ABSTRACT

AYYALA, DINESH. An Investigation of Warm Mix Asphalt Technology in Asphalt Concrete Mixtures. (Under the direction of Dr. N. Paul Khosla.)

The development of sustainable practices in highway construction in recent times have gained impetus with focus on changes in production and recycling of asphalt concrete as a paving material. Amongst such practices, the use of Warm Mix Asphalt (WMA) technology has been gaining importance as an alternative to conventional Hot Mix Asphalt (HMA) due to its many benefits which include lower energy costs, lesser emissions during mix production and construction, longer hauling distances and longer construction periods.

Several research activities have been conducted to study performance of WMA mixes produced using different kinds of technology. These studies are based on analysis of performance test results from both laboratory mixes and field-placed mixes. The results from these studies indicate that performance of WMA mixes is dependent on the materials and WMA technology used, in addition to several other parameters. In the absence of long-term performance data, it is therefore necessary to conduct a detailed analysis of different types of WMA technology with the use of locally available materials.

The research study presented here is based on performance analysis of WMA mixes in comparison with a control HMA mix typically used in asphalt concrete surface course construction in the state of North Carolina. Three types of WMA technology - Sasobit®, Advera® and Foamer device were used in this study. Testing was conducted to evaluate sensitivity of WMA mixes to moisture damage and permanent deformation, which are the two primary modes of distress associated with warm mix asphalt. Performance tests used to characterize the mixes were selected according to current practices and requirements of the North Carolina Department of Transportation.

Moisture damage characterization was performed using the AASHTO T-283 Tensile Strength Ratio (TSR) test. Rutting resistance was evaluated using the Asphalt Pavement Analyzer (APA) test, and the test was also conducted on saturated specimens subjected to a moisture-conditioning procedure similar to the TSR test to study whether moisture in the WMA mix resulted in increased rut depth. Dynamic modulus (E*) test was conducted on specimens compacted to 7 percent air voids and E* was measured in both wet and dry conditions to determine the E* Stiffness Ratio (ESR), which represents the loss of mix stiffness due to moisture conditioning. Dynamic modulus was also measured for all mixes at 4 percent air voids and the measured E* was used as input in the NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide (M-E PDG) to predict rutting and fatigue failure using a model pavement section. Predicted performance data from M-E PDG analysis was used to conduct a cost-benefit analysis for surface course construction. Information from performance testing and cost-benefit analysis was used to identify a suitable WMA technology that enables engineers at NCDOT to design economically-viable, well-performing WMA mixes.

An Investigation of Warm Mix Asphalt Technology in Asphalt Concrete Mixtures

by
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DEDICATION

To my family and friends, to my dad Late Mr. A. Srihari Rao whose dream I am proud to have fulfilled.

BIOGRAPHY

Dinesh Ayyala was born on June 10, 1985 in the town of Madras, India. He was brought up in Visakhapatnam, India where he completed his education till high school. In 2003, he joined the Bachelor of Technology program in Civil Engineering at the Indian Institute of Technology, Roorkee, India. After graduating from IIT Roorkee, he joined the Pennsylvania State University, University Park in 2007 and graduated with Master of Science in Civil Engineering in May 2009. Dinesh joined the Doctor of Philosophy program at North Carolina State University in August 2010, and received his Ph.D. degree in Civil Engineering in August 2014.

Dinesh's research interests include bituminous pavement design and performance testing of asphaltic materials, mechanistic pavement design methods and sustainable asphalt pavement construction.

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Chapter 1

Introduction

Road transportation has always been an important component of global economic growth. Highways have therefore been a valuable infrastructural asset with extensive research being conducted to improve their design, construction and maintenance. Asphalt concrete is a material that is used in the construction of a majority of roads all over the world. Asphalt is a by-product obtained from fractional distillation of petroleum, which is one of the two primary constituents of asphalt concrete. The cost of asphalt used in paving is increasing everyday in conjunction with the rise in crude oil prices. With increased focus on sustainability and to reduce capital and maintenance costs, several alternatives such as recycling, emulsions and warm mix are being thoroughly investigated.

Asphalt concrete can be briefly described as a paving material produced by mixing asphalt binder and aggregates that have been heated to a high temperature. Production costs include those required to heat both the asphalt binder and aggregate to mixing temperature, as well as maintain the mixture at a specified temperature such that it can be compacted in the field. Traditionally, mixing is conducted at temperatures in excess of 150°C ($\sim$ 300°F) in order to reduce viscosity of the asphalt binder and facilitate proper coating of aggregates with the binder.

Warm mix asphalt (WMA) is a term that refers to different kinds of technology that can be used to lower the mixing and compaction temperatures of asphalt concrete [1].

WMA mixes are typically produced at temperatures at least 30°C ($\sim$ 50°F) lower than conventional hot mixes.

The economic and environmental benefits of using WMA as paving material are as follows [2]:

1. Lower Costs: Aggregate typically consist of more than 90% by weight of an asphalt concrete mix. Since aggregates used in warm mix are heated to a much lower temperature, the fuel cost involved in the heating process can be minimized.

2. Lower Emissions: Asphalt cement or asphalt binder consists of hydrocarbon compounds of various molecular weights, which typically have very high boiling points as asphalt itself is obtained as the last fraction during the fractional distillation process. Asphalt however does consist of volatile components (lighter fractions of crude oil) or low molecular weight hydrocarbons which are combustible at typical mixing temperatures. As the mixing temperature increases, more volatile components are subjected to combustion, resulting in greater quantities of hydrocarbon emissions. Warm mix technology lowers mixing and compaction temperatures, which in turn also reduce the quantity of harmful emissions during asphalt concrete production, resulting in cleaner construction.

3. Better Workability: Additives used in warm mix production affect asphalt-aggregate interaction and mix characteristics in many ways (which are described in detail in later sections), resulting in better workability both during mixing and compaction.

4. Improved Performance: Use of warm mix technology leads to better compaction of mix in the field, which in turn affects density of the mix. Mix density is an

important parameter which must be achieved for producing an acceptable mix as well satisfy quality control requirements, and also plays a very important role in the overall performance of the mix.

5. Safety: WMA leads to a more worker-friendly environment due to reduced emissions and lower temperatures used at the batch plant and during construction.

1.1 Classification of Warm Mix Asphalt Technology

Various technologies currently used to produce warm asphalt mixes can be broadly classified into the following categories based on how they modify the production of the mix [1]:

1. Foamed Asphalt - Water is sprayed into hot asphalt to produce asphalt foam which is much greater in volume than the asphalt liquid itself. The increased volume of binder allows effective coating of the aggregates at much lower temperatures than conventional hot mix asphalt. Astec Double Barrel Green and Foamer are two devices most commonly used to produce foamed asphalt in the United States.

2. Asphalt Foaming by Zeolite - Natural or synthetic zeolites are added to the binder to produce foamed asphalt during mixing. Aspha-Min (Aspha-Min GmbH, Germany) and Advera® (PQ Corporation, USA) are synthetic zeolites used in WMA production.

3. Bitumen Viscosity Modifiers - Organic additives are added to reduce viscosity of the asphalt at lower temperatures to enable mixing with aggregates. Sasobit® (Sasol Wax GmbH, Germany) and Licomont BS 100 (Clariant, Switzerland) are used as viscosity modifiers to produce WMA.

4. Chemical Additives - Evotherm (MeadWestvaco, USA) is the most commonly used chemical additive in the United States. The additive is added to the asphalt before mixing to reduce the binder viscosity.

A more comprehensive list of various WMA technology used all over the world is provided in the literature review in Chapter 2.

1.2 Problem Statement

Use of WMA technology is a relatively new practice in the United States, with the first field trials conducted in 2004 [4]. Several research studies have been conducted on laboratory performance of WMA mixes, and there have also been field studies conducted by state highway agencies and the National Center for Asphalt Technology ([3], [5], [6], [7], [8]). However, there is very little information available on the long-term performance data from actual pavements constructed using WMA. Amongst various pavement distresses, susceptibility of the mix to moisture damage and permanent deformation (or rutting) are two prominent distresses which have been identified as problem areas with respect to mix performance.

The physical mechanisms leading to moisture damage and rutting can be explained on the basis of temperature effects on aggregates and asphalt binder [11]. Aggregates are heated to lower temperatures in WMA production, which lead to insufficient drying of the aggregate particles. Some WMA technology such as foaming devices and zeolites also induce moisture during the mixing process. The retention or induction of moisture on the aggregate surface prevents proper adhesion of asphalt binder to the aggregate. This leads to a weaker asphalt-aggregate bond, thereby leading to moisture damage in the mix in the form of stripping. Therefore, anti-strip additives and mineral fillers such as hydrated lime are added to WMA to reduce moisture damage.

Heating of asphalt during the construction process increases its stiffness by means of two mechanisms - volatilization and oxidation, both of which are dependent on the temperature to which asphalt is subjected [11]. Since lower mixing and compaction temperatures are used in WMA, the asphalt binder achieves a lower stiffness than in hot mix asphalt production and subsequently lowers resistance of the mix to permanent deformation.

Performance of WMA is also dependent on the type of materials used. Therefore, it is important to evaluate mix performance using locally available material that is representative of construction material used in a geographical region. The research presented here is based on a laboratory study to evaluate performance of WMA mix containing materials typically used in asphalt concrete surface course construction in North Carolina. The North Carolina Department of Transportation specifies performance test criteria that must be satisfied by an asphalt concrete mix to be accepted for surface courses. It is therefore necessary to study the compatibility of WMA technology with local materials, as well as conformity of WMA mixes to performance criteria before the technology can be used to design mixes for actual field projects.

1.3 Research Methodology

Performance testing of WMA was conducted and test results were compared to a control HMA mix. The various tasks completed during the research activity are described in the flowchart shown in Figure 1.1. Three different warm mix technologies were selected for this research.

1. Sasobit® - Paraffin-wax additive, viscosity modifier

2. Advera® WMA - Manufactured zeolite, which produces micro-foam when mixed with asphalt. Advera® is manufactured in the United States, and has been successfully used in field projects [16]

3. Foamer device - Device used to produce foamed asphalt in the laboratory. The use of Foamer device was recommended by NCDOT as it produces asphalt foam which is very similar in properties to industrial-scale foaming devices

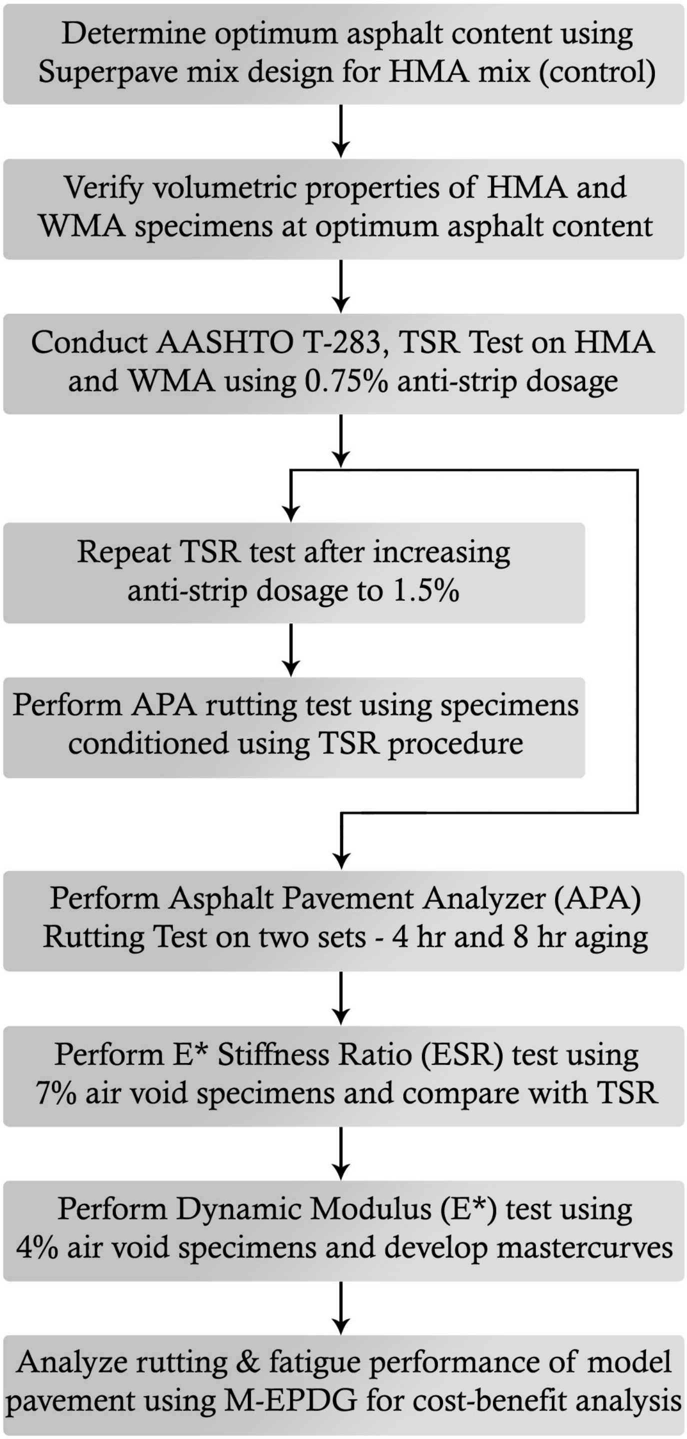

Figure 1.1: Flowchart - Research Methodology

Chapter 2

Literature Review

A review of research on warm mix asphalt and performance testing is presented in this chapter. The objective of this research activity is to congregate research findings on laboratory performance test results of warm mix asphalt produced using different technologies. The factors that impact the performance characteristics of warm mixes are:

- Warm mix technology used - polymer modified, foamed asphalt, zeolite (moisture-inducing additives) or chemical (organic) additives
- Extent of modification - quantity of additive/water used to produce WMA
- Mixing and compaction temperatures - how does lowering the temperature affects the mixture performance for a particular WMA technology
- Type of aggregates used - granite vs. limestone, effect of using anti-strip additives (liquid anti-strip additive vs. hydrated lime)
- Binder grades used - effect of warm mix modification on different PG binder grades
- Performance tests used - different laboratory tests used to evaluate performance of the warm mix, and significance of test procedure on distress quantification

The objective of this literature review is to provide an insight into different WMA technologies and how the factors mentioned above affect mixture performance with respect to rutting, fatigue and moisture susceptibility. Literature review of the history of warm mix asphalt, its inception and comments from early field and laboratory studies has been presented elsewhere [22] and is therefore not expanded in this thesis. Since the mixing and compaction temperatures for WMA are much lower ($\sim 50^{o}$F) than HMA, workability and compactability of the mix is a problem. The research findings from the NCHRP mix design project for WMA [11] show that aggregate coating and compactability (measured by the number of gyrations required to achieve a 92-percent relative density, or 8 percent total air voids in the specimen) is adequate up to temperatures approximately 54^{o}F lower than the planned field compaction temperatures for the WMA. Research studies [12] have shown that WMA produced using Evotherm and zeolite technology can be compacted at temperatures as low as 88^{o}C (190^{o}F). Sasobit, which is an extremely popular warm mix additive, however must be used in mixes at compaction temperatures greater than its melting point of 100^{o}C (212^{o}F) [14], below which the material reportedly crystallizes into a network structure with the binder.

The mixing and compaction temperatures for WMA mixes cannot be developed from viscosity-temperature relationships (results from Rotational Viscometer experiments, typically used for HMA) for most of the technologies due to binder modification [11]. Therefore, it is extremely important to rely on findings from research and recommendations of the WMA technology manufacturers to select the appropriate mixing and compaction temperatures, as well as quantity of WMA additives for a given set of materials.

As stated above, there are various parameters that affect the properties and thereby performance of warm mixes produced using a particular technology. Asphalt pavement construction typically involves use of locally available materials (aggregates), asphalt binder specified for a particular geographical location and traffic level, preferred type of anti-strip additive to reduce moisture susceptibility, in addition to the performance tests prescribed by the state highway agencies (SHAs). Several research projects are being currently undertaken to evaluate performance of WMA produced using various technologies with respect to two primary modes of failure - moisture damage and rutting. Test procedures implemented to quantify mixture performance are selected based on the practices of the SHAs, which seek a better understanding of WMA performance before implementation in actual highway construction.

2.1 Effect of WMA Technology on Mix Performance

The performance of WMA mixtures is dependent on the factors affecting its production, the most important of which is the technology used to produce it. Therefore, the findings from research studies are organized according to WMA technology in the following sections.

2.2 Warm Mix Asphalt Using Sasobit

Sasobit is one of the most widely used warm mix additives, which is used to reduce binder viscosity to enable mixing with aggregates at lower temperatures. Sasobit is available commercially in the form of tiny pellets as shown in Figure 2.1. Sasobit decreases viscosity of the binder at temperatures above its recrystallization temperature (about 100°C) by altering the colloidal structure of the asphalt binder [13]. Results of surface analysis and spectroscopy studies conducted by [13] showed that Sasobit weakened the intermolecular forces between resin and asphaltene components of the asphalt, which leads to reduced viscosity.

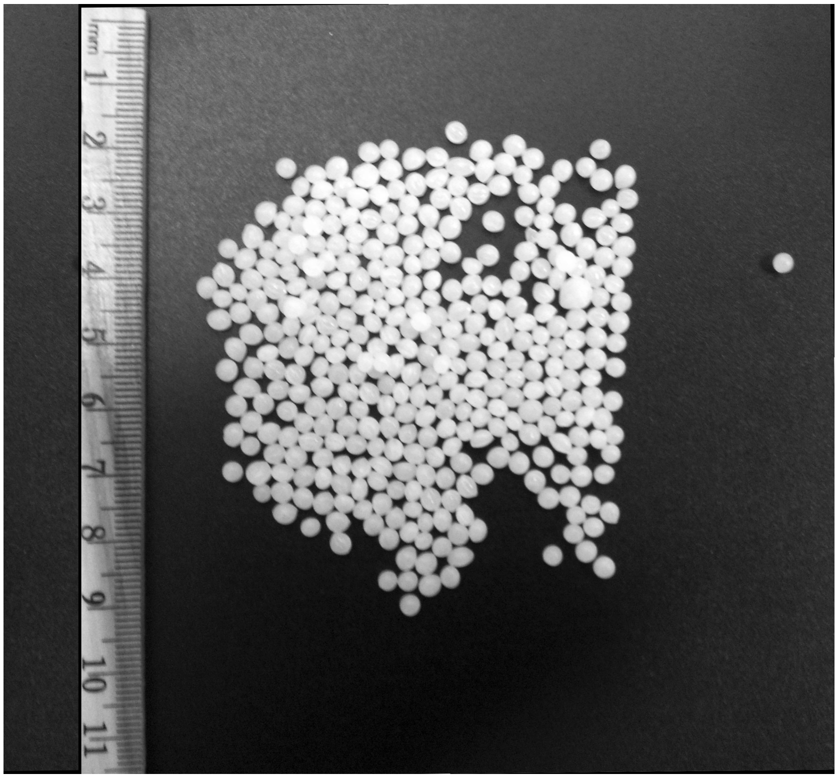

Figure 2.1: Sasobit® Sample

WMA using Sasobit was produced at various mixing and compaction temperatures and performance testing of the mixtures was done using various tests as shown below in Table 2.1. In studies where more than one mixing/compaction temperature was used, each compaction temperature corresponds to the mixing temperature specified to the left of the value.

2.2.1 Effect of Production Parameters on Rutting & Moisture Susceptibility of Sasobit WMA

WMA mixes containing Sasobit were found to resist rutting well due to the structural stability provided by Sasobit to the binder at pavement service temperatures. The test results from various moisture sensitivity and rutting performance tests are shown below in Table 2.2. The Tensile Strength Ratio (TSR) test results are shown as a percentage of the indirect tensile strength retained after moisture conditioning of the warm mix asphalt specimens, whereas APA test results indicate the observed average rut depth in specimens, measured in millimeters. Hamburg wheel tracking tests to measure rutting potential considers a mixture to pass the test if it requires more than 20,000 cycles to pass the stripping inflection point [16]. The results from HWTD indicate the rutting rate in millimeters per hour (mm/hr), unless otherwise stated. E* Stiffness ratio test results indicate the ratio of the stiffness (dynamic modulus, E*) of moisture-conditioned specimens to that of the dry specimens.

Table 2.1: Sasobit WMA Production Parameters Used in Laboratory Studies

Study Conducted By	Mixing Temp (^0F)	Comp. Temp (^0F)	Anti-Strip Additives	Aggregate Type	Binder PG Grade	Quantity (% by wt. of binder)
NCAT [12]	300	265 230 190	Magnabond (0.4%)	Granite, Limestone	64 - 22	1.5
Mass. & Texas DOT [16]	315 285 255	295 265 235	Ad-Here XL9000, Hydrated Lime	Crushed Stone	64 - 22	1.5
NDOR [17]	275	255	None	Limestone, Gravel & Millings	64 - 28	1.5

The performance test results for Sasobit WMA show that the mixes perform well with respect to rutting at intermediate compaction temperatures (265°F). Moisture sensitivity of the mixes is also reduced at this compaction temperature as observed from the Hamburg Wheel Tracking Test [12] and Tensile Strength Ratio ([12], [16], [17]). It is an interesting observation for Sasobit WMA that the tensile strength ratio is highly improved in the presence of an anti-strip additive [12]. The reports and articles reviewed so far have all reported the use of 1.5% Sasobit added by weight of the asphalt binder, as recommended by the manufacturer.

Table 2.2: Rutting and Moisture Sensitivity Test Results for Sasobit WMA

Study	WMA Production Parameters			Test Results
[12] NCAT Hamburg Wheel Tracking Device	Granite	No anti-strip		2.961 mm/hr
	Granite	0.4% Magnabond		0.164 mm/hr
	Limestone	No anti-strip		3.976 mm/hr
NCAT APA Rutting [12]	Granite	Compaction Temperature (°F)	300	4.8 mm
			265	7.7 mm
			230	9.4 mm
	Limestone	Compaction Temperature (°F)	300	10.1 mm
			230	6.5 mm
			230	7.1 mm
NCAT AASHTO T-283	Granite	No anti-strip		68%
	Granite	0.4% Magnabond		94%
	Limestone	No anti-strip		91%
MA & TX DOT Hamburg Wheel Tracking Device [16]	2-hr oven aging	No anti-strip	Sasobit WMA passed 20,000 cycles to SIP at 295°F and 8-hr aging time	
	4-hr oven aging	Hydrated Lime		
	8-hr oven aging	Ad-Here XL9000		
MA & TX DOT E* Stiffness Ratio (ESR) [16]	4-hr oven aging	Compaction Temperature (°F)	265	82%
	8-hr oven aging		265	93%
	4-hr oven aging		235	89%
	8-hr oven aging		235	89%
Nebraska DOR AASHTO T-283 [17]	Limestone			77%

2.3 Warm Mix Asphalt Using Zeolite Additives

Natural zeolites and synthetic zeolites (Advera®) are added to the asphalt binder to produce foamed asphalt which is used in WMA production. Advera® is a synthetic zeolite manufactured by PQ Corporation, USA [10]. It is available in the form of fine powder as shown in Figure 2.2. Advera®, like most other zeolites contains 18 to 22% water by weight, which is released at high temperatures. It is added directly to the hot asphalt binder which causes release of water from the zeolite molecule, thus causing micro-foam bubbles inside the binder. This increased volume helps the binder to evenly coat the aggregate particles during mixing.

Figure 2.2: Advera® Sample

WMA using zeolites was produced at various mixing and compaction temperatures in the research studies as shown below in Table 2.3.

Table 2.3: Zeolite WMA Production Parameters Used in Laboratory Studies

Study Conducted By	Mixing Temp (^0F)	Comp. Temp (^0F)	Anti-Strip Additives	Aggregate Type	Binder PG Grade	Quantity (% by wt. of mix)
Vaitkus et al. [18]		248	None	Dolomite	AC 16 PD	0.1 to 0.6% (wt. of binder)
NCAT Natural Zeolite [12]	300	265 230 190	1.0% & 1.5% Hydrated Lime	Granite, Limestone	64 - 22	0.25
MA & TX DOT Advera® [16]	315 285 255	295 265 235	Ad-Here XL9000, Hydrated Lime	Crushed Stone	64 - 22	0.25
NDOR Advera® [17]	275	255	None	Limestone, Gravel & Millings	64 - 28	0.25

2.3.1 Effect of Production Parameters on Rutting & Moisture Susceptibility of Zeolite-Based WMA

WMA mixes containing zeolites were found to exhibit a high degree of variability in the results of different performance tests. Results from various moisture sensitivity and rutting performance tests are shown below in Table 2.4. Marshall stability test was used to assess performance by [18], hence the values reported indicate the mix stability in kN.

Table 2.4: Rutting and Moisture Sensitivity Test Results for Zeolite-based WMA

Study	WMA Production Parameters			Test Results
Vaitkus et al. Marshall Stability (kN) [18]	Natural Zeolite Aspha-Min		Stability remains relatively constant up to 0.2% by wt. of binder, increases at higher dosages	
NCAT Hamburg Wheel Tracking Device [12]	Granite	No anti-strip		5.139 mm/hr
	Granite	1.5% Hyd. Lime		1.912 mm/hr
	Granite	1.5% Dry. Lime		0.687 mm/hr
	Limestone	No anti-strip		2.835 mm/hr
NCAT APA Rutting Test [12]	Granite	Compaction Temperature (°F)	300	11.2 mm
			265	15.1 mm
			230	12.9 mm
	Limestone	Compaction Temperature (°F)	300	4.8 mm
			230	7.7 mm
			230	9.0 mm
NCAT AASHTO T-283 [12]	Granite	No anti-strip		81%
	Limestone	No anti-strip		51%
	Granite	0.75% LOF 6500		38%
	Granite	1% Lime		77%
	Granite	1.5% Hyd. Lime		87%
	Granite	1.5% Dry Lime		75%
MA & TX DOT Hamburg Wheel Tracking Device [16]	2-hr oven aging	No anti-strip	Advera® WMA passed 20,000 cycles to SIP at 295°F and 8-hr aging time with use of hydrated lime	
	4-hr oven aging	Hydrated Lime		
	8-hr oven aging	Ad-Here XL9000		
MA & TX DOT E* Stiffness Ratio (ESR) [16]	4-hr oven aging	Compaction Temperature (°F)	265	69%
	8-hr oven aging		265	65%
	4-hr oven aging		235	101%
	8-hr oven aging		235	94%
Nebraska DOR TSR Test [17]	Limestone			74%

Various zeolite additives have been used in research to study the performance of WMA. The minimum required quantity of additive is observed to be 0.2% by weight of mix. WMA produced using zeolites exhibit better resistance to moisture damage when granite aggregates are used. This is further improved with the use of hydrated lime as an additive as opposed to a liquid anti-strip additive. Rutting in the mix increases with a decrease in the compaction temperature, which is apparent due to reduction in the mix stiffness. There is also no effect of short-term oven aging on moisture susceptibility, which implies that residual moisture is not a severe problem after compaction in the field.

2.4 Warm Mix Asphalt Using Chemical Additives

Various chemical additives used in WMA production include Evotherm, Iterlow T, Cecabase, etc. WMA using chemical additives was produced at various mixing and compaction temperatures and the mix parameters as shown below in Table 2.5.

2.4.1 Effect of Production Parameters on Rutting & Moisture Susceptibility of Chemical Additives-Based WMA

Performance test results for warm mixes produced using chemical additives are shown below in Table 2.6. Marshall stability test was used to assess mixture performance by [18], hence the values reported indicate the mix stability in kN.

Evotherm was the most preferentially used chemical additive in various research studies conducted on WMA. From the results tabulated above, it is observed that the mixes exhibit good rutting and moisture resistance at compaction temperatures greater than 265°F. Therefore, a minimum compaction temperature needs to be determined after analyzing the performance test results, along with emphasis on test criteria established for the specific state highway agency. Since the results do not show any trend between the observed performance and type of aggregate used, it is important to determine the mixture performance for locally available materials.

Table 2.5: Chemical Additive WMA Production Parameters Used in Laboratory Studies

Study Conducted By	Mixing Temp (^0F)	Comp. Temp (^0F)	Anti-Strip Additives	Aggregate Type	Binder PG Grade	Quantity (% by wt. of mix)
Vaitkus et al. - Iterlow T, Cecabase [18]		248	None	Dolomite	AC 16 PD	0.1 to 0.6% (wt. of binder)
NCAT Evotherm [12]	300	265 230 190	1.0% & 1.5% Hydrated Lime	Granite, Limestone	64 - 22	0.5
MA & TX DOT Evotherm [16]	315 285 255	295 265 235	Ad-Here XL9000, Hydrated Lime	Crushed Stone	64 - 22	0.5
NDOR Evotherm [17]	275	255	None	Limestone, Gravel & Millings	64 - 28	0.5

Table 2.6: Rutting and Moisture Sensitivity Test Results for Chemical Additive WMA

Study	WMA Production Parameters			Test Results
Vaitkus et al. Marshall Stability (kN) [18]	Iterlow T Cecabase		Stability increases at dosages greater than 0.1% by wt. of mix	
NCAT Hamburg Wheel Tracking Device	Granite Limestone	No anti-strip No anti-strip		1.708 mm/hr 3.178 mm/hr
NCAT APA Rutting Test [12]	Granite	Compaction Temperature (°F)	300 265 230	7.5 mm 7.4 mm 12.9 mm
	Limestone	Compaction Temperature (°F)	300 230 230	4.1 mm 6.6 mm 10.3 mm
NCAT AASHTO T-283	Granite Limestone	No anti-strip No anti-strip		96% 62%
MA & TX DOT Hamburg Wheel Tracking Device	2-hr oven aging 4-hr oven aging 8-hr oven aging	No anti-strip Hydrated Lime Ad-Here XL9000	Evotherm WMA passed 20,000 cycles to SIP only at 295°F and 8-hr aging	
MA & TX DOT E* Stiffness Ratio (ESR) [16]	4-hr oven aging 8-hr oven aging 4-hr oven aging 8-hr oven aging	Compaction Temperature (°F)	265 265 235 235	72% 75% 89% 88%
Nebraska DOR AASHTO T-283 [17]	Limestone			70%

2.5 Warm Mix Asphalt Using Asphalt Foaming Technology

Warm mix asphalt is also produced with the help of asphalt foaming devices, of which Astec Double Barrel Green and The Foamer are widely used in the United States. In this study, asphalt foaming was achieved through the use of the Foamer device. The Foamer shown in Figure 2.3 is manufactured by Pavement Technology Inc., USA and is a laboratory-scale foaming device capable of producing limited quantities of asphalt foam.

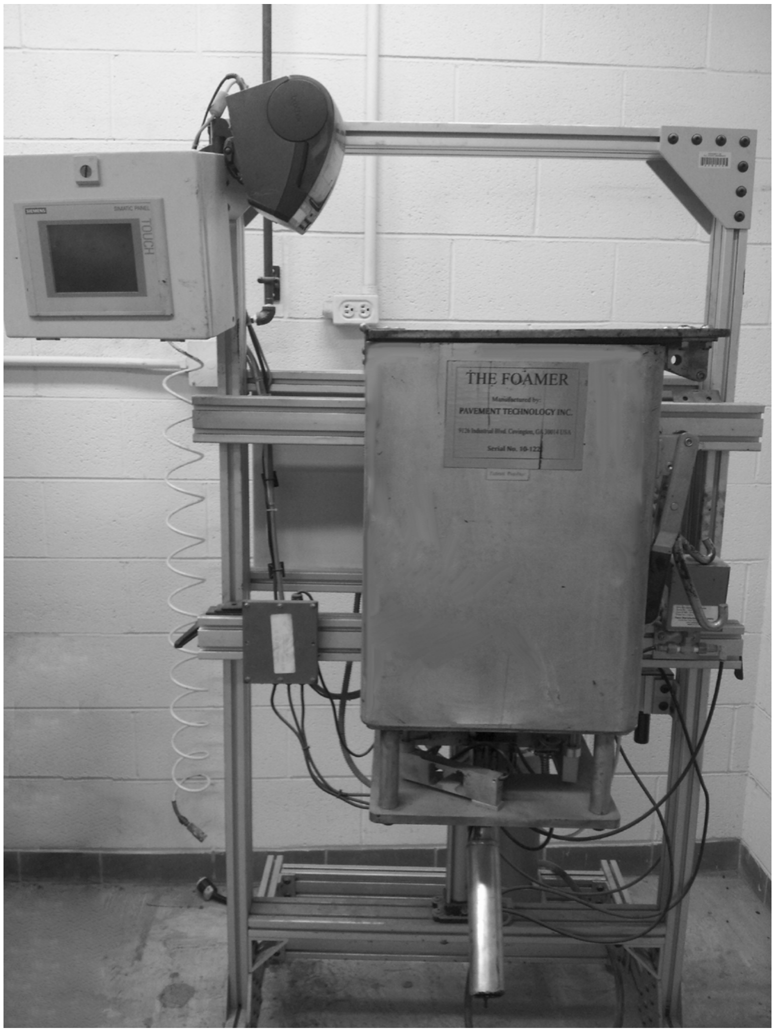

Figure 2.3: The Foamer device

A detailed description of the Foamer device and its features are presented elsewhere [22] and are therefore not presented in this thesis. The tests conducted on laboratory warm mixes produced using various foaming devices at different mixing and compaction temperatures, and the mix parameters as shown below in Table 2.7.

Table 2.7: Foamed Asphalt WMA Production Parameters Used in Laboratory Studies

Study Conducted By	Mixing Temp (^0F)	Comp. Temp (^0F)	Anti-Strip Additives	Aggregate Type	Binder PG Grade	Water content (% by wt. of binder)
ODOT - WLB10 [19]	290	263	None	Natural sand and gravel, Limestone	64-22 70-22	1.8% (Ohio DOT spec)
Kvasnak et al. - Gencor Green [20]	264	N.A.	None	Granite w/ 30% RAP	64-22	1.25%
Middleton et al. - Astec Double Barrel Green [21]	265 to 275	240	None	Unspecified 15% RAP, 15% RAP+ 5% MSM, 50% RAP	80/100A (64-22)	500 cc. water per ton of mix

WMA mixtures prepared using foamed asphalt binders were studied by [19]. The foaming process was performed on a device called the WLB10 (Wirtgen. Inc.,). Mixing and compaction temperatures for WMA were both lowered by 30°F as compared to HMA. Since this is a much smaller reduction than achieved in the other studies, insignificant change in moisture susceptibility was observed, and better workability with respect to compaction was observed for the warm asphalt mixtures.

2.5.1 Effect of Production Parameters on Rutting & Moisture Susceptibility of Foam-Based WMA

WMA mixes containing Sasobit® were found to resist rutting well due to the structural stability provided by Sasobit® to the binder at pavement service temperatures. The test results from various rutting performance tests are shown below in Table 2.8.

Table 2.8: Rutting and Moisture Sensitivity Test Results for Foam WMA

Study	WMA Production Parameters			Test Results
Ohio DOT AASHTO T-283 [19]	Natural Gravel	PG 64-22		85%
	Natural Gravel	PG 70-22		90%
	Limestone	PG 64-22		74%
	Limestone	PG 70-22		72%
APA Test	Natural Gravel	PG 64-22		15.5 mm
	Natural Gravel	PG 70-22		6.4 mm
	Limestone*	PG 64-22		7.6 mm
	Limestone*	PG 70-22		4.3 mm
Kvasnak et al. [20]	AASHTO T-283 Test			76%
	APA Rutting Test			6.1 mm
	Beam Fatigue Test (strain level used)		200 $\mu\epsilon$	7,000,000
			400 $\mu\epsilon$	100,000
Middleton et al. APA Test [21]	Rut depth Dry (Wet) Specimens	Virgin mix		4.8 (8.0) mm
		15% RAP		5.2 (5.2) mm
		15% RAP + 5% MSM		4.1 (7.1) mm
		50% RAP		4.1 (5.6) mm
Middleton et al. AASHTO T-283		Virgin mix		78%
		15% RAP		88%
		15% RAP + 5% MSM		73%
		50% RAP		96%

* Limestone mixes had finer gradation than natural gravel mixes, hence showed lower rutting

WMA is produced using foamed asphalt with the use of various devices, a few of which have been mentioned above. Foamed WMA is particularly tested for performance when recycled asphalt pavement (RAP) and shingles (RAS) are used. Based on the analysis of performance test results on foamed WMA, warm mixes containing RAP exhibit a higher tensile strength ratio (TSR) than virgin mixes. This is due to the stiffer binder contributed by RAP, which increases the force required to induce failure in the specimen. Though the TSR results vary with the PG binder grade used and type of aggregate, APA test results show that the mixes perform well with respect to rutting.

2.6 Summary of Findings from Literature Review

Based on the performance of Sasobit® WMA mixtures from rutting and moisture sensitivity tests, Sasobit® WMA exhibits better compatibility with limestone aggregates as compared to granite aggregates. There is also no effect of aging time on the moisture sensitivity due to the technology not imparting additional moisture to the mix, therefore the recommended WMA aging time of 2 hours [11] should be used. The use of anti-strip additive also decreases moisture damage in Sasobit® WMA, which is evident from the TSR values passing the 80% criterion required by most state highway agencies.

The moisture susceptibility tests on WMA produced using zeolites show that higher TSR values are obtained with granite aggregates as compared to limestone aggregates. There is also a significant improvement in the TSR with a two-stage addition of hydrated lime as an anti-stripping agent. WMA produced using zeolites also show much higher rutting when compared to Sasobit® mixtures when granite aggregates are used, and lower rutting when limestone aggregates are used.

Hydrated lime is a better anti-strip additive than liquid anti-strip with respect to improvement in moisture resistance of zeolite WMA. This is due to the low saturated tensile strength of specimens containing liquid anti-strip additives, which can be attributed to a reduction in binder viscosity. Aging time does not affect the stiffness of moisture-conditioned Advera® mix, therefore increasing its ESR at lower aging/compaction temperatures. The results from the study conducted by [18] showed that the Marshall stability of the mixes decreased up to 23% for different zeolites in comparison with HMA produced using the same asphalt. Flow number results did not show any significant variability among the different WMA mixes as well as HMA. It is observed that the manufacturer recommendation of 0.25% zeolite by weight of mix produces a warm mix that shows satisfactory performance.

WMA produced using Evotherm exhibits better moisture damage resistance and rutting performance with granite aggregates. Moisture susceptibility test results from literature show that WMA mixes containing limestone aggregate fail the TSR criterion of 80% without the use of an anti-strip additive. There is no significant difference between aggregate types from the rut test results of APA and Hamburg Wheel Tracking devices. Foaming technology is being commercially used to produce warm mix asphalt with the help of various devices. The water content typically used is 1.5 - 2% by weight of binder, which results in an optimum volume expansion of the asphalt. Several research studies have shown that laboratory rutting of the mixes are below the general failure criteria established, whereas moisture susceptibility tests show that foamed WMA mixes retain less than 80% of their dry tensile strength after conditioning. Therefore, greater emphasis needs to be placed on moisture testing of the mixes as compared to rutting.

Chapter 3

Materials Used and Properties

The materials used in this research and their properties are described in this chapter. Materials used for preparing asphalt concrete mixes in the laboratory included aggregates, asphalt binder and anti-strip additive. Details of warm-mix additives and Foamer device have been described in Chapter 2.

3.1 Aggregate Properties and Gradation

Virgin aggregates used in this study were granite aggregate from Martin-Marietta quarry in Garner, North Carolina. Three stockpiles were used to develop the final aggregate blend - #78-M coarse aggregate, dry screenings and manufactured sand. Baghouse fines were added at 1.5% by weight of the aggregate blend, and were added as a replacement of the fine fraction of dry screenings.

A job mix formula for a plant HMA mix based on aggregates from the same source, including recycled asphalt material was provided by NCDOT Materials & Tests Division. Since no recycled material was used in this study, the final blend gradation was developed using only the three virgin aggregate stockpiles. Aggregate gradation for each stockpile was determined using washed sieve analysis according to AASHTO.

Table 3.1 shows the laboratory-determined gradations for all three stockpiles, as well that provided in the JMF. The calculated gradations shown in this table represent the average of three samples on which washed sieve analysis was conducted. It can be observed that the two values differ greatly, and this difference increases as the sieve size becomes finer. This difference was due to the laboratory samples of aggregate used for sieve analysis not being representative of the stockpiles. Therefore, the blend gradation provided in the JMF was used as the design gradation. In order to achieve this gradation as well as reduce variability during specimen preparation, the aggregates were oven-dried and sieved into separate fractions. The aggregate batches required for specimens were prepared by blending individual sieve-size fractions according to percentages in the JMF.

Table 3.1: Aggregate Gradation

Sieve Size		% Passing - Sieve Analysis			% Passing - JMF		
U.S.	S.I.	78-M	Dry Scr.	Wet Scr.	78-M	Dry Scr.	Wet Scr.
$\frac{3}{4}$"	19.0 mm	100.0	100.0	100.0	100	100	100
$\frac{1}{2}$"	12.5 mm	100.0	100.0	100.0	100	100	100
$\frac{3}{8}$"	9.5 mm	95.0	100.0	100.0	93	100	100
#4	4.75 mm	36.3	100.0	100.0	41	99	100
#8	2.36 mm	6.4	87.1	85.3	7	87	82
#16	1.18 mm	3.0	66.1	62.9	2	65	55
#30	600 μm	1.8	49.6	43.5	1	48	38
#50	300 μm	1.5	36.6	25.3	1	32	23
#100	150 μm	1.2	25.0	9.9	1	19	9
#200	75 μm	0.7	16.5	3.4	0.4	10.6	2.6

3.2 Asphalt Binder

The asphalt binder used in this study is a performance grade asphalt PG 64-22 supplied by NuStar refinery in Wilmington, North Carolina. The asphalt PG binder grade was used in accordance with NCDOT specification for design of asphalt concrete mixtures for traffic level B, designed to handle a design traffic of 0.3 to 3 Million ESALs (NCDOT 2010 Standard Specifications for Roads and Structures, 2010, Table 610-4: *Superpave Applicable Virgin Asphalt Grades*). Asphalt binder specific gravity (G_b) used in this study was 1.034 as specified by the supplier.

3.3 Anti-Strip Additive

AdHere LOF-6500, a chemical anti-strip additive was used in this study at a rate of 0.75% by weight of asphalt binder as recommended by NCDOT. The anti-strip agent was added directly to the binder before mixing with the aggregates. For warm mixes that did not pass the NCDOT minimum criterion of 85% indirect tensile strength retained in the AASHTO T-283 Moisture Susceptibility Test, the anti-strip dosage was increased to 1.5% by weight of binder.

Chapter 4

Asphalt Concrete Mix Design

This chapter describes the asphalt concrete mix design for control HMA mix and verification of volumetrics and workability analysis for WMA mixes. The control HMA mix used in this study is an S9.5B mix, designated by the NCDOT as a 9.5 mm nominal maximum aggregate size mix for use in surface courses that handle traffic volume of 0.3 to 3 Million ESALs (Traffic level B, NCDOT 2010 Standard Specifications for Roads and Structures, 2010, Table 610-3: *Superpave Mix Design Criteria*).

4.1 Design Aggregate Structure

The design aggregate structure used for mix design is shown below in Table 4.1. Figure 4.1 shows the FHWA 0.45 power chart for the design gradation.

Aggregate specific gravities were measured according to AASHTO T 84-88, "Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate" and AASHTO T 85-88, "Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate". According to NCDOT specification, the coarse fraction of the aggregates was selected as that retained on the #4 (2.36 mm) sieve, and the fraction passing the #4 sieve was selected as fine fraction. The measured specific gravities of the coarse and fine fractions of aggregate were 2.620 and 2.638. From Table 4.1, the combined bulk specific gravity ($G_{sb,blend}$) of the blend for 24% coarse fraction and 76% fine fraction was calcu-

Table 4.1: Design Aggregate Structure - Gradation and Percent Passing Limits

Sieve Size		Percent Passing	Lower Limit	Upper Limit
U.S.	S.I.			
$\frac{3}{4}$"	19.0 mm	100		
$\frac{1}{2}$"	12.5 mm	100	100	
$\frac{3}{8}$"	9.5 mm	97	90	100
#4	4.75 mm	76	32	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	8

lated as 2.634. This value compares very well to that given in the JMF of 2.630, and the difference can be attributed to the presence of RAP in the JMF.

4.2 Mixing and Compaction Temperatures

Mixing and compaction temperatures for HMA were determined from rotational viscometer test on virgin binder and comparison of test results with those provided in the asphalt supplier specification sheet. Results of rotational viscometer tests on asphalt binder have been elaborated elsewhere [22], and are therefore not included. A mixing temperature of 163°C (325°F) and compaction temperature of 149°C (300°F) were used for HMA.

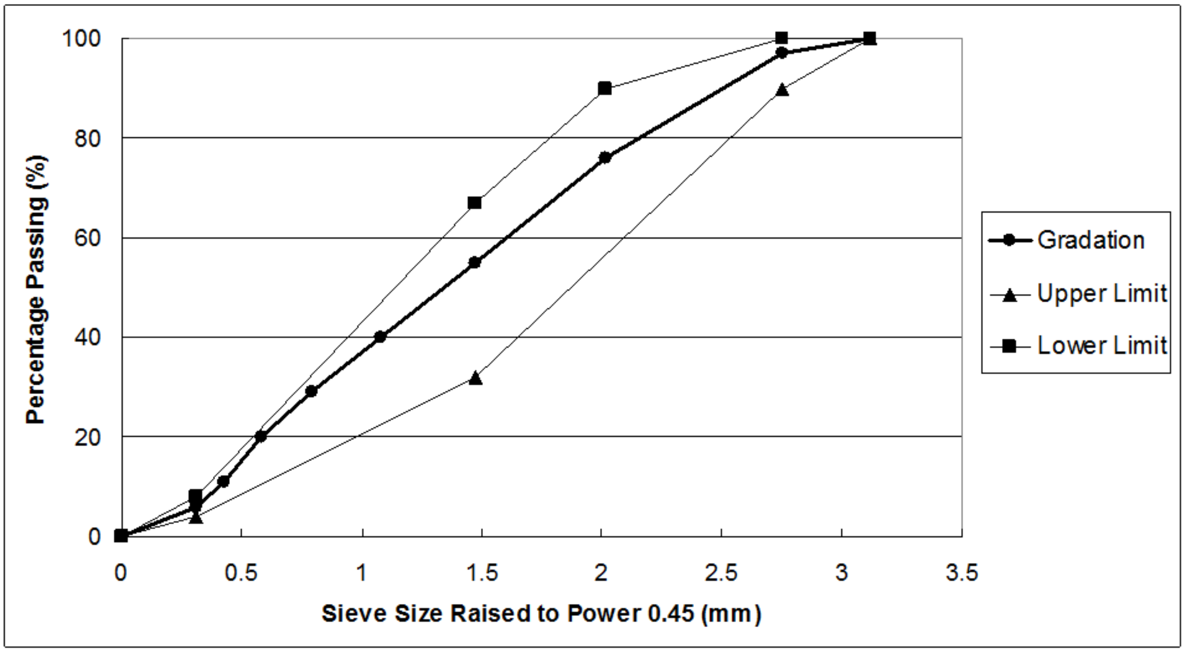

Figure 4.1: FHWA 0.45 Power Chart - Blend Aggregate Gradation

The mixing and compaction temperatures for WMA were determined from manufacturer recommendations and literature review. Rotational viscometer cannot be used to determine these temperatures for warm mixes as the conventional viscosity measurement method does not differentiate between neat and modified binders. The inability to determine production temperatures for WMA using the rotational viscometer was also reported in NCHRP's findings in their special report on mix design considerations for warm mix asphalt [11].

Sasobit® is completely soluble in asphalt at temperatures greater than 115°C (239°F) [9]. Advera® has been used to lower production temperatures by 50 - 70°F, and the typical production temperature used is 135°C (275°C) [10]. Therefore, based on manufacturer recommendations and temperatures reported in several published articles in literature, a mixing temperature of 135°C (275°F) and compaction temperature of 120°C (248°F) were selected for all three WMA mixes.

Table 4.2 shows a summary of mixing and compaction temperatures for HMA and WMA mixes used in this study.

Table 4.2: Mixing and Compaction Temperatures for HMA and WMA Mixes

Mix Type	Mixing Temp. (°C)	Compaction Temp. (°C)
Hot Mix Asphalt (Control)	163	149
Sasobit® WMA	136	120
Advera® WMA	136	120
Foamer WMA	136	120

4.3 Determination of Optimum Asphalt Content

The design asphalt content or optimum asphalt content (OAC) was determined for the control HMA mix using the selected aggregate structure and mixing and compaction temperatures. The mix design provided in the JMF reported a 5.7% OAC by weight of mix which included 20% RAP. Hence, specimens were compacted at three different asphalt contents - 5.2%, 5.7% and 6.2% in order to determine the optimum asphalt content. Two specimens were compacted for each of the three asphalt contents, and two loose mix samples were additionally prepared for measuring the theoretical maximum specific gravity, G_{mm} (rice specific gravity) of the mix. The HMA mix was conditioned for 2 hours ± 5 minutes at compaction temperature (149°C) for both compacted specimens as well as loose mix samples according to AASHTO R30, "Standard Practice for Conditioning of

Hot Mix Asphalt (HMA)".

Rice specific gravity test on loose mix samples was performed according to AASHTO T209-05, "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)". Specimens for measurement of mix volumetrics were compacted using the Superpave Gyratory Compactor to a design gyration level, N_{des} of 65 gyrations as per NCDOT specifications (NCDOT 2010 Standard Specifications for Roads and Structures, 2010, Table 610-3: *Superpave Mix Design Criteria*). The specimen heights were also recorded at an initial gyration level, N_{ini} of 7 gyrations. The bulk specific gravity of specimens, G_{mb} was measured according to the procedure outlined in AASHTO T 331, "Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method". Table 4.3 shows the calculated volumetric properties of HMA at the three asphalt contents.

From the volumetric plot of air voids versus asphalt content, the optimum asphalt content was calculated as 6.0% by weight of mix. The calculated OAC was also used as the design asphalt content for WMA mixes. This decision was based on NCHRP's recommendation for design of WMA mixes that asphalt content determined for a similar HMA mix need not be modified for WMA [11].

4.4 Verification of Mix Design

After determining the optimum asphalt content, specimens were prepared for verification of volumetric properties of both HMA and WMA mixes. Table 4.4 shows the summary of volumetric properties of all four mixes at OAC.

Table 4.3: HMA Mix Volumetric Properties - Selection of Design Asphalt Content

Volumetric Property of Mix			
% **Asphalt Binder - Total Mix**	**5.2**	**5.7**	**6.2**
G_{mb} @ N_{des}	2.296	2.323	2.34
Max. Specific Gravity, G_{mm}	2.457	2.437	2.419
% Voids - Total Mix (VTM)	6.6	4.7	3.3
% Solids - Total Mix	93.4	95.3	96.7
% Solids - By Vol of Agg. Only	82.6	83.2	83.4
% Voids in Mineral Agg. (VMA)	17.4	16.8	16.6
% Voids Filled w/ Binder (VFA)	62.3	72.2	80.3
% G_{mm} at N_{ini} (7)	87.3	88.9	90.5
% G_{mm} at N_{des} (65)	94	95.9	97.5

Details of laboratory density measurement data have been published elsewhere [22] and are therefore not presented here. The data shown in Table 4.4 indicates that Superpave volumetric criteria are satisfied by all four mixes, and that there is no need for modification of the optimum asphalt content for WMA.

Table 4.4: Verification of Volumetric Properties at Optimum Asphalt Content

Volumetric Property of Mix					
Mix Type	HMA	Sasobit®	Advera®	Foamer	Specification
% Asphalt Binder - Total Mix	6	6	6	6	
Bulk Specific Gravity, G_{mb} @ N_{des}	2.328	2.329	2.325	2.316	
Max. Specific Gravity, G_{mm}	2.432	2.427	2.432	2.417	
% Voids in Total Mix (Air Voids)	4.4	4	4.1	4.2	4.0 ± 0.5
% Solids - Total Mix	95.7	96	95.9	95.8	
% Solids - Volume of Agg. Only	83	83.5	83.7	83	
% Voids in Mineral Agg. (VMA)	17	16.5	16.3	17	$> 15.0\%$
% Voids filled w/ asphalt (VFA)	74.2	75.5	75	74.3	65 - 78%
% G_{mm} at N_{ini} (7 gyrations)	83.3	83.7	83.4	88.4	$< 89.0\%$
% G_{mm} at N_{des} (65 gyrations)	95.6	96	95.9	95.8	96%

4.5 Workability and Compactability

No difference was observed in workability and extent of coating of aggregate with asphalt binder during the mixing process for any of the WMA mixes as compared to the HMA mix. A bucket mixer was used for the mixing process and identical mixing time yielded similar coating of aggregate, irrespective of the weight of mix in the drum. No specific scientific measure of workability or extent of aggregate coating was included in the research methodology.

Mix compactability was measured using the change in %G_{mm} as a function of number of gyrations applied during the gyratory compaction process. Compactability was evaluated by measuring the number of gyrations to 92% relative density (or 8% air voids)

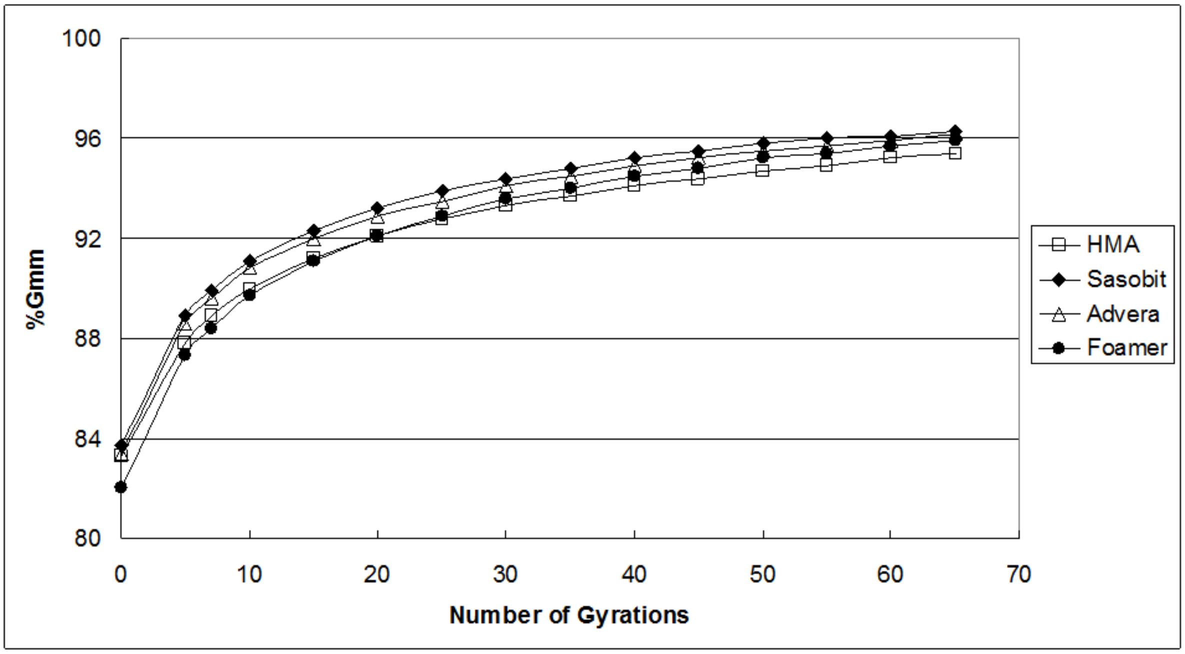

Figure 4.2: Increase in %G_{mm} versus Number of Gyrations

for the specimen (NCHRP WMA report), including sensitivity of mix compaction to temperature. Specimen heights at every 5 gyrations from beginning of the compaction process were recorded for all mix design verification specimens till the N_{des} value of 65 gyrations was reached, as shown in Table 4.5. Figure 4.2 shows increase in %G_{mm} with number of gyrations. The %G_{mm} plot shows that there is no significant difference in the rate of density increase for any of the WMA mixes.

Table 4.5: %G$_{mm}$ as a Function of Number of Gyrations - Compactability Study

No. of Gyrations	%G$_{mm}$ for HMA and WMA Mixes			
Mix Type	HMA	Sasobit®	Advera®	Foamer
0	83.3	83.7	83.4	82
5	87.8	88.9	88.6	87.3
7	88.9	89.9	89.6	88.4
10	90	91.1	90.8	89.7
15	91.2	92.3	92	91.1
20	92.1	93.2	92.9	92.1
25	92.8	93.9	93.5	92.9
30	93.3	94.4	94.1	93.6
35	93.7	94.8	94.5	94
40	94.1	95.2	94.9	94.5
45	94.4	95.5	95.2	94.8
50	94.7	95.8	95.5	95.2
55	94.9	96	95.7	95.4
60	95.2	96.1	95.9	95.7
65	95.4	96.3	96.2	95.9
Final Measured	95.6	96	95.9	95.8

Chapter 5

Moisture Sensitivity Tensile Strength Ratio Test

Moisture sensitivity of WMA was evaluated using the tensile strength ratio (TSR) test, performed according to NCDOT's modified AASHTO T283 procedure, "Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage". In this chapter, details of specimen preparation and conditioning, test results and analysis are presented.

5.1 Tensile Strength Ratio (TSR)

Tensile strength ratio for an asphalt concrete mix is the ratio of median indirect tensile strength of specimens tested in wet or moisture-conditioned state to the median indirect tensile strength of specimens tested in dry or unconditioned state. Specimens for the TSR test are divided into two subsets - dry subset and wet subset. TSR is calculated as shown in Equation (5.1).

$$\text{TSR} = \frac{\text{Median indirect tensile strength of wet subset}}{\text{Median indirect tensile strength of dry subset}} \tag{5.1}$$

Tensile strength of specimens was tested using the Marshall loading equipment. Load was applied on test specimens at a rate of 2 inches per minute using a calibrated hydraulic jack and load-displacement curves were plotted using a plotter.

5.2 Specimen Preparation and Test Procedure

Specimens for the TSR test were prepared according to the AASHTO T283 procedure. Test specimens were compacted to a height of 95 $\pm$ 5 mm and a target air void content of 7 $\pm$ 1% air voids. A minimum of eight specimens were prepared for each mix type - four specimens that satisfied the height and volumetric requirements were selected at random and assigned to the dry subset, and four specimens were tested as the wet subset. Anti-strip agent was added at 0.75% by weight of binder for all mixes. For mixes that did not meet the minimum TSR requirement of 85%,

After mixing, the loose mixes for all specimens were placed in mixing trays and air-cooled at room temperature for a period of 2 hours $\pm$ 5 minutes. The mixes were then placed in a forced air-draft oven at 60°C (140°F) for a period of 24 $\pm$ 0.5 hours in order to simulate long-term aging. Later, the mixes were transferred into another oven at compaction temperature (149°C for HMA and 120°C for WMA mixes) for 2 hours $\pm$ 5 minutes and then compacted using the Superpave gyratory compactor.

5.2.1 Moisture Conditioning Procedure

Moisture conditioning of specimens in the wet subset was conducted according to NC-DOT's modified AASHTO T283 procedure. Specimens were saturated to a moisture content of 70 - 80 percent by placing them in a water bath and applying a vacuum of 10 - 26 inches Hg for about two minutes, and those specimens which exceeded the saturation limit of 80% were discarded. After saturation, specimens were placed in a temperature-controlled water bath at 60°C for 24 $\pm$ 0.5 hours. The specimens were then removed from the 60°C bath and placed in another water bath at 25°C (77°F) for 2 hours ± 5 minutes. The wet-conditioned specimens were taken out of the 25°C water bath, surface-dried and tested for indirect tensile strength.

5.3 Test Results

Table 5.1 shows the summary of peak load, indirect tensile strength and tensile strength ratios for all four mixes. The dimensions, densities, volumetric properties and saturation data for all specimens, as well as statistical analysis of TSR test results have been described in detail elsewhere [22], and are therefore not presented here. Final TSR test results are shown for HMA mix containing 0.75% LOF (anti-strip agent) and 0.75% and 1.5% LOF for the three WMA mixes.

Table 5.1: Tensile Strength Ratio Test Results

Mix Type *	Dry Strength (kPa)	Wet Strength (kPa)	TSR Ratio (%)	Pass/Fail
HMA (0.75)	1037	909	87.7	Pass
Sasobit® (0)	811	233	28.7	Fail
Sasobit® (0.75)	851	827	97.2	Pass
Sasobit® (1.5)	798	812	101.8	Pass
Advera® (0.75)	858	477	55.6	Fail
Advera® (1.5)	760	484	63.7	Fail
Foamer (0.75)	888	700	78.8	Fail
Foamer (1.5)	887	721	81.4	Fail

* Numbers in parantheses indicate % LOF 6500 anti-strip additive dosage by weight of binder

5.4 Discussion

The calculated TSR value for HMA mix was 88% at 0.75% LOF content, which satisfied the minimum requirement of 85% according to NCDOT specification. Sasobit® mix exhibited a TSR of 97% at 0.75% LOF content, which also satisfied the minimum criterion. However, the indirect tensile strength of Sasobit® mix in both dry and wet conditions were lower than that of HMA.

TSR was also determined for the mix at 1.5% LOF by weight of binder to study the effect of increased anti-strip dosage on moisture damage reduction. The increased anti-strip dosage resulted in a higher TSR value of 102%. However, the average indirect tensile strength of both unconditioned and conditioned specimens at 1.5% LOF was lower than that at 0.75% LOF content. TSR test conducted on Sasobit specimens prepared without the use of anti-strip additive resulted in a very low TSR value of 28.7%. Therefore, use of recommended dosage of 0.75% anti-strip agent is sufficient for warm mix asphalt containing Sasobit®.

WMA containing Advera® exhibited a TSR value of 56% at 0.75% LOF content. The use of Advera® lowered the tensile strength of conditioned specimens by about 50%, which resulted in very low tensile strength ratio. Since the mix failed the TSR criterion of 85% at the recommended anti-strip dosage, additional testing was conducted at an increased dosage of 1.5%. Increasing anti-strip dosage to 1.5% increased the TSR to 64%, but still failed to satisfy the minimum criterion. The average conditioned specimen strength did not vary significantly, but the unconditioned specimen strength decreased which resulted in a higher TSR value.

Warm mix prepared using the Foamer device exhibited a TSR of 79% at 0.75% LOF, and the value increased to 81% when the LOF dosage was increased to 1.5%. The mix failed the minimum TSR criterion at both levels of anti-strip dosage. Test results showed that the increase in average indirect tensile strength of both unconditioned and conditioned specimens was statistically insignificant.

Chapter 6

Rutting Resistance

Asphalt Pavement Analyzer Test

Rutting resistance was evaluated using rut depth data from the Asphalt Pavement Analyzer (APA) test. Specimen preparation and testing of specimens was conducted according to AASHTO TP63-09, “Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)”. The APA device was selected as the method for evaluating rutting potential of mixes in accordance with NCDOT Superpave mix design criteria. In this chapter, preparation of specimens, test procedure and results of APA test are presented.

6.1 APA Test Procedure

The Asphalt Pavement Analyzer shown in Figure 6.1 is a loaded wheel tracker device manufactured by Pavement Technology Inc [23], capable of applying repeated wheel-load passes on a set of asphalt concrete specimens. The load is applied using a 100 psi hose and three sets of steel wheels that are placed directly over the specimens. The test is terminated after 8000 cycles (wheel passes) or when the rut depth measured exceeds a pre-determined maximum value. The maximum allowable rut depth for S9.5B mix used in this study is 9.5 mm (NCDOT 2010 Standard Specifications for Roads and Structures, 2010, Table 610-3: *Superpave Mix Design Criteria*).

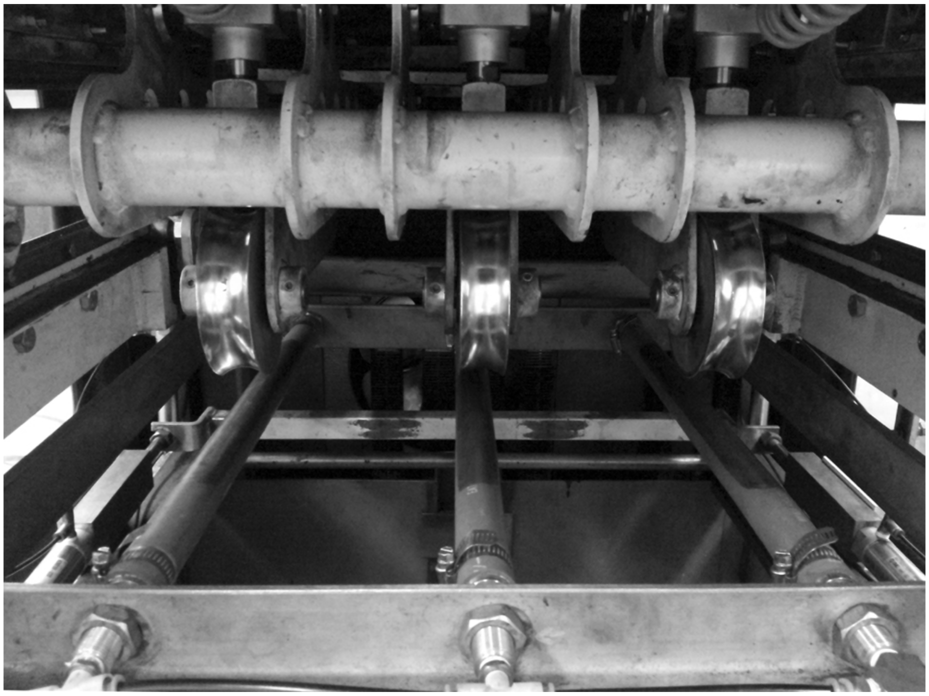

Figure 6.1: Asphalt Pavement Analyzer Device

The test is conducted at the high temperature PG grade of asphalt binder used in the specimens, which is 64°C as PG 64-22 binder was used in this study. Specimens are pre-heated at the test temperature for 5 hours, after which the test is conducted by applying wheel passes at a frequency of 60 cycles per minute. The rut depth in all three wheel paths is measured by means of sensors, and the data is collected by a computer connected to the APA device. Due to unavailability of test equipment at NC State University laboratory, specimens were prepared in the laboratory and delivered to the NCDOT Materials & Tests Division for testing.

6.2 Specimen Preparation

A set of six specimens are required for the APA test, which are placed in three sets of two specimens under each wheel as shown in Figure 6.2. Test specimens were compacted

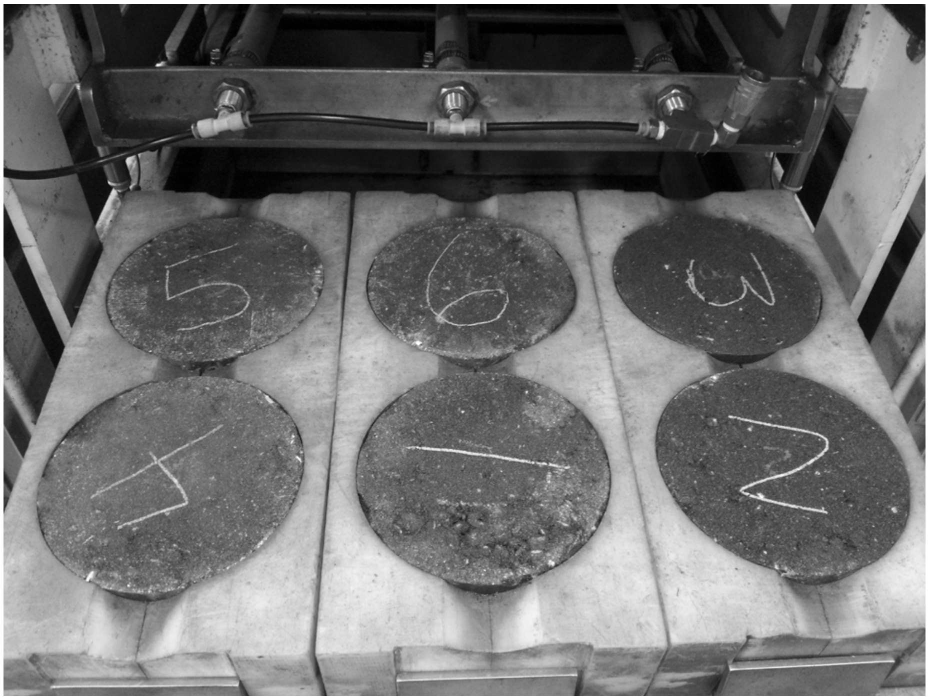

Figure 6.2: APA Rut Test Specimens

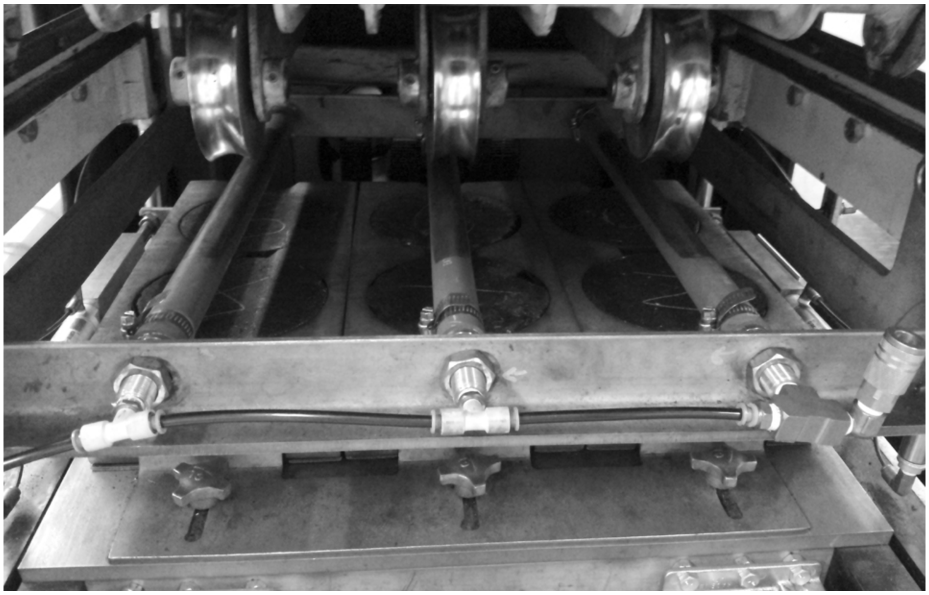

Figure 6.3: APA Rutting Test - Specimen Arrangement

to a height of 75 ± 2 mm and an air void content of 7 ± 0.5%. Details of specimen volumetrics have been mentioned elsewhere [22] and are therefore not described here. Figure 6.3 shows the final test setup in the APA device.

A total of twelve specimens were prepared for each mix type. For the HMA mix, mixes for all twelve specimens were subjected to short-term oven aging of 4 hours according to AASHTO R30, “Standard Practice for Conditioning of Hot Mix Asphalt (HMA)”. WMA mixes were subjected to two different aging times - one subset (Subset A) of six specimens was subjected to 4 hours of aging, and the second subset (Subset B) of six specimens was subjected to 8 hours of aging. The short-term oven aging time was increased for the second subset in order to study the increase in stiffness over time and subsequent increase in rutting resistance, particularly for mixes prepared using water-inducing WMA techniques (Advera® and Foamer mixes).

Eight sets of specimens were tested using the APA device, which are shown below in Table. The alphabetical codes represent the mix type, **H** for HMA specimens, **S** for Sasobit®, **A** for Advera® and **F** for Foamer specimens. The second letter represents the subset based on the mix aging time, as described above.

6.3 Results and Discussion

The rut depth data for all eight sets of specimens were recorded, and the average rut depth and standard deviations were calculated. Test results presented in this document are only the final results, as calculation of standard deviations, rut-depth progression plots and curve-fit effectiveness have been presented in detail elsewhere [22]. Since both sets of HMA specimens were subjected to the same aging time, the rut depth results were calculated as the overall average of the two sets. Table 6.1 shows the APA test results for the mixes.

Table 6.1: Asphalt Pavement Analyzer Test Results

Mix Type	Final Rut Depths (mm)			Overall Rut Depth (mm)
	Left	Center	Right	
HMA - Set A (1)	5.3	-	5.2	5.2
HMA - Set A (2)	4.6	-	5.1	4.8
Sasobit - Set A	4.4	4.4	3.9	4.2
Sasobit - Set B	3.7	3.5	4.6	3.9
Advera - Set A	4.9	-	5.2	5.0
Advera - Set B	4.0	-	5.6	4.8
Foamer - Set A	6.1	5.9	5.8	5.9
Foamer - Set B	4.2	4.4	5.1	4.6

The APA test results showed that the rut-depths at the end of 8000 cycles for all mixes did not exceed the 9.5 mm maximum rut depth criterion. Therefore, all the warm mix asphalt mixes exhibited adequate resistance to rutting, with Sasobit$^{®}$ mix showing better rutting resistance than the control HMA mix, and Foamer specimens showed slightly higher rut depth than the other three mixes.

Increasing aging time resulted in lower rut depths for all three WMA mixes. Foamer mix showed the highest decrease in rut depth with increase in aging time. However, the inference is not practically important, as the 9.5 mm maximum rut depth criterion was satisfied by all mixes even when subjected to a lower aging time.

6.4 APA Test on Moisture-Conditioned Advera® and Foamer Specimens

The physical mechanism underlying moisture damage in asphalt concrete is loss of adhesive bond strength between the asphalt binder and aggregate, which leads to stripping of the binder from aggregate surface. This process is further aggravated in the presence of tire loading which applies a horizontal shear stress on the surface of the asphalt concrete surface. Therefore, APA test was also conducted on specimens in the saturated condition to study the effect of the presence of moisture on increase in rutting.

Advera® and Foamer WMA mixes failed the TSR test, which provides an estimate of moisture damage susceptibility. Therefore, APA rutting test was conducted on moisture-conditioned Advera® and Foamer specimens to evaluate loss in asphalt-aggregate bond strength and whether the accumulated moisture damage did lead to a significant increase in rut depth.

Specimens for this test were prepared in a manner similar to the unconditioned APA test specimens as described in Section 6.2. There is no standard conditioning procedure for performing APA test on specimens in a saturated state, therefore, moisture conditioning of the specimens was conducted according to the procedure outlined for the modified AASHTO T283 Tensile Strength Ratio test, as specimens for both test are compacted to $7 \pm 0.5\%$ air voids.

One set of six specimens each were prepared for Advera® and Foamer mixes, subjected to moisture-conditioning procedure, sealed in plastic bag to prevent loss of moisture and delivered to the NCDOT Materials & Tests Division for testing.

6.4.1 Results

The average rut depth measured for saturated Advera® specimens was 5.2 mm, which is higher than that of unconditioned specimens of 5.0 mm, but significantly lower than the 9.5 mm limit. Similarly, the average rut depth for saturated Foamer specimens was 6.8 mm, which is higher than that of unconditioned specimens of 5.8 mm. The tests on conditioned specimens showed that moisture damage did not have a significant impact on rutting resistance of the mixes, even though both WMA mixes performed poorly in the TSR test. It was inferred from this experiment that the TSR test is not completely representative of moisture damage when characterizing WMA.

Chapter 7

Moisture Sensitivity E* Stiffness Ratio Test

In this chapter, results from performance tests based on dynamic modulus of the mix are presented. Dynamic modulus is a fundamental material property used in various performance prediction models, such as the Mechanistic-Empirical Pavement Design Guide (currently DarWIN M-E) software to predict pavement distresses. It can also be used to directly compare stiffness of different mixes using the E* stiffness ratio (ESR) parameter. Dynamic modulus testing was performed using the Asphalt Mixture Performance Tester (AMPT) device.

7.1 Asphalt Mixture Performance Tester (AMPT)

The AMPT device shown in Figure 7.1 is a computer-controlled hydraulic testing machine [24] capable of applying cyclic loading on cylindrical asphalt concrete specimens over a range of test temperatures and loading frequencies.

The device measures the dynamic modulus, E* which is a ratio of the amplitude of cyclic stress applied to the amplitude of cyclic strain at each test temperature and frequency as well as the phase angle, ϕ. Figure 7.2 shows a sinusoidal loading cycle applied using the AMPT device, where E* is calculated using Equation (7.1):

Figure 7.1: Asphalt Mixture Performance Tester (AMPT) Device

$$E* = \frac{\sigma_0}{\epsilon_0} \tag{7.1}$$

Test specimens for measurement of E* using the AMPT must be fabricated to dimensions of 100 mm diameter and 150 mm height. Specimens in the Superpave gyratory compactor are therefore compacted to a height of 178 mm and diameter of 150 mm, and are later cored and sawed to the required dimensions for testing. The AMPT applies cyclic loading using a hydraulic actuator, which is operated using a computer program to load the specimen in a stress-controlled mode such that the axial strain in the specimen does not exceed a predetermined value.

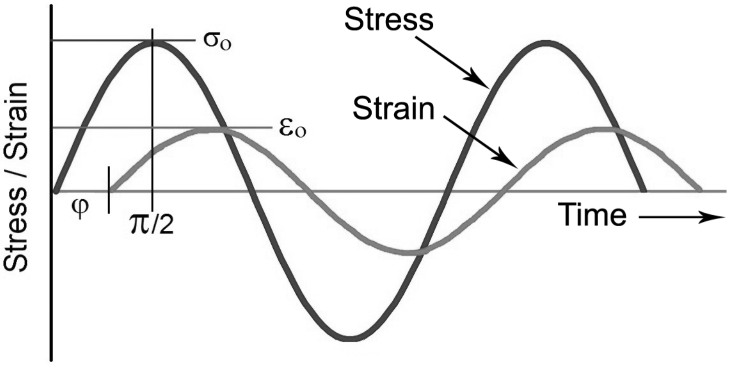

Figure 7.2: Dynamic Modulus, E*

The axial stress is measured by the device through the actuator whose displacement is calibrated to measure the applied load. The axial strain is measured by placing linear variable displacement transducers (LVDTs) along the vertical length of the specimen. The LVDTs are mounted onto the specimen using brass targets so that they measure displacements over a gauge length of 70 mm, which in turn is used to calculate the axial strain. Figure 7.3 shows an AMPT test specimen mounted inside the conditioning chamber of the device. Figure 7.4 shows a schematic representation of LVDTs mounted on an AMPT dynamic modulus test specimen. The strain amplitude is reported as the average of the three LVDTs.

7.2 ESR Test Description

Moisture susceptibility of warm mix asphalt was evaluated using the AASHTO T-283 Tensile Strength Ratio (TSR) test, as described in Section 5. The results from TSR test showed that HMA and Sasobit® WMA satisfied the NCDOT criteria of minimum 85% tensile strength retention after moisture conditioning, whereas Advera® and Foamer mixes failed to satisfy the minimum criterion. Research studies have shown that WMA

Figure 7.3: AMPT Test Specimen in the Test Device

produced using moisture-inducing technology such as zeolites and foamed asphalt perform poorly when subjected to the TSR test. Therefore, a new test called the E* stiffness ratio (ESR) had been propounded as a replacement for the TSR test to evaluate moisture susceptibility, as the results from both tests were found to be statistically insignificant [25].

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

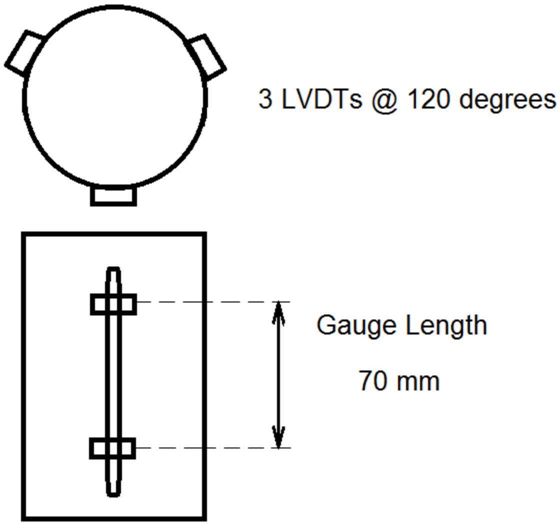

Figure 7.4: Schematic Showing LVDTs Mounted on an AMPT Test Specimen

test temperature.

$$\text{ESR} = \frac{\text{Average } |\text{E*}| \text{ of wet specimens at any test temperature and frequency}}{\text{Average } |\text{E*}| \text{ of dry specimens at any test temperature and frequency}} \tag{7.2}$$

7.3 Specimen Preparation and Conditioning

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

Conditioning of the mixes during specimen preparation and testing was done according to the NCDOT modified AASHTO T-283 procedure. After mixing, the mixes were cooled at room temperature with occasional stirring for two hours and then placed in an oven at 60°C for 24 hours. The mixes were then placed in another oven at compaction temperature for two hours (149°C for HMA and 120°C for WMA) before compaction. For preparing specimens for the wet test, specimens were saturated using vacuum to obtain 70 - 80% saturation. The saturated specimens were placed in a water bath at 60°C for 24 hours. After removal, the specimens were surface-dried and left to air-dry at room temperature for a period of 24 hours. This was to ensure that the surface of specimens was completely dry to allow proper adhesion of brass targets for mounting LVDTs.

Since the ESR test is a non-destructive test unlike the AASHTO T-283 Tensile Strength Ratio test, the same specimens were used for testing in both dry and wet conditions. Dynamic modulus testing of dry specimens for all four mixes was conducted on consecutive days, and testing of wet specimens was conducted exactly one week later for to allow recovery of residual plastic strains in specimens from the dry test. Air voids were measured again for each specimen and no variation was observed.

7.4 Results and Discussion

Table 7.1 shows the results of ESR test for HMA and WMA mixes. The dynamic modulus values shown in the table are averages of three specimens tested for each mix type.

The results show that all mixes, except Advera® mix at a test temperature of 40°C exhibit an ESR greater than 90%. Comparing the ESR, which is a measure of the loss of mix stiffness due to moisture conditioning to the results from TSR test, it was observed that the effect of moisture damage on stiffness was not as significant as indicated by the

TSR test results. The results also show that there is no significant difference between E* values at any temperature and frequency combination for any two mixes.

Table 7.1: E* Stiffness Ratio Test Results

T (°C) ↓	Dry Subset |E*| (Pa.)			Wet Subset |E*| (Pa.)			Average
Freq. →	10 Hz	1 Hz	0.1 Hz	10 Hz	1 Hz	0.1 Hz	ESR (%)
	HMA						
4	1.33E+10	9.67E+09	6.21E+09	1.26E+10	9.02E+09	5.79E+09	93.7
20	5.56E+09	3.04E+09	1.46E+09	5.26E+09	2.81E+09	1.33E+09	92.6
40	1.12E+09	4.38E+08	2.14E+08	1.10E+09	4.56E+08	2.40E+08	104.7
	Sasobit®						
4	1.21E+10	8.40E+09	5.17E+09	1.17E+10	8.16E+09	5.12E+09	97.7
20	4.76E+09	2.42E+09	1.13E+09	4.48E+09	2.26E+09	1.04E+09	93
40	9.62E+08	3.95E+08	2.26E+08	8.90E+08	3.64E+08	1.99E+08	90.9
	Advera®						
4	1.16E+10	7.91E+09	4.70E+09	1.08E+10	7.24E+09	4.17E+09	91.2
20	4.35E+09	2.03E+09	8.19E+08	3.79E+09	1.91E+09	7.24E+08	89.9
40	8.02E+08	2.80E+08	1.32E+08	6.46E+08	2.26E+08	1.05E+08	80.3
	Foamer						
4	1.26E+10	8.67E+09	5.19E+09	1.17E+10	7.93E+09	4.70E+09	91.6
20	4.68E+09	2.25E+09	9.57E+08	4.67E+09	2.31E+09	9.99E+08	102.2
40	8.61E+08	3.35E+08	1.91E+08	9.16E+08	3.59E+08	1.94E+08	105

Table 7.2 shows a comparison of TSR and ESR values for the mixes. ESR results from this study support the observation from other studies that WMA mixes prepared using water-inducing technology (zeolites and foamed asphalt) do not satisfy the tensile strength

ratio criteria, yet their stiffness does not reduce considerably when subjected to similar moisture-conditioning procedure.

Table 7.2: Comparison of TSR and ESR Test Results

Mix Type	TSR (%)	ESR (%)
HMA with 0.75% LOF 6500	87.7	97
Sasobit® with 0.75% LOF 6500	97.2	93.9
Sasobit® with 1.5% LOF 6500	101.8	
Advera® with 0.75% LOF 6500	55.6	87.1
Advera® with 1.5% LOF 6500	63.7	
Foamer with 0.75% LOF 6500	78.8	99.6
Foamer with 1.5% LOF 6500	81.4	

Chapter 8

Dynamic Modulus Test

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

Dynamic modulus test was conducted on HMA and WMA mixes at three temperatures: 0, 20 and 40°C and three frequencies: 10, 1 and 0.1 Hz. The data obtained from the test was used to develop E* mastercurves at a reference temperature of 20°C (70°F) using a non-linear optimization procedure according to AASHTO PP 61-09, “Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)”. Table shows the average dynamic modulus of three specimens for each mix type.

Dynamic modulus data was measured during the test in units of Pa, and was converted to psi for use in the Mechanistic-Empirical Pavement Design Guide (M-E PDG) software. Figure 8.1 shows the E* mastercurves developed for all four mixes at a reference temperature of 70°F.

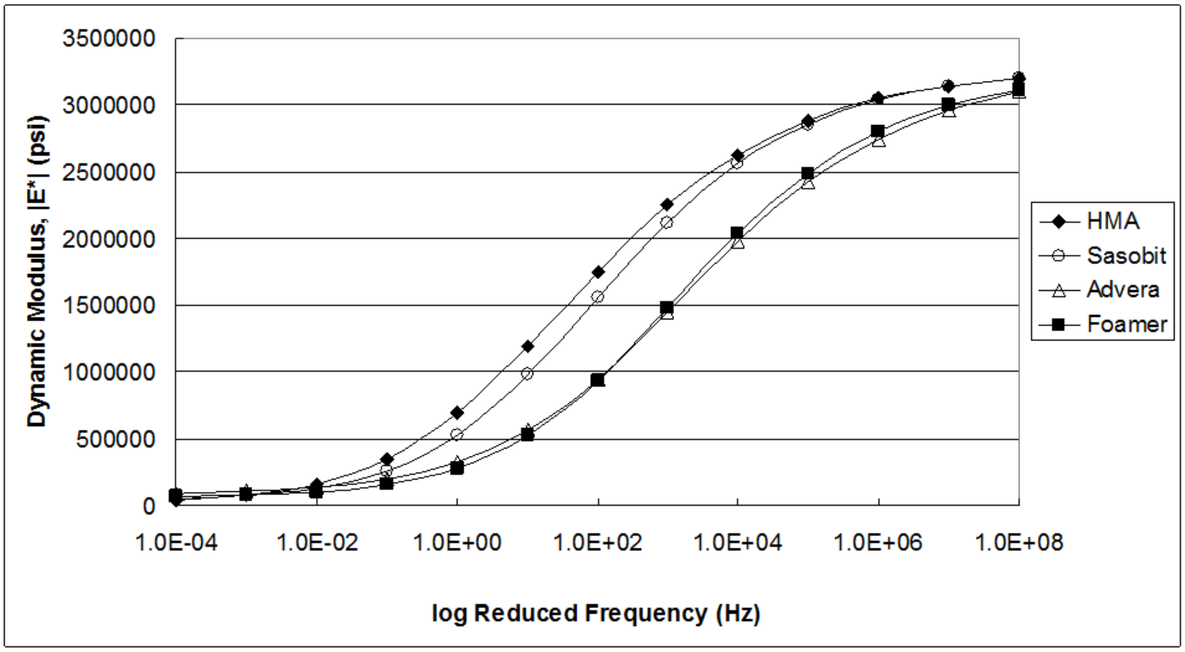

Figure 8.1: Dynamic Modulus Mastercurves (Reference Temperature 70°F

The mastercurves show that HMA mix exhibits the highest stiffness with Sasobit® mix having lower stiffness than HMA. Advera® and Foamer mixes show similar stiffness at all loading frequencies, and are significantly less stiff than HMA and Sasobit®.

The mastercurves were used to obtain E* data at five temperatures: 14, 40, 70, 100 and 130°F and six frequencies: 0.1, 0.5, 1, 5, 10 and 25 Hz for each mix as shown in Table 8.2. This data was used in the M-E PDG software to predict the performance of a model pavement section with respect to two primary distresses - fatigue cracking and rutting.

Table 8.1: Dynamic Modulus Test Results - AMPT Data

Temperature (°C) ↓	Dynamic Modulus, |E*| (Pa.)		
Frequency →	10 Hz	1 Hz	0.1 Hz
HMA			
4	1.72E+10	1.29E+10	8.96E+09
20	8.28E+09	5.08E+09	2.70E+09
40	2.25E+09	9.93E+08	4.91E+08
Sasobit®			
4	1.70E+10	1.20E+10	7.78E+09
20	6.55E+09	3.64E+09	1.82E+09
40	1.95E+09	8.73E+08	4.82E+08
Advera®			
4	1.41E+10	9.94E+09	6.17E+09
20	5.82E+09	2.95E+09	1.32E+09
40	1.28E+09	5.13E+08	2.75E+08
Foamer			
4	1.45E+10	9.91E+09	5.89E+09
20	5.62E+09	2.72E+09	1.13E+09
40	1.01E+09	3.64E+08	1.76E+08

Table 8.2: Dynamic Modulus Test Results - M-E PDG Input Data

Temperature (°F) ↓	Dynamic Modulus, |E*| (psi)					
Frequency →	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
HMA						
4	2336594	2596061	2688699	2863729	2923825	2991239
40	1268978	1660958	1825019	2175364	2309054	2467923
70	349042	572665	695386	1033686	1196237	1418653
100	838340	1392340	175169	299531	375064.8	498568
130	32204	45005	53286	83254	102947	138174
Sasobit®						
4	2220031	2522547	2630469	2832579	2900989	2976786
40	1053153	1459096	1638049	2033617	2188058	2372987
70	261646	429718	529024	826972	981699	1204193
100	81719	118387	142161	226697	280339	372162
130	45738	55084	60922	81328	94428	117684
Advera®						
4	1555221	1922636	2071467	2380883	2496130	2631119
40	603969	870547	1006914	1359659	1520156	1732512
70	200164	278891	326015	476579	562292	696904
100	107620	128759	141458	183513	208984	251941
130	83111	90087	94177	107379	115228	128374
Foamer						
4	1598122	1985491	2138904	2449997	2562798	2692506
40	568616	856179	1004655	1387922	1560605	1786441
70	159918	234375	280657	434251	524338	668180
100	79421	96869	107665	144756	168043	208433
130	60285	65577	68744	79227	85617	96545

8.1 Pavement Performance Prediction Using M-E PDG Software

The M-E PDG (NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide) software was used to predict pavement performance in this study. The pavement section used in this study is a three-layer flexible pavement consisting of an asphalt concrete layer, granular base course and subgrade. Figure 8.2 shows the pavement section, including base and subgrade properties used in the analysis. Traffic parameters, base and subgrade properties typically used for design of NCDOT traffic level B (S9.5B in this study) pavements were used as inputs for M-E PDG analysis. The assumed pavement section was a four-lane highway with two lanes in each travel direction, having a two-way average annual daily truck traffic (AADTT) of 900, operating at 45 mph and increasing at an annual linear growth rate of 3%. Climatic data provided in the software for Raleigh-Durham Airport station was used. Two values of asphalt concrete layer thickness - 3 inches and 4 inches were used.

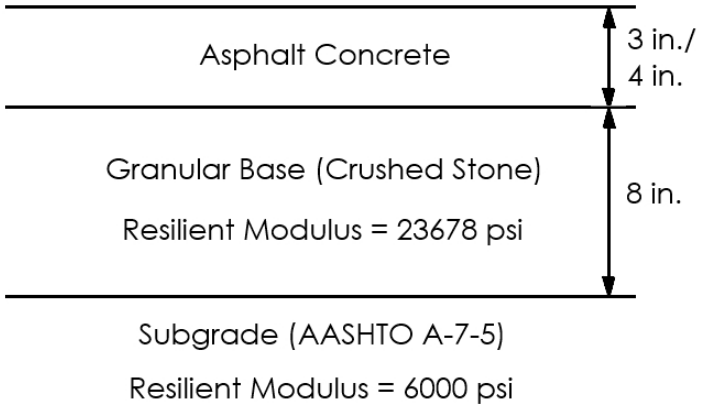

Figure 8.2: Model Pavement Section Used in M-E PDG Analysis

Failure criteria were defined as 10% of total pavement area cracked for fatigue cracking and 0.75 inches for total pavement rutting. M-E PDG runs were conducted using E* data and other inputs using a design life of 20 years for the pavement, and months to failure was obtained with respect to fatigue cracking and rutting for all mixes and the corresponding AC layer thickness. Table 8.3 shows the results from M-E PDG analysis.

Table 8.3: Rutting and Fatigue Failure (in Months) Predicted Using M-E PDG

Mix Type	AC Thickness	Fatigue	Rutting
HMA	3 inches	200	122
	4 inches	No failure	No failure
Sasobit®	3 inches	196	107
	4 inches	No failure	No failure
Advera®	3 inches	145	66
	4 inches	180	180
Foamer	3 inches	161	60
	4 inches	195	146

8.2 Mix Performance Analysis - Rutting

Dynamic modulus of an asphalt concrete mix is an indicator of its stiffness. Therefore, a mix with higher stiffness resists rutting better than a mix with lower stiffness. The predicted number of months to failure with respect to rutting follows the same trend as the variation in stiffness observed in the mastercurves. HMA mix exhibits highest resistance to rutting followed by Sasobit® when 3 inches of asphalt concrete is used.

Advera® and Foamer mixes being much less stiffer than HMA fail very early at 66 and 60 months, respectively. When the thickness of asphalt concrete layer is increased to 4 inches, HMA and Sasobit® mixes do not fail within the design period of 20 years, whereas Advera® mix fails after 180 months (15 years) of service life and Foamer mix fails after 146 months (about 12 years).

8.3 Mix Performance Analysis - Fatigue Cracking

Fatigue failure is governed by two characteristics of the mix - ability of the asphalt layer to exhibit flexure and flexural strength of the mix. A mix with lower stiffness resists fatigue cracking better as the softer asphalt imparts better flexibility under traffic load. It should be noted that all four mixes used in this study (HMA and three WMA mixes) consists of the same aggregate structure and asphalt PG binder grade, effectively making the WMA technology the only variable that controls the mix behavior. From E* data, Advera® and Foamer mixes should theoretically result in extended fatigue life, even greater than HMA and Sasobit® mixes.

However, E* test data in Table 8.1 shows that the actual stiffness of Advera® and Foamer mixes is lower, leading to lower flexural strength of mix. The predicted number of months to failure with respect to fatigue cracking can therefore be explained on the basis of M-E PDG inputs. HMA and Sasobit® mixes do not show fatigue failure within the 20 year design period due to their higher stiffness. Advera® and Foamer mixes result in predicted failure at 180 months (15 years) and 195 months (about 16 years), respectively due to their lower stiffness. The contribution of softer asphalt resulting from evaporation of foamed water from Advera® and Foamer mixes to the mix flexibility is not accounted for in the prediction model. This is due to the fact that asphalt binder stiffness (G* and

δ) cannot be measured on virgin WMA binders using Advera® and Foamer due to rapid evaporation of foam from the binder. The number of months (or years) to failure for each mix was used to perform the life-cycle cost analysis.

Chapter 9

Economic Analysis

The performance prediction results obtained from the previous task were used to perform a life-cycle cost analysis for incorporating different WMA technology in asphalt concrete mix production and construction. The design period used in the M-E PDG analysis was 20 years, which was used to identify the predicted failure of the pavement due to rutting and fatigue. In order to conduct a life-cycle cost analysis, an analysis period of 20 years was used to account for rehabilitation and salvage costs over its entire service life. Since the design of both HMA and WMA are based on the same aggregate structure and same asphalt binder content in the mix, the factors that affect cost and benefit with the use of WMA are:

- Costs - Additives/equipment necessary for incorporation of WMA technology into the mix, rehabilitation costs
- Benefits - Reduction in heating costs from heating aggregate and binder to lower temperature during production and transportation of mix from batch plant to site

In addition to economic benefits, WMA mixes also result in lower emissions during the entire construction process thereby having a less severe impact on the environment.

9.1 Material, Production and Transportation Costs

Material costs for HMA mix is the cost of asphalt concrete mix (S9.5B) per ton of mix. The estimate provided in this study is based on values used in the study conducted on recycled asphalt materials for NCDOT. Sasobit® cost per ton of mix is estimated using 1.5% of the additive by weight of binder, and 6% asphalt binder in the mix by weight from the mix design used in this study. This value may be adjusted to estimate costs for projects where mix design results in a different design asphalt content. Similarly, Advera® cost per ton of mix is estimated using 0.25% of additive by weight of mix. The calculated weights of additives per ton of mix are 0.9 kg of Sasobit® and 2.5 kg of Advera.

Sasobit® and Advera® purchase costs may vary depending on the location to which the material needs to be supplied, as well as the total quantity. Since there is no information available for this purpose, an estimated cost of $3.00 per kg is used for analysis purposes [26]. The estimated costs also include a one-time installation and yearly maintenance cost of equipment such as mechanical stirrers to mix the additive in the asphalt binder.

WMA using Foamer device does not include any material cost, as the technology does not require use of additives. The use of Foamer device however, includes equipment purchase, installation and maintenance costs, which is estimated at $1.00 per ton of mix [26]. The cost of material, additives and equipment for different mixes is shown in Table 9.1. The cost provided for asphalt concrete surface course mix includes overall costs of material, batch plant expenditure such as energy used for heating aggregates and asphalt and mixing operations, regular batch plant equipment maintenance, transportation of hot mix from batch plant to pavement construction site and laying of material on the pavement and compacting it.

Table 9.1: Material Cost for Mix Production

Material	Cost ($ per ton)
Asphalt concrete surface course mix (S9.5B)	50
Sasobit® - additive cost for 0.9 kg per ton of mix	2.7
Advera® - additive cost for 2.5 kg per ton of mix	7.5
Foamer - purchase, installation and maintenance costs	1

The cost of energy consumption during heating of aggregates and asphalt, mixing and transportation of mix is subject to a wide variety of factors, such as plant location, annual productivity, heating equipment used and efficiency, distance from batch plant to construction location, etc. Therefore, an estimate of $10.00 per ton of mix is used in this analysis for HMA construction, and an average reduction of 25% in energy costs, i.e. $7.50 per ton for WMA construction. The costs and benefits for the three WMA technologies are summarized in Table 9.2.

9.2 Intial Cost of Pavements

The initial costs are estimated for a one-mile section of pavement. The pavement is assumed to consist of four lanes, two in each travel direction having a lane width of 12 feet and 2 feet shoulders on the outer sides, resulting in a total paving width of 28 feet. The compacted mix density is assumed to be 142 pcf. The total quantity of asphalt concrete mix required for this paving operation is calculated as 2380 tons for a 3 inch

Table 9.2: WMA Technology - Costs and Benefits Summary ($ per ton of mix)

	HMA	Sasobit®	Advera®	Foamer
Overall mix cost ($ per ton) [27]	50	50	50	50
Technology cost (additives and equipment)	-	2.7	7.5	1
Energy cost	10	7.5	7.5	7.5
Energy savings	-	2.5	2.5	2.5
Total cost per ton	50	50.2	55	48.5

AC surface, and 3175 tons for a 4 inch AC surface layer. Since the assumed pavement layer structure is the same for all mixes, the cost of underlying layers is not accounted for in the cost-benefit analysis. Table 9.3 below shows the initial cost of construction for a one-mile pavement section using the four mixes.

Table 9.3: Initial Pavement Costs ($ per mile)

	HMA	Sasobit®	Advera®	Foamer
Cost per ton ($)	50	50.2	55	48.5
3 inch AC	119,000	119,476	130,900	115,430
4 inch AC	158,750	159,385	174,625	153,988

9.3 Pavement Rehabilitation Cost

The predicted performance for all mixes using a 3 inch AC surface layer showed that the mixes fail before completion of the 20 year design life. Hence, the pavements must be rehabilitated in order to extend the pavement's service life. Rehabilitation costs are estimated as the cost to construct a 2 inch new layer on top of the existing surface, or replace 2 inches from a milled pavement surface excluding the milling costs. The rehabilitation cost per mile of highway is shown below in Table 9.4.

Table 9.4: Rehabilitation Cost for 2-inch Asphalt Concrete Overlay ($ per mile)

	HMA	Sasobit®	Advera®	Foamer
Cost per ton ($)	50	50.2	55	48.5
2 inch surface	79,350	79,667	87,285	76,970

The predicted pavement failure periods in Table 9.5 show that all mixes show early rutting failure as compared to fatigue cracking. Therefore, rutting failure will be used as the criterion to determine the number of rehabilitation activities required. If a pavement requires more than two rehabilitations over the 20 year analysis period, it is deemed unfeasible for construction. In this regard, 3 inch surface courses using Advera® and Foamer WMA fail within 6 years of construction with respect to rutting. Therefore, WMA surface courses using Advera® and Foamer must be constructed using at least 4 inches. It is assumed that the rehabilitated pavement performs similar to a newly constructed pavement for all mixes, as the thickness of the AC layer added/replaced during rehabilitation is similar to the overall pavement thickness.

Table 9.5: Rehabilitation and Salvage Life (in Years) for 3 and 4 inch Pavements

	HMA	Sasobit®	Advera®	Foamer
3 in. AC Surface	HMA	Sasobit®	Advera®	Foamer
Initial service life (years)	10	9	5.5	5
Number of rehabilitations	1	2	-	-
Salvage life (years)	0	7	-	-
4 in. AC Surface	HMA	Sasobit®	Advera®	Foamer
Initial service life (years)	20	20	15	12
Number of rehabilitations	0	0	1	1
Salvage life (years)	0	0	10	4

9.4 Salvage Value and Present Worth

Salvage value of the pavement was calculated using Equation (9.1).

$$\text{Salvage Value } = \frac{Y}{Y_e}\text{ C} \tag{9.1}$$

where Y is the salvage life of the pavement in years

Y_e is the rehabilitation life of the pavement in years

C is one-time rehabilitation cost in \$ per mile

Salvage values calculated for different mixes are shown in Table 9.6.

Present worth for rehabilitation and salvage costs were calculated in order to estimate the total pavement costs over its service period. Rehabilitation costs and salvage costs were converted to their present worth using Equation (9.2):

Table 9.6: Present Worth of Pavement

	HMA	Sasobit®	Advera®	Foamer
3 inch AC Surface, per mile	HMA	Sasobit®	Advera®	Foamer
Initial cost ($)	119,000	119,476	130,900	115,430
Rehabilitation cost ($)	79,350	79,667	87,285	76,970
Initial service life (years)	10	9	5.5	5
Number of rehabilitations	1	2	-	-
Salvage life (years)	0	7	-	-
Salvage Value ($)	-	61,963	-	-
Present Worth	172,606	186,496	Infeasible	Infeasible
4 inch AC Surface, per mile	HMA	Sasobit®	Advera®	Foamer
Initial cost ($)	158,750	159,385	174,625	153,988
Rehabilitation cost ($)	79,350	79,667	87,285	76,970
Initial service life (years)	20	20	15	12
Number of rehabilitations	0	0	1	1
Salvage life (years)	0	0	10	4
Salvage Value ($)	-	-	58,190	25,657
Present Worth	158,750	159,385	196,534	190,353

$$\text{Present Worth } = \frac{F}{(1+i)^n} \tag{9.2}$$

where F is the future amount (cost) after n years

i is the discount rate (assumed to be 4%)

The present worth of pavements shown in Table 9.6 are initial construction, rehabilitation and salvage costs.

9.5 Effect of Thickness on Pavement Failure

Additional runs were conducted using the M-E PDG for different thicknesses of the AC surface layers for all four mixes. The predicted pavement performance data was analyzed to determine the effect of thickness on failure periods for the model pavements. Table 9.7 and Table 9.8 show the number of months to failure for HMA and WMA mixes for varying AC layer thicknesses. The numbers in parantheses show the final distress magnitude at the end of the 20-year design period if the pavement showed no failure with respect to that distress.

Table 9.7: Effect of Thickness on Fatigue Cracking Failure

AC Thickness (in.)	HMA	Sasobit®	Advera®	Foamer
3	200*	196	145	161
4	- (8.39%)	- (8.74%)	180	195
4.25	-	-	217	238
4.5	-	-	- (8.93%)	- (8.09%)
4.75	-	-	- (7.2%)	- (6.69%)
5	-	-	- (5.16%)	- (4.66%)

* Numbers indicate months to failure, numbers in parantheses show distress level at the end of 20 years if no failure occurred

Table 9.8: Effect of Thickness on Rutting Failure

AC Thickness (in.)	HMA	Sasobit®	Advera®	Foamer
3	122*	107	66	60
4	- (0.7)	- (0.72)	161	146
4.25	-	-	198	180
4.5	-	-	240	217
4.75	-	-	- (0.72)	- (0.74)
5	-	-	- (0.69)	- (0.70)

* Numbers indicate months to failure, numbers in parantheses show distress level at the end of 20 years if no failure occurred

From Tables 9.7 and 9.8, it was observed that pavement sections having Advera® and Foamer WMA surface courses required an additional $\frac{1}{2}$ inch thickness in order to exhibit similar fatigue damage as HMA and Sasobit® mixes at the end of 20 years. Both mixes also required an additional $\frac{3}{4}$ inches to exhibit similar rutting as HMA and Sasobit® mixes. The minimum thickness of AC layer required for each mix and the corresponding distress level at the end of 20 years for no-failure criterion are shown below in Table 9.9.

Table 9.9: Minimum AC Thickness and Final Distress Level for No-Failure Criterion

	Minimum Thickness	Fatigue Cracking (%)	Rutting (in.)
HMA	4 in.	8.39	0.7
Sasobit®	4 in.	8.74	0.72
Advera®	4.75 in.	7.2	0.72
Foamer	4.75 in.	6.69	0.74

9.6 Results and Discussion

The cost-benefit analysis for WMA mixes show that surface course construction using Sasobit® provides the most economical alternative to HMA in terms of cost per mile. For Advera® and Foamer mixes, it was found to be economically not feasible to construct 3 inch surface layers. When 4 inches of AC is used, the difference in cost between HMA and Sasobit® mixes is insignificant, whereas Advera® and Foamer mixes incur rehabilitation costs which increase their overall cost per mile.

Chapter 10

Summary and Conclusions

This chapter provides a summary of various activities completed as part of the research presented in this thesis. Based on results from performance tests conducted on WMA mixes and the cost-benefit analysis, recommendations for implementing the WMA technologies used in this research are provided.

10.1 Summary

The objective of this study was to evaluate three WMA technologies, viz. Advera® WMA, Sasobit® and The Foamer for moisture and rutting susceptibility, conduct dynamic modulus tests on them and perform a life cycle cost assessment of the mixtures.

10.1.1 Superpave Mix Design

A job mix formula with 9.5mm nominal maximum aggregate size was chosen. A control HMA mixture was tested alongside the three WMA mixtures. Virgin binder grade used in the study was PG 64-22, which is specified by the NCDOT for mixes designed to handle a traffic level of 0.3 to 3 Million ESALs. All three WMA mixes satisfied the Superpave volumetric criteria at the same design asphalt content determined for the control HMA mix. This showed that no change in asphalt content is necessary to design WMA mixes using the same constituent materials. From analysis of Superpave gyratory compactor readings recorded for specimens compacted using different weights of mix, there was no difference in compactability between HMA and WMA mixes.

10.1.2 Moisture Damage Sensitivity

Moisture sensitivity of the mixtures was tested using the Tensile Strength Ratio (TSR) test. Specimens were compacted to an air void content of 7% and divided into two subsets - one tested in the dry condition and the other subjected to a moisture conditioning procedure according to NCDOT's modified AASHTO T-283 procedure with no freeze-thaw cycle. The test was initially performed on specimens prepared using 0.75% anti-strip additive AdHere LOF6500 by weight of binder. HMA and Sasobit® mixes satisfied the minimum TSR criterion of 85%, whereas Advera® and Foamer failed to satisfy the criterion. Therefore, the test was repeated by increasing the anti-strip dosage to 1.5% by weight of binder. However, Advera® and Foamer mixes still failed to satisfy the 85% TSR criterion.

To verify the reliability of TSR test in assessing moisture damage to WMA mixes, additional testing was conducted by measuring dynamic modulus of specimens compacted to 7% air voids. E* Stiffness Ratio (ESR) is the ratio of dynamic modulus of specimens of specimens measured in wet condition to that measured in dry condition. Since ESR does not entail a standard conditioning procedure, the same procedure used for the TSR test was used to enable comparision of results from the two tests. ESR test results showed that all four mixes retained more than 90% of their stiffness (less than 10% reduction in E* value) when subjected to a similar moisture conditioning procedure, except for Advera® mix at a test temperature of 40°C. The disagreement between the two test results shows that TSR test results cannot be directly used to reject WMA mixes on account of being moisture-susceptible as several well-performing pavement sections constructed using these technologies have been reported in literature.

10.1.3 Rutting Resistance

Rutting resistance was evaluated using the Asphalt Pavement Analyzer device. Specimens were compacted to 7% air voids and tested at the asphalt binder high PG temperature of 64°C. Results from APA test showed that all four mixes showed rut depths much lesser than the allowable maximum rut depth of 9.5 mm according to NCDOT's specification. As Advera® and Foamer mixes failed the TSR test, additional testing was conducted to measure APA rut depths on moisture-conditioned specimens to assess the impact of moisture damage on rutting. Rut depths of moisture-conditioned specimens for the two mixes also did not exceed the 9.5 mm maximum rut depth criteria. Increasing the aging time from 4 hours to 8 hours did not show any appreciable decrease in the measured rut depths for all mixes.

10.1.4 Dynamic Modulus Test using AMPT Device

Dynamic modulus (E*) for all mixes was measured using the AMPT device. Specimens were compacted to an air void content of 4% and dynamic modulus was measured at three temperatures and three frequencies. E* mastercurves were developed using the measured dynamic modulus test data and were used to derive E* inputs for M-E Pavement Design Guide analysis. The E* mastercurves showed that HMA and Sasobit® exhibited similar stiffness, whereas Advera® and Foamer mixes exhibited much lower modulus values than HMA.

10.2 Conclusions

In this research study, three different types of WMA technology - Sasobit®, Advera® and Foamer were evaluated using various performance tests and the costs and benefits of using these technologies were estimated from pavement performance predictions. The conclusion from this study was that Sasobit® WMA performed better than the other two technologies, i.e. Advera® and Foamer with respect to moisture damage and rutting. The cost-benefit analysis also showed that Sasobit® WMA can be produced at lower temperatures at the same cost as HMA pavement. It was found that surface course construction using Advera® and Foamer were infeasible for a 3 inch layer due to multiple rehabilitations. When a 4-inch surface layer was used, HMA and Sasobit® WMA resulted in the same net present worth of pavement for a 20-year design period, and Advera® WMA showed an increase in costs by 23.8%, and Foamer WMA led to a cost increase of 20%.

10.3 Recommendations for Future Work

The following recommendations are made for future studies to extend the application of warm mix technology in asphalt concrete mix production:

1. WMA technologies, especially foamed asphalt has been used in producing asphalt concrete mixes containing higher percentages of recycled asphalt pavement (RAP) material. The allowance for increased use of RAP comes from the ability of the soft binder from warm mix to compensate for the stiffer binder from RAP, thereby improving the performance of the mix when subjected to flexure and lowering the susceptibility of the mix to fatigue cracking.

2. Tensile strength ratio (TSR) test results from several studies show that the test is not a good indicator for assessing the moisture damage potential of warm mixes. Additional tests like ESR have been proposed, but have not been adopted into mainstream practice as a standardized test. Additional research is necessary to de-

velop a standard test, which can better correlate laboratory test results to measured moisture damage in the field.

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