RESEARCH & DEVELOPMENT

An Evaluation of Warm Mix Asphalt Technology for NCDOT Mixes

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16. Abstract

In this research study, mixtures prepared using three WMA technologies - Sasobit®, Advera® WMA and The Foamer were evaluated for volumetric properties, moisture susceptibility and permanent deformation in comparison with a control HMA mixture. Tensile Strength Ratio (TSR) and Asphalt Pavement Analyzer (APA) tests were done to characterize these mixtures. Dynamic Modulus test was conducted on specimens at 7 percent air voids in wet and dry conditions to determine the E* stiffness ratio (ESR) to validate TSR test results and to assess moisture damage sensitivity of the mixes. Dynamic modulus of mix at 4 percent air voids was also measured and used as input in the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to predict pavement performance with respect to fatigue cracking and rutting. The predicted pavement performance data was used to conduct a cost-benefit analysis of use of WMA technology in asphalt concrete surface course construction. Evaluation of long-term performance of WMA mixtures using materials locally available in North Carolina will help NCDOT engineers in identifying the best WMA technology and provide performance data that can be used to design asphalt concrete pavements using WMA.

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EXECUTIVE SUMMARY

Technologies that can contribute to a cleaner and greener globe are of key importance in today's world, especially in construction. Warm Mix Asphalt (WMA), since its introduction, has garnered a lot of attention and interest from the pavement industry as a promising technology to replace the conventional Hot Mix Asphalt (HMA). WMA has great potential to reduce the amount of energy consumed to lay pavements, leading to tremendous economic benefits for the pavement industry in a time of escalating fuel prices. Among many benefits cited, WMA is thought to lessen harmful emissions released during construction, increase hauling distances and lengthen construction-friendly seasons with cooler weather paving.

Numerous studies have been done all over the world to evaluate the performance of WMA in the laboratory as well as in the field. Even so, definitive answers on the feasibility of replacing HMA pavements with WMA are yet to be answered. A major concern for WMA is susceptibility to moisture-induced damage. Some WMA technologies are inherently moisture-based and utilize water to improve workability at lower temperatures. Water can also be retained in the aggregate as a result of lower construction temperatures. This increased presence of moisture in the mixtures can adversely affect their performance. There is a lack of long-term performance data of WMA under traffic loading and environmental stresses. Even though one of the first field demonstrations of WMA was done in North Carolina, the state is yet to adopt it into mainstream construction due to these concerns. There is a need for systematic studies that will help the North Carolina Department of Transportation (NCDOT) make informed decisions on the adoption of WMA in the field and use these promising technologies with more confidence.

In this research study, mixtures prepared using three WMA technologies - Sasobit®, Advera® WMA and The Foamer were evaluated for volumetric properties, moisture susceptibility and permanent deformation in comparison with a control HMA mixture. Tensile Strength Ratio (TSR) and Asphalt Pavement Analyzer (APA) tests were done to characterize these mixtures. Dynamic Modulus test was conducted on specimens at 7 percent air voids in wet and dry conditions to determine the E* stiffness ratio (ESR) to validate TSR test results and to assess moisture damage sensitivity of the mixes. Dynamic modulus of mix at 4 percent air voids was also measured and used as input in the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to predict pavement performance with respect to fatigue cracking and rutting. The predicted pavement performance data was used to conduct a cost-benefit analysis of use of WMA technology in asphalt concrete surface course construction. Evaluation of long-term performance of WMA mixtures using materials locally available in North Carolina will help NCDOT engineers in identifying the best WMA technology and provide performance data that can be used to design asphalt concrete pavements using WMA.

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CHAPTER 1 INTRODUCTION AND PROBLEM STATEMENT

1.1 Background

Sustainability is of key importance in today's world. Technologies that can contribute to a cleaner and greener globe are the need of the day, especially in construction. Warm Mix Asphalt (WMA), since its introduction, has garnered a lot of attention and interest from the pavement industry due to its tremendous economic and environmental benefits.

The various WMA technologies seek to reduce the temperature of mixing and compaction of asphalt concrete. Thus, WMA has great potential in reducing the amount of energy consumed for pavement construction, leading to economic benefits for the pavement construction industry in a time of escalating fuel prices. Lesser fuel requirements also suggest lessening of harmful emissions released during construction. With reduced emissions, asphalt plants have a higher probability of being located in nonattainment areas. These technologies can also further reduce operating costs by saving money spent on emission control. Lower temperature construction may present opportunities for longer hauling distances as well as help prolong the construction-friendly season in cooler parts of the world.

WMA mixtures are generally prepared using additives like Sasobit®, Evotherm™, etc. or by using devices like the Double Barrel® Green System, The Foamer, etc. Numerous studies have been conducted comparing the performance of WMA in the field. In USA, several state Departments of Transportation have investigated WMA including California [1], Texas [2] and Virginia [3]. In 2004, the first field demonstrations of WMA in USA were carried out using Aspha-Min zeolite in Orlando, FL and Charlotte, NC.

A Warm Mix Asphalt Technical Working Group (WMA TWG) was formed by the National Asphalt Pavement Association (NAPA) and Federal Highway Administration (FHWA) in 2005 to "evaluate and validate WMA technologies and to implement proactive WMA policies, practices, and procedures that contribute to a high quality, cost effective transportation infrastructure" [4]. The National Center for Asphalt Technology (NCAT) at Auburn University has been prominent conducting research on different WMA technologies. It has evaluated popular technologies like Sasobit® [5], Aspha-Min® Zeolite [6] and Evotherm® [7] in the laboratory and constructed field trial sections in various states in association with their respective DOTs. Eleven technical reports related to WMA studies have been published by NCAT since 2005. WMA sections have also been placed and studied using the accelerated pavement-testing facility of the NCAT Pavement Test Track.

Even though the potential benefits of WMA are numerous, they are accompanied by questions on material performance. Due to lower mixing temperatures, water can remain trapped in the aggregate. This raises a flag on the performance of these mixtures in the field with concerns over increased moisture-induced damage. These concerns are especially with WMA technologies that introduce moisture in the mixtures through additives or foaming devices. In addition, although lower mixing temperatures will subject the mixtures to lesser oxidative hardening, the reduced hardening may increase their susceptibility to permanent deformation.

1.2 Need for Study

WMA is relatively a new technology and is still moving from state-of-the art stage to state-of-the-practice. Initial reports of WMA were presented in 1999-2001 in Europe and the very first field trials in USA were conducted in 2004 [8]. Although the use of WMA technologies is very appealing in terms of its contributions to green construction, performance of these mixtures under long-term traffic loading and environmental stresses is unknown. As with any construction material, testing the compatibility of this technology with locally available material is essential.

To help NCDOT address the various concerns associated with large-scale use of WMA in the field, a thorough study on the performance of WMA mixtures is required. There is an urgent requirement to evaluate mixtures using popular WMA technologies and materials from North Carolina. The results of such a study can give performance data needed to design asphalt concrete pavements using WMA and allow NCDOT engineers to use these technologies with more confidence.

1.3 Organization of Report

The goal of this research study is to evaluate three WMA technologies- viz., Sasobit®, Advera® WMA and The Foamer by verifying their volumetric properties as well as characterizing their moisture and rutting susceptibilities using the Tensile Strength Ratio (TSR) and Asphalt Pavement Analyzer (APA) tests respectively.

This report details the study and is organized into eight chapters. Chapter 2 focuses on literature review of the topic under consideration. Chapter 3 summarizes the research approach and the methodology followed. In chapter 4, properties of the constituent materials are evaluated. Volumetric properties of the test mixtures are verified in chapter 5. Chapter 6 describes the TSR test done for evaluating the susceptibility of the mixtures to moisture-induced damage. In chapter 7, the rutting potentials of the mixtures are analyzed with the help of APA. Finally, chapter 8 provides a summary of results and concludes the thesis with recommendation for further studies.

CHAPTER 2 LITERATURE REVIEW

In this chapter, a comprehensive literature review on Warm Mix Asphalt (WMA) technologies is presented. The main focus of this task was to collect information about various technologies available for producing WMA. Of particular importance are factors such as ease of use, mixing and compaction temperatures, and laboratory and in-situ performance of these mixtures. The numerous benefits associated with the use of WMA in comparison to HMA are also presented. A summary of conclusions and recommendations from previous work in this area has been compiled and presented.

2.1 Background and History of Warm Mix Asphalt

With the importance of reducing carbon footprints, reducing harmful emissions and saving fuel in today's world, the pavement industry has been looking for various ways to reduce the temperature of mixing and compacting asphalt concrete. The Warm Mix Asphalt Scan Summary Report published in 2007 by the Federal Highway Administration (FHWA) identified green construction, improvement in field compaction and worker safety as the major concerns that drove the development of WMA in Europe [9]. The scan report has also identified WMA mixtures as those produced at temperatures from 20 – 30°C lower than HMA to slightly above 100°C. This temperature range distinguishes WMA from "half warm" and "cold mix" asphalt. Figure 2-1 is a pictorial representation of classification of asphalt concrete mixtures by production temperature as shown in the WMA scan report.

WMA mixtures employ an additive or a process that facilitates their production at lower temperatures than the conventional HMA that is manufactured normally between 300 to 350°F. Reductions of mixing and compaction temperatures by 50 to 100°F have been documented [8]. The major advantages of implementing WMA include reduced emissions, lower energy consumption and increased workability, among others.

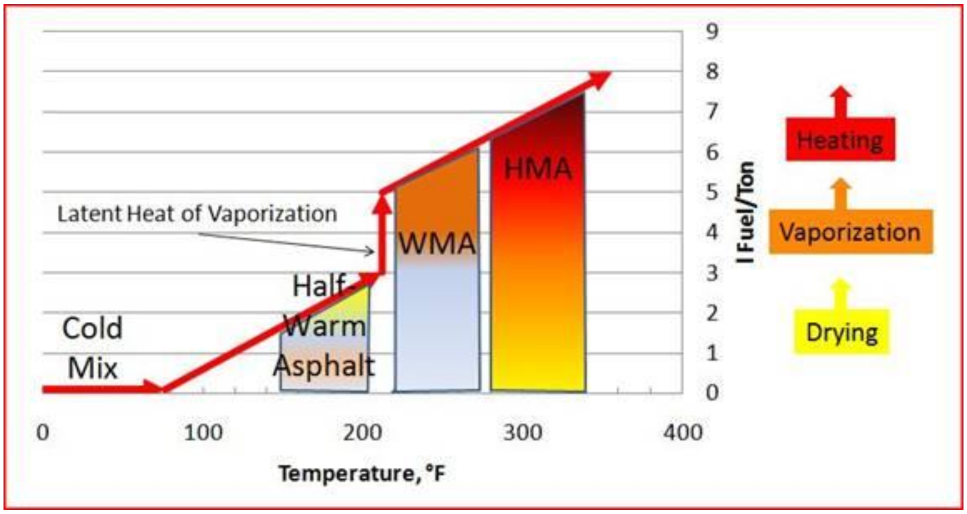


Figure 2-1 Classification of Asphalt Concrete by Approximate Temperature Ranges
[Image courtesy: WMA Scan Summary Report, 2007 [9]*]*

Warm mix asphalt technologies have been used for more than a decade in Europe with good results. Initial reports of WMA technologies in Europe were presented in 1999-2001 [8]. In 2002, the first European Scan tour was conducted, which introduced WMA technologies to USA. In 2003, NAPA featured WMA at its Annual Convention and the National Center for Asphalt Technology (NCAT) began research on the performance of WMA produced using Sasobit® and Aspha-Min®. Evotherm™ was later added to this list. In 2004, the first field demonstrations and pilot installations of WMA in USA were conducted in Charlotte, North Carolina; Nashville, Tennessee; and Orlando, Florida [11]. In 2005, a Warm Mix Asphalt Technical Working Group was formed jointly by NAPA and FHWA to provide national guidance on the implementation of WMA in USA [4].

NCAT published reports on its evaluation of Aspha-Min® Zeolite and Sasobit® in 2005 and on Evotherm™ in 2006. A second WMA Scan tour to Europe sponsored by United State Department of Transportation (USDOT), American Association of State Highway and Transportation Officials (AASHTO) and National Cooperative Highway Research Program (NCHRP) was conducted in 2007 [9]. Since then, numerous studies and field trials on WMA have been conducted all over North America.

2.2 Production of WMA

A summary of popular technologies used to produce WMA in Europe has been prepared by the FHWA [4]. The summary also includes a description of various additives used in WMA production and projects completed/currently being undertaken in the United States to study the properties of warm mix asphalt concrete. FHWA described the various warm-mix additives in terms of their physical and chemical properties, recommended percentage of additive and mechanism by which the additives modify the asphalt binder. The products listed by FHWA include Aspha-Min®, WAM-Foam®, Sasobit®, Evotherm™, Advera® WMA and Asphaltan B®. A review of WMA prepared by the Texas Transportation Institute has identified eight WMA technologies available in USA [12].

Vaitkus et al. have compiled a list of various warm mix asphalt production technologies used world-wide [13]. They have divided them into four categories based on the mechanism of production. WMA is generally produced by either foaming the asphalt or reducing its viscosity. These processes allow the asphalt binder to coat the aggregates at lower temperatures. A modified list of some WMA technologies compiled by Vaitkus et al is shown below:

I. ***Foaming Asphalt using Water***: These technologies are based on either spraying water in the hot binder or mixing wet sand into the asphalt mix. They include:

- WAM Foam® (joint venture of Shell, UK and Kolo-Veidekke, Norway)
- Terex® Warm Mix Asphalt System (Terex, USA)
- Double Barrel® Green (Astec Industries, USA)
- LEA – Low Energy Asphalt (McConnaughay Technologies, USA)
- LEA-CO – Low Energy Asphalt (LEA-CO, France) –LEA for the Europe market
- EBE (Fairco, Spain)
- EBT (EiffageTP, USA)
- LEAB (Royal BAM Group, Netherlands)
- Ultrafoam GX (Gencor Industries, USA)
- LT Asphalt (Nynas, Sweden)
- The Foamer (Pavement Technology, Inc. USA)

II. ***Foaming Asphalt using Zeolites***: Zeolites are aluminosilicate minerals containing microscopic pores, in which water can he held. This internally held water is released upon heating. This property of zeolites has been used to foam asphalt binders. Commonly used zeolites for this purpose are:

- Aspha-Min® (Aspha-Min GmbH, Germany) – synthetic zeolite
- Advera® WMA Zeolite (PQ Corporation, USA) – synthetic zeolite
- Natural zeolite

III. ***Organic Additives***: This group of WMA technologies is based on organic compounds that can modify certain properties of asphalt binder to improve its workability at reduced temperatures. They are added to the hot asphalt binder and the following ones have been used to produce WMA:

- Sasobit® – a Fischer-Tropsch wax (Sasol Wax GmbH, Germany)
- Asphaltan B® – a low molecular weight esterified wax (Romonta GmbH, Germany)
- Licomont BS 100 – a mixture fatty acid derivatives (Clariant, Switzerland)

IV. ***Chemical Additives***: These are inorganic chemicals that are also used to modify the properties of asphalt. The following ones have been successfully used to produce WMA.

- Iterlow T (Iterchimica SRL, Italy)
- Rediset® WMX (AkzoNobel, The Netherlands)
- Cecabase RT® (CECA, France)
- Evotherm™ (MeadWestvaco, USA)
- Revix arba Evotherm 3G (MeadWestvaco Mathy-Ergon license, USA)

In the present study, one technology each from the first three categories was selected. Evaluation of three WMA technologies- The Foamer, Advera® WMA and Sasobit® was performed in this research study. A detailed description of these three technologies is given below.

2.2.1 The Foamer Device

The Foamer is a device manufactured by Pavement Technology, Inc. (PTI) based in Covington, Georgia, USA [14]. The device feeds hot asphalt cement and water into a reaction chamber. The cold water acts on the hot binder, producing foam. The foamed asphalt comes out of the chamber at desired temperature. A photograph of The Foamer and its diagrammatic representation are shown in Figure 2-2.

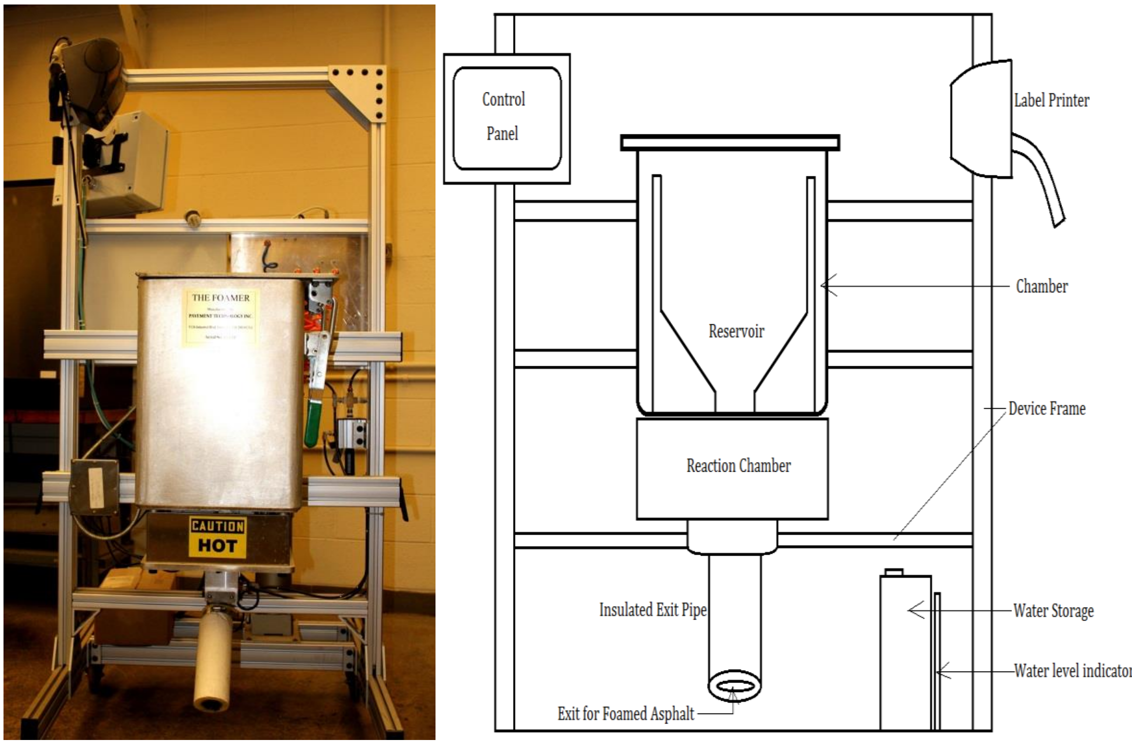


Figure 2-2 "The Foamer" Device and Schematic Representation

The device is capable of accepting standard 1 quart and 1 gallon cans of binder at room temperature and heating it as per requirement in its reservoir. The reservoir is lined with a disposable bag made with high temperature polymer to facilitate easy clean-up. In this study, pre-heated asphalt was poured into the lined reservoir. Temperature of the reservoir and exit pipe is controlled using the electronic display control panel mounted on the device, a schematic representation of which is shown in Figure 2-3. The "setup" menu allows the necessary information including target temperatures and required weight of binder to be entered and the "control" menu shows the current status of the device. The "Foam" button pops up when the set temperature parameters have been achieved and the device is ready to produce foamed asphalt. The water used for producing foam is stored in a water storage chamber at the bottom of the device. The manufacturer recommends addition of 2% water content by weight of asphalt to produce the best foaming action. Due to cooling effect of water on the binder, it is recommended that the exit temperature be set higher than the reservoir temperature.

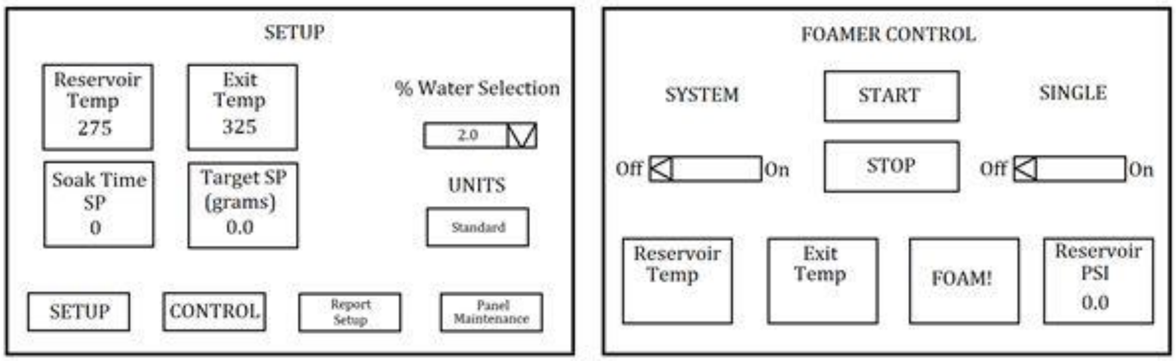


Figure 2-3 Schematic Representation of Control Panel Displays in "The Foamer"

In foamed asphalt, the presence of bubbles makes the binder more workable at lower temperatures. This allows the binder to evenly coat aggregate particles while mixing. It has been observed that by foaming the asphalt, the volume of the binder is increased, further increasing the workability. The larger bubbles dissipate fast and the effect is temporary, thus, delay in mixing once the foamed asphalt is produced should be avoided. Figure 2-4 shows a photograph of foamed asphalt produced in this study using this device. For ease in mixing, the foamed asphalt was made to fall directly on to the heated aggregate from the exit chamber. The weight of the binder was controlled by using an external weighing scale underneath the exit chamber of the device.

Figure 2-4 Foamed Asphalt Produced by "The Foamer"

2.2.2 Advera® WMA

Advera® WMA is a synthetic zeolite manufactured and marketed in North America by PQ Corporation, headquartered in Malvern, Pennsylvania, USA. [15]. It is a hydrated aluminosilicate which contains 18 to 21% water and is obtained as a fine white powder. This hydro-thermally crystallized water is released upon heating above 100°C. Upon addition to the asphalt concrete mixture, this released water causes micro-foaming making the mixture more workable at lower temperatures. PQ Corporation recommends adding Advera® WMA at a rate of 0.25 % by weight of the mixture. The manufacturer reports a potential 50 to 70°F reduction in production temperatures from that of typical HMA at 300 – 350°F [16].

Addition of the zeolite doesn't affect the mixture is any visible manner and the PG grade of the asphalt binder remains unchanged. Use of Advera® WMA is also reported to lead to reduced odor and blue smoke production with up to 60% reduction in VOC's, CO_2, SO_X and NO_X emissions and energy savings up to 30%. Figure 2-5 shows a sample of Advera® WMA additive used in the study.

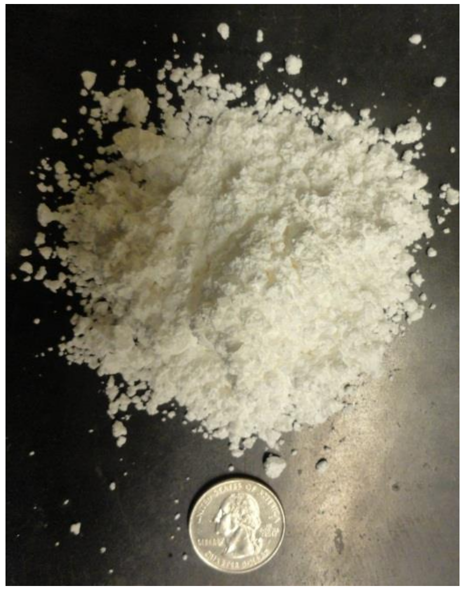


Figure 2-5 Sample of Advera® WMA as Obtained from PQ Corporation

2.2.3 Sasobit®

Sasobit® is a crystalline, long-chain aliphatic polymethylene hydrocarbon (paraffin wax) manufactured by Sasol Wax, South Africa [4]. It is obtained using Fischer-Tropsch process from coal gasification. It is also known as FT hard wax [5]. It modifies the asphalt binder by reducing its viscosity and thereby improving its flow. It has a melting point of 210°F and due to its similarity in structure to paraffin waxes found in crude oil, it is soluble in asphalt at temperatures above 248°F [17]. Sasobit® has a longer hydrocarbon chain lengths and finer crystalline structure than natural bituminous paraffin waxes [4]. At temperatures below its melting point, it forms a lattice structure in the binder and thus, does not separate out on storage, increasing the shelf-life of the modified binder. This is a good advantage that Sasobit® has over the other two WMA technologies described above.

Sasol Wax reports that Sasobit® can reduce plant mixing temperatures to 250°F (i.e., 32 - 97°F or 18 - 54°C reduction in working temperature), leading to savings of up to 19% in fuel costs [17]. Sasol Wax recommends addition of Sasobit® at more than 0.8% but less than 3% by weight of the binder to achieve desired reduction in viscosity [5]. It is available in the form of small pellets (prills) for direct addition into the mixture and is also available in flakes upon request. Figure 2-6 shows a sample of Sasobit® prills used in this study. NCAT study on

Sasobit® found that Sasobit®-modified binders modified have a different performance grade compared to that of the base asphalt cement [5].

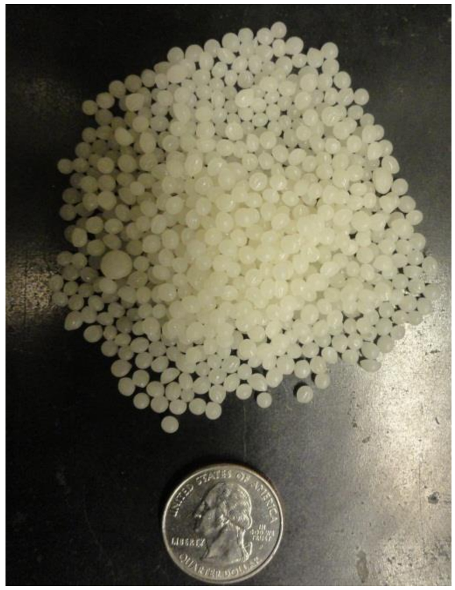


Figure 2-6 Sample of Sasobit® as Obtained from Sasol Wax

A summary of the three WMA technologies used in this study with recommended amounts of additive and mixture production temperatures is shown in Table 2-1.

Table 2-1 Comparison of WMA Technologies Used

Technology	Manufacturer	Recommended Amount of Additive	Mixture Production Temperature
The Foamer	Pavement Technology, Inc., USA	2% water by weight of binder	~ 275°F
Advera® WMA	PQ Corporation, USA	0.25% by weight of mixture	~ 250°F
Sasobit®	Sasol Wax, South Africa	0.8 to 3% by weight of binder	~ 250°F

2.3 Advantages of WMA

The interest in using WMA for pavement construction is sustained by the many advantages it has over HMA. Reduced fuel costs and harmful emissions are the two major ones that are often cited. Savings in fuel costs are quoted from 20 to 35% with some technologies reporting possible economy of 50% or higher [9]. The higher the cost of fuel used, the greater the savings. However, savings in terms of fuel costs is offset by initial investment for plant modification and/or continuous additional costs for additives. Systematic studies on life cycle cost assessment of WMA are needed to give credence to these values.

Field demonstrations of WMA have shown noticeable reduction in dust, odor and blue smoke [8]. Expected reductions in specific emissions are [9]:

- Carbon dioxide (CO_2): 30 – 40 %
- Sulfur dioxide (SO_2): 35 %
- Volatile Organic Compound (VOC): 50 %
- Carbon Monoxide (CO): 10 – 30 %
- Nitrogen Oxides (NO_X): 60 – 70 %
- Dust: 20 – 25 %

With reduced air pollution, working conditions for the plant/paving crew are improved and the industry can garner support from the ecologically-conscious citizens of today [12]. With reduced harmful emissions, it opens avenues for asphalt plants to be located in urban and non-attainment areas and increase the ease of obtaining permits for them. Paving can be carried out on days previously out-of-bounds due to air quality restrictions. These benefits are definitely advantageous to the contractor.

Due to lesser difference between ambient and mixture temperatures, hauling distances can potentially be increased and paving operations can be carried on in cooler weather, extending the paving season. It expands the market for pavement construction industry and contractors can reap in additional monetary benefits.

WMA has also shown material performance benefits over HMA. With lower mixture production temperatures, binder ageing and oxidative hardening of mixture during production and placement can be reduced. This lengthens the pavement service life by decreasing susceptibility to cracking with increased pavement flexibility. The lower production temperatures and shorter heating times can also reduce thermal segregation problems.

Since WMA technologies focus on making the mixture more workable, they have very high potential in benefitting stiff mixtures like those with higher percentages of Recycled Asphalt

Pavement (RAP) content. The conjunction of two sustainable technologies like WMA and RAP can be very beneficial to the contractors and simultaneously help the green construction industry. The increased workability of these mixtures can also reduce the compaction effort required in pavement construction.

2.4 Performance of WMA Mixtures

Many research studies have been carried out on different WMA mixtures both in the laboratory as well as in-situ, comparing their performance with conventional HMA mixtures. Questions still exist, particularly with respect to moisture susceptibility, which need more delving into. Since WMA is produced at lower temperatures, it is thought that water (already existing in the aggregate and/or introduced during foaming) may remain trapped in the aggregate, thus increasing moisture susceptibility of these mixtures. Also, reduction in oxidative hardening leading to increased pavement flexibility and decreased susceptibility to cracking has raised additional concerns over increased rutting potential of these mixtures. Clarity in designing a WMA mixture and deviations from HMA mix design procedure, if any, is also needed.

2.5 Mixture Design and Volumetric Properties

National Cooperative Highway Research Program (NCHRP) project 09-43 was conducted to provide recommendations on mix design practices for WMA [18]. A preliminary procedure for designing WMA mixtures was subsequently tested and modified based on results obtained from two phases of testing, including field validation. In 2011, the project’s findings were published in NCHRP Report 691. The research project made the key finding that a stand-alone WMA mix design procedure was not necessary. The project also compiled a set of special considerations while designing mixtures using WMA, given in Appendix A of NCHRP Report 691 and published as separate report NCHRP Report 714 [19].

Regarding selection of binder grade for WMA, there are indications that WMA additives can change the performance grade of the base asphalt that is used. NCAT study on Sasobit® [5] recommends engineering the modified binder to meet the Performance Grade requirements. The study used a base binder of PG 58-28, which upon modification with 2.5% Sasobit® yielded a grade of PG 64-22. NCHRP 09-43 did a series of tests on binder grade and its results from a comparative study of recovered binders from the field show only a small difference between

WMA and HMA sections. Thus, they recommend using the same grade of binder for the same environmental and traffic conditions even for WMA mixtures with 100°F lower production temperatures. However, even in their study, Sasobit® modified binders showed an increase in high temperature grade with minute loss/no change in low temperature grade [19]. They also stressed the need for more study in this area.

Findings from the three NCAT studies on Aspha-Min® [6], Sasobit® [5] and Evotherm® [7] was summarized in 2006 by Hurley and Prowell [20]. In their study, the optimum asphalt content used for WMA mixture design was determined using unmodified binder. Their findings showed that the resulting air voids were lower than estimated values and surmised that the optimum asphalt content for WMA binders may be different from that of HMA. They also performed a statistical analysis which showed that the Superpave Gyratory Compactor (SGC) is insensitive to compaction temperature.

NCHRP 09-43 project’s work on binder content concluded that there was no statistically significant difference in average design binder content between HMA and WMA mixtures made with the same aggregates and binder [19]. However, they found that binder absorption in WMA is 10% lesser than that of HMA mixtures.

Table 2-2 shows differences in design of dense-graded WMA mixtures in comparison to their HMA counterparts. A comparison of specimen fabrication procedures is shown in Table 2-3. These tables have been obtained from NCHRP Report 714 based on the findings of NCHRP 09-43 project.

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

Step	Description	Major WMA Differences
1	Gather Information	1. WMA Process 2. Additive rates 3. Planned Production Temperature
2	Select asphalt binder	1. Recommended limit on high-temperature stiffness of recycled binders 2. May consider low-temperature grade improvement when using blending charts
3	Determine compaction level	Same as HMA
4	Select nominal maximum aggregate size	Same as HMA
5	Determine target VMA and design air voids value	Same as HMA
6	Calculate target binder content	Lower asphalt absorption due to lower temperatures
7	Calculate aggregate volume	Same as HMA
8	Proportion aggregate blends for trial mixtures	Same as HMA
9	Calculate trial mixture proportions by weight and check dust/binder ratio	Same as HMA
10	Evaluate and refine trial mixtures	1. WMA process-specific specimen fabrication procedures 2. Lower short-term aging temperature 3. Evaluate coating and compactability in lieu of viscosity-based mixing and compaction temperatures
11	Compile mix design report	Same as HMA

Table 2-3 Comparison of Specimen Fabrication Procedures for WMA and HMA

(Source: NCHRP Report 714)

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

Workability and compactability of WMA mixtures were studied by Bennert et al. in 2010 [21]. A prototype HMA workability device developed by University of Massachusetts, Dartmouth was used to measure workability of the mixtures using torque values exerted on a paddle shaft. Results from this test showed that with fall in mixture temperature below 230-240°F, increased amounts of WMA additives resulted in lower torque values, indicating better workability of these mixtures. Marshall compactor results also exhibited the same trend. Gyratory compactor readings were used to compare workability using height of specimens with mm/gyration values. These results did not follow expected trends with 1% Rediset and Sasobit showing better workability than 2% Rediset and Sasobit mixtures.

2.5.1 Binder Characterization

Biro et al. studied the effect of WMA additives Aspha-Min and Sasobit® on midrange rheological properties of asphalt binders [10]. They characterized PG 64-22 binders from five different sources with viscous flow measurements, various creep and recovery tests and frequency and temperature sweep tests after incorporating the WMA additives. In this study, modified binders using Aspha-Min showed no significant change in flow properties, stiffness and response to creep as compared to virgin binders. Sasobit® was found to affect the flow, and increase the stiffness and penetration resistance and lower the phase angle of the virgin asphalt binders. Both the additives increased the viscosity of binders at 60°C and lowered compliance values but did not have any significant effect on the complex modulus (G*) of the binders. These effects were attributed to mineral filling effect of Aspha-Min and recrystallization of Sasobit® in the binder at mid-range temperatures.

Liu and Li investigated the low-temperature performance of WMA produced using Sasobit® [22]. This study aimed at determining suitability for climatic conditions of Northern Alaska and hence, low temperature performance was of interest. They used three Sasobit® contents (0.8%, 1.5% and 3% by weight of binder) with PG 58-28 polymer-modified binder. Bending Beam Rheometer (BBR) tests on Pressure Aging Vessel (PAV) aged binders, Direct Tension Test (DTT) on unaged binders and Asphalt Binder Cracking Device (ABCD) tests on unaged and aged binders were carried out. The authors found that with increase in Sasobit® content, creep stiffness of the binder increased while m-value, tensile strength and strain at failure decreased, indicating increased susceptibility to low temperature cracking. However, ABCD tests on both unaged and PAV aged binders did not indicate any trends between cracking temperatures and Sasobit® contents.

2.5.2 Laboratory Mixture Characterization

NCAT studies on WMA have found positive findings in their performance evaluation of WMA mixtures. NCAT reports on the investigation of and Sasobit® [5] and Aspha-Min® Zeolite [6] were published in June 2005 and on Evotherm® [7] in June 2006. Densification data for all WMA mixtures showed lower air void contents at lower compaction temperatures, indicating greater compaction of mixes containing additives. Resilient modulus values were not affected in Sasobit® and Zeolite mixtures, while Evotherm® mixtures exhibited a significant increase in resilient modulus. Sasobit® and Evotherm® mixtures exhibited a decrease in rutting potential as compared to conventional HMA mixtures as measured using the Asphalt Pavement Analyzer (APA). Addition of anti-stripping agents or hydrated lime improved resistance to moisture susceptibility in all WMA mixtures.

In their review of WMA, Chowdhury et al. provide discussion about allowing curing of compacted specimens before testing [12]. For HMA specimens, there are no curing requirements before testing a compacted specimen. Chowdhury et al. cite a 1994 study conducted by Maccarrone et al. to underscore the potential need for a cure-time for compacted specimens prepared using moisture-dependent WMA technologies (foaming technologies) [12]. Without the cure-time, excess moisture may not be expelled and there may be a possibility of falsely predicting unacceptable results from testing these specimens. Meanwhile, strength gain test results of NCAT studies on additive-based WMA technologies showed no significant increase in strength over time (test conducted after 2 hours, 4 hours and one-day increments up to five days) [20]. This is in line with the claim by Chowdhury et al. that compacted specimens of additive-based WMA mixtures probably do not require cure-time before testing.

An evaluation of WMA produced using Aspha-Min® through laboratory tests and ME-PDG was performed by Goh et al. in 2008 [23]. In this study, four types of mixtures were prepared using combinations of amounts of Aspha-Min® (0.3% and 0.5% by weight of mixture) and compaction temperature (100°C and 120°C). PG 64-22 asphalt binder was used in all mixtures. Dynamic modulus tests on these mixtures indicated that E* of three WMA mixtures did not have a significantly differ from that of the control mixture. They found that WMA with 0.5% Aspha-Min®, compacted at 120°C had a higher E* than the control mixture. ME-PDG evaluation with Level 1 inputs based on the Dynamic Modulus results and assumed values of creep compliance was used to predict the performance with respect to rutting. All WMA mixtures showed lower predicted rut depths than the control. Since the ME-PDG analysis used many assumptions, the authors recommended further study based on these promising results.

A study published by Xiao et al. in 2009 investigated moisture damage in WMA containing moist aggregate [24]. Mixtures containing two types of WMA additives (Aspha-Min® and Sasobit®), two moisture contents (0% and ~0.5% by weight of dry aggregate), and three hydrated lime contents (0%, 1% and 2% by weight of dry aggregate) was studied. Indirect Tensile Strength (ITS) test was performed on these mixtures using both unconditioned (dry) and conditioned (wet) specimens. Under identical conditions, no significant differences in dry and wet ITS values were observed amongst the WMA mixtures. Mixtures with moist aggregate exhibited a loss of dry ITS, which could be improved by the addition of hydrated lime. The effect of WMA additives on deformation resistance and toughness was also not found to be statistically significant.

Punith et al. studied the effects long-term aging in foamed WMA mixtures containing moist aggregate [25]. WMA mixtures were prepared by two foaming water contents (2% and 3% by weight of binder) as well as Aspha-Min®. Aggregates with a moisture content of about 0.5% by weight of dry aggregate were included in the study. Two hydrated lime contents (1% and 2% by weight of dry aggregate) and a liquid anti-stripping agent were also used. Half of the samples prepared were subjected to long-term aging as specified by AASHTO R30. Dry and wet ITS values of all mixtures were determined. The authors noted that WMA mixtures required lesser compactive effort and exhibited lesser dry ITS values as compared to the control mixture. With long-term aging, the dry ITS values increased. With ageing, the wet ITS of WMA exceeded that of aged control mixtures. They also observed that WMA mixtures with the highest moisture content (3% foaming water and ~0.5% aggregate moisture) slightly lower wet ITS than other WMA mixtures. Hydrated lime was found to be more effective in increasing moisture resistance than liquid anti-strip additive.

Results from IDT of Sasobit® modified WMA mixtures conducted by Liu and Li indicated that low temperature tensile strengths (0°C, -10°C and -20°C) decreased with increased Sasobit® content [22]. This is in line with binder tests performed in the same study. However, thermal cracking analysis of the mixtures indicated that there was only a slight decrease in cracking temperature with increase in Sasobit® content and concluded that Sasobit® is suitable for use in Northern Alaska, where low temperature cracking resistance is crucial.

Mogawer et al. studied the moisture susceptibility of four types of WMA mixtures. Advera (added at 0.25% by weight of mixture), Evotherm, Sasobit and SonneWarmix (added at 0.5%, 1.5% and 1% by weight of binder respectively) mixtures with PG 64-22 binder were evaluated in this study. Hamburg wheel-tracking device (HWTD) was used to characterize the mixtures using combinations of three different aging times and temperatures. Stripping inflection point of less than 10,000 load cycles was taken to indicate susceptibility to moisture-induced damage. The performance of all mixtures improved with increase in aging times and temperatures. Addition of hydrated lime or liquid anti-strip additive improved the WMA HWTD results. The study recommended a minimum aging time of 4 hours for WMA mixtures to provide them with adequate stiffness to resist moisture-induced damage.

2.5.3 In-Situ Studies

In association with the respective state DOTs, NCAT has conducted in-situ studies on WMA in Ohio [26], Michigan [27], Tennessee [28], Missouri [29], Wisconsin [30], Colorado [31] and Washington [32] between 2006 and 2010. Field sections with Sasobit® mixtures were constructed in the first six projects, Evotherm™ in five projects, Advera® WMA and Aspha-Min® in two projects. Astec Double Barrel Green™ system was also used in Tennessee and Maxam Equiment's AquaBlack™ foaming system was used in Washington. Generally, all these studies have indicated a positive performance of WMA mixtures in the field. Table 2-4 provides a brief summary of the major results obtained from these studies. In this table, the performance of each WMA mixtures is compared to that of the control HMA and reported as same, higher or lower than HMA.

A field trial of WMA was conducted in Alabama using Evotherm™ Dispersed Asphalt Technology (DAT) in 2007 [33]. RAS and RAP were also incorporated in these mixtures. These plant-produced mixtures were compared to HMA mixtures by laboratory evaluation. Characterization of the mixtures using conditioned and unconditioned indirect tensile strengths, APA rut depths, Hamburg wheel tracking results, dynamic modulus, flow number and creep compliance test results predicted better performance of HMA as compared to WMA. However, the ITS values of WMA field cores showed comparable values to that of HMA after one year. This indicated that WMA mixtures may be subject to a curing effect, improving its performance with time.

Table 2-4 Summary of NCAT In-Situ Studies

State	**WMA Technology**	**In-Situ Study Results**				
		APA-based Rutting	*TSR-based Moisture Damage*	*HWTD Stripping Inflection Points*	*Dynamic Modulus*	*General Comments*
OH	Aspha-Min	Same	Higher	Higher	Lower	As-constructed, in-place densities higher for WMA
	Evotherm	Higher	Higher	Mostly Higher	Lower	
	Sasobit	Same	Higher	Higher	Same	
MI	Sasobit	Same	Same	Same	Same	No evidence of rutting or moisture damage in the field
TN	Advera	Same	Lower	Lower	Lower	Bleeding, Raveling in HMA and Advera after 1 year. WMA binders aged more than HMA.
	Astec DBG	Higher	Higher	Same	Lower	
	Evotherm	Lower	Lower	Lower	Lower	
	Sasobit	Higher	Lower	Higher	Lower	
MO	Evotherm	Same	Same	Lower	Same	Minimal rutting and cracking in all
	Sasobit	Lower	Same	Same	Same	
	Aspha-Min	Higher	Lower	Same	Lower	
WI	Evotherm	Higher	Same	Same	Lower	No difference in field rutting
	Sasobit	Lower	Same	Same	Same	
CO	Advera	--	Lower	--	Lesser	Same field performance for all, even with very cold climate
	Sasobit	--	Same	--	Lesser	
	Evotherm	--	Lower	--	Lesser	
WA	AquaBlack	Same	Same	Same	Same	No rutting, cracking observed after 13 months. Similar to HMA

Goh and You compared the performance of samples from an in-situ demonstration of HMA and WMA produced using 1.5% Sasobit® in Michigan using APA rutting tests [34]. The compaction temperatures of HMA and WMA were 152°C and 126.7°C respectively. The Sasobit® mixtures exhibited similar rutting potential as HMA in these tests.

Saboundjian et al. described paving a low volume road with WMA in Alaska in the late-season of 2008 [35]. This was Alaska's first roadway construction to use WMA. The project utilized PG 58-28 polymer modified binder with 1.5% Sasobit® by weight of binder. An adjacent roadway project was constructed using HMA. The production temperatures of WMA and HMA were 265°F and 315°F respectively. The WMA mixture was shipped 800 miles to the project site on barges in heated containers. Addition of Sasobit® changed the binder grade to PG 70-22, decreasing its low temperature reliability. Since the construction was on a low volume road, this was thought to have no detrimental effects. The WMA mixtures required lesser compactive effort than HMA in the field. Dynamic modulus and flow number tests conducted on specimens compacted from these mixtures revealed an increase in $|E^*|$ and FN values for Sasobit® mixtures. Thus, the WMA mixtures were expected to have higher resistance to permanent deformation. The TSR values of HMA and Sasobit® mixtures were also found to be similar. No problems in pavement performance were reported within one year of construction and field evaluations of smoothness and rut depth turned up similar results for both pavements.

A field study of WMA was conducted in Virginia to evaluate the installation and initial performance of three trial sections of WMA, two produced using Sasobit® and one using Evotherm ET [36]. WMA and HMA field cores were extracted at set intervals, whose air voids were generally not different. Recovered binder tests from these cores showed lower rate of stiffness gain in Sasobit® cores than HMA with Evotherm ET cores mostly exhibiting no difference.

2.6 Environmental and Economic Analyses

In a low volume pavement construction project in Alaska, the mixing plant operator reported a consumption of 0.5 gallons of fuel per ton of WMA produced as opposed to 1.5 gallon of fuel per ton needed to produce HMA [35]. The mix-binder costs for Sasobit® and HMA were 60/750 and 70/720 US Dollars/ton. Lesser fumes were visually observed in the field while constructing the WMA pavement, but no quantitative emission data were collected.

A report published by Ball [37] as a part of New Zealand Transport Agency Research compiled the environmental and financial benefits and disadvantages of different WMA manufacture methodologies. According to the findings from the report, pre-existing publications have indicated that 44% of the total energy needed for constructing an HMA pavement is consumed by fuel and electricity expended in heating the aggregate and bitumen (approximately 277MJ/ton of mix). This study concludes that currently, the balance of savings and costs of manufacturing WMA using available technologies results in warm mixes being more expensive than the equivalent standard hot mixes. The study emphasized the need for further research to lower the production costs of WMA.

CHAPTER 3 RESEARCH APPROACH AND METHODOLOGY

3.1 Research Objectives

The objective of this research study was to characterize and evaluate the performance of three different Warm Mix Asphalt technologies and compare them to conventional Hot Mix Asphalt for a North Carolina mixture. The three technologies investigated were additives Sasobit® and Advera® WMA and foaming asphalt binder using "The Foamer". The specific research objectives of this study were to:

- Verify the volumetric properties of WMA mixtures with same job mix formula as that of HMA.
- Determine moisture susceptibility of WMA mixtures using the Tensile Strength Ratio (TSR) test and compare their performance to HMA.
- Characterize and compare the rutting potential of the mixtures using Asphalt Pavement Analyzer (APA) test.
- Evaluate the performance of the mixtures using the Dynamic Modulus test.
- Perform a life cycle cost assessment of WMA pavements and assess the economic benefits of using WMA.

Task 1: Material Acquisition and Testing

In this research task, the materials needed to complete this study were selected and procured. To ensure that the results are most applicable to NCDOT, selected materials were a representation of those used for asphalt pavement construction in North Carolina. For facilitating a one-to-one comparison of all the mixtures, the three WMA mixtures as well as the HMA mixture were prepared using the same aggregate and virgin binder. Asphalt Concrete Surface Course, Type RS 9.5B as per NCDOT specifications was selected as the Job Mix Formula (JMF) for all the mixtures. Granite aggregate and PG 64-22 binder were used in this study. Sasobit® and Advera® WMA additives were procured from Sasol Wax and PQ Corporation respectively. As specified by NCDOT, anti-strip additive AD-here® LOF 6500 and bag-house fines were also obtained for incorporation into mixture design.

Task 2: Establishment of Mixture Production Temperatures

In this task, temperature-viscosity relationships were developed for the virgin PG 64-22 binder using the Rotational Viscometer. The results obtained were compared with the mixing and compaction temperatures specified in the JMF. The test was also done on Sasobit®-modified binder to see if the viscometer results indicated feasibility of lowering the production temperatures. For the foamed binders prepared using Advera® WMA and The Foamer, this test was not feasible due to their mechanism of production.

Task 3: Superpave Mixture Design

Design of the four mixtures and verification of their volumetric properties were performed in this task. The aggregate gradation was specified by NCDOT in the given JMF. The optimum asphalt content was obtained by compacting HMA mixtures at different asphalt contents and verifying the percent air voids. For the ease of comparison, the mixture design for the three WMA mixtures was kept uniform with that of HMA. Once the asphalt content was determined, volumetric properties were verified for each mixture including percent air voids, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}). It was ensured that these values were within acceptable ranges for all mixtures.

Task 4: Moisture Susceptibility Test

Once the mixture design was completed in Task 3, Tensile Strength Ratio (TSR) test was performed. The test involved preparing two sets of specimens- one unconditioned and the other soaked in a water bath at 60°C for 24 hours (conditioned). They were then tested to failure and the ratio of the tensile strength of the conditioned set to that of the unconditioned set was reported. NCDOT requires the mixtures to have a minimum TSR of 85% to pass. In those mixtures where the TSR was less than 85%, the dosage of anti-strip additive was doubled and the test repeated to see if any improvement in TSR values were realized.

Task 5: Rutting Resistance Test

The four mixtures were characterized in this research task using Asphalt Pavement Analyzer tests for rutting potential. The results from these tests were used to compare the various mixtures for their performance.

The number of specimens (replicates) prepared for mix characterization using TSR and APA tests is shown in the matrix below in Table 3-1.

Table 3-1 Specimen Replicates Matrix - APA and TSR Tests

Mixture Technology	No. of Replicates for			
	TSR Test		*APA Test with ageing time of*	
	Uncond. Set	Cond. Set	4 hours	8 hours
HMA	4	4	12	-
Sasobit®	4	4	6	6
Advera® WMA	4	4	6	6
The Foamer	4	4	6	6

Task 6: Dynamic Modulus Test

Dynamic modulus (E*) was measured using the Asphalt Mixture Performance Tester (AMPT) device. Specimens were prepared at two air void contents - 4 percent and 7 percent. The specimens with 7 percent air voids were first tested in dry condition for E*, and later subjected to moisture conditioning using similar procedure to the TSR test and tested in wet condition. The ratio of dynamic modulus values in wet condition to those in dry condition were used to calculate the E* stiffness ratio or ESR of the mixes. The ESR test was conducted to assess the moisture damage to mixes with respect to dynamic modulus values, and compare them to the TSR test results.

E* measured for specimens at 4 percent air voids was used as input in the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to predict the pavement performance. Dynamic modulus was measured for three test specimens for each mix, and the average values were used in the analysis.

CHAPTER 4 MATERIAL EVALUATION

This chapter details the work done in Task 1 of the research project. Details of the materials used in the research study, viz. the aggregates, virgin binder and additives, along with their properties are provided.

4.1 Aggregates

Granite aggregate from Martin Marietta Materials Quarry at Garner, North Carolina was used in this study. Three different stockpiles - #78M coarse aggregate, dry screenings and manufactured sand were selected to create the aggregate gradation specified in the JMF. The aggregates used were all virgin materials as use of Recycled Asphalt Pavement (RAP) was eliminated from the JMF in this study.

A washed sieve analysis was carried out on representative samples obtained from the three aggregate stockpiles to verify their gradation in accordance with the procedure detailed in ASTM C136-06, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates" and ASTM C117-04, "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing". Table 4-1 through Table 4-3 show the results of the washed-sieve analysis and the gradation specified by the supplier for #78 M coarse aggregate, dry screenings and manufactured sand, respectively.

From the results, it can be seen that the gradations obtained differ from the specified one for all the three different stockpiles. The values were not consistent even within the three samples taken for the sieve analysis to warrant a reported change in specified gradation. The finer aggregates typically exhibit greater variation from the specified gradation and among themselves. It was also observed that there was some difficulty in obtaining a representative sample from each type of stockpile. Due to these reasons and since laboratory experimental work demands high consistency and uniformity amongst all the samples, the different aggregates used in the study were oven-dried and fractioned into their constitutive particle sizes before using them to prepare test specimens.

Table 4-1 Specified Gradation of #78 M Coarse Aggregate and Washed Sieve Analysis

Sieve Size		% Passing (from washed sieve analysis)			% Passing (Specified)
		Sample 1	Sample 2	Sample 3	
¾ “	19.0 mm	100	100	100	100
½ “	12.5 mm	100	100	100.0	100
3/8 “	9.5 mm	95	95	95	93
#4	4.75 mm	36	37	36	41
#8	2.36 mm	6.0	6.6	6.7	7.0
#16	1.18 mm	2.5	3.2	3.3	2.0
#30	600 µm	1.5	1.8	2.0	1.0
#50	300 µm	1.1	1.6	1.8	1.0
#100	150 µm	0.8	1.2	1.5	1.0
#200	75 µm	0.5	0.7	0.9	0.4

Table 4-2 Specified Gradation of Dry Screenings and Washed Sieve Analysis

Sieve Size		% Passing (from washed sieve analysis)			% Passing (Specified)
		Sample 1	Sample 2	Sample 3	
¾ “	19.0 mm	100	100	100	100
½ “	12.5 mm	100	100	100	100
3/8 “	9.5 mm	100	100	100	100
#4	4.75 mm	100	100	100	99
#8	2.36 mm	84.0	84.3	87.5	87.0
#16	1.18 mm	60.3	59.9	68.4	65.0
#30	600 µm	41.2	40.1	49.3	48.0
#50	300 µm	23.0	23.8	29.1	32.0
#100	150 µm	8.5	9.8	11.3	19.0
#200	75 µm	3.7	3.2	3.3	10.6

Table 4-3 Specified Gradation of Manufactured Sand and Washed Sieve Analysis

Sieve Size		% Passing (from washed sieve analysis)			% Passing (Specified)
		Sample 1	Sample 2	Sample 3	
¾ "	19.0 mm	100	100	100	100
½ "	12.5 mm	100	100	100	100
3/8 "	9.5 mm	100	100	100	100
#4	4.75 mm	100	100	100	100
#8	2.36 mm	85.8	88.6	86.8	82.0
#16	1.18 mm	63.6	68.7	66.0	55.0
#30	600 µm	47.3	52.5	49.0	38.0
#50	300 µm	35.7	39.3	34.8	23.0
#100	150 µm	24.1	28.2	22.8	9.0
#200	75 µm	15.5	19.9	14.2	2.6

Baghouse fines were added to the aggregates at 1.5% by weight of the total aggregates. These fines were included in the percent of aggregate passing #200 sieve size and replaced the dry screenings portion of the virgin aggregate.

The bulk specific gravity of the aggregates was verified according to the procedure outlined by 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". For the purpose of these tests, fractions of aggregates retained above the #4 sieve were considered to be coarse aggregates. Those below the #4 sieve size were considered as fine aggregates. Baghouse fines were also included in the fine aggregate portion. The specific gravity of the coarse fraction (24% of total aggregate weight) was found to be 2.620 and that of the fine fraction (76% of total aggregate weight) to be 2.638. The combined bulk specific gravity (G_{sb}) of the aggregate used in this study was thus found to be 2.634, which is comparable to the value provided in the JMF- 2.630. The difference in values may be attributed to the elimination of RAP from the JMF in this study. The design aggregate gradation used in the study is presented in Chapter 5.

4.2 Asphalt Binder

The asphalt binder used in this study was supplied by NuStar Asphalt Refining Company from their River Road Terminal in Wilmington, NC. The virgin asphalt used to prepare the HMA mixtures had a Superpave performance grading of PG 64-22, a common grade utilized in North

Carolina. The same binder was modified appropriately for use in the three different WMA mixtures. The manufacturer-reported specific gravity of the virgin binder used in this study is 1.034.

4.3 Additives

4.3.1 Anti-strip Additive

The JMF recommended use of 0.75% anti-strip additive in the mixtures. The additive used in this study was AD-here® LOF 6500 manufactured by ArrMaz Custom Chemicals. In mixtures subjected to TSR test for moisture susceptibility, the dosage of the additive was doubled for those mixtures that did not meet the minimum 85% TSR requirement.

4.3.2 WMA Additives

As mentioned earlier, two of the WMA technologies studied in this research project were based on additives. The organic additive Sasobit® manufactured by Sasol Wax and the zeolite Advera® WMA manufactured by PQ Corporation were used in this study. Sasobit® was incorporated at 1.5% by weight of binder, while the Advera® WMA mixtures were modified using 0.25% additive by weight of the mixture. WMA mixtures prepared using The Foamer did not require any additives, but 2% water by weight of binder was used for foaming the binder. Table 4-4 summarizes the utilization of additives in the research study, with the exception of the moisture susceptibility test where an increased dosage of anti-strip additive was used.

Table 4-4 Summary of Amount of Additives Used

Additive	Amount	Mixtures Modified
Liquid Anti-strip	0.75% by weight of binder	All
Sasobit®	1.5% by weight of binder	WMA using Sasobit®
Advera® WMA	0.25% by weight of mixture	WMA using Advera® WMA
Water	2% by weight of binder	WMA using The Foamer

CHAPTER 5 EVALUATION OF JOB-MIX FORMULA

In this chapter, the work done in Tasks 2 and 3 are elaborated. The optimum design asphalt content (OAC) was determined for the HMA mixture using Superpave mix design method. The design asphalt content was used to verify the volumetric properties of the WMA mixtures.

5.1 Aggregate Gradation

As per NCDOT specifications, both HMA and WMA were designed as Asphalt Concrete Surface Course, Type RS 9.5B mixtures. The design aggregate gradation used in this study is shown in Table 5-1 and Figure 5-1.

Table 5-1 Aggregate Gradation with Percent Passing and Sieve Size

Sieve Size		% Passing	Control Points
2"	50.0 mm	100	
1 ½ "	37.5 mm	100	
1 "	25.0 mm	100	
¾ "	19.0 mm	100	
½ "	12.5 mm	100	100 -
3/8"	9.5 mm	97	90 - 100
#4	4.75 mm	76	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	4.0 – 8.0

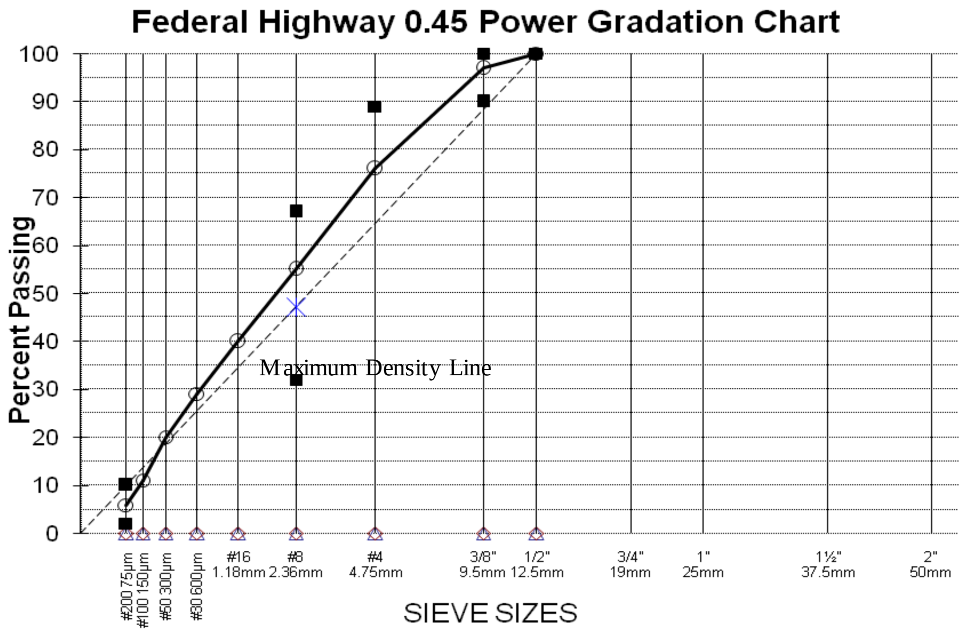


Figure 5-1 Percent Passing vs. Sieve Sizes Raised to 0.45 Power

5.2 Mixing and Compaction Temperatures

The mixture production temperatures for the HMA and WMA mixtures were established using information provided by the asphalt cement supplier, temperature-viscosity relationships from Rotational Viscometer tests, recommendations from WMA technology manufacturers and literature reviews.

5.2.1 Hot Mix Asphalt

The binder supplier NuStar Asphalt Refining Company, in their report of analysis of the virgin PG 64-22 asphalt, recommended mixing temperature between 159°C – 165°C and compaction temperature between 147°C – 152°C for the HMA mixture. To verify these values, viscosity determinations were done as per the procedure in AASHTO T 316-06, "Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer". Two samples of virgin binder were tested between 135°C and 175°C with viscosity readings taken at every 10°C intervals. The viscometer gives viscosity values in centipoise. These readings (converted to Pa.s) are shown in Table 5-2.

Table 5-2 Rotational Viscometer Readings for Virgin Asphalt (PG 64-22)

Temperature (°C)	Viscosity (Pa.s)		Average Viscosity (Pa.s)
	Sample 1	*Sample 2*	
135	0.625	0.608	0.617
145	0.414	0.404	0.409
155	0.263	0.259	0.261
165	0.175	0.162	0.169
175	0.11	0.107	0.109

These viscosity readings were plotted on a semi-logarithmic scale and the relationship between viscosity and temperature was found as shown in Figure 5-2. The range of viscosity (measured in Pa.s) for mixing and compaction is given in Asphalt Institute SP-2 [38] as follows:

- Mixing range: 0.17 + 0.02 Pa.s
- Compaction range: 0.28 + 0.03 Pa.s

The corresponding temperature ranges for these viscosity values can be obtained from the rotational viscometer data.

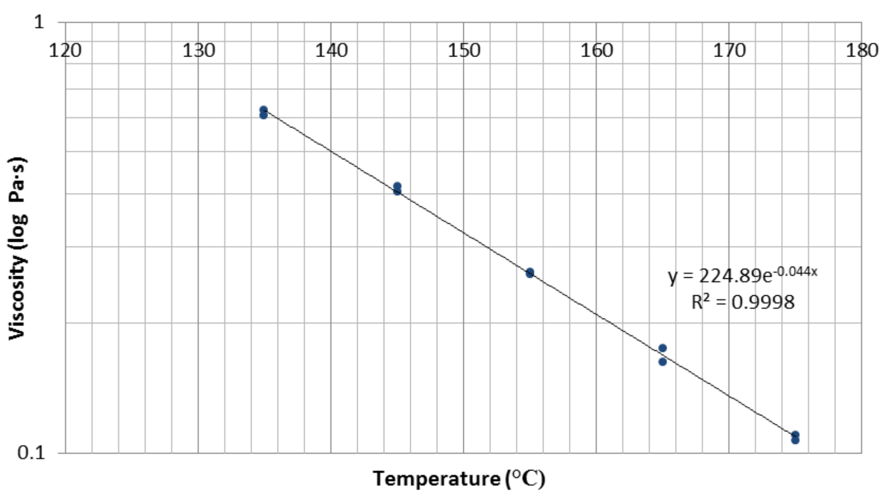


Figure 5-2 Temperature-Viscosity Relationship for Unmodified PG 64-22 Binder

Based on the relationship obtained in Figure 5-2, the equation to obtain temperature from viscosity is:

$$T = 22.727 \ln\left(\frac{224.89}{\eta}\right) \quad \text{… (Equation 5-1)}$$

where, T is temperature in °C and

η is viscosity in Pa.s.

The temperature ranges for mixing and compaction are determined from the regression equation 5-1 and the results are shown in Table 5-3.

Table 5-3 Mixing and Compaction Temperature Ranges for Virgin PG 64-22 Binder from Rotational Viscometer Results

Viscosity (η Pa.s)	Temperature (T°C)
0.15 (= 0.17 - 0.02)	166
0.19 (= 0.17 + 0.02)	161
0.25 (= 0.28 - 0.03)	155
0.31 (= 0.28 + 0.03)	150

Thus, the average mixing and compaction temperature ranges for the unmodified binder are 161 – 166°C and 150 – 155°C respectively. The original JMF used mixing and compaction temperature ranges of 152 – 157°C and 142 – 146°C. The rotational viscometer based ranges are very similar to the binder supplier reported values (159 – 165°C and 147 – 152°C). Hence, the supplier-specified mixing and compaction ranges were used for preparing the HMA mixtures. Mixing and compaction temperatures were fixed at 163°C and 149°C respectively for the HMA mixtures.

5.2.2 Warm Mix Asphalt

In step 10 of its special mix design considerations for WMA, NCHRP report 714 notes that viscosity-based mixing and compaction temperatures are not used for WMA mixtures [19]. The report recommends that mixing and compaction of WMA mixtures should be carried out at the planned production temperature. Sasobit® suppliers Sasol Wax have reported plant mixing temperatures as low as 120°C (~250°F). Advera® WMA specifications released by PQ Corporation indicate production temperatures of 130°C (266°F). A Pavement Technology, Inc. representative suggested foaming the asphalt at around 135°C (275°F) while installing The Foamer device at NC State University for conducting this study. Studies on WMA conducted by

NCAT have recommended minimum field mixing and compaction temperatures of 135°C (275°F) and 121°C (250°F) respectively [20]. Based on the available information, WMA mixing and compaction temperatures of 135°C and 120°C were selected in this study. A summary of production temperatures for all four mixtures is shown in Table 5-4.

Table 5-4 Mixing and Compaction Temperatures for HMA and WMA

Mixture Technology	Mixing Temperature	Compaction Temperature
HMA	163°C	149°C
Sasobit®	135°C	120°C
Advera ® WMA	135°C	120°C
The Foamer	135°C	120°C

5.3 Optimum Asphalt Content

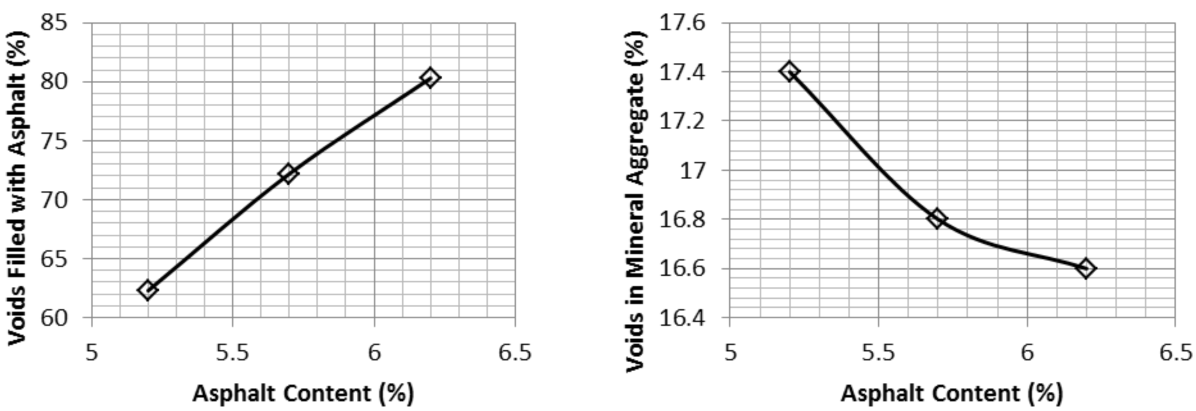
Once the mixing and compaction temperatures were determined, the optimum asphalt content was estimated by fabricating specimens over a range of binder contents. Two HMA specimens each were compacted at 5.2%, 5.7% and 6.2% asphalt contents. Two loose mixtures at each binder content were also prepared for determining the Rice specific gravity (Gmm) according to AASHTO T 209-05, "Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)". The mixtures were compacted to 65 gyrations using the Superpave Gyratory Compactor (SGC) as per NCDOT specifications for S9.5B surface mixes (Initial gyrations, $N_{ini} = 7$ and Design gyrations, $N_{des} = 65$). The volumetric properties of these compacted specimens including the bulk specific gravity (Gmb) and percent air voids were determined. Properties of the fabricated specimens at various binder contents are shown in Table 5-5.

Table 5-5 Mixture Properties Various Asphalt Contents

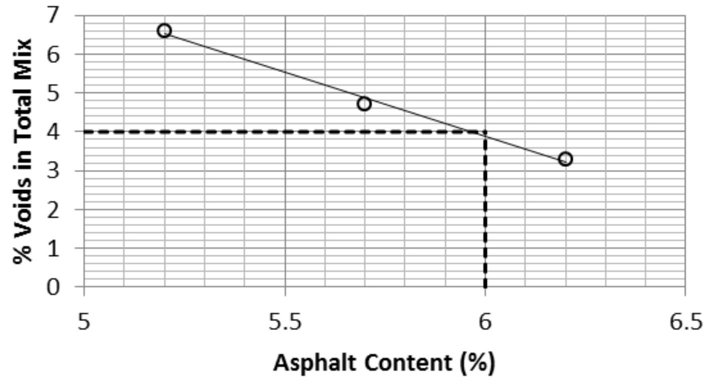
Asphalt Content (%)	Specimen	Height at N_{ini}	Height at N_{des}	G_{mm}	G_{mb} Estimated	G_{mb} Measured
5.2	1	124.7	115.8	2.457	2.308	2.294
	2	124.7	115.7		2.312	2.298
5.7	1	123.9	114.9	2.437	2.341	2.327
	2	124.3	115.1		2.333	2.319
6.2	1	123.3	114.7	2.419	2.358	2.340
	2	123.4	114.4		2.359	2.340

Volumetric properties at the three trial asphalt contents were plotted as shown in Figure 5-3. A summary of average volumetric properties is provided in

Table 5-6.



5-3 (a) %VFA vs. Asphalt Content *5-3 (b) %VMA vs. Asphalt Content*



5-3 (c) %VTM vs. Asphalt Content

Figure 5-3 Plots of Volumetric Properties for Trial Asphalt Contents

Table 5-6 Mixture Properties at N_{design} for Estimation of Optimum Asphalt Content

Mix Properties at N design	% Asphalt Binder in Total Mix		
% Asphalt Binder - Total Mix	5.2	5.7	6.2
G_{mb} @ Ndes	2.296	2.323	2.340
Max. Specific Gravity, Gmm	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 Nini (7)	87.3	88.9	90.5
% G_{mm} at Ndes (65)	94.0	95.9	97.5

From Figure 5-3, the optimum asphalt content was determined to be 6% by weight of the mixture. The same optimum binder content was used for the Warm Mix Asphalt mixtures based on recommendations from NCHRP 09-43 project, which found that the difference in average design binder content for HMA and WMA mixtures was not statistically significant [19]. Using the same optimum binder content also facilitated ease in comparing properties of the four mixtures considered in the study. The reference JMF recommended a design asphalt content of 5.7%. Since RAP was eliminated from the mix design in this study, increased value of optimum asphalt content is as expected.

5.4 Verification of Volumetric Properties

For the optimum asphalt content determined (6% by weight of mixture), three specimens each were compacted at 6% binder content for the HMA and all WMA mixtures at N_{des} value of 65 gyrations as specified in the JMF. Two loose mixtures each were also prepared to determine the Rice specific gravity. The volumetric properties of the compacted specimens from each mixture type were determined using the procedure detailed 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". Properties of the HMA, Sasobit®, Advera ® WMA and The Foamer specimens are detailed in Table 5-7.

Table 5-7 Mixture Properties at OAC (6%)

Mixture Type	Specimen	Height at N_{ini} (7)	Height at N_{des} (65)	G_{mm}	G_{mb} Estimated	G_{mb} Measured
HMA	1	132.8	115.8	2.432	2.326	2.335
	2	132.9	115.7		2.325	2.322
	3	133.1	116.1		2.324	2.326
Sasobit®	1	132.9	116.0	2.427	2.330	2.322
	2	132.8	115.2		2.351	2.336
	3	133.2	115.1		2.341	2.329
Advera® WMA	1	132.4	114.6	2.432	2.348	2.334
	2	133.0	115.1		2.345	2.333
	3	133.2	115.2		2.341	2.329
The Foamer	1	125.8	115.8	2.417	2.327	2.320
	2	126.2	115.9		2.322	2.313

	3	126.1	115.9		2.325	2.315

The average mixture volumetric properties for the four mixtures are summarized below in Table 5-8. The design traffic level specified in the JMF is 0.3 to 3 million ESALs (equivalent single axis load). The Superpave volumetric mixture design requirements at this traffic level [38] are also summarized in Table 5-8. It can be seen that all mixtures- HMA and WMA, meet the design specifications.

Table 5-8 Mixture Volumetric Properties at OAC for N_{des} Gyrations

Mix Properties at N_{des}	Asphalt Concrete Mix Technology				Volumetric Requirements
	HMA	Sasobit	Advera	Foamer	
% Asphalt Binder - Total Mix	6	6	6	6	
G_{mb} @ N_{des}	2.328	2.329	2.325	2.316	
Max. Specific Gravity, Gmm	2.432	2.427	2.432	2.417	
% VTM	4.4	4.0	4.1	4.2	4.0 ± 0.5
% Solids- Total Mix	95.7	96.0	95.9	95.8	
% Solids- Vol. of Agg. Only	83.0	83.5	83.7	83.0	
% VMA	17.0	16.5	16.3	17.0	> 15.0%
% VFA	74.2	75.5	75.0	74.3	65-78%
% G_{mm} at N_{ini} (7)	83.3	83.7	83.4	88.4	≤ 89.0%
% G_{mm} at N_{des} (65)	95.6	96.0	95.9	95.8	96%

From Table 5-8, it can be seen that the volumetric properties of HMA and WMA mixtures are similar. The data obtained support NCHRP project 09-43 recommendations on designing the optimum asphalt content for WMA mixtures using virgin binder and adopting the HMA mixture design procedure for WMA [19].

Workability of the WMA mixtures was similar to that of HMA even though the production temperatures are significantly lower. No differences in mixing time or difficulties in coating of aggregates were observed. The compaction effort for the different mixtures was compared using specimen heights at fixed intervals of gyrations in the SGC. Heights of each specimen were noted during compaction and the $\%G_{mm}$ calculated at these levels as shown in Table 5-9. The evolution of $\%G_{mm}$ attained for each mixture type was plotted in Figure 5-4. Similar values of $\%G_{mm}$ were observed for both WMA and HMA mixtures at every gyration level. This shows that WMA mixtures are as workable as HMA mixtures even with lower production temperatures.

Table 5-9 %G_{mm} Attained with Number of Gyrations

No. of Gyrations	% G_{mm}			
	HMA	*Sasobit®*	*Advera®*	*Foamer*
0	83.3	83.7	83.4	82.0
5	87.8	88.9	88.6	87.3
7	88.9	89.9	89.6	88.4
10	90.0	91.1	90.8	89.7
15	91.2	92.3	92.0	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	94.0
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	96.0	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	96.0	95.9	95.8

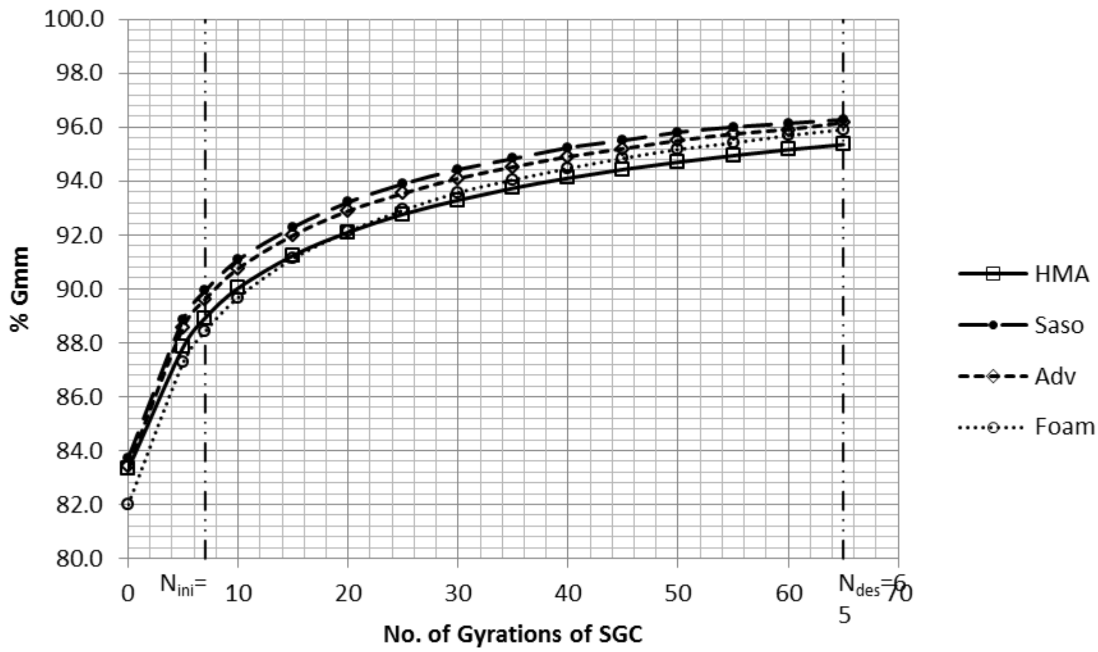


Figure 5-4 Evolution of %G_{mm} with Number of Gyrations

CHAPTER 6 TENSILE STRENGTH RATIO TEST

This chapter describes the processes involved in characterizing the mixtures for moisture-induced damage using the Tensile Strength Ratio (TSR) test. Tensile Strength Ratio for each mixture type was measured in accordance with modified AASHTO T 283, "Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage" followed by NCDOT. This test is performed to determine whether asphalt concrete mixture is susceptible to moisture damage and to assess the effectiveness of the anti-strip additive.

6.1 Specimen Preparation

To perform this test, two specimen subsets were prepared for each mixture, with 6 specimens in each subset, i.e. a total of 12 specimens per mixture type. The specimens were compacted to target air void content of 7 ± 0.5% with 150 mm diameter and 95 mm height. All the mixtures included 0.75% LOF 6500 liquid anti-strip additive by weight of binder.

As detailed in the standard test procedure, after mixing the binder with the aggregate at the appropriate mixing temperature (163°C for HMA and 135°C for WMA mixtures), the loose mixture was allowed to cool down for two hours at room temperature before being cured at 60°C for 16 hours. After the curing period, the mixture was heated to the appropriate compaction temperature (149°C for HMA and 120°C for WMA mixtures) for two hours. The mixtures were then compacted to 95 ± 5 mm height in the Superpave Gyratory Compactor.

6.2 Test Procedure

The air void content of each compacted specimens was determined using AASHTO T 331 procedure, "Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method". From each subset of samples, two specimens whose air voids exhibited the farthest deviation from the target 7% air void content were discarded.

The "conditioned" subset was vacuum-saturated with water to 70 - 80 percent saturation. If the saturation levels of the specimens exceeded 80%, they were discarded. The specimens were then placed in a water bath at 60°C for 24 hours. They were then cooled to room temperature by soaking in a water bath at 25°C for two hours. The unconditioned samples were maintained at 25°C in air and tested.

The specimens were diametrically loaded at 50.8 mm (2 in.) per minute using a Marshall Loader (shown in Figure 6-1). The testing jig and the orientation of the specimen are shown in Figure 6-2. The "unconditioned" subset acted as the control and they were tested at 25°C without any treatment. The peak load value was noted and the tensile strength was calculated for each specimen. The median of these values was denoted as the representative tensile strength for that subset. The tensile strength ratio was calculated for each mixture as shown below:

$$\text{TSR} = \frac{\text{Median Tensile Strength of Wet Subset}}{\text{Median Tensile Strength of Dry Subset}} \quad \ldots \text{(Equation 6-1)}$$

The broken surfaces of the samples were visually examined for evidence of stripping. NCDOT requires a minimum TSR value of 85% for a mixture to pass this test. Those mixtures which did not pass this test were repeated with an increased amount of anti-strip additive.

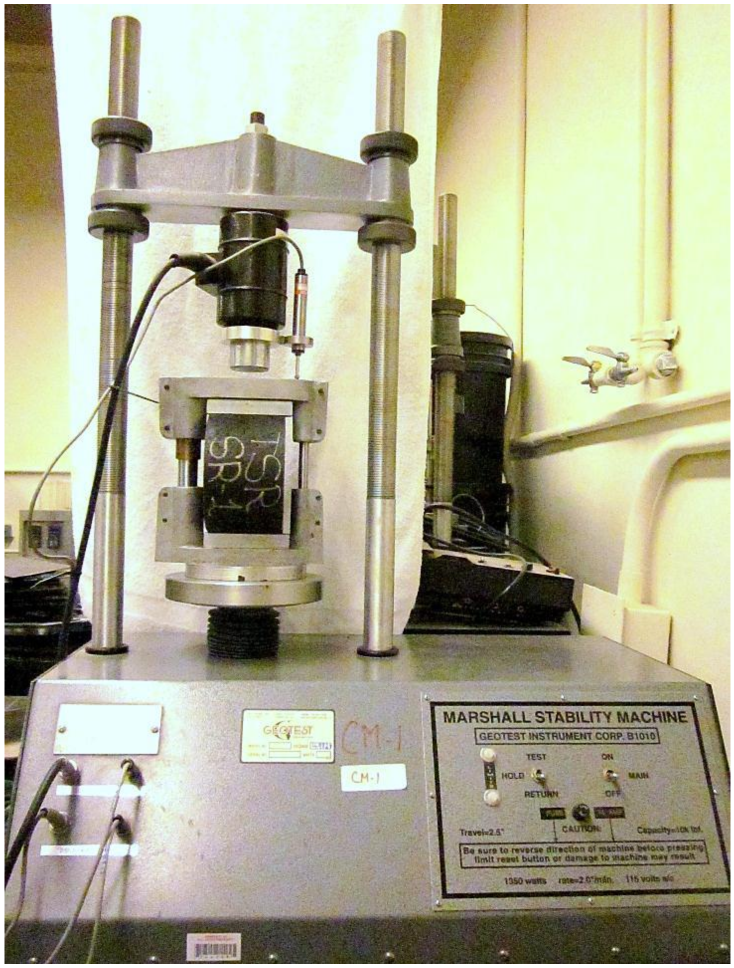


Figure 6-1 Marshall Loader Used for Testing Moisture-Induced Damage

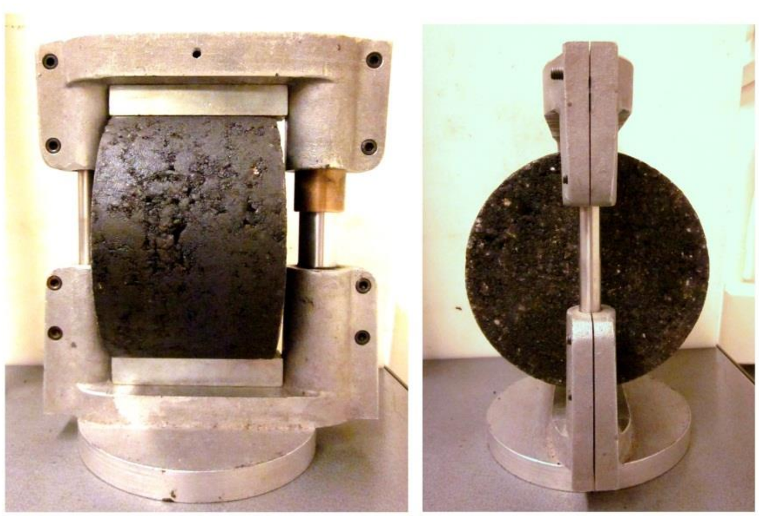


Figure 6-2 Indirect Tensile Strength Test Jig for Marshall Loader

6.3 Test Results

For the specimen nomenclature used in this report, the first character represents type of binder- i.e., C – conventional asphalt (virgin PG 64-22), S – Sasobit®, A – Advera® WMA and F – Foamer, and the second character indicates whether the specimen belongs to the unconditioned (U) subset or the conditioned (C) subset. Table 6-1 through

Table 6-7 show the worksheets used for calculating the TSR for each mixture. Visuals of broken surfaces of select conditioned specimens prepared using WMA mixtures are shown in Figure 6-3.

Table 6-1 HMA Mixture TSR Worksheet- with 0.75% Anti-Strip Additive

Mix Type: 9.5B HMA

Additive Grade: Ad-Here 6500 LOF Additive Dosage: 0.75%

Specimen Number	CU 1	CU 2	CU 3	CU 4	CC 1	CC 2	CC 3	CC 6
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	95.0	95.0	95.0	95.0	95.0	95.0	95.0	95.0
Dry Mass in Air (g)	3788.9	3783.3	3786.6	3784.6	3783.4	3789.6	3788.9	3787.0
Bulk Specific Gravity	2.239	2.245	2.229	2.245	2.252	2.253	2.248	2.251
Max. Specific Gravity	2.432	2.432	2.432	2.432	2.432	2.432	2.432	2.432
Air Voids (%)	7.5	7.4	7.4	7.4	7.4	7.4	7.5	7.4
Volume Air Voids (cc)	125.91	124.23	124.23	124.23	124.23	124.23	125.91	124.23
Peak Load (N)	22200	23210	24220	23210	***	***	***	***
Dry TS (kPa)	991.80	1036.9	1081.9	1036.9	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3871.1	3877.3	3877.7	3874.7
Calc. SSD at 80% Sat.	***	***	***	***	3883.6	3889.8	3890.4	3887.2

SSD Mass (g)	***	***	***	***	3875.3	3880.9	3882.5	3880.5
Vol. of water abs. (cc)	***	***	***	***	91.9	91.3	93.6	93.5
% Saturation	***	***	***	***	78.1	72.8	73.8	74.6
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	20850	19850	21530	19850
Wet TS (kPa)	***	***	***	***	931.46	886.65	961.80	886.65

	Avg. VTM ()	Avg. % Sat.	Median TS (kPa)
Unconditioned Subset	7.4	***	1036.9
Conditioned Subset	7.4	74.9	909.1
Tensile Strength Ratio (85% min)	87.7%		

Visual Stripping (check one)	None	Minor	Moderate	Severe
		X		

Table 6-2 WMA Mixture TSR Worksheet- Sasobit® with 0.75% Anti-Strip Additive

Mix Type: 9.5B Sasobit®

Additive Grade: Ad-Here 6500 LOF Additive Dosage: 0.75%

Specimen Number	SUA1	SUA2	SUA3	SUA4	SCA1	SCA2	SCA3	SCA4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	94.75	94.75	94.75	94.75	95.75	95.75	95.75	95.75
Dry Mass in Air (g)	3764.7	3780.6	3775.5	3779.1	3764.1	3773.3	3767.7	3778.5
Bulk Specific Gravity	2.238	2.252	2.248	2.253	2.250	2.256	2.256	2.262
Max. Specific Gravity	2.427	2.427	2.427	2.427	2.427	2.427	2.427	2.427
Air Voids (%)	7.8	7.2	7.4	7.2	7.3	7.0	7.1	6.8
Volume Air Voids (cc)	130.60	120.55	123.90	120.55	123.52	118.44	120.13	115.06
Peak Load (N)	***	19160	18820	18820	***	***	***	***
Dry TS (kPa)	***	858.23	843.17	843.17	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3850.3	3856.5	3851.4	3859.1
Calc. SSD at 80% Sat.	***	***	***	***	3862.6	3868.4	3863.4	3870.6

SSD Mass (g)	***	***	***	***	3850.0	3854.9	3843.9	3861.7
Vol. of water abs. (cc)	***	***	***	***	85.9	81.6	76.2	83.2
% Saturation	***	***	***	***	69.8	68.6	63.8	72.3
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	17820	18490	18820	19160
Wet TS (kPa)	***	***	***	***	789.67	819.47	834.37	849.26

	Avg. VTM		Avg. % Sat.		Median TS. (kPa)
Unconditioned Subset	7.3		***		850.7
Conditioned Subset	7.0		68.2		826.9
Tensile Strength Ratio (85% min)	97.2%				
Visual Stripping (check one)	None	Minor		Moderate	Severe
		X			

Table 6-3 WMA Mixture TSR Worksheet- Sasobit® with 1.5% Anti-Strip Additive

Mix Type: 9.5B Sasobit®

Additive Grade: Ad-Here 6500 LOF Additive Dosage: 1.50%

Specimen Number	SUB1	SUB2	SUB3	SUB4	SCB1	SCB2	SCB3	SCB4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	94.75	94.75	94.75	94.75	95.75	95.75	95.75	95.75
Dry Mass in Air (g)	3739.1	3770.2	3767.9	3797.7	3773.6	3766.7	3776.0	3755.0
Bulk Specific Gravity	2.233	2.248	2.243	2.261	2.258	2.263	2.258	2.261
Max. Specific Gravity	2.427	2.427	2.427	2.427	2.427	2.427	2.427	2.427
Air Voids (%)	8.0	7.4	7.6	6.8	7.0	7.2	7.0	6.8
Volume Air Voids (cc)	133.95	123.01	127.26	113.86	118.44	121.83	118.44	115.05
Peak Load (N)	***	17480	17140	18150	***	***	***	***
Dry TS (kPa)	***	782.94	767.89	813.06	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3856.3	3851.4	3858.5	3836.1
Calc. SSD at 80% Sat.	***	***	***	***	3868.1	3863.5	3870.3	3847.7

SSD Mass (g)	***	***	***	***	3857.8	3860.3	3856.0	3854.4
Vol. of water abs. (cc)	***	***	***	***	84.2	93.6	80.0	99.4
% Saturation	***	***	***	***	71.3	77.4	67.9	85.7
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	19160	18150	18490	***
Wet TS (kPa)	***	***	***	***	849.26	804.57	819.47	***

	Avg. VTM (%)		Avg. % Sat.		Median TS. (kPa)
Unconditioned Subset	7.3		***		798.00
Conditioned Subset	7.1		72.2		812.02
Tensile Strength Ratio (85% min)	101.8%				
Visual Stripping (check one)	None	Minor	Moderate		Severe
		X			

Table 6-4 WMA Mixture TSR Worksheet- Advera® with 0.75% Anti-Strip Additive

Mix Type: 9.5B Advera® WMA

Additive Grade: Ad-Here 6500 LOF   Additive Dosage: 0.75%

Specimen Number	AUA1	AUA2	AUA3	AUA4	ACA1	ACA2	ACA3	ACA4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	94.75	94.75	94.75	94.75	95.75	95.75	95.75	95.75
Dry Mass in Air (g)	3779.6	3784.8	3784.1	3783.2	3771.4	3786.8	3778.8	3783.8
Bulk Specific Gravity	2.259	2.264	2.263	2.262	2.251	2.265	2.262	2.263
Max. Specific Gravity	2.432	2.432	2.432	2.432	2.432	2.432	2.432	2.432
Air Voids (%)	7.1	6.9	6.9	7.0	7.4	6.9	7.0	6.9
Volume Air Voids (cc)	118.88	115.53	115.53	117.20	125.21	116.75	118.44	116.75
Peak Load (N)	19160	18820	19160	19160	***	***	***	***
Dry TS (kPa)	858.23	843.17	858.23	858.23	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3859.4	3868.2	3861.5	3865.9
Calc. SSD at 80% Sat.	***	***	***	***	3872.0	3879.8	3873.3	3877.6

SSD Mass (g)	***	***	***	***	3856.0	3861.7	3865.4	3871.3
Vol. of water abs. (cc)	***	***	***	***	84.6	74.9	86.6	87.5
% Saturation	***	***	***	***	67.3	64.4	73.5	74.6
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	10760	12440	10760	10760
Wet TS (kPa)	***	***	***	***	476.78	551.28	476.78	476.78

	Avg. VTM		Avg. % Sat.		Median TS. (kPa)
Unconditioned Subset	7.0		***		858.23
Conditioned Subset	7.0		70.0		476.78
Tensile Strength Ratio (85% min)	55.6%				
Visual Stripping (check one)	None	Minor	Moderate	Severe	
			X		

Table 6-5 WMA Mixture TSR Worksheet- Advera® with 1.5% Anti-Strip Additive

Mix Type: 9.5B Advera® WMA

Additive Grade: Ad-Here 6500 LOF Additive Dosage: 1.50%

Specimen Number	AUB1	AUB2	AUB3	AUB4	ACB1	ACB2	ACB3	ACB4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	94.75	94.75	94.75	94.75	95.75	95.75	95.75	95.75
Dry Mass in Air (g)	3778.3	3777.3	3776.6	3774.2	3785.6	3778.1	3781.1	3783.7
Bulk Specific Gravity	2.244	2.248	2.252	2.253	2.265	2.261	2.262	2.265
Max. Specific Gravity	2.432	2.432	2.432	2.432	2.432	2.432	2.432	2.432
Air Voids (%)	7.0	7.0	7.4	7.3	6.8	7.0	7.0	6.9
Volume Air Voids (cc)	117.20	117.20	123.90	122.23	115.06	118.44	118.44	116.75
Peak Load (N)	16810	16810	17140	16810	***	***	***	***
Dry TS (kPa)	752.83	752.83	767.89	752.83	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3866.7	3861.5	3863.8	3865.1
Calc. SSD at 80% Sat.	***	***	***	***	3878.2	3873.4	3875.6	3876.7

SSD Mass (g)	***	***	***	***	3869.3	3866.4	3869.5	3869.0
Vol. of water abs. (cc)	***	***	***	***	83.7	88.3	88.4	85.3
% Saturation	***	***	***	***	72.2	74.1	74.8	73.4
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	12100	11090	10760	10420
Wet TS (kPa)	***	***	***	***	536.38	491.68	476.78	461.88

	Avg. VTM		Avg. % Sat.		Median TS. (kPa)
Unconditioned Subset	7.2		***		760.36
Conditioned Subset	7.0		73.6		484.23
Tensile Strength Ratio (85% min)	63.7%				
Visual Stripping (check one)	None	Minor		Moderate	Severe
				X	

Table 6-6 WMA Mixture TSR Worksheet- Foamer with 0.75% Anti-Strip Additive

Mix Type: 9.5B Foamer

Additive Grade: Ad-Here 6500 LOF Additive Dosage: 0.75%

Specimen Number	FU 1	FU 2	FU 3	FU 4	FC 1	FC 2	FC 3	FC 4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	94.75	94.75	94.75	94.75	95.75	95.75	95.75	95.75
Dry Mass in Air (g)	3772.5	3780.2	3785.0	3784.3	3755.1	3756.2	3797.2	3767.3
Bulk Specific Gravity	2.247	2.254	2.255	2.240	2.248	2.244	2.274	2.258
Max. Specific Gravity	2.417	2.417	2.417	2.417	2.417	2.417	2.417	2.417
Air Voids (%)	7.6	7.3	7.3	7.3	7.6	7.7	6.5	7.2
Volume Air Voids (cc)	128.93	122.23	122.23	122.23	115.06	118.44	118.44	116.75
Peak Load (N)	20170	19830	19830	19500	***	***	***	***
Dry TS (kPa)	903.4	888.34	888.34	873.28	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3845.1	3847.4	***	3852.6
Calc. SSD at 80% Sat.	***	***	***	***	3858.6	3860.4	***	3864.8

SSD Mass (g)	***	***	***	***	3845.9	3850.7	***	3853.0
Vol. of water abs. (cc)	***	***	***	***	90.8	94..5	***	85.7
% Saturation	***	***	***	***	70.6	72.5	***	70.3
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	15800	15460	***	15800
Wet TS (kPa)	***	***	***	***	700.27	685.37	***	700.27

	Avg. VTM		Avg. % Sat.		Median TS. (kPa)
Unconditioned Subset	7.4		***		888.34
Conditioned Subset	7.4		71.1		700.27
Tensile Strength Ratio (85% min)	78.8%				
Visual Stripping (check one)	None	Minor		Moderate	Severe
				X	

Table 6-7 WMA Mixture TSR Worksheet- Foamer with 1.5% Anti-Strip Additive

Mix Type: 9.5B Foamer

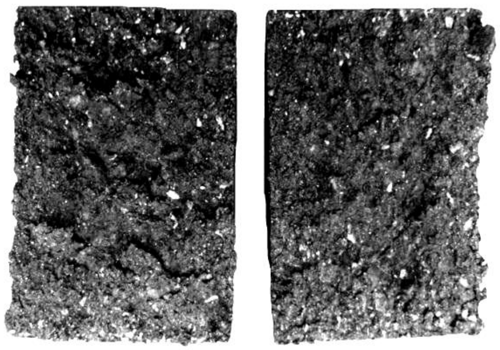
Additive Grade: Ad-Here 6500 LOF Additive Dosage: 1.50%

Specimen Number	FU 1	FU 2	FU 3	FU 4	FC 1	FC 2	FC 3	FC 4
Diameter (mm)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Height (mm)	95.0	95.0	95.0	95.0	95.0	95.0	95.0	95.0
Dry Mass in Air (g)	3771.2	3778.5	3773.6	3768.8	3765.5	3768.0	3770.8	3765.7
Bulk Specific Gravity	2.250	2.258	2.255	2.249	2.250	2.253	2.251	2.247
Max. Specific Gravity	2.417	2.417	2.417	2.417	2.417	2.417	2.417	2.417
Air Voids (%)	6.9	6.6	6.7	7.0	6.9	6.8	6.9	7.0
Volume Air Voids (cc)	115.84	110.80	112.48	117.52	115.84	114.16	115.84	117.52
Peak Load (N)	20180	19850	19510	19850	***	***	***	***
Dry TS (kPa)	901.63	886.60	871.58	886.60	***	***	***	***
Calc. SSD at 70% Sat.	***	***	***	***	3846.6	3847.9	3851.9	3848.0
Calc. SSD at 80% Sat.	***	***	***	***	3858.2	3859.3	3863.5	3859.7

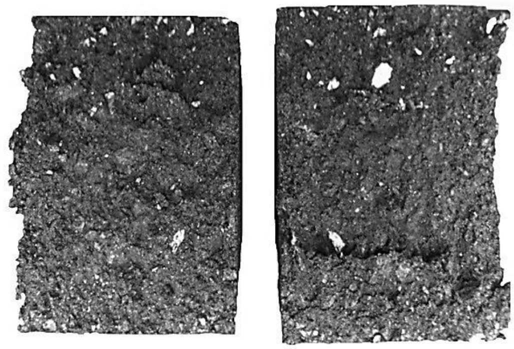
SSD Mass (g)	***	***	***	***	3852.8	3852.8	3857.7	3855.3
Vol. of water abs. (cc)	***	***	***	***	87.3	84.8	86.9	89.6
% Saturation	***	***	***	***	75.4	74.3	75.0	76.2
Conditioned 24 hours in water bath at 140°F (60°C)								
Peak Load (N)	***	***	***	***	16150	16150	15810	16490
Wet TS (kPa)	***	***	***	***	721.31	721.31	706.28	736.33

	Avg. VTM	Avg. % Sat.	Median TS. (kPa)
Unconditioned Subset	6.8	***	886.60
Conditioned Subset	6.9	75.2	721.31
Tensile Strength Ratio (85% min)	81.4%		

Visual Stripping (check one)	None	Minor	Moderate	Severe
			X	



Sasobit® with 0.75% LOF 6500



Sasobit® with 1.5% LOF 6500

Advera® WMA, 0.75% LOF 6500

Advera® WMA, 1.5% LOF 6500

Foamer with 0.75% LOF 6500

Foamer with 1.5% LOF 6500

Figure 6-3 Broken Surfaces of Conditioned TSR Specimens for WMA Mixtures

A summary of TSR test results is shown in Table 6-8 and Figure 6-4.

Table 6-8 Summary of TSR Tests for Moisture Susceptibility

Mixture Type	Median Indirect Tensile Strength (kPa)		TSR (%)	Pass/Fail (Min. 85%)
	Conditioned	*Unconditioned*		
HMA with 0.75% LOF 6500	909	1037	87.7	Pass
Sasobit® with 0.75% LOF 6500	827	851	97.2	Pass
Sasobit® with 1.5% LOF 6500	812	798	101.8	Pass
Advera® WMA with 0.75% LOF 6500	477	858	55.6	Fail
Advera® WMA with 1.5% LOF 6500	484	760	63.7	Fail
Foamed Asphalt with 0.75% LOF 6500	700	888	78.8	Fail
Foamed Asphalt with 1.5% LOF 6500	721	887	81.4	Fail

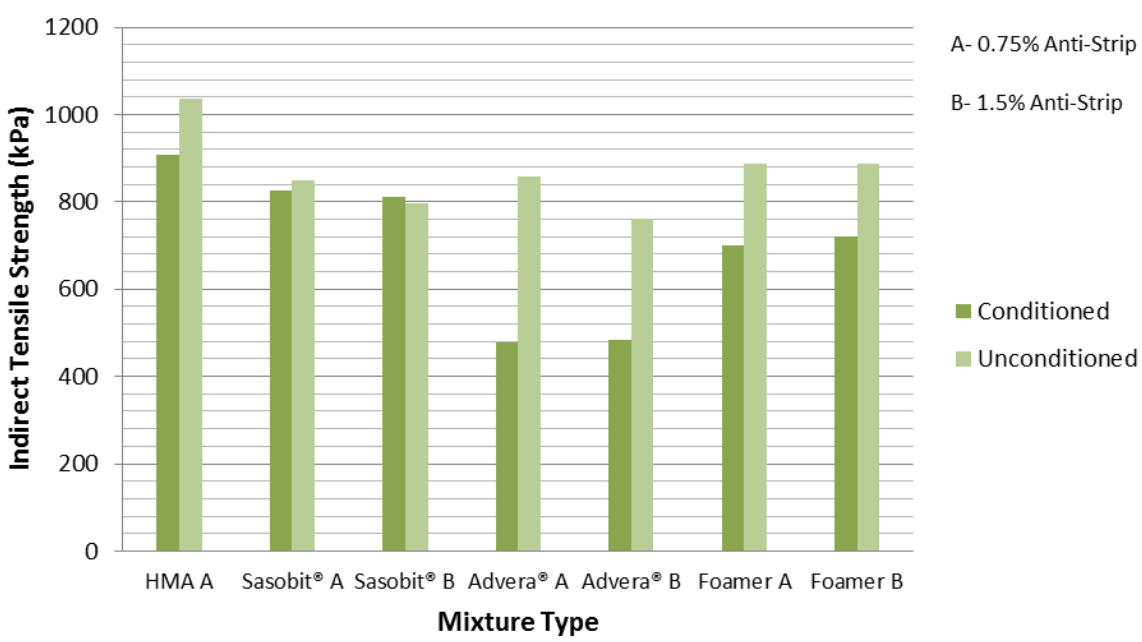


Figure 6-4 Indirect Tensile Strength Values for Different Mixture Types

6.4 Discussion of Test Results

The results of the TSR test were analyzed as a 3x2x2 multi-factor experiment using the statistical analysis software, SAS. The three factors used in the design were:

i. Type of technology used in mixture production, represented as "Type" with 4 levels - "HMA", Advera® WMA- "Adv", The Foamer- "Foam" and Sasobit®- "Saso".
ii. Moisture conditioning applied, represented as "Treatment" with 2 levels – conditioned "Cond" and unconditioned "Uncond".
iii. Amount of anti-strip additive, represented as "LOF"- 0.75% (normal- "N") and 1.5% (double- "D").

The indirect tensile strength values "Tensile_Str" were modeled as a function of Type, Treatment and LOF along with first and second-order interactions. The results of this procedure in SAS are summarized in Table 6-9.

Comparing the p-values with a significance level (α) of 5%, it can be seen that effect of mixture type, treatment and amount of anti-strip additive on tensile strength values are statistically significant. This implies that, as is expected, the value of tensile strength is dependent on type of mixture, moisture conditioning as well as amount of anti-strip additive. The analysis also shows that all three first-order interactions of the factors are significant. The three implications of these interactions are:

iv. The effect of mixture type on tensile strength values depends on moisture-conditioning of the samples and vice versa (Type*Treatment)
v. The effect of mixture type on tensile strength depends on the amount of anti-strip additive added and vice versa (Type*LOF)
vi. The effect of moisture conditioning on tensile strength depends on the amount of anti-strip additive and vice versa (Treatment*LOF).

The second-order interaction (Type*Treatment*LOF) is not found to be statistically significant at 5% significance level.

Table 6-9 Multi-Factor ANOVA of TSR Test Results Using SAS

The SAS System		
The GLM Procedure		
Class Level Information		
Class	**Levels**	**Values**
Type	4	Adv Foam HMA Saso
Treatment	2	Cond Uncond
LOF	2	D N
Number of Observations Read	52	
Number of Observations Used	52	

Dependent Variable: Tensile_Str

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	13	1171758.617	90135.278	159.91	<.0001
Error	38	21419.349	563.667		
Corrected Total	51	1193177.966			

R-Square	Coeff. of Var	Root MSE	Tensile_Str Mean
0.982048	3.014663	23.74167	787.5400

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Type	3	610234.7236	203411.5745	360.87	<.0001
Treatment	1	350657.3447	350657.3447	622.10	<.0001
Type*Treatment	3	185072.9408	61690.9803	109.45	<.0001
LOF	1	5732.6553	5732.6553	10.17	0.0029
Type*LOF	2	7464.6688	3732.3344	6.62	0.0034
Treatment*LOF	1	10479.4055	10479.4055	18.59	0.0001
Type*Treatment*LOF	2	2116.8764	1058.4392	1.88	0.1668

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Type	3	529491.4098	176497.1366	313.12	<.0001
Treatment	1	277005.5885	277005.5885	491.43	<.0001
Type*Treatment	3	188939.9810	62979.9937	111.73	<.0001
LOF	1	5574.4656	5574.4656	9.89	0.0032
Type*LOF	2	7762.6512	3891.4256	6.90	0.0028
Treatment*LOF	1	10085.6251	10085.6251	17.89	0.0001
Type*Treatment*LOF	2	2116.8784	1058.4392	1.88	0.1668

To estimate the values of these effects, the values were re-analyzed in SAS as a one-factor ANOVA as shown in Table 6-10. The factor TSR_Mixture labels the specimens by mixture type, moisture conditioning as well as amount of anti-strip additive present. For example, "Adv Cond D" refers to a specimen from the conditioned subset of Advera® WMA mixture with double (1.5%) liquid anti-strip.

Table 6-10 One-Factor ANOVA of TSR Test Results Using SAS

The SAS System		
The GLM Procedure		
Class Level Information		
Class	**Levels**	**Values**
TSR_Mixture	14	Adv Cond D, Adv Cond N, Adv Uncond D, Adv Uncond N, Foam Cond D, Foam Cond N, Foam Uncond D, Foam Uncond N, HMA Cond N, HMA Uncond N, Saso Cond D, Saso Cond N, Saso Uncond D, Saso Uncond N
Number of Observations Read	52	
Number of Observations Used	52	

Dependent Variable: Tensile_Str

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	13	1171758.617	90135.278	159.91	<.0001
Error	38	21419.349	563.667		
Corrected Total	51	1193177.966			

R-Square	Coeff. of Var	Root MSE	Tensile_Str Mean
0.982048	3.014663	23.74167	787.5400

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TSR_Mixture	13	1171758.617	90135.278	159.91	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TSR_Mixture	13	1171758.617	90135.278	159.91	<.0001

It is of interest to test the significance the effects of amount of anti-strip additive and moisture conditioning on tensile strength values for each mixture type. The effect of amount of liquid anti-strip on moisture conditioning was also tested separately for each mixture type. The results obtained are shown in Table 6-11.

Table 6-11 Estimates of Linear Combination of Factors of TSR Test in SAS

Parameter- Effect of	Estimate	Std. Error	t Value	Pr > |t|
LOF 6500 on Conditioned Advera Mixtures	-3.725000.	16.7878965	-0.22	0.8256
LOF 6500 on Unconditioned Advera Mixtures	-97.870000	16.7878965	-5.83	<.0001
LOF 6500 on Conditioned Foamer Mixtures	26.004167	18.1330029	1.43	0.1597
LOF 6500 on Unconditioned Foamer Mixtures	-1.737500	16.7878985	-0.10	0.9181
LOF 6500 on Conditioned Sasobit Mixtures	1.240833	18.1330029	0.07	0.9458
LOF 6500 on Unconditioned Sasobit Mixtures	-60.226667	19.3849955	-3.11	0.0036
LOF 6500 on Advera Mixtures	-50.797500	11.8708369	-4.28	0.0001
LOF 6500 on Foamer Mixtures	12.133333	12.3555568	0.98	0.3323
LOF 6500 on Sasobit Mixtures	-29.492917	13.2719991	-2.22	0.0323
Moisture conditioning on Advera Mixtures	311.987500	11.8708369	26.28	<.0001
Moisture conditioning on Foamer Mixtures	179.165833	12.3555588	14.50	<.0001
Moisture conditioning on HMA Mixtures	120.235000	16.7878965	7.16	<.0001
Moisture conditioning on Sasobit Mixtures	-5.736250	13.2719991	-0.43	0.6680

The values which are statistically significant at 95% confidence level are highlighted. Pairwise differences in unconditioned and conditioned tensile strengths of different mixtures were also evaluated as shown in Table 6-12.

Table 6-12 Pairwise Differences in Unconditioned and Conditioned Tensile Strengths

Parameter- Difference in	Estimate	Std. Error	t Value	Pr > |t|
Conditioned TS of HMA and Advera	421.235000	16.7878985	25.09	<.0001
Conditioned TS of HMA and Foamer	221.336667	18.1330029	12.21	<.0001
Conditioned TS of HMA and Sasobit	93.447500	16.7878985	5.57	<.0001
Conditioned TS of Foamer and Advera	214.762917	12.3555588	11.38	<.0001
Conditioned TS of Sasobit and Advera	330.210417	12.3555588	26.73	<.0001
Conditioned TS of Sasobit and Foamer	115.507500	12.8219693	9.01	<.0001
Unconditioned TS of HMA and Advera	182.410000	16.7878985	10.81	<.0001
Unconditioned TS of HMA and Foamer	148.535000	16.7878985	8.85	<.0001
Unconditioned TS of HMA and Sasobit	188.685000	18.1330029	10.41	<.0001
Unconditioned TS of Foamer and Advera	81.941250	11.8708369	6.90	<.0001
Unconditioned TS of Sasobit and Advera	12.546667	12.8219693	0.98	<.0001
Unconditioned TS of Sasobit and Foamer	-69.394583	12.8219693	-5.41	<.0001

All pairwise differences, except that between average unconditioned tensile strengths of Sasobit® and Advera® WMA mixtures are significant the 95% confidence level. The TSR test results and the statistical analysis results are discussed in detail for each mixture type.

HMA Mixtures

The TSR test was performed on Hot Mix Asphalt specimens containing 0.75% Anti-Strip Additive (AD-Here LOF 65-00) by weight of asphalt binder. The TSR value obtained for this mixture was about 88%, which satisfies the NCDOT minimum requirement of 85%. Visual observation of the broken faces of tested specimens also did not reveal much evidence for stripping. Thus, as per the test criteria, these mixtures are expected to show good resistance to moisture-induced damage. The test was not repeated with doubled amount of anti-strip additive as the minimum TSR criterion was already met. The tensile strengths of moisture conditioned HMA specimens are on average, 120.23 kPa less than the unconditioned specimens. This difference is statistically significant. Of all the mixtures tested, the individual tensile strength values were highest for this mixture for both unconditioned and conditioned sets. Even the median tensile strength of the conditioned subset of HMA specimens was higher than all the tensile strength values for WMA mixtures.

Sasobit® Mixtures

The WMA mixtures prepared using Sasobit® have performed exceedingly well. These specimens are the only ones to not show a significant effect of moisture conditioning on the tensile strength values. The TSR values are close to 100%. Greater than 100% TSR value of the mixture using 1.5% LOF could be due to variation in the measured air void content of the specimens. As the mixture is fine, it was difficult to achieve 70% saturation in the conditioned set even after multiple attempts. This could also have contributed to the high TSR value. Visual inspection of broken faces of the specimens after testing showed very little stripping of binder from the aggregates.

By reducing the viscosity of the binder, Sasobit® can increase the effectiveness with which the aggregate particles are coated. With efficient coating, binder stripping will reduce. Sasol Wax has combined Sasobit® and SBS (Polystyrene-butadiene-styrene) to create a product called Sasolwax® Flex, which claims to reduce the need for anti-stripping agents based on these principles [39]. NCAT study on Sasobit® has also observed an increase in TSR value with the use of anti-strip additive in Sasobit® mixtures. They tested mixtures containing granite aggregate and PG 64-22 binder modified with Sasobit®. After the use of 0.4% Magnabond liquid anti-stripping agent, the TSR values rose from 71% to 94% [5]. Thus, further studies on the performance of Sasobit® mixtures without the use of anti-strip agents need to be done.

Even though the TSR percentage values are higher for Sasobit® mixtures than those for HMA, both sets of conditioned as wells as unconditioned median tensile strength values for Sasobit® mixtures are less than that of even the conditioned HMA set. Therefore, the resistance of Sasobit® mixtures to moisture-induced damage may not necessarily be more than that of HMA. The median tensile strength value for unconditioned HMA specimens was found to be 1036.9 kPa while the Sasobit® mixtures had median tensile strengths of 850.7 kPa and 798 kPa with 0.75% and 1.5% anti-strip additive dosage respectively.

Increasing the amount of liquid anti-strip significantly reduced the average tensile strength values of the unconditioned specimens by about 60 kPa while the strength of the conditioned Sasobit® specimens remained almost unaffected. A part of this difference can be attributed to difference in air void contents of the specimens. This reduction in tensile strengths is not desirable as the stiffness of the mixture is being compromised. Therefore, any increase in TSR values by the addition of higher percentages of liquid anti-stripping agent could be a result of reduced dry tensile strengths. This may not be a desired improvement as the actual strength of the mix in the unconditioned state is decreasing. Thus, increasing the amount of anti-stripping agent to improve the TSR value is not recommended.

Advera® WMA Mixtures

The WMA specimens made using Advera® WMA did not satisfy the minimum TSR criterion as specified by the NCDOT. Advera® specimens exhibited the lowest TSR values of all the mixtures at 55.6% and 63.7% for 0.75% and 1.5% anti-strip additive contents, respectively. Visual examination of the broken faces of these specimens exhibited moderate to severe stripping. For Advera® specimens, increase in anti-strip dosage from 0.75% to 1.5% led to a significant reduction in unconditioned mix strength. Increasing the anti-strip dosage did not affect the tensile strength of conditioned subset significantly. Overall, the addition of anti-strip additive affected the tensile strength values for Advera® mixtures significantly. The effect of moisture conditioning is very pronounced in these specimens. There is a wide disparity in the tensile strength values of the unconditioned and conditioned samples, indicating the lower resistance to moisture-induced damage.

Being a zeolite, Advera® WMA induces microscopic moisture bubbles when mixed with the heated asphalt binder. This foaming property is exploited while using it for mixing and compacting mixtures at lower temperatures. Cohesive failure of asphalt can occur due to residual moisture left behind in the specimen after the foaming process. Previous studies with moisture-inducing WMA zeolite technologies have observed failing TSR results [6], [40], [41].

However, WMA mixtures prepared using Advera® for the Massachusetts WMA study that failed the minimum TSR requirement according to AASHTO T-283 did not exhibit any moisture susceptibility for in-situ pavement sections constructed in the state of Massachusetts [41]. This indicates that the TSR test may not be able to fully capture the moisture-susceptibility of warm mix asphalt mixtures.

Foamer Mixtures

Specimens prepared using The Foamer device resulted in TSR ratios of 78.8% and 81.4% for 0.75% and 1.5% of anti-strip additive. Although this value does not satisfy the NCDOT minimum criterion of 85%, the foamed asphalt mixture with 1.5% LOF 65-00 passes the minimum Superpave requirement as per Sp-2 [38]. Ali (2010) has reported a TSR value of 75% for WMA mixtures prepared using foamed asphalt and limestone aggregate [42]. The better performance of mixtures prepared using The Foamer as opposed to Advera® WMA may be due to the size of moisture bubbles introduced in the binder by the two technologies. Since the water bubbles introduced by zeolites like Advera® WMA are microscopic, they may be retained in the mixture even after mixing and compaction of the specimens is completed. The foam produced by devices like The Foamer quickly dissipates in the process of mixing. On an average, Foamer specimens exhibited indirect tensile strength values of about 82 kPa and 215 kPa more than Advera® specimens for the unconditioned and conditioned subsets respectively. There was no significant difference between unconditioned tensile strengths of Foamer and Sasobit specimens.

6.5 General Comments

An internet-based survey was conducted by Mogawer et al. to collect information about moisture susceptibility of WMA from different state DOTs [40]. All the respondents indicated that no problems were observed with respect to moisture susceptibility of WMA mixtures in the field. However, almost all studies reviewed have indicated non-compliant TSR values for WMA mixtures in laboratory evaluations. This indicates that the traditional TSR may not be the best indicator for assessing the moisture susceptibility of WMA mixtures.

The difference in moisture susceptibility of field and laboratory-prepared WMA mixtures is explained by Austerman et al. in terms of lower stiffness of laboratory-prepared WMA mixes as compared to conventional HMA mixes [41]. Hamburg Wheel Tracking Device (HWTD) is an alternative to AASHTO T-283, as shown by Hurley et al. [20] and Austerman et al. [41]. Results from both these studies report significant reduction in moisture susceptibility of WMA mixtures compared to TSR measured using AASHTO T-283. Encouraging results on the use of E* Stiffness Ratio (ESR) using Dynamic Modulus tests as an indicator of moisture susceptibility have been reported by Nadkarni et al. [43].

CHAPTER 7 RUT DEPTH USING APA TESTING

This chapter provides the details of Asphalt Pavement Analyzer (APA) tests conducted on the four mixtures for characterizing their rutting potential. All four mixtures were tested for susceptibility to permanent deformation using the procedure detailed in AASHTO TP 63-09, "Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)".

7.1 Testing Equipment

The Asphalt Pavement Analyzer is manufactured by Pavement Technology, Inc. [44]. This Loaded Wheel Tester (LWT) can be used to evaluate permanent deformation (rutting), fatigue cracking and moisture susceptibility of asphalt concrete mixtures. Figure 7-1 shows the APA device used for testing specimens in this study.

The APA has three sets of wheels (left, center and right) and tests 6 cylindrical specimens at a time with 2 specimens tested simultaneously under each wheel. The wheels of APA apply repetitive linear loads through 100 psi pressurized hoses. The test is normally run to 8000 cycles and the average rut depth for each position is tracked with every cycle.

7.2 Specimen Preparation

Twelve specimens were prepared for each of the four mixture types. The specimens were compacted to 7.0 ± 0.5 percent air voids with a height of 75 ± 2 mm height. The pre-determined mixing and compaction temperatures were used- 163°C and 149°C for HMA, and 135°C and 120°C for WMA mixtures, respectively. After mixing, the 12 samples prepared for each mixture were divided into two sets- A and B. Subset A specimens for all four mixtures were aged for 4 hours at 135°C according to AASHTO R30, "Standard Practice for Mixture Conditioning of Hot Mix Asphalt". Subset B of WMA mixtures were aged for 8 hours.

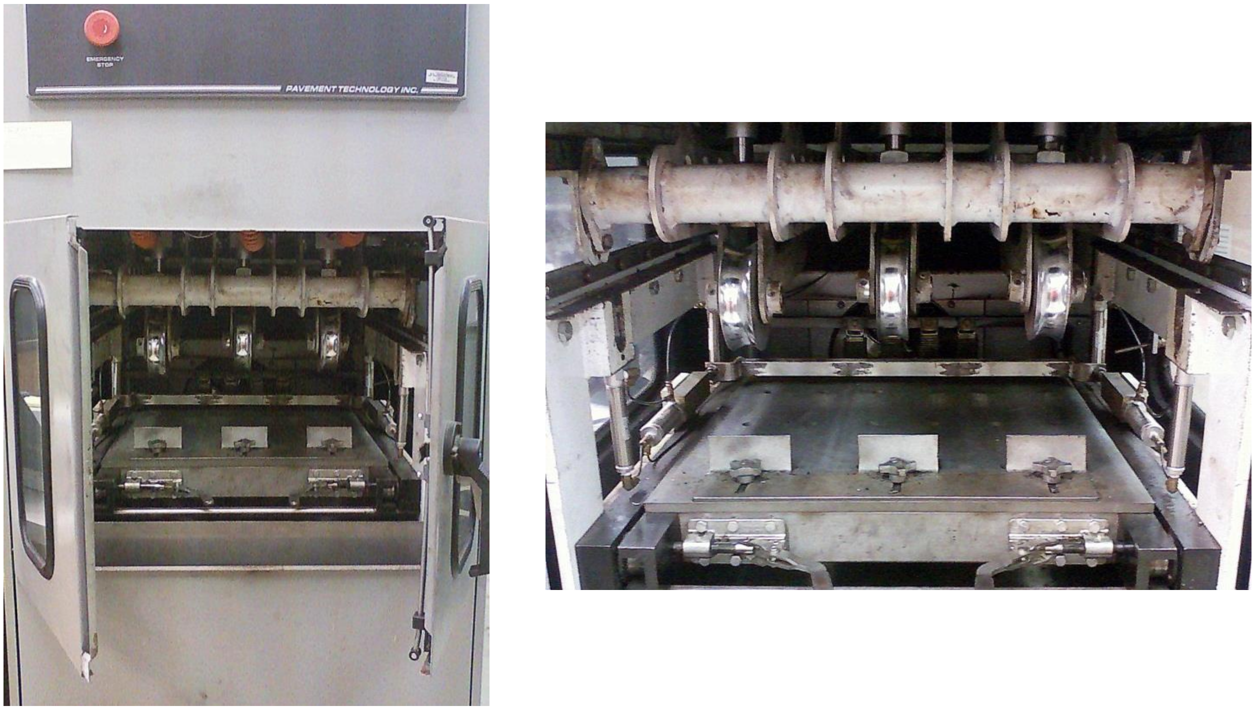


Figure 7-1 Asphalt Pavement Analyzer Used for Testing Rutting Susceptibility

Ageing time for all HMA specimens in both subsets was kept constant at 4 hours. As per the protocol, unconditioned specimens were tested. A matrix of APA test samples is given in Table 7-1**Error! Reference source not found.**. For specimen nomenclature, the prefix "H" was given for HMA mixtures, "S" for Sasobit®, "A" for Advera® WMA and "F" for specimens prepared using The Foamer device. This prefix was followed by the letter "A" or "B" to help identify the specimen's corresponding subset.

Table 7-1 Matrix of APA Test Specimens

Mixture Technology	**No. of APA Test Replicates**		**Specimen Nomenclature**	
	4 hour ageing	*8 hour ageing*	*4 hour ageing*	*8 hour ageing*
HMA	12	-	HA, HB	-
Sasobit®	6	6	SA	SB
Advera® WMA	6	6	AA	AB
The Foamer	6	6	FA	FB

Before running APA tests, the bulk specific gravity and percent air voids of all specimens were measured using the procedure 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".

The percent air voids of the APA specimens for HMA, Advera ® WMA, The Foamer and Sasobit® mixtures are summarized in Table 7-2.

Table 7-2 Specimen Air Voids for APA Test

HMA		**Advera® WMA**		**The Foamer**		**Sasobit®**	
Specimen Number	***Air Voids %***	***Specimen Number***	***Air Voids %***	***Specimen Number***	***Air Voids %***	***Specimen Number***	***Air Voids %***
HA 1	7.5	AA 1	7.5	FA 1	7.0	SA 1	7.1
HA 2	7.2	AA 2	7.3	FA 2	6.8	SA 2	7.0
HA 3	7.1	AA 3	7.1	FA 3	6.8	SA 3	6.9
HA 4	7.4	AA 4	7.2	FA 4	7.4	SA 4	7.0
HA 5	7.3	AA 5	7.1	FA 5	6.6	SA 5	7.0
HA 6	7.1	AA 6	7.3	FA 6	7.0	SA 6	7.2
Average = 7.3		*Average = 7.2*		*Average = 6.9*		*Average = 7.0*	
HB 1	7.2	AB 1	7.5	FB 1	6.9	SB 1	7.3
HB 2	7.3	AB 2	7.2	FB 2	6.7	SB 2	7.5
HB 3	7.2	AB 3	7.2	FB 3	6.6	SB 3	7.3
HB 4	7.4	AB 4	7.3	FB 4	6.8	SB 4	7.4
HB 5	7.3	AB 5	7.1	FB 5	6.8	SB 5	7.0
HB 6	7.0	**AB 6**	7.4	FB 6	6.8	SB 6	7.1
Average = 7.2		*Average = 7.3*		*Average = 6.8*		*Average = 7.3*	

7.3 Test Procedure

The APA test specimens were prepared at NC State University and tested by NCDOT Materials and Tests Unit. The APA test for rutting susceptibility is performed at the high temperature grade of the binder used. Since the binder used in this study was PG 64-22, the tests were conducted at 64°C. The specimens were preheated to 64°C for 5 hours before the test. The APA was set to exert 120 lbf. (533.8 N) of load on each wheel with a hose pressure of 120 psi. At a time one set of six specimens were tested to 8000 cycles of wheel passes. Testing was performed at a frequency of 60 wheel passes per minute. Figure 7-2 shows a typical specimen after testing. The average rut depth of two specimens under each wheel position- left, right and center were measured for every cycle pass by an automated rut-depth measurement system. At the end of the test, the standard deviation between the final rut depth averages at each position was computed.

AASHTO TP 63-09 specifies that this value should be less than 2.0 mm to report rut-depth for a mixture as the overall average of the three test positions.

Figure 7-2 Rutted Specimen after Performing APA Test

7.4 Test Results

The average rut depths obtained under each wheel position along with standard deviation for the four mixtures are shown in Table 7-3. Standard deviations amongst all the test run averages were within the specified limit of 2.0 mm. Since HMA sets A and B are identical in ageing time and average percent air voids, the overall rut depth of HMA can be considered as the average of these two sets.

Table 7-3 Summary of APA Test Results

Mixture Type	Final Rut Depths (mm)			Standard Deviation (mm)	Total Average (mm)
	Left	*Center*	*Right*		
HMA - A	5.3	4.5	5.2	0.4	5.0
HMA - B	4.6	3.6	5.1	0.8	4.4
Advera - A	4.9	4.8	5.2	0.2	5.0
Advera - B	4.0	4.2	5.6	0.9	4.6
Sasobit - A	4.4	4.4	3.9	0.3	4.2
Sasobit - B	3.7	3.5	4.6	0.6	3.9
Foamer - A	6.1	5.9	5.8	0.1	5.9
Foamer - B	4.2	4.4	5.1	0.5	4.6

The evolution of rutting under wheel load repetitions are presented in Figure 7-3 through Figure 7-10. The rut-depth values for each wheel position were fitted using second-order polynomial curves. The R^2 values of the curve fitting are summarized in Table 7-4. The R^2 values for HMA mixture are very low for the center wheel data, indicating problems that can clearly be seen in Figure 7-3 and Figure 7-4. To a lesser extent, these errors can also be seen for Advera® WMA specimens in Figure 7-6 and Figure 7-7.

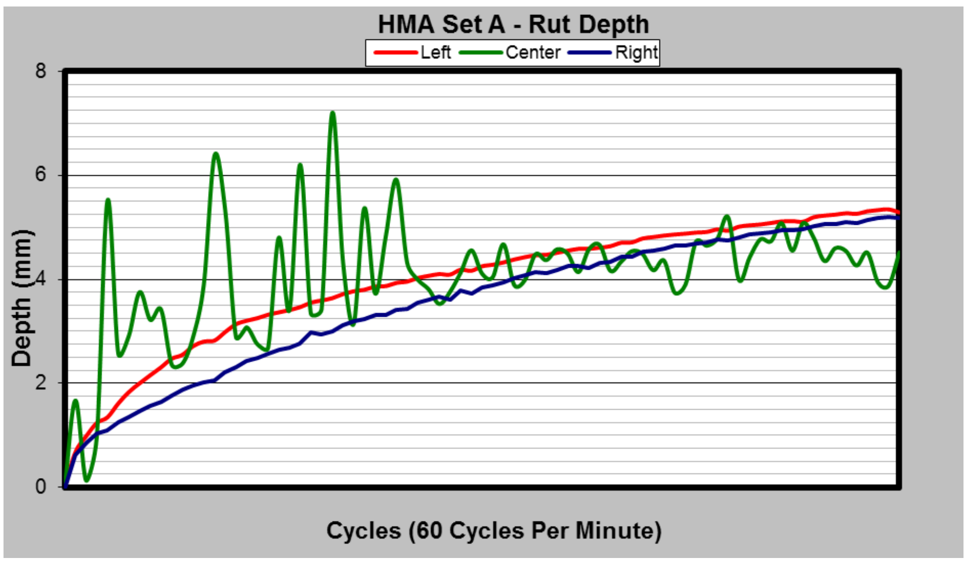


Figure 7-3 APA Rut Depth vs. Number of Cycles - HMA Set A

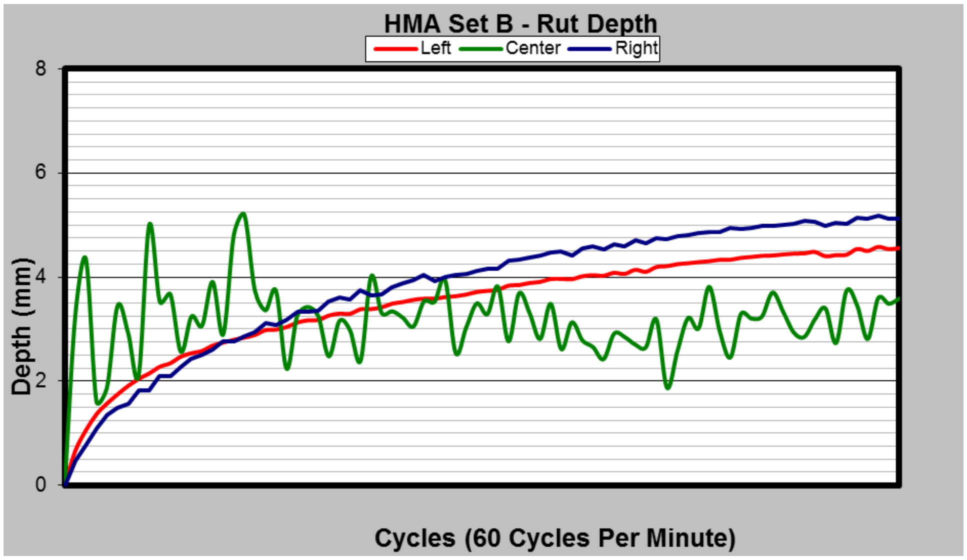


Figure 7-4 APA Rut Depth vs. Number of Cycles - HMA Set B

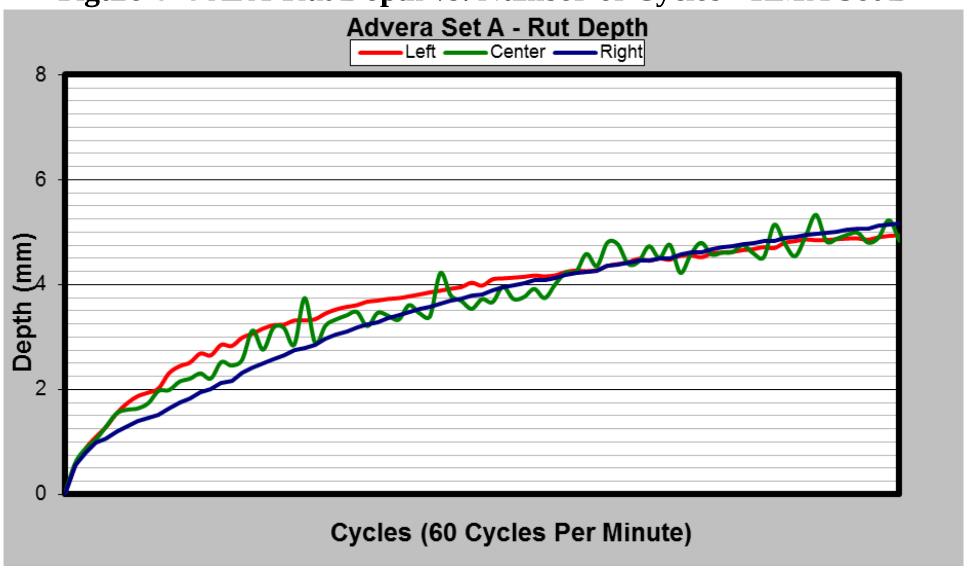


Figure 7-5 Figure 4 APA Rut Depth vs. Number of Cycles – Advera® Set A

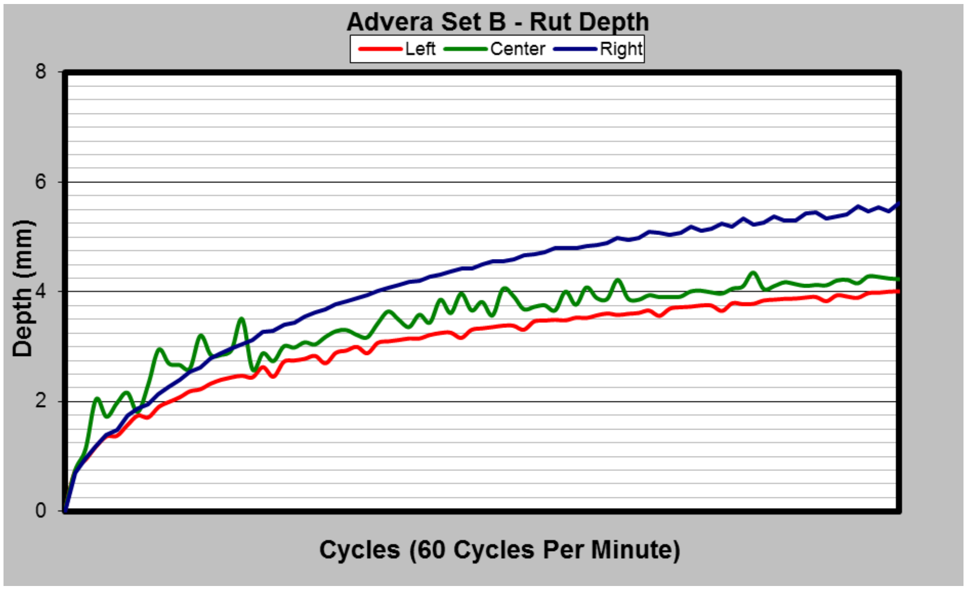


Figure 7-6 APA Rut Depth vs. Number of Cycles – Advera® Set B

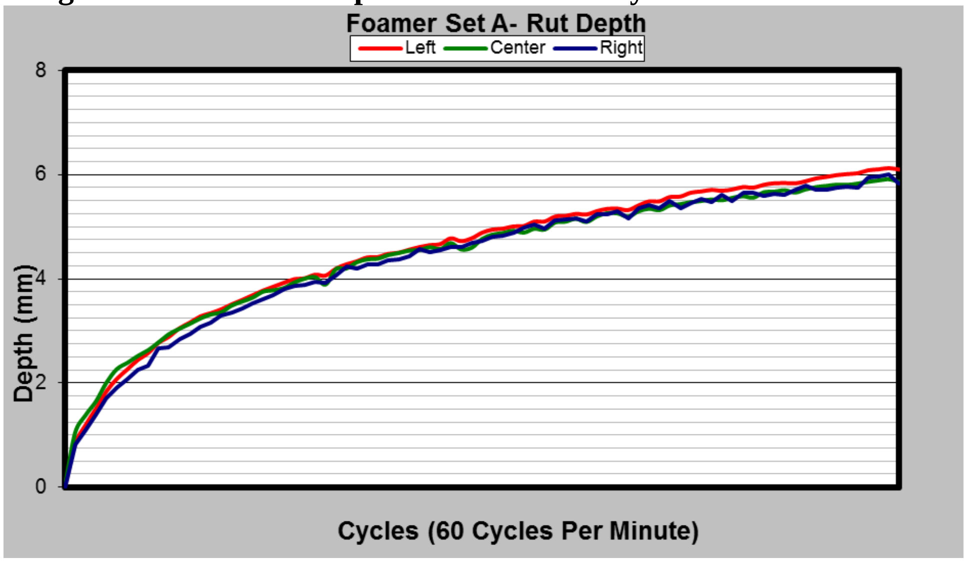


Figure 7-7 APA Rut Depth vs. Number of Cycles - Foamer Set A

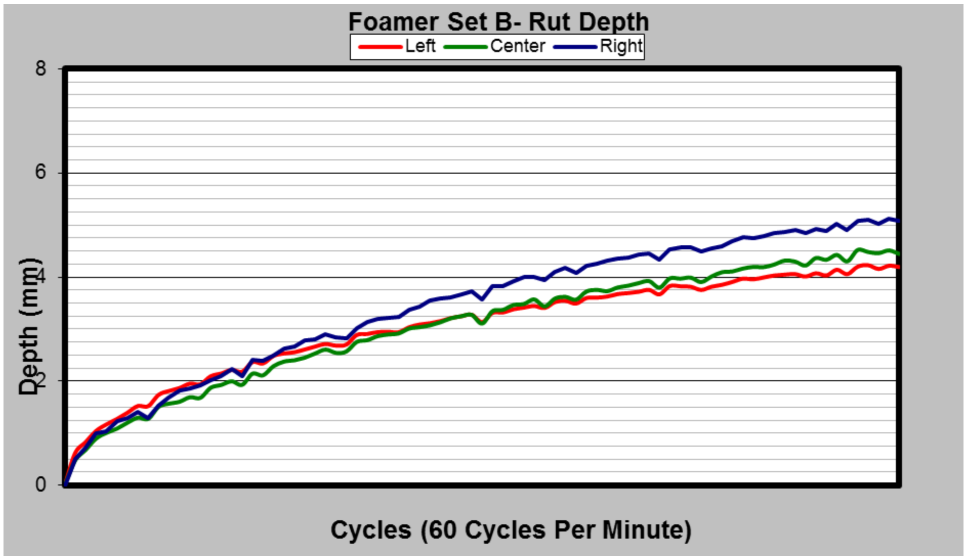


Figure 7-8 APA Rut Depth vs. Number of Cycles - Foamer Set B

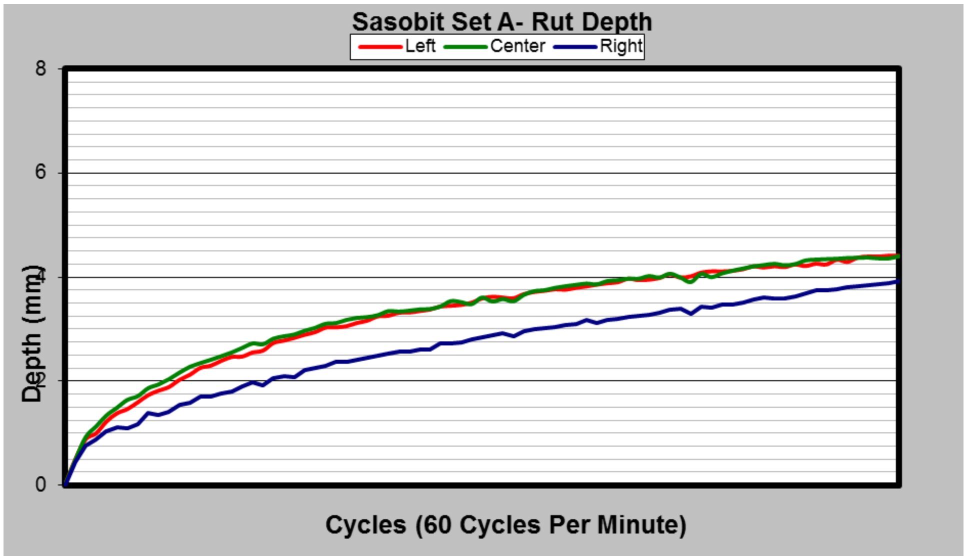


Figure 7-9 APA Rut Depth vs. Number of Cycles – Sasobit® Set A

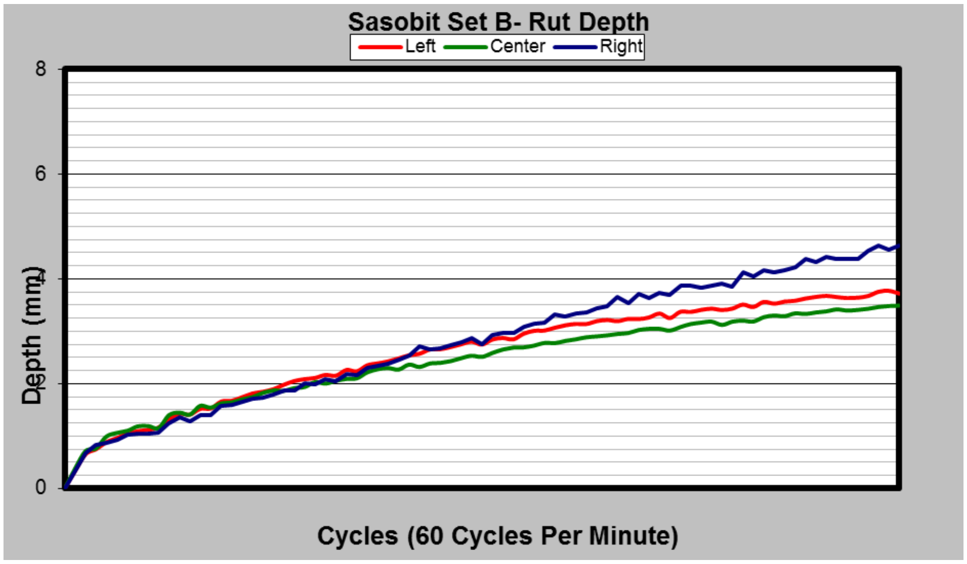


Figure 7-10 APA Rut Depth vs. Number of Cycles – Sasobit® Set B

Table 7-4 R^2 Values for Second Order Polynomial Fit of APA Rut Depth Values

Mixture Type	**R^2 Value For Second-Order Polynomial Fit**		
	Left	*Center*	*Right*
HMA - A	0.965	0.346	0.994
HMA - B	0.951	0.004	0.979
Advera - A	0.960	0.953	0.995
Advera - B	0.957	0.874	0.982
Sasobit - A	0.973	0.961	0.984
Sasobit - B	0.992	0.985	0.995
Foamer - A	0.962	0.959	0.969
Foamer - B	0.978	0.991	0.994

Since the R^2 values are very low for the center wheel data as compared to those of left and right wheel positions for HMA mixtures, the overall average rut depth values were recomputed after eliminating the center wheel data. Inconsistent data points were also eliminated for Advera®

WMA mixtures. The recalculated rut-depth values for all mixtures after eliminating the inconsistent center wheel data for HMA and Advera® WMA specimens are presented in Table 7-5.

Table 7-5 Corrected Overall Rut Depths from APA Tests

Mixture Type	Final Rut Depths (mm)			Overall Rut Depth (mm)	Overall Rut Depth (in.)
	Left	*Center*	*Right*		
HMA - A	5.3	***	5.2	5.1	0.20
HMA - B	4.6	***	5.1	4.8	0.19
Advera - A	4.9	***	5.2	5.0	0.20
Advera - B	4.0	***	5.6	4.8	0.19
Sasobit - A	4.4	4.4	3.9	4.2	0.17
Sasobit - B	3.7	3.5	4.6	3.9	0.15
Foamer - A	6.1	5.9	5.8	5.9	0.23
Foamer - B	4.2	4.4	5.1	4.6	0.18

7.5 Discussion of Test Results

Figure 7-11 shows the APA rut depth values for different mixtures as a function of ageing time. NCDOT criterion for mixture acceptance is 12.5 mm or lower rut depth from APA Test. It should be noted that all mixtures comfortably pass this criterion with average rut depths of less than 6 mm (half of that of the allowable 12.5 mm).

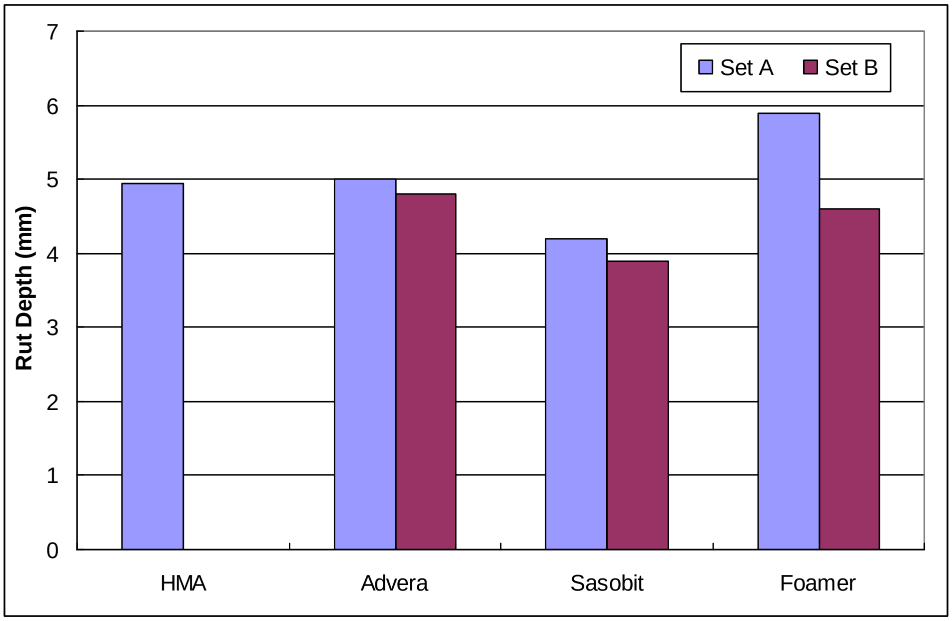


Figure 7-11 APA Rut Depth Comparison between HMA and WMA Mixtures

As is expected, extending the ageing from 4 to 8 hours for WMA mixtures decreases the rut depth due to stiffening of the mixture. The difference between rut depth values due to increase in ageing time is maximum for WMA produced using The Foamer. Even so, this decrease in APA rut depth is not meaningful in practice as even the 4 hour ageing values are significantly smaller than maximum allowable specification of 12.5 mm.

Two interesting observations can be made based on the APA test results:

i. There is a clear contradiction between the results of TSR and APA tests. TSR test results indicated a very low indirect tensile strength and TSR for Advera® WMA and Foamer mixtures, yet the rutting potential of these mixtures is not very different from the control HMA mixtures.

ii. Despite their low mixing and compaction temperatures with a reduction of about 25°C in production temperatures, WMA mixtures provide equivalent or better rutting resistance than HMA mixtures.

7.6 APA Test on Conditioned Specimens

Since there were indications that the TSR test may not adequately represent the performance of WMA mixtures, it was of interest to perform APA tests on moisture-conditioned samples. APA rutting potential values of conditioned specimens would verify the results of the TSR test. Since only Advera® WMA and Foamer mixtures exhibited failing results in the TSR test, moisture-conditioned specimens for these mixtures were tested in APA to evaluate their rutting potential.

A set of 6 APA test specimens were prepared following the standard method (four hour ageing before compaction, 7.0 ± 0.5 percent air voids with a height of 75 ± 2 mm height, using pre-determined mixing and compaction temperatures). Before testing, the air voids of the specimens were determined. Table 7-6 shows the percent air voids of these specimens. After recording the air void contents, the specimens were subjected to the same moisture conditioning treatment as that followed in the TSR tests, i.e. vacuum-saturation with water to 70 – 80% saturation and placement in a 60°C water bath for 24 hours. The specimens were then sealed in plastic bags to prevent loss of moisture and transported to the NCDOT Materials and Tests Unit for APA testing.

Table 7-6 Conditioned Specimen Air Voids for APA Test

Advera® WMA (Conditioned)		**The Foamer (Conditioned)**	
Specimen Number	***Air Voids %***	***Specimen Number***	***Air Voids %***
AC 1	7.5	FC 1	6.9
AC 2	7.5	FC 2	7.0
AC 3	7.3	FC 3	6.8
AC 4	7.0	FC 4	6.6
AC 5	7.0	FC 5	6.1
AC 6	7.3	FC 6	6.5
Average = 7.3		*Average = 6.7*	

The APA test procedure followed for conditioned specimens was the same as that for the unconditioned samples, as described in section **Error! Reference source not found.**. The results of these tests are summarized in Table 7-7. Figure 7-12 and Figure 7-13 show the evolution of rut depth for the moisture-conditioned Advera and Foamer specimens, respectively.

Table 7-7 Summary of APA Test Results for Moisture-Conditioned Samples

Mixture Type	**Final Rut Depths (mm)**			**Standard Deviation (mm)**	**Overall Rut Depth (mm)**	**Overall Rut Depth (in.)**
	Left	*Center*	*Right*			
Advera	5.3	4.6	5.7	0.6	5.2	0.20

(Conditioned)						
Foamer (Conditioned)	5.6	6.4	8.4	1.5	6.8	0.27

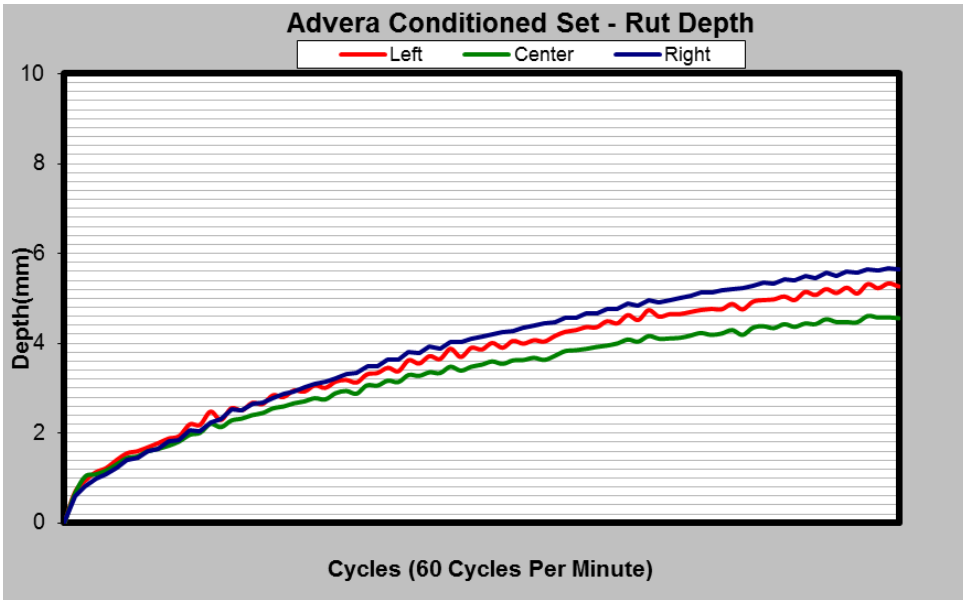


Figure 7-12 APA Rut Depth vs. Number of Cycles – Advera Conditioned Set

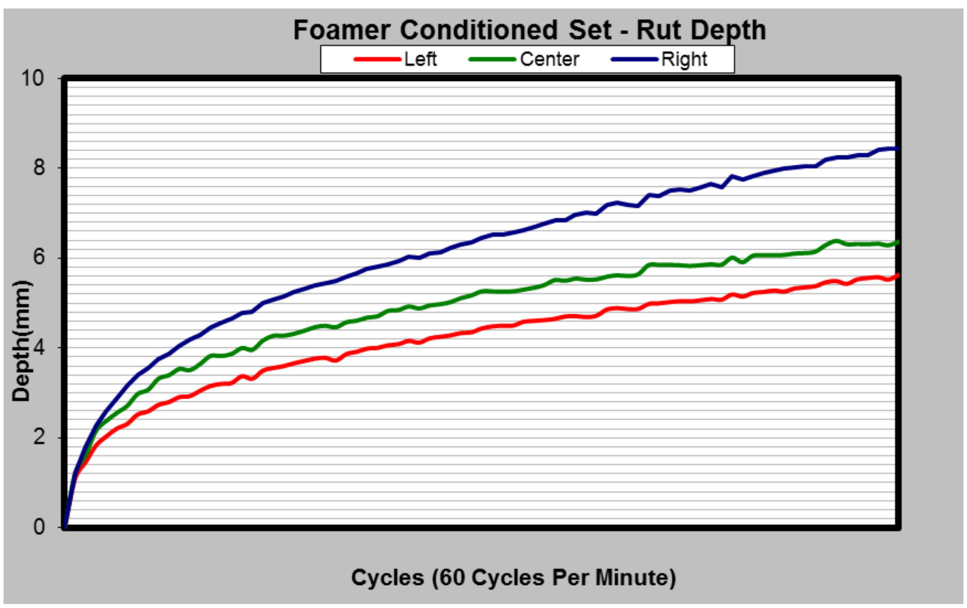


Figure 7-13 APA Rut Depth vs. Number of Cycles – Foamer Conditioned Set

The Foamer set exhibited a comparatively higher standard deviation of the average rut depths at different wheel positions; however, the values for both mixtures were within the specified limit of 2.0 mm. A comparison of APA rut depths for Advera and Foamer mixtures with and without moisture-conditioning is shown in Figure 7-14 (four hours of mixture ageing before compaction).

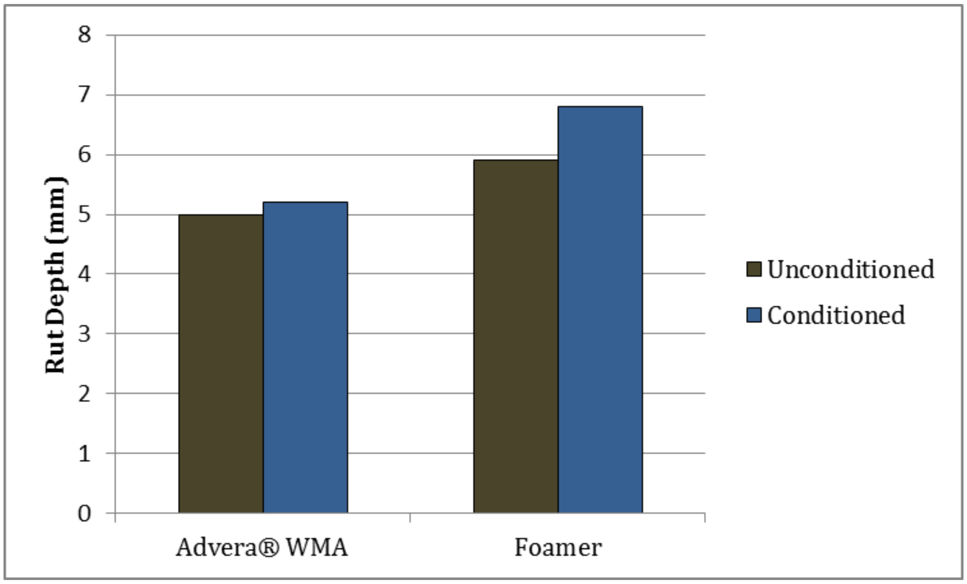


Figure 7-14 APA Rut Depths for Advera and Foamer Mixtures with and without Moisture Conditioning

Both Advera® WMA and Foamer mixtures still pass the NCDOT criterion of maximum 12.5 mm APA rut depths. Advera® WMA mixtures exhibit almost the same average rut depth values for both the sets (5.0 mm and 5.2 mm for unconditioned and conditioned sets, respectively). Foamer specimens exhibited an increase of average rut depths of 0.9 mm, i.e. from 5.8 mm in the unconditioned set to 6.8 mm in the conditioned set.

From the results, it can be seen that the conditioned sets of both mixtures have performed well in the APA test, contradicting their failing TSR test results. It is apparent that the validity of TSR test for evaluating moisture susceptibility (at least in the current form) of WMA mixtures needs further investigation. With comparable APA rut depth values as HMA- even with moisture conditioning, WMA mixtures have performed similar to HMA mixtures despite being produced at significantly lower temperatures.

CHAPTER 8 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.

8.1 Asphalt Mixture Performance Tester (AMPT)

The AMPT device is a computer-controlled hydraulic testing machine [45] 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 8-1 shows a sinusoidal loading cycle applied using the AMPT device, where E* is calculated using Equation 7-1:

$$E^* = \frac{\sigma_0}{\varepsilon_0} \quad \text{... Equation 7-1}$$

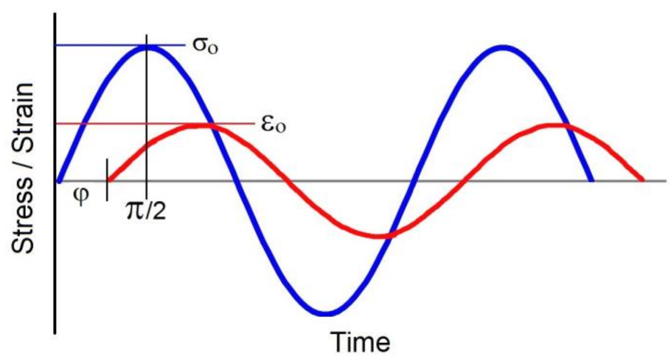


Figure 8-1 Dynamic Modulus, E* of Asphalt Concrete Mix

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. 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 8-2 shows a schematic representation of LVDTs mounted on an AMPT dynamic modulus test specimen. The strain amplitude is reported as the average of the three LVDTs.

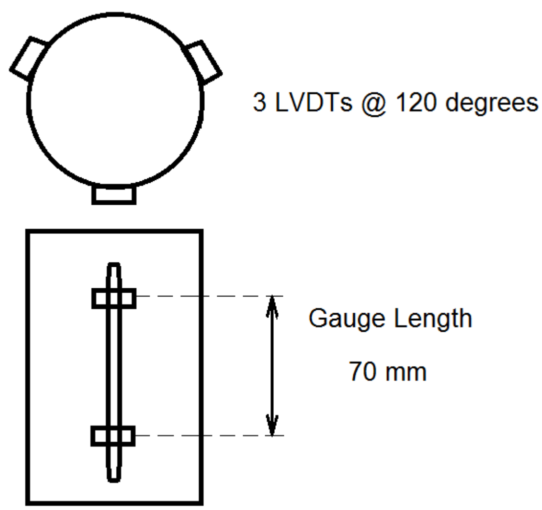


Figure 8-2 Arrangement of LVDTs on AMPT Test Specimen

8.2 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 6. 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 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 [43] .

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 test temperature.

$$\text{ESR} = \frac{\text{Average}\,|E^*|\,\text{of wet specimens at any test temperature and frequency}}{\text{Average}\,|E^*|\,\text{of dry specimens at any test temperature and frequency}} \quad \text{... Equation 7-2}$$

8.3 Specimen Preparation and Conditioning

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

Conditioning of the 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^{o}C for 24 hours. The mixes were then placed in another oven at compaction temperature for two hours (149^{o}C for HMA and 120^{o}C for WMA) before compaction. For preparing specimens for the wet test, specimens were saturated using vacuum to obtain 70 - 80% saturation. The saturated specimens were placed in a water bath at 60^{o}C for 24 hours. After removal, the specimens were surface-dried and left to air-dry at room temperature for a period of 24 hours. This was to ensure that the surface of the specimens was completely dry to allow proper adhesion of brass targets for mounting LVDTs.

Since the 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.

8.4 ESR Test Results

Table 8-1 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.

Table 8-1 E* Stiffness Ratio Test Results

Mix Type	Temp (^oC)	Dynamic Modulus (Pa)						Average ESR (%)
		Dry Conditioned			Wet Conditioned			
Frequency (Hz)		10	1	0.1	10	1	0.1	
HMA	4	1.33E10	9.67E09	6.21E09	1.26E10	9.02E09	5.79E09	93.7
	20	5.56E09	3.04E09	1.46E09	5.26E09	2.81E09	1.33E09	92.6
	40	1.12E09	4.38E08	2.14E08	1.10E09	4.56E08	2.40E08	104.7
Sasobit	4	1.21E10	8.40E09	5.17E09	1.17E10	8.16E09	5.12E09	97.7
	20	4.76E09	2.42E09	1.13E09	4.48E09	2.26E09	1.04E09	93
	40	9.62E08	3.95E08	2.26E08	8.90E08	3.64E08	1.99E08	90.9
Advera	4	1.16E10	7.91E09	4.70E09	1.08E10	7.24E09	4.17E09	91.2
	20	4.35E09	2.03E09	8.19E08	3.79E09	1.91E09	7.24E08	89.9
	40	8.02E08	2.80E08	1.32E08	6.46E08	2.26E08	1.05E08	80.3
Foamer	4	1.26E10	8.67E09	5.19E09	1.17E10	7.93E09	4.70E09	91.6
	20	4.68E09	2.25E09	9.57E08	4.67E09	2.31E09	9.99E08	102.2
	40	8.61E08	3.35E08	1.91E08	9.16E08	3.59E08	1.94E08	105

The results show that all mixes, except Advera mix at a test temperature of 40^oC 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 8-2 shows a comparison of TSR and ESR values for the mixes. ESR results from this study support the observation from other studies [41] that WMA mixes prepared using water-inducing technology (zeolites and foamed asphalt) do not satisfy the tensile strength ratio criteria, yet perform satisfactorily in the field.

Table 8-2 Comparison of TSR and ESR Test Results

Mix Type	TSR	ESR (Average)
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® WMA with 0.75% LOF 6500	55.6	87.1
Advera® WMA with 1.5% LOF 6500	63.7	
Foamed Asphalt with 0.75% LOF 6500	78.8	99.6
Foamed Asphalt with 1.5% LOF 6500	81.4	

CHAPTER 9 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^{o}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^{o}C (70^{o}F) using a non-linear optimization procedure according to AASHTO PP 61-09, *"Standard Practice for Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)"*. Table 9-1 shows the average dynamic modulus of three specimens for each mix type.

Table 9-1 Dynamic Modulus Test Results - 4 Percent Air Voids

Mix Type	Temperature (^{o}C)	Dynamic Modulus (Pa)		
HMA	4	1.72E10	1.29E10	8.96E09
	20	8.28E09	5.08E09	2.70E09
	40	2.25E09	9.93E08	4.91E08
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

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 9-1 shows the E* mastercurves developed for all four mixes at a reference temperature of 70^{o}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.

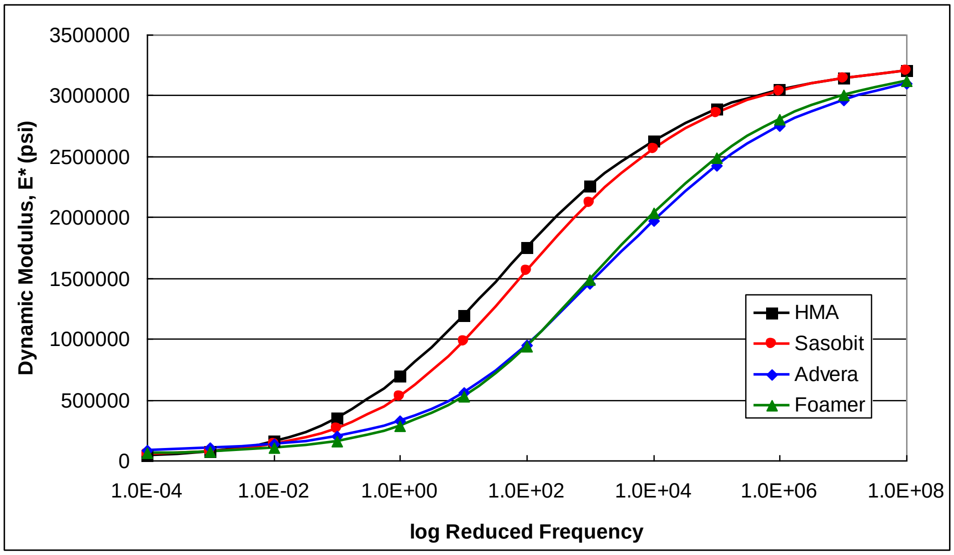


Figure 9-1 E* Mastercurves - 4 Percent Air Voids

The mastercurves were used to obtain E* data at five temperatures: 14, 40, 70, 100 and 130^{o}F and six frequencies: 0.1, 0.5, 1, 5, 10 and 25 Hz for each mix as shown in Table 9-2. 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.

9.1 Pavement Performance Prediction - 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 9-2 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.

Table 9-2 E* Data from Mastercurves for Use as M-E PDG Input

Frequency (Hz) → Temperature (^oF) ↓	0.1	0.5	1	5	10	25
HMA	Dynamic Modulus (Values in psi)					
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	Dynamic Modulus (Values in psi)					
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	Dynamic Modulus (Values in psi)					
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	Dynamic Modulus (Values in psi)					
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

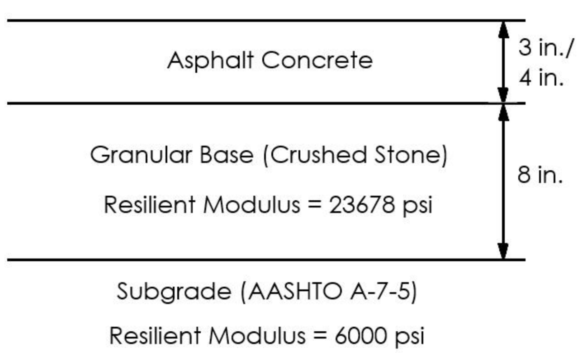


Figure 9-2 M-E PDG Pavement Layer Structure

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 the 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 9-3 shows the months to failure as obtained from M-E PDG analysis.

Table 9-3 M-E PDG Fatigue and Rutting Failure Prediction (Months to Failure)

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

9.2 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).

9.3 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 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 10 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.

10.1 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 [46]. 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 [47]. 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 [47]. The cost of material, additives and equipment for different mixes is shown in Table 10-1.

Table 10-1 Material Cost for Mix Production

Material	Cost ($ per ton)
Asphalt concrete surface coarse mix (S9.5B)	50.0
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	1.0

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

The costs and benefits for the three WMA technologies are summarized in Table 10-2.

Table 10-2 WMA Technology - Costs and Benefits Summary ($ per ton of mix)

	HMA	Sasobit	Advera	Foamer
Technology cost (additives and equipment)	-	2.7	7.5	1.0
Energy cost	10.0	7.5	7.5	7.5
Energy savings	-	2.5	2.5	2.5
Total cost per ton	50.0	50.2	55.0	48.5

10.2 Initial 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 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 10-3 below shows the initial cost of construction for a one-mile pavement section using the four mixes.

Table 10-3 Initial Pavement Costs ($ per mile)

	HMA	Sasobit	Advera	Foamer
Cost per ton, $	50.0	50.2	55.0	48.5
3 inch AC	119,000	119,476	130,900	115,430
4 inch AC	158,750	159,385	174,625	153,988

10.3 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 10-4.

Table 10-4 Rehabilitation Costs ($ per mile)

	HMA	Sasobit	Advera	Foamer
Cost per ton, $	50.0	50.2	55.0	48.5
2 inch surface	79,350	79,667	87,285	76,970

The predicted pavement failure periods in Table (pavement life table) 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 10-5 HMA and WMA Surface Rehabilitation Period and Salvage Life

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

10.4 Salvage Value and Present Worth

Salvage value of the pavement was calculated using the equation:

$$Salvage\,Value = \frac{Y}{Y_e} C \qquad \text{... Equation 10-1}$$

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 ($ per mile)

Salvage values calculated for different mixes are shown in Table 10-6.

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 the equation:

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

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 10-6 are initial construction, rehabilitation and salvage costs.

Table 10-6 Cost-Benefit Summary, Salvage Value and Present Worth

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

10.5 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 11 SUMMARY AND CONCLUSIONS

11.1 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. This interim project report describes results of moisture and rutting susceptibility tests.

A job mix formula with 9.5mm nominal maximum aggregate size was chosen. A control HMA mixture was tested alongside the three WMA mixtures. Moisture sensitivity of the mixtures was tested using the Tensile Strength Ratio test. The rutting susceptibility of the mixtures was evaluated using the Asphalt Pavement Analyzer. The specimens used in these tests were laboratory-mixed and laboratory-compacted (LMLC). The volumetric properties along with TSR and APA test results were also compared. The volumetric properties measured give further credence to the literature supporting the use of same mix design principles for WMA and HMA. The TSR values for moisture-based WMA technologies (Advera® WMA and The Foamer) did not meet the minimum acceptance criteria in this study; however APA tests their on moisture-conditioned specimens yielded satisfactory results. The APA results of all mixtures, both WMA and HMA, are much lower than the maximum 9.5 mm allowed by NCDOT criterion. ESR test results show that WMA mixes subjected to moisture conditioning retain more than 90% of their dry stiffness at most test temperatures. The E* mastercurves developed using dynamic modulus test data show that HMA and Sasobit exhibit similar stiffness, whereas Advera and Foamer mixes exhibited much lower modulus values than HMA.

11.2 Conclusions

1. Workability of WMA mixtures was found to be similar to HMA mixtures even though WMA mixtures use lower mixing and compaction temperatures.

2. Volumetric properties including percent air voids, VMA, VFA, bulk and maximum specific gravities of all four mixtures are similar despite significant differences in mixing and compaction temperatures between HMA and WMA. This confirms the findings of

NCHRP 09-43 project that mix design for WMA mixtures does not require a change in procedure from that of HMA.

3. Significant differences in indirect tensile strengths have been observed between the mixtures. HMA and Sasobit® mixtures passed the TSR test, exceeding the minimum requirement of 85%. WMA mixtures produced using Advera® WMA and The Foamer failed this criterion even with a 100% increase in anti-strip additive dosage.

4. Rut depth values from the Asphalt Pavement Analyzer have indicated good performance of WMA mixtures, on par with that of HMA.

5. Increase in ageing times from 4 to 8 hours for WMA mixtures did not have a significant effect on APA rutting performance.

6. Moisture-conditioned samples of Advera® WMA and The Foamer performed well in the APA test, contradicting the TSR test results.

7. Between the WMA technologies studied in this research work, Sasobit® exhibited the best performance for both TSR and APA tests.

8. ESR test results show that WMA mixes subjected to moisture conditioning retain more than 90% of their dry stiffness at most test temperatures.

9. The E* mastercurves developed using dynamic modulus test data show that HMA and Sasobit exhibit similar stiffness, whereas Advera and Foamer mixes exhibited much lower modulus values than HMA.

10. A cost-benefit analysis conducted using predicted pavement performance from M-E PDG analysis showed that the cost of Sasobit WMA over a 20 year pavement service life is similar to HMA mix, and is independent of the thickness of the asphalt concrete layer. Advera and Foamer mixes, however, lead to increased cost due to requirement of a minimum of 4 inches of surface course and early rehabilitation compared to HMA and Sasobit mixes.

11.3 Recommendations for Further Studies

1. There are indications that the TSR test may not accurately represent the moisture susceptibility of WMA mixtures. Failure of WMA technologies, especially the moisture-based ones, in the laboratory TSR tests contrast with their good performance in the APA tests and their reported good performance in the field. The results of moisture-conditioned APA tests have underscored the need for further study on TSR testing for WMA mixtures. More research is needed to accurately represent moisture-susceptibility of these mixtures in the laboratory.

2. Sasobit® mixtures have performed exceedingly well in this study. Their TSR test results surpassed those of HMA mixtures. Testing of this mixture should be repeated without the use of anti-stripping additives. If Sasobit® mixtures perform satisfactorily without the use of anti-stripping additives, then these mixtures will become more economical.

11.4 Implementation and Technology Transfer Plan

This research study was based on locally available materials and thus is directly applicable to North Carolina pavement structures. The dynamic modulus master curves are available for all four mixtures and will give the stiffness values at any desired temperature or rate of loading. Economic analysis helps in comparing costs and benefits of the four mixtures. Using this information, as per the respective pavement performance predictions, NCDOT engineers can design 9.5B surface mixtures with any appropriate WMA technology. As can be seen from the cost-benefit analysis, Sasobit and HMA mixtures are expected to perform similarly.

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