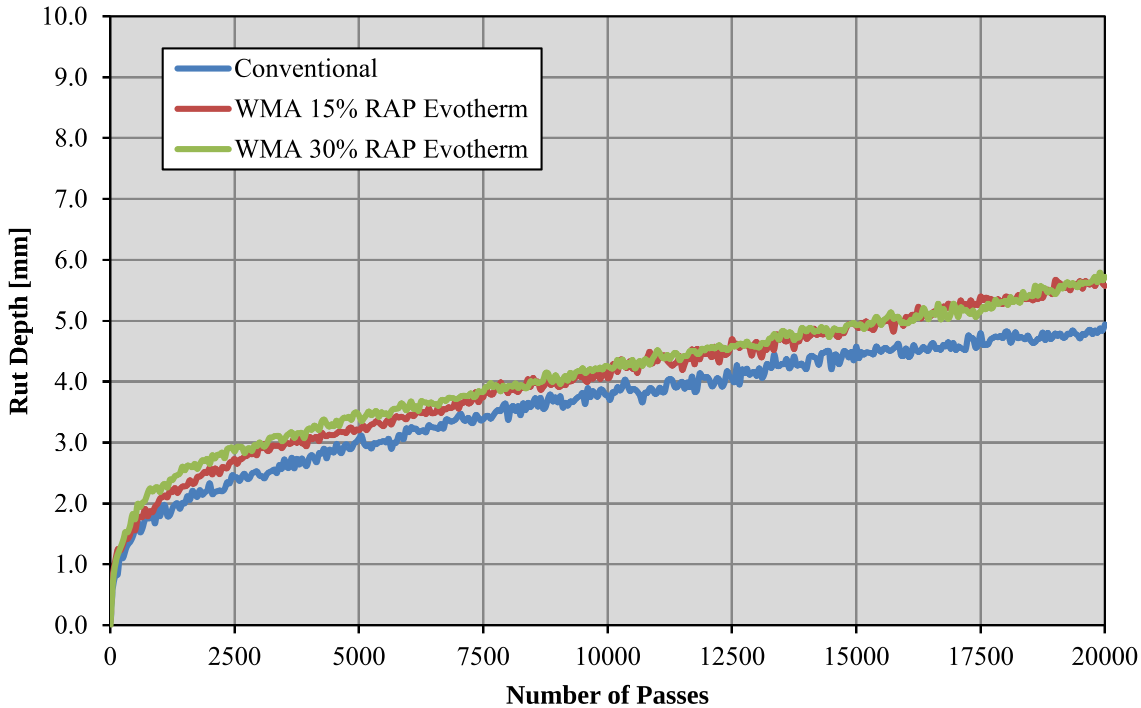
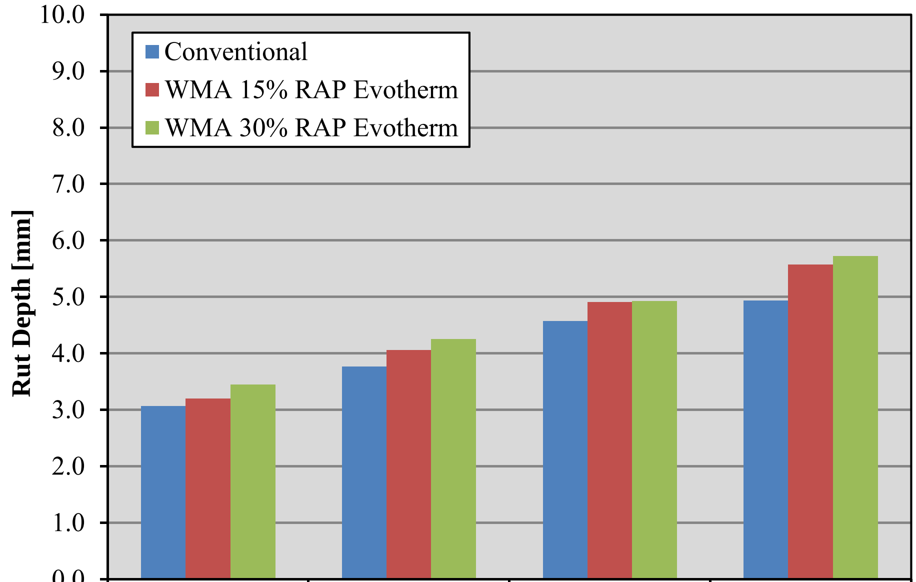


Figure 10
LA – 3121 LWT results

As can be seen, no stripping was observed during testing. Hence, evaluation of the stripping inflection point, stripping slope, and creep slope evaluation was not performed. Figure 11 presents the rut depths at different number of passes. The addition of Evotherm® to both the 15% and 30% RAP mixtures slightly increased the rut depths when compared to the conventional mixture. It is noted that both conventional and WMA mixtures passed the DOTD rut depth failing criteria of 6.0 mm at 20,000 passes.



	5000	10000	15000	20000
Conventional	3.1	3.8	4.6	4.9
WMA 15% RAP Evotherm	3.2	4.1	4.9	5.6
WMA 30% RAP Evotherm	3.4	4.3	4.9	5.7

Number of Passes

Figure 11
LA – 3121 LWT results at various passes

Indirect Tensile Strength (ITS). The ITS test was conducted to evaluate the fracture resistance of asphalt mixtures. Three replicates for both aged and unaged specimens were tested at 25°C and the ITS, indirect tensile strain and toughness index (TI) were calculated. Higher ITS, IT strain and TI values represent strong and fracture resistant mixtures. These higher values represent a higher resistance to fatigue fracture. The testing results are presented in Table 5 and Table 6.

Figures 12 and 13 present the mean ITS and toughness index (TI) values for both aged and unaged samples. The error bars represent the maximum and minimum values results for each test. An increase in strength for aged mixtures can be observed, while the indirect tension (IT) strain decreased with aging. These are indications that the aging process made the mixtures stiffer and more brittle. The increase in the strength of the mixtures with aging is attributed to the oxidizing effect of asphalt binder during the aging procedure, which stiffens the binder resulting in a stiffer mixture. It is also observed that the increase in the strength with aging was minimal for the WMA mixtures compared to that of corresponding control HMA mixtures.

The two WMA mixtures for the unaged specimens showed similar or slightly higher ITS values than their corresponding control HMA mixtures while the two WMA mixtures for the aged specimens showed lower ITS values than their corresponding control HMA mixtures. Incorporation of higher percentages of RAP did not show steep increase in the strength of the mixture. The two WMA mixtures had similar IT strain values as their corresponding HMA mixtures. There was no effect of foaming or additives on the performance of the mixtures. Similar trend was observed in the TI values. Both WMA mixtures for both aged and unaged specimens possessed similar or better TI values to that of their control HMA mixtures.

Table 5
LA – 3121 Unaged ITS results

UNAGED				
Conventional				
Replicate #	Voids [%]	IT Strength [psi]	IT Strain [%]	Toughness Index
1	7.4	144.2	0.78	0.81
2	7.1	138.7	0.62	0.79
3	7.5	121.1	1.03	0.84
Average	**7.3**	**134.7**	**0.81**	**0.81**
Coeff. of Variation (%)	3	9	26	3
WMA 15% RAP Evotherm®				
Replicate #	Voids [%]	IT Strength [psi]	IT Strain [%]	Toughness Index
1	7.1	139.6	0.88	0.84
2	7.3	135.9	1.00	0.89
3	7.3	130.2	1.03	0.87
Average	**7.2**	**135.2**	**0.97**	**0.87**
Coeff. of Variation (%)	2	4	8	3
WMA 30% RAP Evotherm®				
Replicate #	Voids [%]	IT Strength [psi]	IT Strain [%]	Toughness Index
1	7.2	140.2	0.75	0.83
2	7.5	135.7	0.88	0.87
3	7.0	134.3	1.01	0.86
Average	**7.2**	**136.7**	**0.88**	**0.85**
Coeff. of Variation (%)	3	2	15	2

Table 6
LA – 3121 aged ITS results

AGED				
Conventional				
Replicate #	Voids [%]	IT Strength [psi]	IT Strain [%]	Toughness Index
1	9.6	148.4	0.45	0.70
2	8.3	154.5	0.58	0.76
3	9.1	148.6	0.54	0.75
Average	**9.0**	**150.5**	**0.52**	**0.73**
Coeff. of Variation (%)	7	2	13	4
WMA 15% RAP Evotherm®				
Replicate #	Voids (percent)	IT Strength [psi]	IT Strain [%]	Toughness Index
1	7.4	141.0	0.44	0.81
2	-	131.1	0.69	0.81
3	7.6	114.5	0.82	0.87
Average	**7.5**	**128.8**	**0.65**	**0.83**
Coeff. of Variation (%)	2	10	30	4
WMA 30% RAP Evotherm®				
Replicate #	Voids [%]	IT Strength [psi]	IT Strain [%]	Toughness Index
1	7.4	133.9	0.64	0.83
2	7.8	131.4	0.89	0.86
3	8.6	154.2	0.76	0.83
Average	**7.9**	**139.8**	**0.76**	**0.84**
Coeff. of Variation (%)	8	9	16	2

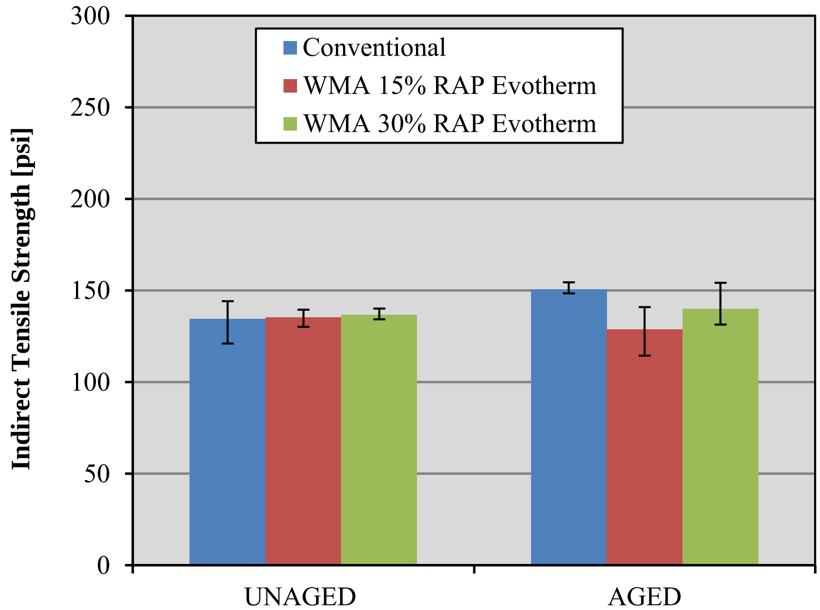


Figure 12
LA – 3121 indirect tensile results

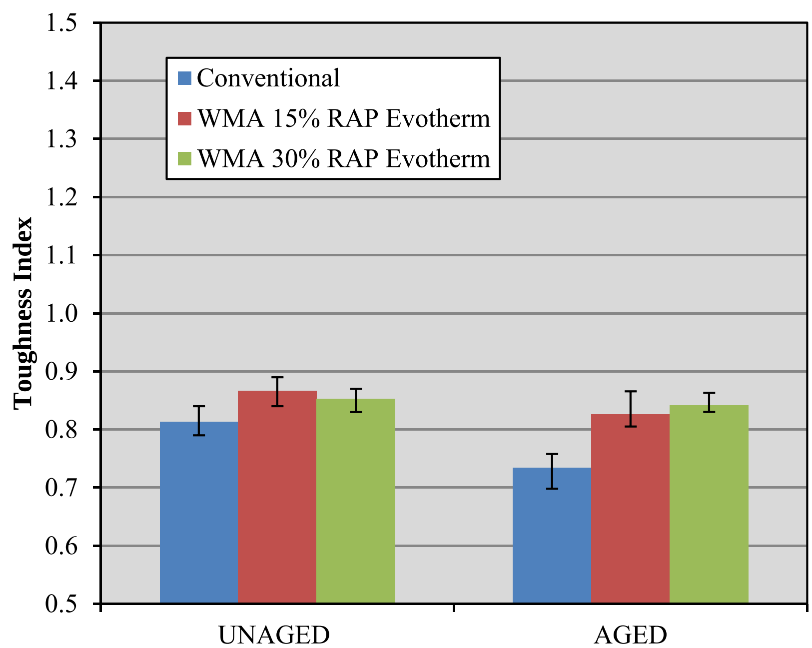


Figure 13
LA – 3121 toughness index results

Dissipated Creep Strain Energy Results. The Dissipated Creep Strain Energy (DCSE) test was conducted to evaluate the crack (fracture) resistance properties of the asphalt mixtures. Two mechanistic tests, indirect resilient modulus (MR) followed by indirect tensile strength (ITS), were conducted at a single test temperature of 10°C. Poisson's ratio, resilient modulus, and initial and failure strains were computed to calculate the elastic energy and initial energy. A higher DCSE value represents a mixture that can hold higher energy before fracture initiates. Thus, a higher DCSE value represents a fracture (crack) resistant mixture.

Table 7 summarizes the DCSE test results for each of the mixtures. During the test procedure the extensometers presented some issues that tampered the final results. For this reason, the data from some of the replicates could not be used in this analysis.

Figure 14 graphically represents the DCSE values along with their corresponding error limits. Mixtures with a DCSE value greater than 0.75 KJ/m^3 did not reveal cracking in the pavement. Hence, mixtures with lower DCSE values are considered susceptible to fracture. It is observed that all the mixtures met the failure criteria of 0.75 KJ/m^3.

The WMA mixtures exhibited higher DCSE values than their corresponding control HMA mixtures, indicating the Evotherm® technology increased the fracture resistance of the mixtures. However, it is noteworthy that both the WMA and HMA mixtures had DCSE values higher than 0.75 KJ/m^3.

Table 7
LA – 3121 DCSE test results

Conventional						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	2146544	1773	349	0	0.26	1.94
2						
3						
Average	2146544	1773	349	0	0.26	1.94
CV [%]	n/a	n/a	n/a	n/a	n/a	n/a
WMA 15% RAP Evotherm®						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1078733	3044	248	0	0.28	2.41
2	1380171	2300	356	0	0.25	2.57
3						
Average	1229452	2672	302	0	0.26	2.49
CV [%]	17.3	19.7	25.3	0	6.8	4.7
WMA 30% RAP Evotherm®						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1303260	2417	310	0	0.28	2.33
2	1484832	1998	356	0	0.27	2.16
3						
Average	1394046	2207	333	0	0.27	2.24
CV [%]	9.2	13.4	9.8	0	3.3	5.4

* µstrain: microstrain

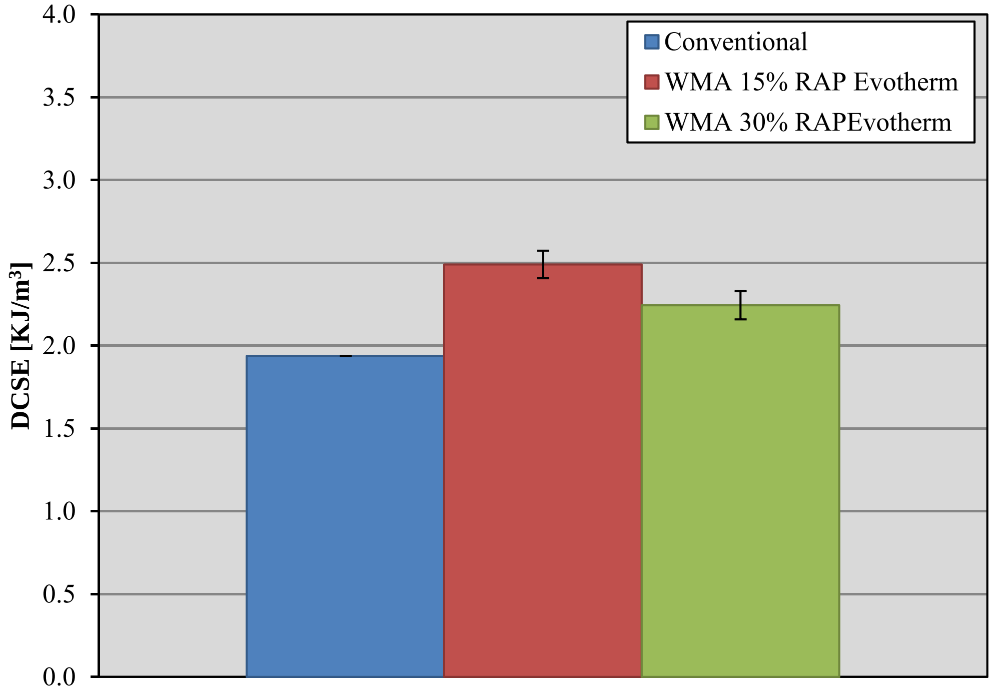


Figure 14
LA – 3121 DCSE results

Semi-Circular Bending Test Results. The semi-circular bend (SCB) test was conducted to evaluate the fracture resistance properties of asphalt mixtures. Long-term aged specimens with three different notch depths were tested at a single test temperature of 25°C. The peak load, peak strain, and the area under stress-strain curve till peak load were used in computing the critical strain energy (J_c). A higher J_c value represents a fracture resistant mixture. This is explained by the fact that the effective depth of specimen above notch decreases with increase in notch size. The recorded peak loads are inversely proportional to the notch depth. Table 8 shows the peak load, area as well as the corresponding J_c for all three mixtures.

Figure 15 presents the computed J_c values for all the mixtures evaluated. As determined from previous studies a J_c value greater than or equal to 0.5 is considered as a fracture resistant mixture. It is observed that the WMA 30% RAP mixture failed to meet the criteria of 0.5 KJ/m^2. The lowest value was recorded for the WMA 30% RAP specimens, which suggests that in addition to the contribution of the Evotherm®, the additional RAP material might have played a role in the lower J_c value.

Table 8
LA – 3121 SCB test results

Conventional							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.429	0.667	0.659	1.418	0.796	0.647	0.8
2	0.970	0.894	0.629	1.289	0.973	0.764	
3		0.906	0.659		0.916	0.908	
Average	1.199	0.822	0.649	1.354	0.895	0.773	
CV [%]	27.0	16.4	2.7	6.7	10.1	16.8	
WMA 15% RAP Evotherm®							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.861	0.759	0.499	0.928	1.236	0.777	0.5
2	0.783	0.592	0.577	1.074	0.885	0.507	
3	0.746	0.773	0.583	0.883	0.900	0.537	
Average	0.797	0.708	0.553	0.962	1.007	0.607	
CV [%]	7.4	14.2	8.4	10.4	19.8	24.3	
WMA 30% RAP Evotherm®							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.83	0.73	0.69	1.05	1.13	1.01	0.2
2	0.86	0.70	0.55	1.19	1.01	0.85	
3	1.01	0.75	0.65	1.19	0.95	1.08	
Average	0.90	0.73	0.63	1.14	1.03	0.98	
CV [%]	10.9	3.1	11.4	6.8	9.2	11.9	

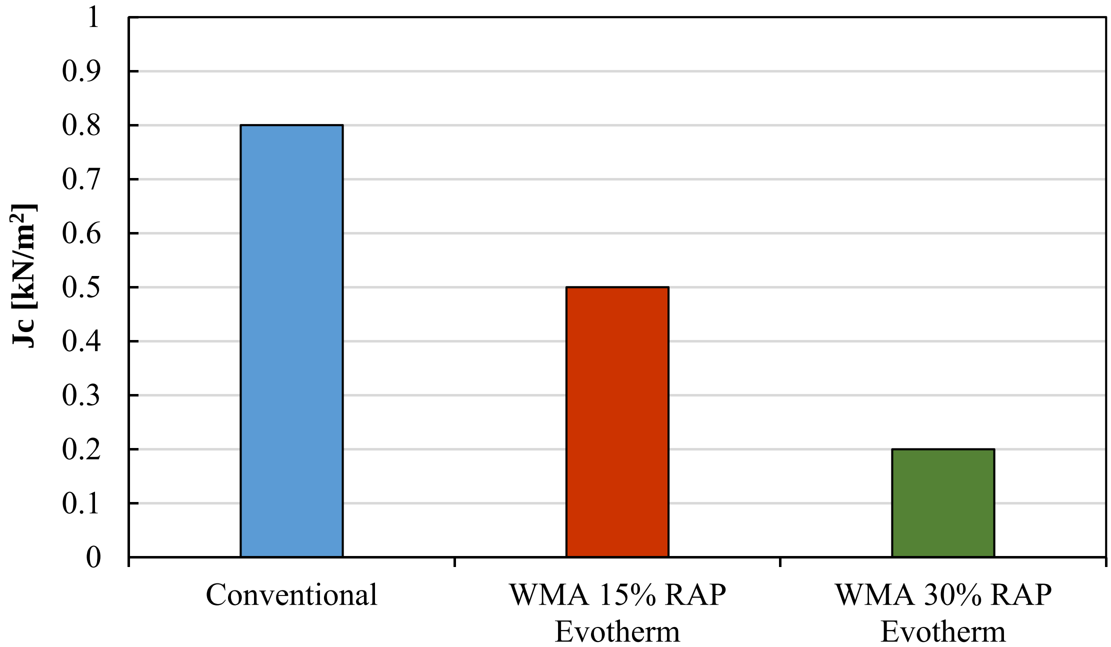


Figure 15
LA – 3121 critical values of the J-Integral

Dynamic Modulus Test Results. The axial dynamic modulus (|E*|) test was conducted on three replicate samples for each mixture to evaluate the viscoelastic behavior of the asphalt mixtures. The test was performed at five temperatures (i.e., -10, 4.4, 25, 37.8, and 54.4ºC) and six frequencies (i.e., 25, 10, 5, 1, 0.5, and 0.1 Hz). Two properties, |E*| and phase angle (δ), were obtained from this test. In general, the |E*| increased with increase in frequency and decreased with increasing temperature. The average results are shown in the following tables.

The average dynamic modulus results were then normalized to facilitate the comparison. The WMA values were divided by the corresponding conventional HMA at temperature and frequency. The results are shown in Figure 16 through Figure 20.

The warm mixtures showed lower modulus when compared to the conventional HMA mixture. Even the WMA 30% RAP mixture presented lower moduli in spite of the additional RAP material. The Evotherm® is believed to have caused this drop in stiffness. To give an overall view of the viscoelastic behavior of the three mixtures, the mastercurves are shown in Figure 21.

Table 9

LA – 3121 conventional dynamic modulus results

Conventional			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	23040	2.02
	10	22124	3.81
	5	21361	4.81
	1	19379	6.37
	0.5	18459	6.95
	0.1	16631	8.23
4.4	25	17293	5.84
	10	15696	8.57
	5	14536	10.01
	1	11952	12.98
	0.5	10842	14.29
	0.1	8360	17.27
25	25	6874	17.68
	10	5483	21.45
	5	4580	23.77
	1	2790	29.04
	0.5	2220	30.47
	0.1	1279	31.87
37.8	25	2680	27.31
	10	1879	30.24
	5	1444	31.29
	1	748	32.45
	0.5	578	31.40
	0.1	334	27.66
54.4	25	711	32.84
	10	477	33.08
	5	377	31.32
	1	219	27.07
	0.5	178	24.70
	0.1	130	19.53

Table 10
LA – 3121 WMA 15% RAP Evotherm® dynamic modulus results

WMA 15% RAP Evotherm®			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	21967	1.68
	10	21106	4.01
	5	20338	5.00
	1	18297	6.78
	0.5	17363	7.49
	0.1	15104	9.45
4.4	25	15912	7.26
	10	14545	10.27
	5	13241	12.01
	1	10407	15.85
	0.5	9228	17.52
	0.1	6609	21.41
25	25	5657	21.13
	10	4394	25.03
	5	3502	27.20
	1	1938	31.32
	0.5	1476	32.13
	0.1	801	31.12
37.8	25	1823	30.55
	10	1233	32.67
	5	920	32.94
	1	471	32.10
	0.5	377	29.82
	0.1	246	24.36
54.4	25	552	32.19
	10	379	30.45
	5	302	28.81
	1	192	23.12
	0.5	172	19.89
	0.1	138	14.81

Table 11
LA – 3121 WMA 30% RAP Evotherm® dynamic modulus results

WMA 30% RAP®			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	23419	1.74
	10	22474	3.90
	5	21672	4.90
	1	19591	6.55
	0.5	18646	7.20
	0.1	16288	8.87
4.4	25	16573	6.71
	10	15057	9.43
	5	13919	11.01
	1	11153	14.42
	0.5	9980	15.94
	0.1	7418	19.52
25	25	6860	18.87
	10	5519	22.29
	5	4516	24.66
	1	2682	29.74
	0.5	2106	30.95
	0.1	1152	31.59
37.8	25	2419	28.66
	10	1687	30.92
	5	1272	31.78
	1	653	32.16
	0.5	508	30.68
	0.1	313	25.85
54.4	25	712	31.75
	10	481	30.80
	5	380	28.73
	1	221	24.83
	0.5	194	22.04
	0.1	157	16.62

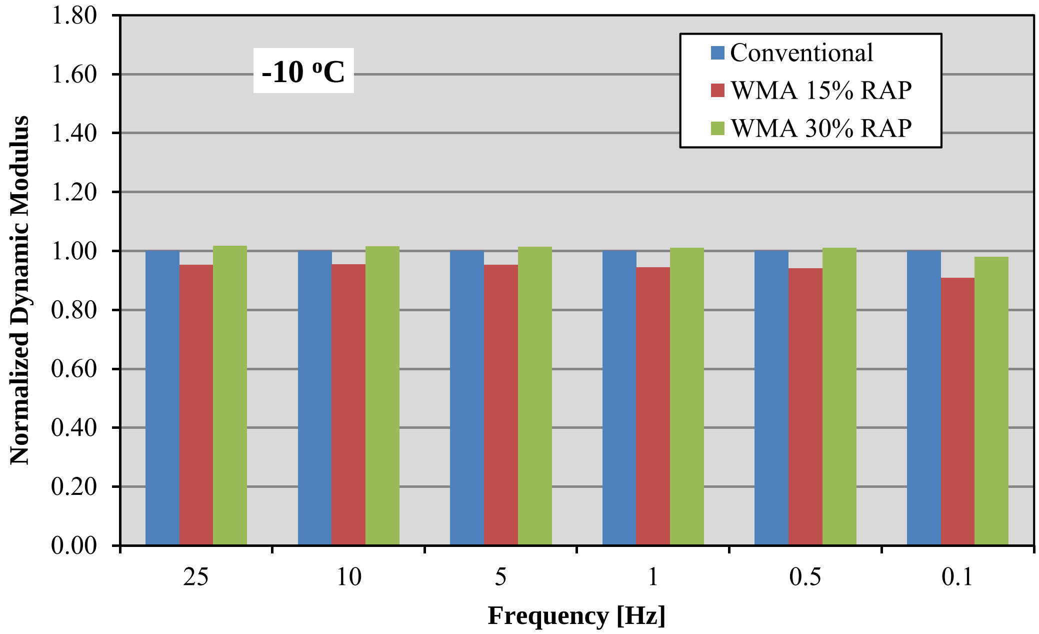


Figure 16
LA – 3121 normalized dynamic modulus at -10°C

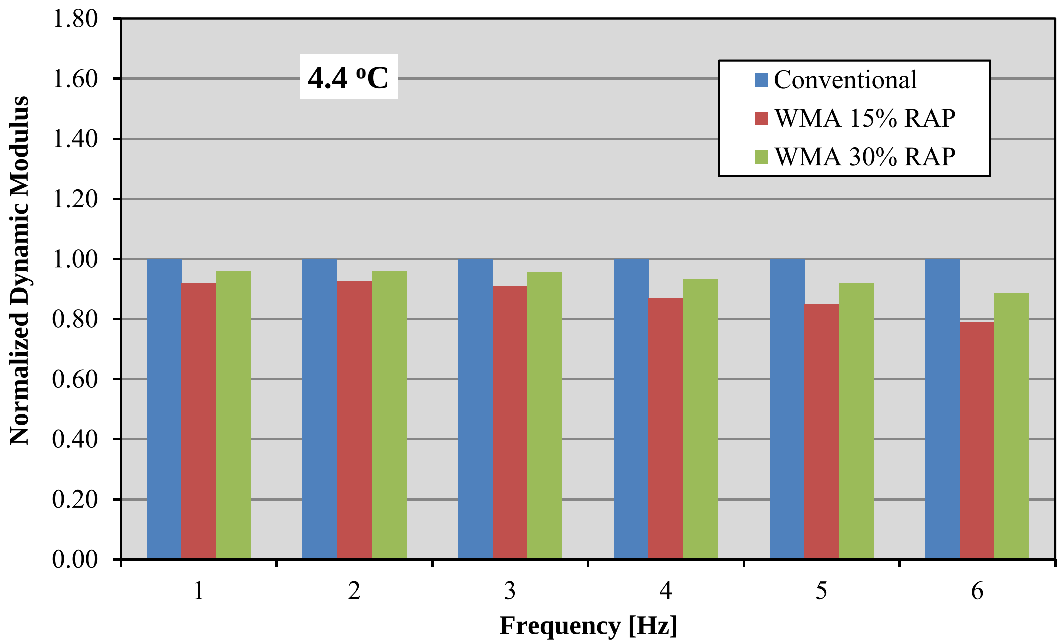


Figure 17
LA – 3121 normalized dynamic modulus at 4.4°C

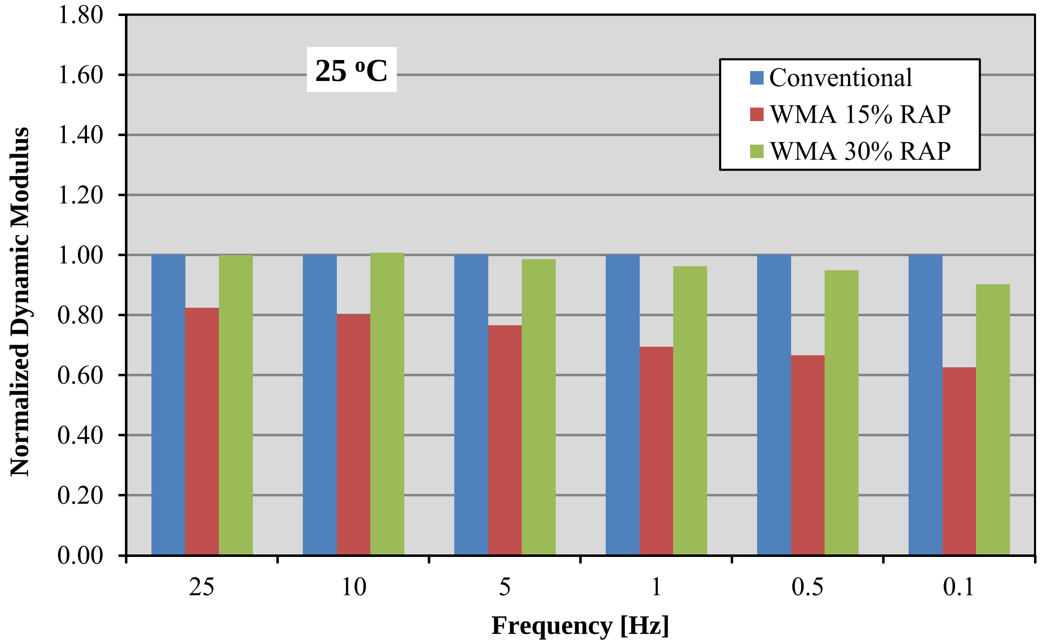


Figure 18
LA – 3121 normalized dynamic modulus at 25ºC

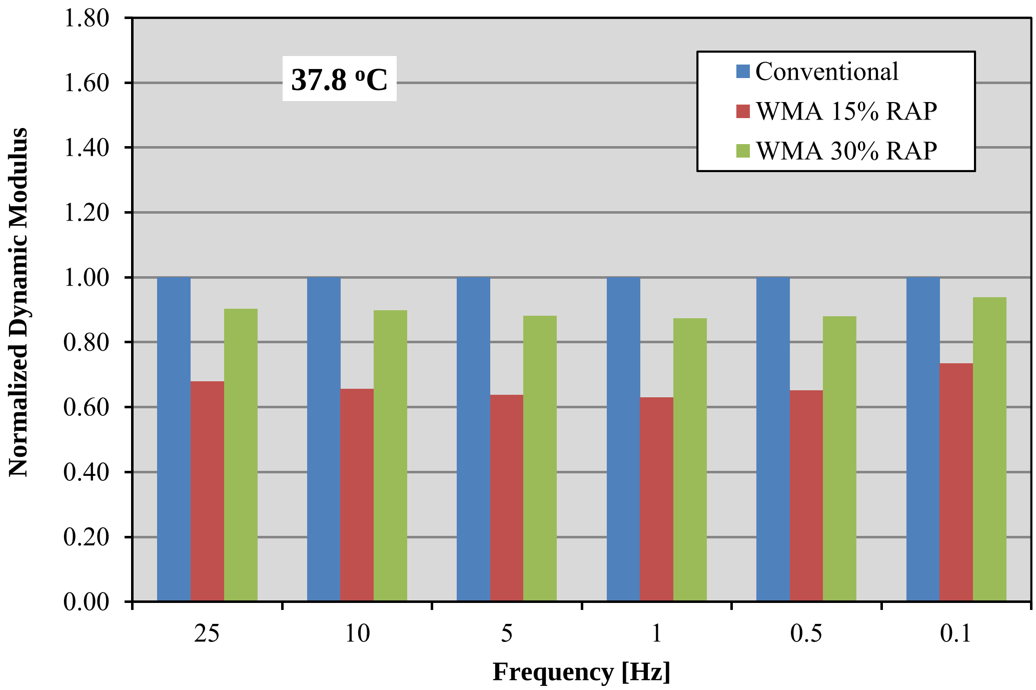


Figure 19
LA – 3121 normalized dynamic modulus at 37.8ºC

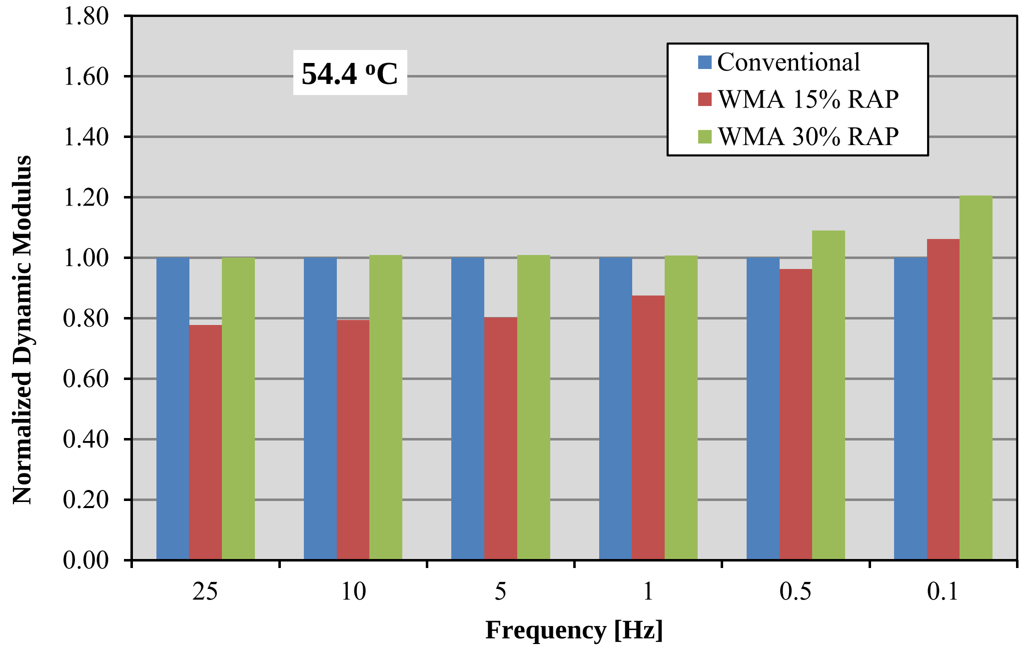


Figure 20
LA – 3121 normalized dynamic modulus at 54.4ºC

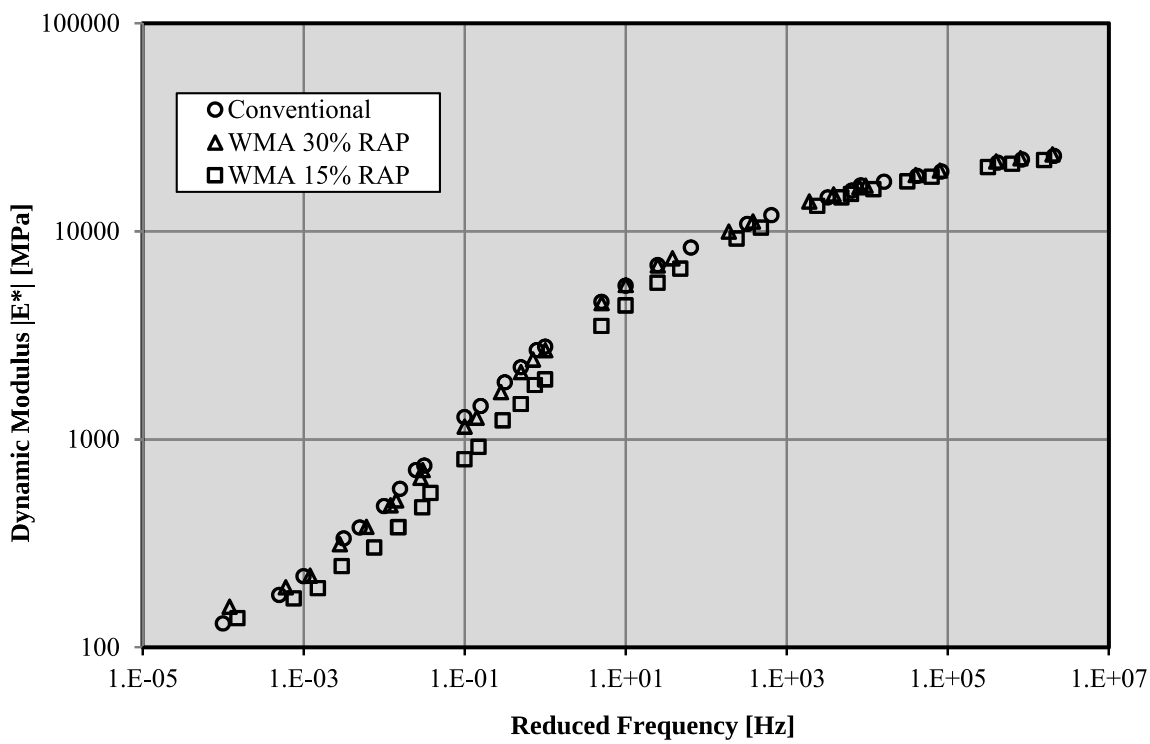


Figure 21
LA – 3121 mastercurves at 25ºC

As can be seen, the aforementioned differences in modulus are more accentuated at lower frequencies, which are equivalent to the intermediate and high temperatures. It is believed that the higher testing temperatures might have mobilized the WMA agent, consequently reducing the viscosity of the mixtures.

Modified Lottman Test Results. The Modified Lottman test was performed to evaluate the moisture induced damage of the asphalt mixtures. Two sets of samples, conditioned and unconditioned (control) specimens, were tested for each of the mixtures to compute the tensile strength and the tensile strength ratio (TSR). A higher TSR value represents a durable (moisture damage resistant) mixture. A mixture with a TSR value of 80% or higher is considered moisture damage resistant. Table 12 summarizes the Modified Lottman test results. The mean tensile strength values for the controlled and the conditioned specimens and the TSR values of the asphalt mixtures are presented in the table.

The TSR values are shown in Figure 22. It is seen that the WMA mixtures had a better performance in terms of moisture susceptibility compared to the HMA. It is noted that the WMA with 30% RAP was the only mixture that met the DOTD specification of 80% TSR. It is also worth noting that, in general, these mixtures have a conditioned IDT strength equal to or greater than 100 psi, a strength value associated with well-performing mixtures for Louisiana climate conditions.

Table 12
LA – 3121 Modified Lottman test results

Conventional		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	161.8	108.6
2	172.0	95.0
3	170.9	127.2
Average	168.2	110.3
CV [%]	3.3	14.7
TSR [%]	**65.6**	
WMA 15% RAP Evotherm®		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	131.7	93.3
2	134.6	91.9
3	134.9	101.9
Average	133.7	95.7
CV [%]	1.3	5.6
TSR [%]	**71.6**	
WMA 30% RAP Evotherm®		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	162.4	146.1
2	167.4	143.9
3	160.5	135.0
Average	163.4	141.7
CV [%]	2.2	4.1
TSR [%]	**86.7**	

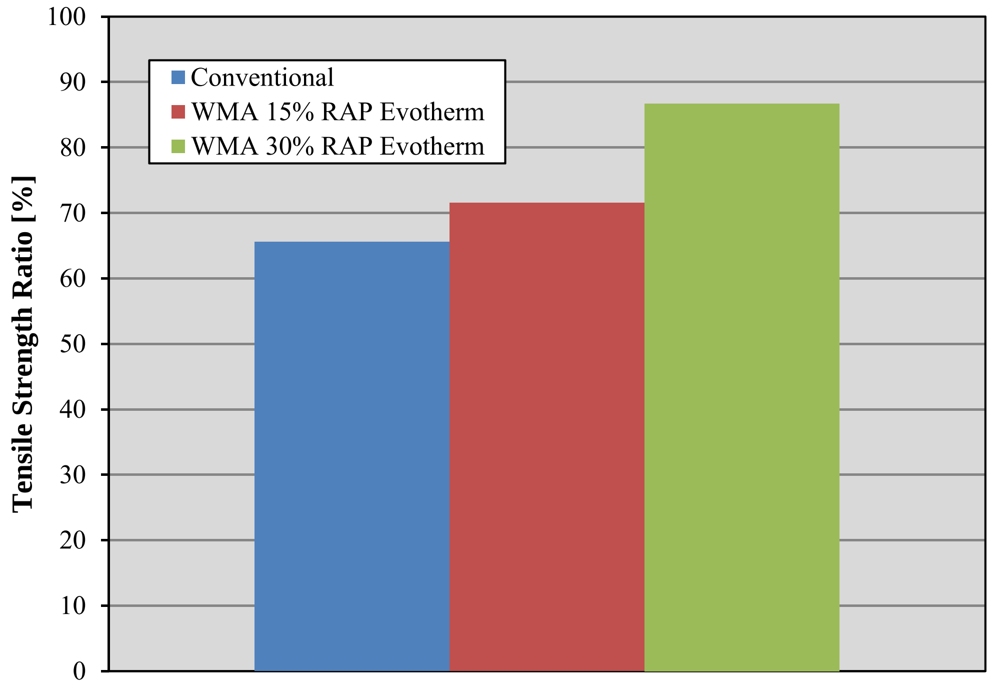


Figure 22
LA – 3121 TSR results

US – 171

The US - 171 project was comprised of four mixtures and two different WMA types. Two of the WMA mixtures used the foaming process and in one of the mixtures the Rediset ® additive was incorporated into the mixtures. The control HMA mixture contains 15% RAP. The two WMA foaming mixtures incorporated 15% and 30% RAP; whereas, the WMA Rediset had 15% of RAP added to its composition. The test results are shown as follows.

Flow Number. Table 13 presents the flow number results for the four mixtures along with their respective average values and coefficients of variation.

Table 13
US – 171 flow number test results

Conventional	
Replicate #	**Flow Number**
1	436
2	449
3	478
Average	454
CV [%]	4.7
WMA 15% RAP Foaming	
Replicate #	**Flow Number**
1	349
2	296
3	431
Average	359
CV [%]	19.0
WMA 30% RAP Foaming	
Replicate #	**Flow Number**
1	1080
2	452
3	840
Average	791
CV [%]	40.1
WMA 15% RAP Rediset	
Replicate #	**Flow Number**
1	648
2	390
3	419
Average	486
CV [%]	29.1

Large variations could be noted in the tests, especially with the WMA 30% foamed mixture. The higher percentage of reclaimed material might have caused the disturbance in the results. Despite the relatively high data scatter, none of the mixtures presented tertiary creep; hence, no signs of stripping could be attributed to the mixtures. Considering only the mixtures that had the same RAP content (15%), one can state that the WMA 15% RAP Rediset mixture did not show major differences from the conventional HMA; whereas, the 15% RAP foamed mixture had a lower flow number indicating its strongest susceptibility to rutting in the field. It is noted this project was constructed during a cold/wet season and the WMA 15% RAP was chosen for the remainder of the project once the test sections were complete.

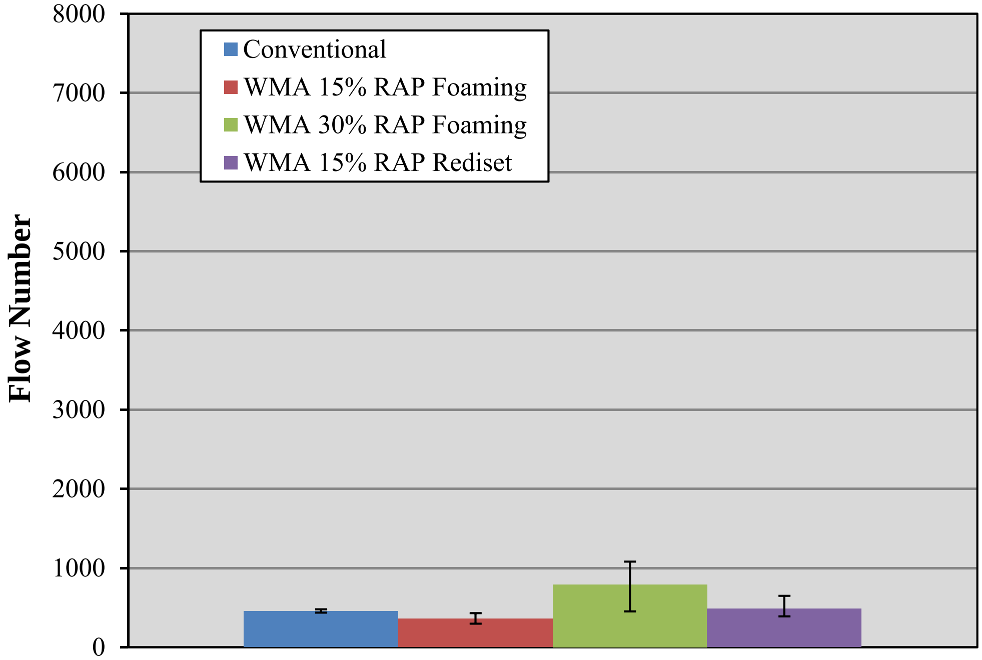


Figure 23
US – 171 Flow number test results

Loaded Wheel Tracking Test (LWT). See Figure 24 for results from the LWT test. The WMA 15% RAP foamed mixture showed more permanent deformation, while the WMA 15% Rediset had virtually the same rutting profile as the conventional HMA. The WMA 30% RAP was the only mixture to pass the 6.0 mm limit for Louisiana mixtures.

The trend observed by the F_N test results was similar to the LWT test results. The mixtures with a lower F_N had the higher rut depths and vice versa. This behavior suggests that for this set of mixtures both WMA process/additive and RAP content played a major role in their ability to resist permanent deformation. As can also be noticed, no stripping was observed during testing. Therefore, evaluation of the stripping inflection point, stripping slope and creep slope evaluation was not performed.

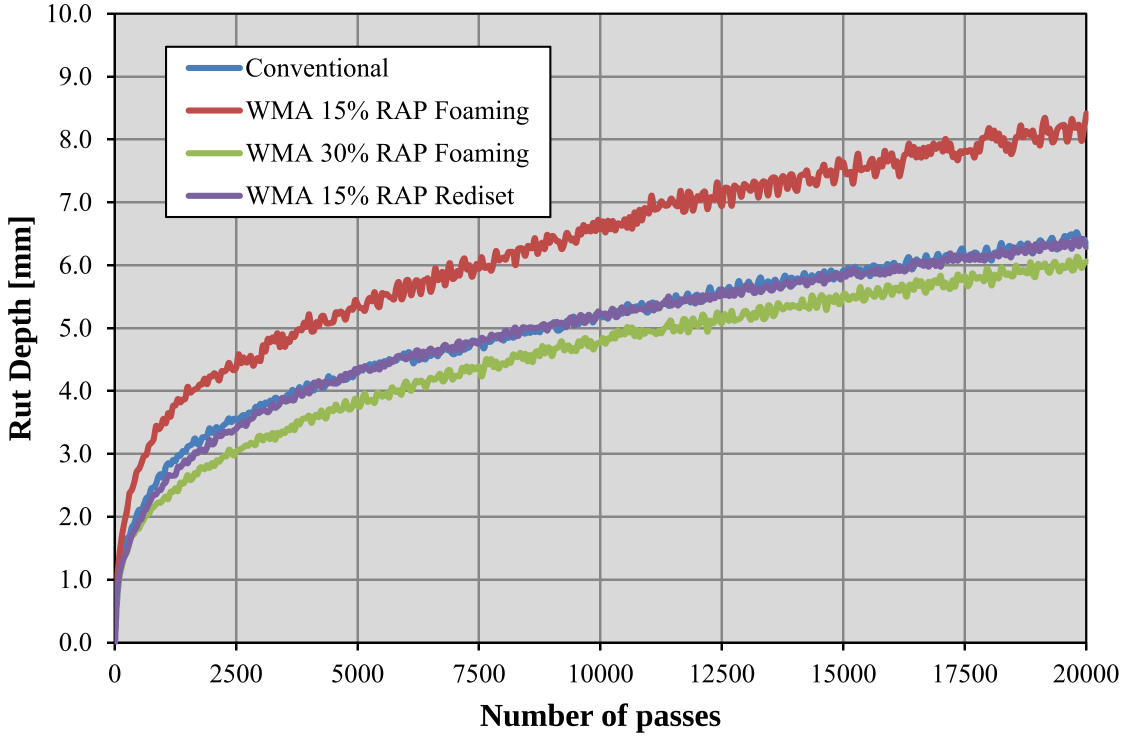
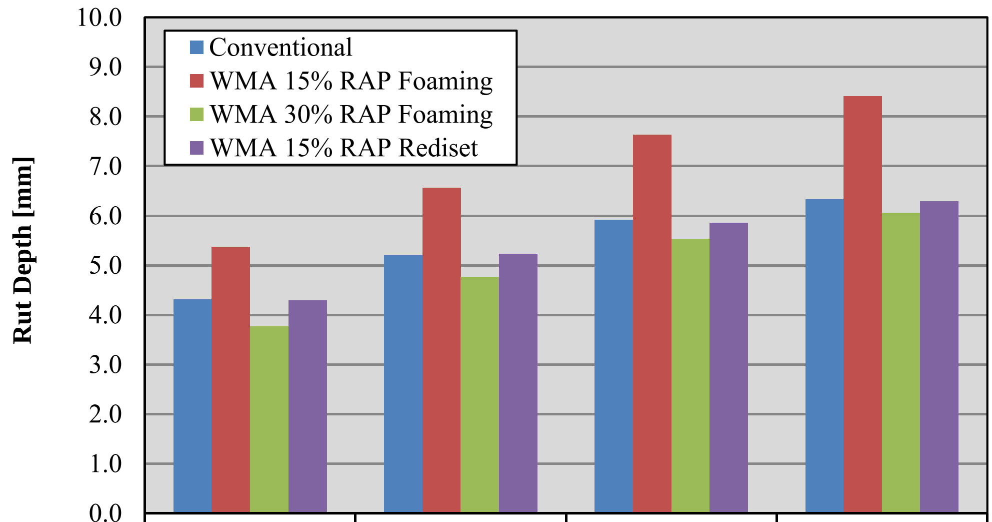


Figure 24
US – 171 LWT results

Figure 25 shows the rut depth at various passes. In this figure, it is possible to see that the WMA 15% RAP foamed mixture did not meet the 6.0-mm criteria; whereas, the remaining mixtures failed by a few tenths of millimeters, which in practical terms could be disregarded and considered to have met the criteria.



	5000	10000	15000	20000
Conventional	4.3	5.2	5.9	6.3
WMA 15% RAP Foaming	5.4	6.6	7.6	8.4
WMA 30% RAP Foaming	3.8	4.8	5.5	6.1
WMA 15% RAP Rediset	4.3	5.2	5.9	6.3

Number of Passes

Figure 25
US – 171 LWT results at various passes

Indirect Tensile Strength (ITS). The unaged and aged ITS results are shown in the following tables. One of the WMA 30% RAP foamed specimens could not be tested due to an operator mistake. The IT strength and toughness index are seen in Figure 26 and Figure 27 along with their respective error limits.

An increase in strength for aged mixtures can be observed, while the IT strain decreased with aging. These are indications that the aging process made the mixtures stiffer and more brittle. It is also observed that the increase in the strength with aging was lesser for the WMA mixtures than that of the corresponding conventional HMA mixture.

The three WMA mixtures showed similar or slightly higher ITS values than their corresponding control HMA mixture. Incorporation of higher percentages of RAP did not show steep increase in the strength of the mixture. The three WMA mixtures had similar IT strain values as their corresponding HMA mixture. There was no effect of foaming or additives on the performance of the mixtures. Similar trend was observed in the TI values. All of the WMA mixtures possessed similar or better TI values to that of their control HMA mixture.

Table 14
US – 171 unaged ITS test results

UNAGED				
Conventional				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.3	129.7	0.56	0.81
43	7.4	117.2	1.02	0.87
44	7.5	108.9	0.77	0.88
Average	**7.4**	**118.6**	**0.78**	**0.85**
CV (%)	1.1	8.8	29.2	4.9
WMA 15% RAP Foaming				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.1	149.6	0.55	0.80
43	6.8	143.3	0.59	0.80
44	6.8	139.6	0.79	0.83
Average	**6.9**	**144.1**	**0.65**	**0.81**
CV (%)	2.6	3.5	20.3	1.8
WMA 30% RAP Foaming				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.1	136.4	0.73	0.83
43	7.2	148.6	0.77	0.84
44				
Average	**7.2**	**142.5**	**0.75**	**0.83**
CV (%)	1.6	6.1	3.3	1.3
WMA 15% RAP Rediset				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.3	148.3	0.65	0.83
43	7.4	117.7	0.95	0.86
44	7.4	147.7	0.57	0.81
Average	**7.4**	**137.9**	**0.72**	**0.84**
CV (%)	1.0	12.7	28.3	2.7

Table 15
US – 171 aged ITS test results

AGED				
Conventional				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
45	7.4	168.4	0.71	0.81
46	7.1	140.6	0.61	0.75
47	7.3	154.6	0.50	0.78
Average	**7.3**	**154.5**	**0.60**	**0.78**
CV (%)	2.2	9.0	16.7	3.9
WMA 15% RAP Foaming				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
45	7.0	168.1	0.56	0.79
46	7.3	157.4	0.68	0.82
47	6.8	152.5	0.53	0.72
Average	**7.0**	**159.4**	**0.59**	**0.78**
CV (%)	3.2	5.0	14.0	6.4
WMA 30% RAP Foaming				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
45	7.2	171.0	0.55	0.80
46	7.5	151.6	0.47	0.75
47	7.2	158.2	0.39	0.69
Average	**7.3**	**160.2**	**0.47**	**0.74**
CV (%)	2.7	6.1	17.5	7.3
WMA 15% RAP Rediset				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
45	7.2	126.5	0.50	0.80
46	7.4	155.5	0.64	0.85
47	6.8	150.5	0.48	0.74
Average	**7.1**	**144.2**	**0.54**	**0.80**
CV (%)	4.2	10.7	16.0	6.6

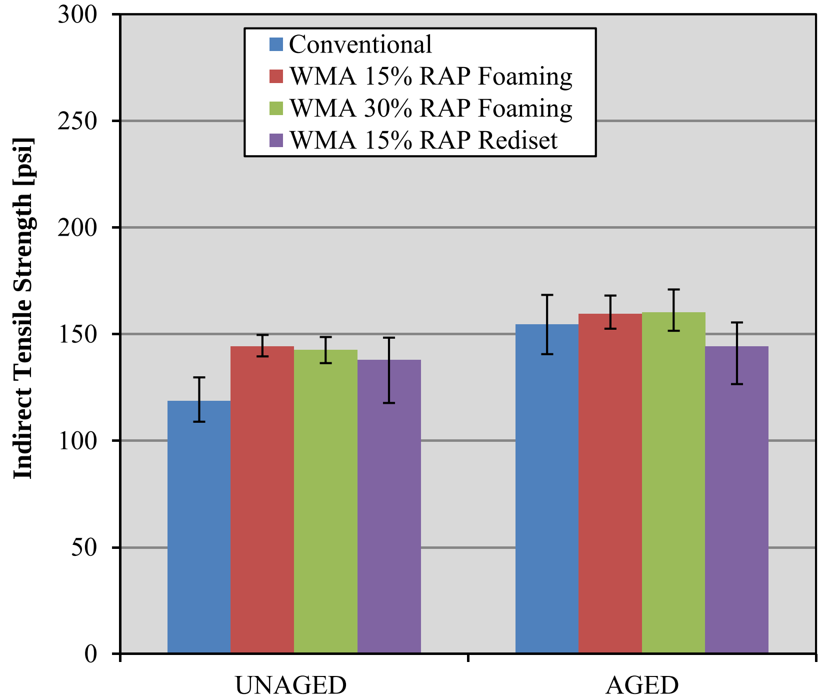


Figure 26
US – 171 indirect tensile results

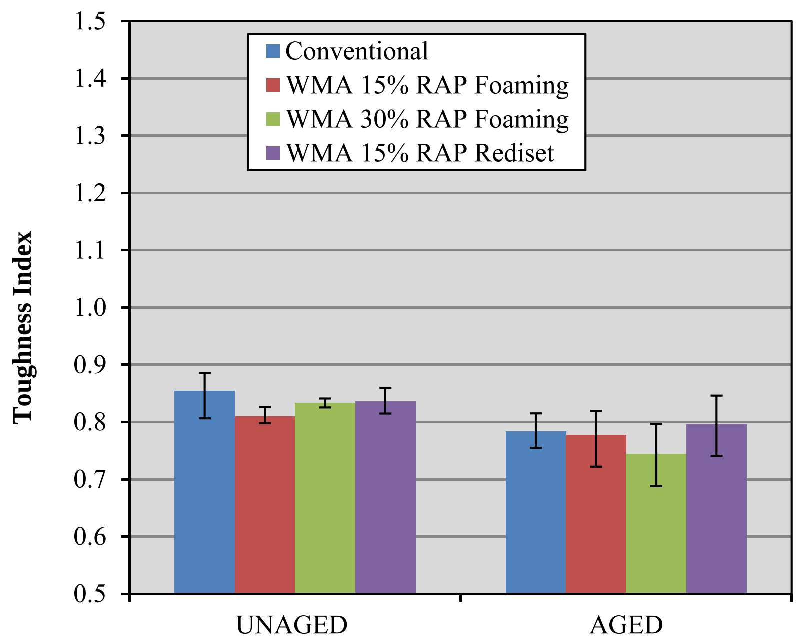


Figure 27
US – 171 toughness index results

Dissipated Creep Strain Energy Results. The two WMA mixtures that had 15% RAP in their composition exhibited lower DCSE values than their corresponding control HMA mixture. This indicates that both the foaming and the Rediset decreased their fracture resistance. The WMA 30% RAP foamed mixture exhibited a slight improvement in the fracture resistant performance of the asphalt mixture. It is also worth noting that all WMA and HMA mixtures had DCSE values higher than 0.75 KJ/m3. As seen in the figures, the WMA mixture with a higher percentage of RAP than the control HMA mixture showed better fracture resistance, as reflected in high DCSE values.

Table 16

US – 171 DCSE test results

Conventional						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1418211	2753	333	2519	0.26	2.89
2	1305113	3010	350	2741	0.22	3.31
3	1312274	2059	331	1807	0.20	2.06
Average	1345199	2607	338	2356	0.22	2.75
CV [%]	4.7	18.9	3.2	20.7	13.1	23.1
WMA 15% RAP Foaming						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1686641	1123	297	947	0.26	0.97
2	1572473	2073	322	1868	0.26	2.07
3	1590729	1856	351	1635	0.25	1.98
Average	1616614	1684	323	1483	0.25	1.67
CV [%]	3.8	29.6	8.4	32.3	2.9	36.6
WMA 30% RAP Foaming						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1758381	2623	384	2405	0.24	3.19
2	1761808	2275	376	2061	0.29	2.67
3	1764240	2384	387	2165	0.33	2.89
Average	1761476	2427	383	2210	0.29	2.92
CV [%]	0.2	7.3	1.5	8.0	14.5	8.9
WMA 15% RAP Rediset						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1407622	1066	341	825	0.28	0.97
2	1302420	2485	305	2251	0.27	2.37
3	1838726	1789	414	1564	0.35	2.23
Average	1516256	1780	353	1546	0.30	1.86
CV [%]	18.7	39.9	15.6	46.1	14.2	41.6

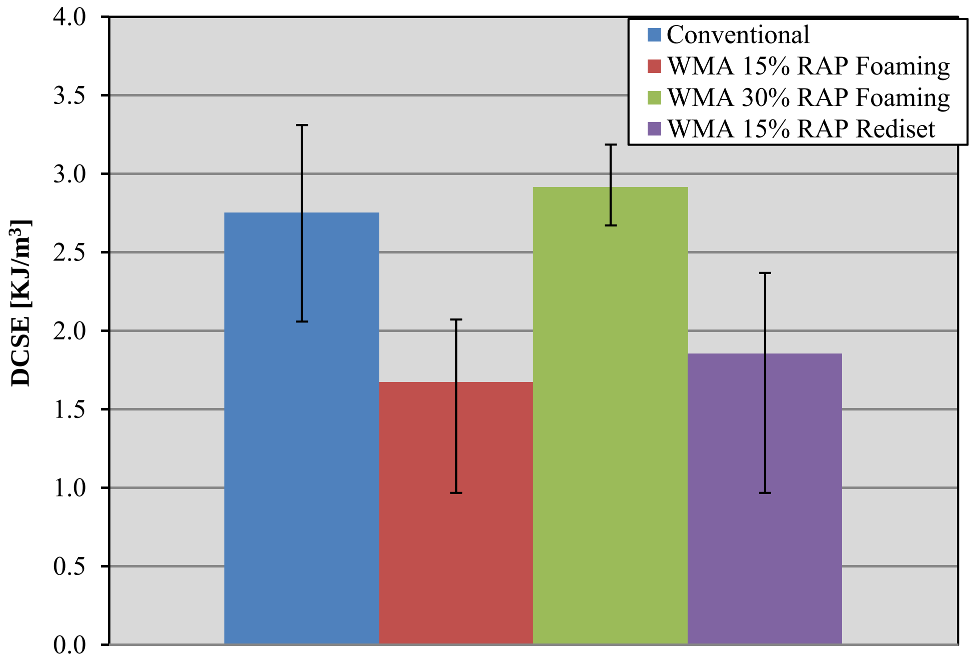


Figure 28
US – 171 DCSE results

Semi-Circular Bending Test Results. Table 17 shows the peak load, area, as well as the corresponding J_c for all four mixtures. Figure 29 presents the computed J_c values for all of the mixtures evaluated. Conventional and WMA 15% RAP Rediset mixtures met the J_c criteria of 0.5 KJ/m^2. Further, the J_c values for mixtures WMA 15% RAP foaming and WMA 30% RAP foaming were 0.3 and 0.4 KJ/m^2, respectively.

Table 17
US – 171 SCB test results

Conventional							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.531	0.572	0.252	0.333	0.474	0.205	0.5
2	0.694	0.590	0.359	0.601	0.521	0.261	
3	0.726	0.343	0.372	0.577	0.328	0.320	
Average	0.650	0.502	0.328	0.503	0.441	0.262	
CV [%]	16.0	27.5	20.0	29.5	22.8	21.9	
WMA 15% RAP Foaming							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.586	0.562	0.433	0.459	0.428	0.279	0.3
2	0.628	0.385	0.426	0.537	0.354	0.321	
3	0.686	0.503	0.332	0.504	0.341	0.175	
Average	0.633	0.483	0.397	0.500	0.374	0.258	
CV [%]	8.0	18.7	14.2	7.9	12.5	29.2	
WMA 30% RAP Foaming							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.833	0.519	0.475	0.722	0.299	0.379	0.4
2	0.635	0.727	0.449	0.546	0.605	0.360	
3	0.745	0.573	0.474	0.694	0.565	0.342	
Average	0.737	0.606	0.466	0.654	0.490	0.360	
CV [%]	13.4	17.8	3.1	14.5	34.1	5.1	
WMA 15% RAP Rediset							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.753	0.570		0.769	0.531		0.6
2	0.723		0.360	0.683		0.286	
3	0.604	0.624	0.277	0.436	0.471	0.173	
Average	0.693	0.597	0.319	0.629	0.501	0.230	
CV [%]	11.4	6.4	18.4	27.4	8.5	34.8	

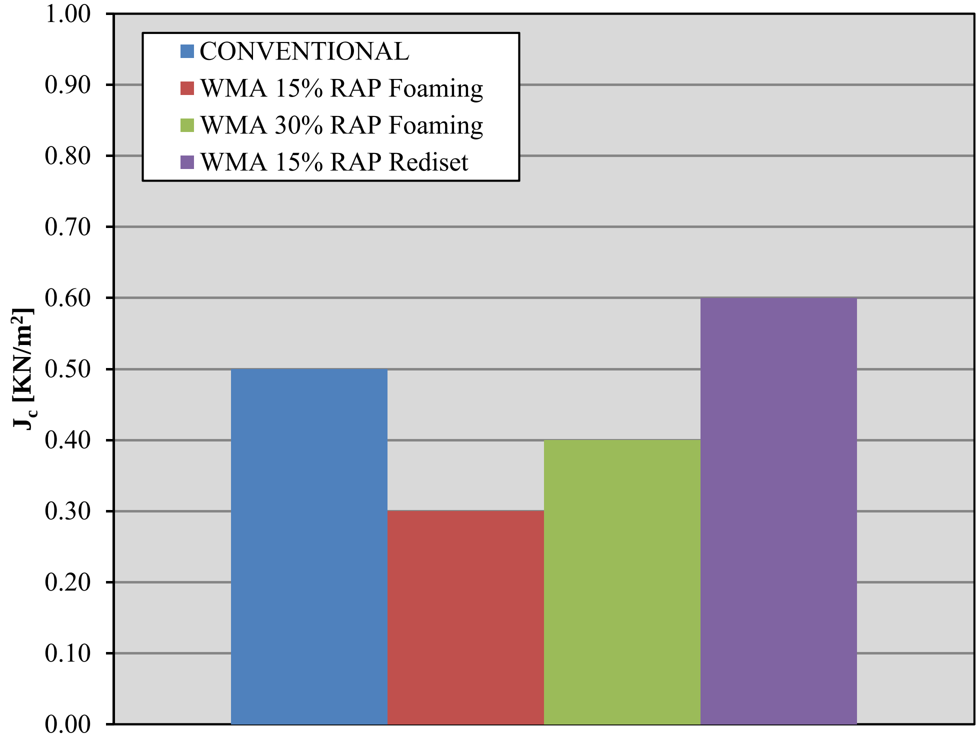


Figure 29
US – 171 Critical values of the J-Integral

Dynamic Modulus Test Results. The axial dynamic modulus (|E*|) test results conducted on three replicate samples for each mixture to evaluate the viscoelastic behavior of the asphalt mixtures is show in Table 18 through Table 21. The test was performed at five temperatures (i.e., -10, 4.4, 25, 37.8, and 54.4ºC) and six frequencies (i.e., 25, 10, 5, 1, 0.5, and 0.1 Hz). The average results for |E*| and phase angle (δ) are given. The average dynamic modulus results were then normalized to facilitate the comparison. The WMA values were divided by the corresponding conventional HMA at temperature and frequency. The results can be seen in Figure 30 through Figure 34.

Table 18

US – 171 conventional dynamic modulus results

Conventional			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	19099	0.97
	10	18649	2.60
	5	18086	3.43
	1	16784	4.96
	0.5	16146	5.54
	0.1	14389	6.97
4.4	25	16454	8.21
	10	15072	9.63
	5	14027	10.71
	1	11503	13.55
	0.5	10412	14.97
	0.1	7949	18.68
25	25	5165	18.94
	10	4060	22.41
	5	3359	24.78
	1	1972	28.91
	0.5	1544	29.50
	0.1	1006	29.57
37.8	25	2247	29.86
	10	1530	31.99
	5	1161	32.20
	1	633	29.24
	0.5	516	27.29
	0.1	401	20.44
54.4	25	611	28.86
	10	447	25.98
	5	368	22.75
	1	278	17.30
	0.5	258	14.81
	0.1	255	11.51

Table 19

US – 171 WMA 15% RAP foaming dynamic modulus results

WMA 15% RAP Foaming			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	19925	0.57
	10	19410	2.19
	5	18759	3.00
	1	17259	4.46
	0.5	16694	4.94
	0.1	14895	6.28
4.4	25	15781	7.28
	10	14436	9.05
	5	13383	10.26
	1	10900	13.22
	0.5	9885	14.59
	0.1	7466	18.22
25	25	6149	19.93
	10	4890	24.02
	5	3992	26.42
	1	2272	31.44
	0.5	1741	32.55
	0.1	975	31.38
37.8	25	2204	30.54
	10	1550	32.51
	5	1178	32.89
	1	638	30.48
	0.5	500	27.99
	0.1	333	21.36
54.4	25	643	29.86
	10	449	27.25
	5	369	24.22
	1	268	17.91
	0.5	240	15.43
	0.1	208	11.69

Table 20

US – 171 WMA 30% RAP foaming dynamic modulus results

WMA 30% RAP Foaming			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	20139	0.86
	10	19389	2.69
	5	18772	3.45
	1	17423	4.91
	0.5	16811	5.44
	0.1	15055	6.78
4.4	25	13626	4.99
	10	12530	7.53
	5	11604	8.85
	1	9391	11.81
	0.5	8427	13.13
	0.1	6362	16.66
25	25	6198	18.82
	10	4984	22.52
	5	4132	24.89
	1	2489	29.74
	0.5	1962	31.16
	0.1	1122	30.21
37.8	25	2633	28.50
	10	1812	31.05
	5	1405	31.54
	1	771	30.17
	0.5	603	28.26
	0.1	380	22.11
54.4	25	658	30.19
	10	466	27.96
	5	379	25.33
	1	267	19.59
	0.5	241	17.02
	0.1	197	13.06

Table 21
US – 171 WMA 15% RAP Rediset dynamic modulus results

WMA 15% RAP Rediset			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	17796	1.49
	10	17314	3.08
	5	16888	3.82
	1	15637	5.34
	0.5	15181	5.86
	0.1	13695	7.19
4.4	25	15765	8.13
	10	14423	9.54
	5	13369	10.60
	1	10900	13.37
	0.5	9876	14.76
	0.1	7602	18.56
25	25	5260	18.16
	10	4164	21.90
	5	3299	23.89
	1	1891	27.99
	0.5	1474	28.83
	0.1	844	27.78
37.8	25	2324	29.64
	10	1583	31.54
	5	1211	31.73
	1	680	29.41
	0.5	548	26.60
	0.1	377	20.00
54.4	25	618	28.27
	10	444	25.54
	5	374	22.45
	1	280	16.92
	0.5	260	14.56
	0.1	225	11.20

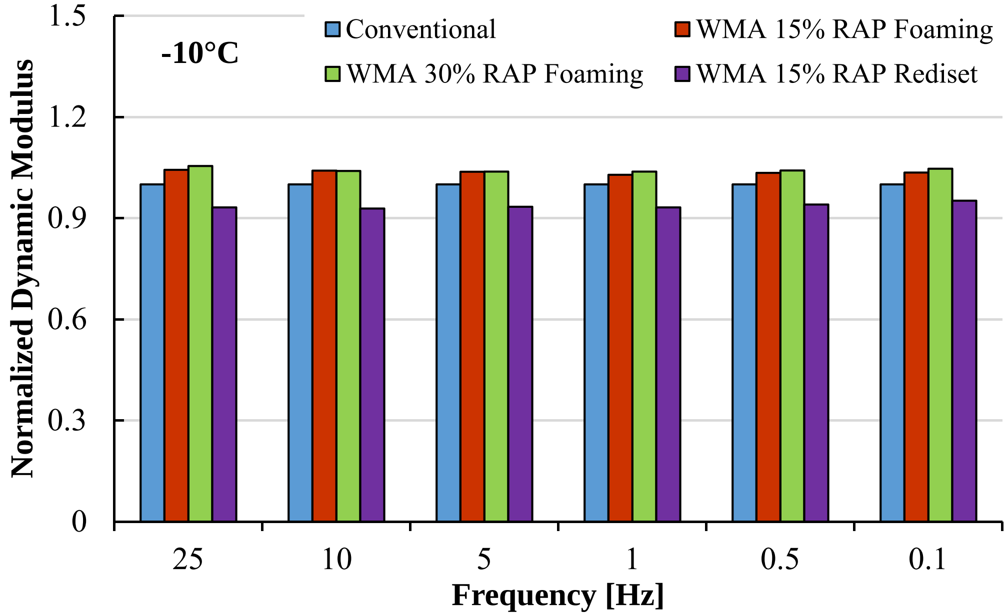


Figure 30

US – 171 normalized dynamic modulus at -10ºC

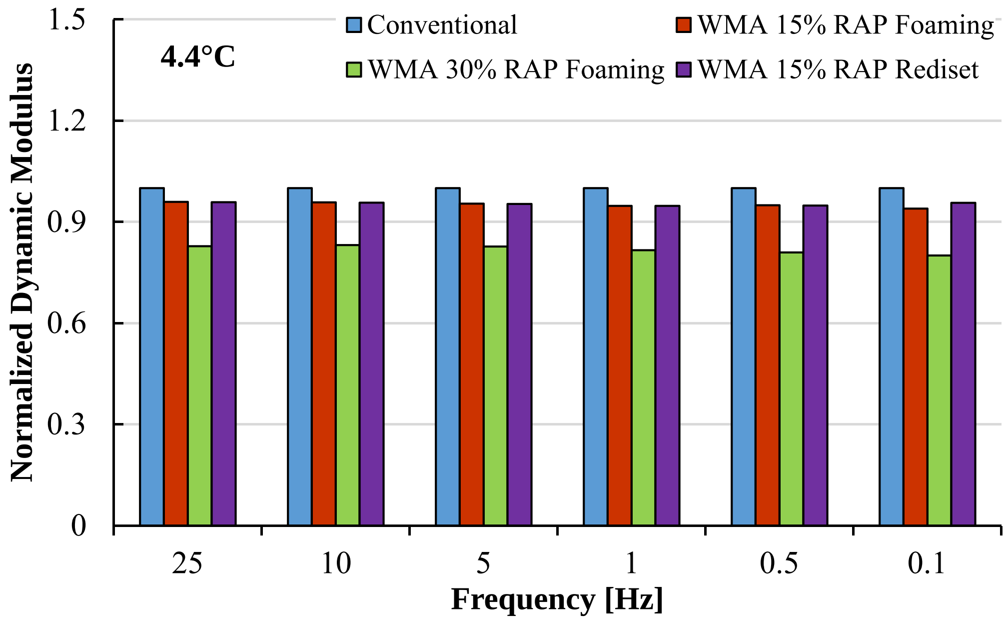


Figure 31

US – 171 normalized dynamic modulus at 4.4ºC

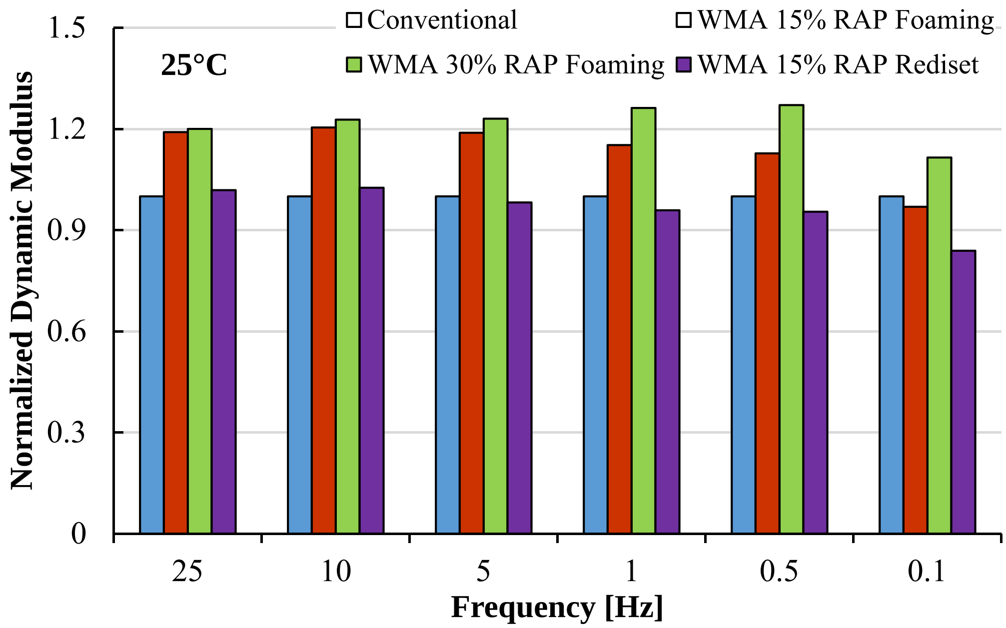


Figure 32
US – 171 normalized dynamic modulus at 25°C

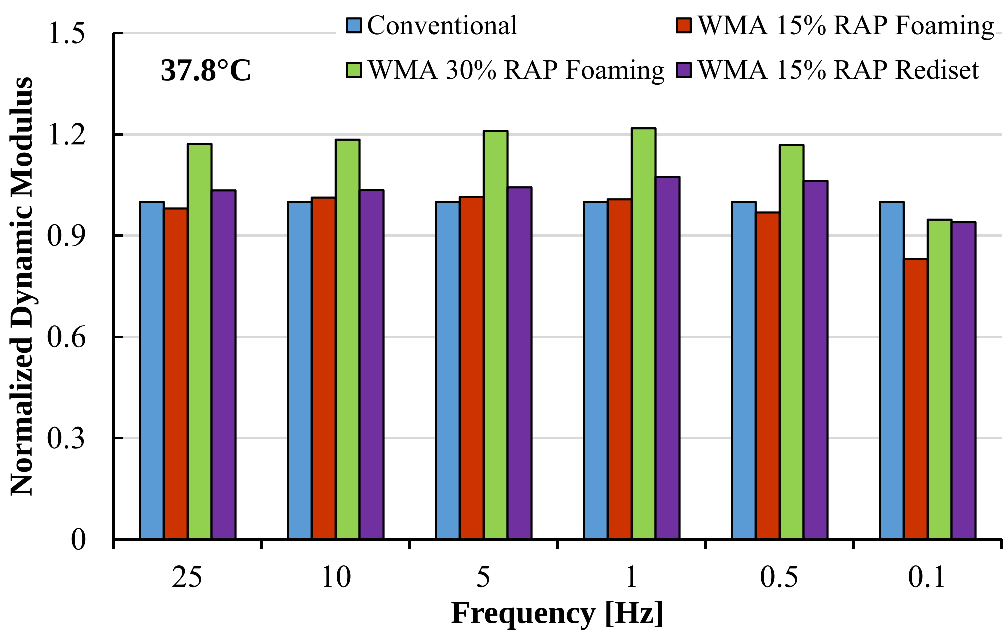


Figure 33
US – 171 normalized dynamic modulus at 37.8°C

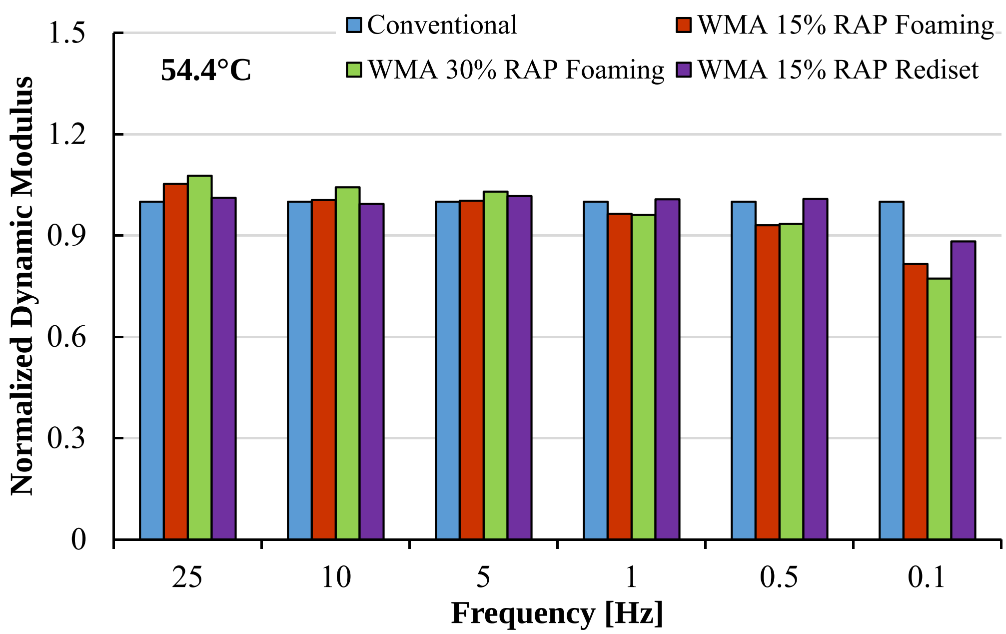


Figure 34
US – 171 normalized dynamic modulus at 54.4ºC

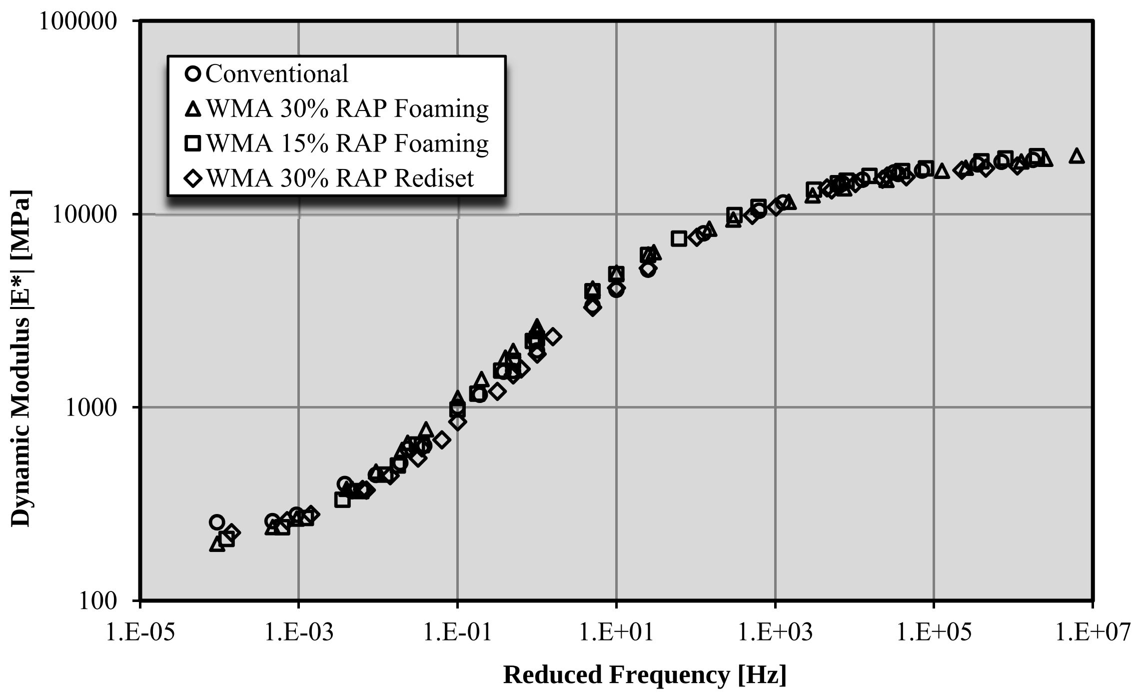


Figure 35
US - 171 mastercurves at 25ºC

Modified Lottman Test Results. The Modified Lottman test was performed to evaluate the moisture induced damage of the asphalt mixtures. Two sets of samples, conditioned and unconditioned (control) specimens, were tested for each of the mixtures to compute the tensile strength and the TSR. Table 22 summarizes the Modified Lottman test results. The mean tensile strength values for the controlled and the conditioned specimens and the TSR values of the asphalt mixtures are presented in the table. None of the mixtures passed the TSR ratio requirement. The conventional and WMA with 30% RAP performed the best.

Table 22
US – 171 WMA Modified Lottman results

Conventional		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	148.3	118.5
2	161.0	111.7
3	148.5	122.2
Average	152.6	117.5
CV [%]	4.7	4.6
TSR [%]	**77.0**	
WMA 15% RAP Foaming		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	136.9	96.0
2	130.9	87.3
3	156.5	90.4
Average	141.4	91.3
CV [%]	9.5	4.8
TSR [%]	**64.5**	
WMA 30% RAP Foaming		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	176.9	127.9
2	160.3	132.0
3	158.1	122.5
Average	165.1	127.5
CV [%]	6.2	3.7
TSR [%]	**77.2**	
WMA 15% RAP Rediset		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	121.9	83.4
2	119.0	84.3
3	123.3	85.6
Average	121.4	84.4
CV [%]	1.8	1.3
TSR [%]	**69.5**	

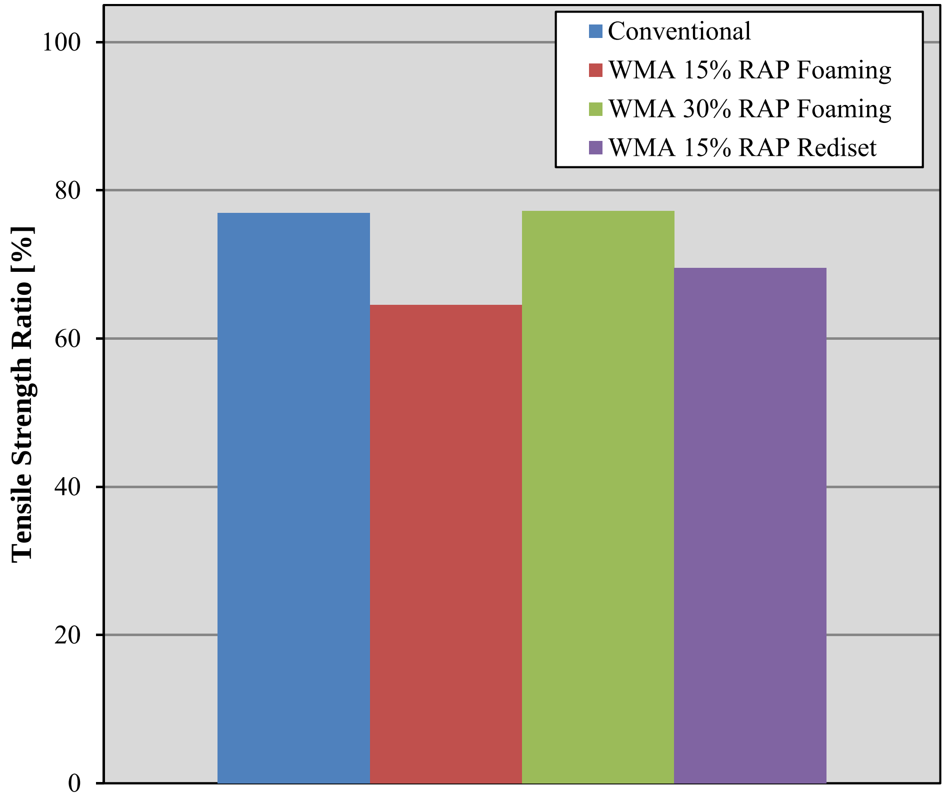


Figure 36
US – 171 TSR results

LA – 116

The LA – 116 project was comprised of two HMA mixtures with different RAP contents and two corresponding WMA types. The two WMA mixtures used the foaming process in addition to Latex modified binder meeting the DOTD PG70-22M requirements. The control HMA mixtures contain 15% and 20% RAP. The two WMA foaming mixtures incorporated the same amount respectively. The test results are shown as follows.

Flow Number. Table 23 presents the flow number results for the four mixtures along with their respective average values and coefficients of variation. The 20% RAP mixtures had lower flow number when compared to the 15% ones. None of the mixtures presented tertiary creep; hence, no signs of stripping could be attributed to the mixtures. The reclaimed material may have impacted the rutting performance of the mixtures.

Table 23
LA – 116 flow number test results

Conventional 15% RAP		
Replicate #	**Air Voids**	**Flow Number**
1	6.2	5284
2	6.3	5513
3		
Average	6.3	5398.5
CV [%]	1.1	3.0
WMA 15% RAP Foaming+Latex		
Replicate #	**Air Voids**	**Flow Number**
1		
2	7.8	3754
3	7.4	5102
Average	7.6	4428
CV [%]	3.7	21.5
Conventional 20% RAP		
Replicate #	**Air Voids**	**Flow Number**
1	6.0	1772
2	6.1	1668
3	6.1	2249
Average	6.1	1896
CV [%]	1.0	16.3
WMA 20% RAP Foaming+Latex		
Replicate #	**Air Voids**	**Flow Number**
1	6.0	2037
2	6.0	2150
3	5.9	1841
Average	6.0	2009
CV [%]	1.0	7.8

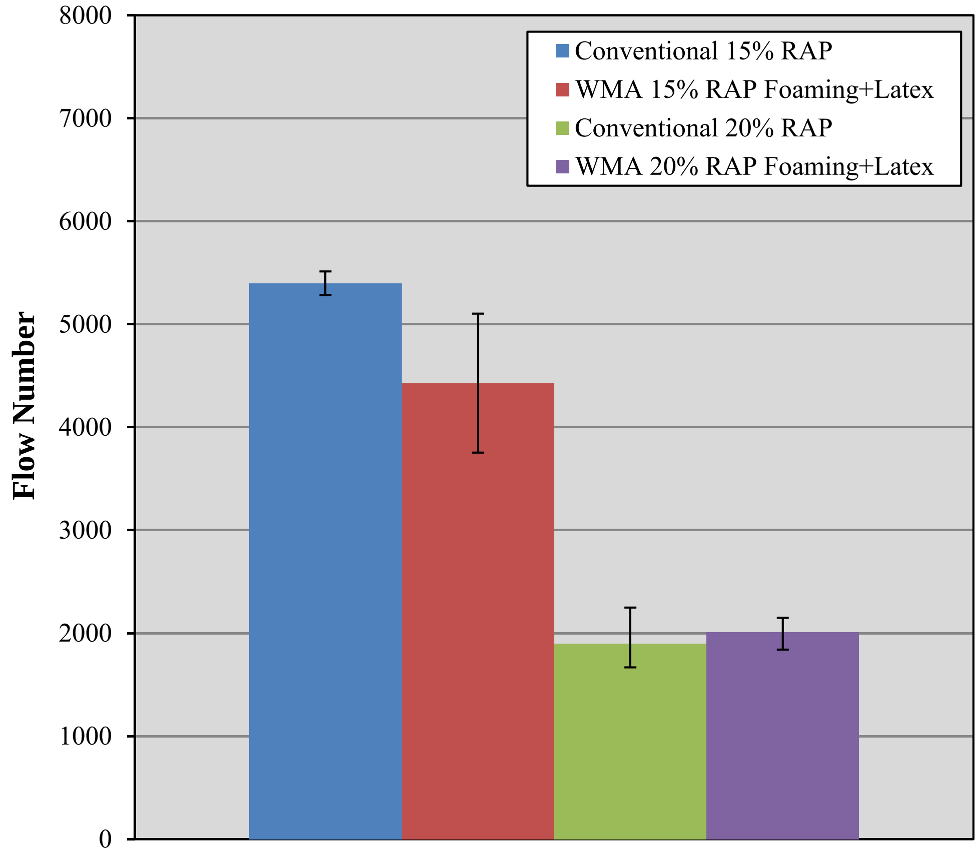


Figure 37
LA – 116 flow number test results

Loaded Wheel Tracking Test. The results from the LWT test are presented in the following figure. Overall, all the mixtures had a very good performance in regard to rutting. None of the mixtures exceeded the 6.0-mm rut depth at 20,000 passes limit established by the DOTD requirements.

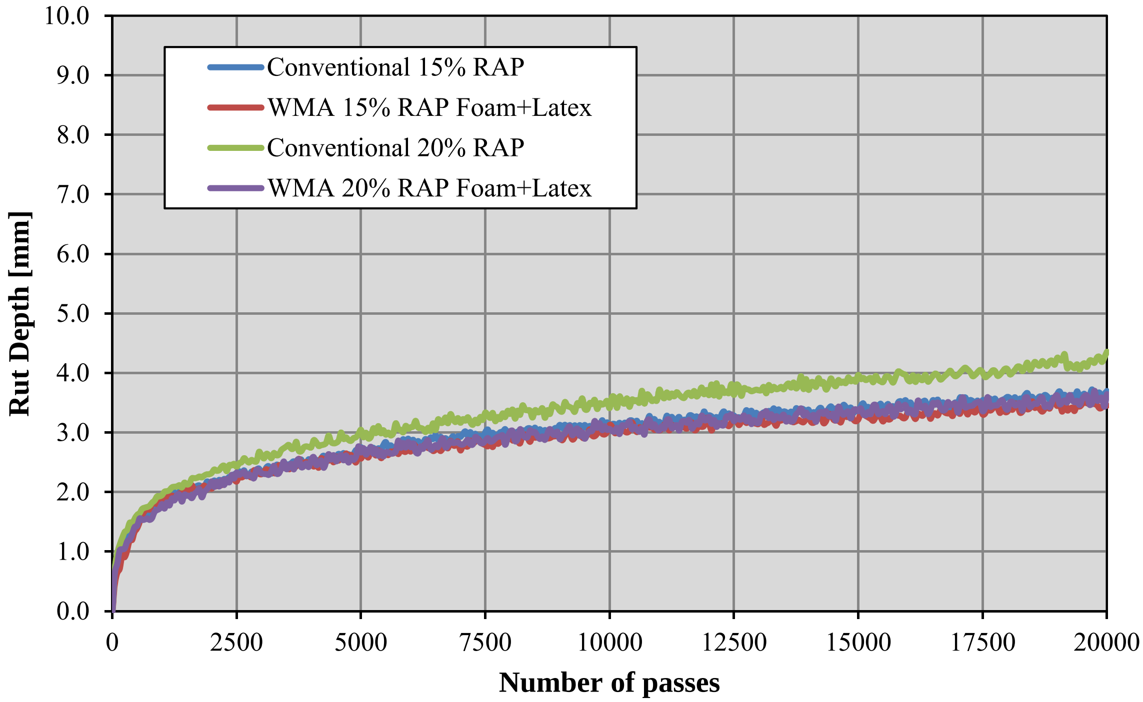
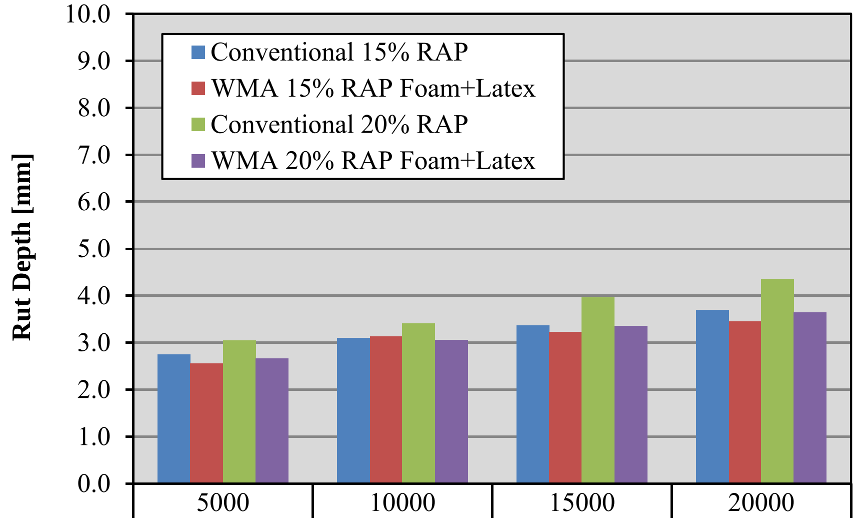


Figure 38
LA – 116 LWT results

As can be observed, no stripping occurred during testing. Therefore, evaluation of the stripping inflection point, stripping slope and creep slope evaluation was not performed.

Figure 39 shows the rut depth at various passes. In this figure, it is possible to see that all mixtures had rutting profiles that can hardly be distinguished from one another. The RAP, as well as the foaming process and the Latex additive did not seem to have affected the rutting performance of the mixtures.



	5000	10000	15000	20000
Conventional 15% RAP	2.8	3.1	3.4	3.7
WMA 15% RAP Foam+Latex	2.6	3.1	3.2	3.5
Conventional 20% RAP	3.0	3.4	4.0	4.4
WMA 20% RAP Foam+Latex	2.7	3.1	3.4	3.6

Number of Passes

Figure 39
LA – 116 LWT results at various passes

Indirect Tensile Strength. The IT strength and toughness index are seen in Figure 40 and Figure 41 along with their respective error limits.

In general, a slight increase in strength for aged mixtures can be observed, while the IT strain decreased slightly with aging. These could be indications that the aging process made the mixtures stiffer and more brittle. However, the difference is not substantial. It is also observed that the increase in the strength with aging was proportional for both the WMA mixtures and the corresponding conventional HMA mixtures.

The two WMA mixtures showed similar or slightly higher ITS values than their corresponding control HMA mixtures. Incorporation of higher percentages of RAP did not show substantial increase in the strength of the mixture. The two WMA mixtures had similar IT strain values as their corresponding HMA mixtures. There was no apparent effect of foaming and the Latex on the performance of the mixtures. A similar trend was observed in the TI values. Both WMA mixtures possessed similar or better average TI values to that of their control HMA mixtures. Nonetheless the variation was very large, which makes the results to be virtually equivalent from a statistical point of view.

Table 24

LA – 116 unaged ITS test results

UNAGED				
Conventional 15% RAP				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
37	6.90	155.18	1.73	0.64
38	6.60	179.55	1.74	0.69
39	6.60	185.29	1.84	0.71
Average	**6.7**	**173.3**	**1.77**	**0.68**
CV (%)	2.6	9.2	3.4	5.2
WMA 15% RAP Foaming+Latex				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
37	6.70	184.18	1.87	0.74
38	6.60	144.10	1.56	0.84
39	6.80	190.36	1.80	0.70
Average	**6.7**	**172.9**	**1.74**	**0.76**
CV (%)	1.5	14.5	9.3	9.5
Conventional 20% RAP				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
43	7.30	173.74	1.89	0.73
44	7.40	176.46	1.87	0.73
45	7.40	176.67	1.84	0.74
Average	**7.4**	**175.6**	**1.87**	**0.73**
CV (%)	0.8	0.9	1.2	0.3
WMA 20 RAP Foaming+Latex				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
37	7.30	164.26	1.95	0.80
38	7.30	187.70	1.77	0.67
39	7.50	166.50	1.73	0.66
Average	**7.4**	**172.8**	**1.82**	**0.71**
CV (%)	1.6	7.5	6.7	11.3

Table 25
LA – 116 aged ITS test results

AGED				
Conventional 15% RAP				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.30	200.66	1.63	0.59
43	7.00	213.68	1.69	0.64
44	6.60	206.17	1.73	0.63
Average	**7.0**	**206.8**	**1.68**	**0.62**
CV (%)	5.0	3.2	3.1	3.5
WMA 15% RAP Foaming+Latex				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	6.70	210.48	1.84	0.69
43	7.20	179.18	1.82	0.69
44	6.80		1.74	0.67
Average	**6.9**	**194.8**	**1.80**	**0.68**
CV (%)	3.8	11.4	2.8	2.0
Conventional 20% RAP				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
47	7.30	184.16	1.53	0.57
48	7.50	189.49	1.82	0.67
49	7.00	201.86	1.90	0.70
Average	**7.3**	**191.8**	**1.75**	**0.65**
CV (%)	3.5	4.7	11.2	10.9
WMA 20 RAP Foaming+Latex				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
42	7.40	181.85	1.79	0.67
43	7.40	212.92	1.42	0.77
44	7.30	186.36	1.87	0.67
Average	**7.4**	**193.7**	**1.69**	**0.70**
CV (%)	0.8	8.7	14.0	8.1

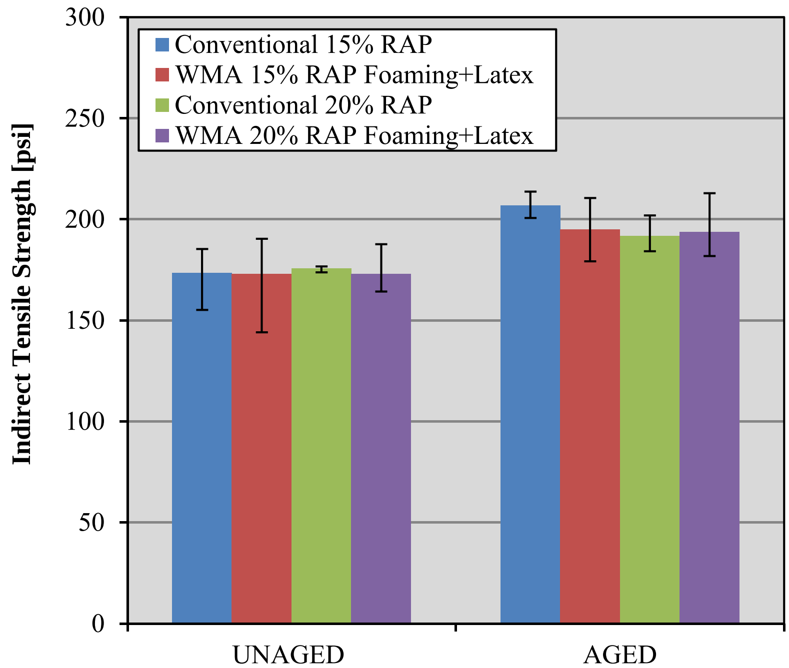


Figure 40
LA – 116 indirect tensile results

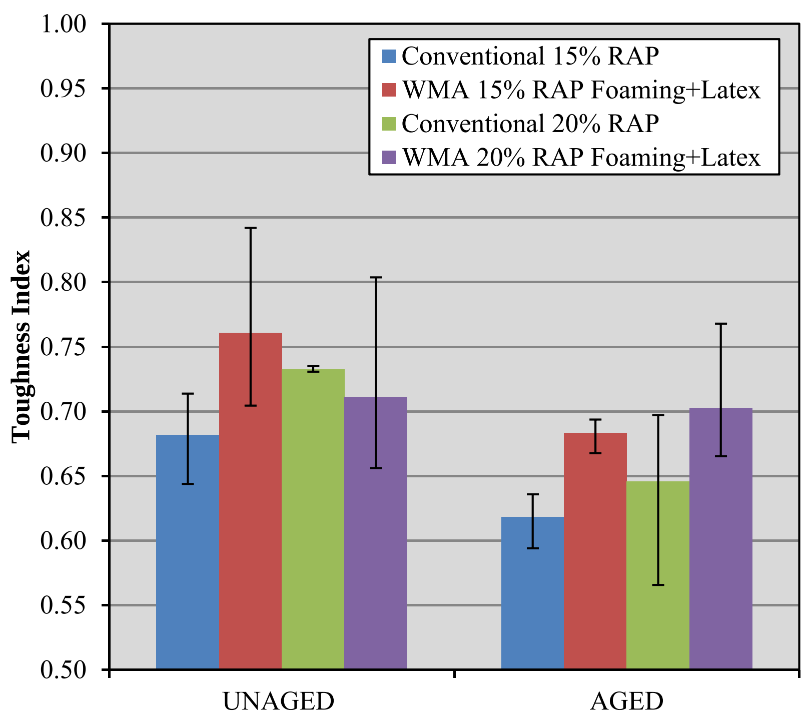


Figure 41
LA – 116 toughness index results

Dissipated Creep Strain Energy (DCSE) Test. Figure 42 shows the results of the DCSE test. The WMA 15% RAP mixtures exhibited a lower DCSE value than its corresponding control HMA mixture; however, the HMA and WMA mixtures with 20% RAP exhibited similar DSCE values. It is noted that all of the mixtures met the minimum of 0.75 KJ/m^3 to ensure acceptable cracking performance of the mixture *[38]*.

Table 26
LA – 116 DCSE test results

Replicate #	Resilient Modulus [psi]	Failure Strain [µstrain]	ITS [psi]	Initial Strain [µstrain]	Poisson's Ratio - µ	Dissipated Energy [KJ/m^3]
Conventional 15% RAP						
1	2244350	1598	414	1413	0.26	2.02
2	2099001	1292	409	1097	0.24	1.55
3	2062399	1551	418	1349	0.26	1.95
Average	2135250	1481	414	1286	0.25	1.84
CV [%]	4.5	11.1	1.1	13.0	5.1	13.8
WMA 15% RAP Foaming+Latex						
Replicate #	Resilient Modulus [psi]	Failure Strain [µstrain]	ITS [psi]	Initial Strain [µstrain]	Poisson's Ratio - µ	Dissipated Energy [KJ/m^3]
1	2201733	1373	452	1168	0.23	1.82
2	1773111	1448	377	1235	0.23	1.61
3	1710066	1643	322	1454	0.19	1.62
Average	1894970	1488	384	1286	0.21	1.68
CV [%]	14.1	9.4	16.9	11.7	11.2	7.1
Conventional 20% RAP						
Replicate #	Resilient Modulus [psi]	Failure Strain [µstrain]	ITS [psi]	Initial Strain [µstrain]	Poisson's Ratio - µ	Dissipated Energy [KJ/m^3]
1	2326505	1233	432	1048	0.30	1.56
2	2283178	984	376	819	0.27	1.06
3						
Average	2304841	1109	404	933	0.28	1.31
CV [%]	1.3	15.9	9.7	17.3	6.8	26.8
WMA 20% RAP Foaming+Latex						
Replicate #	Resilient Modulus [psi]	Failure Strain [µstrain]	ITS [psi]	Initial Strain [µstrain]	Poisson's Ratio - µ	Dissipated Energy [KJ/m^3]
1	1982418	1313	350	1136	0.33	1.37
2	1867569	885	407	667	0.18	0.94
3	1731017	1437	352	1234	0.19	1.50
Average	1860335	1212	370	1012	0.23	1.27
CV [%]	6.8	23.9	8.6	29.9	36.2	23.3

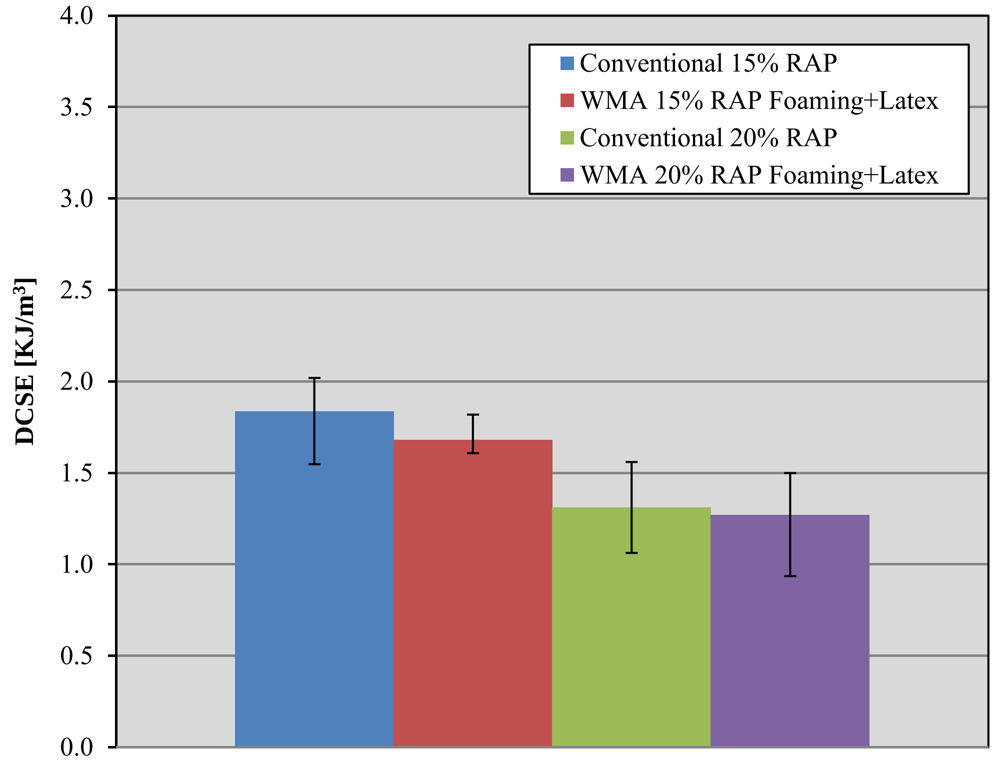


Figure 42
LA – 116 DCSE results

Semi-Circular Bending Test Results. Table 27 shows the peak load area, as well as, the corresponding J_c for all four mixtures. Figure 43 presents the computed J_c values for all of the mixtures evaluated. All mixtures evaluated met the J_c value 0.5 KJ/m^2 except for is 0.Mixture WMA 15% RAP Foaming+Latex, where the J_c value was 0.4 KJ/m^2.

Table 27
LA – 116 SCB test results

CONVENTIONAL 15% RAP							
Replicate #	**Peak Load [KN]**			**Area [KN *mm]**			**J_c [KN /m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.981	0.705	0.649	0.571	0.353	0.301	0.5
2	0.971	0.835	0.565	0.702	0.414	0.248	
3	1.068	0.942	0.859	0.658	0.632	0.360	
Average	1.007	0.828	0.691	0.644	0.466	0.303	
CV [%]	5.3	14.3	21.9	10.3	31.4	18.5	
WMA 15% RAP Foaming+Latex							
Replicate #	**Peak Load [KN]**			**Area [KN *mm]**			**J_c [KN /m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.042	0.856	0.562	0.479	0.482	0.223	0.4
2	1.240	0.811	0.606	0.578	0.444	0.328	
3	1.286	0.890	0.661	0.681	0.532	0.292	
Average	1.189	0.852	0.609	0.579	0.486	0.281	
CV [%]	10.9	4.7	8.2	17.5	9.0	19.0	
CONVENTIONAL 20% RAP							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.401	0.789	0.714	0.827	0.374	0.324	0.6
2	1.367	0.970	0.569	0.616	0.497	0.252	
3	1.226	0.963	0.623	0.662	0.521	0.322	
Average	1.331	0.907	0.635	0.702	0.464	0.299	
CV [%]	7.0	11.3	11.5	15.8	17.1	13.8	
WMA 20% RAP Foaming+Latex							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.618	0.690	0.556	0.232	0.466	0.257	0.5
2	0.773	0.436	0.584	0.400	0.150	0.268	
3	0.785	0.760	0.374	0.429	0.389	0.194	
Average	0.725	0.629	0.505	0.353	0.335	0.240	
CV [%]	12.9	27.1	22.6	30.1	49.1	16.6	

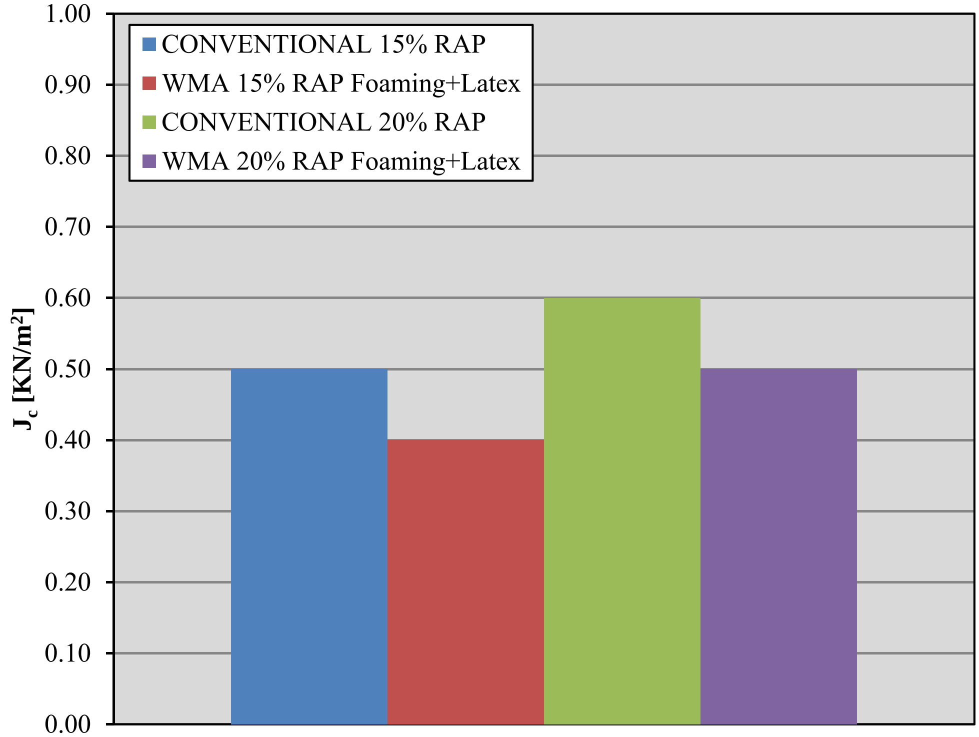


Figure 43
LA – 116 Critical values of the J-Integral

Dynamic Modulus Test Results. The axial dynamic modulus (|E*|) test results conducted on three replicate samples for each mixture to evaluate the viscoelastic behavior of the asphalt mixtures are show in Table 28 through Table 31. The test was performed at five temperatures (i.e., -10, 4.4, 25, 37.8, and 54.4ºC) and six frequencies (i.e., 25, 10, 5, 1, 0.5, and 0.1 Hz). The average results for |E*| and phase angle (δ) are given. The average dynamic modulus results were then normalized to facilitate the comparison. The WMA values were divided by the corresponding conventional HMA at temperature and frequency. The results can be seen in Figure 44 through Figure 48. It is seen that the WMA 15% RAP Foaming + Latex had higher dynamic moduli values at high temperatures (37.8 **ºC** and 54.4 **º**C) when compared to the rest of the mixtures. On the other hand, the 20% RAP Foaming + Latex had achieved the highest dynamic moduli values at -10 **ºC** when compared to the other mixtures at the same temperature. However, the comparison against all the mastercurves did not show a clear distinction among all mixtures.

Table 28
LA – 116 conventional 15% RAP dynamic modulus results

Conventional 15% RAP			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	27546	0.47
	10	26918	2.32
	5	26370	2.91
	1	24822	4.27
	0.5	24024	4.83
	0.1	21834	6.17
4.4	25	21585	7.48
	10	19863	8.74
	5	18507	9.72
	1	15386	12.21
	0.5	13995	13.40
	0.1	10930	16.66
25	25	9123	20.71
	10	7449	23.25
	5	6246	24.85
	1	3979	28.81
	0.5	3228	29.84
	0.1	1831	32.33
37.8	25	3981	30.18
	10	2921	32.17
	5	2244	32.94
	1	1129	34.53
	0.5	835	34.36
	0.1	419	33.90
54.4	25	1012	36.61
	10	612	37.85
	5	439	36.73
	1	207	33.91
	0.5	161	31.67
	0.1	96	26.94

Table 29
LA – 116 WMA 15% RAP Foaming + Latex dynamic modulus results

WMA 15% RAP Foaming + Latex			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	27580	0.31
	10	26949	2.09
	5	26404	2.71
	1	24887	3.99
	0.5	24115	4.49
	0.1	22020	5.92
4.4	25	21739	7.34
	10	20160	8.50
	5	18901	9.36
	1	15880	11.65
	0.5	14499	12.71
	0.1	11570	15.67
25	25	9304	19.54
	10	7753	21.67
	5	6608	23.11
	1	4390	26.72
	0.5	3607	27.72
	0.1	2140	30.40
37.8	25	4339	27.85
	10	3302	29.67
	5	2637	30.55
	1	1399	32.60
	0.5	1049	32.75
	0.1	520	33.25
54.4	25	1257	34.69
	10	772	36.62
	5	561	35.98
	1	270	34.10
	0.5	206	32.58
	0.1	121	28.94

Table 30
LA – 116 conventional 20% RAP dynamic modulus results

Conventional 20% RAP			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	27761	0.33
	10	27237	1.76
	5	26786	2.18
	1	25530	3.30
	0.5	24889	3.68
	0.1	23142	4.78
4.4	25	22120	7.09
	10	20654	8.18
	5	19489	8.98
	1	16619	11.11
	0.5	15355	12.14
	0.1	12433	15.00
25	25	9798	18.59
	10	8236	20.73
	5	7152	22.16
	1	4856	25.92
	0.5	4004	27.03
	0.1	2368	30.03
37.8	25	4642	27.93
	10	3450	29.96
	5	2710	31.01
	1	1438	33.12
	0.5	1081	33.15
	0.1	532	33.30
54.4	25	1347	35.96
	10	834	37.69
	5	601	36.95
	1	269	35.58
	0.5	194	34.32
	0.1	100	31.07

Table 31

LA – 116 WMA 20% RAP foaming + latex dynamic modulus results

WMA 20% RAP Foaming + Latex			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	32450	0.47
	10	31264	1.95
	5	30286	2.38
	1	27747	3.45
	0.5	26538	3.92
	0.1	23481	5.14
4.4	25	23615	7.31
	10	21694	8.60
	5	20146	9.67
	1	16474	12.14
	0.5	14854	13.29
	0.1	11313	16.46
25	25	9087	20.08
	10	7505	22.24
	5	6421	23.71
	1	4197	27.41
	0.5	3422	28.43
	0.1	1983	31.00
37.8	25	4277	29.22
	10	3205	31.17
	5	2514	32.06
	1	1324	33.89
	0.5	1000	33.69
	0.1	498	33.44
54.4	25	1111	35.54
	10	691	37.24
	5	502	36.32
	1	236	34.04
	0.5	177	32.35
	0.1	97	28.69

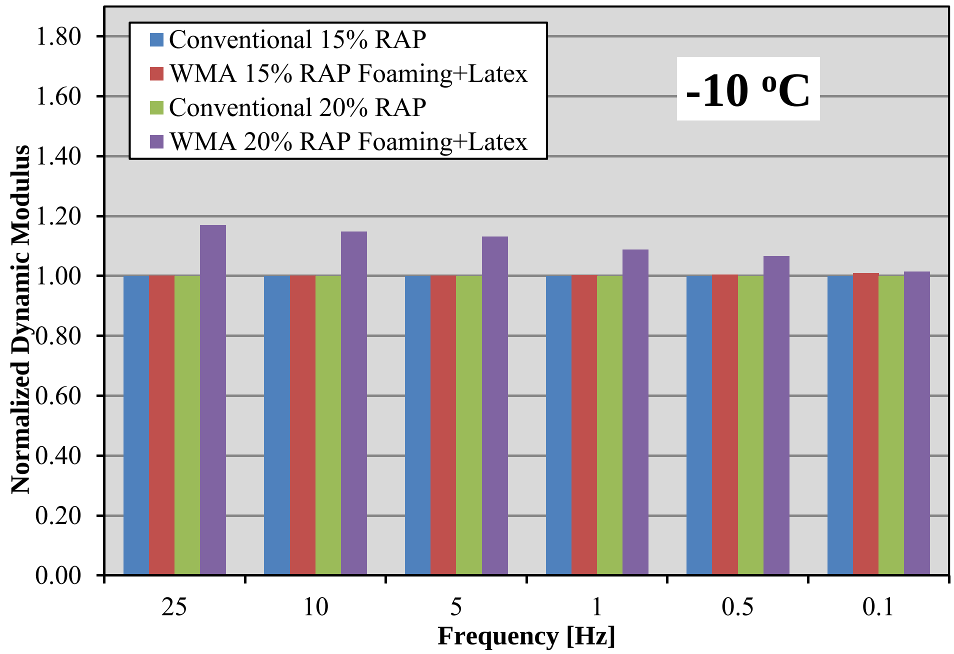


Figure 44

LA – 116 normalized dynamic modulus at -10ºC

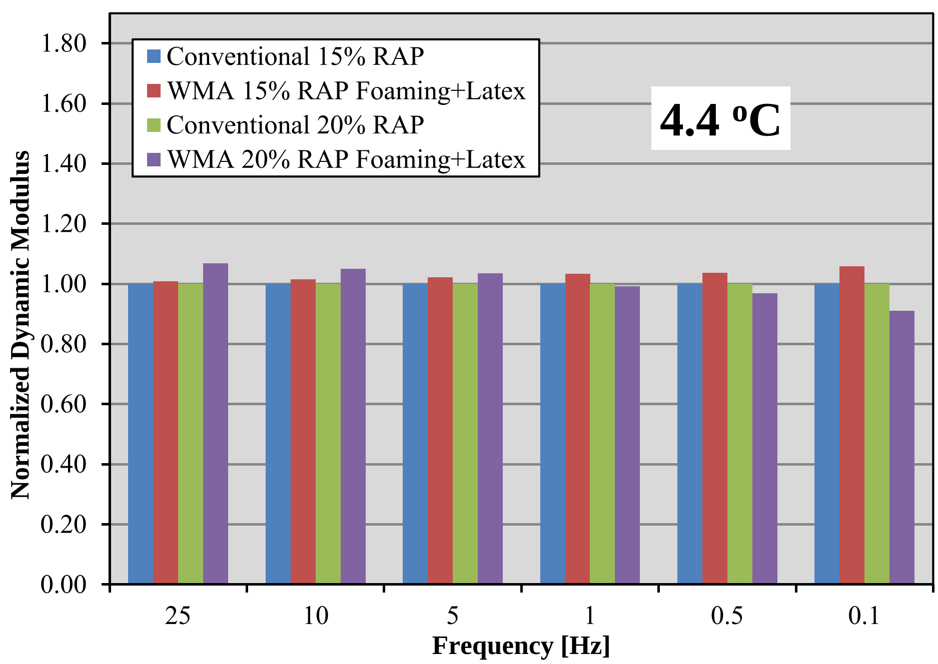


Figure 45

LA – 116 normalized dynamic modulus at 4.4ºC

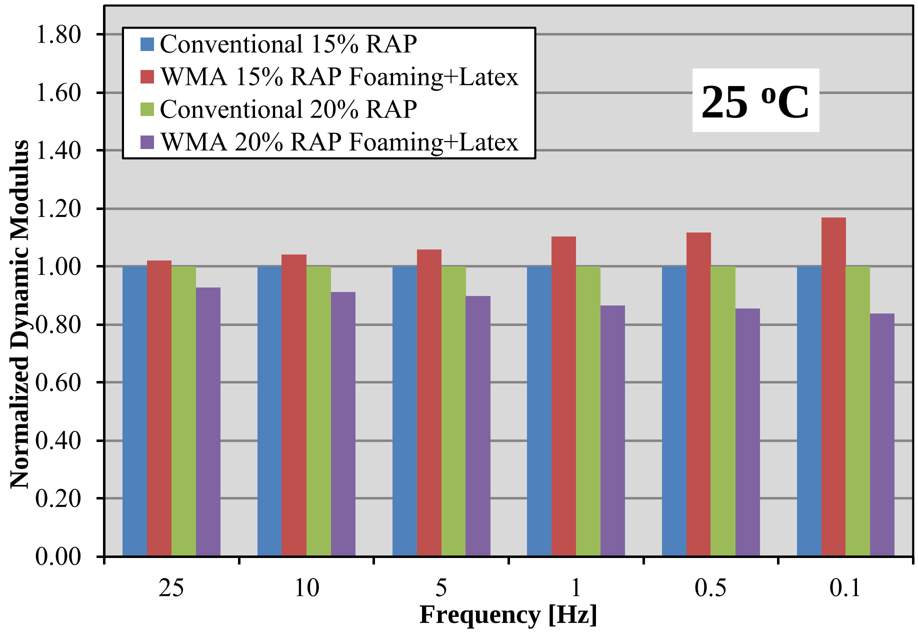


Figure 46
LA – 116 normalized dynamic modulus at 25°C

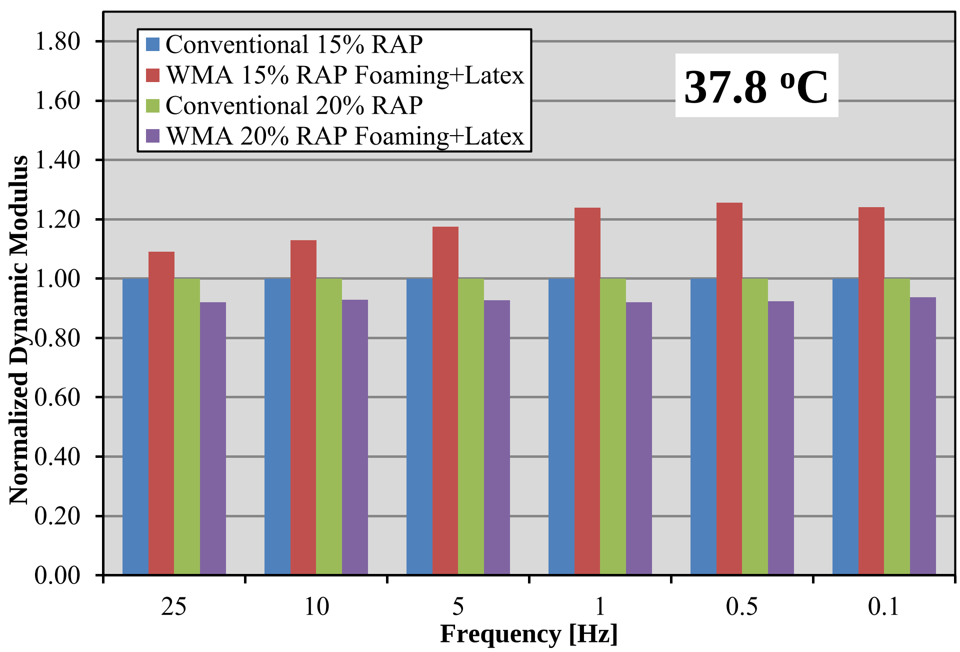


Figure 47
LA – 116 normalized dynamic modulus at 37.8°C

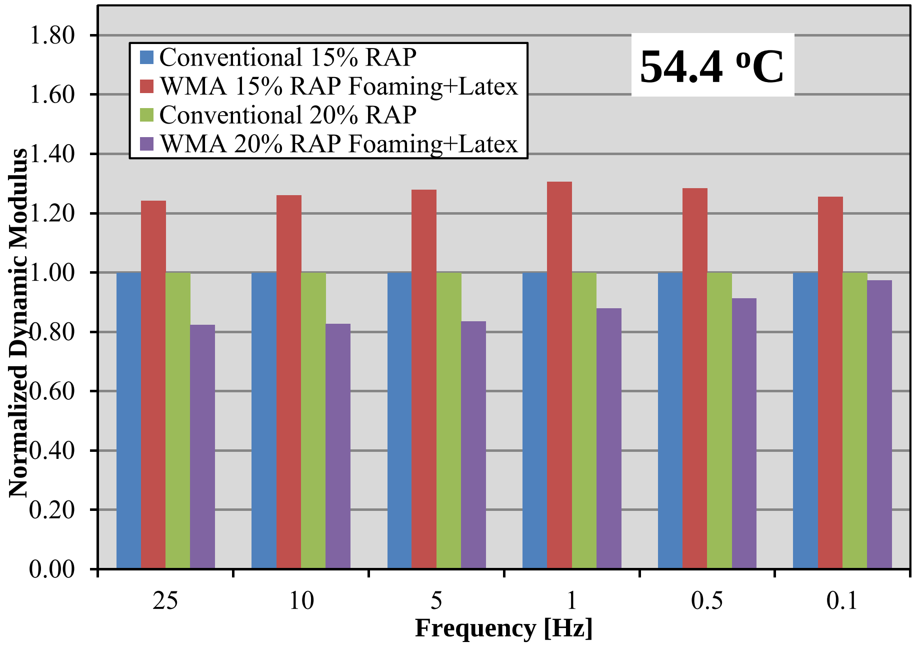


Figure 48
LA – 116 normalized dynamic modulus at 54.4ºC

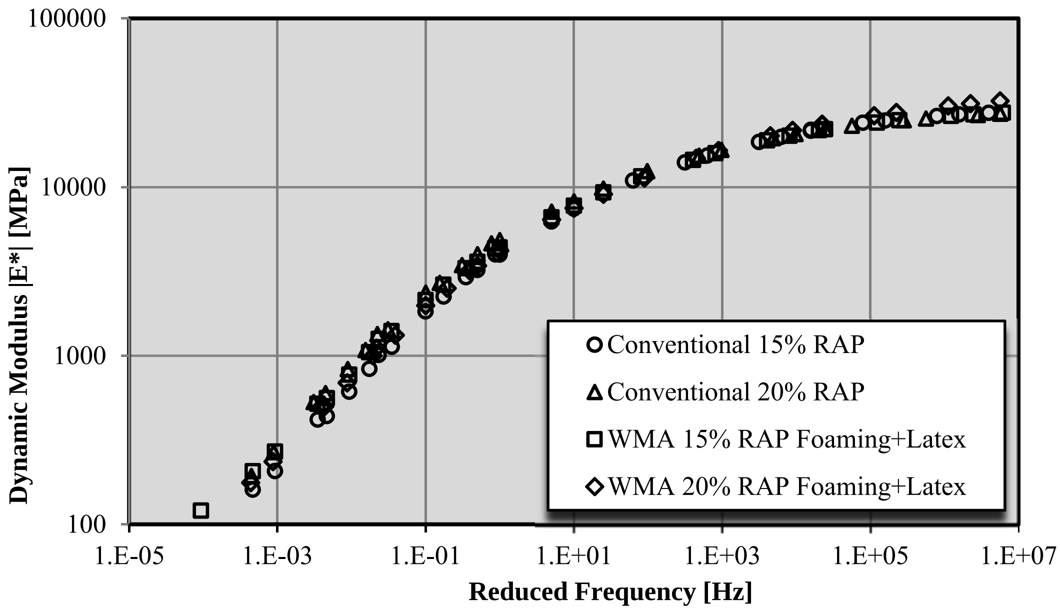


Figure 49
LA – 116 mastercurves at 25ºC

Modified Lottman Test Results. Table 32 summarizes the Modified Lottman test results. All of the mixtures had comparable results. The WMA 20% RAP Foaming + Latex was the sole mixture to fail the 80% criteria.

Table 32

LA – 116 WMA Modified Lottman results

Conventional 15% RAP		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	211.2	188.4
2	230.9	177.7
3	236.8	200.7
Average	226.3	188.9
CV [%]	5.9	6.1
TSR [%]	**83.5**	
WMA 15% RAP Foaming+Latex		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	238.2	189.5
2	205.1	178.2
3	183.1	163.9
Average	208.8	177.2
CV [%]	13.3	7.2
TSR [%]	**84.9**	
Conventional 20% RAP		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	219.5	186.3
2	221.1	168.1
3	220.9	186.8
Average	220.5	180.4
CV [%]	0.4	5.9
TSR [%]	**81.8**	
WMA 20% RAP Foaming+Latex		
Specimen ID	Control Tensile Strength [psi]	Conditioned Tensile Strength [psi]
1	196.4	138.4
2	216.2	165.2
3	213.0	169.4
Average	208.6	157.7
CV [%]	5.1	10.6
TSR [%]	**75.6**	

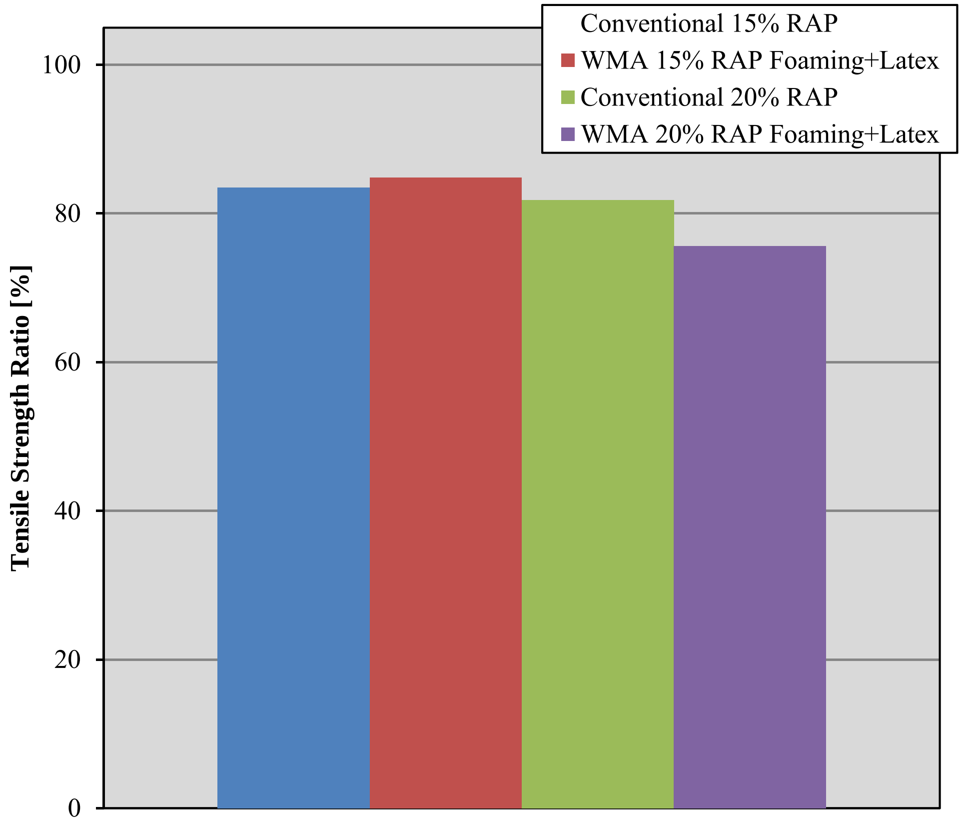


Figure 50
LA – 116 TSR results

LA – 10

The LA – 10 project was comprised of one HMA mixture and one corresponding WMA mixture both with 20% RAP. The test results are shown as follows.

Flow Number. Table 33 presents the flow number results for the two mixtures along with their respective average values and coefficients of variation. This test showed a large variability on both mixtures. In spite of that, the average flow numbers were very close to each other. None of the mixtures presented tertiary creep; hence no signs of stripping could be attributed to the mixtures.

Table 33
LA – 10 flow number test results

Conventional		
Replicate #	**Air Voids**	**Flow Number**
1	9.1	384
2	8.0	788
3	8.6	776
Average	8.6	649
CV [%]	6.2	35.4
WMA 20% RAP Evotherm®		
Replicate #	**Air Voids**	**Flow Number**
1	6.7	592
2	6.8	390
3	6.3	856
Average	6.6	613
CV [%]	3.8	38.1

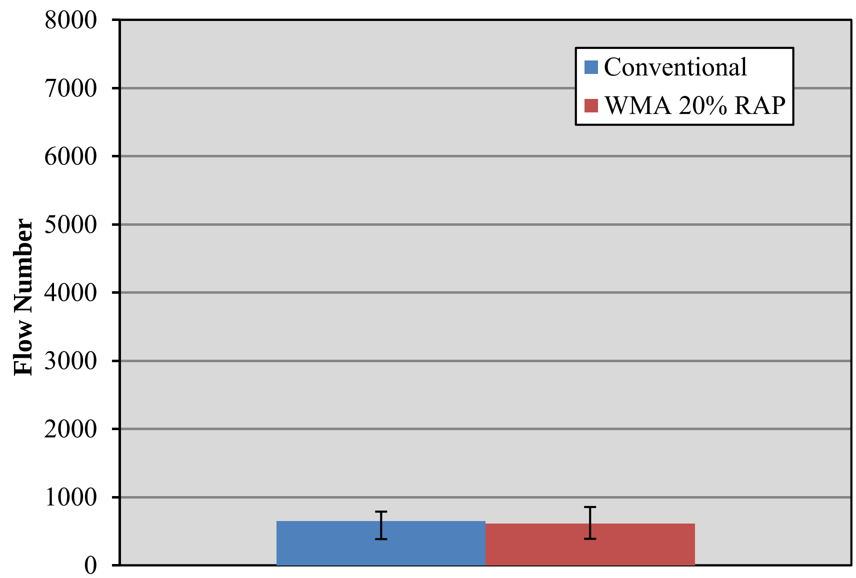


Figure 51
LA – 10 flow number test results

Loaded Wheel Tracking Test. The results from the LWT test are presented in the following figure. Both mixtures showed very little permanent deformation. None of the mixtures exceeded the 6.0 mm rut depth at 20,000 passes limit established by the DOTD requirements.

Figure 53 shows the deformation per number of passes where it can be seen that the WMA mixture had slightly more permanent deformation than the conventional mixture. No inflection point was observed in any of the two mixtures hence no stripping was believed to have happened. Consequently, no evaluation of the stripping inflection point, stripping slope, and creep slope was carried out.

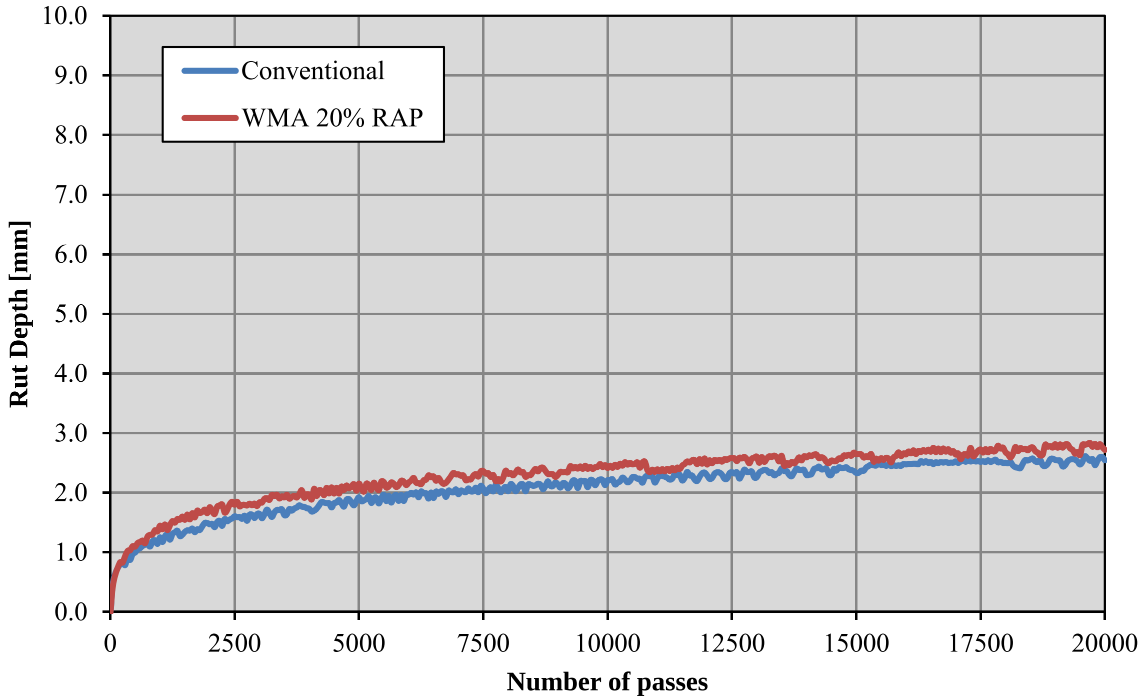


Figure 52
LA – 10 LWT results

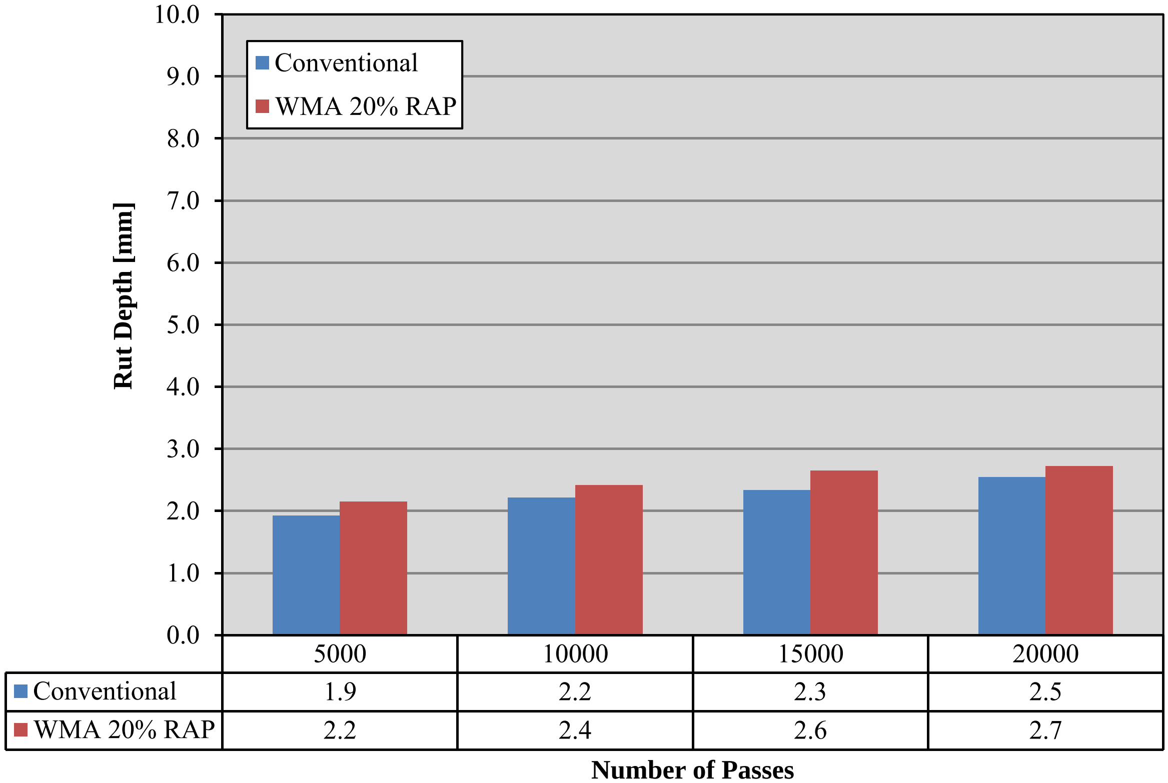


Figure 53
LA – 10 LWT results at various passes

Indirect Tensile Strength. The ITS results are shown in Tables 34 and 35. Figure 54 shows aged and unaged samples; whereas, the TI values are shown in Figure 55. An increase in strength for aged mixtures can be observed, while the IT strain decreased with aging. These are indications that the aging process made the mixtures stiffer and more brittle. It is also observed that the increase in the strength with aging was higher for the WMA mixture compared to that of the corresponding control HMA mixture.

The WMA mixture showed a slightly higher ITS value than its corresponding conventional HMA mixture. For IT strain, WMA exhibited a higher variability than the conventional mixture at the unaged condition; however, a lower variability at the aged condition was observer, Tables 34 and 35. The WMA mixture possessed a similar or better TI value to that of its control HMA mixture, but once again the variability was higher on the WMA mixture.

Table 34
LA – 10 unaged ITS test results

UNAGED				
Conventional				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
1	7.5	154.88	0.49	0.79
2	7.5	153.54	0.62	0.80
3	7.3	146.46	0.61	0.78
Average	**7.4**	**151.6**	**0.57**	**0.79**
CV (%)	2	3	12	1
WMA 20% RAP Evotherm®				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
1		158.95	0.68	0.81
2		153.43	1.83	0.78
3		153.09	1.89	0.81
Average		**155.2**	**1.47**	**0.80**
CV (%)		2	46	2

Table 35
LA – 10 aged ITS test results

AGED				
Conventional				
Sample No.	Voids [%]	IT Strength [psi]	IT Strain [%]	TI
4	7.0	163.88	0.46	0.75
5	7.4	184.11	0.61	0.75
6	7.5	184.16	0.52	0.70
Average	**7.3**	**177.4**	**0.53**	**0.73**
CV (%)	3	7	15	4
WMA 20% RAP Evotherm®				
Sample No.	Voids (percent)	IT Strength [psi]	IT Strain [%]	TI
4		208.55	0.49	0.75
5		183.72	0.45	0.65
6		203.40	0.45	0.72
Average		**198.6**	**0.47**	**0.71**
CV (%)		7	5	7

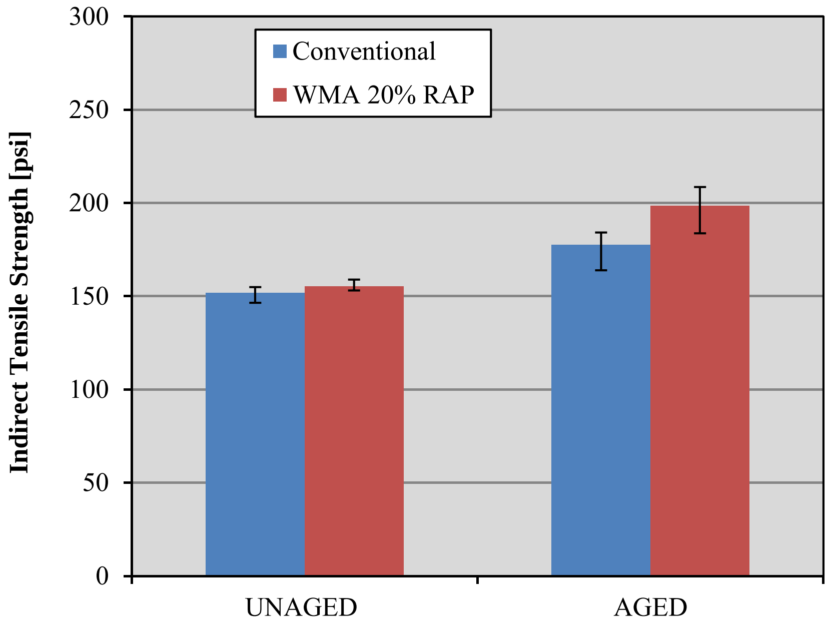


Figure 54
LA – 10 indirect tensile results

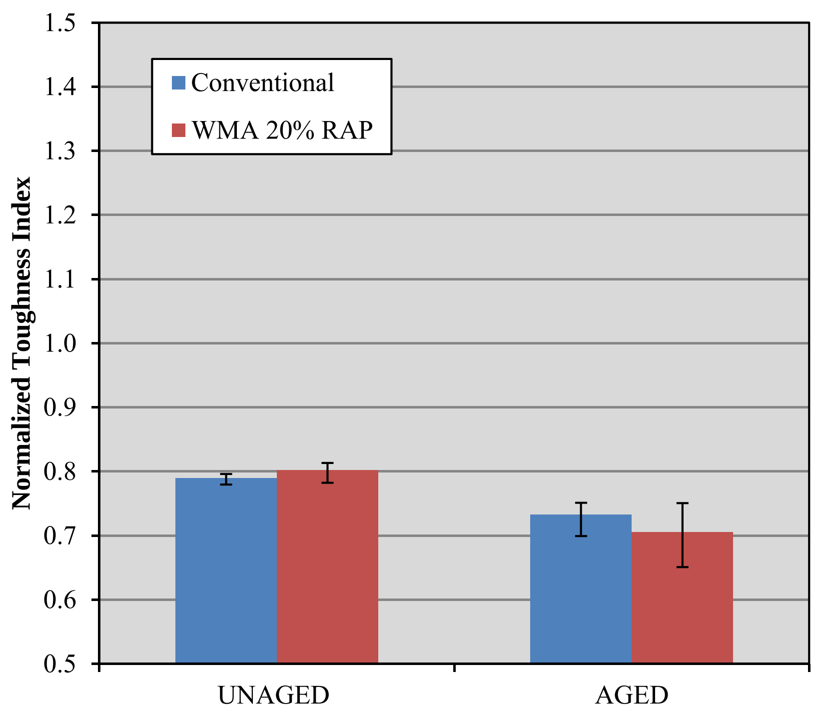


Figure 55
LA – 10 toughness index results

Dissipated Creep Strain Energy Results. Table 36 summarizes the DCSE test results for each of the mixtures. Figure 56 shows the DCSE values along with their corresponding error limits. It is observed that all the mixtures met the failure criteria of 0.75 KJ/m3, which is an indication of low susceptibility to failure by fracture in the field.

The WMA mixture exhibited slightly lower DCSE values than its corresponding control HMA mixture, which nonetheless presented less variability in the results.

Table 36
LA – 10 DCSE test results

Conventional						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1346892	1484	288	1270	0.20	1.26
2	1332659	2074	303	1846	0.20	1.93
3	1464954	1868	280	1677	0.29	1.62
Average	1381502	1809	290	1598	0.23	1.60
CV [%]	5.3	16.6	4.0	18.5	20.5	20.9
WMA 20% RAP Evotherm®						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1536146	1406	368	1166	0.16	1.48
2	1971905	1272	362	1088	0.31	1.36
3	1514314	1505	362	1266	0.17	1.58
Average	1674122	1394	364	1173	0.21	1.47
CV [%]	15.4	8.4	0.9	7.6	40.0	7.6

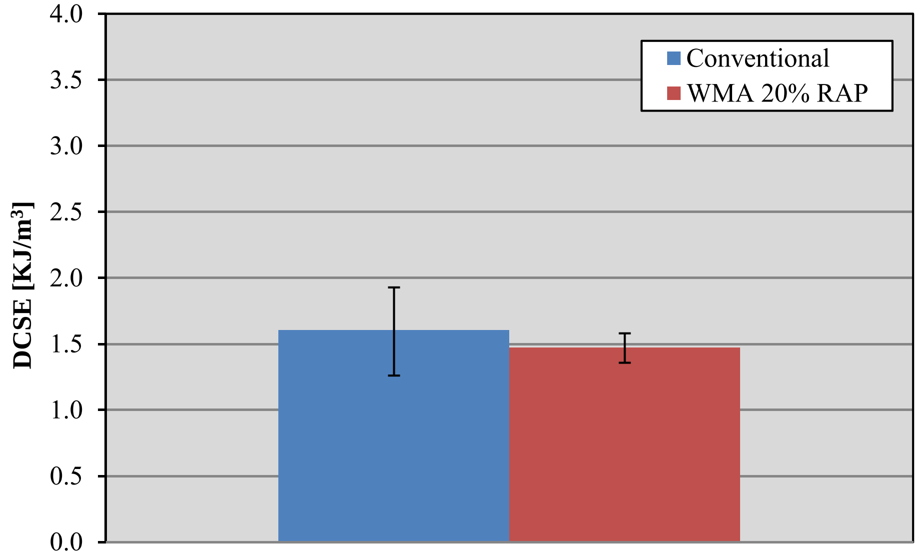


Figure 56
LA – 10 DCSE results

Semi-Circular Bending Test Results. The semi-circular bend test was conducted to evaluate the fracture resistance properties of the two mixtures. The peak load, peak strain, and the area under stress-strain curve till peak load were used in computing the critical strain energy (J_c). A higher J_c value represents a more fracture resistant mixture. Table 37 shows the peak load area, as well as the corresponding J_c for both mixtures. As seen in Figure 57**,** the average J_c was similar for both mixtures and met the J_c value criteria of 0.5 KJ/m^2. The WMA additive did not have any influence on the fracture resistance of the mixtures.

Table 37
LA – 10 SCB test results

Conventional							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.150	0.836	0.747	0.788	0.378	0.432	0.5
2	1.140	0.978	0.508	0.643	0.410	0.234	
3	1.204	0.806	0.710	0.747	0.427	0.416	
4	1.072	0.886	0.593	0.696	0.527	0.311	
Average	1.142	0.876	0.639	0.718	0.435	0.348	
CV [%]	4.8	8.6	17.2	8.8	14.8	26.8	
WMA 20% RAP Evotherm®							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.079	0.986	0.748	0.438	0.539	0.286	0.5
2	1.004	0.712	0.684	0.484	0.280	0.253	
3	1.329	0.925	0.696	0.771	0.446	0.334	
4	1.254	0.883	0.561	0.580	0.415	0.282	
Average	1.167	0.877	0.672	0.568	0.420	0.289	
CV [%]	12.9	13.4	11.7	26.0	25.5	11.6	

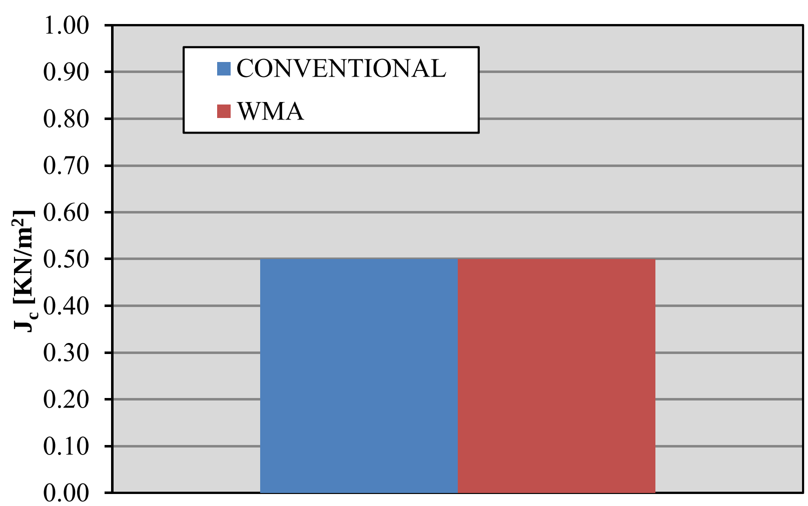


Figure 57
LA – 10 Critical values of the J-Integral

Dynamic Modulus Test Results. The dynamic modulus results for the two mixtures are presented in the Table 38 and 39 as follows. The average dynamic modulus results were then normalized to facilitate the comparison. The WMA values were divided by the corresponding conventional HMA at each corresponding temperature and frequency. The results are shown as Figures 58 through 62.

Except for the highest temperature (54.4ºC), the WMA showed slightly higher moduli at all other frequencies and temperatures. However, as can be seen in the comparison between the two mastercurves (Figure 63), the difference is not significant and the two curves are almost indistinguishable from one another.

Table 38
LA – 10 conventional dynamic modulus results

Conventional			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	21489	2.16
	10	20511	4.21
	5	19698	5.13
	1	17683	6.73
	0.5	16787	7.35
	0.1	14617	8.91
4.4	25	14133	6.87
	10	12719	9.52
	5	11696	10.98
	1	9365	14.11
	0.5	8407	15.46
	0.1	6385	18.54
25	25	5410	18.57
	10	4340	21.44
	5	3582	23.35
	1	2231	27.75
	0.5	1816	28.35
	0.1	1155	27.56
37.8	25	2300	25.04
	10	1710	26.64
	5	1379	27.01
	1	855	26.14
	0.5	699	24.97
	0.1	489	20.88
54.4	25	800	25.20
	10	609	23.39
	5	516	21.46
	1	388	18.28
	0.5	355	16.60
	0.1	293	13.48

Table 39
LA – 10 WMA 20% RAP Evotherm® dynamic modulus results

WMA 20% RAP Evotherm®			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	23314	1.81
	10	22367	3.86
	5	21538	4.88
	1	19445	6.53
	0.5	18496	7.17
	0.1	16200	8.82
4.4	25	14801	6.49
	10	13329	9.14
	5	12321	10.55
	1	9991	13.61
	0.5	9031	14.88
	0.1	6918	17.95
25	25	5977	18.08
	10	4890	21.31
	5	4022	23.38
	1	2482	28.06
	0.5	2031	28.65
	0.1	1248	28.50
37.8	25	2755	25.01
	10	1993	27.16
	5	1596	27.84
	1	940	27.73
	0.5	764	26.67
	0.1	527	22.29
54.4	25	824	26.20
	10	593	24.46
	5	499	22.37
	1	365	18.55
	0.5	331	16.82
	0.1	281	13.06

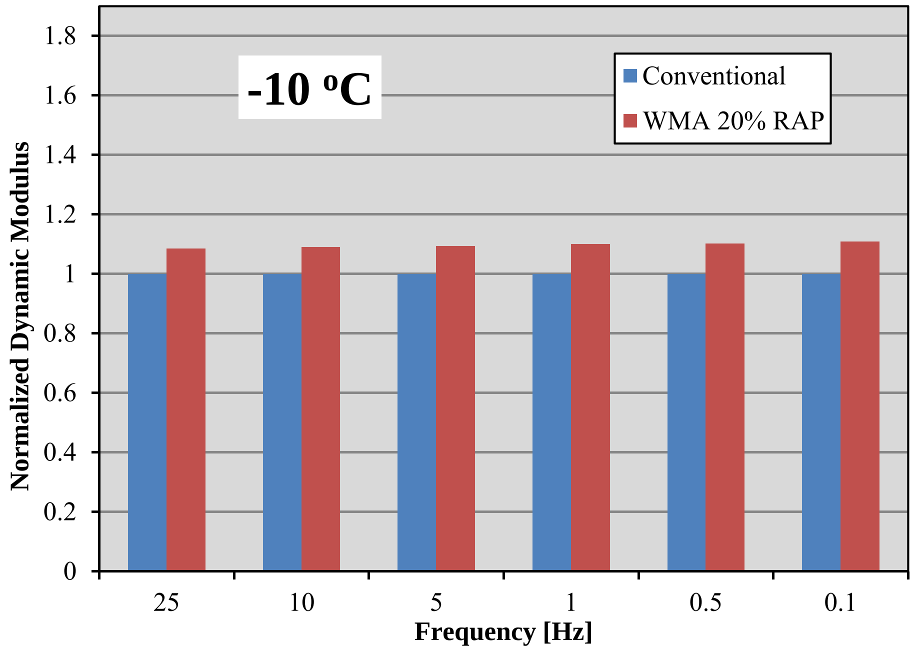


Figure 58

LA – 10 normalized dynamic modulus at -10ºC

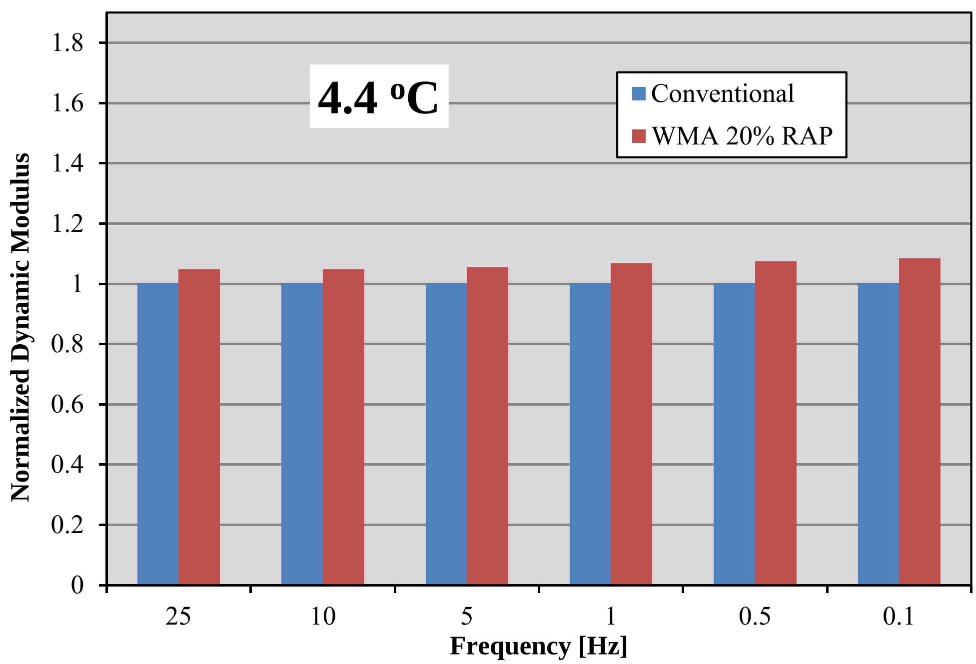


Figure 59

LA – 10 normalized dynamic modulus at 4.4ºC

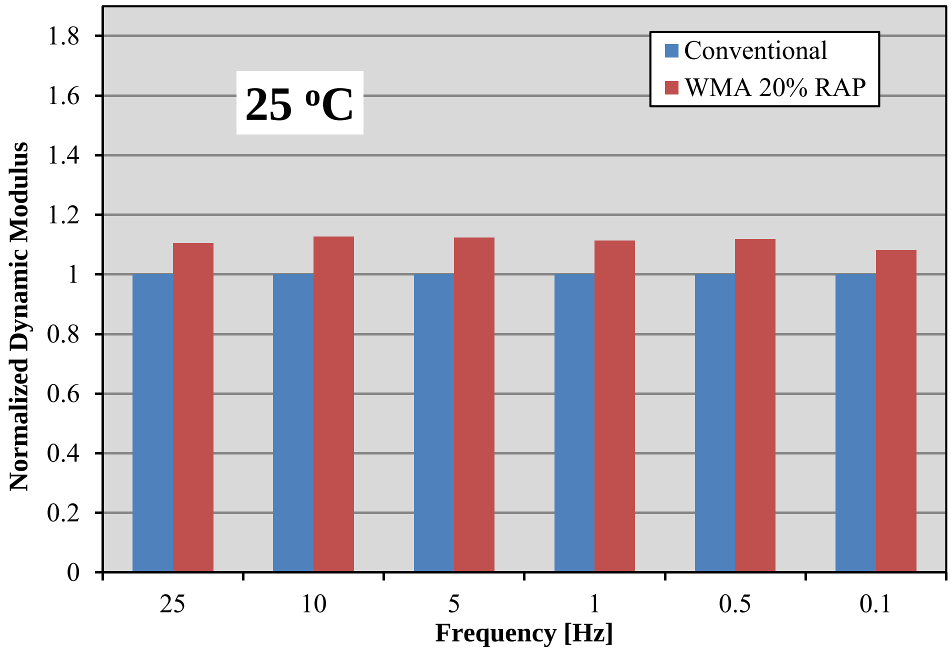


Figure 60
LA – 10 normalized dynamic modulus at 25°C

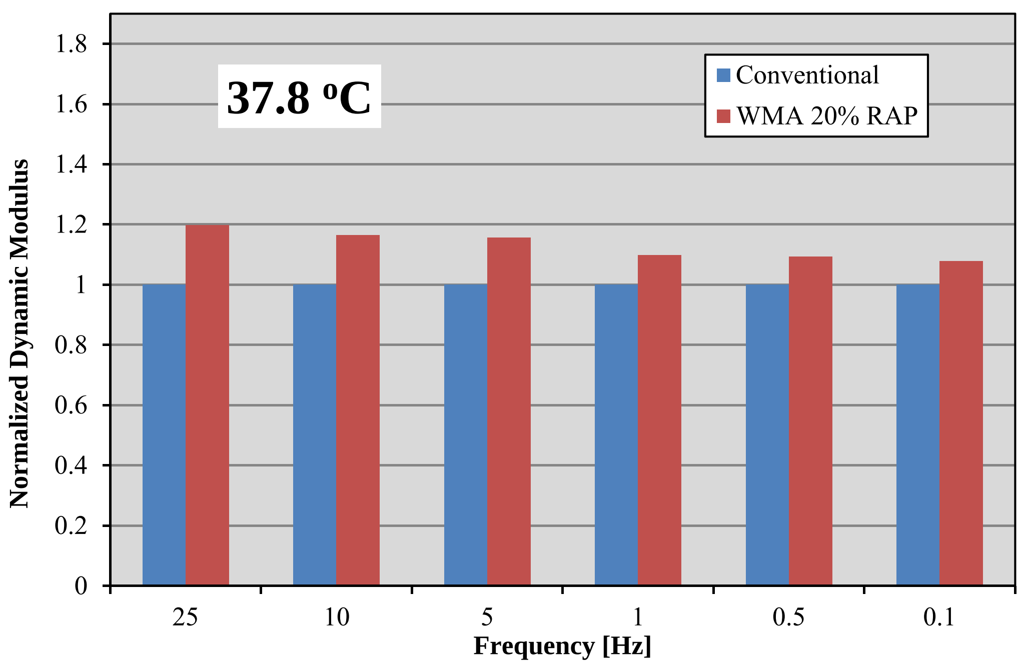


Figure 61
LA – 10 normalized dynamic modulus at 37.8°C

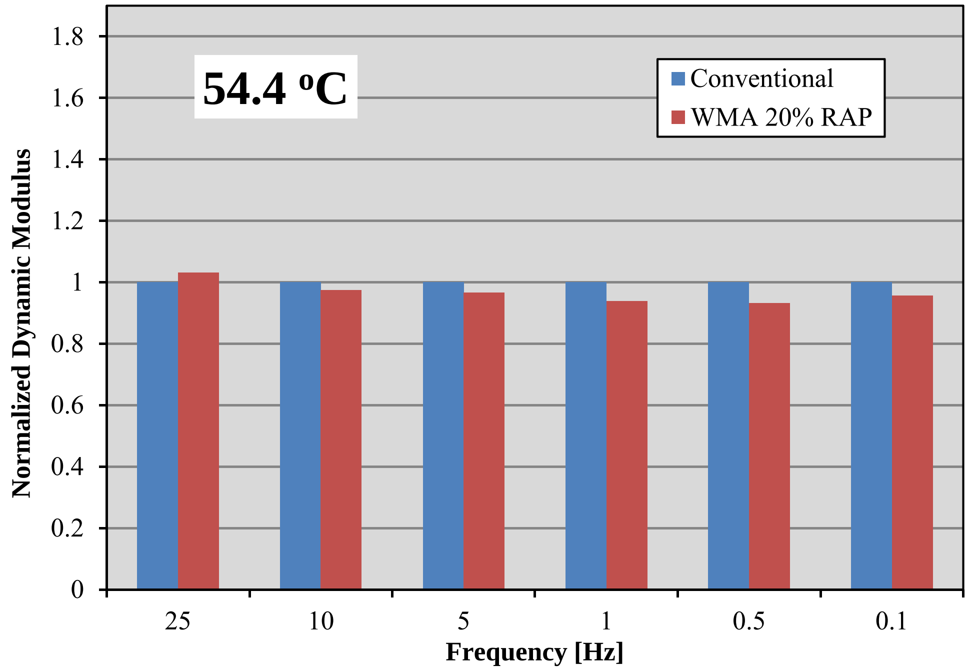


Figure 62
LA – 10 normalized dynamic modulus at 54.4ºC

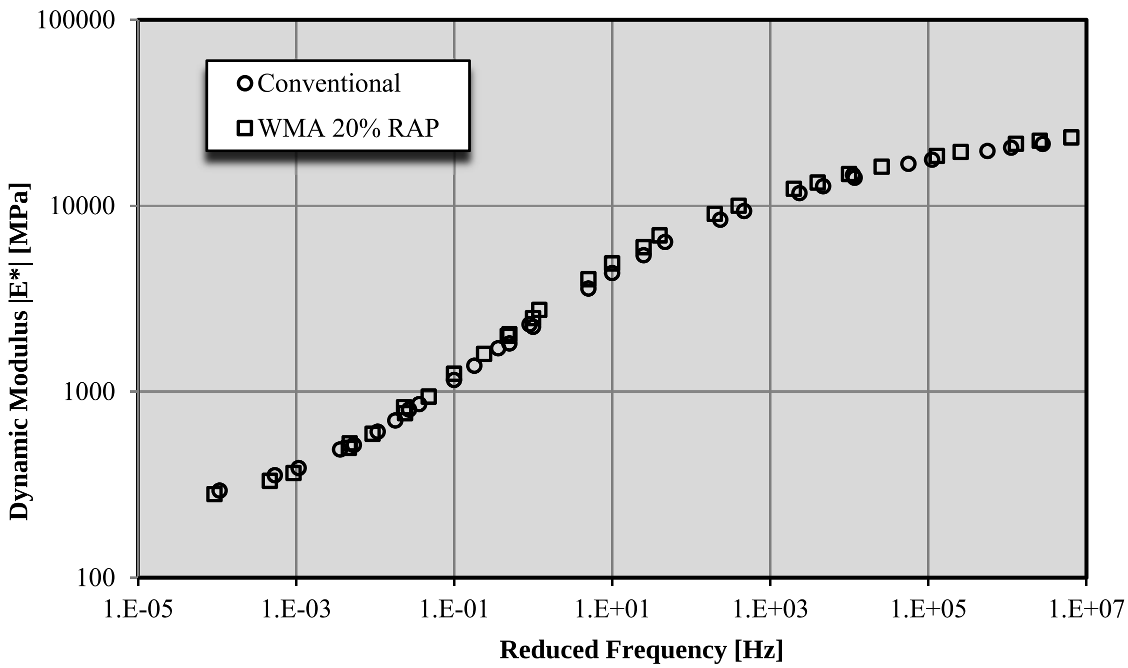


Figure 63
LA – 10 mastercurves at 25ºC

Modified Lottman Test Results. Table 40 summarizes the Modified Lottman test results. The mean tensile strength values for the controlled and the conditioned specimens and the TSR values of the asphalt mixtures are shown.

The TSR values are shown in Figure 64. It is seen that the conventional HMA mixtures had a better performance in terms of moisture susceptibility compared to the WMA. It is noted that the WMA did not meet the DOTD specification of 80% TSR. Despite the lower TSR values for the WMA mixture, it is worth noticing that all the conditioned IDT strengths were equal to or greater than 100 psi, a strength value associated with well-performing mixtures for Louisiana climate conditions.

Table 40
LA – 10 WMA Modified Lottman results

Conventional		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	182.4	162.9
2	175.2	144.2
3	181.8	137.7
Average	179.8	148.3
CV [%]	2.2	8.8
TSR [%]	**82.5**	
WMA 20% RAP Evotherm®		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	210.9	143.7
2	204.4	131.1
3	204.3	132.3
Average	206.5	135.7
CV [%]	1.8	5.1
TSR [%]	**65.7**	

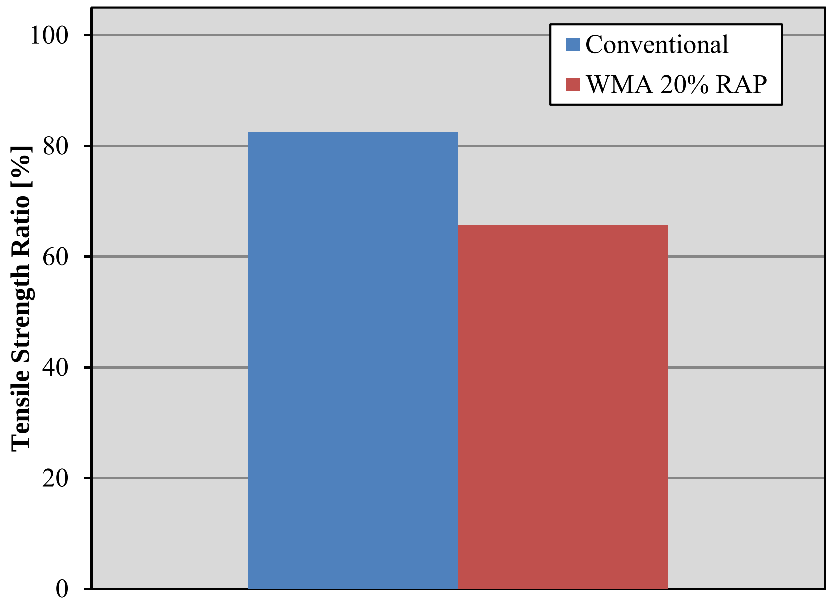


Figure 64
LA – 10 TSR results

US – 90

The US – 90 project consisted of two mixtures, similarly to the previous project. Both mixtures had 15% RAP, and the results are presented as follows.

Flow Number. Table 41 presents the flow number results for the two mixtures, along with their respective average values and coefficients of variation. The table is followed by Figure 65, which graphically shows the averages and error boundaries for both mixtures. The conventional HMA mixture presented a better performance when compared to the WMA counterpart. The WMA mixture also showed more scatter in the test results.

Table 41
US – 90 Flow number test results

Conventional		
Replicate #	**Air Voids**	**Flow Number**
1	8.8	2551
2	8.6	2706
3	8.6	2784
Average	8.7	2680
CV [%]	1.2	4.4
WMA 15% RAP Evotherm®		
Replicate #	**Air Voids**	**Flow Number**
1	7.9	1721
2	8.3	1439
3	8.0	2064
Average	8.0	1741
CV [%]	2.4	18.0

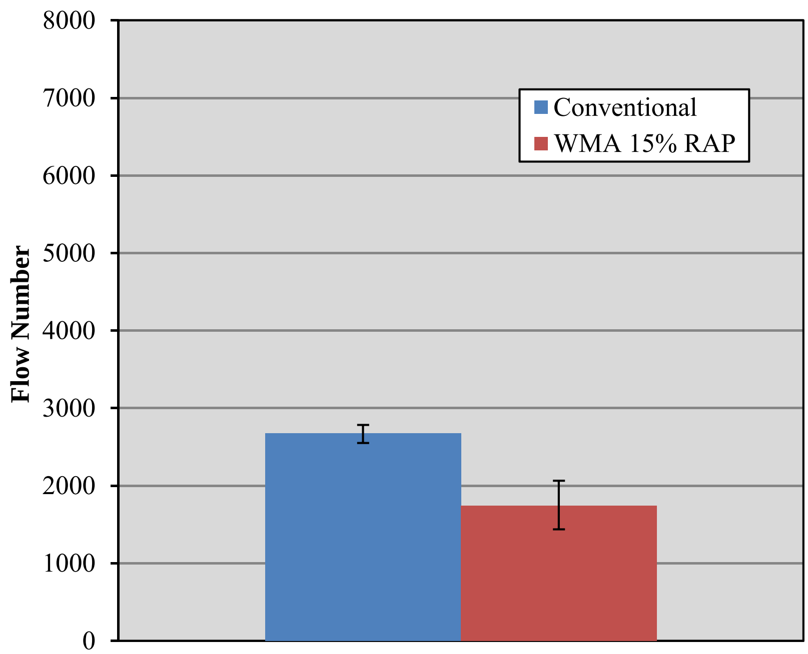


Figure 65
US – 90 Flow number test results

Loaded Wheel Tracking Test. The trend seen by the LWT test results was similar to the one observed in the flow number test results. Mixtures with a higher flow number had the lower rut depths and vice versa. This behavior suggests that the WMA additive impacted the ability to resist permanent deformation. As can also be noticed, no stripping was observed during testing. Therefore, evaluation of the stripping inflection point, stripping slope and creep slope evaluation was not performed. Figure 67 shows the rut depth at various passes. Both mixtures performed well and exhibited similar trend.

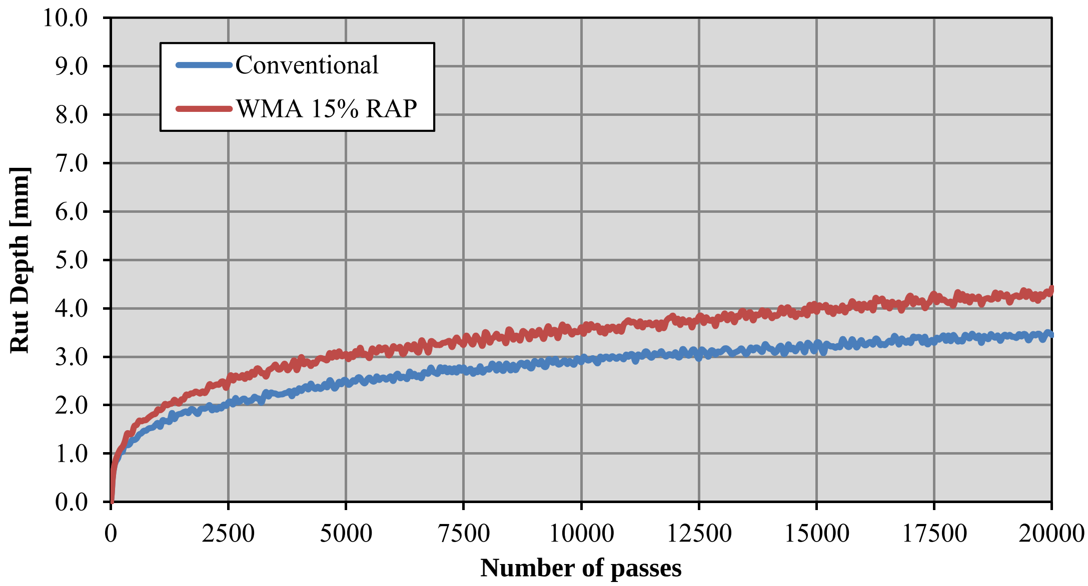
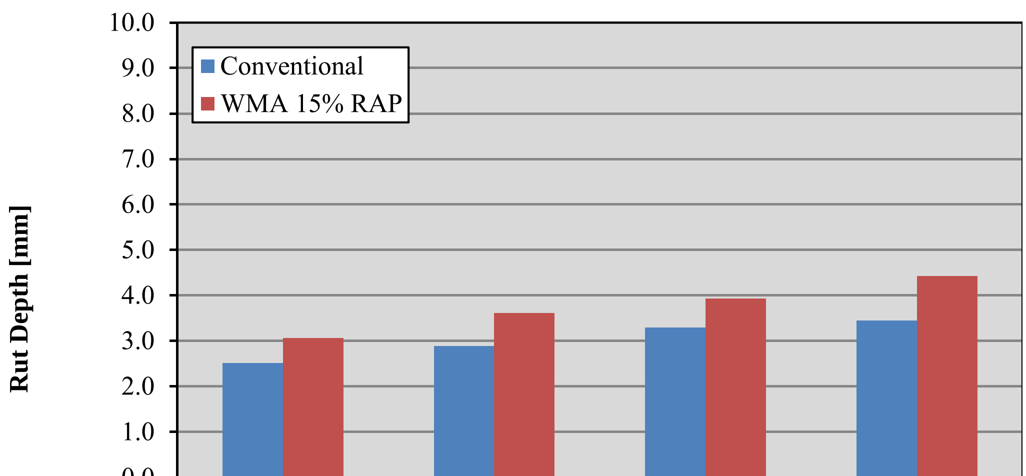


Figure 66
US – 90 LWT results



	5000	10000	15000	20000
Conventional	2.5	2.9	3.3	3.5
WMA 15% RAP	3.1	3.6	3.9	4.4

Number of Passes

Figure 67
US – 90 LWT results at various passes

Indirect Tensile Strength. The unaged and aged ITS results are shown in the following tables. The IT Strength and Toughness index are seen in Figure 68 and Figure 69 along with their respective error limits.

An increase in strength of the WMA mixture with aging can be observed, whereas the control HMA mixture did not seem to have its strength increased with aging. The toughness index followed the same trend.

Table 42

US – 90 unaged ITS test results

UNAGED			
Conventional			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	163.3	0.76	0.73
2	148.1	0.51	0.63
3	133.6	0.58	0.80
Average	**148.3**	**0.62**	**0.72**
CV (%)	10	21	12
WMA 15% RAP Evotherm®			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	172.9	0.952	0.759
2	177.3	0.76	0.83
3	181.8	0.666	0.759
Average	**177.3**	**0.79**	**0.78**
CV (%)	3	18	5

Table 43

US – 90 aged ITS test results

AGED			
Conventional			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	138.8	0.45	0.73
5	150.5	0.45	0.71
6			
Average	**144.7**	**0.45**	**0.72**
CV (%)	6	1	2
WMA 15% RAP Evotherm®			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	212.0	0.37	0.67
5	222.3	0.47	0.68
6	212.9	0.46	0.73
Average	**215.7**	**0.43**	**0.69**
CV (%)	3	13	5

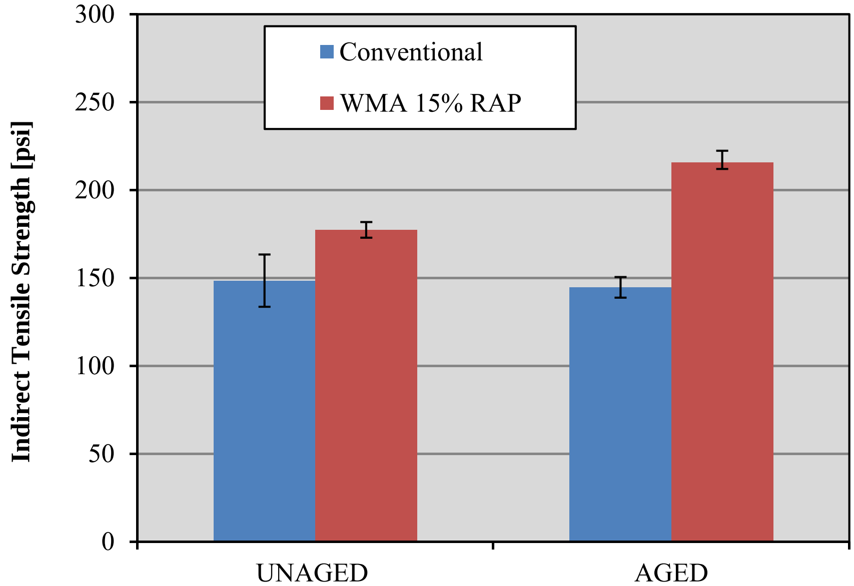


Figure 68
US – 90 indirect tensile results

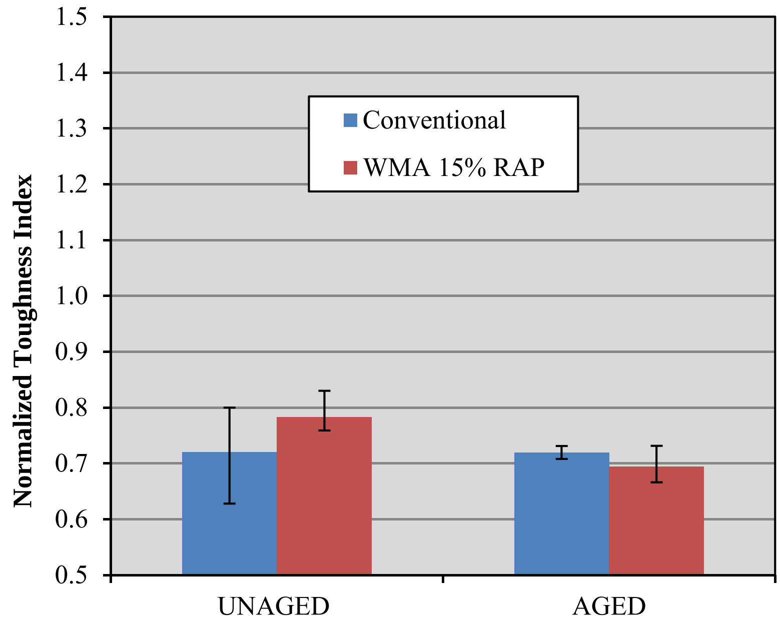


Figure 69
US – 90 toughness index results

Dissipated Creep Strain Energy Results. The WMA mixture exhibited higher DCSE values than its corresponding control HMA mixture. However, the results showed high variability as seen in Figure 70. It is also worth noting that both the WMA and HMA mixtures had average DCSE values higher than 0.75 KJ/m^3.

Table 44
US – 90 DCSE test results

1	1708044	1014	290	844	0.27	0.84
2	2935035	1358	318	1250	0.28	1.37
3	2005861	564	324	403	0.30	0.45
CV [%]	28.9	40.7	5.8	50.9	5.6	52.1
1						
2	1720371	1477	342	1278	0.31	1.51
3	2169779	977	349	816	0.33	0.98
CV [%]	16.3	28.8	1.5	31.2	3.6	29.8

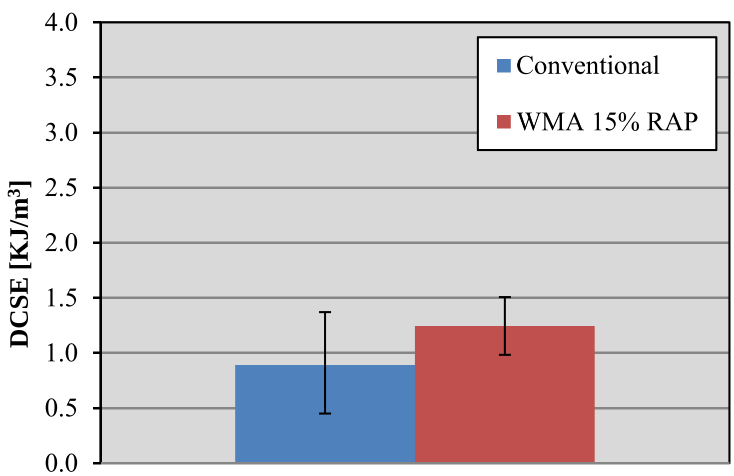


Figure 70
US – 90 DCSE results

Semi-Circular Bending Test Results. Table 45 shows the peak load, area and, the corresponding J_c for both mixtures. Figure 71 presents the computed average J_c values for both mixtures evaluated. Mixture WMA 15% RAP Evotherm® had higher J_c value than the conventional mixture. This may indicate that the WMA additive did improve the fracture resistance.

Table 45
US – 90 SCB test results

Conventional							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	0.4
1	0.818	0.549	0.518	0.570	0.282	0.250	
2	0.976	0.638	0.491	0.533	0.399	0.238	
3	0.854	0.723	0.496	0.550	0.347	0.295	
4	0.787	0.580	0.387	0.413	0.293	0.159	
Average	0.859	0.623	0.473	0.517	0.331	0.235	
CV [%]	9.7	12.3	12.3	13.7	16.3	24.0	
WMA 15% RAP Evotherm®							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	0.5
1	0.913	0.699	0.515	0.666	0.403	0.315	
2	1.091	0.825	0.536	0.723	0.548	0.331	
3	0.835	0.788	0.383	0.458	0.469	0.190	
4	1.120	0.867	0.564	0.781	0.508	0.302	
Average	0.990	0.795	0.499	0.657	0.482	0.284	
CV [%]	13.9	9.0	16.1	21.4	12.8	22.6	

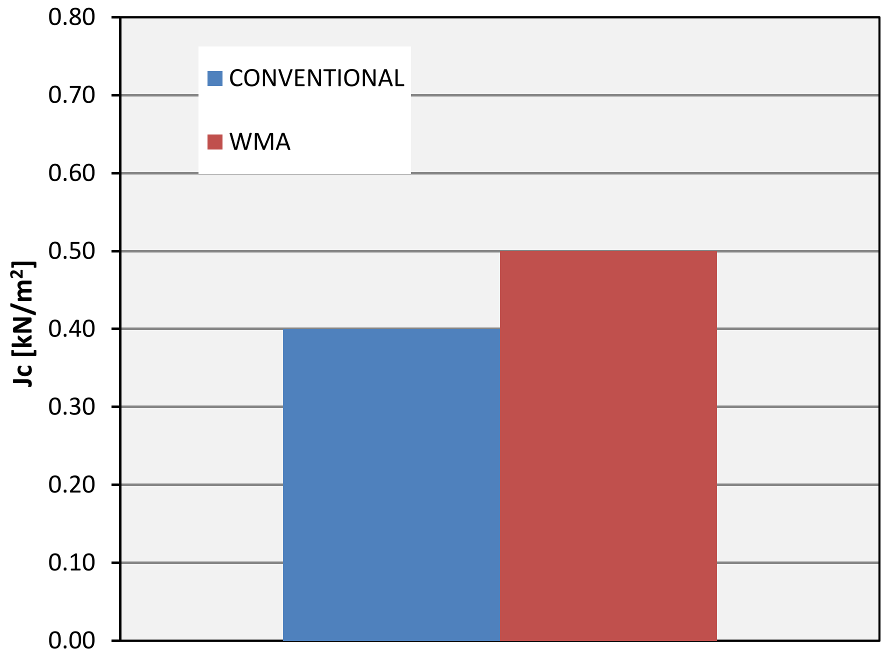


Figure 71
US – 90 critical values of the J-Integral

Dynamic Modulus Test Results. The dynamic modulus results are shown in Tables 46 and 47, giving the average results for |E*| and phase angle (δ). The normalized dynamic modulus results are shown in Figure 72 through Figure 76.

At all frequencies at the temperature -10^{0}C, the WMA mixture had higher dynamic moduli along with all frequencies, except 0.1 Hz, at temperature 4.4^{0}C. The WMA mixture had lower dynamic moduli values at all frequencies at higher temperatures (25^{0}C, 37.8^{0}C, and 54.4^{0}C). The most accentuated differences happened at lower frequencies and higher temperatures. Figure 77 denotes these differences. From that same picture one can point out that the WMA mixtures are expected to have a similar performance at lower temperatures but a poorer performance at intermediate and higher temperatures.

Table 46
US – 90 conventional dynamic modulus results

Conventional			
Temp. [oC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	22677	2.53
	10	21614	4.73
	5	20698	5.71
	1	18471	7.34
	0.5	17497	7.98
	0.1	15228	9.56
4.4	25	15700	9.36
	10	14309	10.46
	5	13268	11.26
	1	10897	13.37
	0.5	9926	14.33
	0.1	7749	16.97
25	25	6044	21.43
	10	4885	23.15
	5	4169	24.12
	1	2766	26.61
	0.5	2342	26.94
	0.1	1471	28.59
37.8	25	2617	29.00
	10	1951	30.40
	5	1582	30.48
	1	909	31.29
	0.5	757	30.37
	0.1	439	29.83
54.4	25	918	31.29
	10	581	33.01
	5	446	32.15
	1	233	30.93
	0.5	190	29.16
	0.1	116	27.21

Table 47
US – 90 WMA 15% RAP Evotherm® dynamic modulus results

WMA 15% RAP Evotherm®			
Temp. [oC]	**Frequency [Hz]**	**|E*| [Mpa]**	**Phase Angle**
-10	25	23594	1.99
	10	22679	4.16
	5	21820	5.19
	1	19598	7.00
	0.5	18598	7.74
	0.1	16123	9.71
4.4	25	16926	9.54
	10	15389	10.98
	5	14240	11.99
	1	11441	15.00
	0.5	10209	16.35
	0.1	7604	20.17
25	25	5954	25.14
	10	4546	27.75
	5	3694	29.07
	1	2093	31.88
	0.5	1638	31.95
	0.1	848	32.25
37.8	25	2264	33.65
	10	1519	35.27
	5	1130	34.94
	1	535	34.03
	0.5	400	32.46
	0.1	209	29.52
54.4	25	586	33.81
	10	335	36.02
	5	239	34.43
	1	125	30.04
	0.5	105	27.66
	0.1	74	24.23

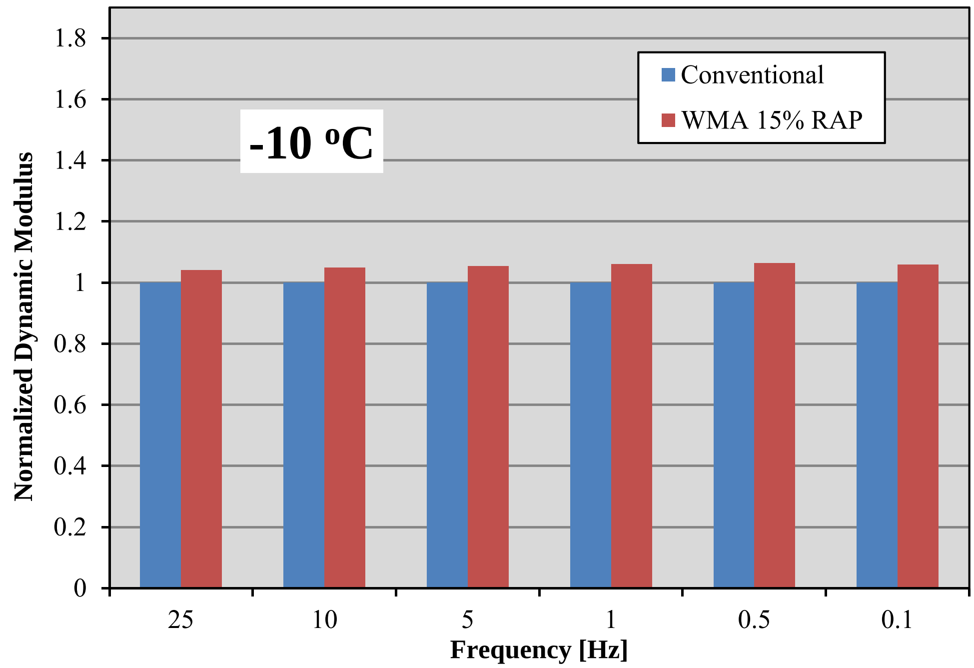


Figure 72

US – 90 normalized dynamic modulus at -10ºC

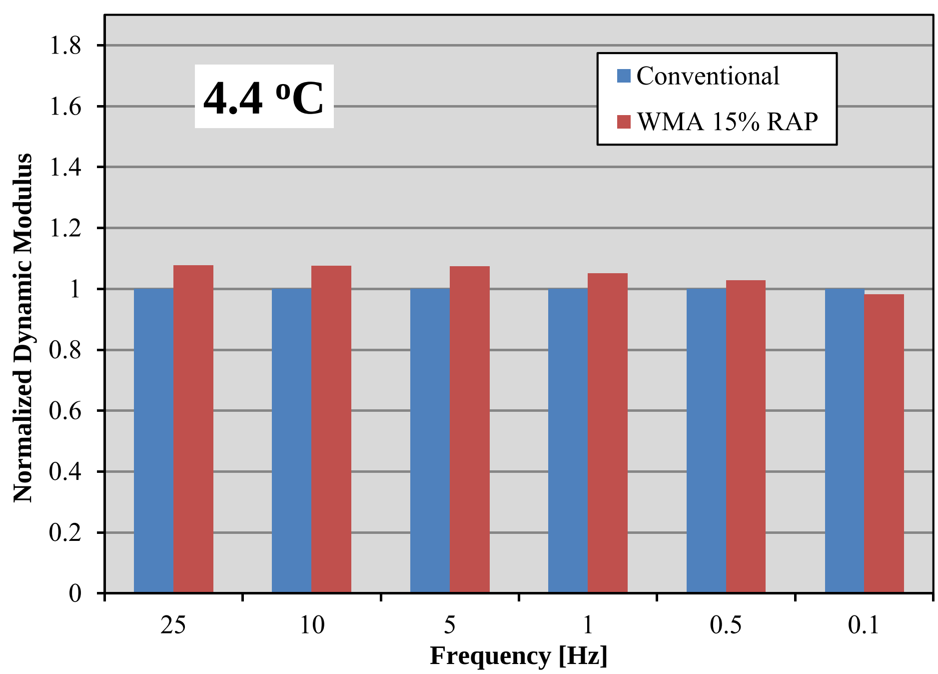


Figure 73

US – 90 normalized dynamic modulus at 4.4ºC

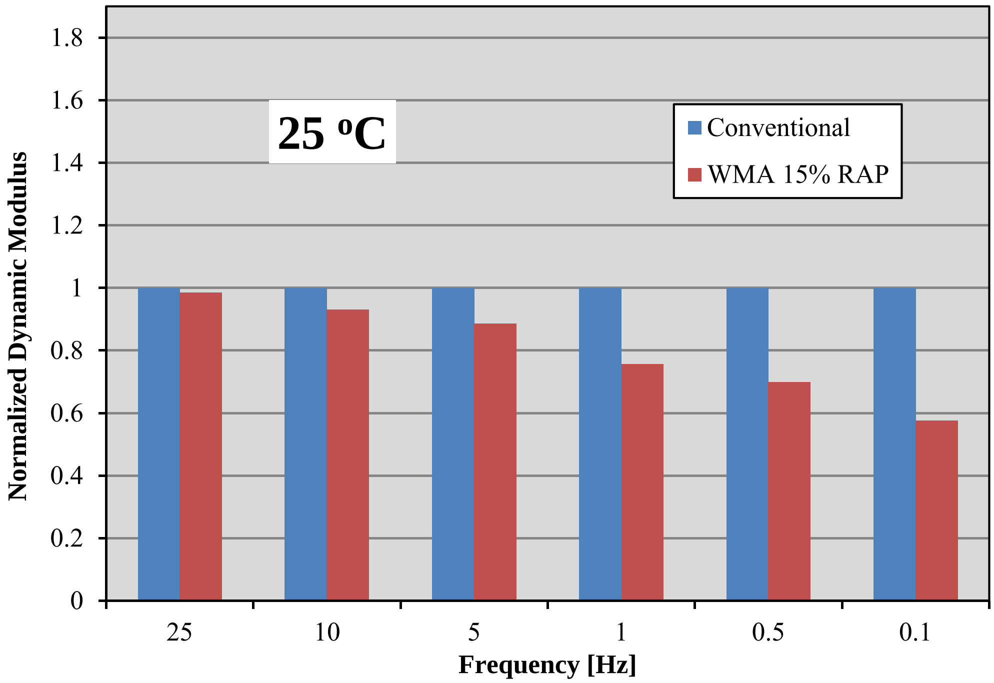


Figure 74

US – 90 normalized dynamic modulus at 25ºC

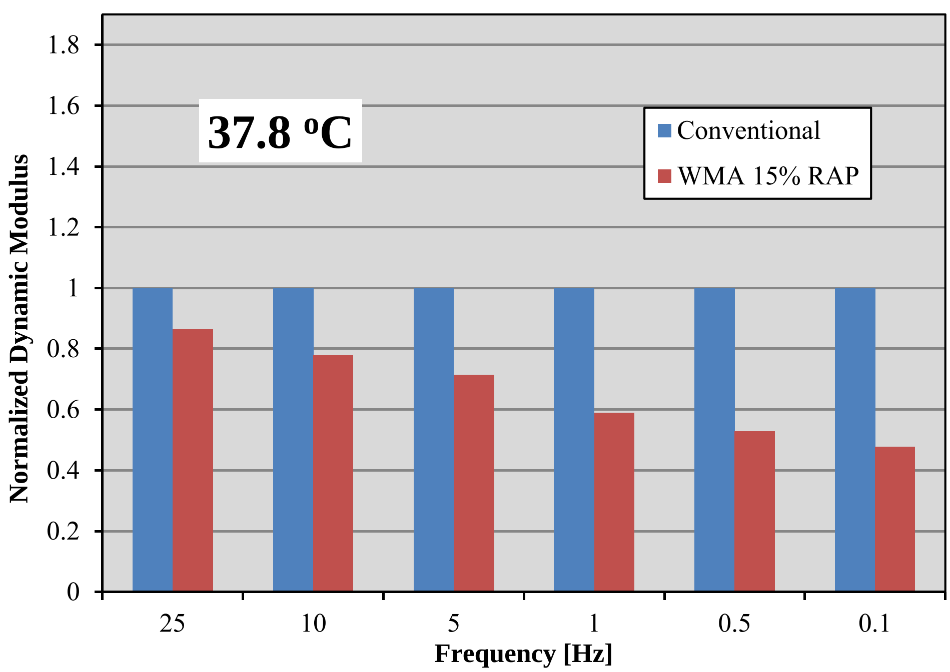


Figure 75

US – 90 normalized dynamic modulus at 37.8ºC

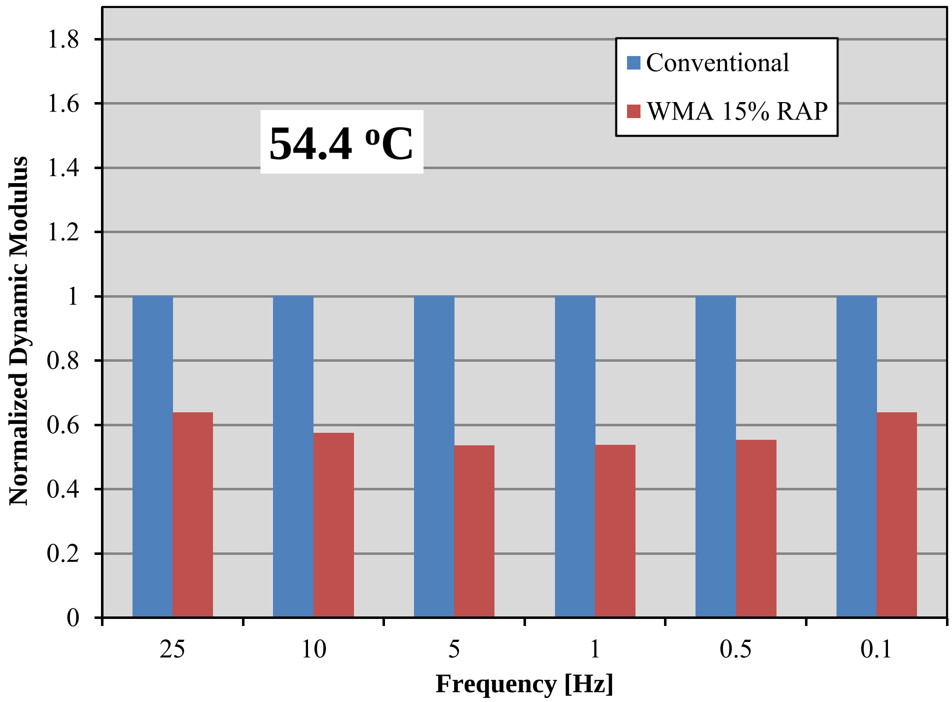


Figure 76

US – 90 normalized dynamic modulus at 54.4ºC

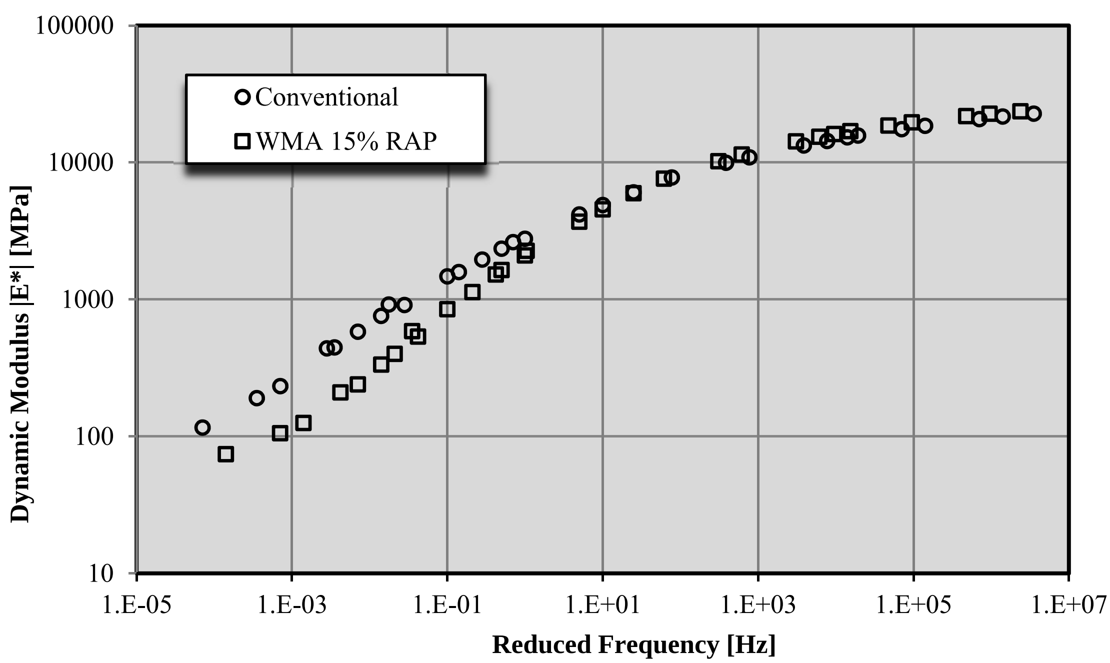


Figure 77

US – 90 mastercurves at 25ºC

Modified Lottman Test Results. Table 48 summarizes the Modified Lottman Test results, presenting the mean tensile strength values for the controlled and the conditioned specimens and the TSR values of the asphalt mixtures are shown.

The TSR values are shown in Figure 78. It is seen that the conventional HMA mixture had similar results in terms of moisture susceptibility compared to the WMA. Both mixtures met the DOTD specification of 80% TSR. The mixtures presented exceptionally high TSR values, which are not commonly observed. The conditioned specimens had strength results very close to the control specimens which in turn yielded the high strength ratios. No other plausible explanation can be given other than the intrinsic variability of the test itself.

Table 48
US – 90 WMA Modified Lottman results

Conventional		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	118.9	119.9
2	115.9	126.0
3	121.1	115.3
Average	118.6	120.4
CV [%]	2.2	4.4
TSR [%]	**101.5 = ~ 100.0**	
WMA 15% RAP Evotherm®		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	119.0	118.2
2	121.1	127.5
3	131.5	118.7
Average	123.9	121.5
CV [%]	5.4	4.3
TSR [%]	**98.0**	

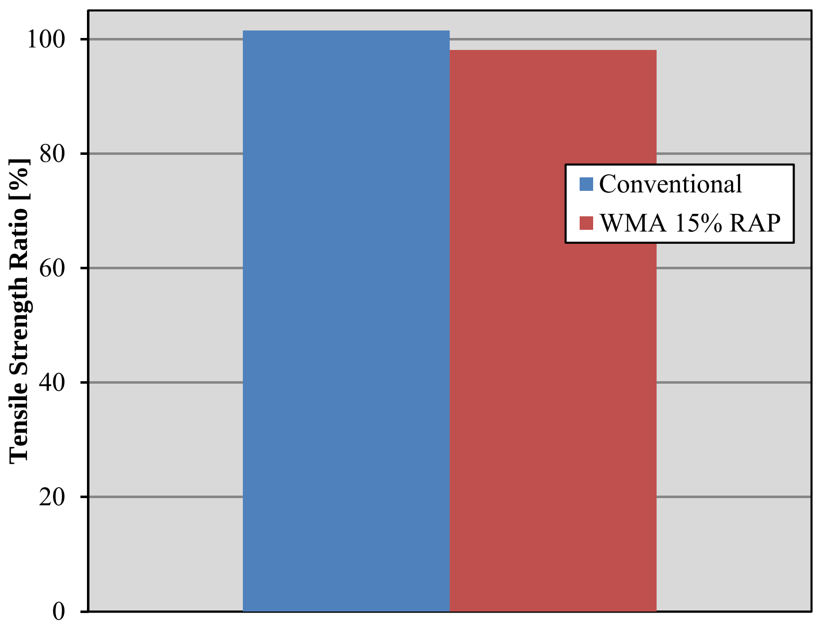


Figure 78
US – 90 TSR results

US – 61

During the course of the US – 61 project, a shortage of granite aggregate happened and the mixtures had to be redesigned to accommodate that. The new mixtures were prepared with sandstone in place of the granite but the contractor did not provide a corresponding HMA mixture for the new design. The US – 61 project was then comprised of five mixtures and three different WMA types.

Flow Number. Table 49 presents the flow number results for the five mixtures along with their respective average values and coefficients of variation.

Large variations could be noted in the tests, especially with the WMA Sasobit Sandstone mixture. Despite the relatively high data scatter, none of the mixtures presented tertiary creep; hence no signs of stripping could be attributed to the mixtures.

Table 49
US – 61 flow number test results

Conventional Granite		
Replicate #	**Air Voids**	**Flow Number**
1		2320
2		1680
3		2510
Average		2170
CV [%]		20.0
WMA Evotherm® Granite		
Replicate #	**Air Voids**	**Flow Number**
1		3778
2		1875
3		2292
Average		2648
CV [%]		37.8
WMA Sasobit Granite		
Replicate #	**Air Voids**	**Flow Number**
1		5907
2		4218
3		5113
Average		5079
CV [%]		16.6
WMA Foaming Sandstone		
Replicate #	**Air Voids**	**Flow Number**
1		3608
2		4817
3		6897
Average		5107
CV [%]		32.6
WMA Sasobit Sandstone		
Replicate #	**Air Voids**	**Flow Number**
1		8067
2		6488
3		7503
Average		7353
CV [%]		10.9

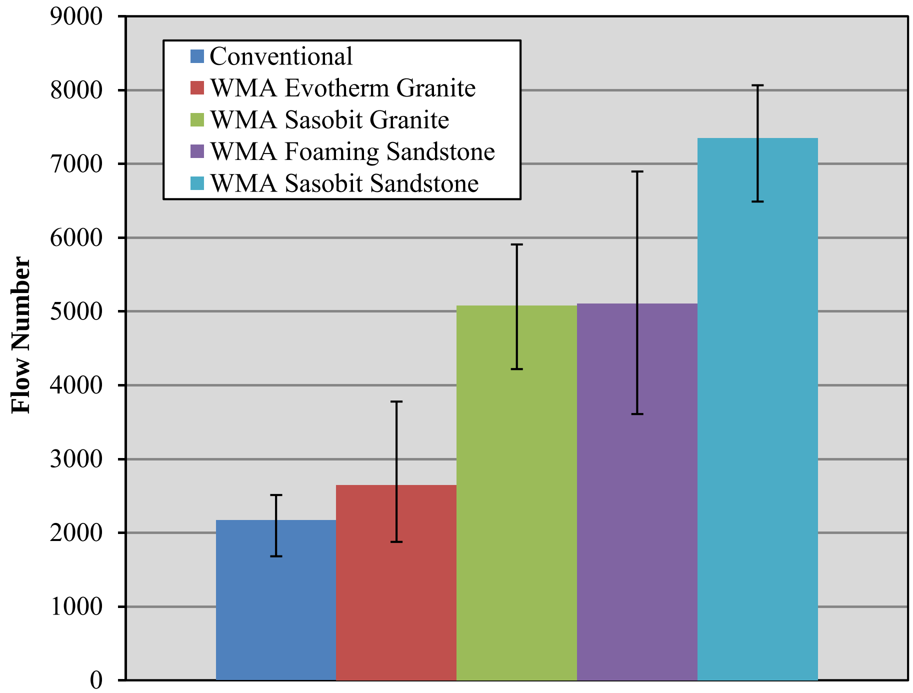


Figure 79
US – 61 Flow number test results

Loaded Wheel Tracking Test. The results from the LWT test are presented in the following figure. In general, the LWT results reflected the same trend seen on the flow number test. The two granite mixtures showed more permanent deformation, while the Sandstone mixture showed less rut depth.

No stripping was observed during testing. Therefore, evaluation of the stripping inflection point, stripping slope and creep slope was not performed. Figure 81 shows the rut depth at various passes. In this figure, it is possible to see that all mixtures stayed below the 6.0 mm rut depth at 20,000 passes limit for Louisiana mixtures.

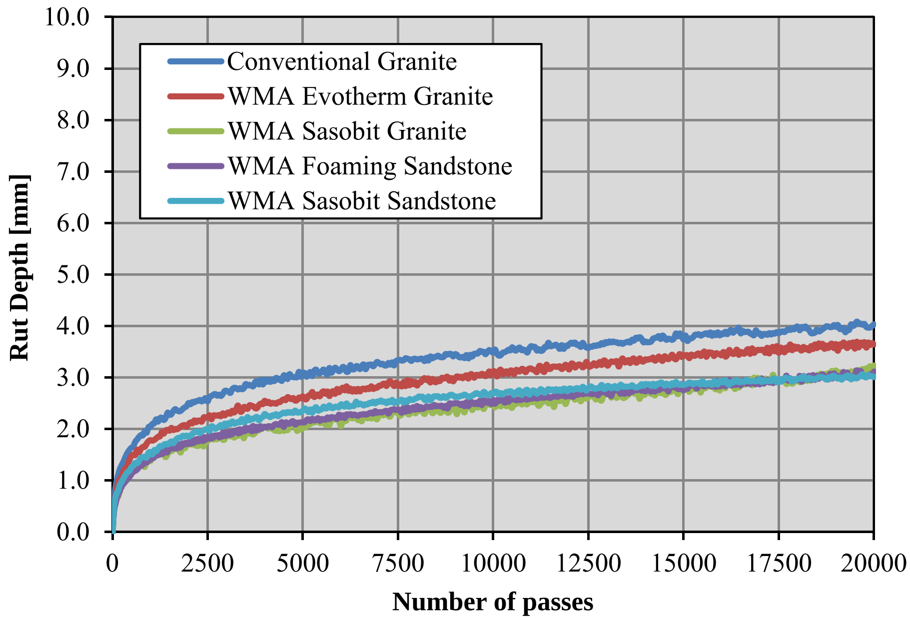
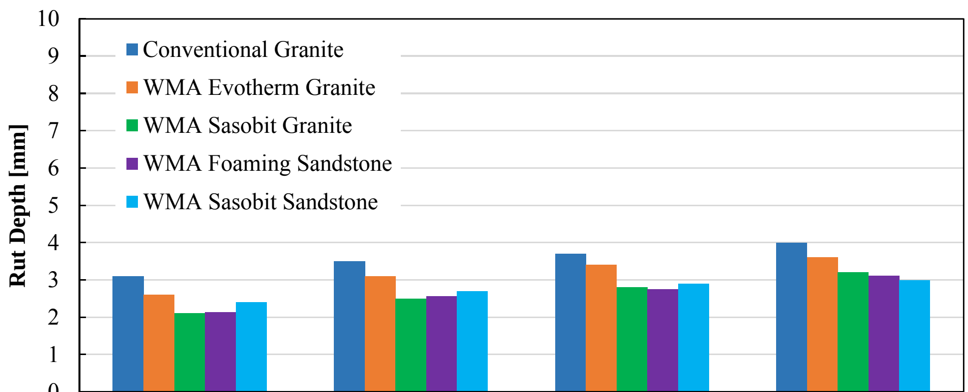


Figure 80

US – 61 LWT results



	5000	10000	15000	20000
Conventional Granite	3.1	3.5	3.7	4
WMA Evotherm Granite	2.6	3.1	3.4	3.6
WMA Sasobit Granite	2.1	2.5	2.8	3.2
WMA Foaming Sandstone	2.1	2.6	2.7	3.1
WMA Sasobit Sandstone	2.4	2.7	2.9	3

Number of Passes

Figure 81

US – 61 LWT results at various passes

Indirect Tensile Strength. The unaged and aged ITS results are shown in the following tables. The IT Strength and Toughness index are seen in Figure 82 and Figure 83 along with their respective error boundaries.

An increase in strength for aged mixtures can be observed, while the IT strain decreased with aging. These are indications that the aging process made the mixtures stiffer and more brittle. It is also observed that the increase in the strength with aging was lesser for the WMA mixtures than that of corresponding conventional HMA mixture.

Table 50
US – 61 unaged ITS test results

UNAGED			
Conventional Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	145.1	1.09	0.91
2	154.6	1.06	0.88
3	162.6	0.83	0.89
Average	**154.1**	**0.99**	**0.89**
CV (%)	6	14	2
WMA Evotherm® Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	186.2	0.97	0.84
2	185.4	0.90	0.86
3	179.7	0.83	0.81
Average	**183.8**	**0.90**	**0.84**
CV (%)	2	8	3
WMA Foaming Sandstone			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	200.2	0.87	0.83
2	196.7	0.99	0.87
3	194.4	0.86	0.85
Average	**197.1**	**0.90**	**0.85**
CV (%)	1	8	2

Table 50

US 61 - unaged ITS test results (continued)

UNAGED			
WMA Sasobit Sandstone			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	173.5	0.83	0.85
2	176.5	0.80	0.85
3	172.6	0.87	0.85
Average	**174.2**	**0.83**	**0.85**
CV (%)	1	4	0
WMA Sasobit Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
1	170.1	0.73	0.84
2	172.7	0.65	0.85
3	171.9	0.61	0.81
Average	**171.6**	**0.66**	**0.83**
CV (%)	1	10	2

Table 51
US – 61 aged ITS test results

AGED			
Conventional Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	201.8	0.79	0.83
5	182.3	0.80	0.85
6	192.0	0.78	0.82
Average	**192.0**	**0.79**	**0.83**
CV (%)	5	1	2
Evotherm® Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	209.7	0.63	0.78
5	214.8	0.52	0.74
6	210.9	0.48	0.72
Average	**211.8**	**0.54**	**0.75**
CV (%)	1	14	4
Foamed Sandstone			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	250.4	0.57	0.73
5	254.6	0.54	0.73
6	253.0	0.60	0.73
Average	**252.6**	**0.57**	**0.73**
CV (%)	1	6	0
Sasobit Sandstone			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	246.5	0.49	0.71
5	236.3	0.49	0.72
6	291.3	0.48	0.73
Average	**258.0**	**0.49**	**0.72**
CV (%)	11	2	2

Table 51
US – 61 aged ITS test results (continued)

AGED			
Sasobit Granite			
Sample No.	IT Strength [psi]	IT Strain [%]	TI
4	198.3	0.66	0.78
5	208.7	0.50	0.76
6	202.8	0.65	0.74
Average	**203.3**	**0.60**	**0.76**
CV (%)	3	15	15

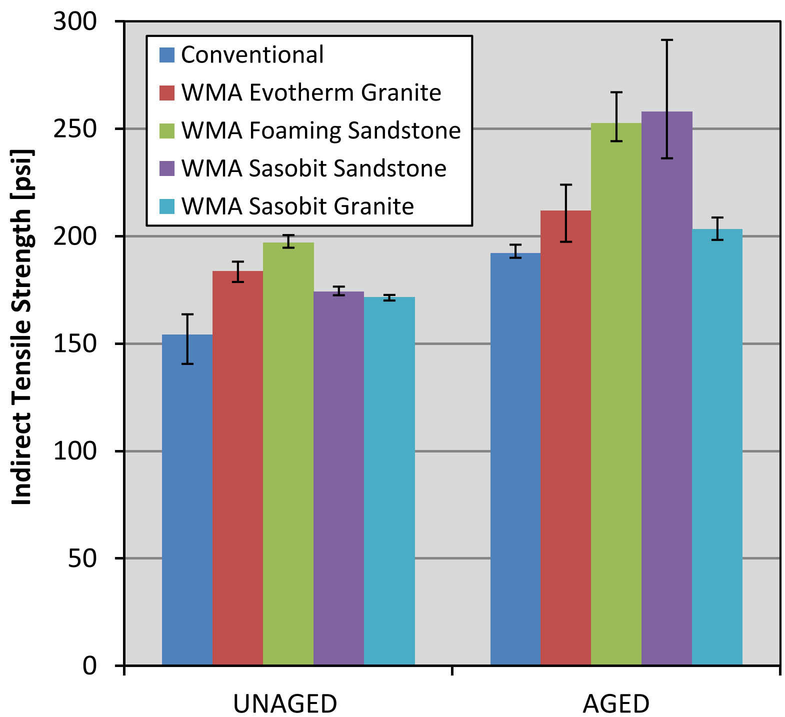


Figure 82
US – 61 indirect tensile results

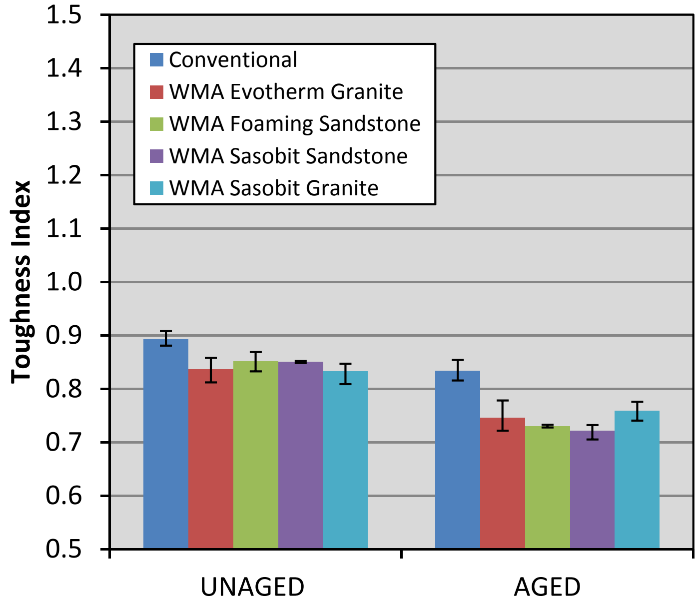


Figure 83
US – 61 toughness index results

Dissipated Creep Strain Energy Results. Table 52 summarizes the DCSE test results for each of the mixtures. Figure 84 shows the DCSE values along with their corresponding error limits. It is observed that all the mixtures met the failure criteria of 0.75 KJ/m^3, which is an indication of low susceptibility to failure by fracture in the field. It is also worth noting that the US – 61 DCSE samples were the last ones to be tested from the entire project.

Table 52
US – 61 DCSE test results

Conventional Granite						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	2086100	1928	474	1926	0.27	3.15
2	1995000	1436	461	1434	0.29	2.28
3	2134700	2029	458	2027	0.31	3.20
Average	2071933	1798	464	1796	0.29	2.87
CV [%]	3.4	17.6	1.8	17.7	6.3	18.0

Table 52
US – 61 DCSE test results (continued)

Evotherm® Granite						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	2026300	971	456	958	0.29	1.51
2	1845000	1739	427	1737	0.29	2.56
3	2042200	1071	465	1680	0.21	2.70
Average	1971167	1260	450	1458	0.26	2.25
CV [%]	5.6	33.1	4.5	29.8	18.3	28.8
Sasobit Granite						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	2091000	1528	470	1526	0.29	2.47
2	2186500	1975	349	1973	0.28	2.38
3						
Average	2138750	1752	410	1750	0.28	2.43
CV [%]	3.2	18.0	20.9	18.1	0.5	2.8
Foaming Sandstone						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	2383500	2146	503	2144	0.29	3.71
2	1883500	1639	427	1635	0.31	2.41
3						
Average	2133500	1893	465	1890	0.30	3.06
CV [%]	16.6	18.9	11.5	19.0	5.0	30.2
Sasobit Sandstone						
Replicate #	**Resilient Modulus** [psi]	**Failure Strain** [µstrain]	**ITS** [psi]	**Initial Strain** [µstrain]	**Poisson's Ratio - µ**	**Dissipated Energy** [KJ/m^3]
1	1844400	1765	462	1762	0.22	2.81
2	2096000	1933	483	1931	0.29	3.22
3	2150800	1934	480	1932	0.31	3.20
Average	2030400	1877	475	1875	0.27	3.07
CV [%]	8.0	5.2	2.4	5.2	17.3	7.5

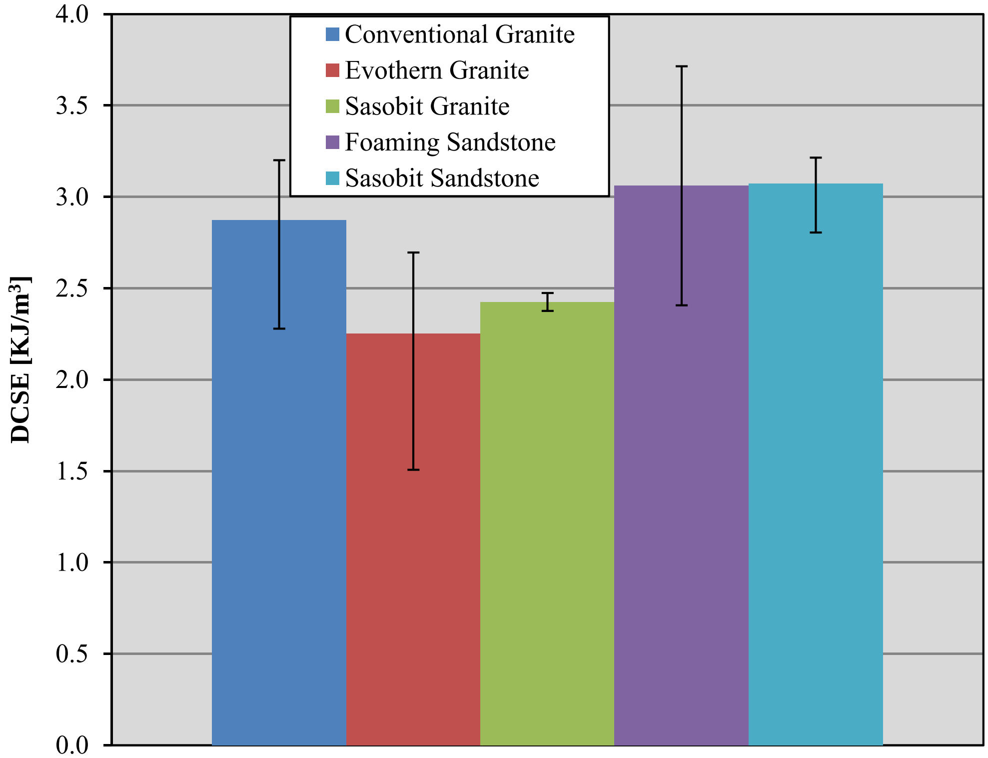


Figure 84
US – 61 DCSE results

Semi-Circular Bending Test Results. The SCB results are shown in Table 53. As seen in Figure 85, the WMA mixtures had similar results among themselves. The conventional HMA mixture presented lower values of J_c when compared to the WMA mixtures.

Table 53
US – 61 SCB test results

Conventional Granite							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.937	0.870	0.562	0.654	0.655	0.437	0.4
2	0.953	0.614	0.516	0.669	0.438	0.337	
3	0.919	0.633	0.600	0.660	0.444	0.382	
4	0.963	0.811	0.641	0.597	0.582	0.451	
Average	0.943	0.732	0.580	0.645	0.530	0.402	
CV [%]	2.0	17.4	9.2	5.1	20.1	13.0	
WMA Evotherm® Granite							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	0.890	0.571	0.492	0.702	0.428	0.400	0.5
2	0.992	0.835	0.494	0.804	0.553	0.400	
3	1.088	0.839	0.536	0.792	0.579	0.424	
4	0.939	0.849	0.512	0.686	0.439	0.311	
Average	0.977	0.774	0.509	0.746	0.500	0.384	
CV [%]	8.7	17.5	4.0	8.1	15.5	13.0	
WMA Sasobit Granite							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.108	0.934	0.584	0.578	0.344	0.217	0.5
2	0.963	0.957	0.765	0.553	0.451	0.406	
3	1.056	0.825	0.715	0.438	0.453	0.307	
4	1.202	0.856	0.542	0.648	0.389	0.134	
Average	1.082	0.893	0.652	0.554	0.409	0.266	
CV [%]	9.2	7.0	16.2	15.7	12.9	44.0	
WMA Foaming Sandstone							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.229	0.881	0.669	0.776	0.521	0.349	0.5
2	1.294	1.079	0.640	0.720	0.572	0.402	
3	1.148	0.889	0.622	0.578	0.509	0.472	
4	1.434	0.956	0.712	0.741	0.552	0.514	
Average	1.276	0.951	0.661	0.704	0.539	0.434	
CV [%]	9.5	9.7	6.0	12.4	5.3	16.8	

Table 53
US – 61 SCB test results (continued)

WMA Sasobit Sandstone							
Replicate #	**Peak Load [KN]**			**Area [KN*mm]**			**J_c [KN/m^2]**
	25.4	31.8	38.1	25.4	31.8	38.1	
1	1.380	1.047	0.754	0.781	0.472	0.302	0.5
2	1.251	0.970	0.636	0.758	0.467	0.332	
3	1.329	0.966	0.683	0.568	0.429	0.396	
4	1.141	0.993	0.729	0.569	0.395	0.422	
Average	1.275	0.994	0.700	0.669	0.441	0.363	
CV [%]	8.2	3.8	7.5	17.4	8.3	15.3	

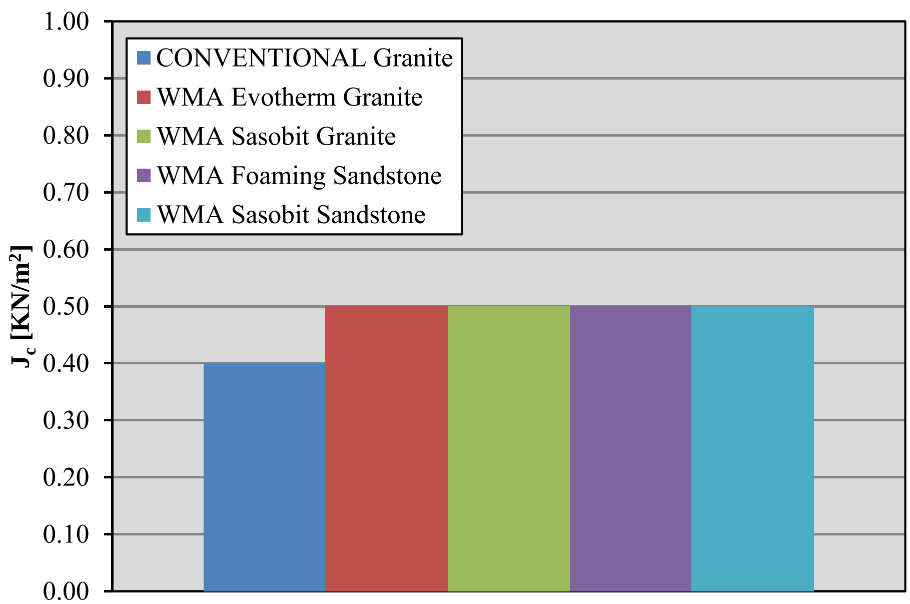


Figure 85
US – 61 critical values of the J-Integral

Dynamic Modulus Test Results. The dynamic modulus results for the five mixtures are presented in Table 54 through Table 58. The normalized values are shown in Figure 86 through Figure 90. All of the results were comparable to each other with the major differences seen at higher temperatures. Despite the different aggregate sources, the sandstone mixtures did not show a substantial difference when compared to the conventional HMA.

Table 54

US – 61 conventional dynamic modulus results

Conventional Granite			
Temp. [ºC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	22255	1.84
	10	21426	4.05
	5	20642	5.11
	1	18554	6.84
	0.5	17604	7.57
	0.1	15316	9.46
4.4	25	16374	6.46
	10	15089	9.28
	5	14043	10.86
	1	11245	14.24
	0.5	10144	15.76
	0.1	7767	19.60
25	25	6961	22.44
	10	5491	24.90
	5	4618	26.51
	1	2847	30.30
	0.5	2248	31.29
	0.1	1200	32.88
37.8	25	3047	31.35
	10	2172	33.14
	5	1650	33.56
	1	811	34.21
	0.5	611	33.08
	0.1	314	30.73
54.4	25	878	35.12
	10	524	36.73
	5	380	35.19
	1	186	31.72
	0.5	150	29.29
	0.1	97	24.48

Table 55
US – 61 WMA Evotherm® granite dynamic modulus results

WMA Evotherm® Granite			
Temp. [oC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	23727	1.56
	10	22830	3.68
	5	22033	4.68
	1	19979	6.36
	0.5	19040	6.97
	0.1	16657	8.87
4.4	25	15909	7.33
	10	14344	10.27
	5	13182	11.97
	1	10393	15.84
	0.5	9247	17.52
	0.1	6755	21.60
25	25	7083	22.80
	10	5605	25.43
	5	4732	27.08
	1	2895	31.03
	0.5	2287	31.83
	0.1	1218	33.39
37.8	25	3205	31.17
	10	2258	33.10
	5	1699	33.56
	1	816	34.19
	0.5	606	33.14
	0.1	308	30.60
54.4	25	767	35.09
	10	439	37.09
	5	315	35.60
	1	155	31.49
	0.5	126	29.01
	0.1	83	24.88

Table 56
US – 61 WMA Sasobit granite dynamic modulus results

WMA Sasobit Granite			
Temp. [oC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	23526	1.26
	10	22813	3.29
	5	22156	4.16
	1	20385	5.55
	0.5	19556	6.07
	0.1	17560	7.37
4.4	25	16682	5.05
	10	15531	7.66
	5	14560	9.01
	1	12184	11.81
	0.5	11152	13.07
	0.1	8829	16.15
25	25	8427	18.82
	10	7013	21.27
	5	5904	22.95
	1	3904	27.09
	0.5	3241	28.30
	0.1	1936	31.21
37.8	25	3859	28.81
	10	2878	31.11
	5	2283	32.07
	1	1196	34.17
	0.5	911	33.83
	0.1	460	33.65
54.4	25	1090	36.38
	10	673	38.31
	5	487	37.45
	1	231	35.54
	0.5	181	33.69
	0.1	109	29.85

Table 57

US – 61 WMA foaming sandstone dynamic modulus results

WMA Foaming Sandstone			
Temp. [oC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	20668	1.78
	10	19924	3.88
	5	19266	4.81
	1	17577	6.28
	0.5	16813	6.88
	0.1	14943	8.35
4.4	25	16139	8.49
	10	14873	9.76
	5	13908	10.66
	1	11607	13.04
	0.5	10596	14.24
	0.1	8215	17.50
25	25	7145	20.67
	10	5855	23.24
	5	4874	24.96
	1	3117	29.02
	0.5	2590	30.18
	0.1	1496	32.22
37.8	25	3006	29.80
	10	2195	31.93
	5	1708	32.49
	1	872	33.75
	0.5	659	33.25
	0.1	337	31.78
54.4	25	893	33.54
	10	534	35.91
	5	390	34.87
	1	193	32.11
	0.5	159	29.74
	0.1	104	25.70

Table 58

US – 61 WMA Sasobit sandstone dynamic modulus results

WMA Sasobit Sandstone			
Temp. [oC]	**Frequency [Hz]**	**|E*| [MPa]**	**Phase Angle**
-10	25	21238	2.06
	10	20460	4.22
	5	19774	5.20
	1	17927	6.67
	0.5	17149	7.30
	0.1	15159	8.77
4.4	25	16156	8.00
	10	14916	9.18
	5	13983	9.98
	1	11796	12.20
	0.5	10827	13.30
	0.1	8575	16.37
25	25	7260	19.61
	10	5947	22.12
	5	5082	23.89
	1	3360	28.15
	0.5	2773	29.26
	0.1	1648	32.10
37.8	25	3339	29.34
	10	2474	31.50
	5	1960	32.27
	1	1065	34.00
	0.5	842	33.21
	0.1	441	32.48
54.4	25	1009	35.33
	10	648	37.10
	5	485	36.04
	1	236	34.07
	0.5	190	31.93
	0.1	116	28.59

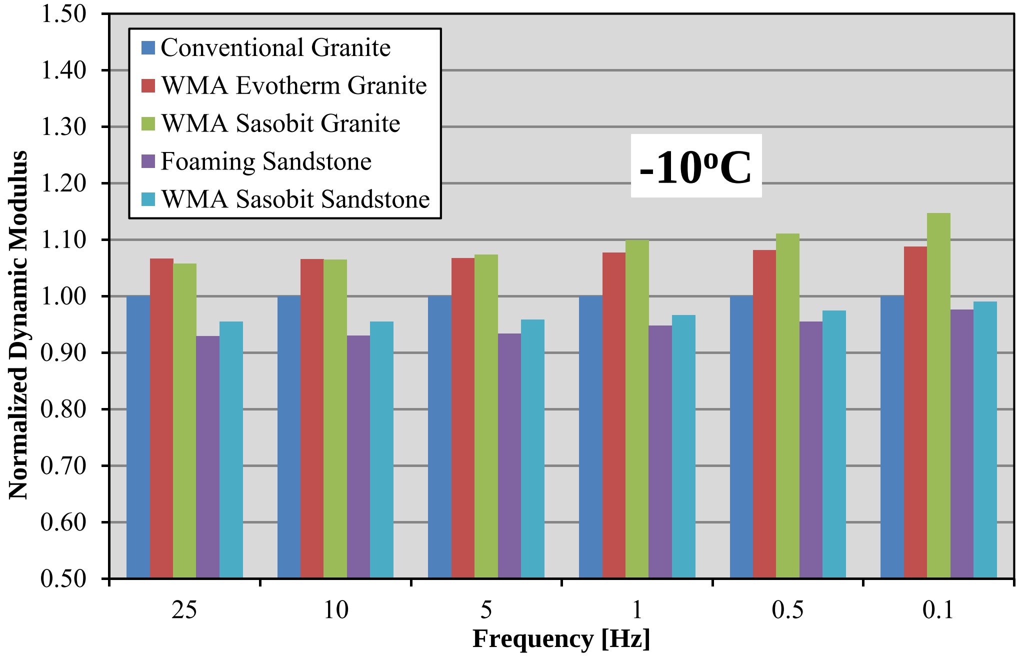


Figure 86

US – 61 normalized dynamic modulus at -10ºC

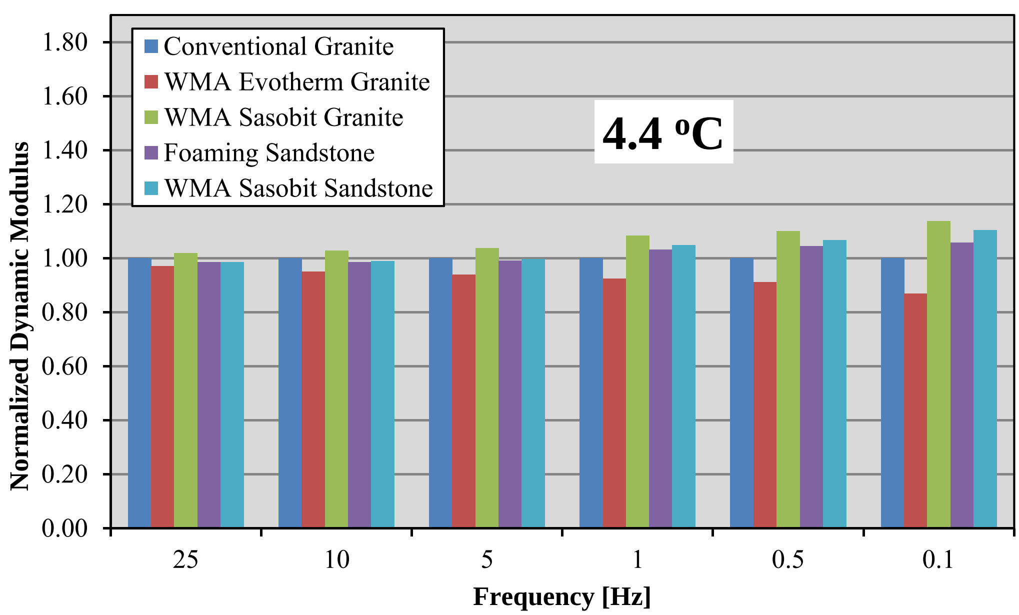


Figure 87

US – 61 normalized dynamic modulus at 4.4ºC

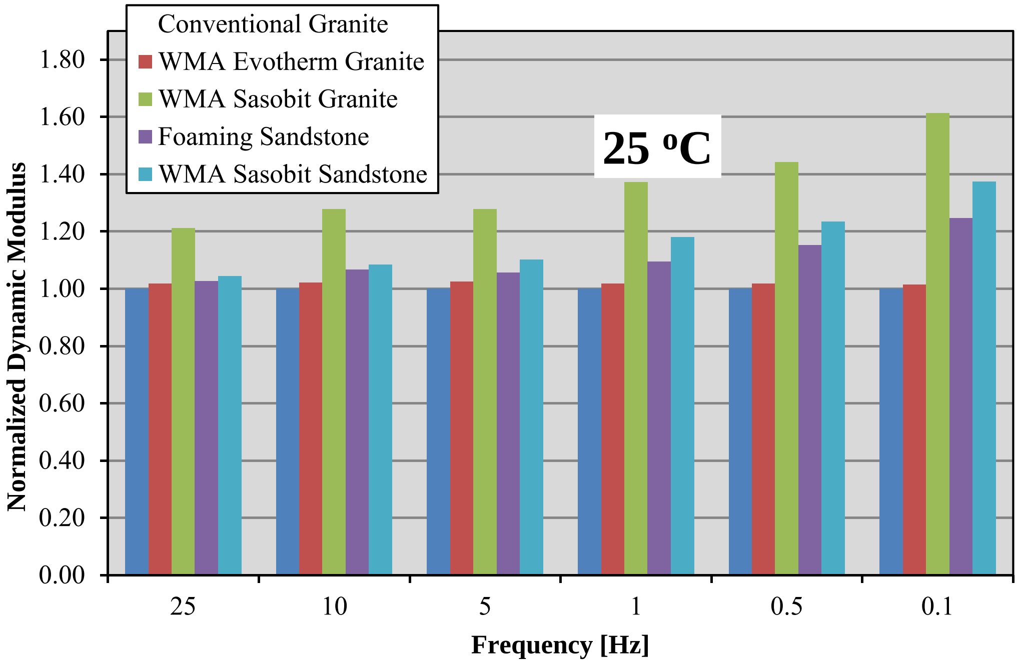


Figure 88

US – 61 normalized dynamic modulus at 25ºC

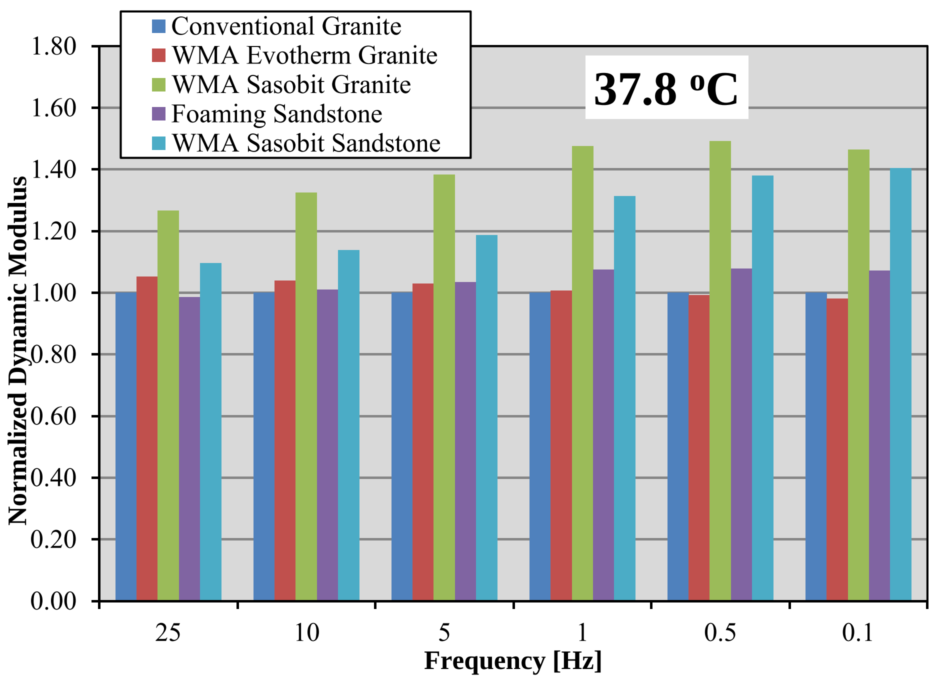


Figure 89

US – 61 normalized dynamic modulus at 37.8ºC

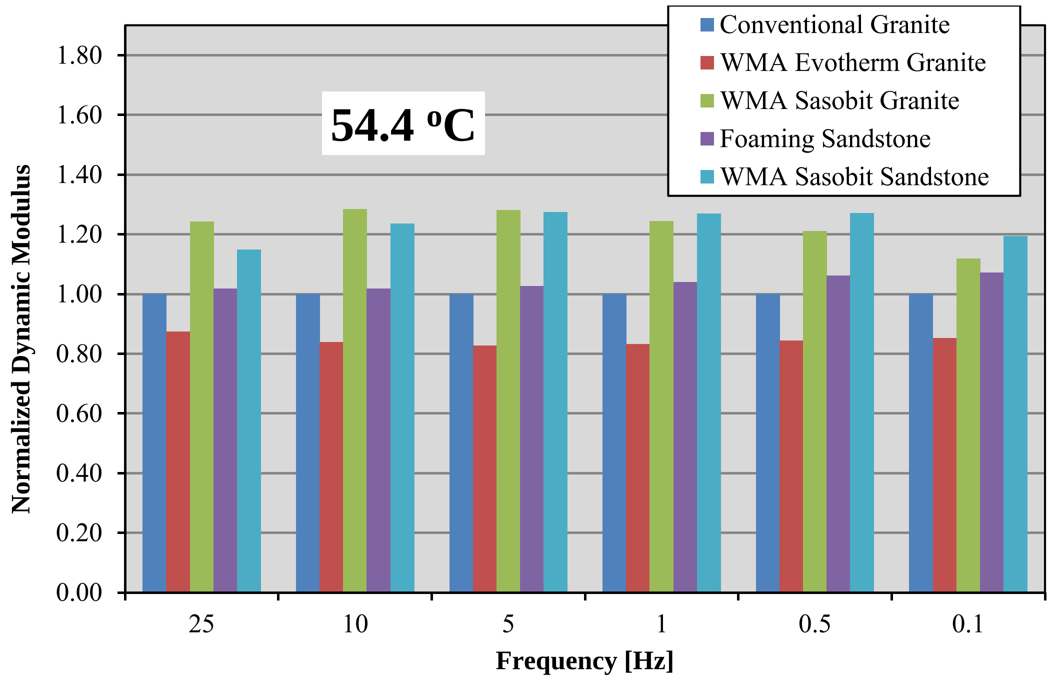


Figure 90
US – 61 normalized dynamic modulus at 54.4ºC

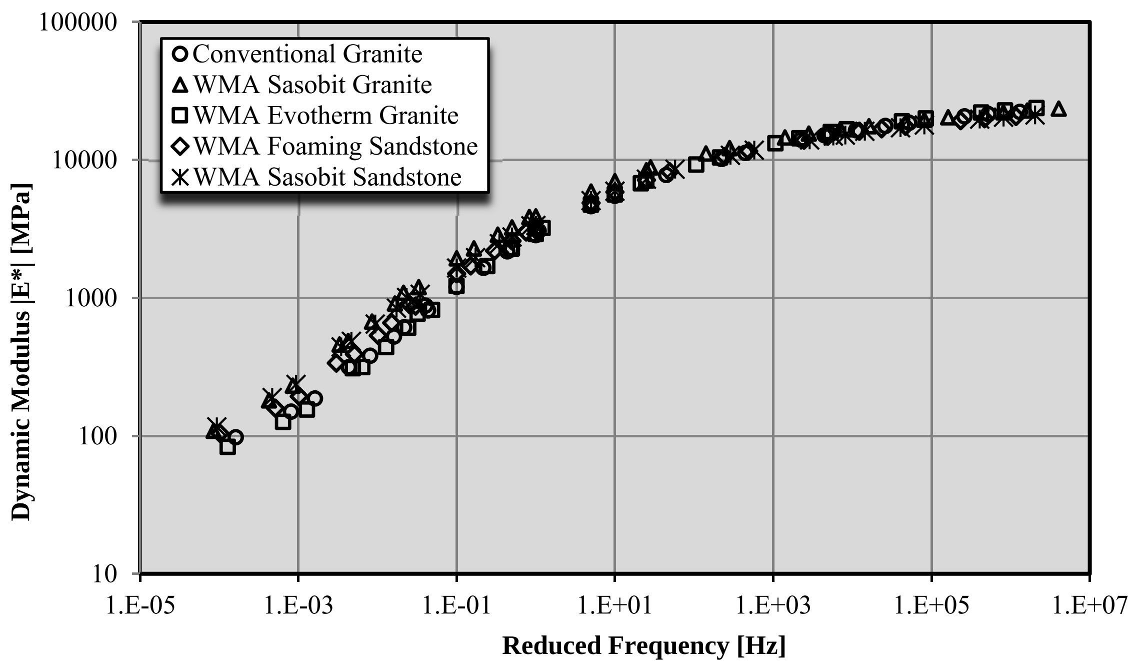


Figure 91
US – 61 Mastercurves at 25ºC

Modified Lottman Test Results. Table 59 summarizes the Modified Lottman Test results. The mean tensile strength values for the controlled and the conditioned specimens and the TSR values of the asphalt mixtures are shown.

The TSR values are shown in Figure 92. It is seen that the WMA granite mixtures had a similar performance in terms of moisture susceptibility compared to the conventional HMA Granite mixture. It is noted that the all mixtures met the DOTD specification of 80% TSR. Moreover, all of the conditioned IDT strengths were equal to or greater than 100 psi, a strength value associated with well-performing mixtures for Louisiana climate conditions.

Table 59
US – 61 WMA Modified Lottman results

Conventional Granite		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	166.3	146.5
2	163.6	156.3
3	153.5	156.0
Average	161.1	152.9
CV [%]	4.2	3.7
TSR [%]	**94.9**	
WMA Evotherm® Granite		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	144.5	138.7
2	148.5	131.9
3	136.4	122.2
Average	143.1	130.9
CV [%]	4.3	6.3
TSR [%]	**91.5**	

Table 59
US – 61 WMA Modified Lottman results (continued)

WMA Sasobit Granite		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	129.3	118.5
2	137.1	122.3
3	136.9	126.6
Average	134.4	122.5
CV [%]	3.3	3.3
TSR [%]	**91.1**	
WMA Foaming Sandstone		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	131.9	159.4
2	187.5	163.6
3	172.9	155.9
Average	164.1	159.6
CV [%]	17.6	2.4
TSR [%]	**97.3**	
WMA Sasobit Sandstone		
Specimen ID	Control	Conditioned
	Tensile Strength [psi]	Tensile Strength [psi]
1	197.2	169.2
2	186.8	180.0
3	186.3	172.1
Average	190.1	173.7
CV [%]	3.2	3.2
TSR [%]	**91.4**	

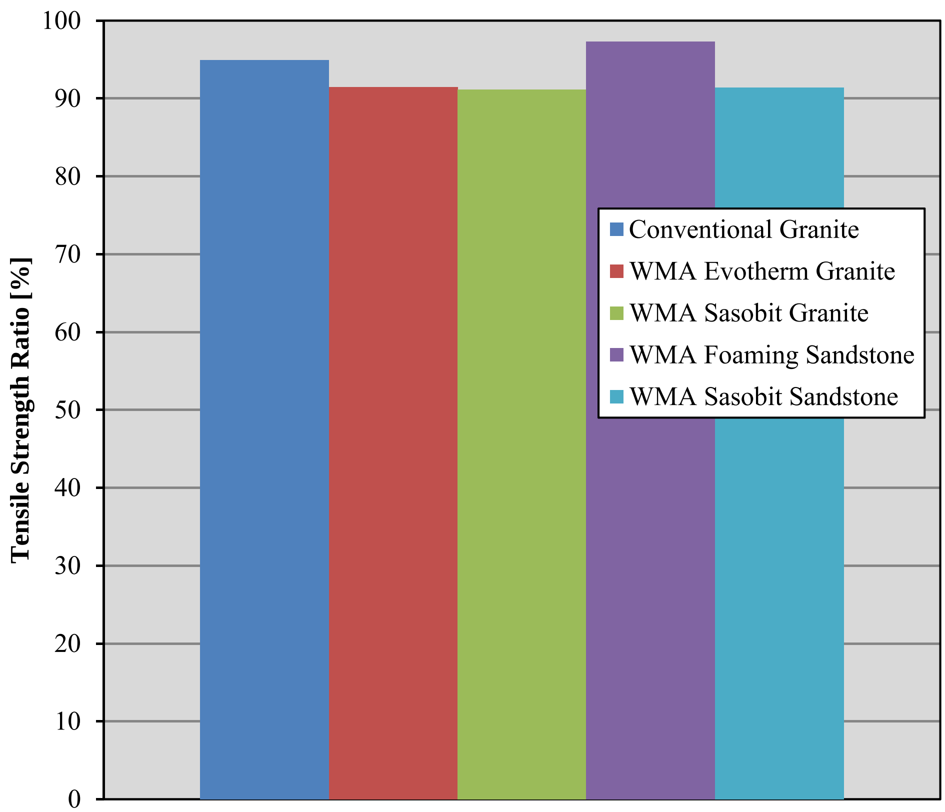


Figure 92
US – 61 TSR results

Overall Considerations

Statistical analyses were conducted on the performance characteristics derived from the mechanistic tests accomplished in this study. A Statistical Analysis Program (SAS) was used for the analysis. The mean values of the performance characteristics obtained from mechanistic testing for each set of specimens were used. Analysis of Variance (ANOVA) with Least Significant Difference (LSD) option and pair wise t-test were performed to draw comparisons between the performance of the WMA mixtures and the control HMA mixtures. A Type I error rate (α) of 0.05 was used to differentiate any significant difference between the mixtures in consideration. This methodology was used to rank the asphalt mixtures comparatively to the conventional HMA mixture respective to each project. The statistical rankings obtained by each mixture were designated by letters A, B, and C. The letter "A" was assigned to mixtures that exhibited significant statistical difference from mixtures with "B", which is statistically different from mixtures with "C". The "A" was assigned to the best performer within a group of mixtures from each field project. The results are shown as follows.

Figure 93
Statistical analysis of flow number results

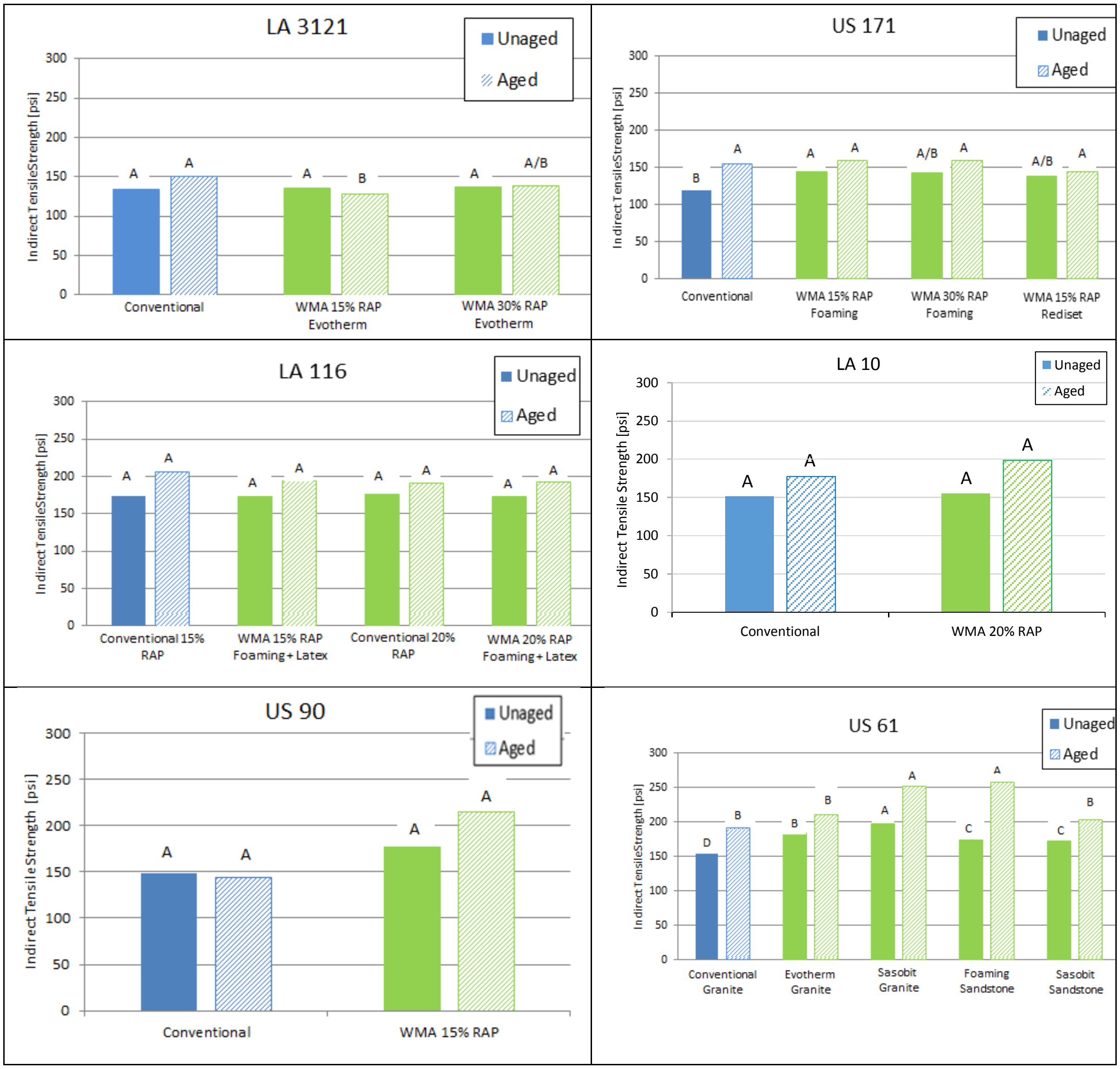


Figure 94

Statistical analysis of ITS results

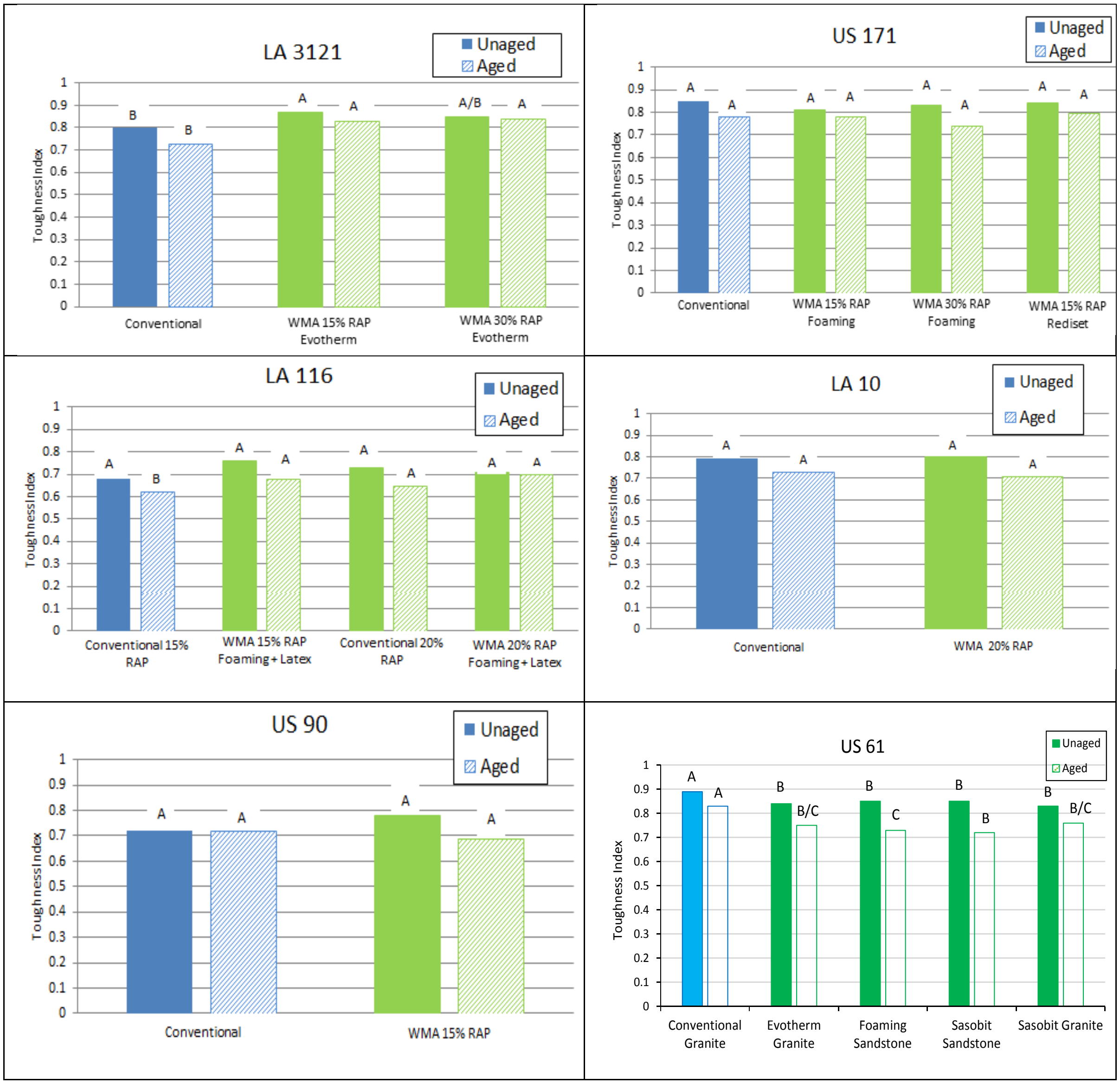


Figure 95
Statistical analysis of toughness index results

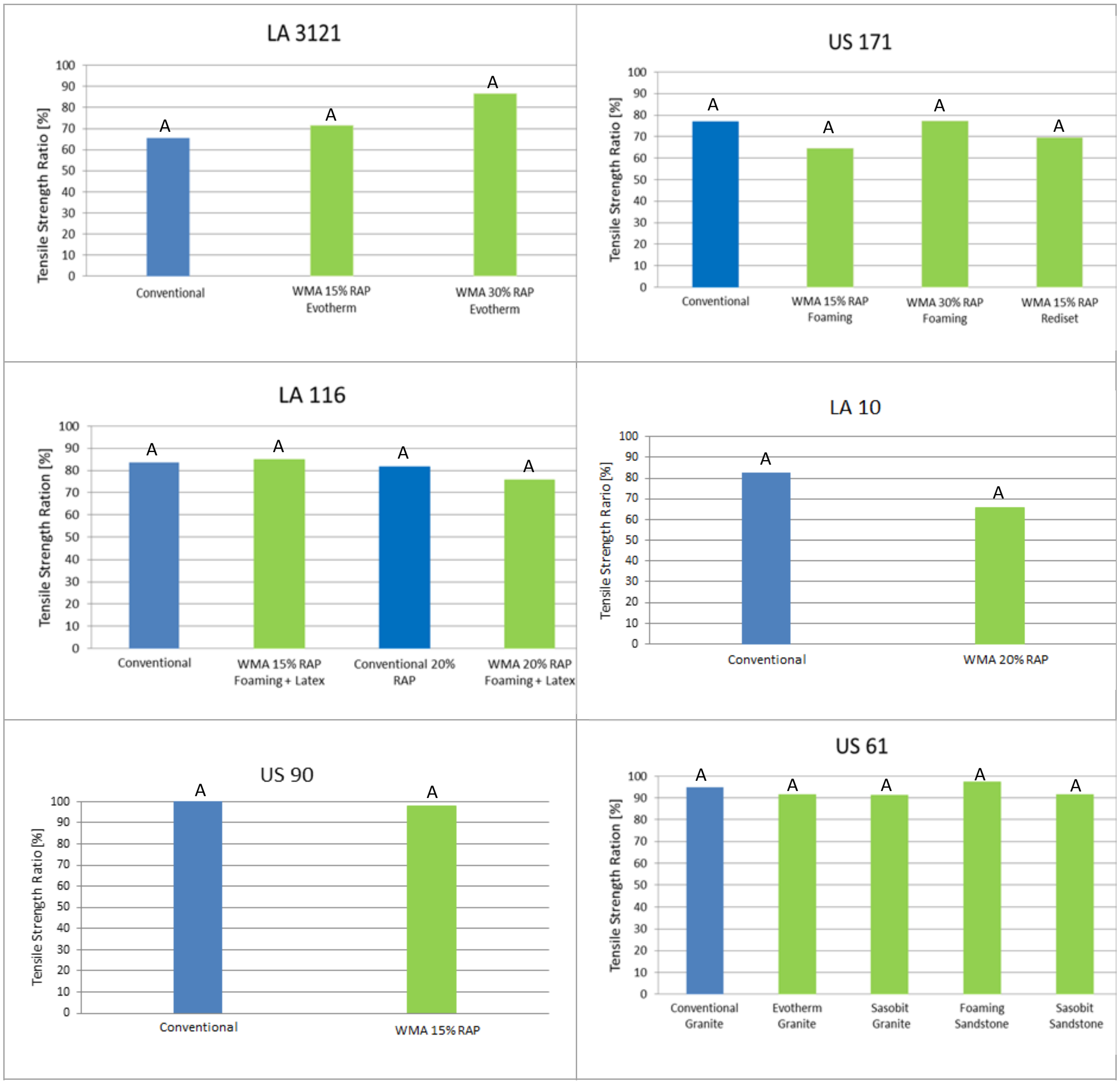


Figure 96
Statistical analysis of Lottman results

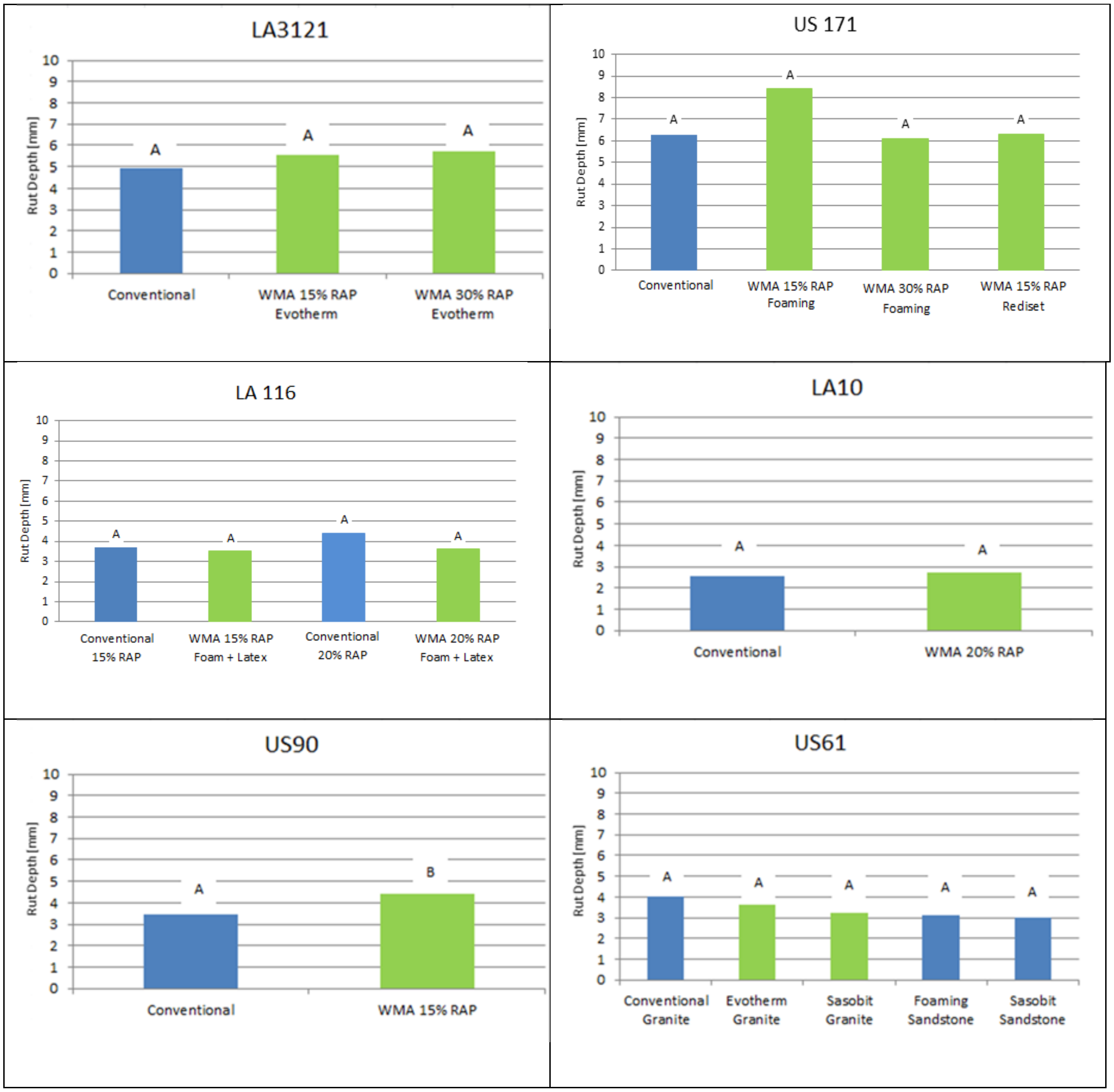


Figure 97
Statistical analysis of LWT results

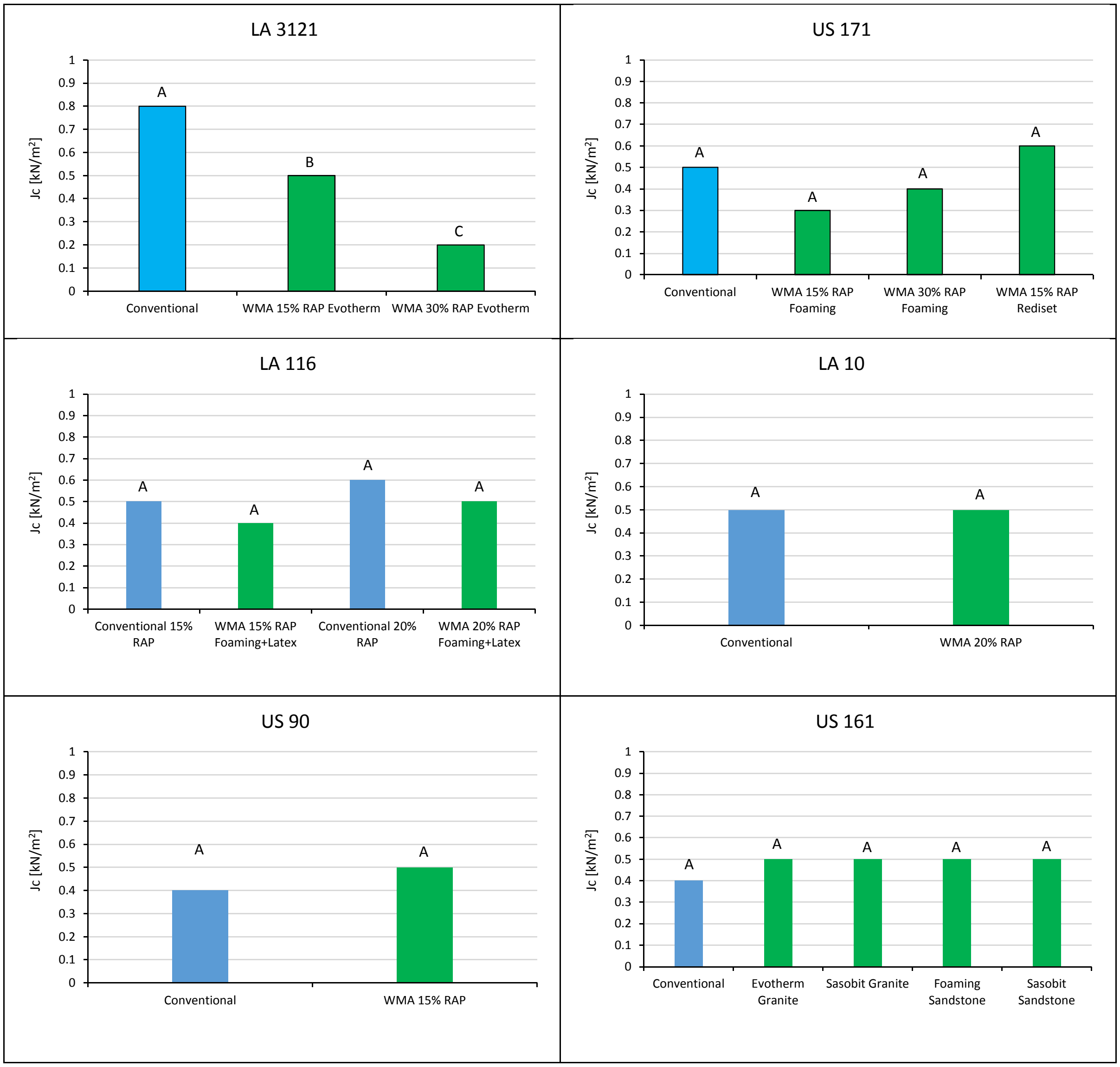


Figure 98
Statistical analysis of SCB results

Comparison of Production and Placement Practices of HMA and WMA Mixtures

One of the objectives of this study was to compare the production and placement practices of HMA and WMA mixtures. To assess differences at the asphalt plant, the following two mixture properties were evaluated: (1) the moisture content in the produced mixture and (2) the percentage of asphalt binder absorbed into the aggregate. At the roadway, the properties measured included: (1) temperature uniformity of the mat, (2) rate of densification, and (3) final density achieved.

Properties Measured at the Asphalt Plant

Moisture Content in the Plant-produced Mix. Since WMA is produced at lower temperatures compared to HMA, there is concern that the reduced heating may not dry the aggregate sufficiently, which could lead to moisture damage in the pavement. DOTD specifies that the moisture content in the produced mixture be less than 0.3% and requires monitoring as part of the plant quality control process. To compare the moisture contents of the WMA mixtures and their corresponding control HMA mixture, moisture data was collected for the US 61 project and is presented in Figure 99. There are five different mixtures: Conventional Granite (HMA/Gran), Evotherm Granite (Evo/Gran), Sasobit Granite (Sas/Gran), Sasobit Sandstone (Sas/SS), and Foaming Sandstone (Foam/SS). The blue and green bars represent the HMA and WMA mixtures, respectively, and are an average of five readings taken per lot of production. The error bars show the 95% confidence interval for the mean. The upper limits of the confidence intervals for all the mixtures were below the maximum specification limit. This indicates that the aggregates were drying adequately in the WMA mixtures.

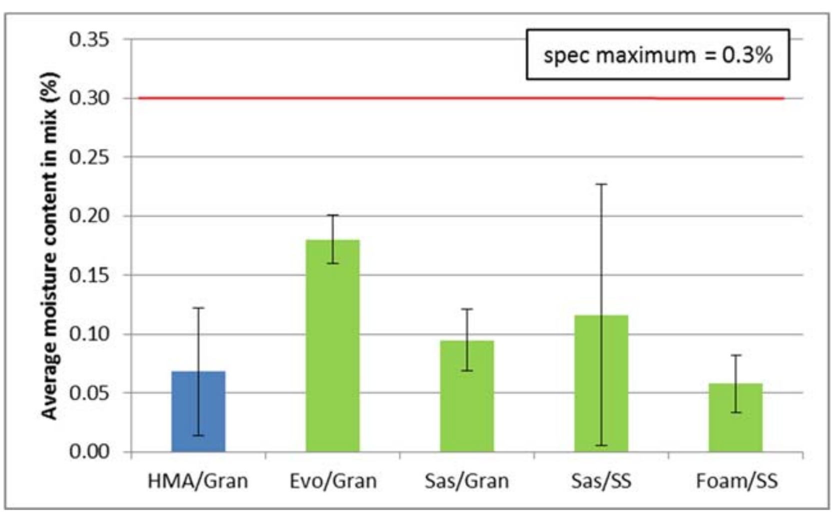


Figure 99
Moisture content in the mixture produced at the plant (US– 61 project)

Asphalt Absorption. It has been reported that lowering the production temperature for WMA mixtures may decrease the absorption of the liquid asphalt into the aggregate (NCHRP Project 9-47A). Figure 100 presents the average percent binder absorbed (Pba) for the HMA and WMA mixtures in the US 61 project. The blue bar represents the HMA and the green bars represent the WMA mixtures. The error bars show the 95% confidence intervals for the data. The Pba for the control HMA/Gran and the WMA mixture Evo/Gran was similar. However, WMA mixture Sas/Gran exhibited higher Pba than both HMA/Gran and Evo/Gran though they were not statistically different. It is noted that the granite aggregate possessed low water absorption of 0.6 percent. On the other hand, WMA mixtures Sas/SS and Foam/SS showed higher Pba values than HMA/Gran, WMA mixture Evo/Gran, and WMA mixture Sas/Gran. This increase is attributed to the high water absorption (1.4%) of the sandstone aggregate. In summary, for the mixtures in the US– 61 project, in general, the Pba for both HMA and WMA mixtures containing granite aggregates were similar.

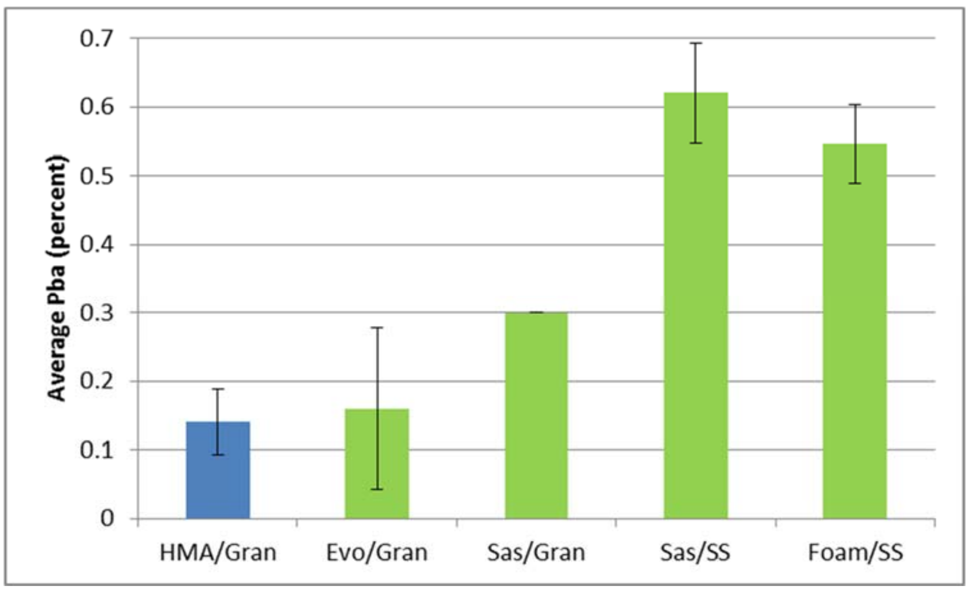
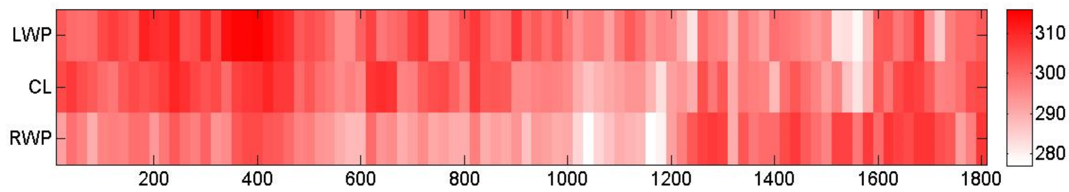


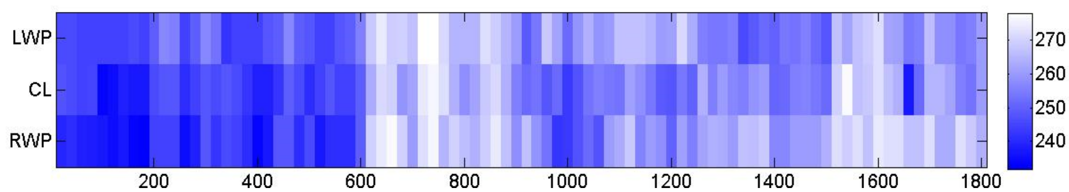
Figure 100
Percent binder absorbed (Pba) in the HMA and WMA mixtures for US 61

Properties Evaluated at the Roadway

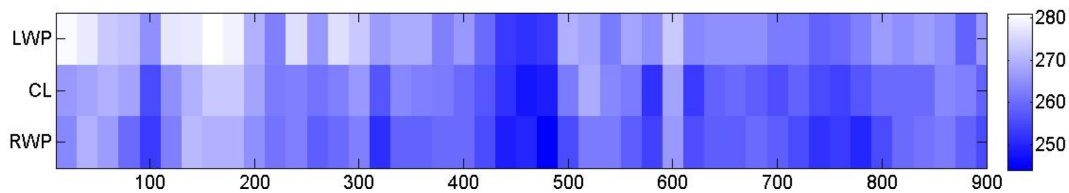
Temperature Uniformity of the Mat. In order to compare the temperature uniformity of the HMA and WMA mats, temperatures were measured at the left wheel path (LWP), center line (CL), and right wheel path (RWP) for the US 61 project. An infrared temperature gun was used for this purpose and readings were taken behind the paver every 20 feet. Figure 101 presents the heat maps generated from this data. The average temperature for the HMA test section was 299°F while the average temperatures for the WMA sections varied between 256°F and 267°F. The standard deviation for the first three WMA sections varied between 7.2°F and 11.9°F and compared favorably with the HMA section standard deviation of 7.1°F. For the Foamed/Sandstone WMA test section, the contractor encountered some wet aggregate in the middle of the production and had to raise the temperature in order to dry it adequately. This is reflected in the heat map as the red colored area in the middle of the test section.



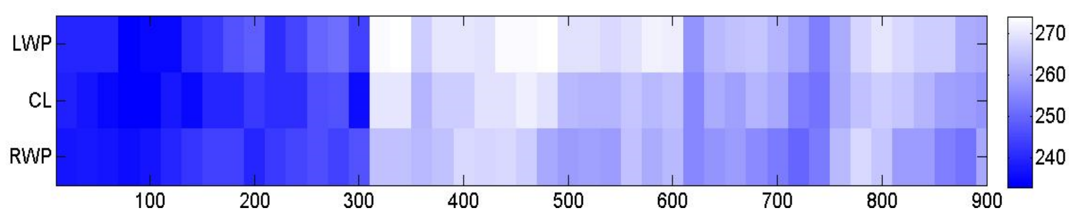
(a) HMA



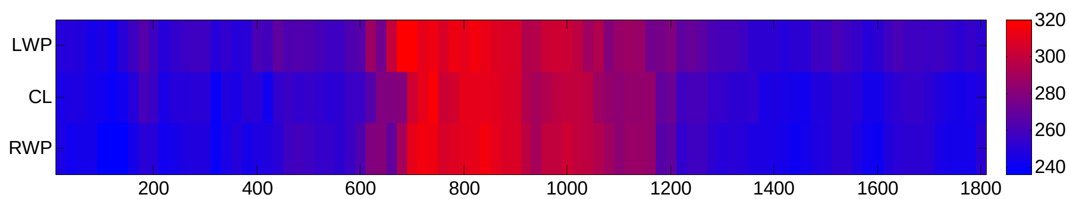
(b) Evotherm®



(c) Sasobit (granite)



(d) Sasobit (sandstone)

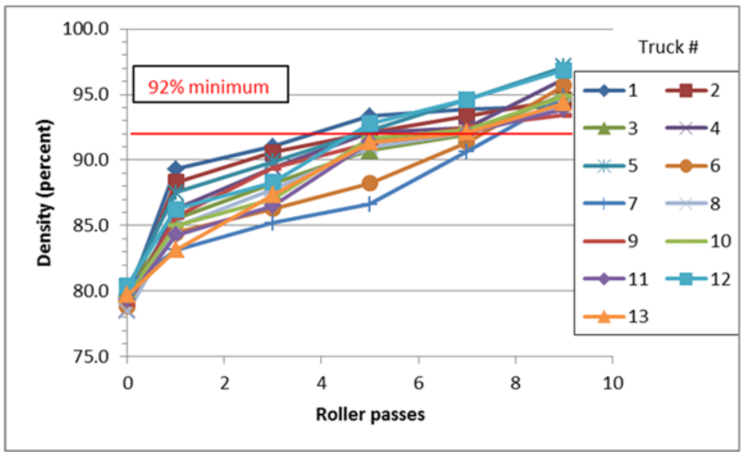


(e) Foamed (sandstone)

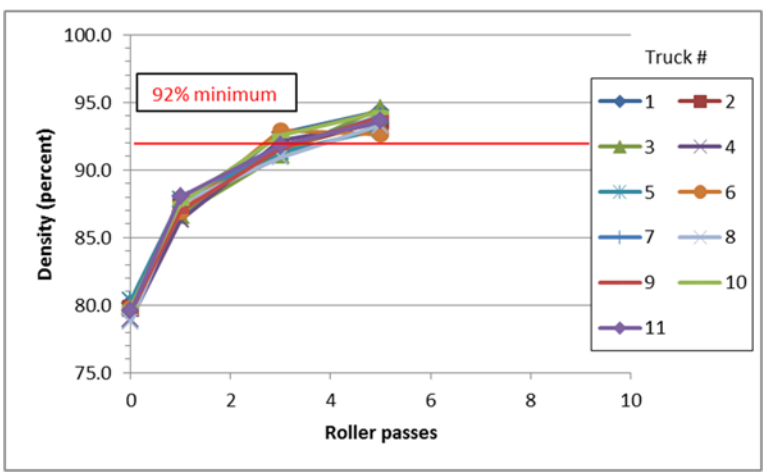
Figure 101
Heat map of the HMA and WMA test sections

Rate of Densification. To evaluate the rate of densification of the HMA and WMA mixtures, nuclear density readings were obtained during the compaction process for the LA 116 project, wearing course mixture. The readings were taken at 0, 1, 3, 5, 7, and 9 passes of the roller and are presented in Figure 102.

The DOTD specification requires a minimum level of compaction of 92% of the theoretical maximum specific gravity of the mixture. The HMA layer required nine passes of the rollers to achieve the minimum density whereas the WMA layer required only five passes of the rollers to achieve the same. Therefore, in this case, the WMA mixture required less passes of the rollers to reach the desired level of compaction.



(a) Densification of the HMA layer



(b) Densification of the WMA layer

Figure 102
Roller passes required for (a) HMA and (b) WMA layers

For the US 61 project, the information available included the number of passes required during each stage of the compaction process, i.e., breakdown, intermediate, and final. Figure 103 presents this information, with the intermediate stage further subdivided into the number of passes of the vibratory and the pneumatic rubber tired roller. During the breakdown stage, the WMA mixtures required two fewer passes of the roller as compared to the companion HMA mixture. This effect was not observed in the subsequent stages of compaction. In summary, for the US 61 project there seemed to be no discernible difference in the compaction effort required for the HMA and WMA mixtures.

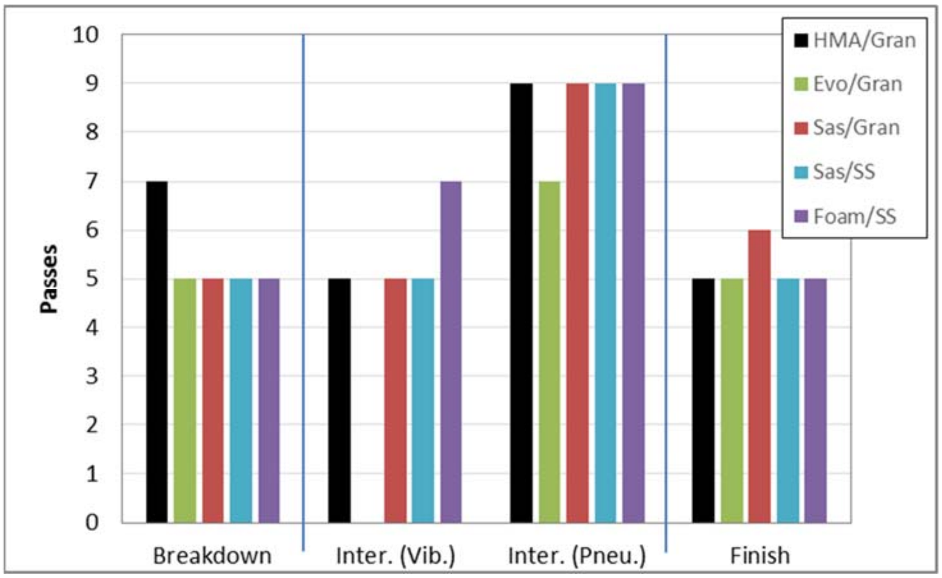


Figure 103
Number of roller passes required for the US 61 project

Final Density. Figures 104 through 107 present the densities obtained in the projects LA 3121, US 171, LA 116, and US 61, respectively. For LA 3121, there are three mixtures: Conventional (Con15), WMA 15% RAP Evotherm (Evo15), WMA 30% RAP (Evo30). For US 171, there are four mixtures: Conventional (Con15), WMA 15% RAP Evotherm (Evo15), WMA 30% RAP (Evo30), and WMA 15% RAP Rediset (Redi15). The LA 116 project has four mixtures: Conventional 15% RAP (Con15), WMA 15% RAP Foaming + Latex (Foam15), Conventional 20% RAP (Con20), and WMA 20% RAP Foaming + Latex (Fom20). For US 61, there are five mixtures, as stated earlier. Density is expressed as a percentage of the theoretical maximum specific gravity. The error bars show the 95% confidence intervals for the mean density. The lower limits of the confidence intervals were higher than the 92% minimum density level required by DOTD in all projects except LA 116. Two of the mixtures in the LA 116 project (Figure 106) had lower limits of their confidence intervals below the 92% minimum level. This could be attributed to the small size of the samples for these two mixtures. The Foam15 (foamed with 15% RAP) and Con20 (conventional with 20 % RAP) mixtures had five and three core samples, respectively. Only one core sample in each of these two mixtures did not meet the 92% minimum requirement. Since the total quantity of mixture produced was less than 3000 tons, payment was based on the average density obtained, resulting in 100% pay. In summary, the WMA mixtures were able to meet the minimum specification requirement of 92% density in most of the cases.

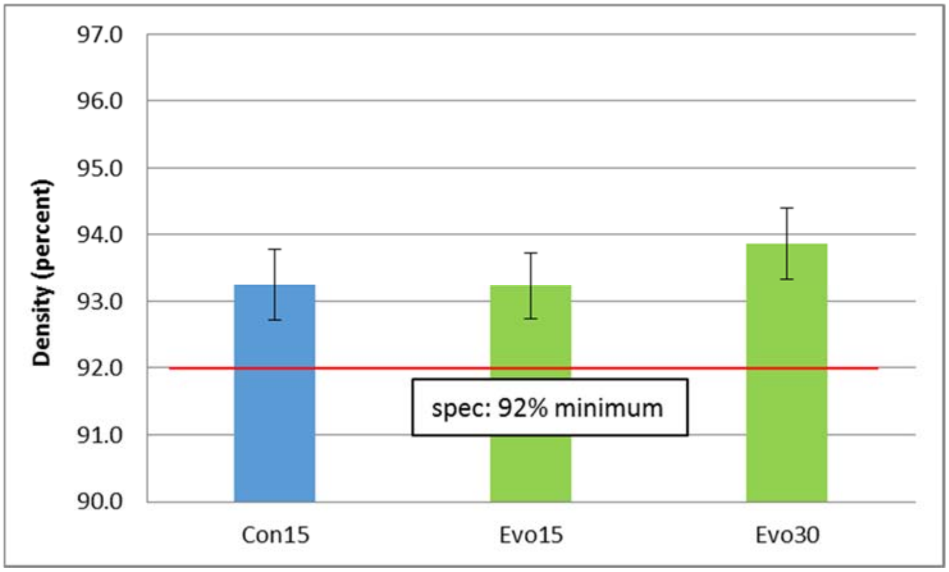


Figure 104
Final densities achieved for the LA 3121 project

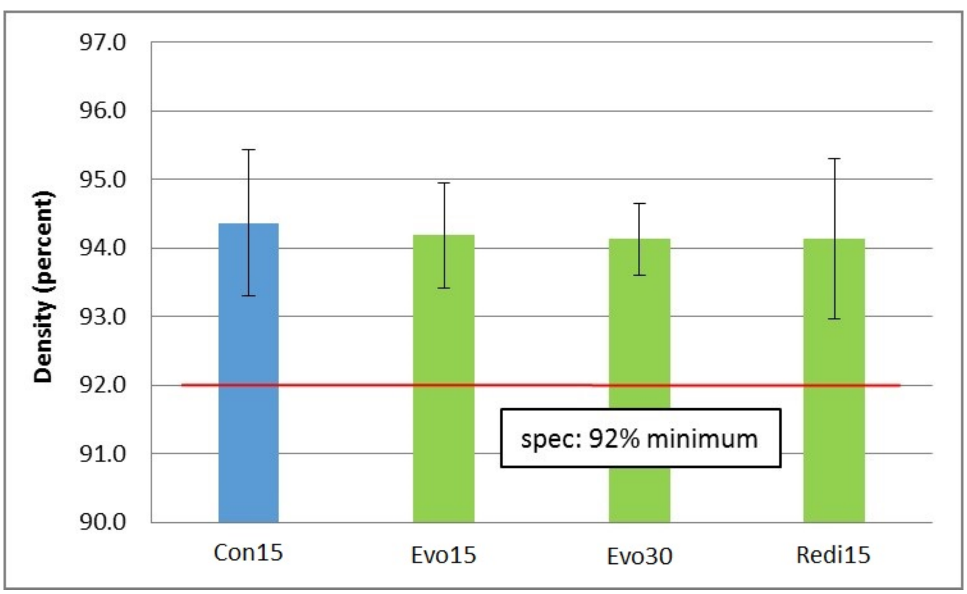


Figure 105
Final densities achieved for the US 171 project

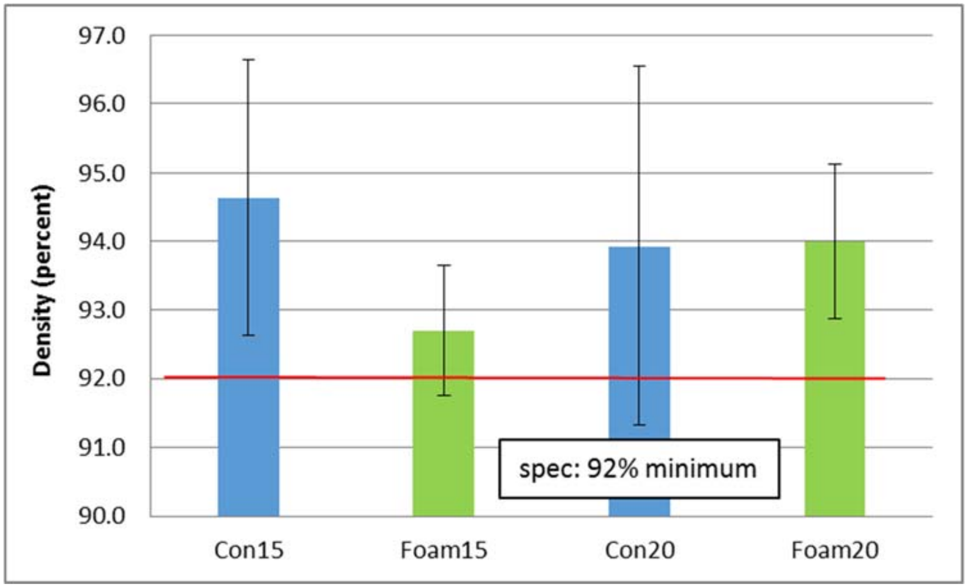


Figure 106
Final densities achieved for the LA 116 project

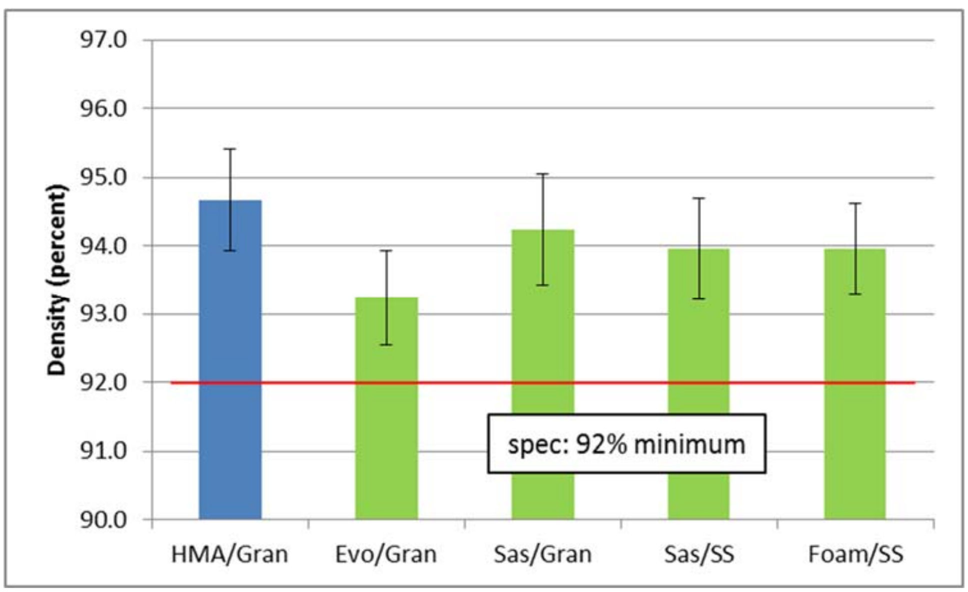
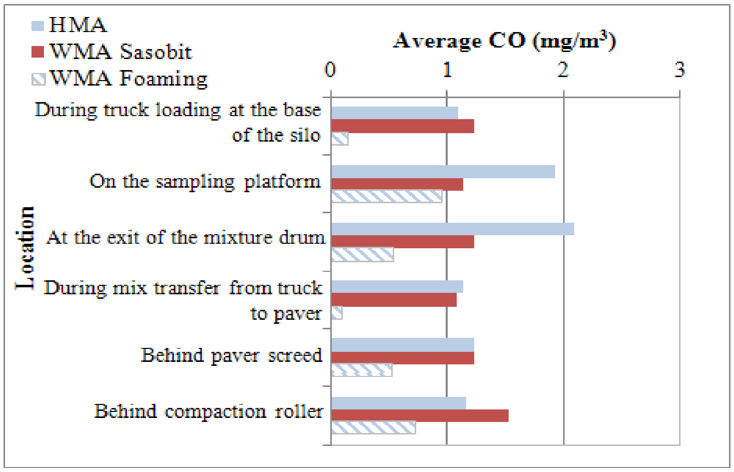


Figure 107
Final densities achieved for the US 61 project

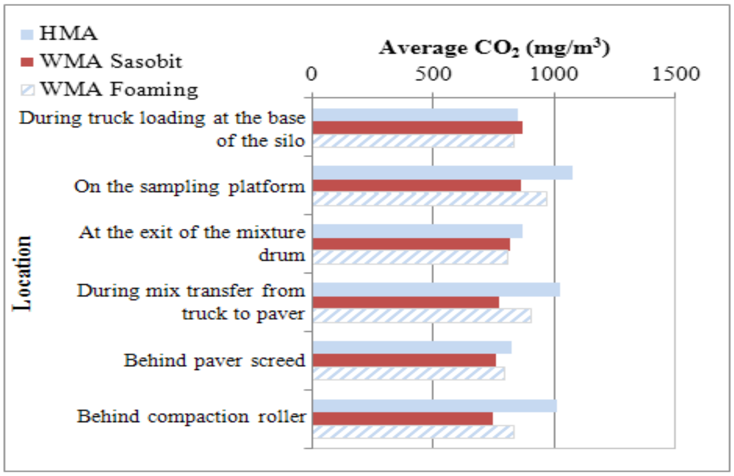
Environmental Evaluation of WMA

CO and CO_2 Measurements

Figure 108 presents the average CO and CO_2 emissions for HMA and WMA measured during production and placement activities. As shown in Figure 108(a), WMA with foaming technology significantly reduced CO emissions during production and placement. WMA with Sasobit also reduced CO emissions, but to a lower extent. With respect to CO_2 emissions and as shown in Figure 108(b), both foaming and chemical WMA technologies resulted in a reduction in air pollutants but at a lower level than what was observed with CO emissions.



(a) Average CO emissions



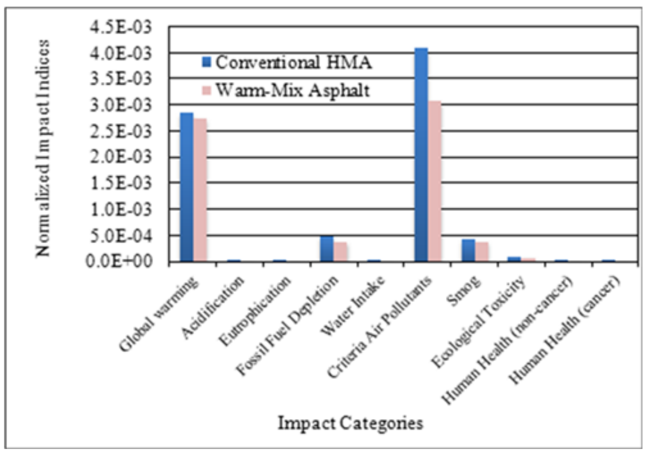
(b) Average CO_2 emissions

Figure 108

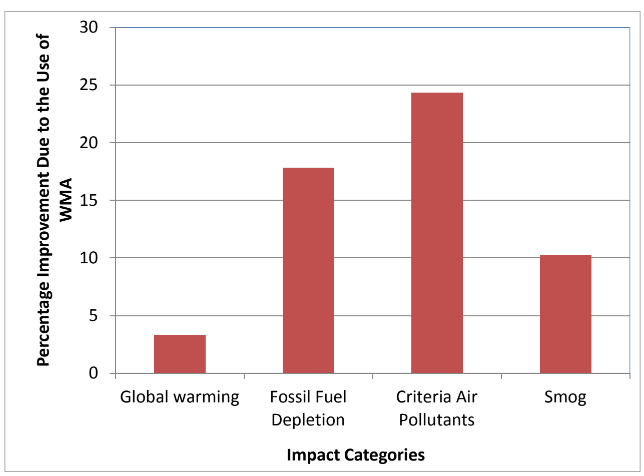
Average CO and CO_2 emissions during production and placement of HMA and WMA

Life-Cycle Assessment

Figure 109(a) presents the normalized impact indices for WMA for the 10 impact categories defined by BEES (33). A lower score indicates a more sustainable alternative. As shown in Figure 109(a), WMA mixtures reduced the environmental impacts over conventional HMA mixtures with respect to global warming, criteria air pollutants, fossil fuel depletion, and smog formation. The impacts on the other indices were negligible. Figure 109(b) presents the percentage improvements in each of these categories due to WMA. It is worth noting that the presented indices relate to the total environmental impacts of the product. While warm-mix asphalt is expected to improve the hot-mix asphalt production category, it will not have a direct effect on the other processes such as aggregate extraction and asphalt refinery processes.



(a) Normalized impact indices



(b) Percentage improvements due to WMA

Figure 109

Environmental impacts of WMA

Changes in Specifications for Implementation of WMA Technology in Louisiana

For the time period between October 2008 and June 2012, over 56,000 tons of WMA were placed, spread out over thirteen projects in Louisiana. Ten of these projects included foaming technologies, while six included various types of chemical additives. Following this experience, DOTD decided to take a permissive approach to allow WMA use in Louisiana, i.e., it is the contractor's choice whether or not to use WMA in a project. The WMA mixture production and placement still has to meet current Louisiana Superpave specifications, with the exception of the temperature requirement. Additionally, the contractor will need to submit a proposal that describes the equipment and additives used, for approval.

CONCLUSIONS

The study presented herein evaluated and quantified the performance of different WMA mixtures from various projects within the State of Louisiana. The experimental plan encompassed seven different testing procedures in which the WMA mixtures were compared against a control HMA. Permanent deformation (rutting), fatigue/fracture cracking, and moisture susceptibility were the three major distress conditions considered in the evaluation of the mixtures. Results obtained from F_N and LWT tests were used to assess the high temperature performance of the mixtures. Results from ITS, DCSE, and SCB were used to evaluate the intermediate temperature performance of the mixtures. Moreover, the |E*| values were used for both intermediate (4.4°C and 25°C) and high temperatures (37.8°C and 54.4°C). The Modified Lottman test results were used to assess the susceptibility to moisture induced damage for the mixtures.

The mechanistic test results were used to obtain different engineering parameters, which were further employed in a statistical analysis to quantify the performance of the WMA as compared to the HMA control mixtures. The major findings and conclusions are listed as follows.

- The dynamic modulus master curves revealed that most of the WMA mixtures had identical or better performance compared to that of the control HMA mixtures at all the test temperatures and frequencies adopted, indicating compatible performance characteristics at high, intermediate, and low temperatures.
- The LWT test results did not indicate any significant differences between the rutting performances of the mixtures. In addition, stripping was not observed for any of the mixtures. All the WMA mixtures exhibited similar performance to that of the control HMA mixtures.
- The flow number test results showed similar permanent deformation performance between the mixtures. The statistical analyses showed that all the WMA mixtures performed at least similar to that of the control HMA mixtures, if not better. Foamed WMA mixture with higher RAP percentages outperformed the control HMA mixture.
- In general, the SCB test results were statistically similar for both HMA and WMA mixtures. Some of the mixtures (both HMA and WMA) did not meet the specification criteria.
- The DCSE results indicated compatible performance of WMA mixtures as compared to that of the control HMA mixtures.

- The ITS test results showed that the WMA mixtures exhibited similar or better performance to that of the control HMA mixtures. All the WMA mixtures had similar or better ITS values as compared to the control HMA mixtures for both aged and unaged specimens. Also, in most of the cases, WMA mixtures exhibited similar or better Toughness Index values.

In general, it can be said that all WMA mixtures included in this study showed comparable performance characteristics to that of HMA mixtures at high, intermediate, and low temperature conditions. The comparatively lower testing results on some of the mixtures were not significant to disqualify their performance as shown in the statistical analysis. Based on the mixtures analyzed in this study, it can be asserted that no major negative impacts can be attributed to the WMA additives employed.

RECOMMENDATIONS

It is recommended that a permissive specification for WMA processes be developed for inclusion in the DOTD *Standard Specifications for Roads and Bridges.* To be considered WMA, a maximum plant mix temperature shall be 300ºF. The absolute minimum placement temperature of the mixture on the roadway shall be 250ºF. A reduction in the placement temperature may be considered when using an approved chemical additive in the mixture

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

α	Type I error rate
Δ_h	horizontal deformation
ε	three percent strain
$\varepsilon 0$	initial strain
εf	failure strain
εp	strain at peak stress
δ	phase angle
^{0}C	Celsius
^{0}F	Fahrenheit
a	notch depth
Ap	area under the curve up to the peak stress
Aε	area under the curve up to 3 percent strain
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt content
ANOVA	Analysis of Variance
b	thickness of specimen
BEES	Building for Environmental and Economic Sustainability
CL	center line
CO	carbon monoxide
CO2	carbon dioxide
Con20	Conventional with 20% RAP
d	diameter
DCSE	Dissipated Creep Strain Energy
DOT	Department of Transportation
DOTD	Department of Transportation and Development
|E*|	dynamic modulus
EE	elastic energy
EPA	Environment Protection Agency
FE	fracture energy
FHWA	Federal Highway Administration
Foam15	foamed with 15% RAP
FN	flow number
GWPi	conversion factor of 1 gram of emission i to its equivalent of CO2
HMA	Hot Mix Asphalt
Hz	hertz

IDT	Indirect Tensile
IT	Indirect Tensile
ITS	Indirect Tensile Strength
J_c	J-integral, critical strain energy
KJ/m2	kilojoule(s) per squared meters
KJ/m3	kilojoule(s) per cubed meters
KN	kilonewton(s)
KN*mm	kilonewton(s) multiplied by millimeter(s)
KN/m2	kilonewton(s) per squared meters
KPa	kilopascal(s)
LA	Louisiana
lbf	pound(s) (force)
LCA	life-cycle assessment
LCI	life-cycle inventory
LCIA	life-cycle impact assessment
LEA	low emission asphalt
LSD	Least Significant Difference
LTRC	Louisiana Transportation Research Center
LWP	left wheel path
LWT	loaded wheel tracking
mi	mass(in grams) of emission i per functional unit
MR	resilient modulus
MEPDG	Mechanistic – Empirical Pavement Design Guide
mg/m3	milligram(s) per cubed meters
mm	millimeter
MPa	megapascal(s)
N	Newton(s)
NCAT	National Center of Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
P	peak load
Pba	percent binder absorbed
PL	Plant Mix- Laboratory Compacted
ppm	parts per million
psi	pounds per square inch
RAP	reclaimed asphalt pavement
RWP	right wheel path

St	tensile strength
SAS	Statistical Analysis System
SCB	semi-circular bend
sec	second(s)
t	thickness
TI	Toughness Index
TSR	Tensile Strength Ratio
TSRST	thermal stress retained specimen test
U	area under the load-deformation curve
U.S.	United States
WMA	Warm Mix Asphalt

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APPENDIX

Specimen Preparation and Test Methods

Specimen Preparation

A loose mixture was short-term oven aged as per Table 60. Subsequently test specimens were fabricated in the Superpave Gyratory Compactor to 7±0.5 percent air voids. Specimen dimensions and the number of specimens made are shown in Table 61. SCB and half of the ITS specimens were long-term oven aged at 85°C for 120 hours per AASHTO R30.

Table 60
Short-term aging procedure

	Temperature (°F)	Time (hours)
HMA	310	2
WMA	270	2

Table 61
Specimen preparation details

Test	**Dimensions**		**Number of specimens**	**Long term aging**
	Diameter (mm)	Height (mm)		
ITS	100	63.5	6	Unaged and aged
SCB	150	57	6	Unaged and aged
DCSE	150	57 (50)*	3	Unaged
E*	150 (100)	178 (150)	3	Unaged
Fn	150 (100)	178 (150)	3	Unaged
LWT	150	60	4	Unaged
Lottman	150	95	6	Unaged

*numbers in parentheses indicate final cut dimensions

Test Methods

Flow Number Test (AASHTO TP79)

This test provides a measure of the asphalt mixtures' resistance to permanent deformation. It involves applying a repeated haversine load with a pulse width of 0.1 second and a rest period of 0.9 second. The amplitude of the load pulse applied is 210 kPa (30 psi) and the test is conducted at 54°C. The flow number is defined as the load cycle number corresponding to the minimum rate of change of permanent strain.

Figure 110
Flow number test setup

Loaded Wheel Tracking (LWT) Test (AASHTO T324)

This procedure is used to measure the rutting and moisture susceptibility of asphalt mixtures. Four cylindrical specimens, two under each wheel of the test machine, are subjected to a reciprocating wheel load of 705 N (158 lb_f). The speed of the wheels is controlled at 52 passes per minute and the specimens are submerged in water at 50°C for the duration of the test. The test is considered done when either the deformation of the specimens under the moving load exceeds 20 mm or the total number of passes reaches 20,000. The rut depth averaged over the middle five data points is reported.

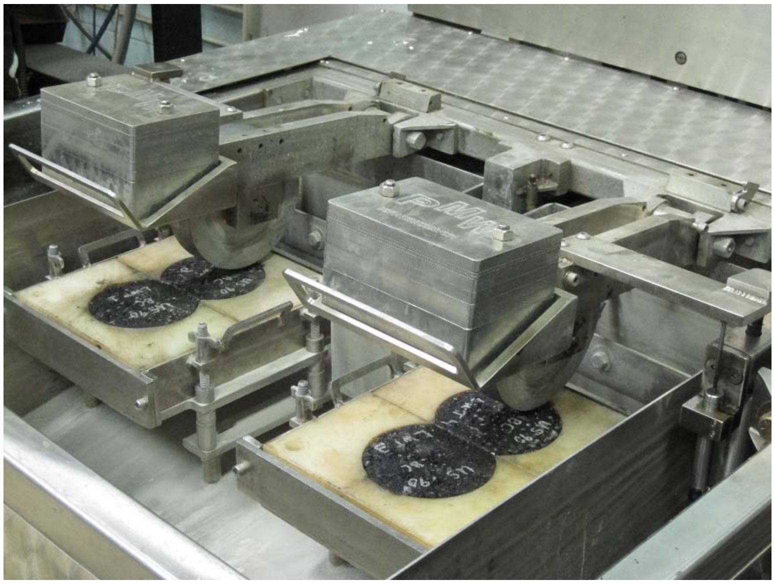

Figure 111
LWT specimens in test machine

Indirect Tensile Strength (ITS) Test

In this test, the specimen is loaded diametrically (indirect tensile mode) at a rate of 2 in. per minute. This causes a tensile strain in the direction perpendicular to the loading. The test is conducted at 25°C. The indirect tensile strength and strain are computed as follows:

$$ITS = \frac{2 * P}{\pi * d * t} \quad (1)$$

$$\varepsilon_f = 0.52 * \Delta_h \quad (2)$$

where,
ITS = indirect tensile strength (psi),
P = peak load (lb_f),
d = diameter of specimen (in.),
t = thickness specimen (in.),
ε_f = failure strain, and
Δ_h = horizontal deformation (in.).

The Toughness Index (TI) is computed by plotting the normalized stress versus strain as shown Figure 113, and performing the following calculation:

$$TI = \frac{A \ - A_p}{\varepsilon - \varepsilon_p} \quad (3)$$

where,
A_ε = area under the curve up to 3 percent strain,
A_p = area under the curve up to the peak stress,
ε = three percent strain, and
ε_p= strain at peak stress.

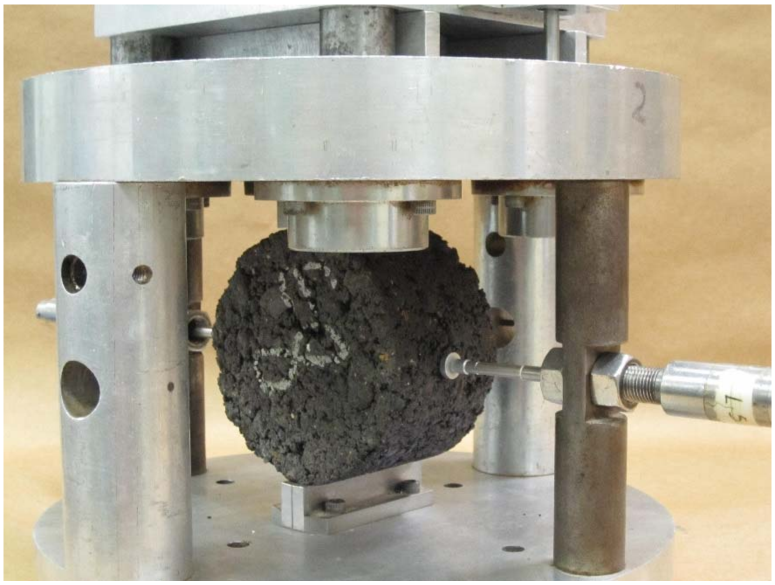

Figure 112
ITS test setup

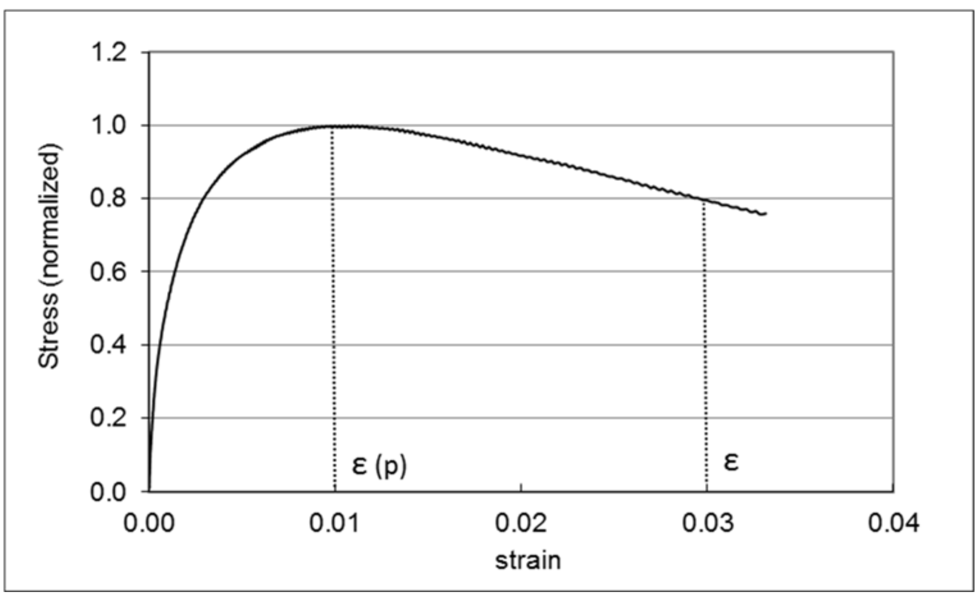

Figure 113
Calculation for toughness index

Dissipated Creep Strain Energy (DCSE) Test

To determine the DCSE parameter of the mixture, two tests are conducted on the same specimen. First, the indirect tensile resilient modulus of the specimen is obtained and then the indirect tensile strength test is performed. The data are analyzed as described below to determine the DCSE parameter:

$$\varepsilon_0 = \frac{M_R * \varepsilon_f - S_t}{M_R} \tag{4}$$

$$EE = \frac{1}{2} * S_t * (\varepsilon_f - \varepsilon_0) \tag{5}$$

$$FE = \frac{1}{2} * S_t * \varepsilon_f \tag{6}$$

$$DCSE = FE - EE \tag{7}$$

where,
M_R = resilient modulus,
S_t = tensile strength,
ε_f = failure strain,
ε_0 = initial strain,
EE = elastic energy,
FE = fracture energy, and
DCSE = dissipated creep strain energy.

Figure 114
Specimen instrumented for the DCSE test

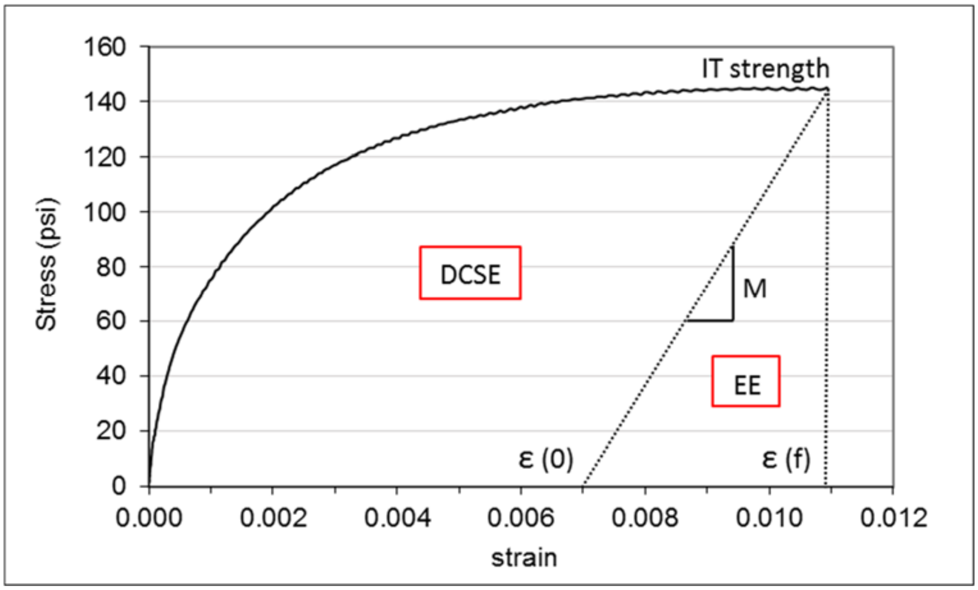

Figure 115
Calculation for DCSE

Semi-Circular Bend (SCB) Test

This test can be used to determine the fracture resistance of asphalt mixtures. Semi-circular specimens are notched and loaded monotonically in a three-point bend loading configuration until failure. The loading rate is 0.5 mm per minute (0.02 in. per minute) and the test is conducted at 25°C. Three notch depths of 25.0, 31.8, and 38.1 mm are used. The resulting load and axial deformation curves are analyzed as described below:

1. The load and deformation graphs are plotted for each specimen and the area under the load-deformation curve until failure is computed. This step is shown in Figure 117.

Figure 116
Test setup for the SCB test

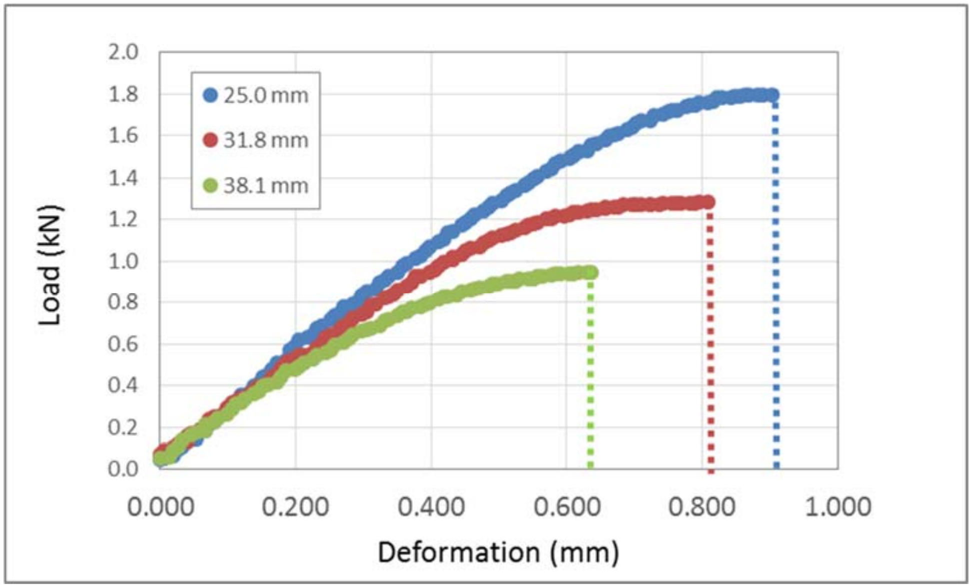

Figure 117
Load-deformation curves

2. The area under the curve is plotted as a function of notch depth; see Figure 118.

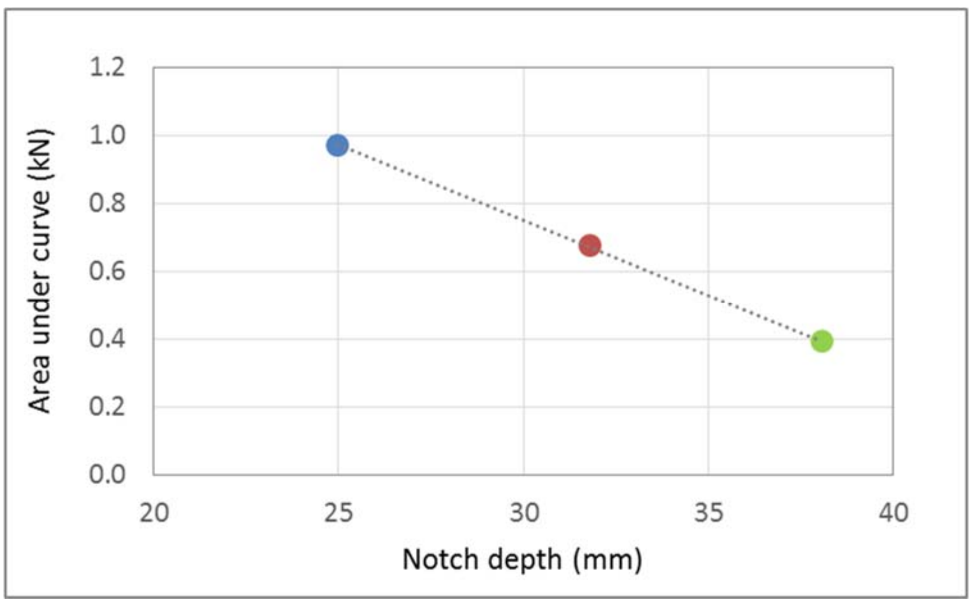

Figure 118
Area under the curve versus notch depth

3. The parameter J_c is computed as follows:

$$J_c = -\frac{1}{b}\frac{dU}{da} \quad (8)$$

where,

b = thickness of the specimen (mm),

U = area under the load-deformation curve (KN*mm), and

a = notch depth (mm).

Note that the slope of the regressed line in Figure 118 is dU/da.

Dynamic Modulus Test (AASHTO T342)

In this test, cylindrical specimens are subjected to a sinusoidal compressive load and the resulting axial deformations are measured. This data is used to compute the dynamic modulus and phase angle. The test is conducted through a sweep of temperatures (-10, 4, 25, 38, and 54°C) and a range of frequencies are each temperature (25, 10, 5, 1, 0.5, and 0.1 Hz).

Figure 119
Dynamic Modulus test setup

Modified Lottman (AASHTO T283)

This procedure is used to measure the change in diametral tensile strength resulting from the effects of saturation and freeze/thaw conditioning of compacted specimens. The set of specimens (6 samples) is divided into two subsets. One subset is tested (subjected to 2 inches/minute diametral loading rate) in the dry condition. The other set is subjected to a freeze (-18°C for 16 hours) and a warm-water cycle (60°C for 24 hours) and then tested. TSR (Tensile Strength Retained) is computed as the ratio of the conditioned indirect tensile strength to the dry indirect tensile strength.

Figure 120
Lottman testing setup

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