RESEARCH & DEVELOPMENT

Impact of WMA Technologies on the Use of RAP Mixtures in North Carolina

Akhtarhusein A. Tayebali, Ph.D., P.E.
N. Paul Khosla, Ph.D.
Haritha Malladi, Ph.D.
Abhilash Kusam

Civil, Construction and Environmental Engineering
North Carolina State University

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Warm Mix Asphalt (WMA) and Recycled Asphalt Pavement (RAP) are two popularly used sustainable technologies in the pavement industry. The use of some WMA technologies may increase the moisture susceptibility of the mixtures, and the use of RAP material can affect long term durability and workability. The combination of WMA and RAP technologies together can address the problems that could arise if these technologies are used individually. Two WMA technologies – Evotherm and Foamer, and three RAP contents – 0%, 20% and 40% were used in this study to produce mixtures. Workability and moisture susceptibility of these mixtures were compared to that of a virgin HMA mixture using compaction data and Tensile Strength Ratio (TSR) respectively. The effectiveness of Evotherm as an anti-strip additive in addition to being a WMA additive was also evaluated using TSR test. Workability and TSR ratio was observed to decrease with increase in RAP content for similar mixtures while the (ITS) Indirect Tensile Strength values increased. With high RAP content, WMA mixtures with standard binder grade performed better than corresponding HMA-RAP mixtures with softer binder.

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EXECUTIVE SUMMARY

There is a large impetus today to use cleaner and more sustainable technologies. In the pavement industry use Warm Mix Asphalt (WMA) in lieu of the conventional Hot Mix Asphalt (HMA) technology can help reduce production temperatures. Increased workability at lower temperatures reduces the energy required to heat raw materials. Lower production temperatures also mean less harmful emissions during the pavement construction and increased haul distances. Various laboratory and field studies have shown improved workability at lower temperatures when WMA technologies are used. However, use of WMA technologies has led to a major concern of moisture susceptibility because of the use of water-based technologies.

Use of recycled material to construct pavements is also a popular way to move towards sustainability. Reclaimed Asphalt Pavement (RAP) material has been used in the pavement industry since decades. By recycling construction materials, the cost involved in transporting them is also lowered. The RAP material gives extra stiffness to the mixture, which can be beneficial to prevent rutting but can decreases workability and long term durability.

It is believed that the use of WMA technologies can eliminate the workability problems associated with the use of RAP material. Since WMA technologies improve the workability of the mixtures, there is a possibility that higher amounts of RAP can be used when WMA technologies are used. With so many new technologies out in the field, it is important to determine the compatibility of WMA technologies in preparing high RAP content. For this, there is a need to study the workability and moisture susceptibility of WMA – RAP mixtures.

This research study focuses on using two WMA technologies, Evotherm 3G and The PTI Foamer, with three different RAP percentages: 0%, 20% and 40%. NCDOT 9.5 B mixtures were prepared with a combination of these WMA technologies and RAP contents. These mixtures were evaluated for workability and moisture susceptibility, and their results were compared with corresponding virgin HMA mixtures. Tensile Strength Ratio (TSR) was

used to evaluate the moisture susceptibility, while the workability was evaluated by $\%G_{mm}$ evolution curves. Additionally, the effectiveness of Evotherm as an anti-strip additive was evaluated by a litmus paper test using StripScan.

TSR was observed to decrease with increase in RAP content for HMA as well as the two WMA technologies, indicating an increase in moisture susceptibility with increasing RAP content. Foamer mixtures showed better workability than Evotherm and HMA mixtures. The workability of mixtures decreased with increase in RAP content for all three types of mixtures. Additionally, Evotherm was observed to work as an anti-strip additive for virgin mixtures. However, higher amounts of RAP necessitate additional amounts of anti-strip additive.

Dynamic modulus tests were conducted to obtain the E* mastercurves for all nine mixtures. They were also used to compute the E* Stiffness Ratio, i.e. the ratio of dynamic modulus values of moisture-conditioned specimens to that of unconditioned specimens, analogous to the Tensile Strength Ratio. The ESR value of HMA mixture with 40% RAP was significantly lower than all the other mixtures. This may be because of the softer binder grade (PG 58-28) used in this mixture as compared to the other mixtures that used PG 64-22 binder.

AASHTOWare Pavement ME software was used to analyze the rutting and fatigue performance of the mixtures for a design life of 20 years. For a typical NCDOT pavement section, none of the mixtures exceeded the threshold failure criteria. Thus, the only difference in production costs between the mixtures will result from differences in technology and additives, screening and processing of RAP and energy savings from WMA.

For every 20% of the mix that is replaced with RAP, saving of around 10% can be expected in the initial cost of production. Despite the additional equipment and/or additive costs, using WMA technology leads to approximately 3% savings. Using both results in a summation of initial savings.

Based on the results of this study, the specific conclusions and recommendations are:

1. Evotherm 3G additives work well as a WMA technology, as expected.

2. In addition to providing the advantages of WMA technology, Evotherm 3G also acts as an anti-strip additive and lowers the moisture susceptibility for the virgin HMA mixture used in this study.

3. When using WMA technologies, it is not necessary to lower the binder grade of the mixture with as high as 40% RAP use in mixtures.

4. However, for higher RAP content in the mixtures, it is recommended that an additional anti-strip additive be added (such as LOF 6500 as used in this study) even when Evotherm 3G is used.

5. Based on analysis of initial cost of production, both WMA and RAP mixtures are more economical.

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1. INTRODUCTION

1.1 Background

In recent years, there has been a huge emphasis on use of recycled material and cleaner construction practices in the construction industry. The pavement industry is also focusing on constructing roads that promote sustainability and economy in construction techniques, causing less damage to the environment. This has resulted in lot of studies aimed at solutions to overcome the challenges associated with the use of recycled material in the construction of new pavements, and also use of other economic and environment-friendly construction techniques.

There has been an upward surge in the use of Recycled Material including Recycled Asphalt Pavement (RAP) material in recent times along with use of Warm Mix Technology (WMA) in producing mixtures. Many studies, conducted on RAP material extracted or recovered from existing pavements on their possible use in construction of new pavements, have shown the successful use of aggregates and binder extracted from RAP material and even the RAP material by itself in the construction of new pavements [29]. The use of RAP material in the construction of new pavements solves the problem of disposal of the material extracted from the damaged pavements as well as the shortage of material required for construction of new pavements. In areas where the quarries and asphalt production plants are not nearby the use of RAP material saves the cost spent on transporting the construction materials.

The use of WMA technology has been around for a while in other parts of the world like Europe and South Africa but it is relatively a new technology in United States as compared to the use of RAP [1]. The main objective of the WMA technology is to lower the mixing and compaction temperatures of the asphalt concrete mixtures by using wax, water or amine based additives, or a foaming device [1]. This reduction in temperatures translates to lower energy consumption for heating the materials and also reduction in the emissions. The reduction in energy leads to significant amount of monetary savings. Reduction in temperature leads to longer haul distances for trucks carrying the WMA plant mix and thus the distance between two adjacent mixing plants can be increased. Due to the reduction in emissions because of the use of WMA technology, there will be savings on costs spent on controlling or reducing the emissions.

The use of RAP material in construction of new pavements has its own drawbacks. The binder present in RAP is aged and oxidized during its service life. The aging and oxidization process makes the binder stiffer and thus decrease the durability of the mixture. NCHRP Report 452 has specifications for the use of softer binder grades when higher RAP contents are used in the mixture to overcome the increased stiffness [27]. The change in binder grade is not very favorable for the contractors since the lower binder grades might not be locally available and it might also lead to increased cost of construction. Use of RAP also poses workability issues, since the material is very stiff, the amount to which RAP should be heated before mixing to ensure proper blending is a debatable question [29]. There is a possibility that the properties of RAP material will change if heated to higher temperatures.

The use of WMA technologies also has caused some concerns. There is a possibility that the moisture is still trapped inside the aggregates as the aggregates are heated to lower temperatures. Water can be trapped inside the mixture when the Foamer or water based WMA technologies are used. This trapped water can result in increased moisture susceptibility of the mixtures produced with WMA technologies. The lower mixing and compaction temperatures also cause less oxidative aging of the mixture. While this can be beneficial for long term durability of the mixture, this can also lead to early permanent deformation [2, 3].

It is believed that the use of WMA and RAP together can help in overcoming the workability and stiffness problems associated with WMA and RAP when used separately. The use of WMA technology lowers the mixing and compaction temperatures, and increases the workability, thus reducing the amount of oxidation in the binder. Hence, this can help in overcoming the increased binder stiffness in RAP mixture due to oxidative aging during its service time [36]. The extra stiffness from RAP can help prevent the early permanent deformation caused in WMA mixtures due to less oxidative aging of the binder. Hence the use of WMA and RAP together can lead to better performing and more durable pavements. The potential significant economic benefits can push the contractors in adopting these sustainable technologies even if a lower binder grade is required.

1.2 Need for Study

It is clear that there are many benefits when RAP and WMA technologies are used together. Important issues such as workability and moisture susceptibility of the RAP – WMA mixtures have to be looked into before the fatigue and rutting performance of the mixtures is quantified. The effect on workability when varying content of RAP is used with different WMA technologies has to be studied. Similarly the effect of different WMA technologies with varying RAP content on the moisture susceptibility has to be investigated.

There is a need for a study that can satisfy the following needs:

- Identify appropriate WMA technologies that can be used for varying RAP proportions.
- Identify the most appropriate binder grade for each WMA–RAP mixture combination.
- Determine the effect of lower mixing and compaction temperatures on workability and moisture susceptibility.
- Determine the effect of addition of RAP and any lowering of binder grade on workability and moisture susceptibility.
- Evaluate fundamental material properties of WMA-RAP mixtures that can be used in pavement performance prediction.
- Compare the costs and benefits of using WMA technologies and RAP in asphalt concrete mixtures.

1.3 Organization of Report

The objective of this study is to evaluate the workability, moisture susceptibility and material performance of virgin mixtures as well as mixtures with two RAP contents—20% and 40%—in combination with HMA, and two different WMA technologies—Evotherm 3G and PTI Foamer. The workability is calculated using the $\%G_{mm}$ evolution curve, while the moisture susceptibility is evaluated using the Tensile Strength Ratio (TSR) Test. The report is organized into 9 tasks: literature review, characterization of materials, Superpave mix design, evaluating workability, comparing moisture susceptibility, determining the effectiveness of Evotherm as an anti-strip additive, dynamic modulus tests and assessing the pavement performance and economic cost-benefits. Section 2 provides details about the materials used in this study. The Superpave mix design of the mixtures involved in this study is elaborated in section 3. The evaluation of workability of mixtures using %G_{mm} curves is discussed in section 4. Moisture susceptibility evaluation using the TSR test is given in section 5 and section 6 evaluates the effectives of Evotherm 3G as an anti-strip additive. In section 7, E* Stiffness Ratios of the mixtures are discussed. In section 8, the dynamic modulus test results, pavement analysis and economic study results are detailed. The summary and conclusions for the research study are detailed in section 9. A comprehensive literature review is detailed in Appendix A.

1.4 Research Objective

The main objective of this research was to evaluate the workability, moisture susceptibility and material performance characteristics of mixtures produced using Warm Mix Asphalt (WMA) technologies with and without using Reclaimed Asphalt Pavement (RAP) material, and to compare with the results from Hot Mix Asphalt with and without RAP for a NC 9.5 B mixture.

Two WMA technologies were used in this study: PTI Foamer and Evotherm 3G additive. Two different RAP contents were used in addition to the virgin mix (no RAP): 20% and 40% RAP. PG 64-22 binder was used for the mixtures with 0% and 20% RAP. PG 58-28 binder was used in addition to PG 64-22 for the mixtures with 40% RAP, since NCHRP Report 452 suggests the use of a softer binder grade when more than 30% RAP is used [27].

Specific objectives of this research study were to:

- Design Superpave mixes for the HMA mixtures with 0%, 20%, and 40% RAP material.
- Verify the volumetric properties of the WMA mixtures using the same job mix formula of the corresponding HMA mixtures.

- Evaluate workability of the mixtures using $\%G_{mm}$ evolution curves.
- Determine moisture susceptibility of the mixtures using Tensile Strength Ratio (TSR) and compare the effects of employing WMA technologies and using RAP on resistance to moisture-damage.
- Evaluate the effectiveness of Evotherm additive as an anti-strip additive using Litmus Paper Test and TSR.
- Use dynamic modulus values on moisture-conditioned and unconditioned specimens to determine the E* Stiffness Ratio.
- Predict the pavement performance of all mixtures using dynamic modulus mastercurves.
- Compare the economics of using WMA and RAP in asphalt concrete mixtures.

Table 1-1 shows details of the mixtures used in this research study.

Table 1-1 Mixture Combinations of WMA Technologies, RAP Contents and Binder Grades Used in This Study

RAP Content	**Binder Type**	**WMA Technology**		
		HMA	Evotherm	Foamer
0%	PG 64-22	HMA, 0% RAP	EVO, 0% RAP	FOAM, 0% RAP
20%	PG 64-22	HMA, 20% RAP	EVO, 20% RAP	FOAM, 20% RAP
40%	PG 64-22	HMA, 40% RAP	EVO, 40% RAP	FOAM, 40% RAP
	PG 58-28	HMA, 40% RAP	EVO, 40% RAP	FOAM, 40% RAP

2. MATERIAL CHARACTERIZATION

The information about all the materials used in this research study is detailed in this section. This includes the source and properties of virgin aggregates, virgin binder, additives and RAP material.

2.1 Aggregates

The virgin aggregates used in the research were from the Martin Marietta Materials Quarry at Garner, North Carolina. The aggregate type was granite. Three stockpiles as given in the JMF were used in addition to the pond fines – #78M Coarse Aggregates, Manufactured Sand and Dry Screenings. The aggregate stockpiles were evaluated for the stockpile gradation and the bulk specific gravity specified in the JMF.

Gradations of the three aggregate stockpiles were verified as per ASTM C136-06, “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates” and ASTM C117-04, “Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing”. These results are shown in in Table 2-1. These aggregates were fractionated into individual sieve sizes and batched as per the JMF aggregate gradation to prepare laboratory samples with minimum variability in aggregate structure. Pond fines were incorporated at 1.5% of the total aggregate weight and replaced the No. 200 passing virgin aggregates.

Bulk specific gravities of the coarse and fine aggregate portions (separated using #4 or 4.75 mm sieve) were measured separately as per AASHTO T 85-88, “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate” and AASHTO T 84-88, “Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate”. For pond fines, the bulk specific gravity provided by the quarry was used. Using an appropriate blend ratio, the combined aggregate bulk specific gravity (G_{sb}) was calculated as shown in the next page.

$$\frac{100}{Gsb} = \frac{c}{G_c} + \frac{f}{G_f}$$

where,

c = percentage of coarse aggregate of the total aggregate

f = percentage of fine aggregate

G_c = specific gravity of Coarse aggregate fraction

G_f = specific gravity of Fine aggregate fraction

The combined aggregate bulk specific gravity of the aggregate was determined to be 2.64.

Table 2-1 Gradation of Aggregate Stockpiles

Sieve Size		**Percentage Passing**		
		Manufactured Sand	*Dry Screenings*	*#78M Coarse Aggregates*
1/2”	12.5 mm	100	100	100
3/8”	9.5 mm	100	100	93
No. 4	4.75 mm	100	97	36
No. 8	2.36 mm	93	77	13
No. 16	1.18 mm	73	59	7
No. 30	600 µm	49	44	5
No. 50	300 µm	24	30	3
No. 100	150 µm	8	19	2
No. 200	75 µm	3	12	2

2.2 RAP Aggregate

In this project two different RAP contents were used: 20% and 40%. The RAP material was divided into coarse and fine RAP as per NCHRP Report 452 to control the variation in aggregate gradation of RAP. The aggregate gradation and binder content for these two RAP fractions were calculated individually. The RAP was fractionated at the US standard

#4 sieve (4.75 mm). In this report, material retained on 4.75 mm sieve will be referred to as coarse RAP while that passing it will be referred to as fine RAP.

2.2.1 Ignition Oven Test

Ignition Oven tests were conducted separately on two RAP fractions to determine the respective asphalt binder content as per AASHTO T 308-05, "Standard Method of Test for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method." Gradation of extracted aggregate from the ignition oven test was measured according to AASHTO T 30-13, "Standard Method of Test for Mechanical Analysis of Extracted Aggregate." It was possible to use the above method for aggregate gradation since the calibration factor in the ignition oven test was 0.50 which is less than 1. The gradations of the coarse and fine RAP fractions from the ignition oven test are shown in Table 2-2. These gradations were used to find a blending ratio for the coarse and fine RAP fractions such that the resultant aggregate gradation resembles the target RAP gradation as specified in the JMF. A blend of one-third (33%) coarse RAP and two-thirds (67%) fine RAP by weight was found to be ideal.

Based on the ignition oven test results, asphalt content was determined to be 3.2% for coarse RAP fraction and 6.4% for fine RAP fraction.

2.2.2 Bulk Specific Gravity of RAP

Firstly, the G_{mm} of the two fractions were measured as per AASHTO T 209 "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt." Back calculation process mentioned in AASHTO R35-04, "Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)" was used to determine the effective and bulk specific gravity (G_{sb}) of each RAP fraction as shown below. Table 2-3 shows the specific gravities of the coarse and fine fractions of RAP.

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$

$$G_{sb} = G_{se} \div \left[\left(\frac{P_{ba} \times G_{se}}{100 \times G_b}\right) + 1\right]$$

Table 2-2 Aggregate Gradation of RAP Fractions

Sieve Size	Percentage Passing		
	Coarse RAP	Fine RAP	JMF RAP Gradation
½" / 12.5mm	100	100	100
$^3/_8$" / 9.5mm	89	100	96
#4 / 4.75mm	42	100	81
#8 / 2.36mm	28	84	65
#16 / 1.18mm	23	66	51
#30 / 600µm	18	48	38
#50 / 300µm	13	33	26
#100 / 150µm	8.4	21	17
#200 / 75µm	5.3	13.3	10.3

Table 2-3 Calculation of Bulk Specific Gravity (G_{sb}) for RAP Fractions

Fraction	G_{mm}	P_b	G_{se}	G_{sb}
Coarse	2.540	3.2	2.672	2.665
Fine	2.435	6.4	2.690	2.683

2.2.3 RAP Handling

A two-step heating procedure was followed for the incorporation of RAP into mix design. This heating procedure was recommended by TTI and FHWA in their project "Performance Evaluation and Mix Design for High RAP Mixtures" (Report # FHWA/TX-11/0-6092-2).

After fractionating the RAP, sampling was done with both coarse and fine RAP fractions to obtain the required amount of coarse and fine RAP for preparing the samples. The RAP fractions were then heated at 60°C for 12 hours. The RAP was then preheated to the mixing target temperature (163°C for HMA and 135°C for WMA) for two hours. After the two hours of heating at mixing temperature, the two fractions were mixed with the virgin aggregate and virgin binder to prepare the mixture for preparing the specimens.

2.2.4 Estimating Material Amounts for RAP Mixtures

When using RAP material it is important to note that the total weight includes both the aggregates and also asphalt. So, when RAP is being added in the mix, it is necessary to ensure that the RAP added has the required weight of recycled aggregates. The amount of binder being contributed from RAP should be subtracted from the total binder requirement for 20% and 40% RAP mixtures to get the amount of virgin binder needed.

The dosages of additives (Evotherm 3G and LOF 6500) have to be calculated based on the total amount of binder in the mix, which includes virgin binder as well as binder contribution from RAP. Hence, the dosage of the additives was calculated using the total binder content and that dose of additive was mixed with the virgin binder.

2.3 Asphalt Binder

The two virgin asphalt binders used in this research study were Superpave Performance grade PG 64-22 and PG 58-28. Both the asphalt binders used in this study were supplied by NuStar Asphalt Refining Company located in River Road Terminal, Wilmington, NC. While PG 64-22 binder was used for mixtures with 0%, 20% and 40% RAP content, PG 58-28 was used only for mixtures with 40% RAP material. The specific gravity of the binders was reported as 1.034 by the manufacturer.

2.4 Additives

Use of an anti-strip additive, 0.75% by weight of binder was recommended in the JMF for all mixtures. The anti- strip additive used in this study was AD-here® LOF 6500, manufactured by ArrMaz Custom Chemicals.

Evotherm mixtures were prepared using 0.5% additive by weight of binder. WMA mixtures prepared using the PTI Foamer did not require any additives, but 2% water by weight of binder was used for foaming the binder. A summary of the additives used abd their dosages are summarized in Table 2-4.

Table 2-4 Summary of Amount of Additives Used

Additive	Amount	Mixtures Modified
Liquid Anti-strip	0.75% by weight of binder	All
Evotherm 3G	0.50% by weight of binder	WMA using Evotherm 3G
Water	2% by weight of binder	WMA using The PTI Foamer

3. SUPERPAVE MIX–DESIGN

This section describes Superpave mix design method of the 12 mixtures. As explained in the research tasks, the optimum asphalt content was found for the HMA mixtures with 0%, 20% and 40% RAP using the Superpave mix design method. The volumetric properties were verified for the corresponding WMA mixtures using the same optimum asphalt content.

3.1 Aggregates

All the HMA and WMA mixtures were designed as Asphalt Concrete Surface Course, Type NCDOT RS 9.5B mixtures. The design aggregate gradation was provided in the JMF provided which is shown in Table 3-1 and Figure 3-1.

Table 3-1 Design Aggregate Gradation as Obtained from JMF (9.5B Mix)

Sieve Size		% Passing	Control Points
2”	50.0 mm	100	
1 ½ “	37.5 mm	100	
1 “	25.0 mm	100	
¾ “	19.0 mm	100	
½ “	12.5 mm	100	100 -
3/8”	9.5 mm	97	90 - 100
#4	4.75 mm	76	90
#8	2.36 mm	55	32 - 67
#16	1.18 mm	40	
#30	600 µm	29	
#50	300 µm	20	
#100	150 µm	11	
#200	75 µm	5.8	4.0 – 8.0

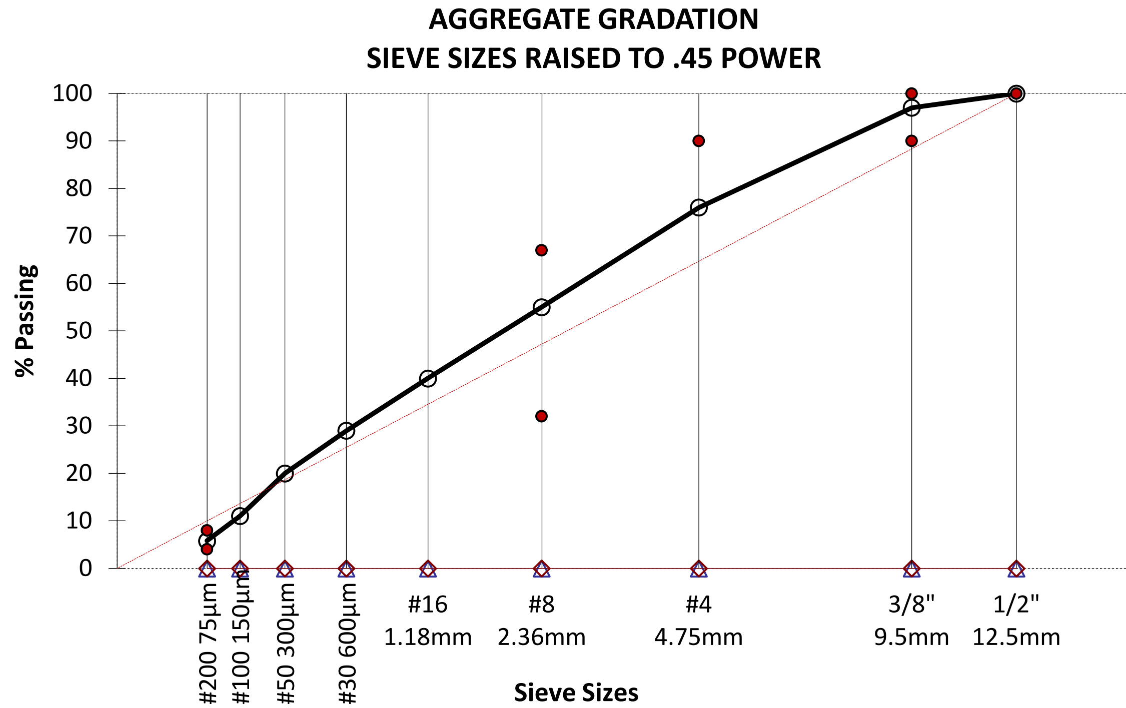

Figure 3-1 Percent Passing vs. 0.45 Power of Sieve Sizes

3.2 Mixing and Compaction Temperatures

The mixing and compaction temperatures for HMA mixtures were 163°C (325°F) and 149°C (300°F), respectively based on a previous NCDOT study [48].

According to NCHRP report 714, mixing and compaction temperatures of WMA mixtures cannot be calculated based on rotational viscosity test results and hence the temperatures reported by the manufacturers are suggested to be used [15]. Since mixtures produced using both Evotherm 3G and the PTI Foamer have mixing and compaction values around 135°C (275°F) and 120°C (248°F) respectively, these values were selected as the mixing and compaction temperatures in this study.

3.3 Optimum Asphalt Content

6.0% binder content by weight of total mix (as specified in the JMF) was used as a starting point for determining the optimum asphalt content for all mixture combinations. With each amount of RAP, the optimum asphalt content for the HMA mixture was first determined.

Using this binder content, the volumetric properties for the corresponding Evotherm® and Foamer mixtures were verified.

Volumetric verification for each RAP amount involved the following steps:

i. Compact two HMA specimens 4500 g total aggregate and design binder content to 65 gyrations using the Superpave Gyratory Compactor (initial gyrations, N_{ini} = 7 and design gyrations, N_{des} = 65 are specified 9.5B mix types).

ii. Prepare two loose mixtures with 2000 g of aggregates and same binder content.

iii. Use the compacted specimens to obtain the average bulk specific gravity (G_{mb}) as per AASHTO TP 69-04, "Standard Method of Test for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method".

iv. Test the loose mixtures to obtain average theoretical maximum specific gravity (G_{mm}) as per AASTO T 209-05, "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures."

v. Calculate the volumetric properties of the mixture including %VTM (Voids in Total Mixture/Air Voids), %VMA (Voids in Mineral Aggregate), %VFA (Voids Filled with Asphalt), $\%G_{mm}$ at N_{ini} and $\%G_{mm}$ at N_{des} using the above two measurements and determine G_{sb} of aggregate blend using aggregate and RAP bulk specific gravities.

vi. Verify the volumetric properties against NCDOT Superpave mix design criteria for S9.5B mix type.

vii. If the volumetric properties for HMA are within specification, repeat the process for Evotherm® and Foamer mixtures.

viii. Adjust design binder contents if WMA mixtures did not meet volumetric specification. For a given RAP amount, the binder content is to be kept constant to ensure comparability between the mixtures.

3.3.1 Volumetric Data of Virgin (0% RAP) Mixtures

Table 3-2 compiles the volumetric data for the virgin HMA, Evotherm® and Foamer mixtures with 6% design binder content. All mixtures used PG 64-22 binder grade. Volumetric properties for all three mixtures were within the specified limits and thus, the optimum asphalt content for 0% RAP mixtures was fixed at 6%.

Table 3-2 Volumetric Properties for 0% RAP Mixtures with 6% PG 64-22 Binder

Volumetric Properties	**Mix Type**			**Volumetric Requirements**
	HMA	Evotherm	Foamer	
G_{sb}	2.640	2.640	2.640	
G_{mb} @ N_{des}	2.330	2.325	2.316	
G_{mm}	2.425	2.420	2.410	
% VTM	3.9	3.9	3.9	4.0 ± 0.5
% VMA	17.0	17.2	17.5	> 15.0%
% VFA	64.8	65.1	65.8	65-78%
% G_{mm} at N_{ini} (7)	89.5	89.3	89.5	≤ 89.0%
% G_{mm} at N_{des} (65)	96.1	96.1	96.1	96%

3.3.2 Volumetric Data of 20% RAP Mixtures

Using the same target aggregate gradation and PG 64-22 binder, G_{mb} and G_{mm} for mixtures with 20% RAP were determined. % Air voids (VTM) of these mixtures are shown Table 3-3. While HMA mixtures had air voids within the specified limit, air voids WMA mixtures were low. Hence, new set of mixtures were with reduced asphalt content of 5.8% were prepared and measured for air voids. % Air voids from these specimens are also shown in Table 3-3. As can be seen, the air voids were higher than specified limit for HMA and Evotherm® mixtures.

Thus, a third set of specimens with 5.9% binder content were prepared and tested. For this binder content, all volumetric properties of HMA, Evotherm® and Foamer mixtures with 20% RAP met specification limits. These values are shown in Table 3-4. Thus, the optimum asphalt content of 20% RAP mixtures was fixed at 5.9%.

Table 3-3 % Air voids in 20% RAP Mixtures with PG 64-22 Binder

Mixture Type	% Binder	% VTM	Specification
HMA	6	3.8	4.0 ± 0.5
Evotherm		3.4	
Foamer		3.4	
HMA	5.8	4.8	
Evotherm		4.8	
Foamer		4.4	

Table 3-4 Volumetric Properties for 20% RAP Mixtures with 5.9% PG 64-22 Binder

Volumetric Properties	Mix Type			Volumetric Requirements
	HMA	Evotherm	Foamer	
G_{sb}	2.647	2.647	2.647	
G_{mb} @ N_{des}	2.320	2.317	2.316	
G_{mm}	2.422	2.414	2.415	
% VTM	4.2	4.0	4.1	4.0 ± 0.5
% VMA	17.5	17.6	17.7	> 15.0%
% VFA	76.0	77.3	76.8	65-78%
% G_{mm} at N_{ini} (7)	88.9	89.2	89.1	≤ 89.0%
% G_{mm} at N_{des} (65)	95.7	95.9	96.0	96%

3.3.3 Volumetric Data of 40% RAP Mixtures

Similar the previous mix designs, the virgin aggregates blended with 40% RAP were mixed with PG 64-22 binder at 6.0% binder content. The same mixtures were also prepared using a softer binder grade, PG 58-28 due to their high RAP content. The air voids determined from these mixtures are shown in Table 3-5.

Similar to 20% RAP mixtures, for 6% binder content, the WMA mixtures exhibited low air void contents while the HMA mixtures were within specification. A second set of mix design specimens of all these six mixtures were prepared with 5.8% design binder content.

This time, the volumetric properties for all mixtures were within the specified limits for both PG 64-22 and PG 58-28 binders. The volumetric data are summarized in Table 3-6 and Table 3-7. The optimum asphalt content of 40% RAP mixtures was fixed at 5.8%.

Table 3-5 Air voids in 40% RAP Mixtures with 6% Binder Content

Mixture Type	Binder Grade	% VTM	Specification
HMA	PG 64-22	3.7	4.0 ± 0.5
Evotherm		3.4	
Foamer		3.3	
HMA	PG 58-28	4.0	
Evotherm		3.4	
Foamer		3.4	

In 40% RAP mixtures, HMA mixture exhibits the greatest difference in volumetric properties at optimum asphalt content with change in binder grade. Air voids reduced by 0.6% for HMA while the difference in air voids for both WMA mixtures were within 0.2%. This indicated better compactability in HMA when softer binder grade was used.

Table 3-6 Volumetric Properties for 40% RAP Mixtures with `5.8% PG 64-22 Binder

Volumetric Properties	Mix Type			Volumetric Requirements
	HMA	Evotherm	Foamer	
G_{sb}	2.655	2.655	2.655	
G_{mb} @ N_{des}	2.316	2.330	2.334	
G_{mm}	2.425	2.437	2.430	
% VTM	4.4	4.4	3.9	4.0 ± 0.5
% VMA	17.5	17.3	17.2	> 15.0%
% VFA	66.9	66.5	66.2	65-78%
% G_{mm} at N_{ini} (7)	88.9	89.2	89.4	≤ 89.0%
% G_{mm} at N_{des} (65)	95.6	95.6	96.1	96%

Table 3-7 Volumetric Properties for 40% RAP Mixtures with 5.8% PG 58-28 Binder

Volumetric Properties	**Mix Type**			**Volumetric Requirements**
	HMA	Evotherm	Foamer	
G_{sb}	2.655	2.655	2.655	
G_{mb} @ N_{des}	2.325	2.330	2.325	
G_{mm}	2.415	2.436	2.424	
% VTM	3.8	4.3	4.1	4.0 ± 0.5
% VMA	17.6	17.3	17.5	> 15.0%
% VFA	66.9	66.5	66.9	65-78%
% G_{mm} at N_{ini} (7)	89.9	89.2	89.2	≤ 89.0%
% G_{mm} at N_{des} (65)	96.2	95.7	95.9	96%

4. EVALUATING WORKABILITY USING %G_{mm}

In this chapter, the compaction heights of mix design specimens at optimum asphalt content were used to evaluate the workability of the mixtures. The Superpave Gyratory Compactor records compaction heights against the number of gyrations; using this data, %G_{mm} corresponding to gyration levels were computed. This compactability was used to compare and rank mixture workability.

4.1 Procedure

The compaction data from the mix design mixtures prepared with the optimum asphalt content was used to rank the mixtures based on their workability. Each specimen was compacted to the design number of gyrations, N_{des} = 65. The %G_{mm} was calculated at every 5 gyration interval, as well as at 7 gyrations. The area under the curve from the first gyration to the point where 92 % G_{mm} is reached is used to calculate the compactability. From literature we know that the area under the curve should be less for a mixture with a better workability and hence the curve which reaches 92% G_{mm} first will have better workability [47]. N92, the number of gyrations to reach 92% G_{mm} were calculated for all the mixtures. N92 was used to rank the mixtures on their workability. Workability is more for mixtures with less N92 value.

4.2 Results

The N92 values for HMA, Evotherm and Foamer mixtures with 0% RAP are 17, 18, and 16 respectively. There was no difference in the %G_{mm} curves at 92%G_{mm} indicating the workability of the HMA, Evotherm and Foamer mixtures to be very similar. Figure 4-1 shows the % G_{mm} curves for 0% RAP mixtures, with the area in between the red lines representing the ± 0.5% air void tolerance zone.

Figure 4-2 shows the %G_{mm} curves for 20% RAP mixtures. For 20% RAP mixtures, the compaction data for optimum asphalt content, 5.9% binder by weight of mix was not available. Hence the curves were plotted with asphalt content of 5.8% binder by weight of mix. The N92 values for 20% RAP mixtures with 5.8% binder by weight of mix were 23, 21 and 20 for HMA, Evotherm and Foamer mixtures respectively. All the curves were inside the tolerance limit when the $\%G_{mm}$ curve for each mixture reached the $92\%G_{mm}$ line indicating that all the mixtures have similar workability.

For 40% RAP mixtures, two different binders were used: PG 64-22 and PG 58-28. The curves for all the six mixtures were plotted together on the same graph, shown in Figure 6-3. The N92 values for the PG 58-28 mixtures with 40% RAP were 16, 19, and 16 for HMA, Evotherm and Foamer mixtures respectively. For PG 64-22 and 40% RAP mixtures the N92 values for HMA, Evotherm and Foamer mixtures were 23, 20 and 18 respectively. The change in N92 numbers is more for HMA mixtures than the Evotherm and Foamer mixtures when the binder grade is changed. The same trend was observed in 40% RAP mixtures as noted in the case of 20% RAP and 0% RAP mixtures. All the other curves were out of the tolerance range of $\%G_{mm}$ values when the curve for HMA mixture with PG 64-22 binder reached the $92\%G_{mm}$ value. For other curves expect for HMA mixture with PG 64-22, all the other curves were in the acceptable range.

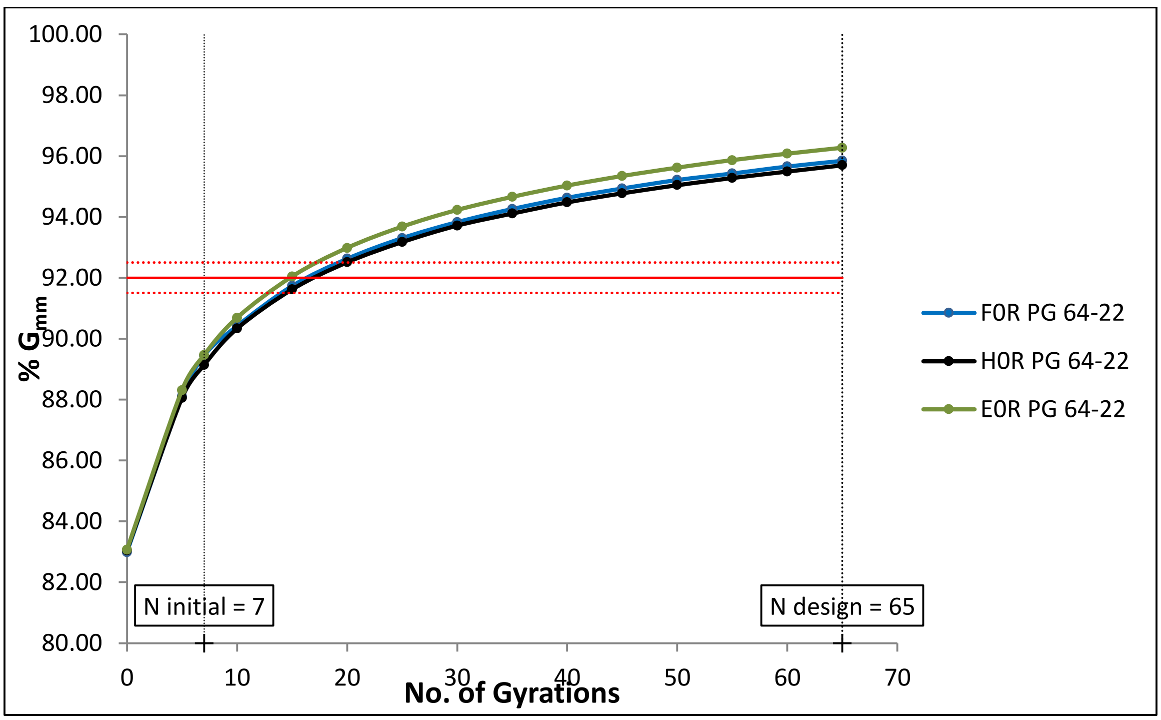

Figure 4-1 $\%G_{mm}$ curves for 0% RAP mixtures

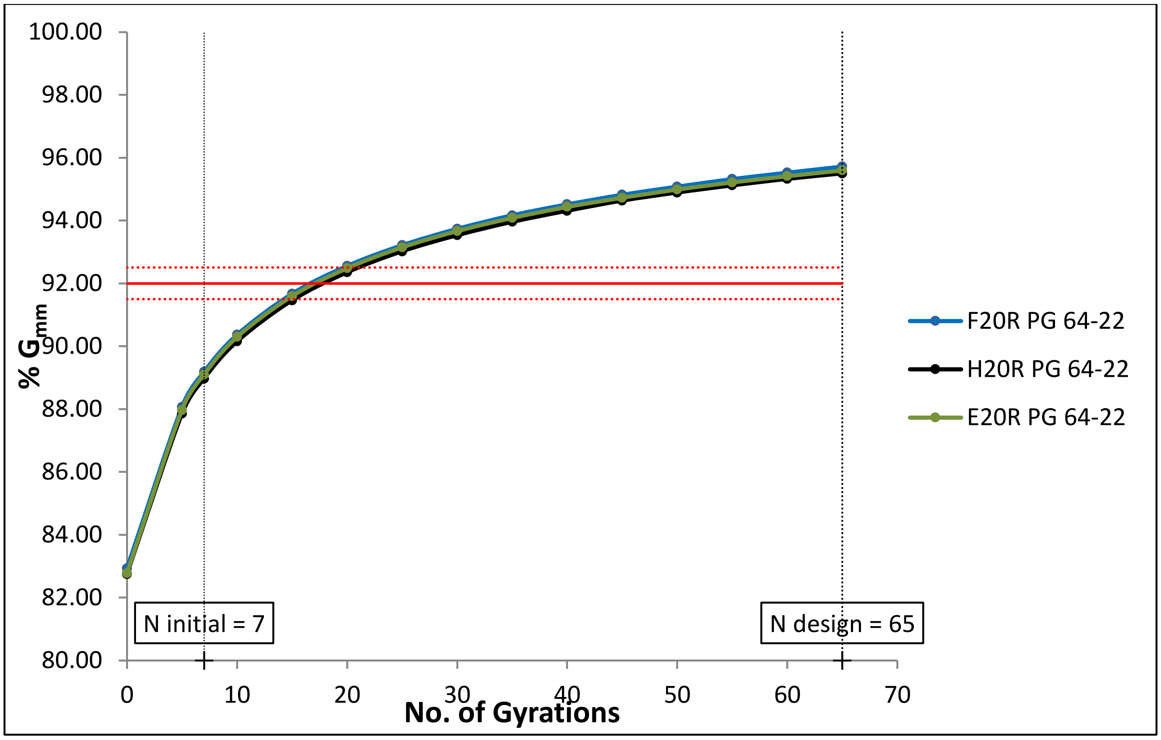

Figure 4-2 %G_{mm} curves for 20% RAP mixtures

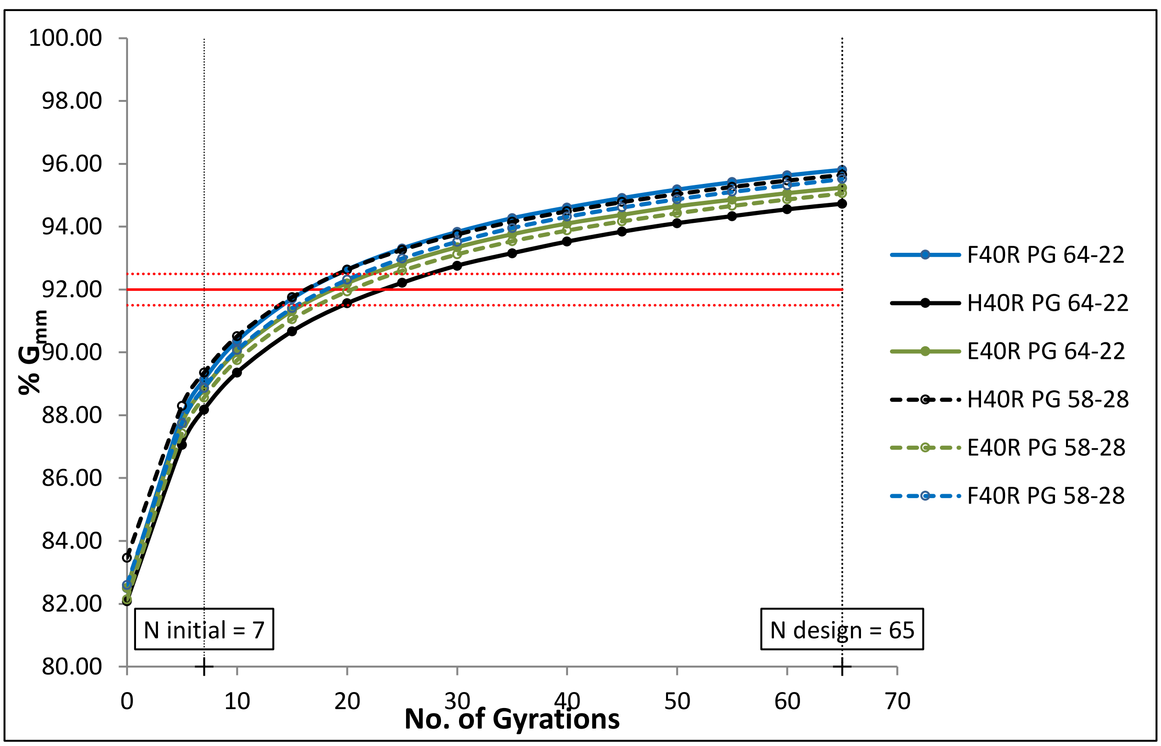

Figure 4-3 %Gmm curves for 40% RAP mixtures

To compare the variation of %Gmm trends within each mixture technology type, the %G_{mm} curves for HMA, Evotherm and Foamer mixtures with varying RAP contents were plotted together. These are shown in Figure 4-4, Figure 4-5 and Figure 4-6, respectively.

For Hot Mix Asphalt mixtures, the workability decreased as the amount of RAP was increased. The N92 values for HMA mixtures were 17 for virgin mixture, 23 for 20% RAP with 5.8% binder content, 16 for 40% RAP with PG 58-28 binder, and 23 for 40% RAP with PG 64-22 binder. The %G_{mm} curves for 0% RAP, 20% RAP and 40% RAP with PG 58-28 all were coinciding, indicating similar workability. But for 40% RAP mixtures with PG 64-22, a significant difference in workability was observed as when the %G_{mm} evolution curves for other HMA mixtures were out of the acceptable range when the curve for 40% RAP and PG 64-22 binder reached 92%G_{mm} value.

The %G_{mm} curves for all the Evotherm mixtures were in the acceptable range, when one of the mixtures reached the 92% G_{mm} value, indicating no significant difference in workability of all the Evotherm mixtures. The N92 numbers for Evotherm mixtures were observed to be 18 for virgin mixture, 21 for 20% RAP with 5.8% binder content, 19 for 40% RAP with PG 58-28 binder, and 20 for 40% RAP with PG 64-22 binder.

The same trend of %G_{mm} curves was followed in the case of Foamer mixtures as observed in Evotherm mixtures, was seen in the case of Foamer mixtures, indicating that the Foamer mixtures also did not exhibit significant difference in workability. The Foamer mixtures showed N92 values of 16 for virgin mixture, 20 for 20% RAP with 5.8% binder content, 16 for 40% RAP with PG 58-28 binder, and 18 for 40% RAP with PG 64-22 binder.

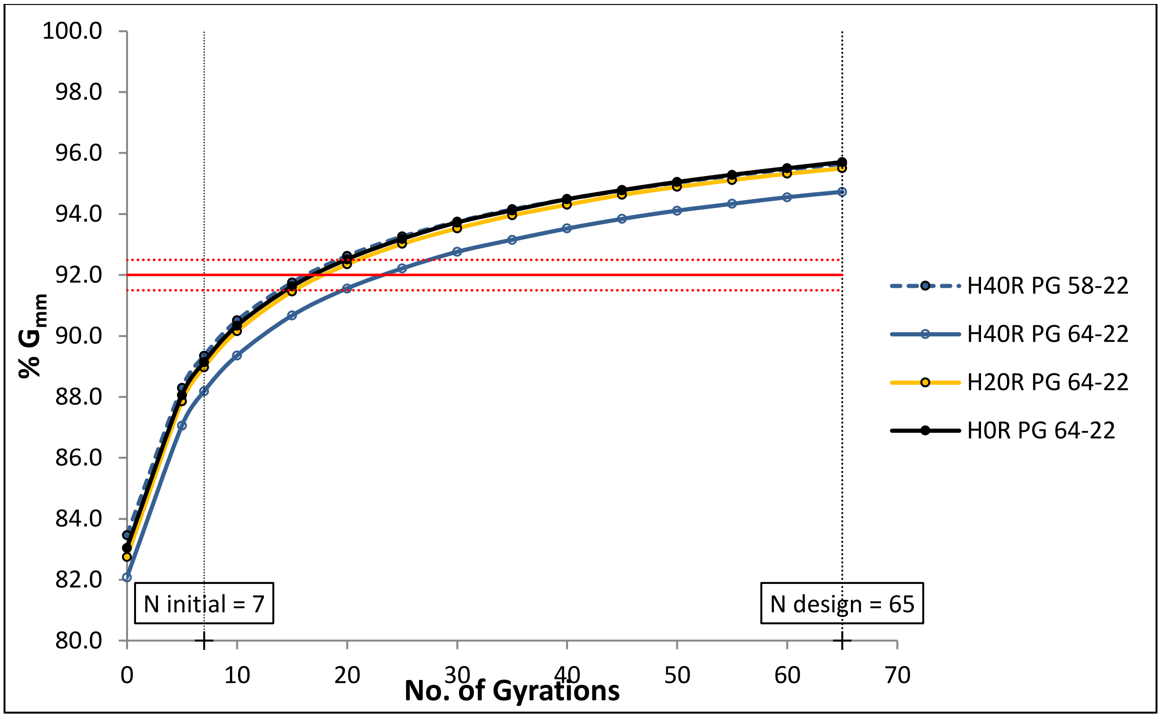

Figure 4-4 %G_{mm} curves for HMA mixtures

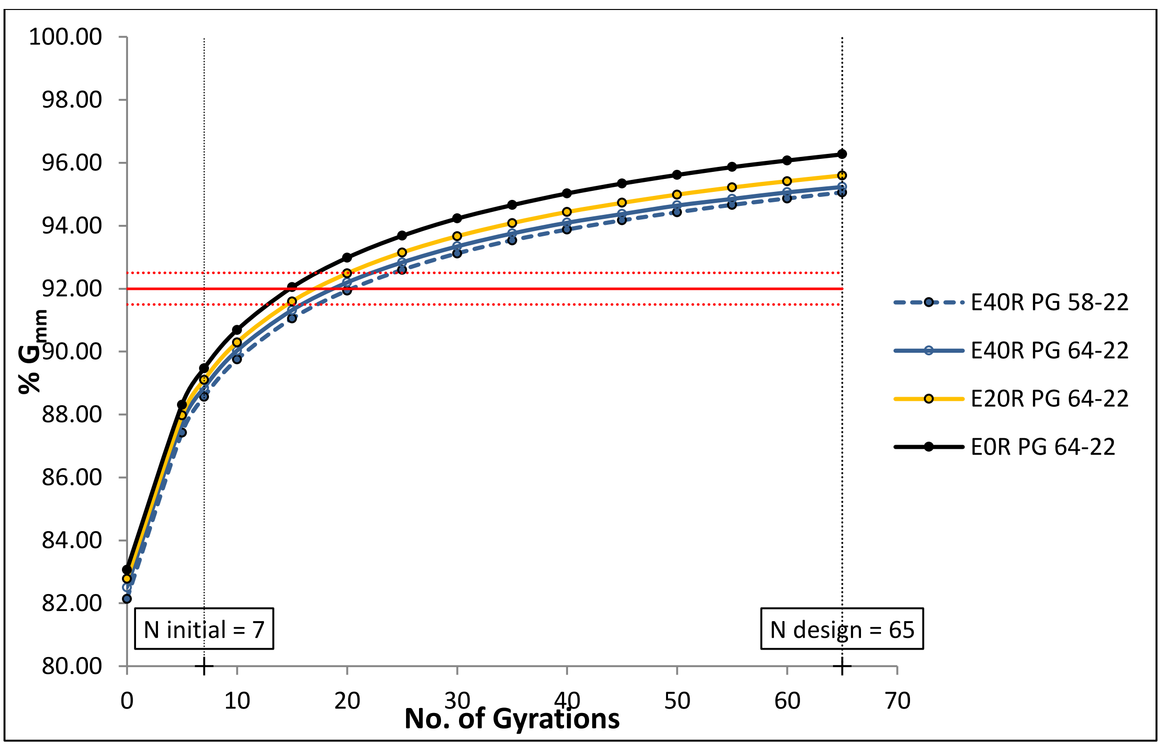

Figure 4-5 %G_{mm} curves for Evotherm mixtures

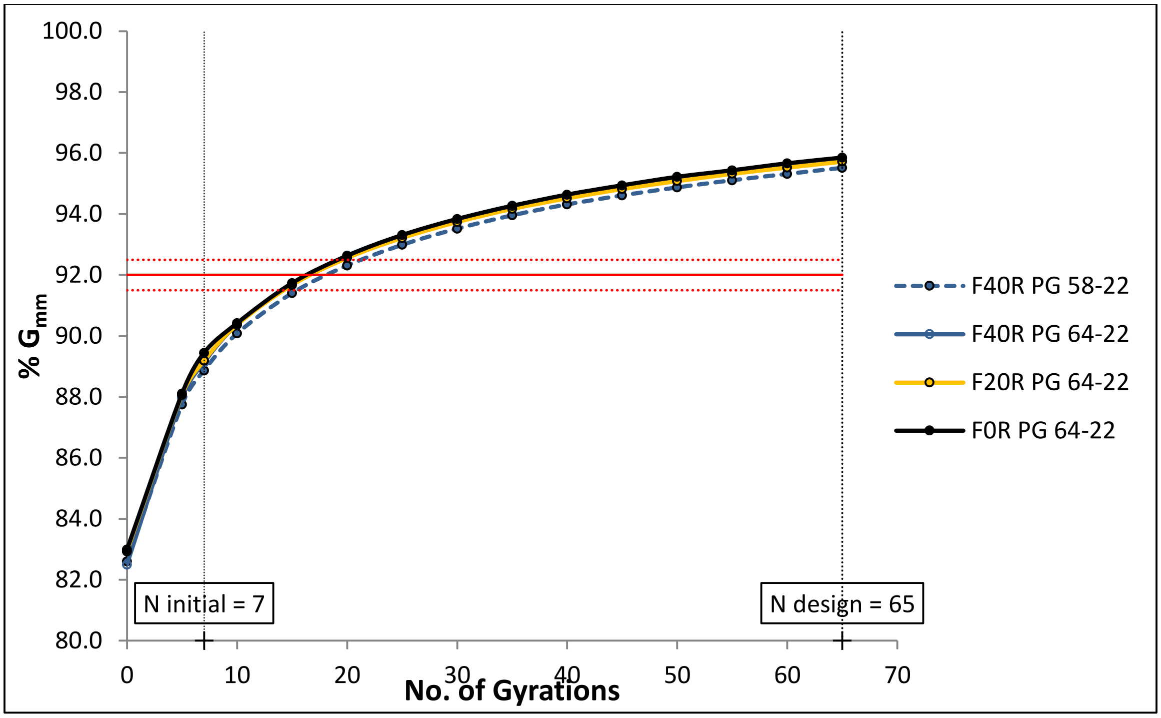

Figure 4-6 %G_{mm} curves for Foamer mixture

4.3 Conclusions

The Foamer and Evotherm mixtures at lower production temperatures showed workability similar to that of HMA mixtures for all three RAP contents. The workability decreased with increase in RAP content in the mixtures for same binder grade. Lowering of binder grade increased the workability of the HMA mixtures significantly but there was no significant difference observed in the workability of the Evotherm and Foamer mixtures when the binder grade was lowered.

5. TENSILE STRENGTH RATIO

This section focusses on characterizing the mixtures based on their moisture susceptibility. Tensile Strength Ratio (TSR) test was used for this purpose. The test was performed according to the guidelines specified by NCDOT, which is a modification of the AASHTO T 283, “Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage.” This test was aimed at determining the variation in moisture susceptibility of asphalt mixtures with varying RAP content, and different WMA technologies.

5.1 Specimen Preparation

The TSR test requires two sets of specimens for every mixture. One set will be tested dry, while the other set will be saturated before testing. 5 specimens were prepared for each set and hence total of 10 specimens were prepared for each mixture. The specimens were prepared as per the standard specifications and were compacted to a target air void content of 7 ± 0.5%. The standard specimen dimensions were 150 mm diameter and 95 ± 5 mm height. The specimens were prepared using the same aggregate gradation which was used for mix design and the optimum asphalt content found out during the Superpave mix design. A liquid anti-stripping additive, LOF 6500, of 0.75% by weight of the total binder (i.e. virgin binder as well as binder contributed from the RAP material in the mixtures where RAP was used) was added to all mixtures.

To calculate the amount of aggregates and weight of asphalt binder needed to prepare the specimens of the required specification, the maximum specific gravity (G_{mm}) values of the respective mixtures were used. For WMA mixtures using Evotherm, the same dosage of 0.5% was used to prepare the specimens.

As per standard specifications, the loose mixtures were prepared at their respective mixing temperatures (163°C for HMA and 136°C for WMA). The specimens were then cooled for 2 hours and cured at 60 °C (140 °F) for 16 hours. After curing, the mixtures were heated for 2 hours to their respective compaction temperatures (149 °C for HMA and 120 °C for

WMA) and then compacted to a height of 95 ± 5 mm using the Superpave gyratory compactor.

5.2 Test Procedure

Two specimens whose air voids had the most deviation from the targeted value of 7.0% were eliminated from the 10 specimens for each mixture. The 8 specimens for each mixture were divided randomly into two sets of 4 specimens each. One set was kept dry and tested at room temperature i.e. 25 °C (77 °F), while the other set was moisture conditioned before testing. According to the NCDOT specifications, the set of specimens which were to be moisture saturated were first vacuum-saturated with water to a saturation level of 70 – 80% and then conditioned in a water bath at 60 °C for 24 hours. After the 24 hours of conditioning, they were cooled for two hours in a water bath at 25 °C (77 °F).

The specimens were set up in a loading jig and load was applied diametrically using a Marshall Loader. They were loaded at a rate of 50.8 mm (2 in.) per minute and the peak load vs deflection data was recorded in a graph. The peak load for each specimen was noted and the indirect tensile strength of the specimen was calculated using the peak load. The median value of the indirect tensile strengths of each set of specimens (conditioned and unconditioned) was taken as the representative indirect tensile strength value of that set. The tensile strength ratio was then calculated for each mixture by taking the ratio of the average indirect tensile strength (ITS) value of conditioned specimens to unconditioned specimens.

$$TSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}}$$

NCDOT requires all its mixtures to pass a minimum TSR value of 85%.

5.3 Test Results and Interpretation

The peak load for a specimen was calculated using the correction factors for the Marshall loader and the peak load reading from the graph. This peak load was used to calculate the ITS value using the following equation.

$$ITS = \frac{2P}{\pi d h}$$

where,

ITS = Indirect Tensile Strength (kPa or psi)

P = Peak Load (kg or lbs)

d = diameter of the specimen (mm or in)

h = height of the specimen (mm or in)

The ITS values for all the specimens were calculated and tabulated. A nomenclature was used to label the specimens where the first letter denotes the type of mixture technology used: H – HMA; E – Evotherm; F – Foamer. The number and letter 'R' succeeding the first letter represent the amount of RAP in the mixture: 0R – 0% RAP; 20R – 20% RAP and 40R – 40% RAP. For example, H0R indicates a HMA mixture with 0% RAP in it.

The individual TSR test results for each mixture combination are summarized in Appendix B. A summary of all TSR test results is shown in Table 5-1 and Figure 5-1.

5.3.1 Virgin Mixtures

The TSR values for the HMA mixtures and WMA mixtures with Evotherm and Foamer were calculated to be 101.4%, 93.8% and 94.4% respectively. All of these values are above the minimum limit for TSR value of 85% as specified by the NCDOT. Hence, as all the virgin mixtures pass the minimum TSR criteria, none of the virgin mixtures are expected to exhibit significant moisture damage in the field.

5.3.2 Mixtures with 20% RAP

The TSR values for the HMA mixtures and WMA mixtures with Evotherm and Foamer were calculated to be 87.7%, 89.9% and 87.4% respectively. All the three different 20% RAP mixtures have a TSR value in the same range. The mixtures with Evotherm showed the highest TSR value and the Foamer mixtures exhibited the lowest TSR value. All of these values are above the minimum limit for TSR value of 85% as specified by the NCDOT. Hence, as all the mixtures with 20% RAP pass the minimum TSR criteria, none of the mixtures with 20% RAP are expected to exhibit significant moisture damage in the field.

5.3.3 Mixtures with 40% RAP

The TSR values for the HMA mixtures, and WMA mixtures with Evotherm and Foamer were calculated to be 90.2%, 85.4% and 74.9% respectively. The HMA mixtures used PG 58-28 while the Evotherm and Foamer were prepared using PG 64-22 binder. The 40% RAP HMA mixtures exhibited the highest TSR value amongst all 40% RAP mixtures with Foamer having the least value. The TSR value for 40% RAP HMA mix is well above the minimum required TSR value by the NCDOT. 40% RAP Evotherm mixture barely crosses the 85% minimum value, while 40% RAP Foamer mixture exhibited TSR value well below the minimum required value by NCDOT. Hence in field, 40% RAP HMA and Evotherm are expected to perform well against moisture damage but 40% RAP Foamer is expected to show significant moisture damage in field as per the TSR test results.

5.4 Conclusion

From the results it is evident that there is a decrease in the TSR values for each type of mixture – HMA, Evotherm and Foamer as the RAP content increases. For the same RAP content, the highest TSR value was exhibited in the case of HMA. The TSR values of Evotherm and Foamer were in the same range for all RAP contents except for 40% RAP. 40% RAP Foamer mixtures exhibited very low TSR values. This can be due to the extremely high Tensile Strength values exhibited by the dry set of specimens of 40% RAP Foamer. The TSR values decreased with the increase in RAP content which might be due to improper blending between the virgin and RAP materials. But in the case of HMA mixtures, there is a decrease in TSR value from virgin to 20% RAP and an increase in TSR value from 20% RAP to 40% RAP mixtures. The increase in TSR value can be due to the use of a softer binder PG 58-28.

The TSR ratio of virgin HMA mixtures exceed 100%, this might be due to pore pressure which results in a higher ITS value for the virgin HMA mixtures saturated with water.

A summary of the TSR values of all the mixtures is given in Table 7-10. The Indirect Tensile Strength values for all the mixtures increase with the increase in RAP content. Again this trend is violated in the case of HMA from 20% RAP to 40% RAP where the values are nearly same. The general increasing trend in the ITS values is due to the addition of RAP material which is stiffer than the virgin material. But this trend was not followed in the case of HMA mixtures as a softer grade binder was used for 40% RAP HMA mixture.

Table 5-1 Summary of TSR test results of all the mixtures

Mixture Type	**Median Indirect Tensile Strength (kPa)**		**TSR (%)**	**Pass/Fail (Min 85%)**
	Conditioned	**Unconditioned**		
HMA 0% RAP (PG 64-22)	1074	1059	101.4	PASS
EVO 0% RAP (PG 64-22)	796	849	93.8	PASS
FOAM 0% RAP (PG 64-22)	1022	1082	94.4	PASS
HMA 20% RAP (PG 64-22)	1292	1473	87.8	PASS
EVO 20% RAP (PG 64-22)	1345	1495	89.9	PASS
FOAM 20% RAP (PG 64-22)	1202	1375	87.4	PASS
HMA 40% RAP (PG 58-28)	1315	1458	90.2	PASS
EVO 40% RAP (PG 64-22)	1360	1593	85.4	PASS
FOAM 40% RAP (PG 64-22)	1503	2006	74.9	FAIL

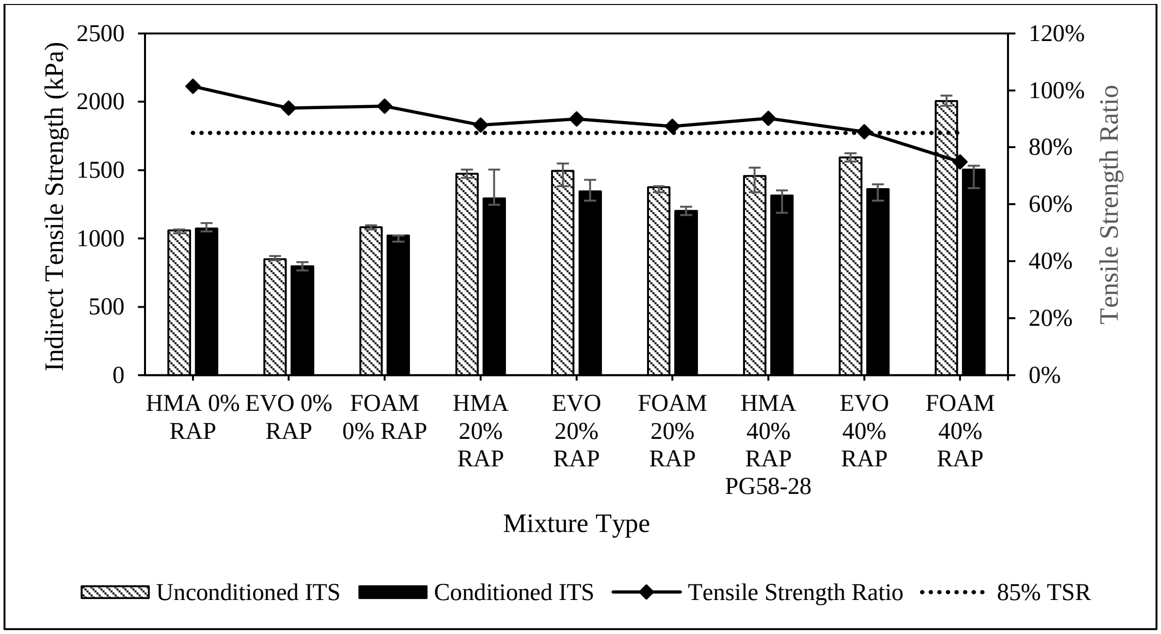

Figure 5-1 ITS values of conditioned and unconditioned samples and TSR Results

6. EVOTHERM AS AN ANTI-STRIP ADDITIVE

MeadWestvaco, manufacturers of Evotherm suggest that in addition to it being a WMA additive, Evotherm can also be used as an anti-strip additive [49, 50]. Kuang,Y performed ITS, dynamic modulus, and Hamburg wheel track tests to evaluate the moisture susceptibility of Evotherm for Iowa mixtures [50]. He aimed at finding the optimum amount of Evotherm required to fulfill the minimum criteria associated with those tests but did not compare the performance of Evotherm with other standard anti-strip additives.

Another important property of any chemical additive is its volatility. The amount of additive left in the mixture, after heating the mixture is important. As the volatility of an additive increases, the amount of additive left in the mixture decreases, and hence the effectiveness of the additive also goes down. Litmus paper test using a StripScan Device can be used to test the volatility of an additive in the mixture.

6.1 Litmus Test Overview

The litmus test uses the color difference caused in the litmus paper caused by the fumes from the mixture containing the additive to measure the amount of additive left in the mixture. A calibration is done using asphalt concrete mixtures with varying additive content. To calculate the color difference in the litmus paper, a spectrophotometer is used to take the readings of the litmus paper before exposure to the fumes from the asphalt concrete mix and after exposure. The difference in color measured by the spectrophotometer is called the color index. Color index is calculated for different additive percentages and a calibration correlation curve (regression equation) is established using the measurements. The mixture with the required quantity of additive is heated for the desired time periods, and the color index is calculated at those time periods. Using this color index and the regression equation, the amount of additive left in the mixture is estimated. In this study StripScan Instrument was used to perform the litmus paper test. It has an inbuilt spectrophotometer which measures color changes in the litmus paper.

6.2 Calibration Procedure

Calibration Procedure to determine antistrip additive content in asphalt mixtures is described below:

1. Required amount of ant-strip additive is incorporated into the asphalt binder
2. 2000 g asphalt mixture samples with binder containing different anti-strip contents were prepared. Two samples were prepared for each additive content in this study.
3. The samples have to be preheated for 1 hour. The lid has to be left open during the pre-heating and the sample has to be agitated every 15-20 minutes.
4. After pre-heating for 1 hour, the sample has to be transferred to the StripScan device. A heating plate in the device maintains the sample temperature at 120°C, which is verified with a thermocouple introduced through a small hole in the can lid.
5. A litmus test strip is brought into contact with the vapors escaping through the lid opening for a period of 3 min. It should be note that before exposing the litmus strip to vapors, it is scanned by the spectrophotometer in StripScan to get the initial reading.
6. After the exposure to the vapors, the litmus strip goes into the StripScan and is scanned by the spectrophotometer inside. The difference in spectrophotometer readings before and after vapor exposure is the color index that corresponds to the amount of anti-strip additive present in the mixture. This color index is recorded by the instrument.
7. The same procedure is repeated for other samples.
8. A correlation curve (regression equation) is established between the additive content and the color index measured by the spectrophotometer.

StripScan device automates the Steps 5 to 8.

6.3 Calibration and Measurement

Four different Evotherm additive contents – 0.0%, 0.25%, 0.5% and 1.0% were used to prepare the mixtures to establish a calibration curve for the Evotherm additive. Two sets of mixtures were prepared for each additive percentage and their color counts were measured. The average count values of each additive percentage were used in developing the calibration equation. The mixtures were preheated for an hour to 120°C (248°F) before their readings were taken during calibration. 120°C simulates the compaction temperature of mixtures with Evotherm additive.

The steps involved in the calibration procedure were followed to measure the amount of additive left in the mixture. The instrument measures the color index and represents it as count.

Since a 0.5% Evotherm additive dosage is recommended, the same dose was chosen to take the measurements. The mixture with Evotherm in it was heated to different time periods. Each time period simulates different field or laboratory conditions. The 2 hour heating represents the normal compaction time in the field, while the 8 hour and 24 hour represent delayed compaction in the field or mixture storage in a silo. Another set of samples were heated similar to how the TSR samples are conditioned. They were allowed to cool at room temperature for 2 hours, followed by 16 hours curing at 60°C (140°F), and then heated to 120°C (248°F) for 2 hours before testing. The amount of the antistrip additive left in the mixture after different heating times was measured using the litmus paper test.

6.4 Results

The averaged color counts for the four different additive contents are presented in Table 6-1. Using these values, a calibration curve was generated. The calibration curve was generated by the StripScan instrument. The curve is also affected by the correction factors for the instrument and also the spectrophotometer inside the StripScan. Figure 6-1 shows the calibration curve.

6.4.1 Calibration Results

The results from the calibration test for the Evotherm are expressed in Table 6-1. Figure 6-1 depicts a graph which shows the variation of color count values with the change in the amount of additive in the mixture. It also includes a curve which is the calibration curve obtained from the StripScan instrument.

Table 6-1 Calibration Test Results for Evotherm Additive

Additive	**StripScan Count**
0	437
0.25	458
0.5	531
1	616

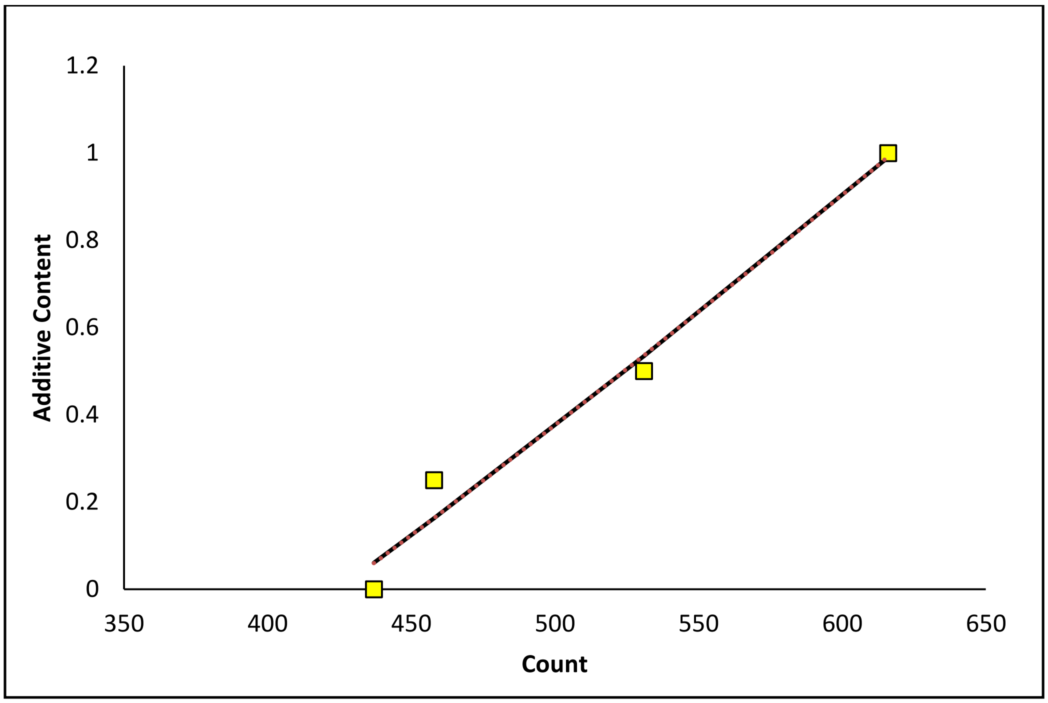

Figure 6-1 Calibration Graph between Additive Content and Count

6.4.2 Calibration Equation

The Calibration Equation from the Instrument for Evotherm is as follows –

$$AC = 1.771 \times 10^{-6} \times c^2 + 0.003335 \times c - 1.736$$

where,

AC = Additive Content

c = Count from the sample

The value of "c" in the calibration equation has a minimum value depending on the spectrophotometer and also the litmus paper to which the spectrophotometer in the instrument is calibrated. There is a difference in the calibration equation obtained by using excel and the regression equation generated by the instrument due to the correction factors involved. In this case the minimum value of c = 425.

The calibration equation obtained by using Excel without using the correction factors is as follows –

$$AC = 2.0 \times 10^{-6} \times c^2 + 0.0035 \times c - 1.785$$

6.5 Measurement Results

Table 6-2 shows the average count values for the mixtures at different heating times and the estimated amount of Evotherm additive present in it. The additive content was estimated by the StripScan using these averaged counts and the calibration curve.

Table 6-2 Count Values and Estimated Additive Content

Heating Time	Count	Additive Content
2 hours	527	0.51%
8 hours	491	0.33%
TSR conditioning	472	0.23%
24 hours	445	0.10%

It is clearly seen that the mixture with additive content of 0.5% still had the same value after two hours heating period, i.e. the time it will be heated before compacted in the field. But when the mixture is heated to 8 hours, the additive content falls to 0.33%, and to 0.10% when heated for 24 hours.

Therefore, it is imperative that the field mixtures containing Evotherm as an anti-strip additive not be subjected to extended heating period to avoid moisture susceptibility of the mixtures. In this regard, Evotherm behaves similar to other liquid anti-strip products like LOF 6500 and MORLIFE that have been previously evaluated for NCDOT.

6.6 TSR Test Results and Conclusion

To test the effectiveness of Evotherm as an anti-strip additive, TSR test was conducted on virgin mixtures by adding just Evotherm and not including any additional anti-strip additive. The results of the TSR test with only Evotherm and no other additional anti-strip additives are given in Table 6-3.

The TSR ratio for mixtures with only Evotherm is 88%, which is still above the minimum required TSR value of 85% as specified by NCDOT.

Table 6-3 TSR Test Results for Mixtures with only Evotherm

Moisture Conditioning	Specimen #	air void content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	EVO 2	6.8	137.31	947	939	88
	EVO 6	7.0	135.13	932		
Wet	EVO 3	7.2	135.13	932	827	
	EVO 5	7.1	104.62	721		

Evotherm as an anti-strip additive has an advantage over other products since it also acts as a WMA additive that facilitates use of lower mixing and compaction temperatures. Therefore, the rate of loss of Evotherm additive from mixtures is slower.

However, it should be noted that based on the TSR results for mixtures with 40% RAP as seen in Table 5-1, which contained Evotherm as well as liquid anti-strip additive, the mixture just passed the NCDOT required specification of 85%. Therefore, the dosage of Evotherm additive may need to be increased in order to accommodate higher RAP contents, or else another additional anti-strip additive must be used.

7. E* STIFFNESS RATIO

In this section, details the performance test based on dynamic modulus ratio of specimens that were specifically prepared to evaluate moisture damage. These specimens were prepared at 7±0.5% air voids. The dynamic modulus values were determined for unconditioned and moisture-conditioned specimens using AASHTO T283 conditioning procedure.

Dynamic modulus is a fundamental material property used in various performance prediction models, such as the Mechanistic-Empirical Pavement Design Guide, to predict pavement distresses. It can also be used to directly compare stiffness of different mixtures using the E* stiffness ratio (ESR) parameter. Dynamic modulus testing was performed using the Asphalt Mixture Performance Tester (AMPT) device.

7.1 Asphalt Mixture Performance Tester (AMPT)

The AMPT device is a computer-controlled hydraulic testing machine capable of applying cyclic loading on cylindrical asphalt concrete specimens over a range of test temperatures and loading frequencies. The device measures the dynamic modulus, E* which is a ratio of the amplitude of cyclic stress applied to the amplitude of cyclic strain at each test temperature and frequency as well as the phase angle, φ. Figure 7-1 shows a sinusoidal loading cycle applied using the AMPT device, where E* is calculated using the following equation.

$$E^* = \frac{\sigma_0}{\varepsilon_0}$$

Test specimens for measurement of E* using the AMPT must be fabricated to dimensions of 100 mm diameter and 150 mm height. Specimens in the Superpave gyratory were first compacted to a height of 178 mm and diameter of 150 mm, and later cored and sawed to the required dimensions for testing as per AASHTO TP 79.

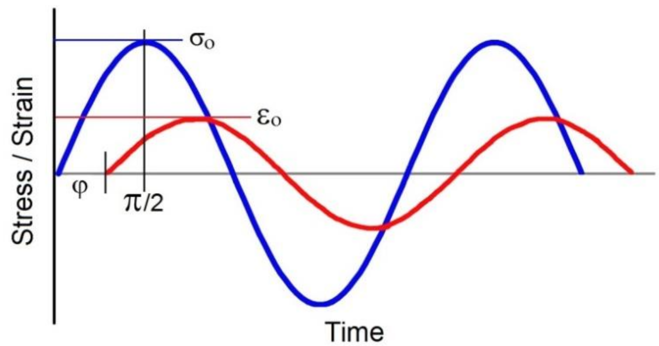

Figure 7-1 Schematic Diagram of Stress and Strain in Asphalt Concrete

The AMPT applies cyclic loading using a hydraulic actuator, which is operated using a computer program to load the specimen in a stress-controlled mode such that the axial strain in the specimen does not exceed a predetermined value. The axial stress is measured by the device through the actuator whose displacement is calibrated to measure the applied load. The axial strain is measured by placing linear variable displacement transducers (LVDTs) along the vertical length of the specimen. The LVDTs are mounted onto the specimen using brass targets so that they measure displacements over a gauge length of 70 mm, which in turn is used to calculate the axial strain. Figure 7-2 shows a schematic representation of LVDTs mounted on an AMPT dynamic modulus test specimen. The strain amplitude is reported as the average of the four LVDTs.

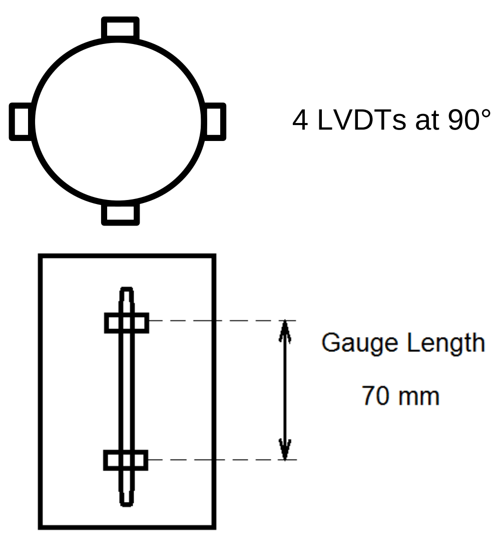

Figure 7-2 Arrangement of LVDTs on AMPT Test Specimen

7.2 ESR Test Description

Moisture susceptibility of virgin and warm mix asphalt mixtures were evaluated using the AASHTO T-283 Tensile Strength Ratio (TSR) test, as described in Section 5. Research studies have shown that WMA produced using moisture-inducing technology such as zeolites and foamed asphalt perform poorly when subjected to the TSR test. Recently, researchers have used E* stiffness ratio (ESR) test evaluate moisture susceptibility [43].

The ESR test is conducted on conditioned and unconditioned subsets of specimens, which are subjected to a conditioning procedure similar to the TSR test. ESR is defined as the ratio of average dynamic modulus of conditioned (wet) specimens to the average dynamic modulus of unconditioned (dry) specimens. Since dynamic modulus using the AMPT is measured at three temperatures and three frequencies for each specimen, ESR values are reported as averages for each test temperature.

$$\mathrm{ESR} = \frac{\text{Average} \,|E^*|\, \text{of wet specimens at any test temperature and frequency}}{\text{Average} \,|E^*|\, \text{of dry specimens at any test temperature and frequency}}$$

7.3 Specimen Preparation and Conditioning

Specimens for ESR test were prepared according to the procedure described in AASHTO TP 79-09, *"Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)"*. The specimens were initially compacted to a height of 178 mm with diameter of 150 mm using the Superpave gyratory compactor, and were cut and cored to dimensions of 150 $\pm$ 2.5 mm height and 100 $\pm$ 1 mm diameter for testing. The target air void content for ESR test was selected as 7 $\pm$ 0.5 % for the finished (cut and cored) specimens to ensure adequate saturation for testing in the moisture-conditioned (wet) state.

Conditioning of the mixtures during specimen preparation and testing was done according to the NCDOT modified AASHTO T-283 procedure. The mixtures were then placed in another oven at compaction temperature for two hours (149^{o}C for HMA and 120^{o}C for WMA) before compaction. For preparing specimens for the wet test, specimens were saturated using vacuum to obtain 35- 45% saturation. The saturated specimens were placed in a water bath at 60^{o}C for 24 hours. After removal, the specimens were surface-dried and left to air-dry at room temperature for a period of 24 hours. This was to ensure that the surface of the specimens was completely dry to allow proper adhesion of brass targets for mounting LVDTs.

Since the dynamic modulus test is a non-destructive test unlike the AASHTO T-283 Tensile Strength Ratio test, the same specimens were used for testing in both dry and wet conditions. First, the dynamic modulus testing of dry specimens for all mixtures was completed. Testing of wet specimens was conducted exactly one week later for to allow recovery of residual viscoelastic strains in specimens from the dry test. Air voids were measured again for each specimen and no variation was observed.

7.4 ESR Test Results

Table 7-1 shows the results of ESR test for HMA and WMA mixtures. The dynamic modulus values shown in the table are averages of two specimens tested for each mix type. The table has three subgroups based on the mixture technology used. The first part shows all the HMA mixtures with increasing RAP contents, followed by Evotherm mixtures and finally the Foamer mixtures. The dynamic moduli obtained from moisture-conditioned specimens are highlighted. For each of the three test temperatures, an average ESR value using the dynamic moduli values of the six frequencies of loading was computed.

Table 9-2 shows a comparison of TSR and average ESR values across all test temperatures for the nine mixtures.

Table 7-1 E* Stiffness Ratio Test Results

9-1 (a) ESR for HMA Mixtures

Mix Type	Temp (ºC)	Specimen State	Dynamic Modulus (MPa)						Average ESR (%)
Frequency (Hz)			25	10	5	1	0.5	0.1	
HMA 0% RAP	4	Dry	15,199	13,736	12,584	9,994	8,943	6,610	99.7
		Wet	15,313	13,674	12,575	9,965	8,867	6,532	
	20	Dry	7,084	5,844	4,995	3,235	2,710	1,666	88.3
		Wet	6,672	5,407	4,547	2,842	2,290	1,330	
	40	Dry	1,728	1,310	1,058	647	534	384	72.4
		Wet	1,377	991	771	445	370	263	
HMA 20% RAP	4	Dry	14,469	13,298	12,343	10,150	9,253	7,209	102.5
		Wet	14,839	13,589	12,568	10,346	9,443	7,532	
	20	Dry	7,595	6,435	5,604	3,893	3,299	2,145	90.5
		Wet	7,188	5,975	5,138	3,480	2,914	1,850	
	40	Dry	2,014	1,535	1,244	755	637	478	88.2
		Wet	1,558	1,194	987	663	619	523	
HMA 40% RAP	4	Dry	18,614	17,074	15,946	13,142	12,239	9,516	69.7
		Wet	13,533	12,266	11,302	9,136	8,215	6,286	
	20	Dry	9,977	8,936	7,829	5,541	4,943	3,376	57.8
		Wet	6,564	5,454	4,699	3,164	2,653	1,664	
	40	Dry	2,782	2,088	1,691	998	833	514	64.5
		Wet	1,812	1,361	1,083	633	517	345	

9-1 (b) ESR for Evotherm Mixtures

EVO 0% RAP	4	Dry	13,613	12,105	10,937	8,346	7,274	5,062	96.3
		Wet	13,138	11,685	10,550	8,016	7,020	4,851	
	20	Dry	5,773	4,544	3,724	2,183	1,730	962	90.2
		Wet	5,341	4,175	3,405	1,956	1,540	835	
	40	Dry	1,198	862	672	410	362	283	80.4
		Wet	1,040	732	560	327	276	201	

9-1 (b) continued

EVO 20% RAP	4	Dry	13,336	12,014	10,991	8,666	7,725	5,680	98.2
		Wet	13,136	11,828	10,824	8,530	7,579	5,515	
	20	Dry	6,234	5,039	4,269	2,691	2,178	1,282	89.7
		Wet	5,753	4,652	3,878	2,399	1,921	1,097	
	40	Dry	1,512	1,106	860	495	410	292	83.9
		Wet	1,276	917	714	411	347	249	
EVO 40% RAP	4	Dry	16,022	14,796	13,826	11,542	10,601	8,352	91.0
		Wet	15,086	13,806	12,762	10,435	9,423	7,249	
	20	Dry	7,865	6,624	5,731	3,871	3,221	2,008	90.8
		Wet	7,379	6,153	5,299	3,504	2,900	1,711	
	40	Dry	2,071	1,538	1,209	685	553	367	80.4
		Wet	1,742	1,262	976	541	433	287	

9-1 (c) ESR for Foamer Mixtures

FOAM 0% RAP	4	Dry	13,895	12,432	11,236	8,593	7,554	5,274	93.6
		Wet	13,190	11,704	10,557	7,991	7,007	4,883	
	20	Dry	5,785	4,584	3,771	2,227	1,773	980	75.5
		Wet	2,561	3,927	3,171	1,799	1,407	771	
	40	Dry	1,131	813	633	381	321	242	81.2
		Wet	973	675	517	301	253	190	
FOAM 20% RAP	4	Dry	13,958	12,642	11,597	9,192	8,192	6,141	96.8
		Wet	13,708	12,327	11,281	8,862	7,891	5,826	
	20	Dry	6,492	5,330	4,532	2,907	2,401	1,461	84.0
		Wet	5,836	4,684	3,905	2,410	1,943	1,116	
	40	Dry	1,417	1,063	860	521	438	327	81.9
		Wet	1,266	903	700	403	341	263	
FOAM 40% RAP	4	Dry	15,734	14,524	13,559	11,242	10,295	8,057	84.8
		Wet	13,714	12,541	11,645	9,518	8,565	6,567	
	20	Dry	7,681	6,418	5,549	3,742	3,084	1,877	85.0
		Wet	6,816	5,632	4,817	3,129	2,572	1,500	
	40	Dry	1,887	1,362	1,047	584	468	301	91.2
		Wet	1,691	1,225	950	528	427	286	

Table 7-2 Comparison of TSR and ESR Test Results

Mix Technology	RAP Content	Binder Grade	TSR (%)	ESR (% Average)
HMA	0%	PG 64-22	101.4	86.6
	20%	PG 64-22	87.7	93.7
	40%	PG 58-28	90.2	64.0
Evotherm	0%	PG 64-22	93.8	89.0
	20%	PG 64-22	89.9	90.6
	40%	PG 64-22	85.4	87.4
Foamer	0%	PG 64-22	94.4	83.4
	20%	PG 64-22	87.4	87.6
	40%	PG 64-22	74.9	87.0

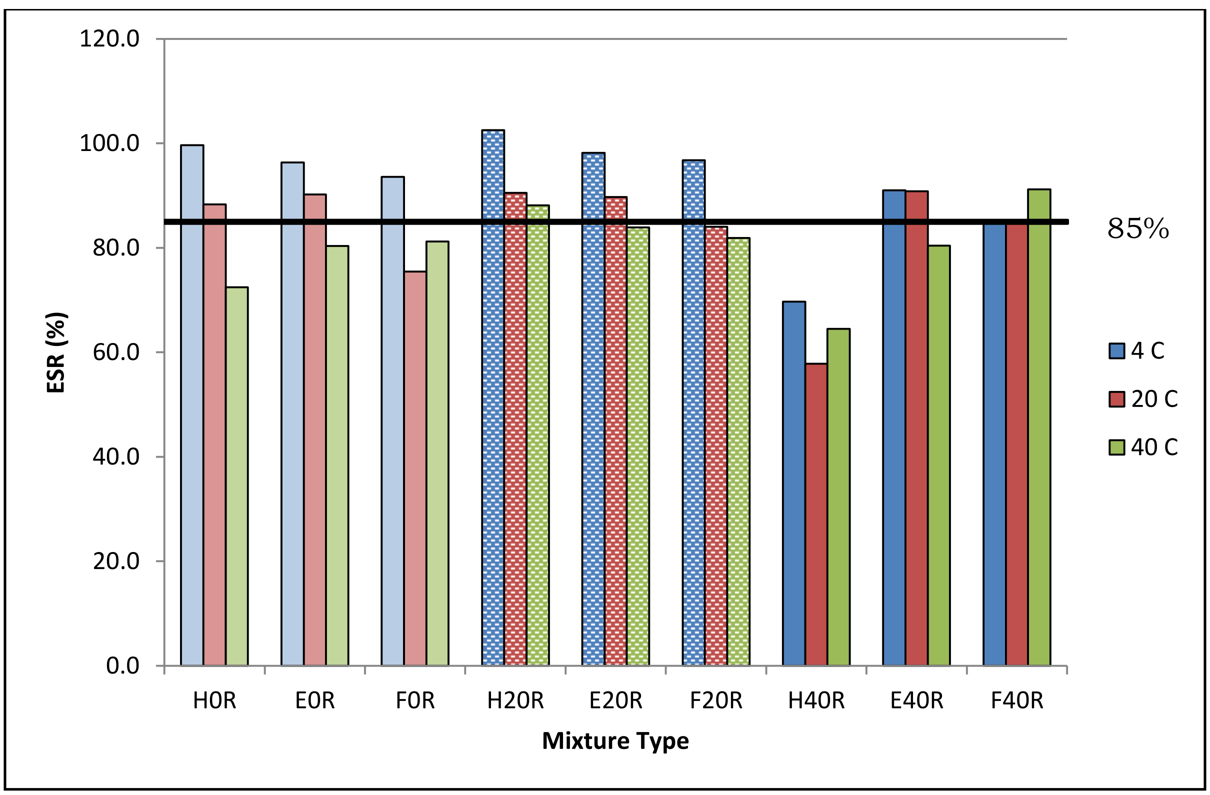

Figure 7-3 Average ESR Values at the Three Test Temperatures

The average ESR value across all test temperatures and loading frequencies was greater than 85% for seven out of the total nine mixtures. For Foamer mixtures with 0% RAP, the average was only slightly below 85%. The HMA mixture with 40% RAP with 64% ESR value behaved substantially differently from the other mixtures. This is the only mixture prepared with a softer PG 58-28 binder while all the other mixtures incorporated PG 64-22 binder. This shows that while the unconditioned dynamic moduli values may be similar for HMA and WMA mixtures, lowering the binder grade may be detrimental to the capacity of the mixture to resist moisture damage as well as other pavement distresses. WMA mixtures work very well in this scenario where the need for binder grade bump is eliminated while simultaneously preserving the mixture's moisture damage resistance.

An interesting observation that can be made from the data in Table 7-1 and Table 7-2 is that as the RAP content increases, the TSR values decrease. However, the E* ratio remains unchanged or actually increases with RAP content. This is probably due to the fact that TSR test measures properties in tension (indirect tension), whereas the E* value is measures in compression mode of loading. Therefore, it appears that the E* ratio (ESR) may not be appropriate in evaluating the moisture sensitivity of mixtures, because compression testing measures more of aggregate structure properties as opposed to the adhesive properties in tensile or flexural mode of loading. Further investigation is needed with E* values evaluated using tensile or flexural tests.

8. DYNAMIC MODULUS TEST

Dynamic modulus (|E*|) is an important parameter used in performance prediction models to predict pavement distresses over a specified design period. In this study, dynamic modulus testing was performed using the AMPT device according to AASHTO TP 79-09, "Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)". Specimen preparation procedure is similar to that used for preparing ESR test specimens, except that the target air voids for the specimens was 4 ± 0.5%.

8.1 Dynamic Modulus Mastercurves

Dynamic modulus test was conducted on HMA and WMA mixtures at three temperatures: 4, 20 and 40^{o}C and six frequencies: 25, 10, 5, 1, 0.5 and 0.1 Hz. The data obtained from the test were used to develop E* mastercurves at a reference temperature of 21^{o}C (70^{o}F) using a non-linear optimization procedure according to AASHTO PP 61-09, *"Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)"*.

Table 8-1 shows the average dynamic modulus of three specimens for each mix type. This table lists the mixtures in increasing order of RAP content (0%, 20% and then 40%) and is color-coded for each WMA technology (grey for HMA, white for Evotherm and green for Foamer, respectively).

Figure 8-7 shows E* mastercurves developed for all four mixtures at a reference temperature of 70^{o}F. For ease of comparison, these mastercurves were grouped into threes by mixture type (Figure 8-1, Figure 8-2 & Figure 8-3) and RAP contents (Figure 8-4, Figure 8-5 & Figure 8-6). Note that H, E and F in these tables refer to HMA, Evotherm and Foamed mixtures, respectively. The letter R and the number preceding it (0, 20 or 40) refers to the amount of RAP present in the mixture.

From Figure 8-1, we can observe that the dynamic modulus values are higher for HMA mixture as compared to the WMA mixtures. As expected, the virgin WMA mixtures are softer than HMA. However, we can observes that the E* mastercurve behavior is similar for all RAP mixtures, at both 20% (Figure 8-2) and 40% (Figure 8-3) RAP contents. Note that 40% RAP HMA mixtures have used a softer binder grade (PG 58-28) while all other RAP mixtures were prepared using PG 64-22. Despite lower production temperatures, HMA and WMA RAP mixtures have similar E* behavior. This reinforces the evidence that lowering of binder grade use in 40% RAP HMA mixture (PG 58-28 from PG 64-22) can be avoided when WMA mixtures are used.

In Figure 8-4, the E* mastercurves for all HMA mixtures are shown. The 40% RAP HMA mixture has the lowest E* values. This may be because of the softer binder grade (PG 58-28) used in this mixture while the 0% RAP and 20% RAP mixtures were prepared using PG 64-22 binder. When the E* mastercurve behavior is compared for the WMA mixtures (Figure 8-5 and Figure 8-6), no specific trend is observed, especially in the test range of loading frequencies (0.1 Hz to 25 Hz).

The mastercurves were used to obtain E* data at five temperatures: -10, 5, 20, 40 and 54°C (14, 40, 70, 100 and 130^{o}F) and six frequencies: 0.1, 0.5, 1, 5, 10 and 25 Hz for each mix as shown in Table 8-2. This data was used in AASHTOWare pavement ME software to predict the performance of a typical pavement section with respect to two primary distresses—fatigue cracking and rutting.

Table 8-1 Dynamic Modulus Test Results - 4 Percent Air Voids

Mix Type	Temp (°C)	Dynamic Modulus (MPa)					
Frequency (Hz)		25	10	5	1	0.5	0.1
H0R	4	20,962	19,398	18,165	15,231	13,879	11,134
	20	10,783	9,172	8,013	5,587	4,755	3,047
	40	2,942	2,205	1,740	975	783	502
E0R	4	16,984	15,530	14,329	11,504	10,319	7,694
	20	8,243	6,757	5,746	3,618	2,906	1,614
	40	1,805	1,274	968	517	424	327
F0R	4	17,846	16,349	15,099	12,279	10,994	8,279
	20	8,412	6,926	5,887	3,704	3,004	1,673
	40	1,866	1,317	1,017	563	478	338
H20R	4	18,461	17,057	15,888	13,338	12,201	9,763
	20	10,125	8,653	7,575	5,374	4,578	3,000
	40	2,986	2,264	1,828	1,061	878	589
E20R	4	18,650	17,104	15,961	13,102	11,933	9,295
	20	9,211	7,686	6,608	4,371	3,610	2,189
	40	2,283	1,681	1,325	757	625	433
F20R	4	18,695	17,228	16,019	12,972	11,611	8,769
	20	8,805	7,377	6,344	4,095	3,385	2,027
	40	1,586	1,785	1,442	798	658	492
H40R	4	16,787	16,129	15,211	11,698	10,779	8,745
	20	9,233	7,206	5,979	3,945	3,525	2,478
	40	3,139	2,388	1,841	996	623	508
E40R	4	16,616	15,814	15,773	13,008	11,867	9,439
	20	9,518	8,071	7,058	4,897	4,153	2,694
	40	2,606	1,938	1,537	865	697	437
F40R	4	17,486	16,189	15,225	12,732	11,656	9,326
	20	9,434	8,179	7,372	5,438	4,769	3,055
	40	3,037	2,280	1,821	1,040	849	556

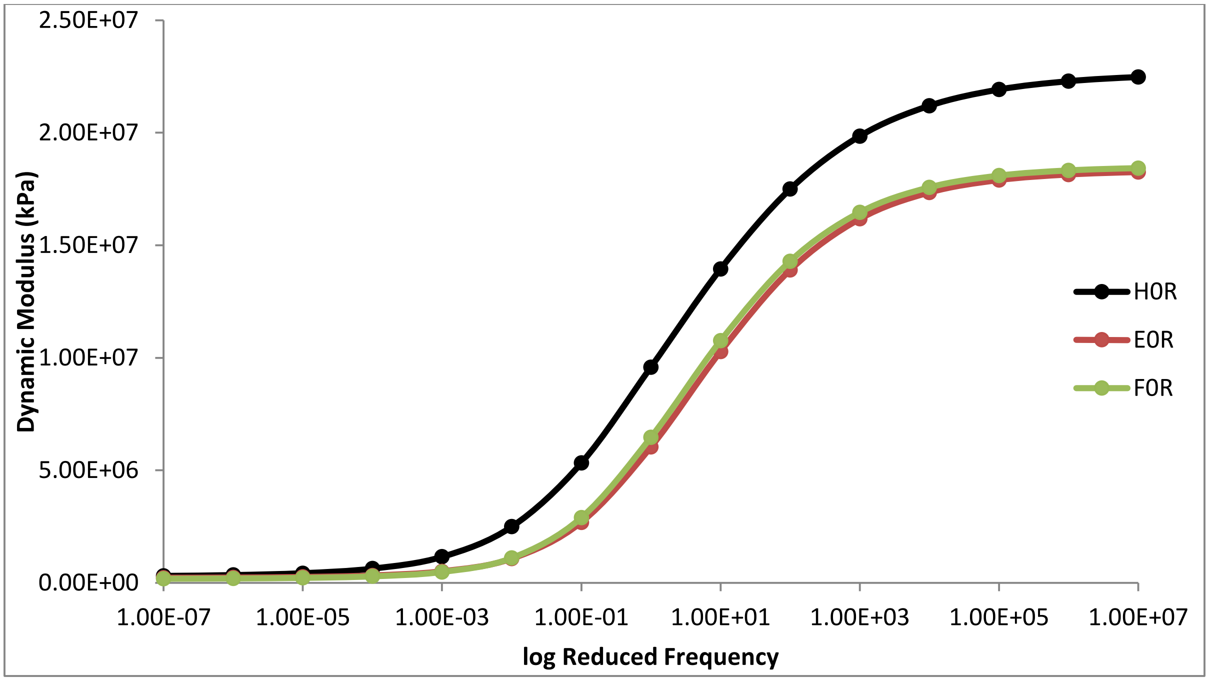

Figure 8-1 E* mastercurves for 0% RAP mixtures (reference temperature 70°F)

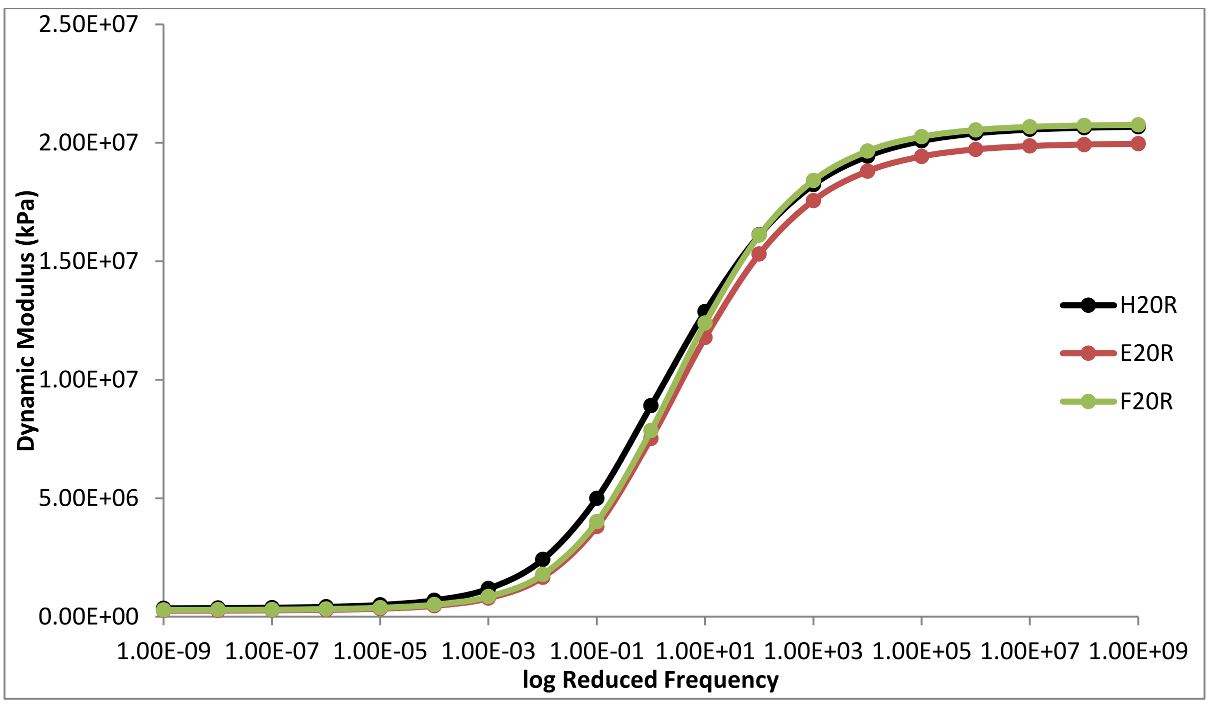

Figure 8-2 E* mastercurves for 20% RAP mixtures (reference temperature 70°F)

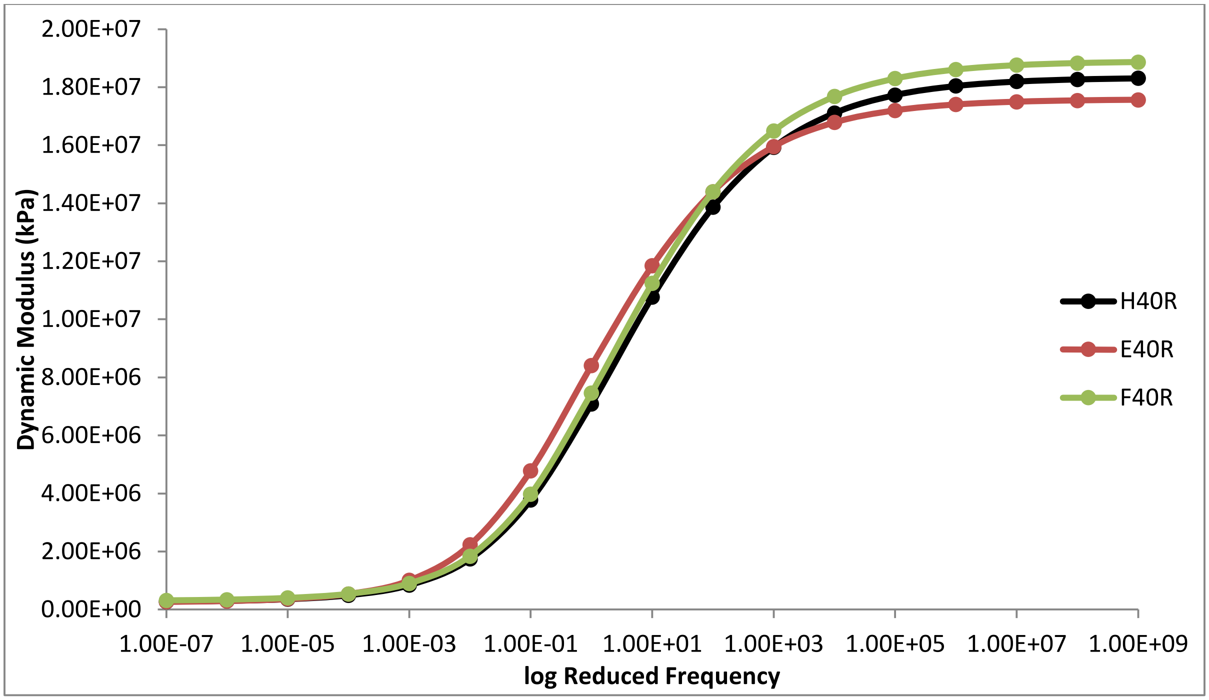

Figure 8-3 E* mastercurves for 40% RAP mixtures (reference temperature 70°F)

NOTE: H40R mixture uses PG 58-28, E40R and F40R mixtures use PG 64-22 binder

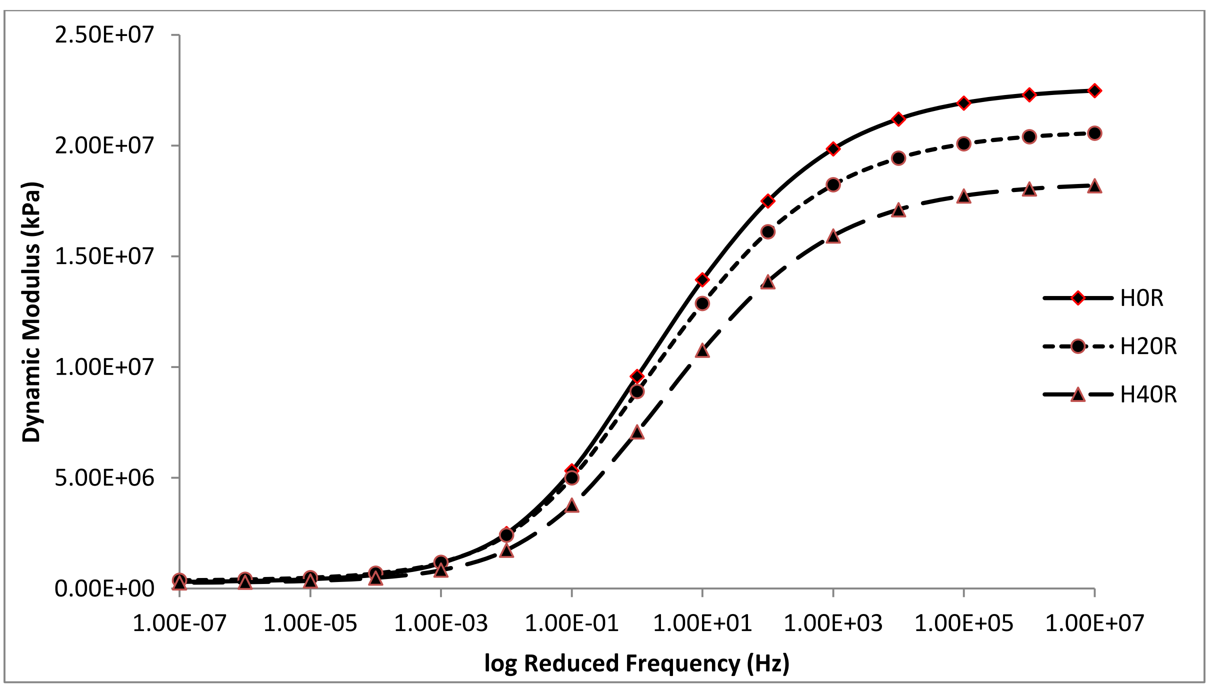

Figure 8-4 E* mastercurves for HMA mixtures (reference temperature 70°F)

NOTE: H40R mixture uses PG 58-28, H0R and H20R mixtures use PG 64-22 binder

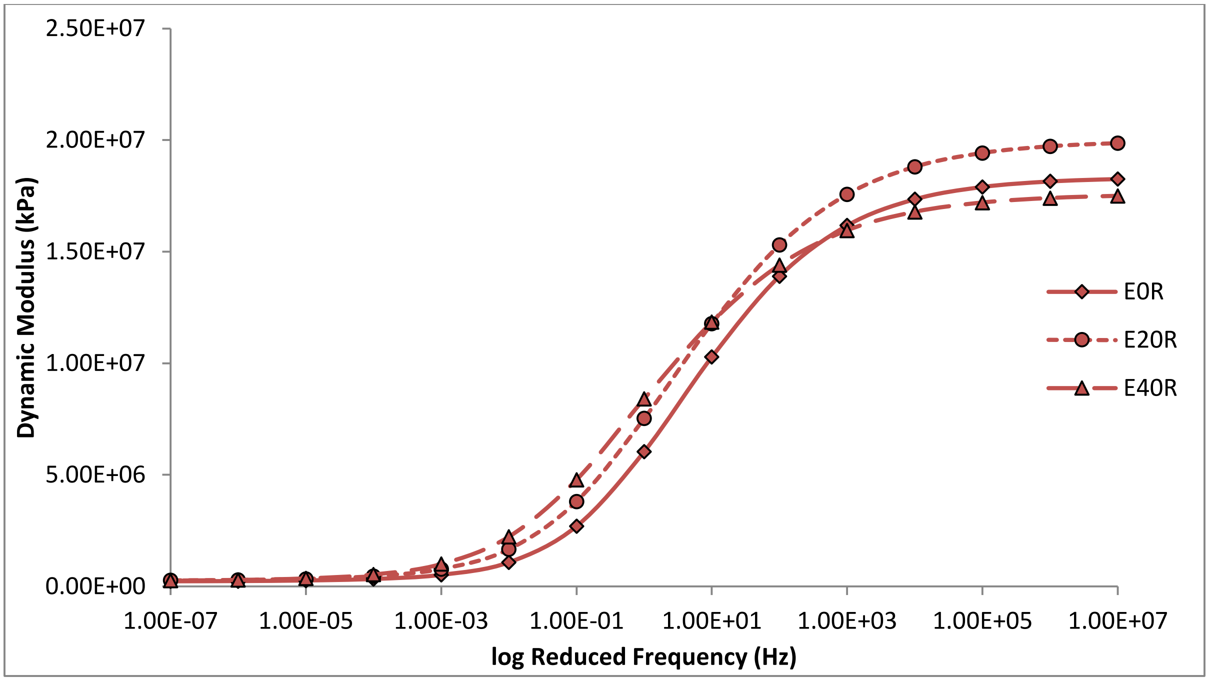

Figure 8-5 E* mastercurves for Evotherm mixtures (reference temperature 70°F)

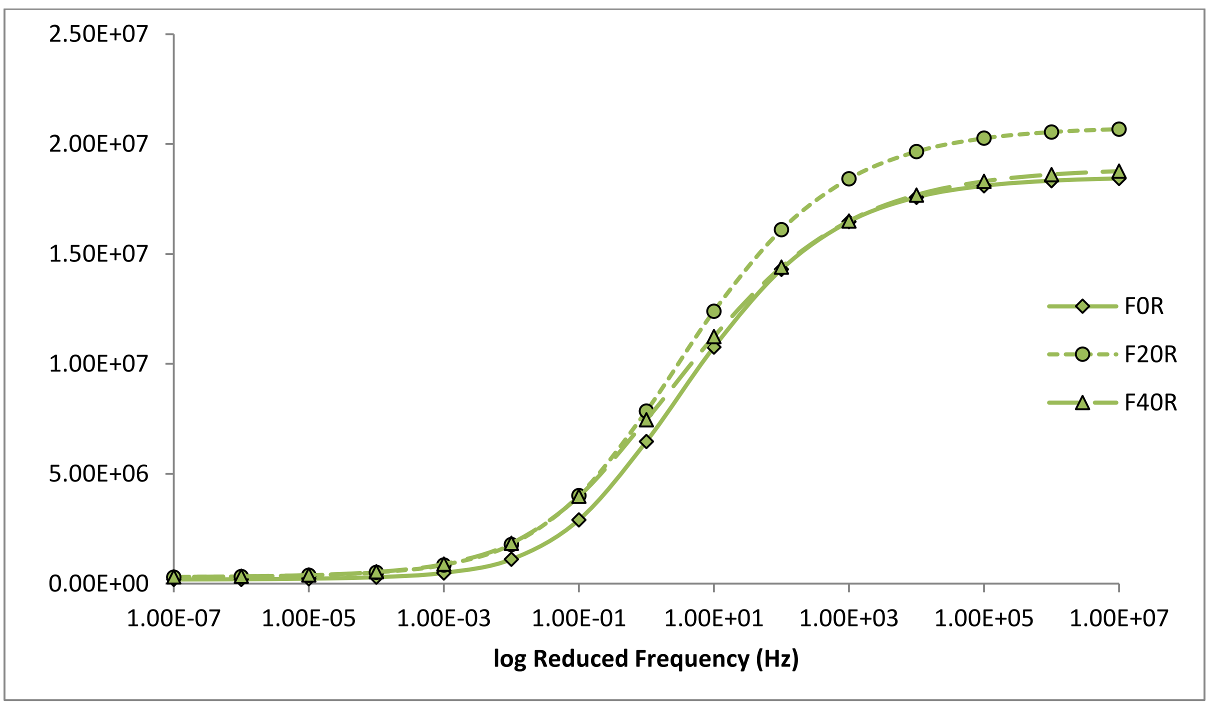

Figure 8-6 E* mastercurves for Foamer mixtures (reference temperature 70°F)

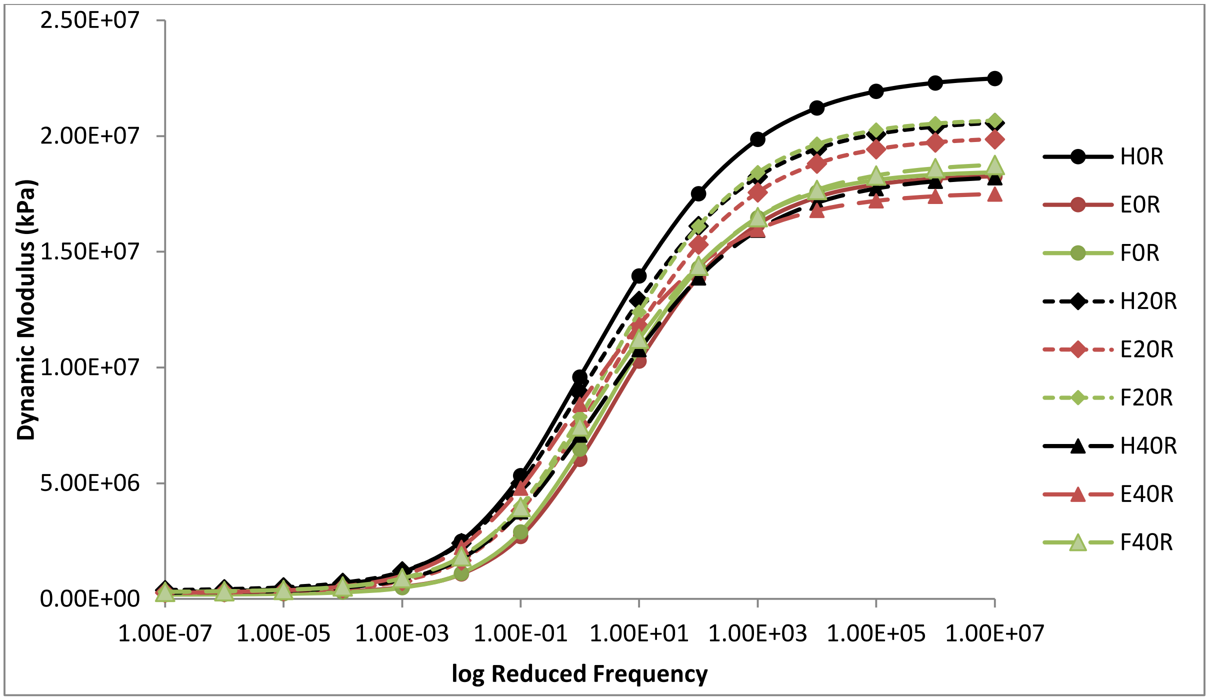

Figure 8-7 E* Mastercurves for all mixtures (reference temperature 70°F)

8.2 Pavement Performance Prediction

The AASHTOWare Pavement ME software, which is based on Mechanistic-Empirical Pavement Design Guide (M-E PDG), was used to predict pavement performance in this study. A typical flexible pavement section for 9.5B mixtures as recommended by NCDOT, in addition to a weaker pavement section was used for evaluating the performance of the mixtures.

The pavement section used in this study is a three-layer flexible pavement consisting of an asphalt concrete layer, granular base course and subgrade. Figure 8-8 shows the pavement section, including base and subgrade properties used in the analysis.

AC (Design Mixture)	3 in.
Asphalt Concrete	2.5 in.
Asphalt Concrete	4 in.
Chemically Stabilized Base (Soil Cement) Resilient Modulus = 2 x 10^6 psi	8 in.

Subgrade (AASHTO A-7-5)
Resilient Modulus = 10,000 psi

Figure 8-8 NCDOT Pavement Layer Structure for Performance Prediction

Traffic parameters, base and subgrade properties typically used for design of NCDOT traffic level B pavements were used as inputs for AASHTOWare analysis. The assumed pavement section was a four-lane highway with two lanes in each travel direction, having a two-way average annual daily truck traffic (AADTT) of 900, operating at 45 mph and increasing at an annual linear growth rate of 3%. Climatic data provided in the software for Raleigh-Durham Airport weather station was used.

A reliability of 90% was targeted for all distresses including fatigue (bottom-up and top-down), rutting (permanent deformation) and thermal cracking for all the analysis. Failure criteria were defined as 25% bottom-up cracking and 0.75 inches for total pavement rutting. Analysis runs were conducted using the E* data from Table 10-2 as Level 1 inputs for the topmost AC layer. Default Level 3 inputs were used for bottom two AC layers. Using a design life of 20 years for the pavement, months to failure was evaluated with respect to fatigue cracking and rutting for all nine mixtures. Table 10-3 shows the failure predictions as obtained from the analysis for the NCDOT pavement structure.

Table 8-2 E* Data from Mastercurves for Use as M-E PDG Input

Frequency (Hz) → Temperature (°F) ↓	25	10	5	1	0.5	0.1
H0R	Dynamic Modulus (Values in MPa)					
-10	20,962	20,962	20,962	20,962	20,962	20,962
5	20,233	18,708	17,138	14,474	12,918	10,178
20	10,482	8,910	7,672	5,400	4,515	2,953
40	2,840	2,129	1,661	943	753	502
54	1,025	774	612	502	502	502
E0R	Dynamic Modulus (Values in MPa)					
-10	16,984	16,984	16,984	16,984	16,984	15,834
5	16,316	14,879	13,364	10,855	9,447	6,881
20	8,272	6,791	5,711	3,597	2,892	1,622
40	1,759	1,250	947	511	421	328
54	521	406	355	327	327	327
F0R	Dynamic Modulus (Values in MPa)					
-10	17,846	17,846	17,846	17,846	17,846	17,738
5	17,359	15,860	14,410	11,776	10,310	7,721
20	8,421	6,939	5,898	3,710	3,011	1,677
40	1,790	1,272	977	549	468	338
54	578	456	381	338	338	338
H20R	Dynamic Modulus (Values in MPa)					
-10	19,073	19,073	19,073	19,073	19,073	18,945
5	18,445	17,030	15,606	13,256	11,893	9,490
20	10,307	8,624	7,468	5,343	4,482	3,033
40	2,877	2,183	1,738	1,040	862	621
54	1,038	800	676	621	621	621
E20R	Dynamic Modulus (Values in MPa)					
-10	18,650	18,650	18,650	18,650	18,650	18,441
5	17,863	16,403	14,866	12,387	10,932	8,294
20	9,149	7,579	6,469	4,295	3,528	2,145
40	2,272	1,678	1,321	756	624	433
54	822	644	525	433	433	433

Table 8-2 Continued

F20R	Dynamic Modulus (Values in MPa)					
-10	19,661	19,661	19,661	19,661	19,661	19,661
5	19,125	17,682	16,128	13,179	11,557	8,610
20	9,126	7,667	6,545	4,261	3,497	2,102
40	2,353	1,722	1,354	783	652	470
54	961	751	624	472	470	470
H40R	Dynamic Modulus (Values in MPa)					
-10	16,790	16,790	16,790	16,790	16,790	16,307
5	16,218	14,792	13,412	11,066	9,875	7,614
20	8,618	7,236	6,270	4,290	3,586	2,297
40	2,522	1,894	1,511	870	712	462
54	944	739	582	461	461	461
E40R	Dynamic Modulus (Values in MPa)					
-10	16,616	16,616	16,616	16,616	16,616	16,405
5	16,242	15,685	14,945	12,457	11,157	8,971
20	9,480	8,037	7,009	4,871	4,132	2,691
40	2,647	1,968	1,563	877	709	442
54	976	753	588	437	437	437
F40R	Dynamic Modulus (Values in MPa)					
-10	17,341	17,341	17,341	17,341	17,341	16,599
5	16,582	15,232	13,817	11,598	10,284	8,066
20	9,054	7,652	6,634	4,566	3,859	2,417
40	2,503	1,938	1,535	888	726	499
54	917	706	572	497	497	497

As can be seen from the failure predictions, none of the mixtures fail the target criteria for either fatigue or rutting. The amount of permanent deformation predicted in the total pavement varies slightly between the mixtures while the fatigue predictions are uniform throughout. The differences in rutting predictions are not significant, in the order of 0.01 inches. As such, the pavement performance between these mixtures could not be distinguished using this thick pavement structure.

Table 8-3 Fatigue and Rutting Failure Prediction for Typical 9.5B Pavement Structure

Mix Type	Rutting (in.) Target: 0.75 in.	Fatigue (%) Target: 25%	Pass/Fail
H0R	0.31	1.45	Pass
E0R	0.34	1.45	Pass
F0R	0.33	1.45	Pass
H20R	0.32	1.45	Pass
E20R	0.33	1.45	Pass
F20R	0.32	1.45	Pass
H40R	0.34	1.45	Pass
E40R	0.33	1.45	Pass
F40R	0.34	1.45	Pass

In order to be able to observe trends in the performance of the mixtures, a weaker pavement structure with three layers as shown in Figure 10-9 was also analyzed.

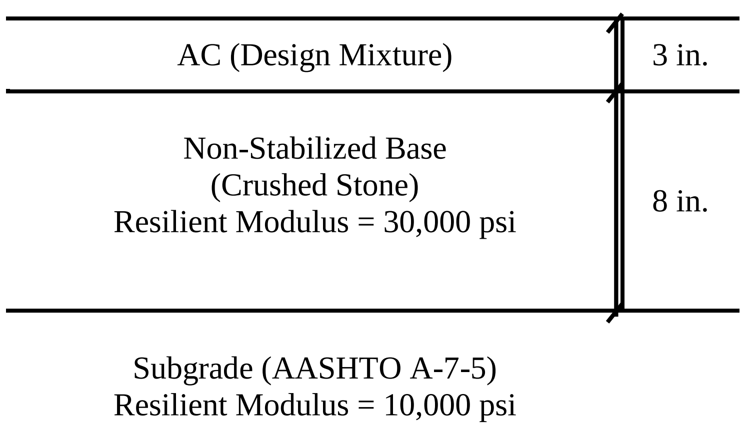

Figure 8-9 Weaker Pavement Layer Structure

The same inputs as used in the previous analysis were given and the rutting and fatigue failure criteria were evaluated. The results from AASHTOWare analysis with this structurally weaker pavement structure are shown in Table 8-4. The resulting rutting and fatigue predictions were normalized for virgin HMA mixture performance as shown in Figure 8-10 and Figure 8-11. By looking at the difference in pavement performance in rutting and fatigue from that of a virgin HMA mixture, we can distinguish the effect of using WMA and RAP in the mixtures.

Table 8-4 Fatigue and Rutting Failure Prediction for a Weak Pavement Structure

Mix Type	Rutting (in.) Target: 0.75 in.	Fatigue (%) Target: 25%	Pass/Fail	Years to Failure
H0R	0.63	23.44	Pass	No Failure
E0R	0.68	25.90	Fail	18
F0R	0.67	25.16	Fail	19
H20R	0.65	24.44	Pass	No Failure
E20R	0.66	24.74	Pass	No Failure
F20R	0.65	24.11	Pass	No Failure
H40R	0.68	27.17	Fail	18
E40R	0.66	25.59	Fail	18.5
F40R	0.67	25.42	Fail	18.5

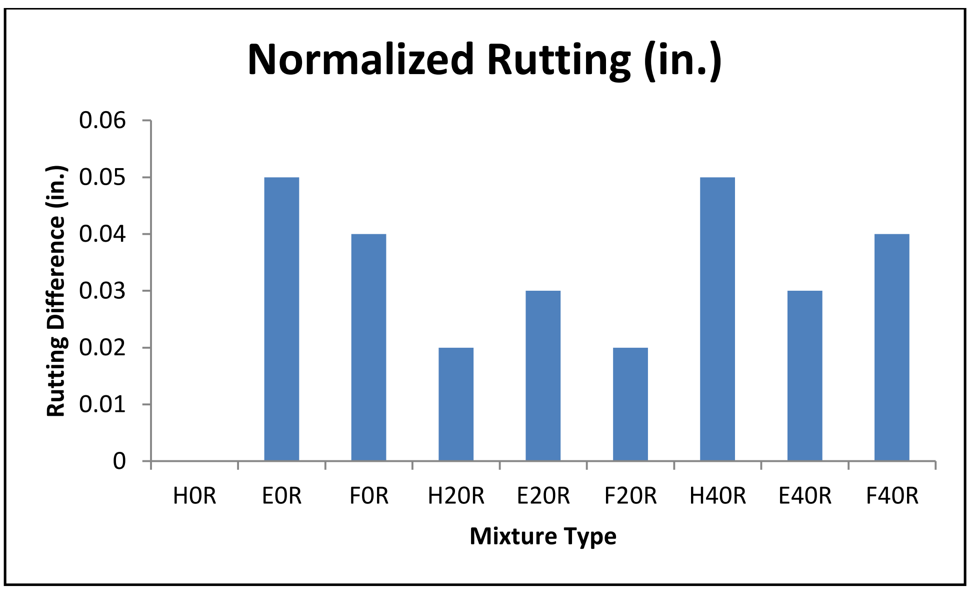

Figure 8-10 Difference in Rutting Depth from HMA 0% RAP Mixture

While rutting depths of all nine mixtures were below the threshold value of 0.75 inches, failure of the pavement was controlled by fatigue cracking. However, in pavements that did experience fatigue failure, it occurred only towards the end of the design life of the pavement: 18-19 years out of a design life of 20 years.

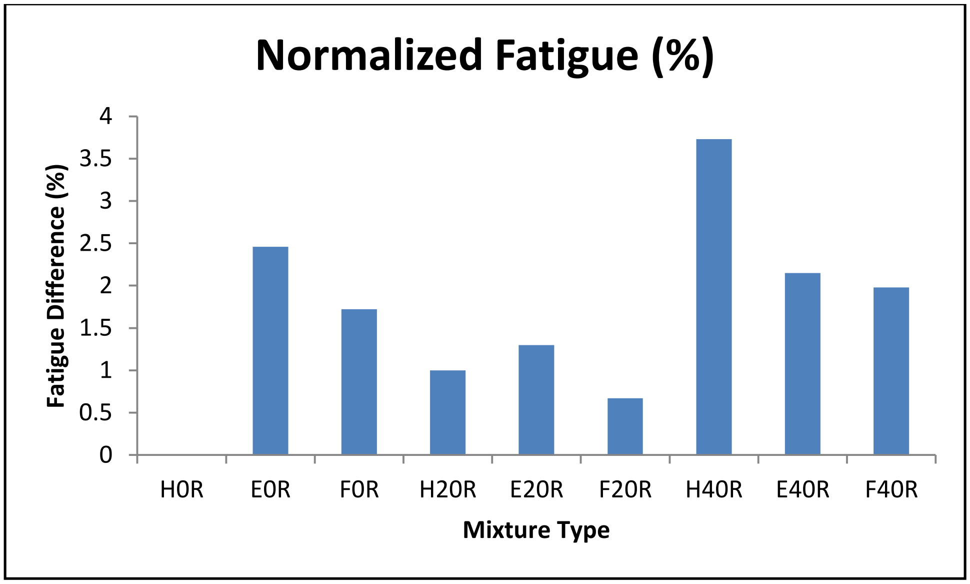

Figure 8-11 Difference in Fatigue Failure from HMA 0% RAP Mixture

Since the only difference in input values between all the analyzed pavements were the Level 1 inputs for the first layer of asphalt concrete, the performance of the pavement in this analysis is dependent on the dynamic modulus values.

Dynamic modulus of an asphalt concrete mix is an indicator of its stiffness. Therefore, a mix with higher stiffness resists rutting better than a mix with lower stiffness. Fatigue failure is governed by two characteristics of the mix - ability of the asphalt layer to exhibit flexure and flexural strength of the mix. A mix with lower stiffness resists fatigue cracking better as the softer asphalt imparts better flexibility under traffic load.

The predicted number of months to failure with respect to rutting follows the same trend as the variation in stiffness observed in the mastercurves. Trends of normalized rutting depths and fatigue failure values of pavements with WMA and RAP mixtures (with respect to the virgin HMA mixture) are similar.

As compared to virgin HMA, the virgin WMA mixtures experience higher rut depths and fatigue. Adding intermediate amounts of RAP (20%) improved the WMA mixture performance. Of all mixtures, the high RAP HMA mixture (40%) exhibited the highest susceptibility to failure. In comparison, the high RAP WMA mixtures performed better, again showing that it is more desirable to use WMA technology to help incorporate higher amounts of RAP rather than using a softer binder grade. These pavement performance results were used to conduct economic analysis of all nine mixtures.

8.3 Economic Analysis

The performance prediction results obtained from the previous task were used to perform a cost analysis for incorporating the WMA technologies and RAP material in asphalt concrete mix production and construction. The design period used in the AASHTOWare analysis was 20 years, which was used to identify the predicted failure of the pavement due to rutting and fatigue. For a typical 9.5B mix pavement section, none of the mixtures exhibited failure before the design period of 20 years. Thus, only the difference in initial material costs was considered. Since the design of both HMA and WMA are based on the same aggregate structure and same asphalt binder content in the mix, the factors that affect cost and benefit with the use of WMA and RAP are:

- Costs - Additives/equipment necessary for incorporation of WMA technology and RAP into the mix.

- Benefits - Reduction in heating costs from heating aggregate and binder to lower temperature during production and transportation of mix from batch plant to site.

In addition to economic benefits, WMA, RAP and WMA-RAP mixtures also result in lower emissions and great environmental benefits during the entire construction process, thereby having a less severe impact on the environment.

Material costs for HMA mix is the cost of asphalt concrete mix (S9.5B) per ton of mix. The estimate provided in this study is based on values used in the study conducted on recycled asphalt materials for NCDOT [52]. Evotherm cost per ton of mix is estimated using 0.5% of the additive by weight of binder, and 6% asphalt binder by weight of mix from the mix design used in this study. This value may be adjusted to estimate costs for projects where mix design results in a different design asphalt content. The calculated weight of Evotherm 3G additive per ton of mix is 0.3 kg. Purchase costs may vary depending on the location to which the material needs to be supplied, as well as the total quantity. Since there is no information available for this purpose, an estimated cost of $3.00

per kg is used for analysis purposes [53]. The estimated costs also include a one-time installation and yearly maintenance cost of equipment such as mechanical stirrers to mix the additive in the asphalt binder.

WMA using Foamer device does not include any material cost, as the technology does not require use of additives. The use of Foamer device however, includes equipment purchase, installation and maintenance costs, which is estimated at $1.00 per ton of mix [53]. The cost of material, additives and equipment for different mixtures is shown in Table 8-5.

Table 8-5 Material Cost for Mix Production

Material	Cost ($ per ton)
Asphalt concrete surface coarse mix (S9.5B)	50.0
Evotherm - additive cost for 0.3 kg per ton of mix	0.9
Foamer - purchase, installation and maintenance costs	1.0

The cost of energy consumption during heating of aggregates and asphalt, mixing and transportation of mix is subject to a wide variety of factors, such as plant location, annual productivity, heating equipment used and efficiency, distance from batch plant to construction location, etc. Therefore, an estimate of $10.00 per ton of mix is used in this analysis for HMA construction, and an average reduction of 25% in energy costs, i.e. $7.50 per ton for WMA construction.

The cost of each of the recycled mixtures was calculated by assuming that recycled mixtures will have a deduction in cost equivalent to the amount of recycled materials in the mixture, but will incur an additional cost for processing recycled material. The additional cost for screening and processing of RAP assumed to be 15% based on average costs around the state. Using these estimates, total production costs of all mixtures are summarized in Table 8-6.

Table 8-6 Costs per Ton of Each Mixture Type

Mixture Type	Material cost per ton (USD)	Energy cost per ton (USD)	Technology cost per ton (USD)	Processing cost per ton (USD)	Total cost per ton (USD)	% Savings
H0R	40	10	0	0	50.0	0.0
E0R	40	7.5	0.9	0	48.4	3.2
F0R	40	7.5	1	0	48.5	3.0
H20R	32	10	0	3	45.0	10.0
E20R	32	7.5	0.9	3	43.4	13.2
F20R	32	7.5	1	3	43.5	13.0
H40R	24	10	0	6	40.0	20.0
E40R	24	7.5	0.9	6	38.4	23.2
F40R	24	7.5	1	6	38.5	23.0

Thus, for every 20% of the HMA mix that is replaced with RAP, saving of around 10% can be expected in the initial cost of production. Despite the additional equipment and/or additive costs, using WMA technology leads to approximately 3% savings. Using both results in a summation of initial savings.

With weaker pavement sections, rehabilitation and salvage values may need to be taken into account. Based on the results from AASHTOWare analysis on the weak pavement section, at the maximum, only one rehabilitation course will be required for some surface mixtures, particularly at high RAP contents.

Even though the savings from using WMA technology is not very significant, it will still lead to extensive environmental benefits. This reduction in carbon footprint of roads and improvement in sustainability will transfer to benefits that cannot be easily monetized but are invaluable nonetheless.

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

This research study evaluated the workability and moisture susceptibility of two WMA technologies – Evotherm 3G and PTI Foamer with three varying RAP content – 0%, 20% and 40% and compared their performance to the corresponding HMA mixtures. A job mix formula for NCDOT 9.5 B mixture was provided by the NCDOT. Tensile Strength Ratio calculated using the modified AASHTO T283 method in order to evaluate the moisture susceptibility for each mixture. % G_{mm} evolution curves were used to evaluate the workability of the mixtures. Additionally the effectiveness of Evotherm additive as an anti-strip additive was also evaluated. Litmus paper test using StripScan Instrument and TSR test were conducted to evaluate the effectiveness of Evotherm as an anti-strip additive.

PG 64-22 asphalt binder was used for all the mixtures except for 40% RAP HMA for which a softer binder grade, PG 58-28 was used as per NCDOT specifications. For WMA mixtures with 40% RAP, adequate compactability indicated that lowering of binder PG grade was not necessary. All the mixtures passed the minimum TSR criteria of NCDOT specifications, expect for 40% RAP Foamer mixture. The mixture with no antistrip additive and just Evotherm also passed the minimum criteria for TSR.

Foamer mixtures showed the highest workability amongst the three mixtures. The workability decreased as the RAP content increased. For 40% RAP HMA mixtures, using a softer binder grade resulted in increased workability while WMA mixtures did not require lowering of binder grade to improve workability.

The volatility of Evotherm from litmus paper test was found to be similar to that of LOF 6500 and Morlife 2200 evaluated in a previous NCDOT study. Evotherm as an anti-strip additive was effective enough for the virgin mixtures to satisfy the minimum TSR criteria of 85% for NCDOT. However, based on TSR test results, with higher amounts of RAP, it may be necessary to either increase the dosage of Evotherm or use an additional anti-strip additive such as LOF 6500 as used in this study.

Dynamic modulus tests were used to compute the E* mastercurves for all mixtures. They were also used to compute the ratio of dynamic modulus between conditioned and unconditioned specimens, analogous to the Tensile Strength Ratio, called the E* Stiffness Ratio (ESR). Based on the dynamic modulus values, pavement performance was analyzed using AASHTOWare Pavement ME software. For a typical S9.5B section used by the NCDOT, none of the mixtures exhibited rutting or fatigue failure within a design life of 20 years. By estimating the total cost per ton to produce a mixture by taking into account material, WMA technology costs, RAP screening and processing costs as well as energy benefits, savings for each mixture was calculated.

The conclusions based on the results of this study are elaborated in the following section.

9.2 Conclusions

i. The volumetric properties of WMA mixtures with 0% and 20% RAP were similar to the corresponding HMA mixtures despite the difference in mixing and compaction temperatures between WMA and HMA mixtures.

ii. For 40% RAP mixtures the compactability for HMA mix improved when a softer grade binder, PG 58-28 was used. The 40% RAP-WMA mixtures did not show much difference in compactability with the change of binder grade, i.e. the compactability was similar for mixtures with PG 64-22 binder and those with PG 58-28 binder.

iii. TSR ratio values for the mixtures decreased as the amount of RAP in the mixture increased. However, in 40% RAP – HMA mixture where a softer binder grade was used, this trend was not followed.

iv. The Indirect Tensile Strength (ITS) values increased with the increase in RAP content. Again, in the case of 40% RAP – HMA, where a softer binder grade was used, this trend was not seen. The ITS values of 40% RAP – HMA were similar to 20% RAP – HMA.

v. The TSR ratio results of virgin mixture with just Evotherm and no LOF 6500, anti-strip additive, passed the minimum value criteria of 85% set by the NCDOT.

vi. The litmus test showed that the volatility of Evotherm was similar to that of LOF 6500 and Morlife 2200 as evaluated in a previous NCDOT study.

vii. The E* stiffness ratios of most mixtures were higher than or close to 85%. Only the high RAP HMA mixture with 40% RAP with PG 58-28 binder behaved substantially differently from other mixtures with 64% ESR value. This further shows that while dynamic moduli may be similar for HMA and WMA RAP mixtures, using a softer binder grade may be detrimental to the capacity of a mixture to resist moisture-induced damage.

viii. Since dynamic modulus is a compression test, it may not be appropriate to test moisture susceptibility using this test as moisture damage is controlled by the adhesive property of asphalt.

ix. As expected, the virgin WMA mixtures are softer than HMA. Despite lower production temperatures, HMA and WMA RAP mixtures show similar E* behavior. This reinforces the evidence that lowering of binder grade use in high RAP HMA mixtures can be avoided with the use of WMA technologies.

x. For every 20% of the HMA mix that is replaced with RAP, saving of around 10% can be expected in the initial cost of production. Despite the additional equipment and/or additive costs, using WMA technology leads to approximately 3% savings. Using both results in a summation of initial savings.

9.3 Final Recommendations

i. Evotherm 3G additives work well as a WMA technology, as expected.

ii. In addition to providing the advantages of WMA technology, Evotherm 3G also acts as an anti-strip additive and lowers the moisture susceptibility for the virgin HMA mixture used in this study.

iii. When using WMA technologies, it is not necessary to lower the binder grade of the mixture with as high as 40% RAP use in mixtures.

iv. However, for higher RAP content in the mixtures, it is recommended that an additional anti-strip additive be added (such as LOF 6500 as used in this study) even when Evotherm 3G is used.

v. Based on analysis of initial cost of production, both WMA and RAP mixtures are more economical.

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Appendix A

LITERATURE REVIEW

A comprehensive literature review on use of Recycled Asphalt Pavement (RAP) material, Warm Mix Asphalt (WMA), and use of RAP with WMA technology is presented in this section. The section focuses on the effect of workability and moisture susceptibility of WMA and RAP mixtures separately. Results from studies on the performance of mixtures incorporating WMA and RAP in conjunction are also summarized.

Warm Mix Asphalt

The lowering of mixing and compaction temperatures of asphalt binder is not a new concept in the asphalt industry. Csanyi, L of Iowa State produced asphalt foamed with steam as early as 1956 [1]. Since then the concept has picked up and various researchers and research institutes have worked on it. New techniques and additives have been developed over the years, some of which have successfully achieved to lower the temperatures. The warm mix asphalt scan report by the federal highway administration (FHWA) in 2007 defines WMA mixtures as mixtures whose production temperatures are 20 – 30°C lower than HMA and slightly above than 100°C [2].

The classification different type of asphalt concrete mixtures on the basis of their production temperatures is pictorially represented as done in the WMA scan report in Figure A-1.

WMA mixtures are produced using an additive or a process which helps lower the production temperatures. A typical reduction of 50 to 100°F in mixing and compaction temperatures from the standard 300 to 350°F has been observed when WMA technology is used [3]. This reduction has many advantages such as low energy requirement to heat the materials, less emission and better workability.

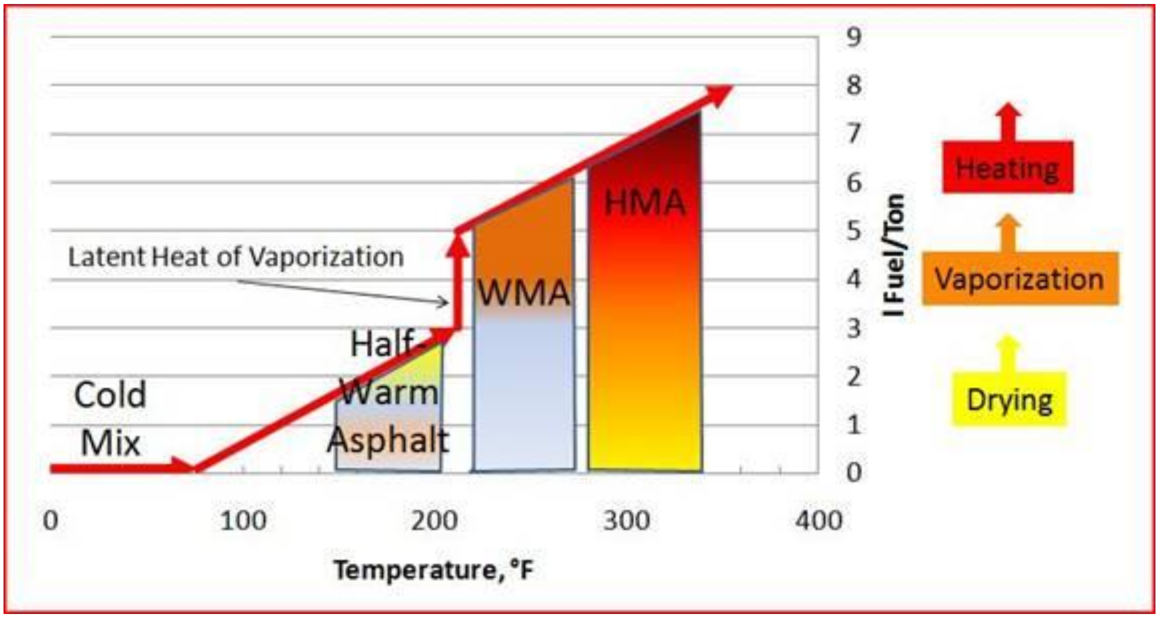

Figure A-1 Classification of Asphalt Concrete by Approximate Temperature Ranges [Image courtesy: WMA Scan Summary Report, 2007] [2]

Even though the concept of reducing temperatures was an old one, the USA started adopting it only in the early 2000s. The first field demonstrations of WMA were conducted in 2004 in Charlotte, Nashville and Orlando [4]. Many studies were conducted by NAPA, FHWA, NCAT and other organizations to come up with guidelines on using the WMA technology in USA and also evaluating various WMA technologies [5].

WMA Production

In a 2012 report published by the FHWA, a summary of commonly used WMA technologies in Europe is given. This comprehensive report also mentions about projects being carried out or completed using various technologies in the United States. Additives such as Aspha-Min®, Advera® WMA, Asphaltan B®, Evotherm™, Sasobit® and WAM-Foam® were listed in the report [5]. A report prepared by Texas Transportation Institute (TTI) in 2008, lists out the programs carried out by various research agencies and NCHRP projects on WMA technology looking at eight major WMA technologies in the United States [6].

Vaitkus et al looked into various WMA technologies and divided them into four categories based on their mechanism – foaming using water, foaming using zeolites, organic additives and chemical additives [7]. The technologies which use injection of water into the binder or mix were categorized as foaming asphalt using water. Some examples include WAM Foam®, Terex® Warm Mix Asphalt System, Astec Double Barrel® Green, LEA – Low Energy Asphalt, Gencor Ultrafoam GX and the PTI Foamer. Some technologies use zeolites, which are aluminosilicate mineral having microscopic pores which hold water. When the zeolites are heated, water is released from the pores and hence this injected water helps foam the asphalt binder. Some examples are Aspha-Min®, Advera® WMA Zeolite and natural zeolite. Some WMA technologies use organic compounds to modify the asphalt binder and improve the workability so that it can be used at lower temperatures. Some common examples of such organic additives are Sasobit® Wax, Asphaltan B® wax and Licomont BS 100 which is a mixture fatty acid derivative. The fourth category consists of inorganic chemicals used to attain the required workability at lower temperatures. Some examples of such chemical additives include Interlow T, AzkoNobel's Rediset® WMX, Cecabase RT®, Evotherm^{TM} and Revix arba Evotherm 3G.

Two WMA technologies were selected in this present study, the PTI Foamer and Evotherm 3G. The first is an asphalt foaming device, while the latter is a chemical additive.

The PTI Foamer

The foaming device used in this study is called the Foamer, which is manufactured by Pavement Technology, Inc. (PTI) [8]. The Foamer has separate inlets for hot asphalt and water. The water and hot asphalt react resulting in foamed asphalt. The foam asphalt then exits through an insulated exit pipe at the desired exit temperature.

The PTI Foamer and its representative schematic diagram are shown in Figure A-2.

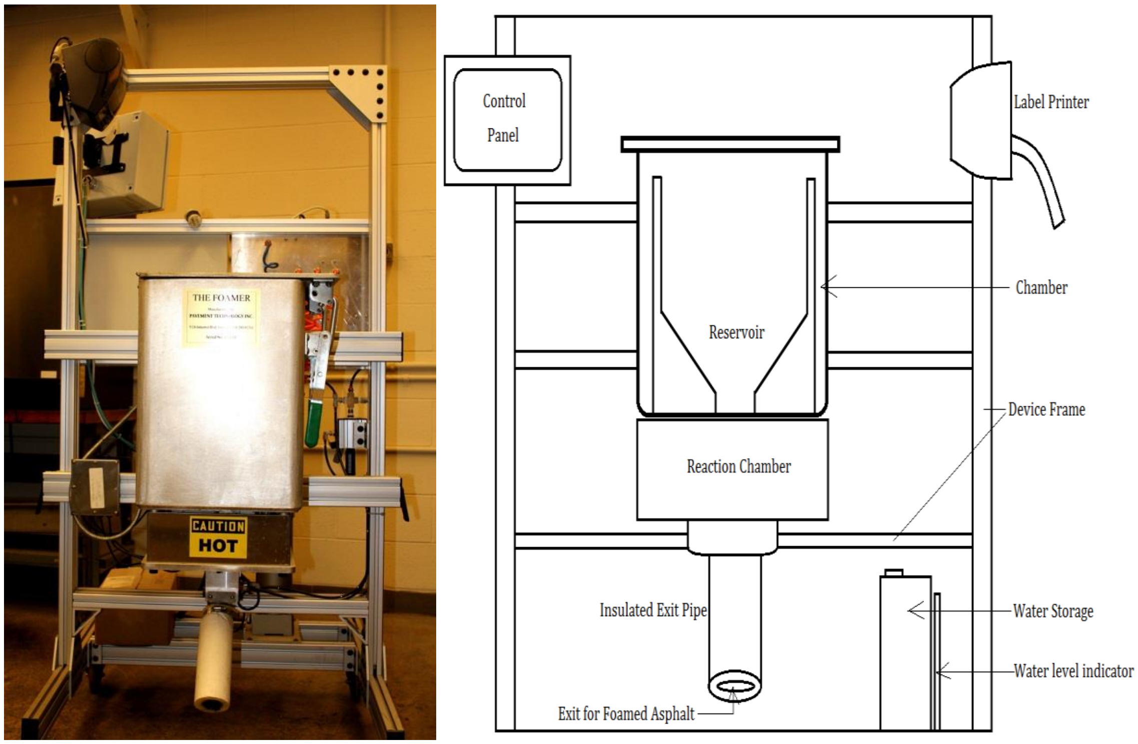

Figure A-2 “The Foamer” Device and Its Schematic Representation [48]

The device has a reservoir at the top where the asphalt is poured and heated to the required temperature. The reservoir has to be lined with a polymer bag which is resistant to high temperatures. The bag is used to ease cleanup of residual binder in the reservoir. Once the reservoir is lined with the polymer bag, the asphalt temperature and the exit temperature are set in the controller. The temperatures inside the reservoir lined with bag and the point of exit are controlled using a thermocouple. Preheated asphalt was poured into the lined reservoir after a temperature close to the required asphalt temperature was reached in the Foamer device.

Figure A-3 shows the setup function of the controller where the temperatures, target binder, water content can be selected. The Foamer control function displays the current status of the Foamer. Once ready to mix using the foamed asphalt, the start option has to be selected under the Foamer control function menu. Once the reservoir and exit tubes have reached the required temperature, the “foam” option will flash indicating the device is reduce to produce the foamed asphalt. The water required for foaming is stored in a chamber at the bottom of the device. Before the device is switched on it is recommended to check the water level in the chamber and to fill it up if it is below the mark. It is also suggested that the water inside the chamber be cleaned regularly. 2% water content by weight of asphalt is recommended to be added by the manufacturer for the best foaming action. To avoid any decrease in temperature of the asphalt binder when the water comes into contact, it is recommended that the exit temperature be set higher than the reservoir temperature.

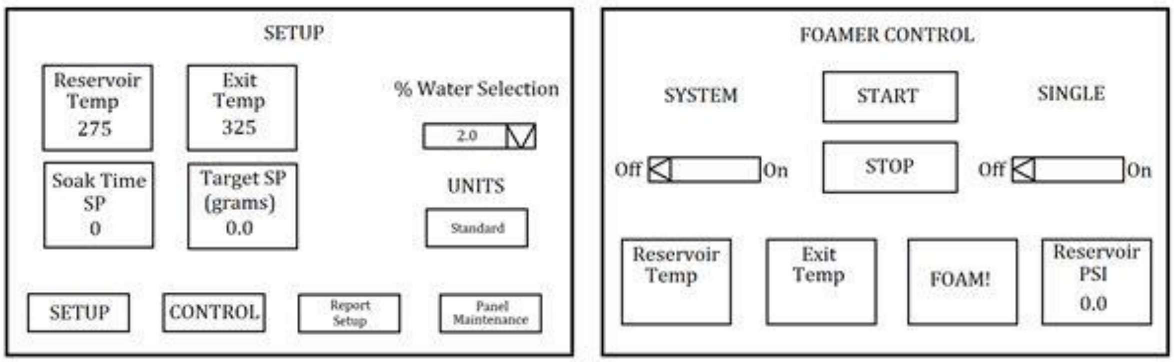

Figure A-3 Schematic Representation of Control Panel Displays in "The Foamer" [48]

Due to the foaming effect, the volume of the asphalt binder is increased, and the presence of the bubbles make the binder more workable and evenly coat the aggregate particles during mixing. This increase in volume is just a temporary effect and the bubbles dissipate fast. Thus once the foamed asphalt is produced it has to mixed quickly to avoid loss in workability.

Foamed asphalt on the aggregates is shown in Figure 2-4. The foamed asphalt was directly poured into the aggregate mixing drum with the heated aggregates in it. To control the weight of the foamed asphalt, an external weigh scale was kept under the mixing drum.

Figure A-4 Foamed Asphalt Produced by "The Foamer"[48]

Evotherm

Evotherm® is a chemical additive manufactured by MeadWestVaco Corporation (MWV) and is used as a WMA additive. As per the manufacturer, when Evotherm is used as a WMA additive, the mixtures can be produced at temperatures 100 to 130°F (50 to 75°C) less than the temperatures used in the case of HMA [9]. According to the manufacturer, MWV, increased workability, easy compactability, performance equal to or better than HMA, increased RAP usability; and reduced wear and tear on the hot mix equipment due to lower processing temperatures. According to them the roads can be opened to traffic quicker than in the case of HMA.

A study conducted on Evotherm warm mix technology showed a 40 – 60% decrease in CO_2 and 80 – 97% reduction in job site emissions. Plant stack testing have shown reductions up to 46% in CO_2, 30% in VOC, 34% in PM, 58% in NO_x and 81% in SO_x. Overall Evotherm projects have documented more than 55% energy savings [10].

According to the report, Evotherm can be incorporated through three convenient forms – Evotherm ET (Emulsion Technology), Evotherm DAT (Dispersed Asphalt Technology) and Evotherm 3G (Third Generation). Emulsion technology incorporates asphalt into the mix as an emulsion and offers temperature reductions up to 100°F. In dispersed asphalt technology, Evotherm is injected in the mixing plant as a concentrated solution with temperature reduction of 85 - 100°F. Evotherm 3G is introduced into the asphalt as an additive and hence is water free. It offers a 60 – 85°F reduction in temperatures and is added at 0.4 to 0.7% by weight of the asphalt binder. Evotherm 3G was selected for the project because of the ease of use in a laboratory setting.

Lab Studies

In June 2006, report by NCAT on the investigation of Evotherm WMA Technology, it was found that WMA mixtures had lower air voids at lower compaction temperatures and hence indicating better compaction when compared to mixtures with no additives [11]. It also reported a decrease in moisture susceptibility in WMA mixtures when an anti-stripping agent like hydrated lime is used.

Bennert et al. studied the effect on workability and compactability when WMA mixtures were used in 2010 [17]. A workability device was developed at the University of Massachusetts, Dartmouth to measure the workability using torque values exerted on a paddle shaft. The study reported that to lower the torque exerted as the mixing temperature decreases, the amount of WMA additive has to be increased. Workability was measured in terms of compactability using Gyratory Compactor readings. The height (mm)/gyration values of specimens were used to find out the workability. But in this case the results did not follow the expected trends as the workability decreased from 1% Rediset and Sasobit to 2% Rediset and Sasobit.

Table A-1 Comparison of Specimen Fabrication Procedures for WMA and HMA (Source: NCHRP Report 714) [15]

Step	Description	HMA	WMA	Comment
1	Batch Weight Calculation	X	X	Must calculate WMA additive content for some processes
2	Batch aggregates	X	X	Must batch WMA additive for some processes
3	Heat aggregates and asphalt binder	X	X	Use planned production temperature for WMA
4	Mix aggregates and binder	X	X	Procedure is WMA process specific
5	Short-term oven conditioning	X	X	WMA uses lower temperature
6	Compact laboratory specimens	X	X	WMA uses lower temperature
7	Calculate volumetric composition of laboratory specimens	X	X	
8	Adjust aggregate proportions to meet volumetric requirements	X	X	
9	Evaluate coating and compactability	NA	X	Used in WMA design in place of viscosity-based mixing and compaction temperatures
10	Conduct performance testing	X	X	Moisture sensitivity for all mixtures, rutting resistance for design traffic levels of 3 m ESALs or greater

National Cooperative Highway Research Program (NCHRP) project 09-43 was sponsored to come up with new guidelines for mix design when WMA technologies are used [14]. Two reports NCHRP Report 691 and Report 714 were published as a result [14, 15]. The reports suggest that there is no requirement for a new procedure when mix design of a mixture with WMA Technology is done. Some special considerations while designing WMA mixtures were compiled.

According to studies by Hurley and Prowell in 2006, when the optimum asphalt content of HMA mixture was used, the WMA mixtures exhibited lower air voids than estimated [16]. Hence they suggested that optimum asphalt content might be different for HMA and WMA mixtures. But a NCHRP 09-43 report on binder content showed there was no statistically significant difference in the design binder content of HMA and WMA [15]. However the binder absorption reduced in the case of WMA mixtures as compared to HMA mixtures, with reduction values of about 10% being observed.

The differences in design of dense – graded WMA mixtures compared to dense – graded HMA mixtures and the difference in specimen fabrication procedures are highlighted in NCHRP Report 741 and NCHRP 09-43 project. These differences are shown in Tables A-1 and A-2, respectively.

Table A-2 Major Differences in Design of Dense-Graded WMA Mixtures (Source: NCHRP Report 714) [15]

Step	Description	Major WMA Differences
1	Gather Information	1. WMA process 2. Additive rates 3. Planned production temperature 4. Planned compaction temperature
2	Select Asphalt Binder	1. Recommend limit on high-temperature stiffness of recycled binders. 2. May consider low-temperature grade improvement when using blending charts.
3	Determine Compaction Level	Same as HMA
4	Select Nominal Maximum Aggregate Size	Same as HMA
5	Determine Target VMA and Design Air Voids Value	Same as HMA
6	Calculate Target Binder Content	1. Lower asphalt absorption due to lower temperatures
7	Calculate Aggregate Volume	Same as HMA
8	Proportion Aggregate Blends for Trial Mixtures	Same as HMA
9	Calculate Trial Mixture Proportions by Weight and Check Dust/Binder Ratio	Same as HMA
10	Evaluate and Refine Trial Mixtures	1. WMA process-specific specimen fabrication procedures. 2. Lower short-term aging temperature. 3. Evaluate coating and compactability in lieu of viscosity-based mixing and compaction temperatures.
11	Compile Mix Design Report	Same as HMA

Field Studies

Evotherm was one of the technologies studied in the NCHRP 09-49A project where field performance of warm mix technologies was evaluated in Montana. Three ways to save money by using Evotherm were identified – fuel savings at the plant, faster paving operation and incentive pay. In this study the mixing temperatures were 50 °F lower than the conventional 325 °F and hence reducing fuel costs at the mixing plant. The number of roller passes to achieve the target density were reduced hence resulting in faster paving operation. The average density of the cores from the road was found to be 94.3% and hence resulting in contractors getting incentive pay. Improved coating was also noticed on the jobsite and the mixing plant [9].

Evotherm was used to pave a 2-inch thick pervious pavement mix for a parade deck of Marine Corps Recruit Depot on Parris Island, S.C. Evotherm was used as a substitute to the dense graded mix involved costly storm water modelling. The use of Evotherm helped prevent drain down as the temperatures of the asphalt were lowered and the fibers could hence be removed from the mix design without compromising on the adhesion, and aggregate – asphalt binding. Hence Evotherm is replacing the fibers from porous pavements stone matrix asphalt and also open graded friction courses [9].

Evotherm WMA was used to pave in conditions with cold morning temperatures and 90 minute haul in California on U.S. 50. The required density was achieved with only two roller passes behind screed of 210 °F. This helped finish the paving in one day instead of the estimated two days and hence U.S.50 was reopened to traffic ahead of time [9].

A report published in June 2006 by the National Center for Asphalt Technology on evaluation of the Evotherm® performance as a WMA technology reported improved compactability [11]. However the mixtures with Evotherm showed lower indirect tensile strength value, their TSR values were satisfactory when granite aggregates were used. But the use of limestone aggregates significantly lowered the TSR values. The TSR values were improved with limestone aggregates once MWV modified the additive mixture according to limestone aggregates.

An evaluation of various WMA technologies including Evotherm in Ohio [12] showed increased moisture susceptibility for all WMA mixtures and lower values for Evotherm mixtures compared to HMA. Evotherm ET pavements showed largest reduction in mixing temperatures in an in-situ study conducted involving other WMA technologies in St. Louis, Missouri [13].

NCAT conducted in-situ studies on WMA in Ohio [18], Tennessee [19], Missouri [20], Wisconsin [21], Colorado [22] and Washington [23] between 2006 and 2010. Table A-3 gives a summary of the major results of Evotherm, Astec Double Barrel Foamer and AquaBlack WMA technologies and compared to their HMA counterpart. A comparison of the two WMA technologies used in this research study is done in Table A-4.

Table A-3 Summary of NCAT In-Situ Studies

State	**WMA Technology**	**In-Situ Study Results**		
		TSR-based Moisture Damage	*HWTD Stripping Inflection Points*	*General Comments*
OH	Evotherm	Higher	Mostly Higher	WMA showed higher densities
TN	Astec DBG	Higher	Same	HMA – Bleeding after one year, WMA binders aged more
	Evotherm	Lower	Lower	
MO	Evotherm	Same	Lower	No Damage
WI	Evotherm	Same	Same	No Damage
CO	Evotherm	Lower	--	Lower Moisture Damage
WA	AquaBlack	Same	Same	No Damage

Table A-4 Comparison of WMA Technologies Used

Technology	Manufacturer	Recommended Amount of Additive	Mixture Production Temperature
The Foamer	Pavement Technology, Inc., USA	2% water by weight of binder	~ 275°F
Evotherm 3G	MeadWestvaco Corporation, USA	0.5% by weight of binder	~ 250°F

RAP material

RAP material has been in use extensively used in the United States as well as around the world in large quantities. It is estimated that the resurfacing and widening projects result in the removal of about 100 million metric tons of asphalt pavement. This material can be used in building pavements, embankments and shoulders [24].

In a report published in 1997 by Kandhal, the asphalt recycling and reclaiming association says that there are five ways for recycling - Cold planning, hot recycling, cold in-place, hot in-place and full depth reclamation [33].

In cold planning the existing pavement is either ripped off or milled and then the material is taken to a plant for recycling. In the plant, asphalt mix is produced in a central plant using this recycled material, virgin aggregate, virgin asphalt and emulsion or water. The mix is then transported to the site and laid down. In Hot mix asphalt recycling the reclaimed material from an existing pavement is combined with new materials and a rejuvenator if required in a drum or batch mixing plant to produce hot asphalt mix. In cold in-place recycling the existing pavement material is used without applying any heat and the transporting the materials is not required. Emulsion is added as a recycling agent or a binder to the recycled materials. In Hot in-place recycling the existing pavement is heated and softened before milling to required depth. The virgin hot mix asphalt mixture is added along with rejuvenating agent if required to the milled material. This can be done in a single pass or multiples passes where the Reclaimed Material is compacted again and then a new layer is laid. In full depth reclamation the existing asphalt pavement and a pre estimated amount of base material is treated to produce a stabilized base course. It is a cold mix recycling process where different types of additives such as asphalt emulsions and chemical agents are added to improve the base by stabilizing it [33].

The addition of rejuvenating or emulsifying agent is necessary to activate the asphalt in the reclaimed asphalt pavement material so that it can react with the virgin asphalt to ensure that there is proper blending [25]. The reuse of RAP obtained from old and damaged pavements leads to high level of savings in terms of material and energy. Since the alternative to using RAP is to pay and dump it in a landfill or waste it, use of higher percentages of RAP effectively while meeting the required standards can be highly cost saving [25]. Su et al. successfully demonstrated the feasibility of use of RAP content up to 40% in Japan's airport surface courses. Celauro et al. demonstrated that under appropriate control RAP content up to 50% could be used in all pavement courses in Italy [25]. According to Tao and Mallick, Maine DOT was able to utilize drum plants for producing hot mixtures which contain up to70% RAP [34]. We can infer from these results that under proper supervision and guidelines, higher percentages of RAP can be incorporated into hot mix asphalt while still meeting the standards.

NCHRP Report 452 provides revised guidelines with procedures to incorporate the RAP material into mixtures based on the Superpave mix design [26, 27]. Extensive testing of the RAP binder is not recommended when less amount of RAP is being incorporated into the mixtures. But when higher amount of RAP material is being used, then the RAP binder has to undergo Superpave binder tests to determine the allowable amount of RAP that can be added to the virgin binder so that there is proper blending between the virgin binder and the binder from the RAP. The overall binder grade also has to be checked when high amount of RAP material is being used.

The main parameters that affect the properties of a recycled mix are the amount of aging the RAP binder has undergone and the amount of RAP material to be added to the mix. As per NCAT Report 95–1, it is observed that the recycled mixtures age at a slower rate than the ones with virgin binder. RAP mixtures were observed to be less susceptible to moisture-induced damage than the virgin binder mixtures and exhibit better durability and have less internal friction [31]. Aggregates in RAP have lower angularity and smoother surface texture due to wearing of the aggregates in the field. There are issues with the gradation of RAP material specially the No. 200 sieve size. Results from in-situ studies have shown very slight difference between Recycled Asphalt Concrete Pavement and Virgin Binder Pavement suggesting that RAP retains most of the properties of the virgin materials [31].

The amount of RAP material to be used also depends on the source. Various factors like the temperature, air voids and also the properties of mix at source do affect the properties of binder, aggregates and also the mix [25].

The blending of RAP into the Virgin Material can be done using three methods – black rock, total blending, and real world. In black rock method, only the aggregate from RAP materials are used without the RAP binder for mixing with the virgin materials. In total blending method, RAP binder and virgin binder are assumed to mix uniformly and completely. According to NCHRP Report 452, total blending is assumed when higher RAP content is being used and under this blending due to the excess amount of RAP the mix performance is affected significantly [27]. In the real world method, the results were found to be closely matched to total bending and depend upon the amount of RAP material. A rejuvenator is used for total blending and the amount required depends on the amount of RAP material being used [32].

Bonaquist developed a method to evaluate if total blending occurs [32]. In this method the dynamic modulus of mix is used to compare with an expected dynamic modulus value obtained from Hirsch model (which was developed by Christensen et al.). Hirsch model uses the shear modulus of totally blended RAP binder to estimate the dynamic modulus. Total blending is assumed if the estimated and measured dynamic moduli match. According to NCHRP Report 452, mixtures with low RAP content are treated as black rock. At higher RAP contents the aged RAP binder is seen to significantly to affect the mix performance properties [27].

Binder properties using various Superpave binder tests are an important control factor on the utilization and incorporation of RAP material. The second important control when using RAP is aggregate gradation. High RAP content cannot be used if it causes the gradation of the final mix to deviate out of specified guidelines. It is recommended that the RAP material is fractionized if higher RAP contents are being used. This controls the amount and size fractions of RAP aggregate introduced into the mix and since different size fractions of RAP have different binder percentages, fractionating allows greater control of the aged binder introduced to the mix [27].

NCHRP Report 425 identifies Binder property as an important control facto on the utilization and incorporation of RAP material. These are the properties obtained from the basic Superpave testing used to find the PG (performance grade) of a binder. In the report a three tiered solution was proposed to help in selection of the PG grade of virgin binder to be used with different grades of the recovered RAP binders and the percentage of RAP that will be used [27]. This is given in Table A-5.

Table A-5 Binder Selection Guidelines for RAP Mixtures (Source NCHRP Report 452) [27]

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	PG xx-22 or lower	PG xx-16	PG xx-10 or higher
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	20-30%	15-25%	10-15%
Follow recommendations from blending charts	>30%	>25%	>15%

Aggregate Gradation required and that of the RAP the second important control factor according to the report. High RAP content cannot be used if it causes the gradation of the final mix to deviate out of specified guidelines. It is recommended that the RAP material is fractionized if higher RAP contents are being used. This controls the amount and size fractions of RAP aggregate introduced into the mix and since different size fractions of

RAP have different binder percentages, fractionating allows greater control of the aged binder introduced to the mix [27].

According to Feiping, with the increase of RAP content in the binder the viscosity increases while the use of a soft base binder decreases the viscosity. Experimental results showed that $G^*\sin\delta$ value increases with the increase in RAP content. The RAP content also increases the mixing and compaction temperatures of the mix. The bond between binder and aggregate increases when RAP material is used and hence the ITS value also increases [24].

In the NCAT Report 95–1, it is observed that the recycled mixtures age at a slower rate than the ones with virgin binder. RAP mixtures were observed to be less susceptible to moisture-induced damage than the virgin binder mixtures and exhibited better durability and had less internal friction [40]. Results from in-situ studies have shown very slight difference between Recycled Asphalt Concrete Pavement and Virgin Binder Pavement, suggesting that RAP retains most of the properties of the virgin materials [40].

Studies on RAP-WMA

As we have seen that one of the major problems of including RAP in hot mix asphalt was the mixing and compaction temperatures. And as it is a known fact that the WMA has lower mixing and compaction temperatures, the use of RAP-WMA technology can eliminate the increase in mixing and compaction temperatures due to the addition of RAP materials in the mix.

It is thought that combining WMA technologies with higher percentages of RAP is advantageous because, the high temperatures associated with conventional HMA production are lowered, preventing further aging and stiffening of the RAP and virgin binders [37].

According to various researchers and engineers the aged RAP binder in the WMA and RAP mix will decrease the fatigue life but the aging of virgin binder produced at lower temperatures in Warm Mix Asphalt will be less than that of a virgin binder produced at higher temperatures in HMA. So a balance is required between these two aspects to use

RAP materials and WMA technology together as both these technologies are aimed at saving resources and lowering the energy required for production [28, 29].

According to an experimental study conducted by J. Wielinski, A. Hand, and D. M. Rausch, it was found that if the binders were aged at a lower temperature then the aging of the binder decreases. In Warm Mixes as the mixing and compaction temperatures are less hence the aging in the binder also decreases. It was also found out that this change in temperature had not much effect on the binder's G*/sinδ value. Hence the reduction in the temperatures will not have much effect on the rutting resistance of the binder. Moreover the presence of aged binder in form of RAP binder will compensate for this soft warm mix binder [41].

An experiment was conducted in California where hot mix asphalt and warm mix asphalt using the Foamer mixtures were prepared using the Hveem mix design. In both of the mixtures 15% RAP was also added. This experiment showed that Hveem mix design method could be used for designing warm mix asphalt using Foamer. The mix produced satisfied the required mechanical properties but had low initial stiffness and higher rutting. It was also seen that the effect on stiffness due to lower temperatures was less compared to the effect of temperature on rutting. As we know that WMA needs time to cure and attain full strength so there is need for continued monitoring of these pavements for their service time before concluding [41].

In an experimental study by Kim et al. it was seen that the viscosity of recycled binder at 60°C increased when Sasobit® was added to it hence showing better resistance to rutting. The creep compliance values were lower for Sasobit®-modified recycled binders than for the recycled binders without Sasobit®. The recycled binders in which Sasobit® was added showed lower phase angles and higher complex moduli than the normal recycled binders in the Frequency sweep test [25].

Mallick et al. used Sasobit to produce mixtures at lower temperatures (125 and 135°C) and successfully added 75% RAP into base course at Worchester. Three binder grades, one for control and others for rejuvenating RAP binder were used (PG 64 -22, PG 52 -28, and PG 42 -42). Results from volumetric properties, tensile strength, and seismic modulus tests indicated that warm mixtures with 75% RAP can be produced with properties similar to HMA recycled mixtures [38].

Mallick and Tao also performed field study with 100% RAP in base course with different percentages of Sasobit and Advera WMA zeolite [34]. Tests to determine volumetric properties, seismic modulus, ITS, and workability using torque tester were done. They found that it was possible to achieve satisfactory workability with 100% RAP-WMA. The RAP binder viscosities were lowered due to the modifiers, but showed a probable stiffening effect at low temperatures. The ITS and seismic modulus values of WMA mixtures were higher than control HMA. They observed an increase in workability with the addition of the Warm Mix additives at temperatures as low as 110°C but when the temperatures reached below 80°C, a more stiffening effect was seen [34].

Lee, Amirkhanian, Park and Kim researched the effects of WMA additives Sasobit® and zeolite on binder properties of asphalt binder blends including 15% RAP [39]. They found that the addition of Sasobit® reduced the viscosity of the binder blends while the addition of zeolite had the opposite effect. DSR testing shown that WMA additives increase stiffness and thus, improve rut resistance for the same virgin binder grade. However, intermediate temperature DSR testing revealed reduced resistance to fatigue cracking upon addition of WMA additives for the original binder grade. The increase in binder stiffness can be compensated for by using a lower (and thus softer) binder grade. BBR testing also showed that recycled binders containing WMA additives had reduced resistance to low temperature cracking.

The Maryland State Highway Administration produced an asphalt pavement section of road using 45% RAP in the base course, SMA in the intermediate course, and 35% RAP in the surface course with 1.5% Sasobit by weight of total binder as a modifier. The stiffness and the WMA and HMA control mixtures were found to be statistically similar [35].

In Orlando, FL, a test section was constructed using 20% RAP and zeolite as a modifier. The zeolite reduced production and compaction temperatures by 19°C (39°F). The in-place densities at these temperatures were similar to control RAP produced at HMA temperatures [36].

A case study was done by Copeland, D'Angelo, Dongré, Belagutti and Sholar in association with the Florida DOT to evaluate field performance of WMA and HMA mixtures with high RAP content in December 2007. The study compared mixtures with 45% RAP with and without using WMA technology using water injection method. Performance grading of the binders, dynamic modulus, and flow number values were determined in the study. They found consistent results that the high RAP-WMA mixture was softer than the high RAP-HMA control mixture. They also noticed that the blending of RAP with the virgin material was complete in the case of HMA mixture but in the case of WMA mix the blending was incomplete [37].

William et al. conducted tests with RAP binder mixed with WMA binders produced by using Zeolite and Sasobit®. Both WMA additives exhibited a tensile strength retained ratio of at least 80%. But the addition of WMA in RAP mixtures showed a decrease in the tensile strength ratio of the mixtures [25]. They also observed that the stiffness is higher for binders with Sasobit as compared to those without Sasobit. They also indicated that the binder with Sasobit also had more resistance to penetration at mid-range temperatures [25].

Evotherm was used to help eliminate the use of vibratory compactor in San Antonio, Texas on a bridge deck of I-35. The mix had 16% RAP and 4% RAS material and PG64-22 grade binder was used and Evotherm was also added to the mixture. The mixing temperature at the plant was lowered by 70 °F and the workability of the mix was excellent at the time of placement. Only static mode rollers were used to achieve densities around 94% [9].

With many WMA additives showing good and increased workability and compactability when used with RAP material, including Evotherm, it is necessary to study the behavior of the North Carolina mixtures when Evotherm and PTI Foamer Technologies are used along with RAP.

Studies on Workability

Researchers have been attempting to measure since the 1970s. Marvillet and Bougault presented their work in AAPT in 1978 on workability. According to the paper workability depends on binder and aggregate properties. They also noticed the effect of testing equipment as well as the temperature [42]. They developed an instrument which measures the torque resistance offered by a mix and measured workability based on the resistance. The main results from the study were that workability increased as the binder viscosity decreased, change in asphalt content has no direct effect on workability, increase in filler content decreases the workability, and mixtures with angular aggregates have less workability compared to mixtures with semi-angular or rounded aggregates.

Since it was shown that viscosity and workability were correlated directly, researchers started focusing on measuring workability in terms of viscosity. This went on until the use of modified asphalt started picking up. Since the viscosities of modified binders were very high than the unmodified binders and the mixing and compaction temperatures were based on the workability being expressed as viscosity of the binder, a need for a new way to measure workability came up [43].

De Sombre et al came up with a new method to measure the compaction temperature in 1998 [44]. The shear stress was calculated in the Hot Mix Asphalt using Mohr-Coulomb equation. According to the study the shear stresses for all mixtures decrease with increase in temperature to a minimum value and then start increasing. The temperature where this minimum value is achieved was determined to be the compaction temperature for the mixture.

In NCAT Report 03-03 published in April 2003, Gudimettla et al. worked on developing the use of compactability as the basis for workability [43]. They developed a new method, where a paddle was pushed through the asphalt mixture and recorded the torque required to maintain a given rate of revolution. They also used shear ratios calculated for the asphalt mixtures from the Superpave gyratory compactor to find out the workability. They found out that both the methods gave the same results. They concluded that at a given temperature, aggregate type, nominal maximum aggregate size and binder type affected the workability of the mixtures. They observed that workability was less for cubical and angular granite as compare to semi-angular gravel. The workability decreased as the nominal maximum aggregate size increase and also as the binder grade increased.

A study was conducted by NCAT to find relationships between laboratory measured characteristics of HMA and Field Compactability [45]. They found that the number of gyrations to reach field density for specimens compacted to field lift thickness had the greatest impact in finding out field compaction. Other significant factors that influenced were are fine aggregate ratio, primary control sieve index, number of gyrations to 92 percent G_{mm} and percent passing 0.075 mm sieve.

A device to look at the workability during mixing was developed by UMass, Dartmouth called Asphalt Workability device. The workability is calculated by the amount of torque required to maintain a constant mixing speed which is measured by the device [46]. But this device has been proven to be insensitive to WMA additives or additive concentration at the mixing and compaction temperatures of WMA mixtures. But it can differentiate at temperatures below 220°F (105°C).

The number of gyrations required to reach 92% G_{mm}, N92 has been proposed to evaluate workability of asphalt mixtures [14]. In addition to that Bahia et al came up with a device called the Gyratory Pressure Distribution Analyzer (GPDA). This device is fit into the gyratory compactor and monitors the resistive forces of mixtures during compaction. A Construction Force Index (CFI) is calculated using these measurements. This Index can also be represented as the area under the curve in a G_{mm} evolution curve from N_{ini} to 92 percent G_{mm} [47].

Laboratory experiments by Hanz et al [46], Faheem et al [47], and field calibrations by NCAT [45] and Bonaquist et al [14] have indicated that N92 and CFI are sensitive to WMA additives and the compaction temperatures. It is also seen that the area under the curve from N_{ini} to 92 percent G_{mm}, N92 can be used to rank the mixtures based on their workability. Since this study looks at comparing the workability of various mixtures with different WMA technologies and different RAP contents, the N92 parameter can be used to do that.

Appendix B

TENSILE STRENGTH RATIO RESULTS

In this appendix, the individual results for each mixture type for Tensile Strength Ratio tests are shown.

Table B-1 Tensile Strength Values for 0% RAP HMA Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	H0R 2	7.1	150.39	1037	1059	**101.4**
	H0R 3	6.9	154.75	1067		
	H0R 6	6.8	154.75	1067		
	H0R 7	6.7	152.57	1052		
Wet	H0R 4	7.1	161.28	1112	1074	
	H0R 5	6.9	156.92	1082		
	H0R 8	6.8	154.75	1067		
	H0R 9	6.7	152.57	1052		

Table B-2 Tensile Strength Values for 0% RAP Evotherm Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	E0R 3	6.7	122.05	842	849	**93.8**
	E0R 4	6.6	124.23	857		
	E0R 5	6.6	126.41	872		
	E0R 7	6.6	122.05	842		
Wet	E0R 1	6.6	115.51	796	796	
	E0R 2	6.6	119.87	826		
	E0R 9	6.5	111.16	766		
	E0R 10	6.7	115.51	796		

Table B-3 Tensile Strength Values for 0% RAP Foamer Mixture

Moisture Conditioning	Specimen#	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	F0R 3	6.9	159.1	1097	1082	**94.4**
	F0R 4	6.9	154.75	1067		
	F0R 8	6.9	159.1	1097		
	F0R 9	7.0	154.75	1067		
Wet	F0R 5	6.9	148.21	1022	1022	
	F0R 6	6.8	141.67	977		
	F0R 7	6.9	148.21	1022		
	F0R 10	6.9	148.21	1022		

Table B-4 Tensile Strength Values for 20% RAP HMA Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	H20R 4	6.6	217.95	1503	1473	**87.7**
	H20R 5	6.6	209.23	1443		
	H20R 7	6.7	215.77	1488		
	H20R 9	6.6	211.41	1458		
Wet	H20R 1	6.8	180.9	1247	1292	
	H20R 2	6.7	187.44	1292		
	H20R 8	6.7	217.95	1503		
	H20R 10	6.7	187.44	1292		

Table B-5 Tensile Strength Values for 20% RAP Evotherm Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	E20R 3	6.8	215.77	1488	1495	**89.9**
	E20R 4	6.7	217.95	1503		
	E20R 6	6.6	224.49	1548		
	E20R 10	6.7	200.51	1383		
Wet	E20R 1	6.8	196.16	1352	1345	
	E20R 2	6.7	207.05	1428		
	E20R 5	6.6	193.98	1337		
	E20R 9	6.7	185.26	1277		

Table B-6 Tensile Strength Values for 20% RAP Foamer Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	F20R 6	6.7	198.34	1368	1375	**87.4**
	F20R 8	6.8	200.51	1382		
	F20R 9	6.7	200.51	1382		
	F20R 10	6.8	193.98	1337		
Wet	F20R 1	6.7	170.00	1172	1202	
	F20R 2	6.8	178.72	1232		
	F20R 3	6.7	174.36	1202		
	F20R 5	6.7	174.36	1202		

Table B-7 Tensile Strength Values for 40% RAP HMA Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	H40R 1	7.1	193.98	1337	1458	**90.2**
	H40R 4	6.7	211.41	1458		
	H40R 7	6.7	211.41	1458		
	H40R 10	6.9	220.13	1518		
Wet	H40R 2	6.9	172.18	1187	1315	
	H40R 5	6.9	191.8	1322		
	H40R 6	6.7	196.16	1352		
	H40R 9	6.7	189.62	1307		

Table B-8 Tensile Strength Values for 40% RAP Evotherm Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	E40R 3	7.0	235.39	1623	1593	**85.4**
	E40R 4	6.8	226.67	1563		
	E40R 7	6.7	228.85	1578		
	E40R 8	6.7	233.21	1608		
Wet	E40R 1	7.1	185.26	1277	1360	
	E40R 2	7.0	202.69	1397		
	E40R 9	6.9	200.51	1382		
	E40R 10	7.0	193.98	1337		

Table B-9 Tensile Strength Values for 40% RAP Foamer Mixture

Moisture Conditioning	Specimen #	Air Void Content	ITS (psi)	ITS (kPa)	Average Subset ITS (kPa)	TSR (%)
Dry	F40R 2	6.6	294.23	2029	2006	**74.9**
	F40R 4	6.6	287.7	1984		
	F40R 7	6.6	296.41	2044		
	F40R 9	6.5	285.52	1969		
Wet	F40R 1	6.7	198.34	1368	1503	
	F40R 3	6.5	222.31	1533		
	F40R 6	6.5	215.77	1488		
	F40R 8	6.5	220.13	1518		