ABSTRACT

KUSAM, ABHILASH. Laboratory Evaluation of Workability and Moisture Susceptibility of Warm Mix Asphalt Technologies with Reclaimed Asphalt Pavement Material. (Under the direction of Dr. Akhtarhusein A. Tayebali).

In this current world there is a need to use cleaner and more sustainable technologies. One such technology which might soon replace the conventional Hot Mix Asphalt technology is Warm Mix Asphalt Technology (WMA), which helps reduce production temperatures. It also helps increase workability at lower temperatures thus reducing the energy required to heat the materials. Lower production temperatures also mean less harmful emissions during the pavement construction, and also 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 a very long time. By recycling construction materials, the cost involved in transporting them is also lowered. The RAP material gives extra stiffness to the mixture, which is beneficial to prevent rutting but in turn decreases the 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 very important to

find out 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 compared to the workability and moisture susceptibility of the corresponding HMA mixtures. Tensile Strength Retention Ratio test was done to evaluate the moisture susceptibility, while the workability was evaluated by $\%G_{mm}$ evolution curves. The effectiveness of Evotherm as an anti-strip additive was evaluated by a litmus paper test using StripScan.

TSR ratio was observed to decrease with increase in RAP content for HMA as well as the two WMA technologies. Foamer mixtures showed better workability than Evotherm and HMA mixtures. The workability decreased with increase in RAP content for all three types of mixtures. The volatility of Evotherm additive was measured using the litmus paper test. The results were observed to be similar to that of LOF 6500 and Morelife 2200 anti-strip additives from a previous study conducted at North Carolina State University. Evotherm can work as an anti-strip additive for 0% RAP mixtures since the TSR ratio was above the minimum limit required by NCDOT.

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Laboratory Evaluation of Workability and Moisture Susceptibility of Warm Mix Asphalt Technologies with Reclaimed Asphalt Pavement Material

by
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DEDICATION

To my parents

BIOGRAPHY

Abhilash Kusam was born in 1989 to Dr. K Sudhakar Reddy and K Vasundhara. He grew up in the university town of Kharagpur, West Bengal, India. After receiving his Bachelor of Engineering (Hons) degree in Civil Engineering from Birla Institute of Technology and Science, Pilani, India in 2011, he joined the Indian Institute of Technology, Kharagpur, India for his Masters. He joined North Carolina State University for his M.S. degree in fall 2012 to continue his passion for research. He has been working in the field of pavement materials under the guidance of Dr. Akhtarhusein Tayebali since then.

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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 which promote sustainability and construction techniques which are more economical and less damaging 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 environmental 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 either 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 mixes produced with WMA technologies. The lower mixing and compaction temperatures also means 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 mixes 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 binder grade on workability and moisture susceptibility.

1.3 Organization of Thesis

The objective of this study is to evaluate the workability and moisture susceptibility of mixes with three varying RAP content – 0%, 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 thesis is organized into 6 tasks – literature review, characterization of materials, Superpave mix design, evaluating workability, evaluating moisture susceptibility, and quantification of Evotherm as an anti-strip additive. The literature review related to the study is detailed in chapter 2. Chapter 3 explains the study’s research approach and methodology and chapter 4 focuses on the characterization of the materials used in this research study. The Superpave mix design of the mixtures involved in this study is explained in chapter 5. The evaluation of workability of mixtures using $\%G_{mm}$ curves is discussed in Chapter 6. Moisture susceptibility evaluation using the TSR test is given in chapter 7 and chapter 8 describes quantification of Evotherm additive. The summary and conclusions for the research study are detailed in chapter 9.

2. 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 chapter. The chapter 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.

2.1 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 2.1

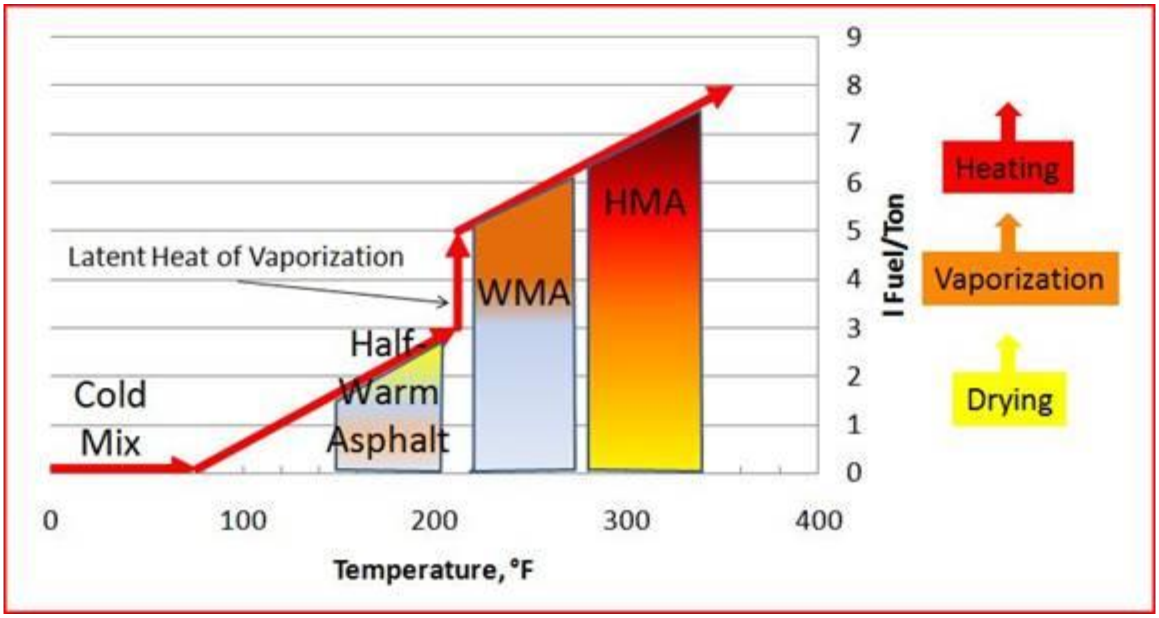

Figure 2-1 Classification of Asphalt Concrete by Approximate Temperature Ranges [Image courtesy: WMA Scan Summary Report, 2007] [2]

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.

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].

2.2 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™ 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.

2.2.1 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 2.2

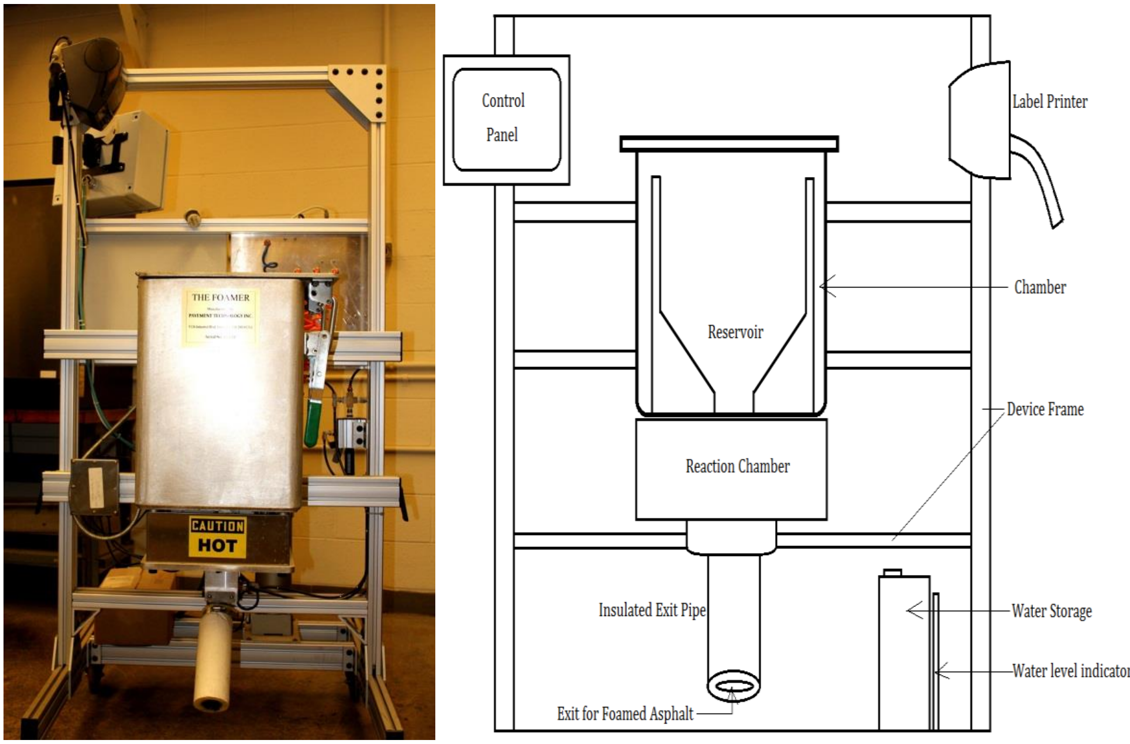

Figure 2-2 “The Foamer” Device and Its Schematic Representation [48]

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 2-3 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.

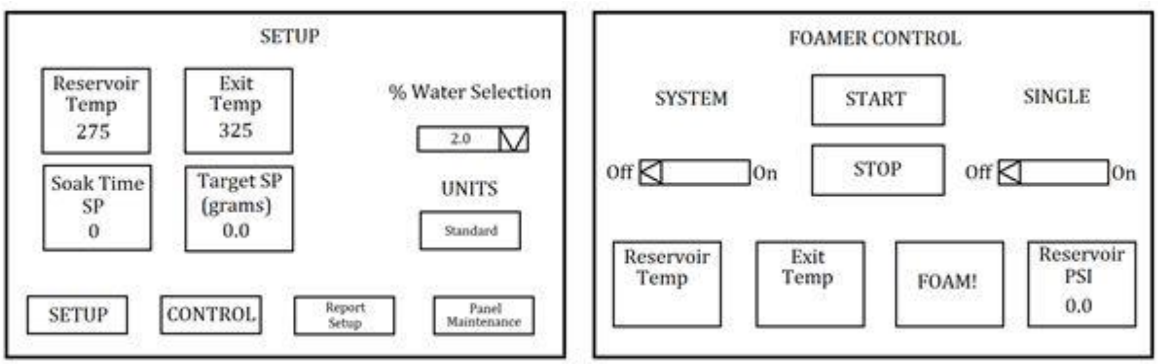

Figure 2-3 Schematic Representation of Control Panel Displays in “The Foamer” [48]

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 2-4 Foamed Asphalt Produced by “The Foamer”[48]

2.2.2 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.

2.3 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.

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 [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 Table 2-1 and Table 2-2 respectively.

Table 2-1 Comparison of Specimen Fabrication Procedures for WMA and HMA (Source: NCHRP Report 714)

Step	Description	HMA	WMA	Comment
1	Batch Weight Calculation	X	X	Must compute WMA additive content in 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 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

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

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

2.4 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 2-3 gives a summary of the major results of Evotherm, Astec Double Barrel foamer and AquaBlack WMA technologies and compared to their HMA counterpart.

Table 2-3 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

A comparison of the two WMA technologies used in this research study is done in Table 2-4.

Table 2-4 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

2.5 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 mixes 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 mixes age at a slower rate than the ones with virgin binder. RAP mixes were observed to be less susceptible to moisture-induced damage than the virgin binder mixes 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, mixes 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 2-5.

Table 2-5 Binder Selection Guidelines for RAP Mixtures (Source NCHRP Report 452)

	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*sinδ 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 mixes age at a slower rate than the ones with virgin binder. RAP mixes were observed to be less susceptible to moisture-induced damage than the virgin binder mixes 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].

2.6 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 $G^*/\sin\delta$ 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 mixes were prepared using the Hveem mix design. In both of the mixes 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 mixes 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 mixes with 75% RAP can be produced with properties similar to HMA recycled mixes [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 mixes 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 mixes 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 mixes 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 mixes when Evotherm and PTI Foamer Technologies are used along with RAP.

2.7 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 stress for all the 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.

3. RESEARCH APPROACH AND METHODOLOGY

3.1 Research Objective

The main objective of this research was to evaluate the workability and moisture susceptibility of mixes 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 N.C. 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 – 20% and 40% RAP. PG 64-22 binder was used for the mixes with 0% and 20% RAP. PG 58-28 binder was used in addition to PG 64-22 for the mixes with 40% RAP, since NCHRP Report 452 suggests the use of a softer binder grade when more than 30% RAP is used. The Tensile Strength Ratio (TSR) test was used to measure the moisture susceptibility. The Tensile Strength Ratio (TSR) test or the Modified Lottman test follows the procedure mentioned in AASHTO T283 guideline, “Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage.” The specific research objective of this research study were to:

- Superpave Mix Design for the HMA mixes 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.
- Characterize the mixtures based on workability using the $\%G_{mm}$ evolution curves.

- Determine moisture susceptibility of the mixtures using Tensile Strength Ratio Test and compare the moisture susceptibility of WMA mixtures with the HMA mixture of similar RAP content.
- Quantifying the Evotherm additive as an anti-strip additive using Litmus Paper Test and TSR test.

Table 3-1 gives a matrix of all the mixtures involved in this research study.

Table 3-1 Matrix of Mixture Types

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

3.2 Research Methodology

In this research study, a sequence of tasks were followed to complete the research objectives. These steps involved the acquisition and evaluation of the materials used in the study and also testing and analyzing the mixes for their properties.

Task 1. Material Acquisition and Evaluation

The materials used in this study were selected and supplied by North Carolina Department of Transportation (NCDOT). The Virgin and RAP materials used to prepare the HMA and WMA mixes in the lab were kept constant throughout the project. Pond Fines from the same aggregate source were also provided for replacing a part of the material passing no. 200 sieve size from the virgin aggregate while producing the mix. The job mix formula (JMF) for RS 9.5B mix was provided by the NCDOT. A gradation similar to that given in the JMF was used for all the mixes. The PG 64-22 and PG 58-28 virgin binders used in this research study were provided by NCDOT. The Warm Mix Additive, Evotherm 3G was procured, while the PTI Foamer in the laboratory was used to produce foamed asphalt for Foam mix. AD-here® LOF 6500 was used as the anti-strip additive in every mix as specified by the NCDOT. The gradations for the aggregate stockpiles were to be evaluated and the total aggregate bulk specific gravity was to be found according to specifications for the virgin aggregates. For RAP material, the aggregate gradation and the binder content in RAP had to be found out. In addition to that, the bulk specific gravity of the RAP material was also found out.

Task 2. Mixing and Compaction Temperatures

The mixing and compaction temperatures for the HMA with 0% RAP were provided in the JMF for PG 64-22 and PG 58-28 binders and 9.5B Mix. The mixing and compaction temperatures for the Warm Mix Asphalt mixes were specified by the Warm Mix technology manufacturer with respect to the binder used. In mixes with RAP, the virgin binder and virgin aggregates had the heating temperatures corresponding to those of the virgin mixes. The mixing temperatures for the RAP material was different than those of the virgin materials. The RAP mixes were compacted at the same temperatures as that of the virgin mixes. The RAP material was handled and heated according to NCAT guidelines.

Task 3. Superpave Mix Design

The Superpave Mix Design for all the 12 mixes mentioned in the matrix earlier was done and the volumetric properties were checked in this task. The aggregate gradation for HMA with 20% RAP was given in the JMF provided by NCDOT. The same aggregate gradation was used for 0% and 40% RAP contents. The virgin HMA mix with 0% RAP was used to calculate the optimum asphalt content. The mix was mixed and compacted using different asphalt contents and the volumetric properties were verified for the different asphalt contents. The optimum asphalt content obtained with HMA was then verified for the WMA mix. The same process was followed to design the mix the 20% and 40% RAP mixtures. The volumetric properties verified in the mix were Volume in Mineral Aggregates (VMA), Volume Filled with Asphalt (VFA), theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) as per NCHRP Report 673.

The mix design for WMA mixes was done similar to that of HMA mixes according to NCHRP Report 691.

Task 4. Evaluating Workability of Mixtures

The workability was evaluated based on the compactability of the mixtures. Compactability was calculated using N92, the number of gyrations to 92% G_{mm}, and the area under the %G_{mm} curve from the first gyration to 92% G_{mm}. A relative comparison of workability was done between the mixtures. The mixtures of similar RAP content were compared to see the variation in workability with the change of mixture technology, and the mixtures of similar mixture technology were compared to see the variation in workability with increasing RAP content. The compaction data from Superpave gyratory compactor was used to plot the $\%G_{mm}$ curves.

Task 5. Testing for Moisture Susceptibility

The moisture susceptibility was measured using the Tensile Strength Ratio (TSR) test. In this test, tensile strength ratio was calculated as the ratio of indirect tensile strength values of the conditioned specimen to the unconditioned specimen. ASTM code for TSR test was followed to prepare the specimens. The specimens were prepared and the test was run according to the specifications given in the NCDOT QMS Manual 2012 which is a modified version of the AASHTO T283. The moisture conditioned specimen was vacuum saturated to 70-80% and then conditioned in a water bath for 24 hours at 60°C. As per the guidelines in NCDOT QMS Manual 2012 the samples were not subjected to free-thaw cycle, which is suggested in the AASHTO T 283.

Task 6. Effectiveness of Evotherm Additive

This task was done in two parts – Moisture Susceptibility and Litmus Paper Test. The first part of the test involves TSR testing on virgin Evotherm mixtures without any anti strip additive. The results were compared with TSR values of virgin Evotherm mixtures with anti-strip additive, and also HMA mixtures with anti-strip additive. The second task is aimed at measuring the volatility of Evotherm. This task aims to simulate the field conditions and see the amount of Evotherm left in the mixture when the mixture is being laid down in the field. A litmus paper test using Strip Scan instrument manufactured by InstroTek was performed to measure the amount of additive left in the mixture. The test involves a calibration part and a measurement part. A calibration curve is generated using asphalt mixtures with different known additive contents in the calibration part. The measurement part involves estimating the amount of additive in the mixture using this calibration curve.

4. MATERIAL CHARACTERIZATION

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

4.1 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.

Firstly, the aggregate gradations of the three stockpiles was verified. Representative samples from the three stockpiles were taken for this task. 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" procedures were used to do a washed sieve analysis on the dried representative samples to find out the gradation of the virgin aggregate stockpiles.

The gradation of Manufactured Sand, Dry Screening and 78 M as determined are shown in the Tables 4-1 to 4-3. Variability for the samples were low for all three stockpiles. But, the overall gradation for the three stockpiles differed from that given in the JMF by a little extent. Thus, the gradation results as determined in the laboratory were used for preparing samples for further testing. In addition to the three stockpiles, pond fines were used. They were 1.5% of the total aggregate weight and replaced the No. 200 passing virgin aggregates. The pond fines were sieved such that only the portion passing through No. 200 sieve size was used.

Table 4-1 Gradation for Manufactured Sand

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	100
No. 4	4.75 mm	100
No. 8	2.36 mm	93
No. 16	1.18 mm	73
No. 30	600 µm	49
No. 50	300 µm	24
No. 100	150 µm	8
No. 200	75 µm	3

Table 4-2 Gradation for Dry Screenings

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	100
No. 4	4.75 mm	97
No. 8	2.36 mm	77
No. 16	1.18 mm	59
No. 30	600 µm	44
No. 50	300 µm	30
No. 100	150 µm	19
No. 200	75 µm	12

Table 4-3 Gradation for 78M Aggregates

Sieve Size		Percentage Passing
1/2”	12.5 mm	100
3/8”	9.5 mm	93
No. 4	4.75 mm	36
No. 8	2.36 mm	13
No. 16	1.18 mm	7
No. 30	600 µm	5
No. 50	300 µm	3
No. 100	150 µm	2
No. 200	75 µm	2

To calculate the bulk specific gravity of the aggregate gradation, the aggregates from each aggregate stockpile were divided into coarse and fine aggregates using the US Standard #4 sieve (4.75 mm). The bulk specific gravities of the coarse and fine aggregate portions were calculated separately and then a combined specific gravity was calculated using them. For pond fines the bulk specific gravity provided by the quarry was used. The bulk specific gravity of the coarse aggregates was calculated according to the procedure outlined in AASHTO T 85-88, “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate”, while the guidelines mentioned in AASHTO T 84-88, “Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate” were used to calculate the bulk specific gravity of the fine aggregate portion. The combined specific gravity for an aggregate stockpile was calculated using the following equation.

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

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 bulk specific gravity for the total aggregates was calculated using the blend ratio of the stockpiles and their corresponding bulk specific gravities. The blend ratio was calculated using all the three aggregate stockpiles in addition to the pond fines. The bulk specific gravity of the total aggregates came out to be 2.64.

4.2 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 sieve size). 4.75 mm sieve size was chosen taking into consideration the percentage of RAP material passing the sieve size. For 9.5 mm sieve the RAP material passing the sieve size is 96% while for 4.75 mm sieve size it is 81%. Since the amount of material retained on 9.5 mm sieve size was not significant, 4.75 mm sieve was chosen. In this thesis, 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.

4.2.1 Ignition Oven Test

Ignition Oven tests were conducted separately on two RAP fractions to determine the respective asphalt binder content according to the procedure outlined in AASHTO T 308-05, "Standard Method of Test for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method." The aggregate gradation was done on the aggregate extracted from the ignition oven test 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 asphalt content for each RAP fraction – coarse and fine, was found out using the ignition oven test. The asphalt contents were 3.2% for coarse RAP fraction and 6.4% for fine RAP fraction.

The gradations of the coarse and fine RAP fractions from the ignition oven test are shown in Table 4-4. 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. The target RAP aggregate gradation was used in replacing the virgin aggregate when 20% and 40% RAP was used and hence the blend ratio was found such that the resultant gradation will resemble the target RAP aggregate gradation. This target gradation is shown in Table 4-5. A blend of one-third (33%) coarse RAP and two-thirds (67%) fine RAP by weight was found to be ideal.

Table 4-4 Aggregate Gradation of RAP Fractions

Sieve Size	Percentage Passing	
	Coarse RAP	**Fine RAP**
½" / 12.5mm	100	100
$^{3}/_{8}$" / 9.5mm	89	100
#4 / 4.75mm	42	100
#8 / 2.36mm	28	84
#16 / 1.18mm	23	66
#30 / 600µm	18	48
#50 / 300µm	13	33
#100 / 150µm	8.4	21
#200 / 75µm	5.3	13.3

Table 4-5 Aggregate Gradation of RAP

Sieve Size	**Percentage Passing**
½" / 12.5mm	100
$^{3}/_{8}$" / 9.5mm	96
#4 / 4.75mm	81
#8 / 2.36mm	65
#16 / 1.18mm	51
#30 / 600µm	38
#50 / 300µm	26
#100 / 150µm	17
#200 / 75µm	10.3

4.2.2 Bulk Specific Gravity of RAP

Back calculation process mentioned in AASHTO R35-04, "Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA)" was used to determine the bulk specific gravity (G_{sb}) of RAP using the G_{mm} of RAP which was calculated in the laboratory experimentally. The G_{sb} was determined separately for the two RAP fractions. Firstly, the G_{mm} of the two fractions were experimentally calculated as per AASHTO T 209 "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt." Then, the effective specific gravity, G_{se} was determined using the asphalt contents (P_b) of the respective fractions. Taking the binder absorption (P_{ba}) to be 0.1% (as specified by NCDOT), the bulk specific gravity was determined from the G_{se}. Equations for G_{se} and G_{sb} are shown below. Table 4.6 shows the bulk specific gravity 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 4-6 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

4.2.3 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.

4.2.4 Calculating RAP fractions

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. To meet the JMF gradation requirements, one-third of the total RAP material was taken from coarse RAP fraction, while two-thirds of the total RAP material was taken from the fine RAP fraction. The total amount of binder being contributed from the RAP material should be calculated by adding the binder from coarse RAP material and the binder from fine RAP material. The binder being contributed can be calculated using the binder content values of coarse and fine RAP aggregates from the ignition oven test. The amount of binder being contributed from RAP should be subtracted from the total binder requirement for 20% and 40% RAP mixes to get the amount of virgin binder needed.

4.2.5 Additives in Virgin Binder

The dosage of additives (Evotherm 3G and LOF 6500) have to be calculated based on the total amount of binder in the mix, which is the amount of virgin binder being added in the case of mixes with no RAP content. But in the case of mixes with RAP binder in them, the total amount of binder in the mix will be the sum of the amount of virgin binder added and also the binder from RAP. So when adding additives to the virgin binder in case of mixes with RAP material in them, it is important to consider the total binder which will be going in the mix and not just the virgin binder. Hence the dosage of the additives was calculated using the total binder content and that dose of additive was mixed with the virgin binder.

4.3 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 mixes with 40% RAP material. The virgin binders were modified by adding the Evotherm 3G additive for preparing WMA mixtures. The specific gravity of the binders was reported as 1.034 by the manufacturer.

4.4 Additives

Two additives were used in the research project – Evotherm 3G and LOF 6500. The first one was used as a Warm – Mix additive while the second was used as an anti – strip additive, which is a specification of NCDOT.

4.4.1 Anti – Strip Additive

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.

4.4.2 Warm Mix Additive

Two Warm Mix Asphalt technologies were used in this project – PTI Foamer and Evotherm 3G, out of which only Evotherm 3G is an additive. Evotherm 3G is a water – free warm mix asphalt technology manufactured by MeadWestvaco Corporation. A dosage of 0.5% by weight of binder of the additive was mixed with the 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, their dosage and in what mixes they were used in given in Table 4.7.

Table 4-7 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

5. SUPERPAVE MIX – DESIGN

This chapter describes Superpave mix design method of the 12 mixes. 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.

5.1 Virgin Mixture Design

5.1.1 Aggregates

All the HMA and WMA mixes 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 5-1 and Figure 5-1. A blend ratio for the three aggregate stockpiles and the pond fines was calculated such that the resultant gradation was close to the target gradation and within all the control points.

The bulk specific gravity was calculated using the blend ratios and the bulk specific gravity values of each aggregate stockpile using the following equation.

$$\frac{100}{Gsb} = \frac{a}{G_{78M}} + \frac{b}{G_{MS}} + \frac{c}{G_{DS}} + \frac{1.5}{G_{PF}}$$

where a, b, and c are the blend ratio percentages used for #78M aggregates, Manufactured Sand and Dry Screenings used while arriving at the target aggregate gradation. And G_{78M}, G_{MS}, G_{DS} and G_{PF} are the bulk specific gravities of #78M aggregates, Manufactured Sand, Dry Screenings, and Pond Fines respectively.

Table 5-1 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

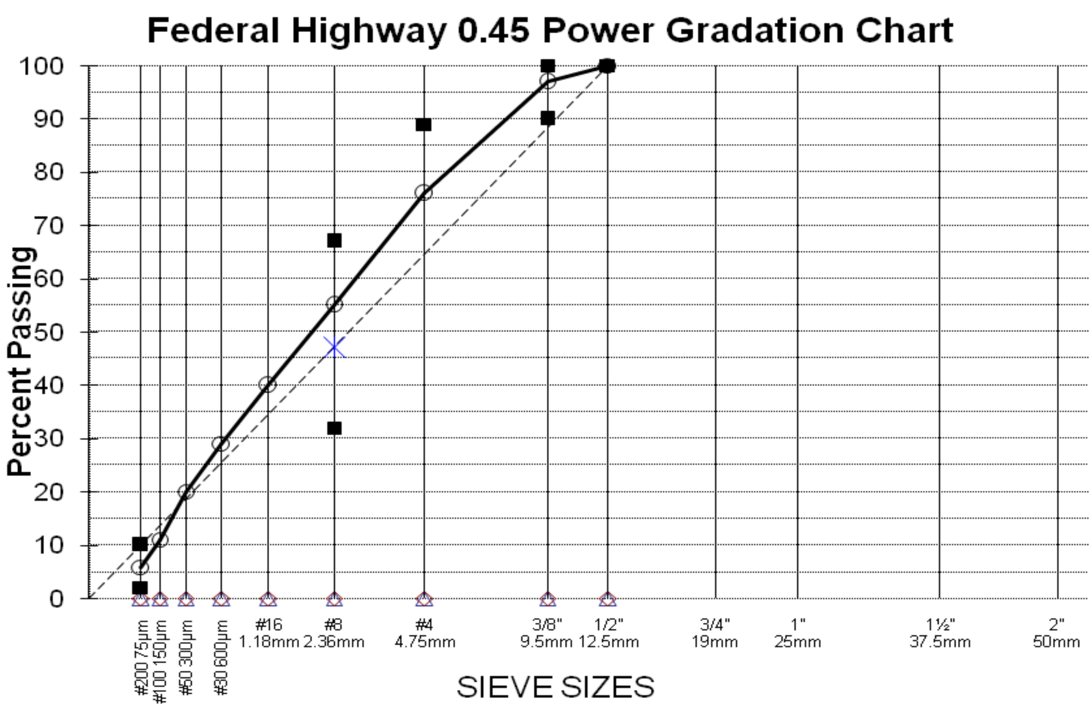

Figure 5-1 Percent Passing vs. 0.45 Power of Sieve Sizes

5.1.2 Asphalt Binder

The mixing and compaction temperatures for the virgin hot mix asphalt were provided by NCDOT for the 9.5 B mix. The mixing and compaction temperatures for PG 64-22 were taken to be 163°C (325°F) and 149°C (300°F) respectively.

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 mixes 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.

5.1.3 Determination of Optimum Asphalt Content

To determine the optimum asphalt content mixtures were prepared using the mixing and compaction temperatures with different binder contents till the volumetric requirements were satisfied. An initial binder content of 6.0% binder content by weight of mix was chosen to prepare the mix. The binder content was fixed on the basis of previous research done at North Carolina State University in an NCDOT project (FY 2011-04: An Evaluation of Warm Mix Asphalt Technologies for NCDOT Mixes) [48]. Here the same virgin aggregates and the same aggregate gradation was used which was used in the current research.

Two compacted specimens were prepared using 4500 g of virgin aggregates and 6.0% by weight of mix asphalt content. The mixtures were compacted to 65 gyrations using the Superpave Gyratory Compactor as specified in the JMF for 9.5 B mix. The initial gyrations,

N_{ini} = 7 and design gyrations, N_{des} = 65 were also specified by NCDOT. The compacted specimens were used to measure the bulk specific gravity (G_{mb}). Two more loose mixtures with the same binder content were prepared with 2000 g of aggregates to measure the rice specific gravity (G_{mm}). These two properties were used to determine the percent air voids in the mixture for 6.0% asphalt content.

5.1.4 Air Voids Calculation

The theoretical maximum specific gravity (G_{mm}) was calculated according to AASTO T 209 - 05, "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures." Two loose mixes were tested according to this procedure to find out the G_{mm} of the mix. AASHTO TP 69-04, "Standard Method of Test for Bulk Specific Gravity and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method," was used to calculate the bulk specific gravity (G_{mb}) of the compacted asphalt mixture specimens. CoreLok® device manufactured by InstroTek Inc. was used to vacuum seal the compacted asphalt mixtures for measuring the bulk specific gravity.

The percentage air voids were calculated using the calculated G_{mm} and G_{mb} values as per the following equation.

$$\%\, Air\ Voids = \frac{G_{mm} - G_{mb}}{G_{mm}}$$

The G_{mm}, G_{mb} and the percent air void values for HMA with 6.0% asphalt content are given in Table 5-2. Since the air void content was between 3.5 and 4.5, volumetric properties were checked for the mix with 6.0% asphalt content.

Table 5-2 Air void content, G_{mb} and G_{mm} for HMA Mixture with 6% PG 64-22

Mixture Type	Average G_{mm}	Measured G_{mb}	Air void content
HMA	2.425	2.330	3.9

5.1.5 Checking Volumetric Properties

Volumetric properties required for the Superpave mix design were calculated for the HMA using the asphalt content of 6.0% as per the NCDOT QMS Manual. The calculated properties were checked with the design requirements specified in Superpave. The design limits for volumetric properties were chosen based on the design traffic level of 0.3 to 3 million ESALs as specified in the JMF. Since all the volumetric properties were within the design limits, the optimum binder content was selected as 6.0%.

According to NCHRP Report 691, the mix design process for WMA mixtures is same as that of HMA mixtures. It also suggests that the volumetric properties for WMA be checked for the optimum binder content from the Superpave mix design of HMA mixture. If the volumetric properties are not satisfied then the mixtures have to be designed similar to HMA mixture design. The Warm Mix Asphalt mixtures were prepared and tested using the asphalt content of 6.0%. The volumetric properties for the WMA mixtures were also within the design limits.

The volumetric properties of the HMA mixture and the WMA mixture with Evotherm and Foamer with 0% RAP material are summarized in Table 5-3.

Table 5-3 Volumetric Properties for 0% RAP Mixtures

Mix Properties at N_{design}	**Asphalt Concrete Mix Technology**			**Volumetric Requirements**
	HMA	Evotherm	Foamer	
G_{mb} @ N_{design}	2.330	2.325	2.316	
Max. Specific Gravity, 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%

5.2 Mixture Design for mixtures with 20% RAP

5.2.1 Aggregates

The aggregate gradation for mixes with 20% RAP material was kept similar to the gradation of virgin aggregate mixtures. The blend ratios for the virgin aggregate stockpiles were multiplied with 0.8 since the virgin aggregates contributed only 80% of the total aggregates in the mixture. Hence the bulk specific gravity was calculated using the bulk specific gravity of the total aggregates and the bulk specific gravity of the RAP aggregates. The bulk specific gravity (G_{sb}) of the RAP aggregates was determined by using the G_{sb} values of coarse and fine

RAP fractions which were one – third and two – thirds in proportion. The bulk specific gravity of the aggregates with 20% RAP material came out to be 2.647.

5.2.2 Asphalt Binder

The mixing and compaction temperatures for the mixtures with 20% RAP were kept same as those of virgin mixtures. Hence, the mixing and compaction temperatures for PG 64-22 were taken to be 163°C (325°F) and 149°C (300°F) respectively in the case of Hot Mix Asphalt. For Warm Mix Asphalt, the mixing and compaction temperatures were taken to be 135°C (275°F) and 120°C (248°F) respectively.

5.2.3 Determination of Optimum Asphalt Content

The process to determine the optimum asphalt content for mixtures with 20% RAP is same as the process for virgin mixtures. An initial binder content of 6.0% binder content by weight of mix was chosen to prepare the mix. The specimens to measure G_{mm} and G_{mb} were prepared similar to those of the virgin mixtures.

5.2.4 Air Voids Calculation

The air void content for the HMA mixture with 20% RAP material at 6.0% asphalt content came out as 3.8 which lies between the acceptable ranges of 3.5 to 4.5. But when the Warm Mix Asphalt mixes were tested, the air void content for both Evotherm and Foamer mixes with 20% RAP and 6.0% asphalt content came out as 3.4. Table 5-4 shows the air void content, G_{mb} and G_{mm} for 20% RAP, HMA and WMA Mixtures with 6% PG 64-22 Binder Content.

Table 5-4 Air void content for 20% RAP Mixtures with 6% PG 64-22

Mixture Type	Air void content
HMA	3.8
Evotherm	3.4
Foamer	3.4

Hence new set of mixtures were prepared by reducing the asphalt content to 5.8%. The air voids for HMA mixtures with 20% RAP and 5.8% asphalt content were measured as 4.8%. The air voids for WMA mixtures with 20% RAP and 5.8% asphalt content came out to be 4.8% and 4.4% for Evotherm and Foamer mixtures respectively. The air voids for 5.8% asphalt content lie outside the 3.5 to 4.5% range for HMA and Evotherm mixes with 20% RAP. Table 5-5 shows the air void content, G_{mb} and G_{mm} for 20% RAP, HMA and WMA Mixtures with 5.8% PG 64-22 Binder Content.

Table 5-5 Air void content for 20% RAP Mixtures with 5.8% PG 64-22

Mixture Type	Air Void Content
HMA	4.8
Evotherm	4.8
Foamer	4.4

So interpolation was used between the 6.0% and 5.8% asphalt content to find the air void content for 5.9% asphalt content for mixes with 20% RAP. Table 5-6 gives the interpolated air void content values for 20% RAP mixtures with 5.9% asphalt content.

Table 5-6 Interpolated air void content for 20% RAP mixes with 5.9% binder

Mixture Type	Air Void Content
HMA	4.3
Evotherm	4.1
Foamer	3.9

5.2.5 Checking Volumetric Properties

Since the interpolated values air void content for asphalt content of 5.9% for 20% RAP mixes were seen to lie in the range of acceptable values, 5.9% asphalt content was chosen to be optimum asphalt content. Hence, the verification of volumetric properties was done at 5.9% asphalt content instead.

The measured air voids for 5.9% asphalt content, 20% RAP mixtures as shown in Table 5-7 were in the acceptable range.

Table 5-7 Measured air void content for 20% RAP mixes with 5.9% binder

Mixture Type	Air Void Content
HMA	4.2
Evotherm	4.0
Foamer	4.1

As the air voids were in the acceptable range, other volumetric properties were calculated. All the volumetric properties were verified to be in the acceptable range for 20% RAP mixtures with 5.9% asphalt content. Table 5-8 summarizes the volumetric properties for 20% RAP mixtures with 5.9% binder content.

Table 5-8 Volumetric Properties for 20% RAP Mixtures with 5.9% Asphalt Content

Mix Properties at N_{design}	Asphalt Concrete Mix Technology			Volumetric Requirements
	HMA	Evotherm	Foamer	
G_{mb} @ N_{design}	2.320	2.317	2.316	
Max. Specific Gravity, 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%

5.3 Mixture Design with 40% RAP

5.3.1 Aggregates

The same aggregate gradation that was used for mixes with 20% RAP material and for virgin aggregate mixtures was used for mixes with 40% RAP material. A multiplication factor of 0.6 was used to find out the blend ratios for the virgin aggregate stockpiles since only 60% of the total aggregate contribution of the mixture was from virgin aggregates. The bulk specific gravity was calculated taking into consideration that 60% aggregates were virgin and 40% were from RAP material. Hence, the bulk specific gravity of the aggregates with 40% RAP material came out to be 2.655.

5.3.2 Asphalt Binder

When more than 30% RAP is used NCDOT recommends using a lower grad binder or leaves it at the discretion of the engineer. Since 40% RAP was being used two different asphalt binders were used – PG 64-22 and a softer grade PG 58-28. PG 64-22 was used to check if the use of WMA technologies can eliminate the lowering of binder grade for high RAP mixtures. The mixing and compaction temperatures for 40% RAP were kept same as those of the virgin mixtures, i.e. 163°C (325°F) and 149°C (300°F) respectively for Hot Mix Asphalt. Similarly for Warm Mix Asphalt, the mixing and compaction temperatures were taken to be 135°C (275°F) and 120°C (248°F) respectively. Since 40% RAP material was being used in the mix, an additional softer binder was used to account for the stiffer binder from the RAP and to check the difference in compactability due to the stiffness between PG 64-22 and PG 58-28.

5.3.3 Determination of Optimum Asphalt Content

The optimum asphalt content for mixtures with 40% RAP material was found using the same procedure used for the virgin mixtures as well as the mixtures with 20% RAP. Mixtures were prepared using an initial binder content of 6% by weight of mixture. Specimens were prepared to measure the G_{mm} and G_{mb} values of the mixture similar to the procedure used for the virgin and 20% RAP mixtures.

5.3.4 Air Voids Calculation

For PG 64-22 at 6.0% binder content, the air void content for the HMA mixture with 40% RAP was calculated to be 3.7%. The air void content for Evotherm and Foamer mixtures came out to be 3.4% and 3.3% respectively. These values are either not in the acceptable range of air void content values of 3.5% to 4.5% or just at the border. For PG 58-28 binder the air void content for HMA with 40% RAP came out to be 4.0%, while that for Evotherm and Foamer mixtures came out as 3.4% for both. Table 5-9 shows the air void content for 40% RAP, HMA and WMA Mixtures with 6% binder content for PG 64-22 and PG 58-28 binders.

Table 5-9 Air Void content for 40% RAP Mixtures with 5.8% PG 64-22

Mixture Type	Air Void Content
HMA	4.4
Evotherm	4.4
Foamer	3.9

Since the air void content of the mixtures were not inside the acceptable range, the binder content was reduced to 5.8% for both the binder grades and the air voids were calculated for those mixtures. The air void content for mixtures prepared with PG 64-22 binder and 5.8% asphalt content were calculated to be 4.4%, 4.4% and 3.9% for HMA, Evotherm and Foamer mixtures respectively. For PG 58-28 binder the air void content for 5.8% asphalt content came out to be 3.8%, 4.3% and 4.1% for HMA, Evotherm and Foamer mixtures respectively. The air void content values for both binder grades, PG 64-22 and PG 58-28, with 5.8% asphalt content for 40% RAP mixtures were within the acceptable range of 3.5% to 4.5%. Table 5-10 shows the air void content 40% RAP, HMA and WMA Mixtures with 5.8% binder content for binder grades PG 64-22 and PG 58-28.

Table 5-10 Air Void content for 40% RAP Mixtures with 5.8% PG 58-28

Mixture Type	Air Void Content
HMA	3.8
Evotherm	4.3
Foamer	4.1

5.3.5 Checking Volumetric Properties

The volumetric properties for all three mixtures with 40% RAP and 5.8% asphalt content were calculated for both the binder grades, PG 64-22 and PG 58-28. Table 5-11 gives a summary of the volumetric properties for 40% RAP Mixtures with 5.8% Binder Content and PG 64-22 Binder. Similarly, Table 5-12 gives a summary of the volumetric properties for 40% RAP Mixtures with 5.8% Binder Content and PG 58-22 Binder

Table 5-11 Volumetric Properties for 40% RAP Mixtures with 5.8% PG 64-22

Mix Properties at N_{design}	Asphalt Concrete Mix Technology			Volumetric Requirements
	HMA	Evotherm	Foamer	
G_{mb} @ N_{design}	2.316	2.330	2.334	
Max. Specific Gravity, 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 5-12 Volumetric Properties for 40% RAP Mixtures with 5.8% PG 58-28

Mix Properties at N_{design}	**Asphalt Concrete Mix Technology**			**Volumetric Requirements**
	HMA	Evotherm	Foamer	
G_{mb} @ N_{design}	2.325	2.330	2.325	
Max. Specific Gravity, 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%

The volumetric properties for all the 40% RAP mixtures with 5.8% binder content for PG 64-22 binder as well as PG 58-28 binder were all within the specified limits. There is no significant difference in the volumetric properties of the WMA mixes with the two different binder grades. But for the HMA mixture, there is a reduction in air voids from 4.4% to 3.8% when the binder grade was changed from PG 64-22 to PG 58-28. There is also an increase in the % G_{mm} at N_{ini} (7) and % G_{mm} at N_{des} (65) values from PG 64-22 to PG 58-28. This changes in the volumetric properties for HMA indicate that the compactability is better for 40% RAP – HMA mixtures when PG 58-28 is used instead of PG 64-22 for this project.

Table 5-13 Matrix of Mixture Types

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

5.4 Compactability for Mixtures with 40% RAP

According to NCDOT's QMS Manual, when more than 30% RAP is used in a mixture, then either a softer binder grade has to be used or the binder grade selection is at the discretion of the engineer. So according to the QMS manual when 40% RAP is being used in a mixture, PG 58-28 binder should be used instead of PG 64-22 for a 9.5 B mixture. This reduction in binder grade is to overcome the increased stiffness due to the high amount of RAP in the mixture. The increased stiffness can lower the workability of the mixture and can lead to improper compaction. As seen in the literature, it is believed that use of WMA additives can help overcome the increased stiffness due to the high amount of RAP and thus eliminating the need to use a softer binder grade. As this research was focused on workability and moisture susceptibility, the workability aspect was looked at in this study. $\%G_{mm}$ evolution curves were used to determine the workability of the mixtures on the basis of compactability of the mixture. $\%G_{mm}$ evolution curves were calculated for all the mixtures with 40% RAP.

Three samples were prepared for all the three different type of 40% RAP mixtures with both the binder grades. Each sample was prepared using the optimum asphalt content of 5.8% by weight of mix and compacted to 65 design gyrations. The evolution of $\%G_{mm}$ was plotted for each mixture with two different binder grades on the same graph to compare their compactability. These evolution curves can identify the difference in workability of the mixtures. If the two curves overlap each other, then the workability of the mixture is same with both the binder grades, and if they do not overlap, then the curve on top will indicate better workability than the curve below it. The average $\%G_{mm}$ of the three samples at every 5 gyrations was calculated and plotted. The $\%G_{mm}$ evolution curves for HMA with 40% RAP mix using both the binder grades are shown in Figure 5-2.

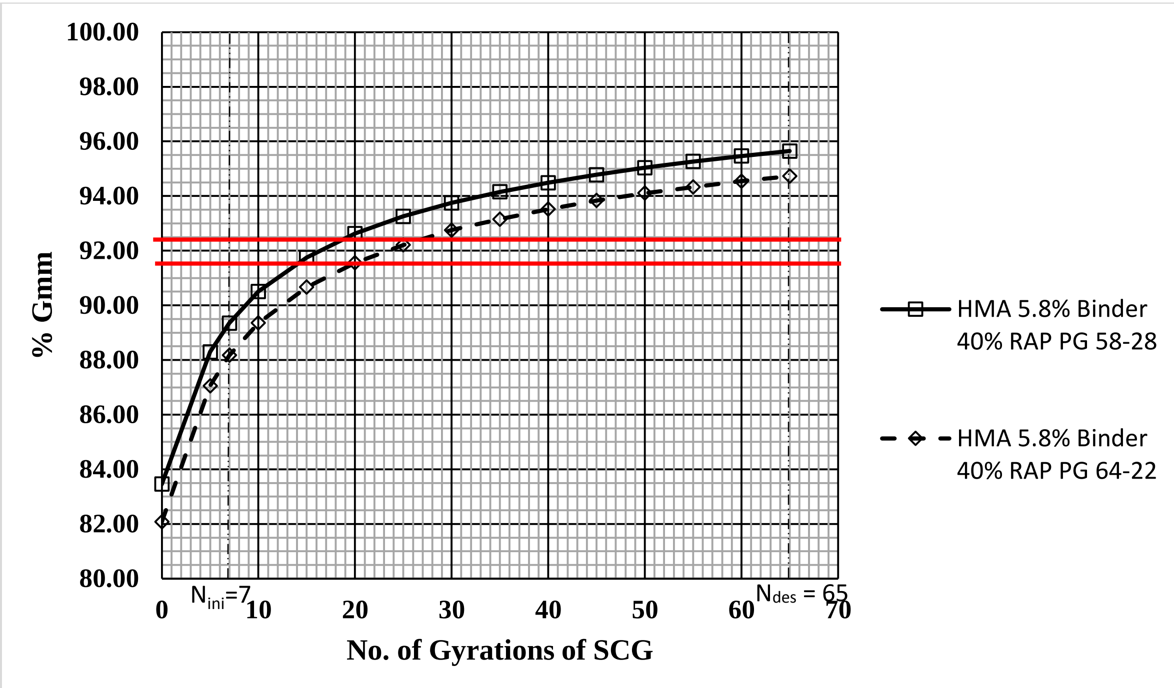

Figure 5-2 Average $\%G_{mm}$ evolution curves for 40% RAP HMA Mixtures with Different Virgin Binder Grades

The gap between the $\%G_{mm}$ evolution curves for 40% RAP HMA mixtures for different binder grade increases as the number of gyrations increases. At the number of gyration where the curve with 40% RAP and PG 58-28 binder reaches $92\%G_{mm}$, the difference between the two curves is more than $1\%G_{mm}$ which is more than the tolerance level of 0.5% G_{mm}. The tolerance level of $0.5\%G_{mm}$ comes from the air void content tolerance of 0.5% specified in the Superpave mix design procedure. The $\%G_{mm}$ evolution curves for 40% RAP HMA mixtures show that there is a difference in workability when the two different binder grades are used. It can be concluded that PG 58-28 binder has significantly more workability than PG 64-22 for 40% RAP HMA mixtures, since the difference in $\%G_{mm}$ at the number of gyration where PG 58-28 reaches the $92\%G_{mm}$ curve is more than the tolerance level of $0.5\%G_{mm}$.

Figure 5-3 shows the % G_{mm} evolution curves for 40% RAP Evotherm. The evolution curves for both the binder grades coincide, indicating that the workability is similar for the 40% RAP Evotherm mixtures for both binder grades. The same trend can be seen in Figure 5-4 which shows the evolution curves for 40% RAP Foamer mixtures. The evolution curves for 40% RAP Foamer mixtures also overlap and hence the workability with the two different binders is similar for 40% RAP Foamer mixtures.

The results from analysis of volumetric properties as well as the % G_{mm} Evolution curves suggest that there is not much difference in the workability and volumetric properties in the case of 40% RAP mixtures with Evotherm and Foamer when the binder grade is decreased from PG 64-22 to PG 58-28. But in the case of 40% RAP HMA mixtures, an improvement in workability and also better in range value of the volumetric properties are seen when the binder grade is changed to PG 58-28 from PG 64-22. Hence it is conclusive that a softer binder grade, PG 58-28 is required in the case of 40% RAP HMA mixtures, while the original PG 64-22 can be used for 40% RAP Evotherm and Foamer mixtures.

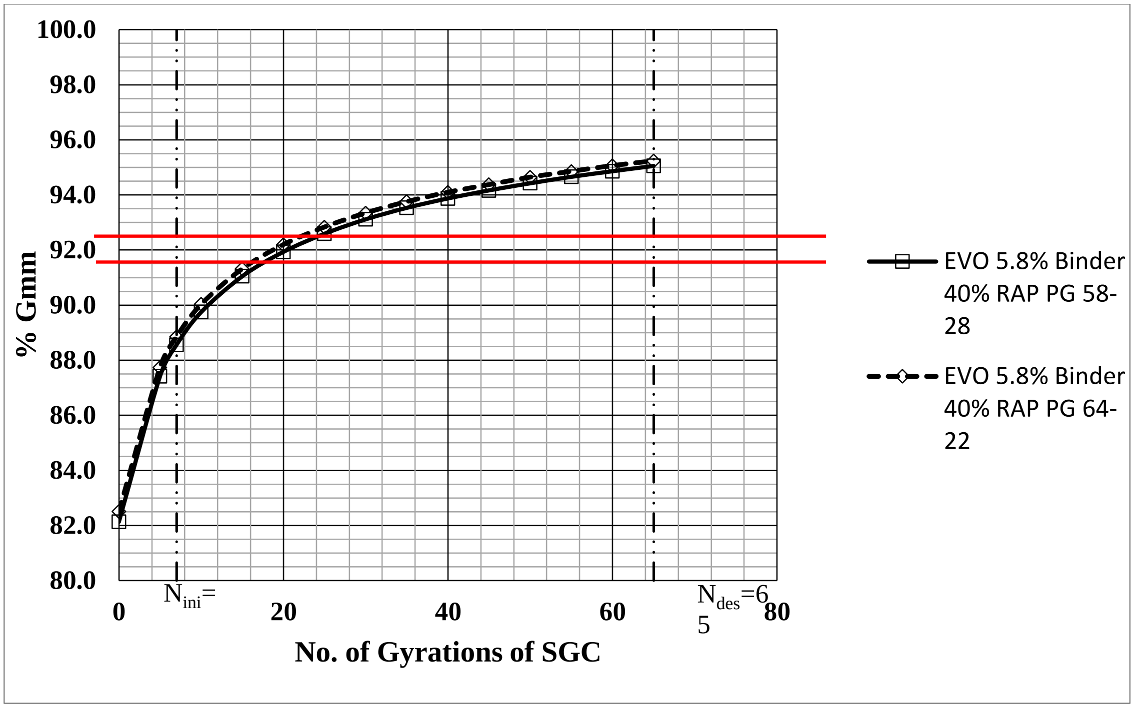

Figure 5-3% G_{mm} Evolution for 40% RAP Evotherm Mixtures with 5.8% Binder Content

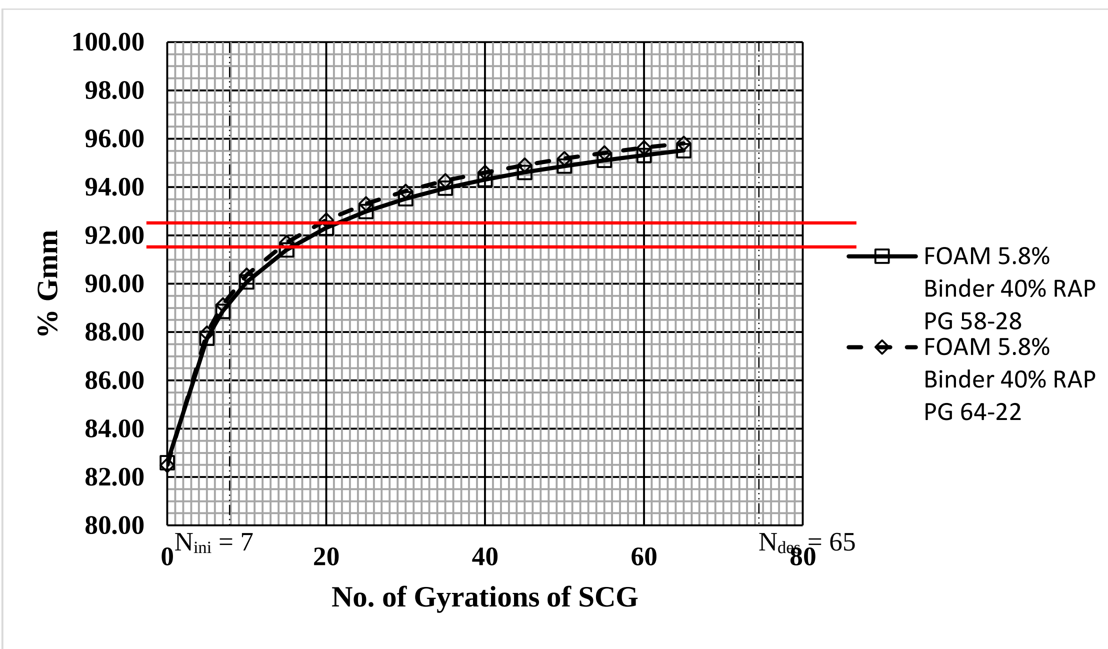

Figure 5-4 % G_{mm} Evolution for 40% RAP Foamer Mixtures with 5.8% Binder Content

A summary of all the air void contents of all the mixtures is given in Table 5-14.

Table 5-14 Summary of air void content of All Mixtures

Rap% Type	**0% PG 64-22** (6% Binder)	**20% PG 64-22** (5.9% Binder)	**40% PG 64-22** (5.8% Binder)	**40% PG 58-28** (5.8% Binder)
HMA	3.9	4.2	4.4	3.8
Evotherm	3.9	4.0	4.4	4.3
Foamer	3.9	4.1	3.9	4.1

6. EVALUATING WORKABILITY OF MIXTURES

This chapter is focused on evaluating the workability of the mixtures based on their $\%G_{mm}$ Evolution curves. The mixtures were categorized in two different ways to rank them on the basis of workability. They were categorized based on the RAP content, and also based on the mixture technology used. Table 6-1 explains the categories in which the mixtures were divided into to measure the workability.

Table 6-1 Matrix of the categories to evaluate workability of mixtures

Category Basis	**Categories**
RAP	0% RAP
	20% RAP
	40% RAP
Mixture Technology	HMA
	Evotherm
	Foamer

6.1 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.

6.2 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 6-1 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.

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. Figure 6-2 shows the %G_{mm} curves for 20% RAP mixtures.

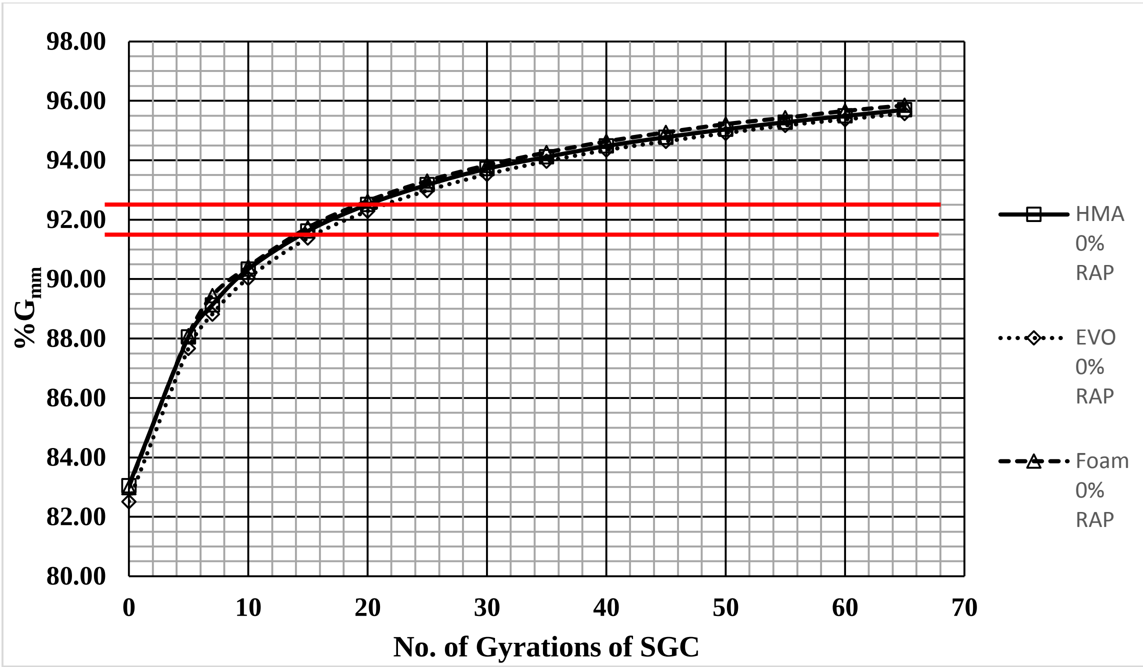

Figure 6-1 %G_{mm} curves for 0% RAP mixtures

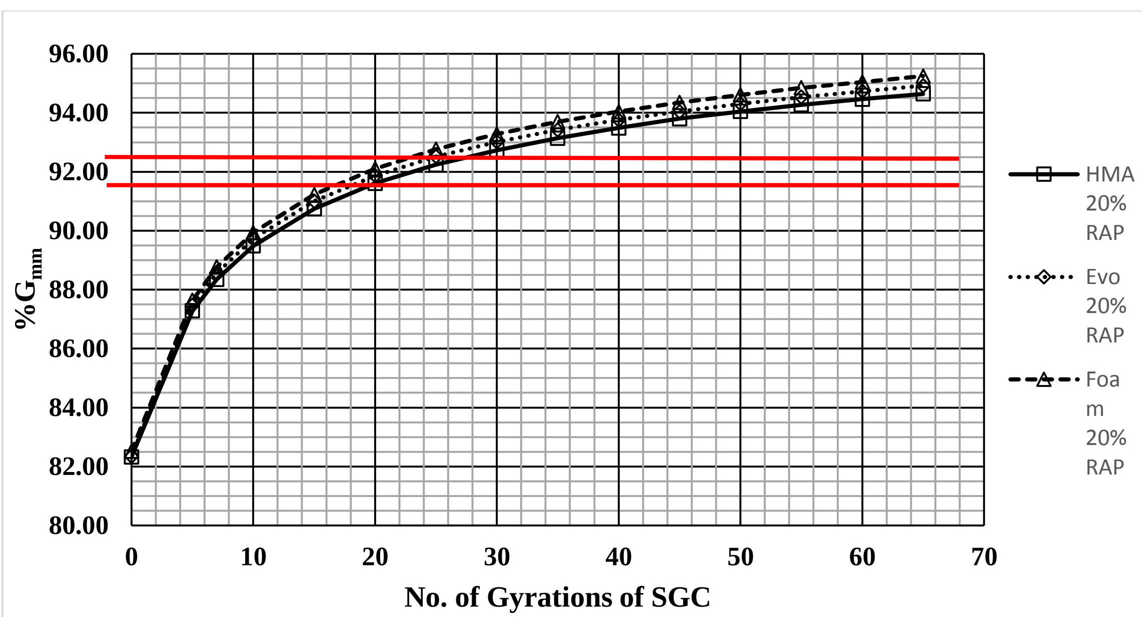

Figure 6-2 %G_{mm} curves for 20% RAP mixtures

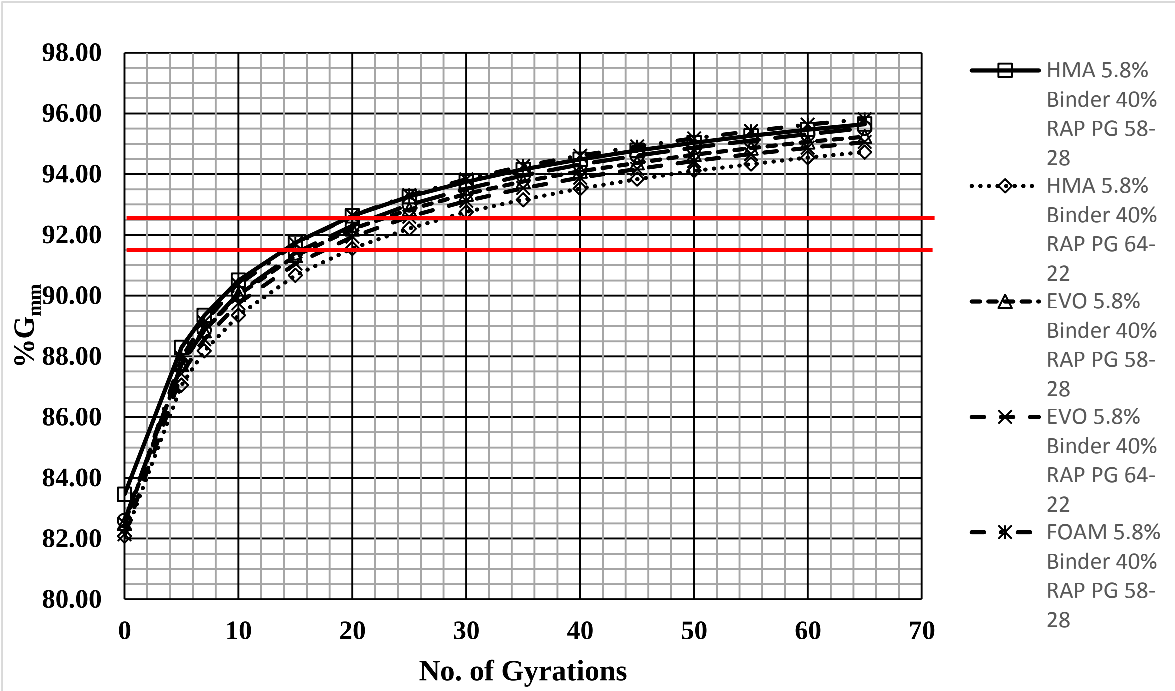

Figure 6-3 $\%G_{mm}$ curves for 40% RAP mixtures

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.

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.

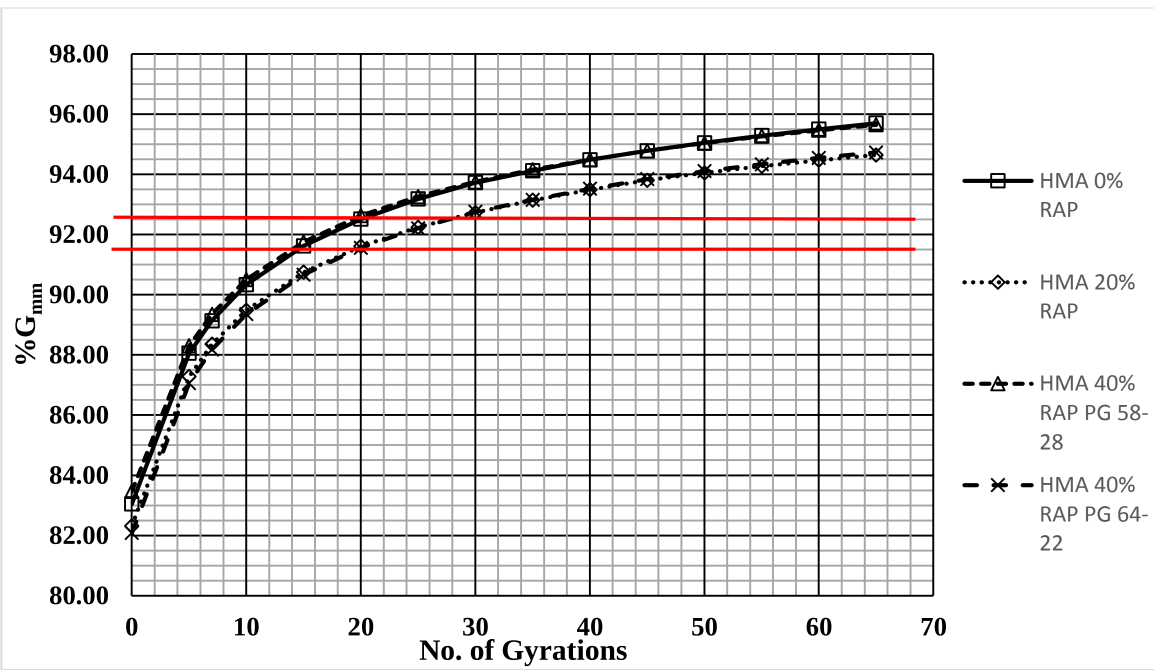

Figure 6-4 $\%G_{mm}$ curves for HMA mixtures

The %G_{mm} curves for all the Evotherm mixtures were in the acceptable range, when one of the mixture reached the 92% G_{mm} value. Hence 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. Thus 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.

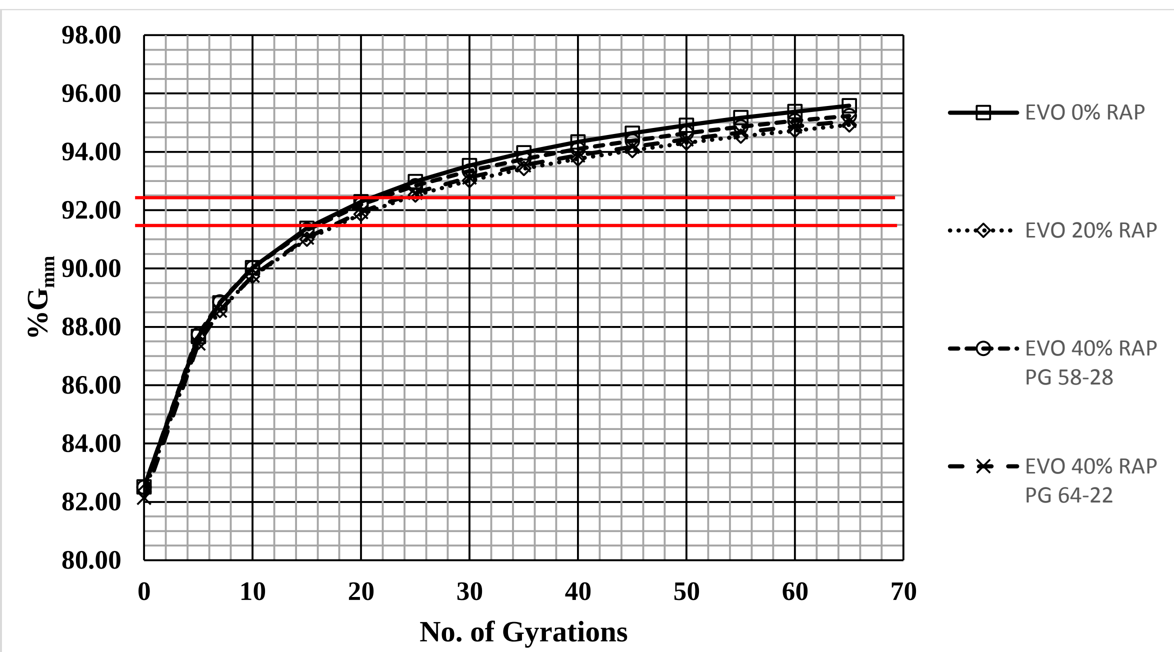

Figure 6-5 %G_{mm} curves for Evotherm mixtures

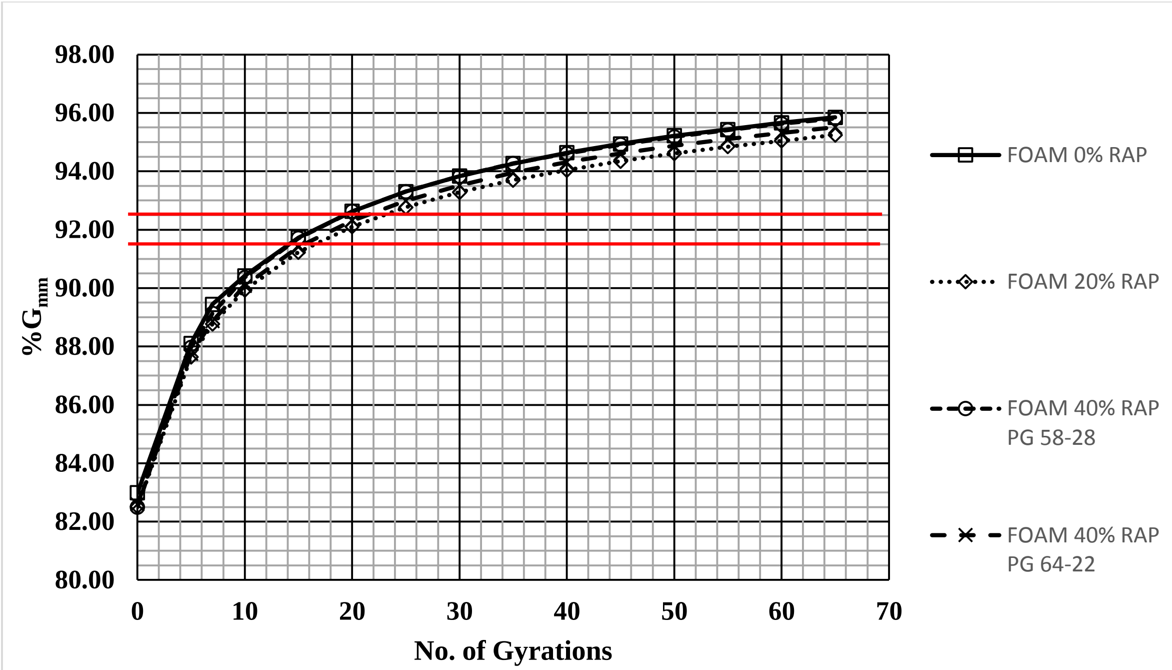

Figure 6-6 %G_{mm} curves for Foamer mixture

6.3 Conclusions

The Foamer and Evotherm mixtures at lower 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.

7. MOISTURE SUSCEPTIBILITY TESTS

This chapter 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.

7.1 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 mixes 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.

7.2 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%.

7.3 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.

$$ITS = \frac{2P}{\pi dh}$$

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.

7.3.1 Virgin Mixtures

Table 7-1 to 7-3 show the TSR test results for 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.

Table 7-1 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 7-2 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 7-3 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		

7.3.2 Mixtures with 20% RAP

Table 7-4 to 7-6 show the TSR test results for 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.

Table 7-4 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 7-5 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 7-6 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		

7.3.3 Mixtures with 40% RAP

Tables 7-7 to 7-9 show the TSR test results for 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.

Table 7-7 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 7-8 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 7-9 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		

7.4 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 every 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.

Table 7-10 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	1074	1059	101.4	PASS
EVO 0% RAP	796	849	93.8	PASS
FOAM 0% RAP	1022	1082	94.4	PASS
HMA 20% RAP	1292	1473	87.8	PASS
EVO 20% RAP	1345	1495	89.9	PASS
FOAM 20% RAP	1202	1375	87.4	PASS
HMA 40% RAP (PG 58-28)	1315	1458	90.2	PASS
EVO 40% RAP	1360	1593	85.4	PASS
FOAM 40% RAP	1503	2006	74.9	FAIL

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.

A graph representing the ITS values of all the mixtures together, to give an idea about the general trend of how the values are varying.

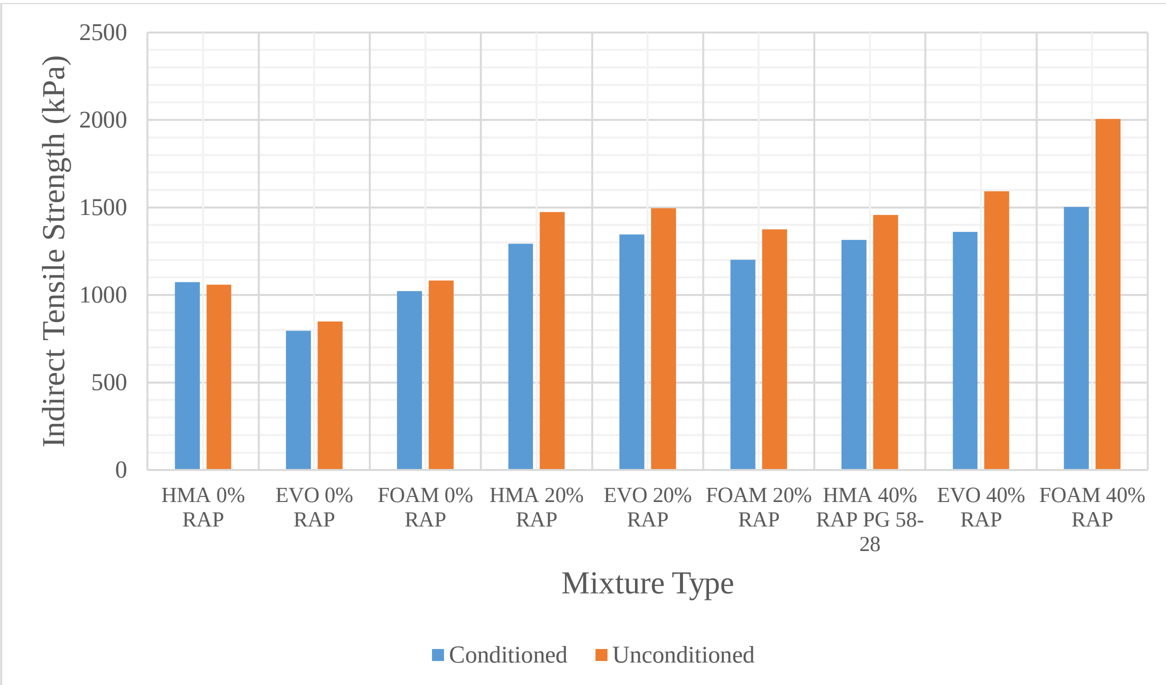

Figure 7-1 Graph representing the Dry and Wet ITS values of all the mixtures

8. Quantifying Evotherm 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 out 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 can be used to test the volatility of an additive in the mixture.

8.1 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.

8.2 Calibration Procedure

Calibration Procedure to determine antistrip additive content in asphalt mixes 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.

8.3 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. 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.

8.4 Results

The averaged color counts for the four different additive contents are presented in Table 8-1. 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 8-1 plots a graph between the additive content and count values while showing the calibration curve.

8.4.1 Calibration Results

The results from the calibration test for the Evotherm are expressed in Table 8-1. Figure 8-1 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 8-1 Calibration Test Results for Evotherm Additive

Additive	Count
0	437
0.25	458
0.5	531
1	616

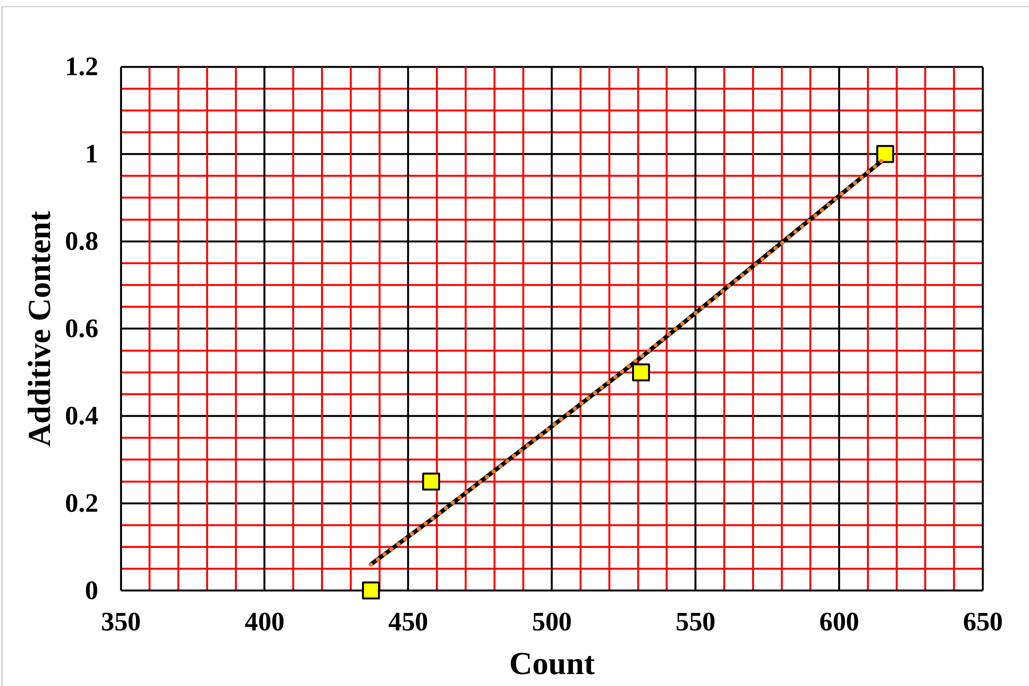

Figure 8-1 Graph between the additive content and count

8.4.2 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 –

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

8.5 Measurement Results

Table 8-2 shows the average count values for the mixes 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 8-2 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, 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 to 24 hours.

8.6 TSR Test Results for Evotherm Mixtures

To test the effectiveness of Evotherm as an anti-strip additive, TSR test was conducted on virgin mixtures by adding just Evotherm and not adding any additional anti-strip additive. The results of the TSR test with only Evotherm and no anti-strip additive are given in Table 8-3. The TSR ratio for mixtures with only Evotherm came out to be 88% which is still above the minimum required TSR value of 85% as specified by NCDOT.

Table 8-3 TSR Test Results for Mixtures with only Evotherm

<table>
<tr><th>Moisture Conditioning</th><th>Specimen #</th><th>air void content</th><th>ITS
(psi)</th><th>ITS (kPa)</th><th>Average
Subset
ITS (kPa)</th><th>TSR (%)</th></tr>
<tr><td rowspan="2">Dry</td><td>EVO 2</td><td>6.8</td><td>137.31</td><td>947</td><td rowspan="2">939</td><td rowspan="4">88</td></tr>
<tr><td>EVO 6</td><td>7.0</td><td>135.13</td><td>932</td></tr>
<tr><td rowspan="2">Wet</td><td>EVO 3</td><td>7.2</td><td>135.13</td><td>932</td><td rowspan="2">827</td></tr>
<tr><td>EVO 5</td><td>7.1</td><td>104.62</td><td>721</td></tr>
</table>

8.7 Conclusions

Volatility of Evotherm measured from the litmus paper test showed results similar to that of the volatility for LOF 6500 and Morlife 2200 anti-strip additives from a previous NCDOT study conducted on a different mixture [51]. TSR ratio for mixtures with LOF 6500 is more than mixtures with just Evotherm, and mixtures with Evotherm and LOF 6500. But mixtures with only Evotherm in them showed a TSR value of 88% which is more than the minimum requirement for NCDOT of 85%.

9. SUMMARY, CONCLUSION and RECOMMENDATIONS

9.1 Summary

This research study was aimed at evaluating the workability and moisture susceptibility of two WMA additives – Evotherm 3G and PTI Foamer with three varying RAP content – 0%, 20% and 40% and compare them to the corresponding HMA mixtures. A job mix formula for NCDOT 9.5 B mixture was provided by the NCDOT. Tensile Strength Retention Ratio calculated by the Modified Lottman Test was used 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 Strip Scan Instrument and TSR test were done 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 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. Lowering the binder content had a significant effect only on HMA mixtures.

The volatility of Evotherm from litmus paper test was found to be similar to that of LOF 6500 and Morlife 2200 from a previous NCDOT study. Evotherm as an anti-strip additive was not as effective as LOF 6500 but it was effective enough for the virgin mixtures to satisfy the minimum TSR criteria of 85% for NCDOT.

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.

iii. TSR ratio values for the mixtures decreased as the amount of RAP in the mixture increased. This was violated in the case of 40% RAP – HMA mixture where a softer binder grade was used.

iv. The Indirect Tensile Strength (ITS) values increased with the increase in RAP content. This again was violated in the case of 40% RAP – HMA, where a softer binder grade was used. 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. In the Litmus Paper test, volatility of Evotherm was found to be similar to that of LOF 6500 and Morlife 2200 from a previous NCDOT study using different mixtures.

9.3 Recommendations for Further Studies

i. The effect of varying the amount of Evotherm in the mixture on workability and moisture susceptibility has to be studied. The litmus paper test can be used to find out the amount of additive that has to be added in places with long hauling distances such that there is the desired amount of additive when the mixture reaches the construction site.

ii. The litmus paper test can be used to compare the effectiveness of anti-strip agent LOF 6500 and Evotherm additive. In addition to the volatility of the additives, other properties like improvement in workability, as well as the ITS, and TSR values of the mixture due to an additive should also be used to compare different additives.

iii. Field correlation of the volatility of the additives measured in the lab should be done.

iv. Correlation between field workability and laboratory measured parameters must be done for mixtures with RAP materials and WMA technologies.

v. The possibility of the use of higher RAP contents has to be investigated by either increasing the dosage of the Evotherm additive, or by using different WMA technology, and or by reducing the asphalt binder grade.

vi. Other tests should be used to evaluate the moisture susceptibility of the mixtures. Most notably the Dynamic Modulus (E*) test can be used to evaluate the moisture susceptibility of the mixtures. And the results from this test can be used to predict long term performance of the mixtures.

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