Investigation of Warm-Mix Asphalt Using Iowa Aggregates

Final Report
April 2011

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16. Abstract

The implementation of warm-mix asphalt (WMA) is becoming more widespread with a growing number of contractors utilizing various WMA technologies. Early research suggests WMA may be more susceptible to moisture damage than traditional hot-mix asphalt (HMA) mixes. The objectives of this study are to test the binder and mix properties of WMA technologies for both field- and laboratory-produced mixes to determine the performance of WMA compared to traditional HMA.

Field- and laboratory-produced mixes were studied. The laboratory-produced mixes compared HMA control mixes with WMA mixes that had the same mix design. The WMA technologies used for the laboratory study were Advera, Sasobit, and Evotherm. The field study tested four WMA field-produced mixes. Each of the four mixes had a corresponding control HMA mix. The WMA technologies used in the field study included: Evotherm 3G/Revix, Sasobit, and Double Barrel Green Foaming. The three main factors for this study were WMA/HMA, moisture-conditioned/not moisture-conditioned, and reheated/not reheated. Mixes were evaluated based on performance tests. Binder testing was performed to determine the rheological differences between HMA and WMA binders to determine if binder grade requirements change with the addition of WMA additives. The conclusions of this study are as follows:

- Reduced mixing and compaction temperatures were achieved.
- Statistical differences were found when comparing tensile strength ratio (TSR) values for both laboratory- and field-produced mixes. In the laboratory, none of the WMA additives performed as well as the HMA. For the field mixes, all TSR values passed Iowa's minimum specification of 0.8 but, on average, WMA is lower compared to HMA TSR values.
- Dynamic modulus results show that, on average, HMA will have higher dynamic modulus values. This means the HMA exhibits stiffer material properties compared to WMA; this may not necessarily mean superior performance in all cases.
- Flow number results show that WMA has reduced flow number values compared to HMA. The only exception was the fourth field mix and weather delayed production of the control mix by nine days. The laboratory mixes showed that flow number values increased significantly with the addition of recycled asphalt pavement (RAP).
- In the laboratory study, Advera reduced TSR values. Given that Advera is a foaming agent, the increase in moisture susceptibility is likely attributed to the release of water necessary for the improvement of the workability of the asphalt mixture.

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INVESTIGATION OF WARM-MIX ASPHALT USING IOWA AGGREGATES

Final Report
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EXECUTIVE SUMMARY

Warm-mix asphalt (WMA) has been on the horizon of new asphalt technologies and now it is at the forefront of many research and field projects. The process of investigating the implementation of WMA is a task that many state and local agencies are now facing. The typical WMA production temperature ranges from 30 to 100°F lower than typical hot-mix asphalt (HMA). This temperature reduction leads to several benefits for asphalt paving. Driving forces for WMA research are the potential for a reduction in energy, fuel consumption, and emissions. In accord with emission reduction is the reduced fuel consumption, which is an attractive economic benefit. Other benefits include longer haul distances, colder weather paving, reduction of asphalt fumes during paving operations, higher recycled asphalt pavement (RAP) content, and a less extreme working environment.

The three main types of WMA are organic wax additives, chemical additives, and plant foaming processes. Presented in this study are performance-testing results from field-produced WMA (and a control HMA) for each of the three main types of WMA technologies. WMA is showing promising results in laboratory testing throughout the US and Canada; however, one particular distress that has been documented in laboratory testing is moisture damage. It is hypothesized that the lower aggregate temperatures do not allow for complete drying of the aggregate and can lead to stripping.

This report contains both a field and laboratory study. There are three main objectives to be addressed in the field-produced WMA portion of this research. The first is to evaluate field-produced WMA mixes with a field-produced control HMA mix. The second is to identify potential quality control/quality assurance (QC/QA) concerns and determine if reheating a WMA mixture to prepare a sample will impact the performance testing results. The third objective is to address the WMA moisture susceptibility concerns. The objectives for the laboratory study include evaluating WMA with various types of Iowa aggregates, making comparisons between technologies and how RAP impacts WMA properties.

The Iowa Department of Transportation (DOT) produced four field WMA mixes and four control HMA mixes, which were used in this research project. Each mix was produced for a different project at different plant locations. The corresponding control mixes to each WMA mix differed only by the WMA additive. For each project, loose HMA and WMA mix was collected at the time of production and binder from the tank was collected for each mix. Field-compacted samples were prepared at the job site and laboratory samples were reheated and compacted at a later date. Indirect tensile strength (ITS) and dynamic modulus samples were procured from each mix produced. Half of the ITS and dynamic modulus samples were moisture-conditioned according to AASHTO T283. In total, 284 samples were procured from the field-produced mixtures for dynamic modulus, flow number, and indirect tensile strength performance testing.

The ITS testing results include peak loads and tensile strength ratios. Each of these values are considered when performing the data analysis. The dynamic modulus testing results will help to determine the material stress to strain relationship under continuous sinusoidal loading. The loadings are applied at various frequencies and temperatures to define the material property

characteristics over a wide range of conditions. Dynamic modulus testing measures the stiffness of the asphalt under dynamic loading at various temperatures and frequencies; thus, it is used to determine which mixes may be more susceptible to performance issues, including rutting, fatigue cracking, and thermal cracking.

The overall findings of these experiments suggest a difference in the performance of HMA and WMA mixes. The binder results show that the mixing and compaction temperatures are reduced and that the benefits of WMA mentioned in the literature review are realized. While the benefits of the technologies continue to drive the production of more WMA mixes, studying the performance testing results will help to show if there is a net benefit to using WMA. Three of the four field mixes indicate superior performance of the HMA mix to that of the produced WMA in many aspects of the tests performed. There were mixed results for the foaming technology because the WMA mix did perform superior in dynamic modulus and flow number tests, but there was a nine day elapse between the production of the foamed WMA mix and the HMA mix due to weather delays. This may have caused a higher degree of variability between the two mixes. The dynamic modulus results show that the interaction of the mix, compaction type, and moisture conditioning are statistically significant in all four field mixes. This suggests that the combination of all three factors play a role in determining material response. The master curves do not display a high degree of overall variability but do show differences in mix responses at high temperatures.

Further investigation of WMA technologies will be beneficial to both contractors and owner agencies. The experiments showed statistical differences between the control and WMA for all four field mixes tested. Three field mixes indicate higher laboratory performance results in the HMA mix. The foamed WMA mix showed improved laboratory performance when compared to the control HMA. As WMA is produced in larger quantities and as WMA technologies begin to be used together, it is important to continue looking at the pavement performance data and performance testing results in order to adapt the QC/QA programs to evolving technologies.

CHAPTER 1. INTRODUCTION

1.1 Background

Warm-mix asphalt (WMA) has been an intensely researched topic within the hot-mix asphalt (HMA) community for several years. Many owner agencies are beginning the process of implementing these technologies and many research projects are investigating the use, performance, and benefits of WMA technologies. The literature review summarizes some of the important research that has taken place, as well as publications that have led to the wide spread use of WMA additives. There are many benefits to the implantation of WMA, but the primary benefit is the lower mixing and compaction temperatures, which can lead to reduced emissions and costs for contractors (D'Angelo et al., 2008). Another benefit of WMA is that the improved workability allows for higher percentages of recycled asphalt pavement (RAP) in a mix. Several studies have shown that WMA is more susceptible to moisture damage than HMA control mixes (Roberts et al,. 1984; Kvasnak, et al. 2009).

The WMA production temperature can range from 30 to 100°F lower than typical HMA (D'Angelo et al., 2008). This temperature reduction leads to several benefits for asphalt paving. Driving forces for WMA are the potential for a reduction in energy, fuel consumption, and emissions. In accord with emission reduction is reduced fuel consumption, which is an attractive economic benefit. Other benefits include longer haul distances, colder weather paving, reduction of asphalt fumes during paving operations, higher recycled asphalt pavement (RAP) content, and a less extreme working environment (D'Angelo et al., 2008). The three main types of WMA are organic wax additives, chemical additives, and plant foaming processes (Hodo et al., 2009). Laboratory and field test results are presented for each of the three types of WMA. WMA is showing promising results in laboratory testing throughout the US and Canada. One potential distress that has occurred in laboratory testing is moisture damage. It is hypothesized that the lower aggregate temperatures do not allow for complete drying of the aggregate and can lead to stripping (Hurley, 2006).

1.2 Problem Statement

The implementation of WMA is becoming more widespread with a growing number of contractors utilizing various WMA technologies. The literature review suggests that some of the benefits of WMA may come at a cost in terms of long-term pavement performance and moisture susceptibility. Asphalt performance tests can be a good way of measuring material responses and those responses can be correlated to pavement performance. There has only been a limited number of studies performed that look at the factors of mix type (HMA/WMA), compaction type (field/laboratory compaction), and whether a sample is moisture-conditioned or not moisture-conditioned. It is important for owner/agencies to know that the WMA technologies and/or the reduction in mixing and compaction temperatures do not hinder the durability and long-term pavement performance.

1.3 Objectives

There are three main objectives to be addressed through this research. The first is to evaluate field-produced WMA mixes with a field-produced control HMA mix. The second is to identify potential quality control/quality assurance (QC/QA) concerns and determine if reheating a WMA mixture to prepare a sample will impact the performance testing results. The third objective is to address the WMA moisture susceptibility concerns.

1.4 Methodology

The experimental plan uses field-produced mixes. Using field-produced mixes gives researchers the ability to use a product that would most simulate the actual pavement. The first objective addresses comparing field-produced WMA mixes with a field-produced control HMA mix. The comparison is done by reviewing data from performance testing. The tests include indirect tensile strength (ITS), dynamic modulus testing, and flow number testing. Binder test results are also reviewed. The second objective is addressed by half of the samples being compacted in the field and the other half being procured from reheated mix and compacted in the laboratory. A statistical analysis of the performance test results will help to determine if reheating the WMA mixes impacts the performance of the material. The third objective is investigated by moisture conditioning half of the samples according to AASHTO T-283 guidelines and comparing the performance testing results.

1.5 Hypothesis

The following hypotheses were formulated and addressed by performing laboratory tests and conclusions were made based on statistical analysis:

- HMA and WMA have different performance testing results due to either a change in viscosity or a reduction in temperature.
- WMA has higher moisture susceptibility, potentially due to the reduction in temperatures causing incomplete drying of aggregates.
- WMA mix performance is dependent on whether samples are field-compacted or reheated and compacted in a laboratory.

As a result of the extensive laboratory testing, these additional hypotheses were addressed:

- How do the various factors of mix type, compaction type, and whether or not a sample has been moisture-conditioned interact with each other to determine the material response?
- How does the difference between HMA and WMA vary over a range of testing temperatures?
- Is the WMA mixing and compaction temperature reduction reflected in binder properties when tests such as rotational viscometer and dynamic shear rheometer are performed?

Answering these questions allows for a better understanding of the materials that are being produced for Iowa roadways.

1.6 Report Organization

This report is divided into nine chapters. The first is an introduction that provides a summary and background information about WMA. The introduction also provides a problem statement, objectives, methodology, and the hypotheses of the research compiled herein. Chapter 2 is the literature review, which highlights the history of WMA and recently-completed WMA research projects. Chapter 3 outlines the experimental plan and discusses the type of WMA additives and the various laboratory tests used throughout the project. Chapter 4 provides field mix details and how samples were collected and prepared. Weather information about the day of production is provided, as well as the procedure used for moisture conditioning. Chapter 5 gives an overview of the binder testing results. Chapter 6 provides the performance testing results from the ITS testing, dynamic modulus testing, and flow number testing. The chapter also includes the developed master curves from dynamic modulus testing. Chapter 7 is the statistical analysis of the data. For the analysis, the statistical analysis methodology is discussed and an analysis of each test result, organized by field mix, is provided. Chapter 8 contains the results and analysis for laboratory-produced mixes. Finally, Chapter 9 provides a summary discussion for each field mix, conclusions, and recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

WMA has been on the horizon of new asphalt technologies and now it is at the forefront of many research and field projects. The process of investigating the implementation of warm-mix asphalt is a task that many state and local agencies are now faced with. The intent of the literature review is to present information about warm-mix asphalt (WMA) for the evaluation of WMA use in the State of Iowa including presenting various WMA technologies and reviewing the findings of laboratory and field tests conducted throughout the world.

There are many reasons why WMA may be useful in Iowa. Included in the literature review is a detailed look at the benefits that WMA has to offer. Some of the benefits include lower plant air emissions and fuel consumption, the possibility of colder weather paving, higher recycled asphalt pavement (RAP) and better working conditions. This literature review also summarizes and discusses the background of WMA, the benefits of WMA, provides an overview of the technologies available, reviews some of the WMA studies and experiments as well as presenting their observations and conclusions.

2.2 Background

2.2.1 Foamed Asphalt Studies Prior to 1985

The Work of L.H. Csanyi

Controlling the properties of foamed asphalt was first developed at Iowa State University and reported in 1959 by Professor L.H. Csanyi (Csanyi, 1959). The unique characteristics of foamed asphalt include: an increase in volume, decrease in viscosity, softer at lower temperatures, change in surface tension that gives the asphalt increased adhesion and the asphalt regains its original properties when the foam breaks. Utilizing the foamed asphalt characteristics required procedures that would control the foaming of the asphalt. Figure 2.1 shows the foamed asphalt nozzle developed by Csanyi. The asphalt is introduced at 280°F at 2.5 pounds of pressure and saturated steam is introduced at 40 pounds of pressure. The foaming characteristics are influenced by the design of the nozzle tip, the quantity and pressure of the steam and the pressure of the asphalt. One nozzle has a discrete discharge capacity and more than one nozzle would be used during the mixing process. Figure 2.2 shows a schematic of the entire mixing process (Csanyi, 1959).

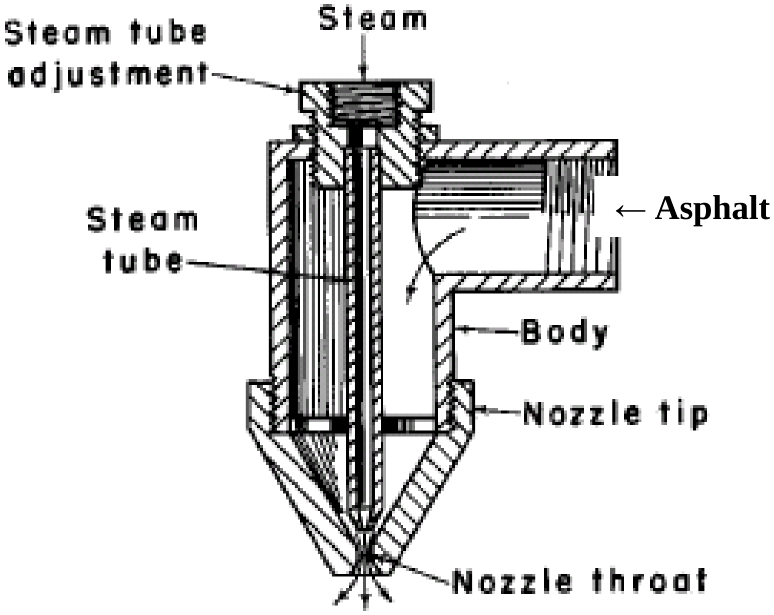


Figure 2.1. Foamed asphalt nozzle (Csanyi, 1959)

The controlled foaming process allows for foamed asphalt studies on various types of mixes which included: standard specification mixes, ungraded aggregate mixes, soil stabilization both in place and in plants, asphalt cement slurry seal coat mixes, and coal briquetting mixes. The tests conducted on standard specification mixes are of the most interest for this literature review. The results of the testing showed that foamed asphalt allowed for a more uniform distribution of the asphalt throughout the mix, aggregate temperatures as low as 240°F could be used without changing the characteristics of the mix and cold mixes may be prepared in which cold, wet aggregates are used (Csanyi, 1959).

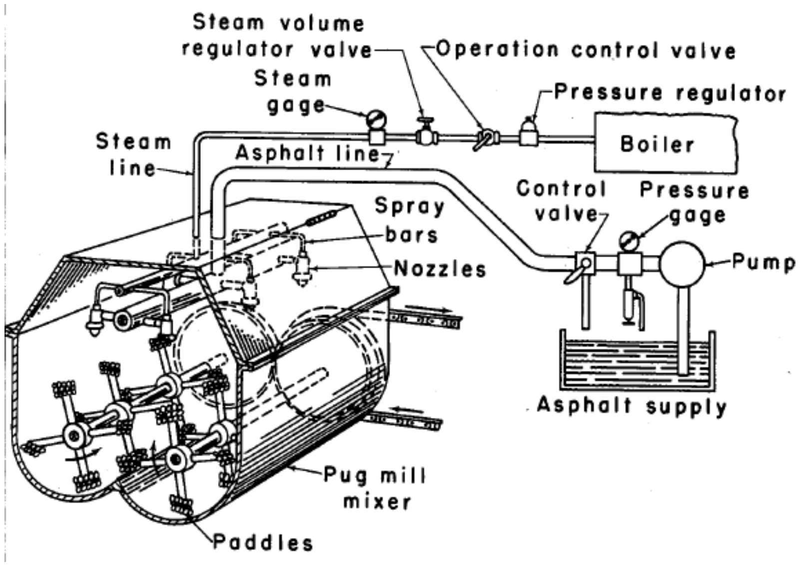


Figure 2.2. Foamed asphalt system (Csanyi, 1959)

Foamed asphalt base stabilization was used in 1961 by the Jay W. Craig Company of Minneapolis for the ball park of the Minnesota Twins. The foamed asphalt allowed for construction work during cooler and more inclement weather of late April and May. Csanyi also used foamed asphalt in surfacing mixes with ungraded aggregate for low volume roads. Using the foamed asphalt for this type of project lead to a savings of 25 to 30 percent in asphalt and the ability to put traffic on the material one hour after it was laid (Csanyi, 1962).

Treating Iowa’s Marginal Aggregates and Soils by Foamix

Csanyi’s patent rights were acquired by Mobil of Australia. Dr. D.Y. Lee of Iowa State University performed a study in 1979-1980 that further investigated the use of foamed asphalt using the new methods developed by Mobil of Australia. Where Csanyi used steam to foam the asphalt, the Mobil technique used water. Dr. Lee's study found that there was no difference between using water or steam except water requires less energy. This study evaluated thirteen aggregates and aggregate blends plus two recycled asphalt pavement materials as well as two asphalt cements for foamed asphalt mixes. Some mixes were gravel and some were soil. One especially noteworthy conclusion of this study was that the addition of small amounts of either hydrated lime or Portland cement improves the resistance to water action of a foamed mix (Lee, 1980).

Evaluation of Recycled Mixtures Using Foamed Asphalt

A study was performed in 1984 at the University of Texas at Austin which evaluated the feasibility of using foamed asphalt to recycle asphalt mixtures and compared to the properties of foamed mixtures with those of conventional cold mixtures. This study concluded that curing temperature, length and moisture conditions dramatically affect the strength of foamed asphalt mixtures that contain sand and salvaged pavement materials. This study also found that the foamed asphalt specimens prepared from both the salvaged pavement materials and the sand exhibited equivalent or superior engineering properties to specimens prepared by using either the emulsions or a cut back (Roberts et al., 1984).

2.2.2 Recent WMA Work

By ratifying the Kyoto protocol, the European Union has pledged to reduce emissions of CO_2 by 15% by 2010 (Jones, 2004). This encouraged the asphalt industry sector in different European countries to take a proactive approach in reducing emissions and reducing consumption of resources as a means of adopting sustainable development ethos (D'Angelo, et al., 2008). Environmental concerns regarding the emissions produced during the production of HMA was one of the factors that led to the development of several technologies in Europe aiming to lower the temperature at which asphalt is produced, mixed, and placed. For instance, the German Bitumen Forum was established in 1997 to launch optimum basis for the evaluation of potential health hazards that arise from dealing with bitumen (Ruhl et al., 2006). One of the first challenges that the forum tackled were means to lower the emissions arising from HMA and reducing the asphalt paving temperature, which was regarded as one of the viable means to accomplish this objective. Along that path, several European companies started to conduct experiments to develop technologies that would enable temperature reduction during the production and mixing of asphalt (Newcomb, 2007).

Additional drivers that further encouraged European agencies to adopt WMA technologies were the potential practical benefits such as improvement in the compactability of the asphalt mixture, hence allowing the extension of the paving season and permitting longer haul distances (D’Angelo et al., 2008; Newcomb 2007). Furthermore, benefits related to improving the working environment in the production and placement stages of HMA are valuable for the welfare of the workers. Reduction in HMA temperature would result in two direct advantages for the labor force: reduction of fumes in surrounding areas to the workers and the ability to operate in a cooler work environment (Newcomb, 2007).

WMA in the United States

NAPA Study Tour, 2002

The National Asphalt Pavement Association (NAPA) sent a study team to Europe to evaluate and research three of the adopted European technologies in the summer of 2002. The NAPA study team visited asphalt production facilities, paving sites and completed road sections in Germany and Norway to study the use of synthetic zeolite, WAM foam, and synthetic paraffin wax additive technologies (Cervarich, 2003). Although the warm mix technologies were regarded as promising, certain questions persisted over its applicability to the United States in terms of climatic conditions, mix designs and construction practices. The need to initiate a research program to assist in answering these concerns was cited along with the necessity to implement demonstration projects that help in validating the performance of these technologies. Moreover, NAPA invited a select group of European experts to introduce the European experience with WMA to the American HMA industry at the 2003 NAPA annual meeting in San Diego (Cervarich, 2003).

2003 NAPA Annual Convention

The invited European delegation comprised a representative of the German Bitumen Forum and representatives from several European companies. A representative of the German Asphalt Pavement Association presented an overview on the use of organic additives such as synthetic paraffin wax in producing warm mixtures. These long chained hydrocarbons are extracted using the Fischer-Tropsch process to be used in reducing the viscosity of the binder and thus the mixing and compaction temperatures. These additives were validated by research conducted in the laboratory and the field spanning about five years.

Representatives from Shell Global Solutions and Kolo-Veidekke presented the WMA technology developed through their joint venture in 1995 named the WAM-Foam® process. This technology was developed on the grounds that European companies were urged to reduce their CO_2 emissions and to utilize the most environmentally friendly alternatives (Cervarich, 2003). WAM-Foam® is obtained from two components, a soft binder and a hard binder during the mixing stage. Firstly, the soft binder is mixed with the aggregates at temperatures ranging between 212° and 250°F, then the hard binder is added resulting in foam that helps lubricate the mixture and improves the workability at low temperatures (Kuennen, 2004). Demonstration projects using WAM-Foam® were performing adequately in Norway from 1999 to 2002 according to the speakers (Cervarich, 2003).

Representatives from the German company Eurovia Services GmbH introduced Aspha-min®, a synthetic zeolite WMA technology. Aspha-min® consists of crystalline hydrated aluminum silicates which help reduce the temperatures of production and placement by about 50°F. The performance of test sections constructed with Aspha-min® did not show notable discrepancies in performance when compared to standard mixtures (Cervarich, 2003).

NCAT WMA Research Program

Following the 2002 NAPA study tour, researching WMA began at the National Center for Asphalt Technology (NCAT) at Auburn University to investigate the methodologies of reducing the production and the placement temperatures of asphalt mixtures (Rea, 2003). This research program was started upon an agreement by NAPA, the Federal Highway Administration (FHWA) and several WMA technology suppliers. The investigations conducted by the research program focused on the feasibility of utilizing WMA technologies in the United States and the findings of those investigations on three technologies: Aspha-min®, Evotherm® and Sasobit® were published by NCAT (Corrigan, 2008).

World of Asphalt Symposium, Nashville, 2004

A three hour demonstration of the Aspha-min® process was conducted at the World of Asphalt conference in Nashville, Tennessee in order to promote the benefits of WMA technologies to the paving industry in the United States. A conventional HMA and Aspha-min® mats were laid. There was a difference of 80°F between the two materials. The paving crew reported that the WMA was easier in handling and placement while attaining the same density (Jones, 2004).

WMA Technical Working Group

A Technical Working Group (TWG) was formed by NAPA and FHWA with the purpose of assessing and validating WMA technologies and implementing WMA strategies and practices in a way that facilitate the sharing of information on various WMA technologies among government agencies and the industry. The group includes representatives from a variety of government agencies and industry bodies such as the FHWA, NAPA, NCAT, State Highway Agencies, State Pavement Associations, HMA industry, workforce, and National Institute for Occupational Safety and Health (NIOSH) (Corrigan, 2008).

The WMA TWG has recognized several important research needs that would require investigation that were incorporated into two projects by the National Cooperative Highway Research Program (NCHRP); NCHRP 09-43 and 09-47 (Corrigan, 2008).

NCHRP 09-43

The 09-43 project, “Mix Design Practices for Warm Mix Asphalt Technologies,” was endorsed by the NCHRP in 2007 with the purpose of developing a manual of practice for the mix design procedure of WMA that would be based on performance. This manual of practice is to be designed suitably to be used by technicians and engineers in the asphalt sector. The targeted mix design procedure is to be compatible with the SuperPave methodology and versatile for utilization with different WMA technologies (Transportation Research Board, 2007). The objectives of this project were planned to be achieved through the accomplishments of two phases. The first phase comprises a number of tasks that are outlined in Figure 2.3. The second phase will commence with the implementation of the experiment approved in task 4 of phase one and based on the outcome of the experiments, a final version of the WMA design method shall be prepared. Consequently, the design method should be validated using data and materials acquired from completed field projects. Currently, phase one has commenced and its outcomes are pending.

NCHRP 09-47

The second NCHRP WMA project is titled "Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies” and began in 2008. The main objectives of this project are to investigate the relationship between the engineering properties of WMA binders and mixtures as well as the practical field performance of WMA pavements. In addition, the project should provide relative relationships between the performance of WMA pavements and those constructed with HMA. The same way, a comparison of the practices and costs associated with the production and the placement of pavements using the HMA and WMA will be conducted (Corrigan, 2008). The project included WMA technologies of different natures and each of these technologies will be used in a minimum of two full scale trials. Full scale trials stipulate the use of a quantity ranging between 1,500 to 5,000 tons of the WMA technology placed with conventional equipment on an in-service road (Transportation Research Board, 2008). Project 09-47 includes two main phases with each phase composed of several tasks. Figure 2.4 shows an outline of the tasks of phase I.

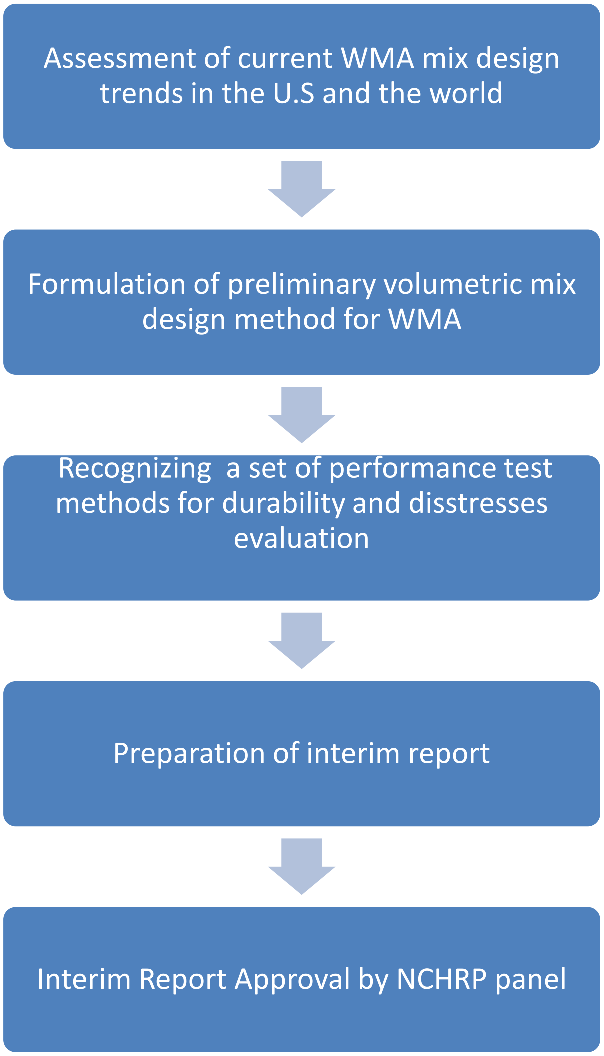


Figure 2.3. Tasks for NCHRP 09-43 phase I (Transportation Research Board, 2007)

Upon the approval of the first phase, the second phase will commence with the execution of the work plan approved in the first phase of the project. Finally, a proposal for the laboratory evaluation of the performance of the WMA technology and a final report summing up the findings and outlining the results of the project will be prepared (Transportation Research Board, 2008).

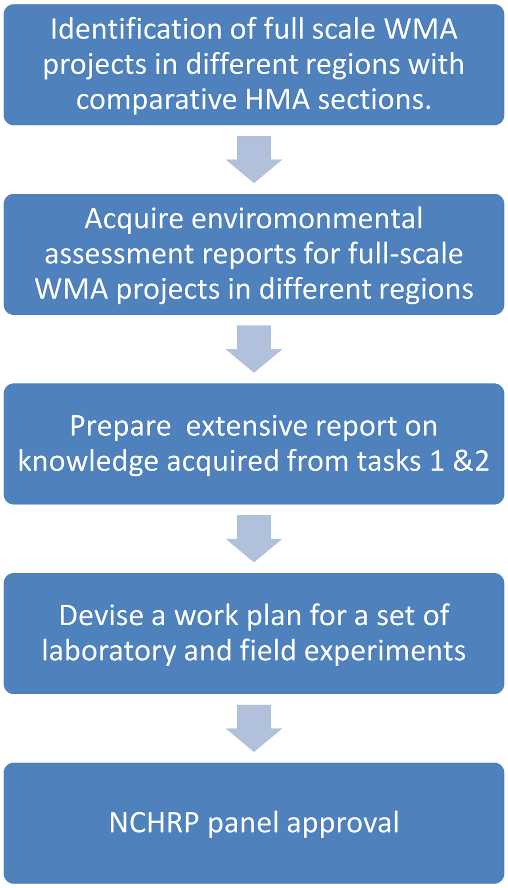


Figure 2.4. Tasks for NCHRP 09-47 phase I (Transportation Research Board, 2008)

2007 FHWA European Scan Tour

Through the International Technology Scanning Program of the Federal Highway Administration, a U.S. materials team, comprised of experts from different agencies and companies, visited the following European countries in 2007: Belgium, France, Germany and Norway with the objective of assessing various WMA technologies. The members of the International Technology Scanning Program represented: FHWA, NAPA, Asphalt Institute, several State DOTs and contractors. The team explored various technologies and held discussions with different agencies with respect to the methods of implementation of these technologies. Technologies encountered during the scan tour can be classified by type: foaming process, chemical additives and organic wax additives. The foaming process technologies introduce small amounts of water to hot asphalt either through a foaming nozzle or a hydrophilic material like zeolite, this water turns into steam and results in an expansion of the binder phase with an associated reduction in the mix viscosity. Table 2.1 outlines the WMA technologies observed in Europe by the FHWA team. The number of processes being developed promotes the need for a system of assessment for new technologies (D'Angelo, et al., 2008).

In all countries visited during the tour, WMA was expected to offer an equivalent performance or even better than HMA. In Norway for instance, the delegates observed six sections built with

WAM-foam technology as shown in Figure 2.5. Generally, the condition of the pavements was very good except for the presence of some rutting that was attributed to the use of studded tires, which is allowed in Norway. The Norwegian Public Roads Administration has provided data on 28 WAM-Foam sections with an age between 2 to 8 years. It was reported that the performance of the WAM-Foam sections was similar to HMA overlays used previously (D'Angelo, et al., 2008).

Table 2.1. Technologies observed in Europe by the scan team (D'Angelo, et al., 2008)

WMA Process	Process Type	Additive	Plant Production Temperature	Reported use in
Sasobit	Organic Wax Additive	2.5% by weight of binder	266-338˚F is recommended	Germany and other countries
Asphaltan-B		2.5% by weight of binder	266-338˚F is recommended	Germany
Licomont		3% by weight of binder	266-338˚F is recommended	Germany
3E LT/ Ecoflex		N/A	54-72 drop from HMA	France
Aspha-min	Chemical Additive	0.3% by total weight of mix	266-338˚F is recommended	France, Germany and U.S.
ECOMAC		N/A	At 113 ˚F	France
LEA	Foaming Process	0.2-0.5% by weight of binder	At < 212 ˚F	France, Spain and Italy
LEAB	Foaming Process	0.1% by weight of binder	At 194˚F	Netherlands
LT Asphalt	Foaming Process	0.5-1.0% by weight of a filler	At 194˚F	Netherlands
WAM-Foam	Foaming Process		230-248˚F	France, Norway and other countries
Evotherm	Chemical Additive		185-239˚F	France, Canada and U.S.

Figure 2.5. Scan team observing a WAM-foam section in Norway (D'Angelo, et al., 2008)

In Germany, there are criteria for incorporating new materials in field trials as it must be installed on the right-hand lane of high traffic roadways with the length of the sections overlaid not less than 1,640 ft. The investigating team observed a number of WMA stone mastic asphalt sections on the Autobahn located between Cologne and Frankfurt. Data on seven sections built with four different WMA technologies was presented to the scan team. Those technologies are Sasobit®, Asphaltan-B®, Aspha-min® and Asphalt modified with Licomont®. The performance of all seven sections was as good as or better than the control sections built with conventional HMA technology.

Moreover, a number of WMA additive suppliers furnished performance data to the scan team for a number of trial sections where the performance of the WMA was on par with the HMA performance if not better (D'Angelo, et al., 2008).

In France, the Department of Eure-et-Loir, a district located southwest of Paris has conducted field trials with Aspha-min® and ECOMAC®. Meanwhile, the city of Paris has performed some experiments with a number of WMA technologies starting from 2004. A toll road operator managing a number of toll roads in the southwest region of Paris built a trial section with Aspha-min® in 2003 on a road that carries a daily traffic of 21,000 vehicles in both traveling directions. The performance of the trial section was satisfactory (D'Angelo, et al., 2008).

The scan team also looked into how different agencies in the visited countries stipulate and integrate WMA into their established specifications and applications. One factor identified by the scan team as very helpful in the process of incorporating WMA into specifications is the fact that most European paving contracts contain a two- to five-year warranty period.

In Norway, the Norwegian Public Roads Administration has permitted the use of WMA as an alternative to HMA on the condition that the WMA pavements must adhere to all specifications stipulated for HMA. Meanwhile, in Germany the incorporation of any constituent materials requires a proof of its “established suitability.” In the case of WMA technologies such as

Sasobit®, Asphaltan-B®, and Aspha-min®, their suitability was acquired from the satisfactory test trials and demonstrations under heavy traffic for a minimum period of five years. Furthermore, a bulletin, “Merkblatt,” came out in August 2006 presenting general remarks and guidelines for using WMA acting as a cornerstone for the formulation of standardized construction method in the future. Finally, in France there is a certain procedure for new technologies to be incorporated into the specification to be available for use. A chart showing the chorological steps of this procedure is illustrated in Figure 2.6 (D'Angelo, et al., 2008).

The scan team has recommended the construction of similar evaluation systems for new products in the United States. The team has also noted that the application of WMA in Europe was not as widespread as they had expected and they cited two reasons for that. The first reason is the fact that the oldest sections built with WMA were just elapsing their workmanship warranty periods hence, contractors are still cautious until they can develop a confidence in the long-term performance of the technology before any further expansion in its utilization. The second reason is the higher cost of using WMA technologies in place of HMA even when fuel savings are taken into consideration (D'Angelo, et al., 2008).

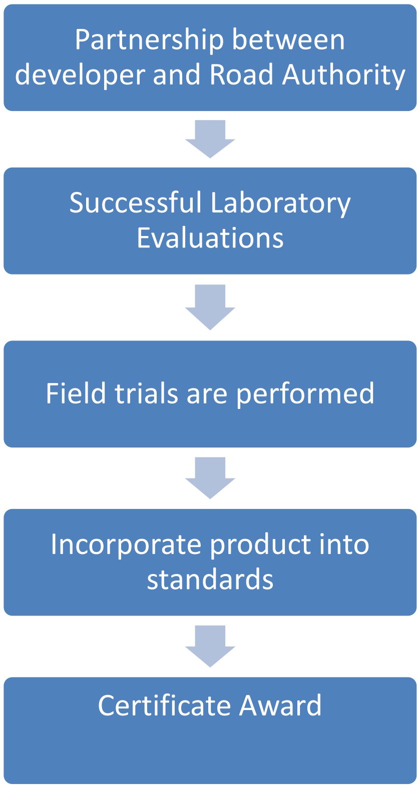


Figure 2.6. Process of incorporating new technologies into existing specifications in France

2.2.3 International WMA Projects

Germany

A runway was refurbished overnight by using the WMA technology, Sasobit®. Sections of 60 m in width and 15 m in length and a thickness of nearly 0.5 m were removed and rebuilt during each night shift (Sasol Wax, 2003; Hansen, 2006; Zettler, 2006).

Two runways in a Hamburg airport in Germany were paved with Stone Mastic Asphalt (SMA) with 3% of Sasobit® added. The first runway was built in July 2001 with a total area of 60,000 m^2. Satisfactory pavement performance along with enhanced compactability was reported despite the significant reduction of pavement temperature by around 30°C. In June 2003, a larger runway in the same airport was paved with SMA that incorporated Sasobit® (Sasol Wax, 2003).

WMA was placed on a runway in a Berlin airport with a total area of 135,000 m^2 and an asphalt layer of about 12 cm in thickness. A 3% dosage of Sasobit was incorporated into the asphalt mix used for this runway which was fully shutdown during the entire span of construction (Sasol Wax, 2004).

Canada

In August 2005, three trial sections of WMA were placed in Montreal, Canada using Aspha-min® zeolite. The HMA control segment was mixed at a 160°C while the Aspha-min® sections were mixed at temperature ranging between 130-135°C. The paving temperature of the Aspha-min® sections was lower (110-125°C) than the hot-mix asphalt (140-150°C) (Davidson, 2007).

Three other projects were placed in 2006 using Aspha-min®. The first was a demonstration project on a section of Autoroute 55 southeast of Drummondville placed using 280 tons of WMA in August. The other two projects were constructed in late November with ambient temperatures ranging between 0 and 5°C. In those two projects zeolite was incorporated into the control HMA and a significant improvement in compaction was reported (Davidson, 2007).

On the other hand, Lafarge Canada conducted some WMA trial experiments using WAM-Foam® technology in northeast Calgary. Meanwhile, seven demonstrations of the Evotherm® technology were conducted in Canada between 2005 and 2007 consuming nearly 10,000 tons of warm mix (Davidson, 2007).

United Kingdom

While the condition of the M6 motorway near Birmingham, United Kingdom was deteriorating alarmingly, any road maintenance and renovation was impossible during peak times of traffic. Thus, the only feasible time for the repair work was at night. Sasobit® WMA technology was used in renovating the damage of nearly one Km over eight night shifts so that proper compaction could be accomplished at relatively lower temperatures thus, the repaired section would need less time to cool down and be able to withstand traffic in a shorter time span than conventional HMA. It was reported that all three layers of the pavement were placed at temperatures lower than the conventional HMA by 20-30°C (Sasol Wax, 2006).

Additionally, a dense base course with a thickness of 20 mm which incorporated WAM Foam was manufactured and laid in 2001. The texture of the WMA mix and its stiffness modulus were reported to be similar to conventional HMA mixtures (Kristjansdottir, 2006).

Norway

In September 2000, the first field trial of WAM-Foam® process was conducted on a major road in Hobøl, Norway. Moreover, on a section of FV 82 road a wearing course of WMA utilizing the WAM-Foam® technology was placed in April 2001. Investigations of the rut depths conducted between 2000 and 2003 have shown that the rut depths of WMA and HMA sections were quite similar (Kristjansdottir, 2006).

2.2.4 WMA Projects in the United States

NCAT

An asphalt demonstration project incorporating Aspha-min® was built in Orlando, Florida in February 2004. It was reported that the use of the warm mix technology has lowered the production and compaction temperatures by 35°F than the temperatures of the control mix. Testing samples from the field in the laboratory obtained results that came in agreement with the laboratory study conducted by the NCAT (Hurley & Prowell, 2005).

On the other hand, two sections, N1 and E9 built in October 2005 using WMA incorporating Evotherm® on the NCAT test track has performed adequately. The WMA mixtures incorporating Evotherm® include two base courses with a thickness of 2 inches that were mixed and placed at 225 ˚F. After 5.6 million ESALs, it was reported that the average rutting observed in the sections constructed with Evotherm® did not exceed 6 millimeters (Zettler, 2006; Crews, 2006; Brown, 2007; Brown 2008).

Ohio

A demonstration project was conducted on sections of SR 541 in Ohio under the supervision of the Ohio Department of Transportation. A section was laid using conventional HMA as the control mix with other sections built using three WMA technologies: Aspha-min®, Sasobit® and Evotherm® (Brown, 2007; Morrison, 2007; Powers, 2007). The Aspha-min® additive was added at 0.3% by total weight of the mix while Sasobit® was added at 1.5% of the total binder at the plant. Environmental testing on the emissions produced by the four sections have shown that the Aspha-min® and Sasobit® had lower emissions of sulfur dioxide, nitrogen oxides, volatile organic compounds and carbon monoxide in comparison to the control mix. On the other hand, the Evotherm® section had produced higher emissions of sulfur dioxide, nitrogen dioxide and volatile organic compounds but it has reduced emissions of carbon monoxide (Morrison, 2007).

Wyoming

Warm-mix asphalt was used in the reconstruction effort of the east road entrance of the Yellowstone National Park, Wyoming under the supervision of FHWA division, Western Federal Lands Highway Division (Wagner, 2007). Three sections with a total distance of approximately 7 miles were laid using a control HMA mix, 8,750 tons of Advera® warm mix and 7,450 tons of Sasobit® warm mix was utilized in the field project. The Sasobit® admixture was added at a rate of 1.5% by weight of the binder while the Advera® additive was added at a dosage of 0.3% by weight of total mix. Results generated from this field trial revealed that the workers did not observe any trouble in handling the warm-mix asphalt and there were no signs of moisture susceptibility in the warm mixtures (Neitzke, 2007).

Missouri

Three warm-mix technologies were utilized in sections of Hall Street, St. Louis, Missouri in 2006. The high temperature of the HMA was the main reason suspected for the formation of bumps in this slow moving traffic region. Hence, Sasobit®, Aspha-min® and Evotherm® additives were used to investigate whether the use of WMA would eradicate the formation of bumps on that street. Under the supervision of the Missouri DOT, a total of 7,000 tons of warm mix were placed with the field compaction temperature varying between 200 and 250°F. In addition to the testing efforts conducted by the contractor and the Missouri DOT, mobile labs from FHWA and NCAT were available to conduct testing on the placed sections. Satisfactory rut depths were reported for the WMA sections and no bumps were observed (Prowell & Hurley, 2007).

Tennessee

A warm mix demonstration project was carried out in the city of Chattanooga, Tennessee in June 2007 using 4,000 ton of warm mix incorporating the Double Barrel Green® technology. The warm mix utilized in that project included 50% recycled asphalt and it was handled at 270°F with lower consumption of fuel and less emissions and odors (Brown, 2007). Sections of roads in Hillsboro Pike were rebuilt using four different WMA technologies: Double Barrel Green®, Advera® zeolites, Sasobit® and Evotherm® (Brown, 2008).

Texas

WMA was demonstrated at the American Public Works Association in September 2007 where 3,000 tons of Evotherm® warm mix was used in applying the final surface of the pavement on top of a lime stabilized subgrade a strong base layer. The warm mix was mixed at 220 to 240°F and placed at 200°F with the compaction taking place without any noted difficulty (Brown, 2008).

The American Public Works Association’s street construction demo of warm mix drew some 250 people last September. “We’ve done about 5,000 tons of warm mix through various demos, so our plant people are very comfortable with the process,” said Harry Bush of Vulcan Materials, which supplied the mix (Brown, 2008). “The temperature of the mat under the paver was about 100 degrees less than normal hot mix. And compaction went very smoothly.”

New York

In Courtland County, New York during September 2006, a demonstration project was conducted utilizing the French WMA technology, Low Energy Asphalt (LEA). The results of the demonstration were satisfactory as the technology permits the discharge of the mix at the plant in the range between 190 and 200˚F (Harder, 2007). Several demonstration projects and trials followed during 2006 and 2007 (Brown, 2007).

2.3 Benefits of Warm-Mix Asphalt

The benefits of WMA are dependent upon which technology is utilized. There are varying degrees of benefits for each different method. This is an overview of the benefits thus far realized by the industry but the specific benefits for each technology, in some cases, are not entirely quantified. Some benefits may not yet be completely economically quantifiable such as emission reduction. Also the benefit may be a variable cost such as the asphalt binder cost. If stricter emissions standards are implemented there may be higher economic potential for WMA. The purpose of this section is to present the potential benefits of WMA. Since WMA technology is in the beginning stages of implementation, there are many questions about benefits that have not yet been answered.

One of the driving forces of WMA research is the potential for it to reduce energy and fuel consumption and therefore reduce emissions. The typical WMA production temperature is in the range of 30 to 100°F lower than typical HMA (Newcomb, 2007). Often times only a slight reduction in temperature is achieved (10 to 15°F) but the reduction can lead to energy savings and significantly reduce emissions. The WMA technology is available for potentially greater temperature reductions (Newcomb, 2007). For WMA production in Europe, the reduction in temperature has led to burner fuel savings that typically range from 20 to 35 percent (D'Angelo, et al., 2008). There is a possibility of greater fuel savings (50 percent or more) when processes such as low-energy asphalt concrete (LEAB) and low-energy asphalt (LEA) are used because the aggregates or a portion of the aggregates are not heated above the boiling point of water (D'Angelo, et al., 2008).

Air Quality

The WMA technology reduces the asphalt’s temperature at the time of paving and there are several resulting benefits. These include an improved and cooler working environment, decreased exposure to asphalt fumes, higher employee retention, and an improved quality of work (Newcomb, 2007). According to the National Institute for Occupational Safety and Health

(NIOSH) website, the current recommended exposure limit (REL) for asphalt fumes is 5mg/m^3 as total particulate matter (TPM) during any 15 minute period (Roberts, Kandhal, Lee, & Kennedy, 1996). The reduced temperatures of WMA will produce fewer fumes and create better paving environments in areas such as tunnels or underground paving (Kristjansdottir, 2006).

In unison with reduction of fumes, is the reduction of odors. As the asphalt production temperatures are reduced through WMA technologies, this would reduce odors commonly associated with plant and paving operations (Newcomb, 2007). Less odors would minimize the impact asphalt paving can have in urban areas.

Environmental Protection Agency Regulations

As the country and the world move to become more sustainable, more requirements about pollution will be implemented. One example of a more stringent air pollution policy is the Clean Air Interstate Rule (CAIR). The CAIR will achieve the largest reduction in air pollution in more than a decade. CAIR emission standards applies to 28 eastern states (including Iowa) and achieving the required reductions is predominately focused on controlling emissions from power plants but states are given the option to meet an individual state emissions budget through measures of the state’s choosing. The Environmental Protection Agency (EPA) has shown that cap-and-trade systems have worked for other programs and will be used in the CAIR for both SO_2 and $NO_{x.}$ Both SO_2 and NO_x are emissions created in the production of HMA. The EPA’s website states the following about the CAIR cap-and-trade for SO_2 and NO_x (U.S. Environmental Protection Agency, 2009):

> *EPA already allocated emission "allowances" for SO_2 to sources subject to the Acid Rain Program. These allowances will be used in the CAIR model SO_2 trading program. For the model NO_x trading programs, EPA will provide emission "allowances" for NO_x to each state, according to the state budget. The states will allocate those allowances to sources (or other entities), which can trade them. As a result, sources are able to choose from many compliance alternatives, including: installing pollution control equipment; switching fuels; or buying excess allowances from other sources that have reduced their emissions.*

The asphalt industry, with WMA technology, would potentially be an example of a “source that has reduced their emissions” causing the asphalt industry to have “excess allowances” and would potentially be able to sell these to a non-compliant pollution source. This strategy would help put an economic value on the emission reductions seen in WMA. The CAIR will be completely implemented by 2015 (U.S. Environmental Protection Agency, 2009). Specifically for Iowa, the CAIR will reduce SO_2 emissions by 5% and NO_x emissions by 49% (U.S. Environmental Protection Agency, 2008).

WMA Paving Benefits

There are numerous paving benefits for WMA. Some of these include: less compaction effort, longer haul distances, and a better workability with high RAP mixes. WMA has been shown in both field and laboratory studies to have similar or better compactability than traditional HMA mixes (Hurley, 2006). A laboratory study conducted at the National Center for Asphalt Technology (NCAT) compared three different WMA additives to traditional HMA. The additives used were Evotherm®, Sasobit®, and Aspha-min®. The study found that all three additives aided in the compaction significantly compared to the control sample with no WMA additive. It was also found that Evotherm® reduced the air void content the most (Hurley, 2006). On a project in Canada, located on Autoroute 55 southeast of Drummondville, Aspha-min® zeolite was found to be a compaction aid in the field in comparison to a similar mix without zeolite (Davidson, 2007). Another study was conducted using the Astec Double Barrel Green® System and found that the WMA foaming technology provided compaction effort similar to HMA mixes but at a lower temperature (Wielinski et al., 2009).

Cooling Rate

Another potential benefit of WMA is longer haul distances. The haul distances can be lengthened for two different reasons. The first is that WMA has a smaller differential between the mix temperature and the ambient temperature which results in a slower rate of cooling as well as better compactability at a lower temperature (D'Angelo, et al., 2008). In the publication, “Warm Mix Asphalt: European Practice,” Sasobit® has been reported to allow a hauling time of nine hours for a project in Australia (D'Angelo, et al., 2008).

Throughout the literature review, little information was found specifically addressing the rate of cooling for WMA. Cooling rates for HMA are variable and depend on at least five factors. These factors are: air temperature, base temperature, mix laydown temperature, layer thickness, and wind velocity (Scherocman, 1996).

Crack Sealant Improvements

Another potential benefit of WMA is increased smoothness when crack sealant is on the underlying layer. This benefit was observed in the field on an Evotherm® project in Fort Worth, Texas. In the past, the Texas Department of Transportation (TxDOT) used a crack sealant on the road and the sealant would expand and create bumps after the application of HMA. The Evotherm® lowered the temperature of the asphalt and the decrease in temperature helped avoid expansion of the sealer thus increasing the smoothness of the roadway (MeadWestvaco, 2008).

Lower Temperature Paving

The Iowa DOT Construction Manual specifies that HMA mixtures shall not be placed after November 15, except with approval of the Engineer (Iowa Department of Transportation, 2008). There are several factors that determine the production temperature for WMA mixes produced during cool weather such as the WMA technology used, ambient conditions, and haul distance but WMA technology provides the ability to pave in cooler temperatures and still obtain density (D'Angelo, et al., 2008). Case studies in Germany have utilized various technologies to place pavement when ambient temperatures were between -3 and 4°C (27 and 40°F). The density results were higher for the WMA when compared to the same compaction effort as the HMA pavement.

Incorporating WMA with RAP Paving

Lower production temperature for RAP mixes is a potential benefit of WMA. The viscosity reducing properties of WMA additives such as Sasobit® or Advera®, has been shown in numerous studies to enhance the workability of RAP mixes. The incorporation of higher RAP percentages could potentially save money because less virgin aggregate and less virgin binder would need to be purchased. This cost savings would be variable due to the potential for high fluctuations in virgin binder prices (Tao & Mallick, 2009). Several studies have incorporated both WMA and RAP and some of these studies will be described in Section 2.5.

To summarize, WMA offers many benefits to the workers, contractors, citizens and government agencies. The lower temperatures create cooler working conditions and reduced worker exposure to fumes. The contractors may benefit from fuel savings. Studies have shown that fuel savings can reach up to 30%. The lower temperatures reduce the amount of odor that the asphalt plants emit. There is an additional benefit because asphalt plants could potentially be placed in areas of non-attainment. This would create shorter haul distances in these areas.

2.4 Emerging and Available Warm-Mix Asphalt Technologies

Presented in this section are the main types of WMA technologies available as well as a discussion of the specific processes and additives for each type. Several studies that have investigated only one specific WMA technology are also discussed in this section. Other studies that investigated several WMA technologies or processes will be discussed in Section 2.5. The technologies presented represent commonly used technologies and may not incorporate all types of processes available worldwide.

There are three main types of WMA technologies. These include foaming, organic wax additives, and chemical processes. Foaming technologies use small amounts of water in the binder to foam the binder which lowers the viscosity. There are several foaming technologies available such as Aspha-min®, WAM-Foam® developed by Shell Petroleum and Kolo-Veidekke and the Astec Double Barrel Green® system. The most common example of an organic wax additive used in WMA is a Fisher-Tropsch wax. These are created by the treatment of hot coal with steam in the presence of a catalyst. The chemical additive used in WMA is in the form of an emulsion and then mixed with hot aggregate. The mixing temperature ranges between 185-240°F (Hodo et al., 2009). The most commonly used chemical additive is Evotherm®. These technologies will be examined in more detail.

The following is an overview representing most WMA technologies available. Each section will discuss the developer, the manufacturer's recommendations, the results of studies which have utilized the technology and the recommendations made in regard to the specific technology tested.

2.4.1 Evotherm®

Evotherm® is a product that was developed by MeadWestvaco in 2003. It is recommended that Evotherm® be added at rate of 0.5 percent by weight of binder (Hurley, 2006). The Evotherm® uses a Dispersed Asphalt Technology (DAT) as the delivery system.

MeadWestvaco states that the DAT system has a unique chemistry customized for aggregate compatibility (Corrigan, 2008). The newest version of Evotherm® is the Evotherm 3G® (also called REVIX^{TM}). As of November 2008, MeadWestvaco is partnering with Ergon Asphalt & Emulsion, Inc., an Ergon Company, and Mathy Construction Company to market Evotherm 3G® (MeadWestvaco, 2008). This is water free and does not rely on binder foaming or other methods of viscosity reduction. Mathy states that the technology is based on work that shows the additives provide a reduction in the internal friction between aggregate particles and the thin films of binders used to produce bituminous mixtures when subjected to high sheer rates during mixing and high shear stresses during compaction (Corrigan, 2008).

Evotherm® production temperature at the plant ranges from 185-295°F (85-115°C). An approximate total tonnage produced to date is over 17,000 tons as of February 2008 (D'Angelo, et al., 2008). The chemistry is currently delivered with a relatively high asphalt residue (approximately 70 percent). Unlike traditional asphalt binders, Evotherm® is stored at 176°F (80°C). In most Evotherm® field trials, the product is pumped directly off a tanker truck (Hurley & Prowell, 2005).

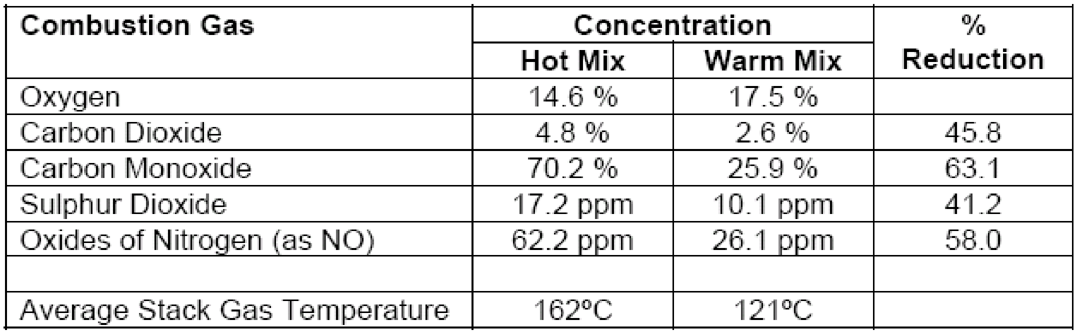
Several laboratory and field studies have been conducted in order to evaluate the performance of Evotherm®. These studies include but are not limited to: NCAT's Evaluation of Evotherm® for use in WMA, McAsphalt Industries Limited evaluated Evotherm® in the field at the city of Calgary, Aurora, and Ramara township, all in Ontario. Field studies were also conducted in Fort Worth and San Antonio, Texas. A case study was performed at NCAT to determine the moisture susceptibility in WMA and Evotherm® DAT was the WMA technology used for that study. The Virginia Department of Transportation (VDOT) conducted a field study where one of the three WMA projects used Evotherm® (Diefenderfer et al., 2007).

Evotherm Field Projects in Canada

The objective of the city of Calgary field study was to compare Evotherm® to HMA and to gain experience with Evotherm®. The target mix temperature for compaction in this study was 203°F (95°C) and the approximate mix temperature to achieve that was 290°F (143°C). This field study concluded that the mix created no issues during production or placement. Compaction is comparable with HMA and the same equipment can be used. The mix process does not present any problems with a batch plant (Davidson, 2006).

The field evaluation in Ramara township in Ontario, Canada had similar objectives to the city of Calgary project. Emissions data was collected during this paving job. A 2 tonne batch plant with baghouse with a production rate of 125 tonnes per hour was used in this study and Evotherm® emulsion arrived onsite at a temperature of 199 to 203°F (93 to 95°C). The plant operator mentioned that the emulsion was slower to pump and that the batch size had to be reduced because of the capacity of the asphalt cement weigh hoper. This is because the emulsion is only 68 to 70 percent asphalt and as a result, 46 percent more liquid material is needed per tonne of mix (Davidson, 2005). The smoke stack data showed that emissions were significantly reduced. Table 2.2 shows the emissions data measured from the smoke stack.

Table 2.2. Ramara township field study: combustion gas sampling results (Davidson, 2005)



Combustion Gas	Concentration		% Reduction
	Hot Mix	Warm Mix	
Oxygen	14.6 %	17.5 %	
Carbon Dioxide	4.8 %	2.6 %	45.8
Carbon Monoxide	70.2 %	25.9 %	63.1
Sulphur Dioxide	17.2 ppm	10.1 ppm	41.2
Oxides of Nitrogen (as NO)	62.2 ppm	26.1 ppm	58.0
Average Stack Gas Temperature	162°C	121°C	

The conclusions reached as a result of this field study are the same as the city of Calgary project and that the mix processes did not cause any problems with the baghouse. Some recommendations are that Evotherm® emulsion should be manufactured between 67 and 69 percent residue to prevent too high of a viscosity that could cause pumping issues.

The next field test was performed by McAsphalt in Aurora, Ontario. The mix was produced in a drum plant with a wet scrubber and a production rate of 225 tonnes per hour. The mix temperature used was approximately 226°F (130°C) The target compaction temperature of 203°F (95°C) (Davidson, 2005). The conclusions were similar to the conclusions stated for the City of Calgary and the Ramara Townships field tests.

Evotherm® Field Projects in Texas

The Texas DOT (TxDOT) performed Evotherm® field test in San Antonio and in Fort Worth. The San Antonio field test was performed with the purpose to evaluate the production, placement, and compaction of WMA compared to HMA and to evaluate the short and long-term performance of WMA compared to HMA (Button, Estakhri, & Wimsatt, 2007). This project was performed on August 31, 2006. The production rate was about 190 tons per hour (HMA production is typically 250 tons per hour for this plant). The lower production rate was due to high moisture content in the aggregate stock piles. Due to the high moisture content in the aggregate, the fuel consumed was the same for the warm mix as for the hot mix. No moisture problems occurred in the baghouse. The WMA was produced at 220°F (104°C) and the control mix was produced at 320°F (160°C). Some of the observations/conclusions made on this project were (Button, Estakhri, & Wimsatt, 2007):

- The HMA had an optimum asphalt content of 4.8 percent and the WMA optimum asphalt content was 4.2 percent.
- The WMA was compacted at temperatures ranging from 170°F to 210°F (77°C to 99°C) and HMA was placed at 305°F (152°C). Nuclear density tests showed 92.1 to 95 percent for WMA and the tests averaged 94.2 percent for the HMA.
- This section was open to traffic 2 hours after placement.
- Cores of the roadway, taken one month after placement, showed that no further densification was occurring.
- Indirect tensile strength (ITS) was performed during mix design and on roadway cores. The control mix had an ITS of around 170 psi. During the mix process the tensile strength for the WMA was 60 psi but the WMA roadway core tensile strengths ranged from 121 to 178 psi.

At the time of the report, all tests were performing well. The TxDOT intends to continue monitoring the long-term performance of the WMA.

Evotherm Studies Performed by NCAT

In June 2006, NCAT presented their final report of a laboratory investigation to determine the applicability of Evotherm® in WMA applications including typical paving operations and environmental conditions commonly found in the United States and to evaluate the performance in quick traffic turn-over situations and in high temperature conditions. Evotherm® and control mixes were produced using both granite and limestone aggregate and binder grades of PG 64-22 and PG 76-22 (Hurley & Prowell, 2005). A 12.5mm nominal maximum aggregate size (NMAS) was used. The mix designs were verified at 300°F (149°C) and then the other combinations were compacted at three lower temperatures, 265°F, 230°F, and 190°F. The optimum asphalt content was 5.1% for granite and 4.8% for limestone by weight of the mixtures. In this study it was found that Evotherm® had little effect on the Maximum Specific Gravity (G_{mm}) of the mixture. The conclusions based on this laboratory study can be summarized as follows (Hurley & Prowell, 2005):

- Evotherm® lowers the air voids in the gyratory compactor for a given asphalt content. This may indicate a need to reduce the optimum asphalt content; however, at the time of this study it is believed that the optimum asphalt content of the mixture should be determined without Evotherm®. It is possible, when reducing the optimum asphalt content, to negate the improved compaction resulting from the addition of Evotherm®.
- Evotherm® improved the compactability in the Superpave Gyratory Compactor (SGC) and a vibratory compactor. Statistical analysis showed an average air void reduction of 1.4 percent and improved compaction noted as low as 190°F.

- Evotherm® increased the resilient modulus of an asphalt mix compared to the control mix at a given compaction temperature and same performance grade (PG) binder.
- Evotherm® decreased the rutting potential compared to the control mixes produced at the same temperature. The rutting potential increased with decreasing mixing and compaction temperature possibly due to the decreased age of the binder. The decreased rutting potential was correlated to improved compaction.
- The Evotherm® indirect tensile strengths (ITS) were lower, in some cases, compared to the control mixes.
- Visual stripping was observed in the control mixes for both the granite and limestone aggregates and visual stripping occurred with the limestone aggregate mix produced at 250°F (121°C) containing the original Evotherm® formula. Low tensile strength ratio (TSR) values were observed with the original Evotherm® formula and the limestone aggregate. The new Evotherm® formula increased the tensile strength and eliminated the visual stripping for the limestone aggregate.

The recommendations based on the Evotherm® laboratory analysis are as follows (Hurley & Prowell, 2005):

- The optimum asphalt content should be determined with a neat binder that has the same grade as the Evotherm® modified binder. Extra samples should be made with the Evotherm® so the production air void target can be adjusted.
- A minimum mixing temperature of 265°F (129°C) and a minimum compaction temperature of 230°F (110°C) are recommended. If mixing is below 265°F (129°C) it is recommended that the high temperature grade should be bumped by one grade to counteract the tendency for increased rutting susceptibility with decreasing production temperatures.
- Moisture sensitivity testing should be performed at anticipated field production temperatures.

This laboratory study will be a helpful model for the future experiments and the recommendations will be useful for future studies. This study is a good example of the type of data that can be expected when performing laboratory testing using Evotherm®.

One of the major concerns with WMA is its susceptibility to moisture damage. The hypothesis is that lower WMA temperatures will not adequately dry out the aggregate causing inadequate bonding between the asphalt binder and aggregate. NCAT performed a study addressing this issue using the Evotherm® DAT technology. The mixes tested were both laboratory- and plant-produced mixes. Both mixes contained limestone aggregate with an optimum asphalt content of 5.2% (Kvasnak et al., 2009). The moisture susceptibility tests used in this study were the indirect tensile strength (ITS) tests and the Hamburg Wheel Tracking Device (HWTD) test. After samples were made, the ITS was measured and the absorbed energy was calculated. The acceptable absorbed energy value is recommended to be 70 or greater for unaged specimens and 55 or higher for aged specimens to be considered acceptable (Kvasnak et al., 2009). The TSR showed the WMA laboratory mix had a TSR of 69 percent and was below the 80% tensile strength ratio criteria. All HMA samples, laboratory- and field-produced, met the passing criteria for this test. All but one of the four WMA plant-produced mix samples exceeded the 80% tensile strength criteria. The HWTD test was only performed on the plant-produced samples. The test showed the HMA mix consistently produced a stripping inflection point above 10,000 cycles and the WMA mix produced a stripping infection point that ranged between 5,000 to greater than 10,000 cycles. This study showed that the WMA moisture susceptibility results improved from the laboratory to the plant. This may be due to the Evotherm® DAT not blending adequately in a laboratory bucket mixer. The results may be better if the Evotherm® DAT had been mechanically blended with the binder prior to mixing. Overall, WMA showed to be more susceptible to moisture damage than HMA but most WMA samples did pass the moisture susceptibility criteria (Kvasnak et al., 2009).

Evotherm Field Projects in Virginia

The final study reviewed that used Evotherm® was a field study in Virginia. This was a 1.5 inch overlay in York County, Virginia performed October 26-November 2, 2006. The base binder used for the emulsion was a PG 70-22 (Diefenderfer et al., 2007). The weather was clear with highs around 60°F and a moderate breeze. The plant used was a Gencor counterflow drum plant. WMA was produced at temperatures ranging from 220°F to 230°F (104°C to 110°C) and approximately 530 tons of WMA were produced. The control HMA was produced at 300 to 310°F (149 to 154°C). This study found that asphalt content of the control mix was lower than that of the Evotherm® mix and no other volumetric differences were seen. The Evotherm® cores had slightly higher air void contents compared to the control but the difference was not statistically significant. Also, estimated voids from the uncorrected nuclear density measurements indicated slightly higher void contents and variability for the Evotherm® section in comparison to the control section. This difference was statistically significant. Finally, Evotherm® specimens did not pass the rutting criteria when tested in the Asphalt Pavement Analyzer (APA) whereas control specimens had acceptable rutting resistance (Diefenderfer et al., 2007).

2.4.2 Sasobit®

Sasobit® is a Fischer-Tropsch paraffin wax. Sasobit® is a product of Sasol Wax, South Africa. Sasol Wax has been marketing Sasobit® in Europe and Asia since 1997 (D'Angelo, et al., 2008). It is described as an "asphalt flow improver." The Fischer-Tropsch (F-T) process produces the fine crystalline, long chain aliphatic hydrocarbon that makes up the product Sasobit®. The production process begins with coal gasification using the F-T process. The gasification of coal involves the treating of white hot hard coal or coke with a blast of steam (Corrigan, 2008). The gasification process produces a mixture of carbon monoxide and hydrogen. As this occurs carbon monoxide is converted into a hydrocarbon mixture with molecular chain lengths of 1 to 100 carbon atoms and greater. There are naturally occurring paraffin waxes but these differ from Sasobit® in the lengths of the carbon chains. Sasobit® hydrocarbon chains range from 40 to 115 carbon atoms and natural paraffin waxes range from 22 to 45 carbon atoms (Corrigan, 2008). The longer chains give Sasobit® a higher melting temperature of approximately 210°F (99°C) and fully dissolve in asphalt at 240°F (116°C). Sasobit® allows a reduction in production temperatures of 18-54°F. Sasol Wax recommends adding Sasobit® at 3 percent by weight of the mix to gain the desired reduction in viscosity and should not exceed 4 percent due to a possible adjustment of the binder's low temperature properties. Direct blending of solid Sasobit® at the plant is not recommended because it will not give a homogeneous distribution of the Sasobit® in the asphalt (Corrigan, 2008).

Sasobit® has been used in both laboratory and field studies. Several studies that have utilized Sasobit® will be discussed. NCAT performed a laboratory study using Sasobit®, the Virginia DOT performed two field studies with Sasobit®, and Sasobit® use was discussed in the FHWA publication about European WMA practice.

NCAT’s Evaluation of Sasobit®

The report for NCAT's evaluation of Sasobit® was released in June 2005. The objectives in this study were to perform a laboratory study to determine if Sasobit® was applicable in typical paving operations and environmental conditions commonly found in the United States and also to evaluate the performance of mixes in quick traffic turn-over situations and high temperature condition (Hurley & Prowell, 2005). In this study, two aggregates (limestone and granite), three binders (PG 64-22, PG 70-22 and PG 76-22) and both a control Sasobit® and Sasoflex® which contains elastomer (SBS polymer) were mixed. Samples were prepared with oven dried aggregate. The mix design was verified at 300°F (149°C) and then the other combinations were then compacted at three lower temperatures (265, 230, and 190°F). Volumetric data showed that Sasobit® had little effect on the G_{mm} of the mixture. The Sasobit® mix tended to have lower air voids than the corresponding control mix in all 18 mix combinations and because of the lower air voids it appears to reduce the design asphalt content. No other changes in volumetric properties were impacted. Binder tests, APA rutting, strength gain, and moisture sensitivity were tested for all of the mixtures. Binder test results show that Sasobit® binders exhibit reduced aging in a rolling thin film oven (RTFO)/dynamic shear rheometer (DSR) test compared to a control binder (Hurley & Prowell, 2005).

The Sasobit® samples showed improved compaction in the vibratory compactor for all but four samples and this may be due to the SBS polymer stiffening the binder. It was found that Sasobit® did not affect the resilient modulus of an asphalt mix compared to the control. The ITS strengths were lower for the Sasobit® compared to the control in some cases. The strength gain experiment tested the rutting susceptibility of samples at different ages. There was no data to indicate that the Sasobit® was gaining strength with time. Moisture susceptibility was measured by HWTD tests and tensile strength ratios (TSR). Moisture susceptibility test results were variable. Reduced tensile strength and visual stripping were observed in both the control and Sasobit® mixes produced at 250°F (121°C). The addition of AKZO Nobel Magnabond (Kling Beta 2912) improved the TSR values to acceptable levels. The recommendations from this laboratory study are (Hurley & Prowell, 2005):

- Modified binder including Sasobit® or Sasoflex® need to be engineered to the desired performance grade. In this study, a PG 58-22 was used and with the addition of 2.5 percent Sasobit® it was modified to a PG 64-22.

- Optimum asphalt content should be determined with a neat binder with the same grade as the Sasobit® modified binder and additional samples should be produced with Sasobit® so the field target density can be adjusted.
- A minimum mixing temperature of 265°F (129°C) and a minimum compaction temperature of 230°F (110°C) are recommended. If the mixing temperature is below 265°F (129°C) then the high temperature grade should be bumped by one grade to counteract the tendency for increased rutting susceptibility with decreasing production temperatures.
- Moisture sensitivity testing should be conducted at the anticipated field production temperatures and an anti-stripping agent should be added to the mix if moisture sensitivity results are not favorable.

Sasobit® Field Studies in Virginia

The first field study by the Virginia DOT was a 1.5 inch overlay in Rappahannock County, Virginia. Approximately 775 tons of WMA was paved. The mix was a 9.5mm NMAS with a PG 64-22 containing 20% RAP and a design asphalt content of 5.5%. Morelife 3300 anti-strip additive was used at 0.5% by weight of binder. Sasobit®, in the form of pills, was added at a rate of 1.5% by weight of binder. The weather conditions on the day of paving were slightly overcast in the morning with temperatures in the upper 60's (°F) and by the afternoon the weather was clear with highs in the low 80's (°F). Stockpiles were damp from a 0.8 in of rain that occurred the day before paving. The plant was an Astec parallel flow drum plant with a coater box. HMA was produced at approximately 300°F (149°C) and Sasobit® was produced at 250°F (121°C) (Diefenderfer et al., 2007).

The second trial was a 1.5 inch overlay on Route 220 in Highland County, Virginia. This was performed on August 14 and 15, 2006. Approximately 634 tons of HMA was produced of which 320 tons was WMA. The weather was sunny on the 14th with high/low temperatures of around 86/68°F. Conditions were variable between plant and paving location on August 15th. The high/low temperature was approximately 72/68°F with overcast skies and an occasional light drizzle. The haul time was approximately 1 hour and 45 minutes. Due to the haul time, HMA was produced at temperatures of approximately 300 to 325°F (149 to 163°C) and WMA was produced at approximately 300°F (149°C). The temperatures behind the screed ranged from 280°F to 300°F for HMA and the temperatures behind the screed for WMA ranged from 250 to 275°F (121 to 135°C) (Diefenderfer et al., 2007).

For both trials, density and permeability testing, volumetrics, APA rut resistance, and TSR values were determined. The following conclusions were made as a result of these field tests (Diefenderfer et al., 2007):

- The use of Sasobit® did not cause substantial changes in volumetric properties.
- Average air void contents in Sasobit® cores were slightly less than control cores but the difference was not statistically significant.
- Permeability was similar for Sasobit® and control samples.
- The TSR test results were inconsistent.

- The rutting resistance of the Sasobit® WMA and HMA was not statistically different.

The Effect of Sasobit on CO_2 Emissions

A laboratory study was conducted at the Worchester Polytechnic Institute to examine how much Sasobit® reduced CO_2 emissions (Mallick et al, 2009). Both a control mix and an identical mix with 1.5% Sasobit® additive were tested. The CO_2 testing was performed by putting equal amounts of sample in separate sealed containers where the CO_2 emissions could be measured using an Accuro pump and 100-3,000 ppm active flow CO_2 Dräger tubes. The statistical analysis showed that at least one of the three independent variables, Sasobit® content, temperature and added asphalt content had a statistically significant effect on CO_2 emissions. The linear regression analysis showed temperatures had a very significant relationship with CO_2 emissions. A statistical analysis of the data showed that Sasobit® is not directly responsible for any difference in CO_2 emissions but the reduction in temperature is significant. This study concluded that within the factors that were tested, the best way to reduce CO_2 emissions was by lowering the temperature of the mix and it was also shown that Sasobit® did not cause unwanted effects on emissions or volumetrics. Also, this study showed that the G_{mm} values were not statistically affected by Sasobit® addition (Mallick et al, 2009).

Sasobit® has been used in many projects and, since 1997, more than 142 projects totaling more than 10 million tons of mix have been paved using Sasobit®. The projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Norway, Russia, Slovenia, South Africa, Sweden, Switzerland, the United Kingdom and the United States. Lastly, Sasobit® was used in deep patches on the Frankfurt Airport in Germany. Twenty-four inches of HMA were placed in a 7.5 hour period. The runway was reopened to jet aircraft at a temperature of 185°F (85°C) (D'Angelo, et al., 2008).

2.4.3 Aspha-min®

Aspha-min® is produced by Eurovia Services GmbH, in Bottrop, Germany. Aspha-min® is a manufactured synthetic zeolite (Sodium Aluminum Silicate) that has been hydro thermally crystallized and is in a fine white powder form. The zeolite is 21 percent water by mass and the water is released in the temperature range of 185 to 360°F (85 to 182°C) The fine spray of water that is released creates a foaming effect in the binder that increases workability and aggregate coating at lower temperatures. The recommended addition rate is 0.3 percent by mass of the mix and there is a potential temperature reduction of 54°F compared to traditional HMA mixes. The reduction can lead to a 30 percent reduction in fuel energy consumption (Corrigan, 2008).

The framework silicates that make up zeolite have large vacancies in their crystalline structure and this allows large cations and water molecules to be stored. The zeolites are characterized by their ability to lose and absorb water without damage to their crystal structures (Corrigan, 2008).

Several studies have been performed using Aspha-min®. These studies include an NCAT laboratory analysis, studies by Eurovia, a laboratory evaluation performed at Michigan Technology University, some discussion from the publication, "Warm Mix Asphalt: European Practice," and a short summary of a field projects in Canada that used Aspha-min®.

NCAT Evaluation of Aspha-min®

NCAT investigated the use of Aspha-min® zeolite in WMA. The objectives of this study were to determine the applicability of Aspha-min® to typical paving operations and environmental conditions commonly found in the United States, including the performance of mixes in quick traffic turn-over situations and high temperature conditions (Brown, 2007). In this study two aggregates (limestone and granite) and two binders (PG 58-22 and PG 64-22) were used. The control mixes had no zeolite and test results were compared to the mixes that contained zeolite. The mix designs were verified at 300°F. (149°C) then each combination was reevaluated at three lower temperatures (265, 230, 190°F).

Volumetric properties, resilient modulus, APA rutting, strength gain and moisture sensitivity were measured for each mix type. The results showed that Aspha-min® zeolite had little effect on G_{mm} of the mixture (Brown, 2007). Aspha-min® aided in compaction and lowered air voids compared to the control mix. Because of the reduced air voids, the addition of Aspha-min® zeolite could potentially reduce the design asphalt content. The resilient modulus tests showed that as air voids increased, the resilient modulus value decreased. A statistical analysis was performed on the data and observation of the F-statistic suggests that the binder grade had the most significant impact on the resilient modulus value and that the addition of zeolite did not significantly affect the resilient modulus. The APA rutting test results showed that adding Aspha-min® zeolite did not increase or decrease rutting potential, the limestone rutted less than the granite and the rut depth increased as the compaction temperature decreased for all factor level combinations (Hurley & Prowell, 2005).

The strength gain data showed no evidence to support the need of a cure time for Aspha-min® mixes. The moisture sensitivity testing consisted of the HWTD test and TSR values. The TSR values showed that zeolite lowered TSR values compared to the control mix and most tests did not satisfy the recommended minimum value for Superpave mixes, the minimum TSR is 0.80. Hydrated lime was used an anti-stripping agent and this brought TSR values to just under the minimum Superpave criteria (Hurley & Prowell, 2005). The results of the HWTD tests showed the striping inflection point was lowered for the Aspha-min® zeolite mixes compared to the control mix. The addition of 1.5 percent dry lime improved the results.

NCAT's study also included a field demonstration project. The project was performed in February 2004 at Hubbard Construction's equipment yard in Orlando, Florida. Aspha-min® was used and added at the rate of 0.3 percent by weight of total mix produced. Both control and warm mix were produced at 130 to 140 tons per hour. Production and laydown temperatures for the Aspha-min® were around 35°F cooler than the control. Plant produced samples were made using the Marshall method and associated volumetrics with TSR values and APA rutting potential of the mixtures evaluated. Results showed that Aspha-min® volumetrics, TSR values and rutting potential were comparable to the control mix values. Performance observations were made in March 2005, one year later. No pavement distress was observed for either the Aspha-min® or the control mix. Cores were taken and the cores showed air voids in the WMA was slightly higher than the control mixture. This could be due to normal variation. The average tensile strength of the Aspha-min® cores was higher than the control cores. In this case, Aspha-min® has performed equally well to the HMA. It should be mentioned that this section of pavement does not receive regular traffic and traffic may contribute to moisture damage (Hurley & Prowell, 2005).

Aspha-min® Field Studies

The producers of Aspha-min® preformed a field study and the following is a summary of their findings. Their conclusions were that Aspha-min® did not create any problems from a storage or handling point of view. No visual differences were seen in the comparison of the zeolite WMA and the HMA three years after paving. The Aspha-min® reportedly lowered carbon dioxide emissions and production temperatures were reduced by 30°C and saved on wear and tear of the plant. It was also noted that on similar Aspha-min projects, ambient temperatures have ranged from above 30°C until nearly freezing (Barthel, Marchand, & Von Devivere, 2009).

A project in Germany used Aspha-min® to produce a base course that contained 45 percent RAP and ambient temperatures ranged from 30 to 37°F (-1 to 3°C) . Mix temperatures behind the paver ranged from 216 to 282°F (102 to 139°C). It was found that WMA increased the compactability of the mix. About 300,000 tons of Aspha-min® has been produced as of February 2008 (D'Angelo, et al., 2008).

Michigan Technological University Aspha-min® Laboratory Study

A study at Michigan Technological University performed a laboratory study to evaluate the performance of WMA made with Aspha-min using the Mechanistic-Empirical Pavement Design Guide (MEPDG) (Wei Goh et al., 2007). Used in this study was a mix with a NMAS of 12.5mm and a PG 64-22 binder. A control mix, WMA with 0.3% Aspha-min® and a WMA with 0.5% of Aspha-min were tested and the test results were put into the MEPDG Program. The study found that Aspha-min® does not affect the dynamic modulus value for the mixtures tested. The WMA decreased the predicted depth of rutting based on the MEPDG Level 1 (most detailed analysis) (Wei Goh et al., 2007). MEPDG modeling does have limitations and more research is needed to determine if the performance simulated by the MEPDG occurs in constructed pavements.

Aspha-min® Field Projects in Canada

The company Construction DJL Inc. is a large hot mix contractor in Quebec and has performed several field projects using Aspha-min® (Davidson, 2007). An Aspha-min® WMA mix and an HMA control mix were placed on city streets in Montreal during August/September 2005. The HMA was mixed at 320°F (160°C) and the WMA was mixed between 226 to 275°F (130-135°C). The laydown temperature was 284 to 302°F (140 to 150°C) for HMA and 230 to 257°F

(110-125°C) for warm mix. During the 2006 construction season, three projects were paved using Aspha-min® WMA. The first project was for demonstration purposes and the last two were placed in late November with ambient air temperatures ranging from 30 to 41°F (-1 to +5°C). In the last two projects, the use of zeolite at the conventional HMA temperature aided in compaction at the lower temperatures that are commonly encountered during the late paving season (Davidson, 2007).

2.4.4 Advera®

Advera® is manufactured by PQ Corporation in Malvern, PA. Like Aspha-min®, Advera® is a manufactured zeolite (Sodium Aluminum Silicate) and 18 to 21 percent of its mass is water entrapped in the crystalline structure. The entrapped water is released at temperatures above 210°F (99°C). The water creates a foaming effect and the amount of water is less than 0.05 percent of the mix. The foaming allows for enhanced workability and because Advera® is inorganic, it does not change the performance grade of the mixture (Corrigan, 2008).

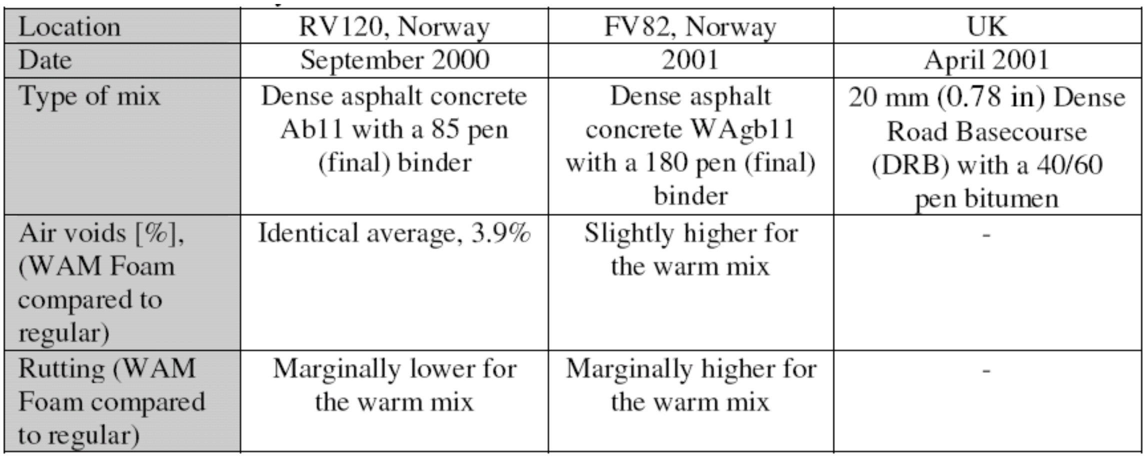
A Federal Highway Administration (FHWA), Western Federal Lands Highway Division project in Yellowstone National Park used both Sasobit® and Advera®. The haul distance was between 50 and 55 miles. The FHWA mobile asphalt testing lab performed tests on the asphalt samples collected from this project. The tests conducted included dynamic modulus and flow number (Corrigan, 2008). Fuel savings were estimated to range from 10 to 20 percent, but the rapidly changing weather and moisture in the aggregate was thought to negatively affect the fuel consumption (Michael, 2007). Advera® is only typically used in the United States but the synthetic zeolite technology has been widely used under the name Aspha-min®. Advera® is a finder gradation of Aspha-min®, with 100% passing the 0.075 mm (#200) sieve (D'Angelo, et al., 2008).

2.4.5 WAM-Foam®

WAM-Foam® is produced by Shell International Petroleum Company, Ltd. London, UK and Kolo-Veidekke, Oslo, Norway (Corrigan, 2008). WAM-Foam® is a two-component system which uses a soft asphalt binder and a hard asphalt binder. First, the aggregate is coated with the softer binder; then the introduction of a foamed hard binder enables lower mixing temperatures (Cervarich, 2003). The crucial step in the successful production of WAM-Foam® is a careful selection of the soft and hard components. It is also emphasized that the initial coating of the aggregate in the first mixing state is critical to prevent water from reaching the binder and aggregate interface. The reduction in plant temperature can lead to a plant fuel savings of 30 percent (Corrigan, 2008).

The United States Patent rights for WAM-Foam® belong to British Petroleum. Plant production temperatures can range from 230°F to 248°F (110°C to 120°C). WAM-Foam® is widely used and projects have reportedly been completed in France, Norway, Canada, Italy, Luxembourg, Netherlands, Sweden, Switzerland and United Kingdom as of February 2008 and at that time over 60,000 tons have been produced (D'Angelo, et al., 2008). It should also be mentioned that the WAM-Foam® production typically requires asphalt plant modifications to implement. Most of the WAM-Foam® research has been conducted by the developers. Table 2.3 gives a summary of some of the WAM-Foam® projects (Kristjansdottir, 2006).

Table 2.3. Summary of WAM-Foam® projects in Europe (Kristjansdottir, 2006)



Location	RV120, Norway	FV82, Norway	UK
Date	September 2000	2001	April 2001
Type of mix	Dense asphalt concrete Ab11 with a 85 pen (final) binder	Dense asphalt concrete WAgb11 with a 180 pen (final) binder	20 mm (0.78 in) Dense Road Basecourse (DRB) with a 40/60 pen bitumen
Air voids [%], (WAM Foam compared to regular)	Identical average, 3.9%	Slightly higher for the warm mix	-
Rutting (WAM Foam compared to regular)	Marginally lower for the warm mix	Marginally higher for the warm mix	-

The City of Calgary did a study using Evotherm® that was mentioned earlier. At the time of this study, a trial section of WAM-Foam® was also produced. Several plant trials were needed to facilitate proper foaming of the hard binder. The mixing temperature was around 110°C and the typical laydown temperature was 100°C. The overall demonstration project was successful and plans for short and long term monitoring have been developed (Johnston, Da Silva, Soleymani, & Yeung, 2006).

2.4.6 Asphaltan B®

This technology is not used in the United States and will thus only be briefly described. The Asphaltan B® is a product of Romonta GmbH, in Amsdorf, Germany. This is created for “rolled asphalt.” Asphaltan B® is created from Monton Wax. The origin of Monton Wax is in certain types of lignite or brown coal deposits formed during the Tertiary Period. The wax is insoluble in water and does not decompose over geologic time. Wax is extracted from coal by a toluene solvent that is distilled from the wax solution and removed with superheated steam. Asphaltan B® has a melting point of approximately 210°F. It acts as an "asphalt flow improver" much like the F-T waxes (Corrigan, 2008).

2.4.7 Double Barrel Green®

The Astec Double Barrel Green® system is made by Astec, Inc. The Double Barrel Green® system is an option that can be included with any new Astec Double Barrel® Drum mixer/dryer or it can be added as a retro fit. Only the addition of water is needed. The system uses water to produce foamed WMA. The temperature can be reduced by approximately 50°F and it is estimated that 14 percent less fuel is needed as a result (Astec, Inc., 2007). The approximate total tonnage produced as of February 2008 was over 4,000 tons (D'Angelo, et al., 2008).

Astec Double Barrel Green® Field Projects

Two paving demonstration projects were performed by Granite Construction from their Indio, California facility in early 2008 (Wielinski et al., 2009). The Astec Double Barrel Green® process was used. The objectives of the demonstration were to:

- Demonstrate that WMA with RAP could be produced and placed at lower temperatures while still having similar mix properties and field compaction as HMA
- Construct HMA and WMA test sections for side by side performance evaluations

HMA and WMA samples were collected. The WMA samples were tested and/or compacted as soon as possible after they had been sampled in an effort to duplicate field compaction temperature. No reheating was performed on WMA. The HMA samples were collected and then compacted immediately or at a later time after reheating. One WMA property that was of considerable interest was the moisture content of the two mixes. It was found there was no significant difference between WMA and HMA mixes and moisture contents ranged from 0.08 to 0.02%. There were some concerns about variation in materials. The sand equivalent (SE) value was 55 for the first day and during the second and third day of production the SE values ranged between 68 and 71. It was observed that the crack sealer that was placed after milling on the WMA demonstration site one, did not swell. All WMA wet mixes met minimum mechanical property requirements. TSR values for both HMA and WMA were low and the WMA values were slightly lower comparatively. It was concluded from the field demonstrations that WMA can be placed, produced, and compacted at lower temperatures while achieving mix properties similar to HMA. Five months after placement the initial performance was excellent (Wielinski et al., 2009).

Evaluation of the Astec Double Barrel Green® System

A study was performed to examine the economic, environmental and mixture performance in order to assess WMA sustainability in Northern America. This study focused on the Astec Double Barrel Green® system. Included in this study were an economic and a mixture performance evaluation of WMA mixes containing RAP and Manufactured Shingle Modifier (MSM^{TM}) produced using the Double Barrel Green® process in Vancouver, British Columbia (Middleton & Forfylow, 2009). This study made the following conclusions:

- The mix properties of the WMA produced with the Double Barrel Green® system were comparable to the HMA mixture.
- The APA testing recorded the rut susceptibility for WMA was sufficient.
- Moisture susceptibility testing using tensile strength testing determined that the Double Barrel Green® process does not negatively influence moisture susceptibility of mixes.
- RAP and MSM^{TM} used with Double Barrel Green® did not significantly influence mix properties or performance based on lab tests.

- A 10 percent reduction in carbon monoxide, carbon dioxide and nitrogen oxides was determined with the process.
- A 24 percent reduction of energy was identified with the process.

2.4.8 Low Energy Asphalt (LEA)

Low Energy Asphalt (LEA) is a foaming technology process. There are three methods used to produce LEA and the method chosen depends on the plant set up. The methods are as follows (Ventura et al., 2009):

- Method 1 - The drying stage only affects the initial portion of the aggregates, which are then coated by bitumen. The remaining cold and wet portion then get added. All constitutive elements of the mix are subsequently mixed.
- Method 2 - The drying stage only affects an initial portion of the aggregates, which are mixed before the coating stage with the remaining moist portion.
- Method 3 - All aggregates are partially dried and then coated by the hot bitumen.

LEA is produced at temperatures less than 100°C (212°F) as of February 2008 over 100,000 tons of WMA have been produced by the LEA process (D'Angelo, et al., 2008).

2.4.9 WMA summary of cost and studies utilizing one WMA technology

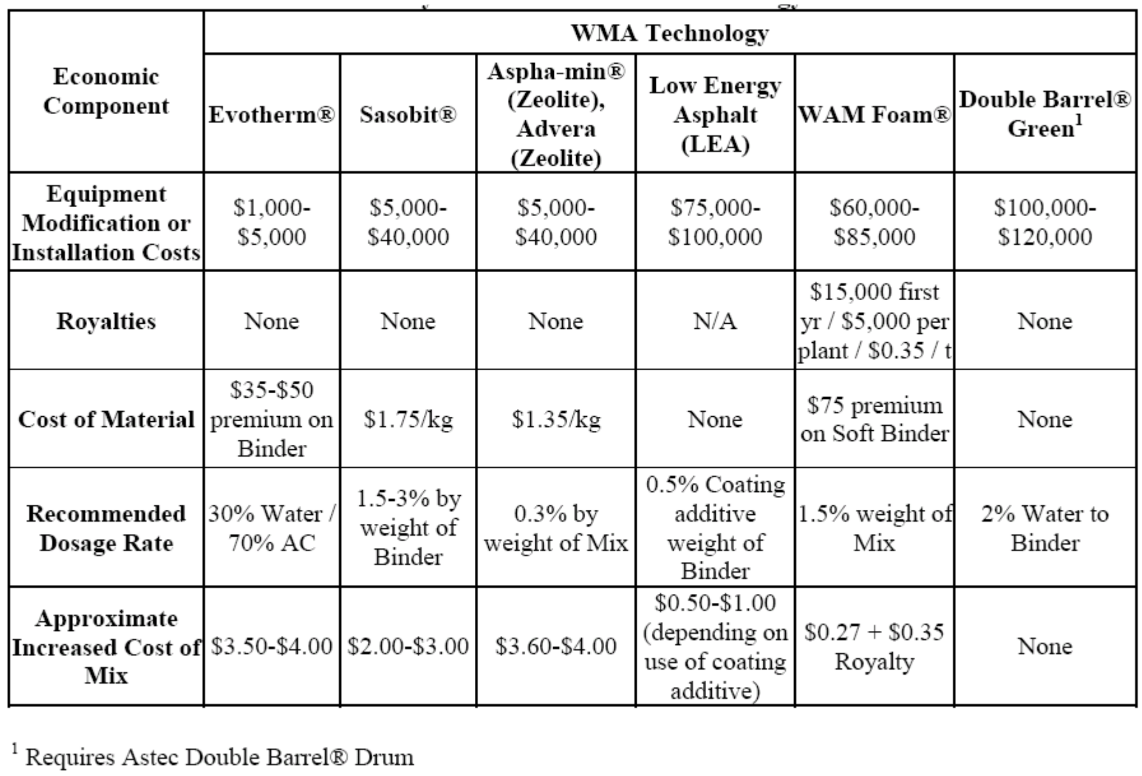
The Evotherm® field projects in Canada proved that it did not present problems to the batch plant (Davidson, 2006) and that plant emissions were reduced (Davidson, 2007). Field projects in Texas showed that the Evotherm® reduced the optimum asphalt content. The Evotherm® mix did not perform as well in ITS testing but the Evotherm® roadway core performed similar to the HMA mix (Button, Estakhri, & Wimsatt, 2007). NCAT performed a laboratory study using Evotherm® and found it improved compaction effort, increased the resilient modulus and decreased rutting potential which correlated with improved compaction. This study also recommended that moisture sensitivity testing should be performed at the production temperatures (Hurley & Prowell, 2005). Overall, Evotherm® has performed well in tests as a WMA additive but there are some concerns with moisture susceptibility.

The NCAT study which uses Sasobit®, a wax additive, showed that it did not appear to affect the G_{mm} but that the modified binder needs to be engineered in order to achieve the correct PG grading (Hurley & Prowell, 2005). Field studies in Virginia showed Sasobit® had similar properties to the control mixture (Diefenderfer et al., 2007). Sasobit® was shown to reduce emissions (Mallick et al, 2009).

Finally, the foamed asphalts are the other main type of WMA additive studied. The foaming can be induced by a synthetic zeolite additive such as Advera® or Aspha-min® or the foaming can be produced through a plant modification such as the Double Barrel Green system. The NCAT study showed that the zeolite additive did not significantly change volumetric properties and strength gain data did not support the need for a cure time (Hurley & Prowell, 2005). In field testing, Aspha-min® reduced emissions and increased compactability as well as used for cold weather paving in Canada (Davidson, 2007). Field studies using the Double Barrel Green System showed WMA had slightly lower TSR values but initial pavement performance was excellent (Wielinski et al., 2009). Another study found no differences between the control and WMA mix and that the foaming process did not significantly influence mix properties or performance based on lab tests (Middleton & Forfylow, 2009).

An important issue to address with WMA is the additional costs of the additive. Table 2.4 summarizes many of the associated costs for each type of WMA technology discussed (except Asphaltan B®).

Table 2.4. Summary of WMA technology costs (Middleton & Forfylow, 2009)



Economic Component	WMA Technology					
	Evotherm®	Sasobit®	Aspha-min® (Zeolite), Advera (Zeolite)	Low Energy Asphalt (LEA)	WAM Foam®	Double Barrel® Green[1]
Equipment Modification or Installation Costs	\$1,000-\$5,000	\$5,000-\$40,000	\$5,000-\$40,000	\$75,000-\$100,000	\$60,000-\$85,000	\$100,000-\$120,000
Royalties	None	None	None	N/A	\$15,000 first yr / \$5,000 per plant / \$0.35 / t	None
Cost of Material	\$35-\$50 premium on Binder	\$1.75/kg	\$1.35/kg	None	\$75 premium on Soft Binder	None
Recommended Dosage Rate	30% Water / 70% AC	1.5-3% by weight of Binder	0.3% by weight of Mix	0.5% Coating additive weight of Binder	1.5% weight of Mix	2% Water to Binder
Approximate Increased Cost of Mix	\$3.50-\$4.00	\$2.00-\$3.00	\$3.60-\$4.00	\$0.50-\$1.00 (depending on use of coating additive)	\$0.27 + \$0.35 Royalty	None

[1] Requires Astec Double Barrel® Drum

Many laboratory and field evaluations have discussed and studied the use and effects of these technologies. The following section will describe studies that used one or more of the WMA technologies to answer questions about how these technologies effect various asphalt pavement properties such as moisture susceptibility, use of RAP, overall performance and compaction.

2.5 Investigations of Warm-Mix Asphalt and Observations

In light of all the potential benefits of WMA, it is necessary that extensive investigations take place in order to evaluate the feasibility of WMA from an economic, societal and performance perspective. Many studies have investigated one or several of these aspects and this section will present some of the studies that have used WMA technology and investigated one of the above aspects. The studies and laboratory experiments incorporating WMA technology have very diverse objectives and various ways of evaluating and comparing the technology. Most studies have a similar HMA mix design as a control and many incorporate RAP into several mixes.

Some concerns are that NCAT studies found optimum asphalt contents via traditional HMA designs procedures, namely that optimum asphalt content can be reduced by 1/2 percent with the addition of WMA (Button, Estakhri, & Wimsatt, 2007). Another study examined at how air voids changed in the field over time. Cores were taken from WMA and control sections and the results are shown in Figure 2.7 (Al-Rawashdeh, 2008).

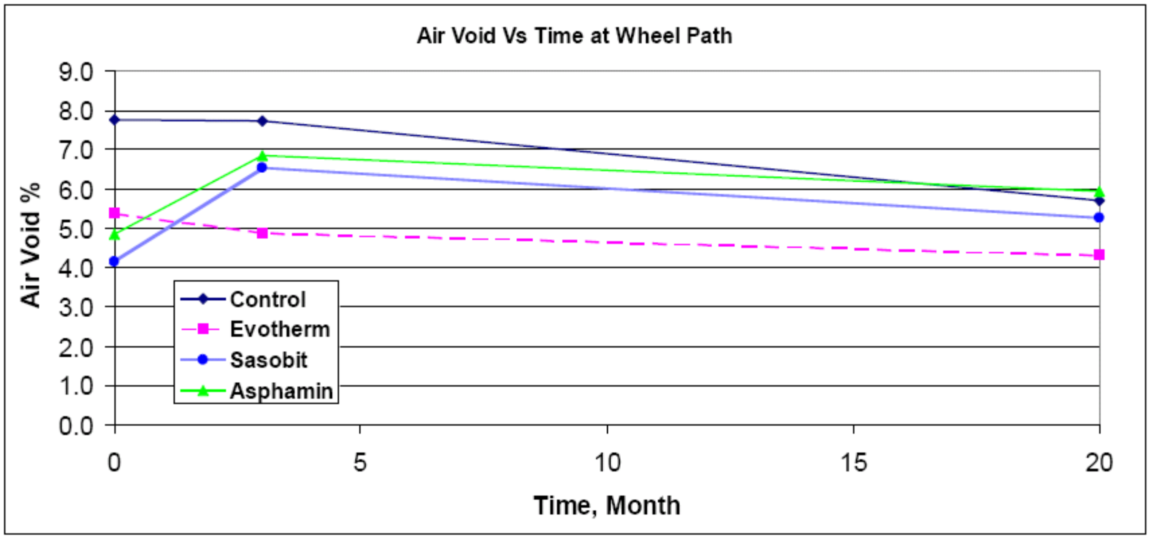


Figure 2.7. Air void percent in cores from field versus time (Al-Rawashdeh, 2008)

There has also been some concern that WMA additives affect the performance grade of the binders. In the case of NCAT's Sasobit® laboratory study, a minimum mixing temperature of 265°F (129°C) is recommended or the high temperature grade should be bumped one PG grade (Hurley & Prowell, 2005).

A study was done to investigate the effect of WMA additives on artificially long-term aged binders. The objectives of this study were to characterize the properties of WMA binders that contained long-term aged binders, using Aspha-min® and Sasobit® as additives. The long term aged binders would be representative of a RAP binder. The binders were aged by RTFO and pressure aging vessel (PAV) tests (Lee, Amirkhanian, Park, & Kim, 2008). Some of the conclusions made in this study were that virgin binder grade plays an important role in determining high failure temperature values of the recycled WMA binders. The DSR tests at intermediate temperatures showed that the WMA additives are not considered to have positive effects on resistance to fatigue cracking of recycled binders. Aspha-min® was found to stiffen the binder and lastly, this study concluded that binders containing recycled binder and WMA additives were observed to have lower resistance to low temperature cracking as determined by bending beam rheometer (BBR) testing. To satisfy current Superpave binder specifications, it is recommended to use a lower virgin binder grade even though the RAP content is only 15% (Al-Rawashdeh, 2008).

There have been several studies recently performed investigating the use of WMA additives and processes with high percentages of RAP. Trials in Germany have used 90 to 100 percent RAP using Aspha-min® zeolite and Sasobit® (D'Angelo, et al., 2008). Three studies were reviewed to investigate the performance of WMA used with RAP. A summary of each of the studies is provided.

Effects of WMA Additives on Workability and Durability of Asphalt Mixture Containing RAP

This study looked at the influence of the dose of two WMA additives (Advera® and Sasobit®) have on composite binder properties, mixture workability and mixture durability (Austerman, Mogawer, & Bonaquist, 2009). Two Superpave mixtures, a 12.5 mm with 10 percent RAP and a 19.0 mm with 25 percent RAP, were used in this study. The objectives were as follows (Austerman, Mogawer, & Bonaquist, 2009):

- Identify and select the most commonly specified WMA additives both nationally and regionally.
- Identify typical high and low dosage rates for the selected WMA additives.
- Evaluate the impact of WMA additives does on the performance grade of the binder.
- Evaluate the impact of WMA additive dose on the viscosity of the binder.
- Evaluate the impact of WMA additive dose on workability of HMA mixtures containing RAP.
- Evaluate the impact of WMA additives dose on the durability (moisture susceptibility resistance) of mixture containing RAP.

The Figure 2.8 shows a diagram that explains the experimental plan of this study. The first tests performed were binder testing to classify the performance grade and viscosity measurements were taken. The binder with 3 percent Sasobit® had the highest reduction in binder viscosity and 0.3 percent Advera® showed an increase in binder viscosity as compared with control. A torque based workability test was performed as well as durability testing using the HWTD. The WMA additives tested in the HWTD did not show the same durability as the control specimens even though the WMA showed improved workability of the control.

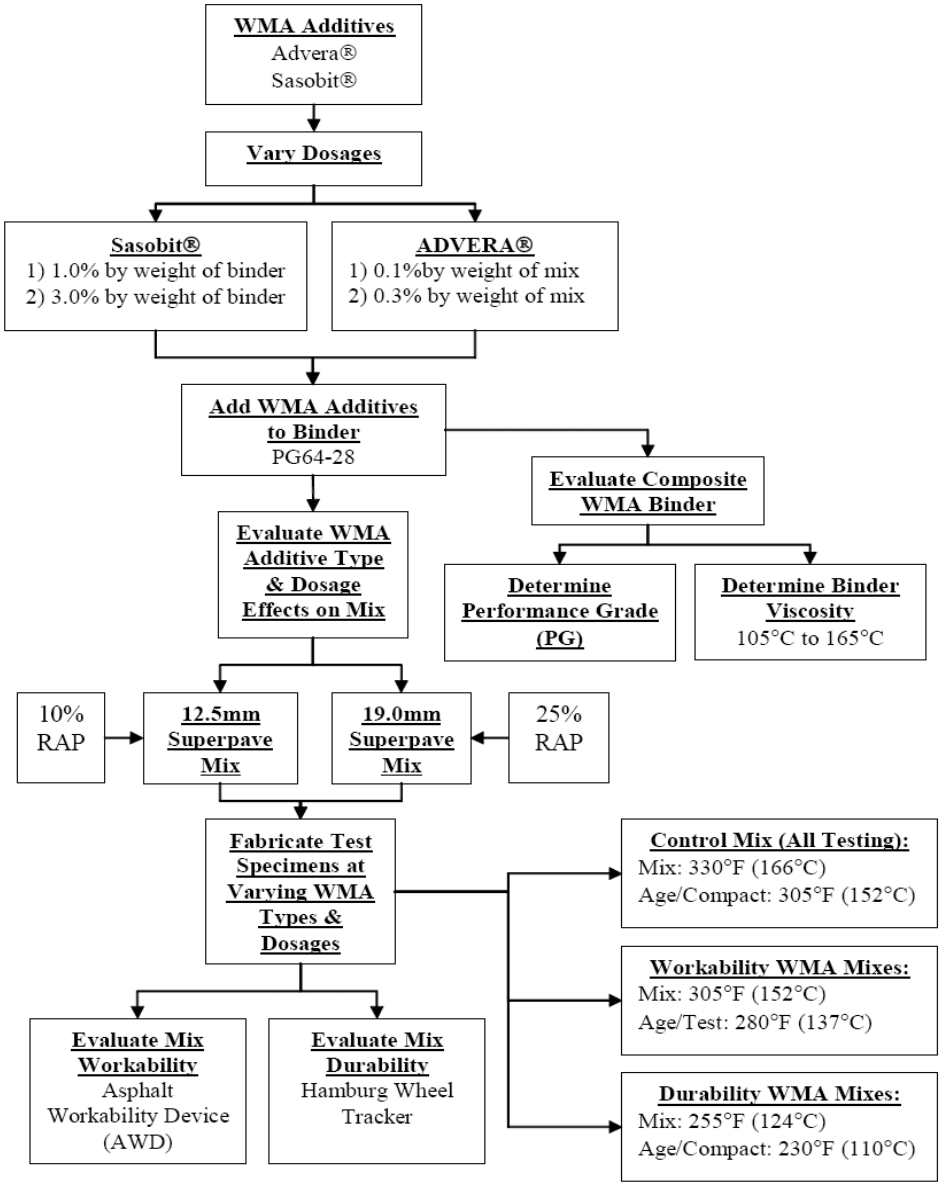


Figure 2.8. Experimental plan for studying the effects of WMA additives on workability and durability of asphalt mixture containing RAP (Austerman, Mogawer, & Bonaquist, 2009)

The conclusions of this study were (Austerman, Mogawer, & Bonaquist, 2009):

- Adding Advera® WMA additive at the dosage tested (0.1% and 0.3%) did not change the performance grade of the base binder. It was found that the addition of 1.5% Sasobit® changed the performance grade of the base binder form a PG 64-28 to PG 70-22 and addition of 3.0% Sasobit® changed the PG 64-28 to a PG 70-16.
- Viscosity testing showed that the addition of Advera® additive to the binder at

any dose had a marginal impact on the viscosity of the binder. The addition of Sasobit® reduced the viscosity of the binder, with the largest viscosity reduction occurring with the 3.0% Sasobit® dose.

- Workability testing showed that the addition of Advera® and Sasobit® additives at different dosages improved the workability of the mixture including the mixture containing 25% RAP.
- Durability testing indicated that the control mixtures exhibited better moisture susceptibility than the mixtures containing WMA additives. This indicates that the addition of anti-stripping agents may be necessary when using certain WMA additives. Lastly, durability testing may be an integral step when developing a mix design procedure for mixtures with WMA additives.

Performance Study of Foamed WMA with High RAP Content

A study was performed by the U.S. Army Engineering Research and Development Center and NCAT that investigated the performance of foamed WMA with high RAP content (Hodo et al., 2009). The objective was to conduct field observations and laboratory testing to determine the applicability of foamed asphalt technology and high RAP content. A literature review was performed for this study and results showed several potential benefits for using foamed asphalt technology with RAP. A couple of the potential benefits for using foamed asphalt technology with RAP is that it is non-proprietary and there could be a significant cost reduction to produce the mix due to the high RAP content (Hodo et al., 2009). Field-compacted mix specimens were collected from a WMA project that used WMA with no RAP and WMA with 50% RAP. The performance of these samples was evaluated by the HWTD and the APA. The test results showed that rutting would not be an issue. One year after the pavement has been in place, the performance of the WMA with 50% RAP is performing well and use of the high RAP content resulted in a significant cost reduction. More research on this subject is needed but the technique of foamed asphalt continues to look promising (Hodo et al., 2009).

Performance of WMA with 100% RAP Mixtures

The final RAP study reviewed was performed at Worcester Polytechnic Institute and investigated the feasibility of using Advera® zeolite and Sasobit H8® with 100 percent RAP mixtures. The WMA mixes and a control mix were compacted at 125°C. Figure 2.9 is a diagram of the testing plan (Tao & Mallick, 2009).

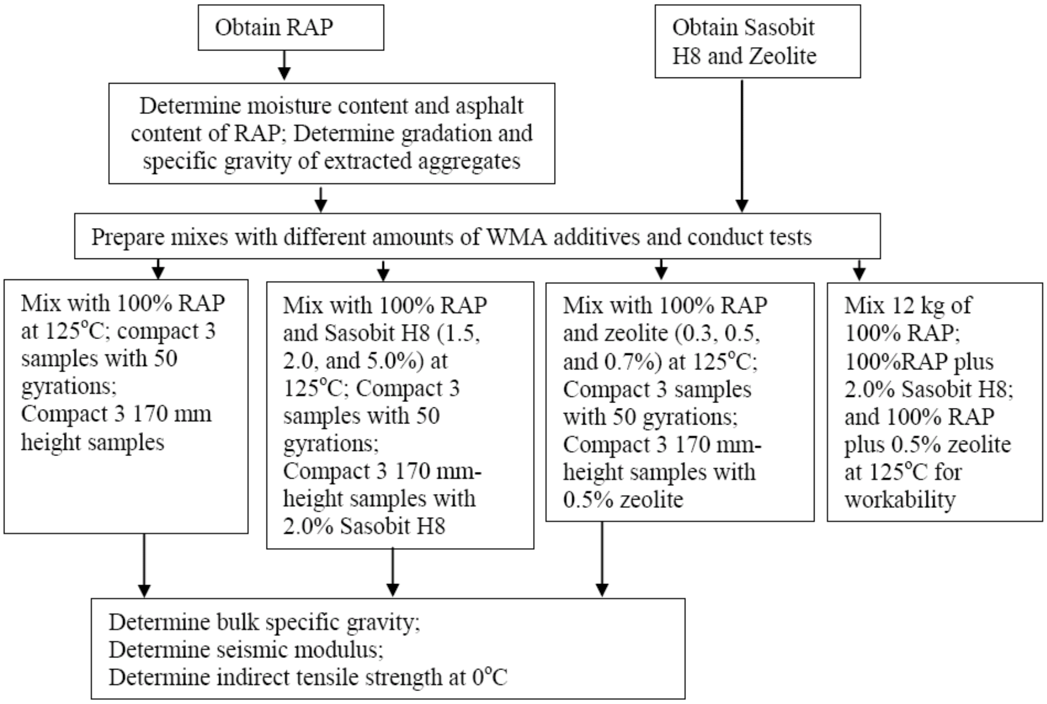


Figure 2.9. Test plan for the evaluation of WMA additive with RAP (Tao & Mallick, 2009)

Overall, this study showed that Sasobit H8® and Advera® improve the workability of the RAP; however, the workability improvement may be limited depending on the NMAS and the percent fines. The study concluded that 100 percent RAP base course is feasible with the aid of the Sasobit or Advera zeolite but long-term performance of WMA modified RAP needs to be determined.

WMA Moisture Susceptibility Studies

Effect of WMA on pavement moisture susceptibility is an especially important topic when considering implementation of WMA. In laboratory studies, it has been shown that WMA could potentially decrease ITS and TSR (Hurley, 2006). Several studies and experiments that have explored this issue but first a more in-depth discussion about moisture damage in asphalt pavements will be presented.

Moisture damage, caused by a loss of bond between the asphalt binder or the mastic and the aggregate under traffic loading, can result in a decrease of strength and durability in the asphalt mixture and ultimately affecting its long-term performance (Xiao, Jordan, & Amirkhanian, 2009). Moisture damage causes stripping of the asphalt pavement (Roberts, Kandhal, Lee, & Kennedy, 1996). Stripping in HMA pavements may be induced by as many as five mechanisms including detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring. There are many variables that can impact a mix's susceptibility to stripping and these include the type of mix, asphalt cement characteristics, aggregate characteristics, environment, traffic, construction practice, the use of anti-strip additives and the common factor is the presence of moisture (Roberts, Kandhal, Lee, & Kennedy, 1996). There are two major types of moisture damage and they are failure of adhesion and failure of cohesion.

A study was performed at Clemson University to investigate moisture damage in WMA mixtures containing moist aggregates (Xiao, Jordan, & Amirkhanian, 2009). The tests performed were the indirect tensile strength (ITS), TSR, deformation and toughness to investigate the mix performance. The experimental plan consisted of two WMA additives (Aspha-min® and Sasobit®), two moisture percentages (0% and ~0.5% by weight of dry aggregate) and three hydrated lime contents (0%, 1% and 2% by weight of dry aggregate). Also, two aggregate types were used (granite and schist) from three aggregate sources and one binder grade (PG 64-22) was used. All specimens were produced at optimum binder content. Some of the findings and conclusions from this study were (Xiao, Jordan, & Amirkhanian, 2009):

- Dry ITS values of the mixtures containing moist aggregate decreased compared to other mixtures. The decrease in ITS values was offset when hydrated lime was added.
- Wet ITS and TSR values showed that the addition of lime played a key role in improving the ITS and TSR values regardless of the mixture with or without moisture.
- In general, statistical analysis showed no significant difference in ITS values (dry or wet) amongst three types of WMA mixtures (control, Aspha-min®, and Sasobit®) under identical conditions.
- The deformation resistance of mixtures decreased when the aggregate contained moisture. The addition of hydrated lime increased the deformation resistance and the effect of WMA additive on deformation resistance was generally not significant.

Implementation Strategies

New technologies such as WMA can often take years to implement. There are many new technologies emerging every year and research can be very time intensive. The idea of a central database of new technology studies and experiment reports for governmental highway agencies have been discussed (Morgan, Peterson, Durham, & Surdahl, 2009). It is speculated that the number of hours researching will be reduced dramatically if such a database existed. A study was performed and recommendations of how to efficiently evaluate new technologies were provided. The evaluation includes a four step process of the following: 1) Preliminary Evaluation, 2) Program Formulation, 3) Evaluation and 4) Implementation (if accepted) and Remaining Tasks (Morgan, Peterson, Durham, & Surdahl, 2009).

Part of incorporating WMA into the asphalt paving industry is implementation. A potentially useful tool when implement sustainable technologies could be Green Roads. Green Roads presents evaluation guidelines for quantifying sustainable practices with roadway design and construction. The evaluation is based on a credits system but more studies are needed to more accurately distribute credits (Muench, Anderson, & Söderlund, 2009). The evaluation manual is currently accessible through the green roads website (Green Roads, 2007).

2.6 Literature Review Summary

The history of WMA shows an increasing use of the technology over the last decade. The driving force of WMA technologies are the many potential benefits and especially the reduction in fuel cost and emissions. The benefits could potentially impact a company's bottom line by saving them money, create a better working environment because of the reduction in fumes and create less impact on the surrounding community during the construction process. Before all of these benefits can be fully realized, it must be shown that WMA technologies produce mixes that are of the same performance caliber as the traditional HMA mixes.

The literature presented an overview of commonly used WMA technologies and presented field and laboratory studies presented with many of the technologies. Other studies were presented that investigated several WMA technologies to evaluate the WMA potential for moisture susceptibility and the use of WMA in mixtures containing high percentages of RAP. The various WMA additives, even though they work differently, have similar impacts on the mix. The studies that investigated the use of the WMA technologies had similar reasons for using the additives and the advantages for chemical, wax, and foamed modified WMA binders were virtually the same:

- Improves compactability
- Reduces emissions
- Decreases rutting potential due to the compaction improvements
- Improves workability in standard WMA mixes and mixes with high RAP content

One overlying disadvantage to the technologies is the moisture susceptibility concern. This is a concern mentioned in almost every study reviewed. Other disadvantages become more technology specific. Studies found that adding Evotherm can change the optimum binder content. Sasobit may change the binder grade and thus binders need to be engineered. The overall consensus of field and laboratory studies is that while the WMA technology looks very promising for the industry, more research and long-term performance studies are needed to ensure that pavement performance is equivalent to HMA mixes.

CHAPTER 3. EXPERIMENTAL PLAN

3.1 Experimental Plan for Field Produced Asphalt

The objectives of the research were to evaluate WMA technologies produced in the field for Iowa DOT projects and make recommendations that address which WMA technologies meet performance expectations and address potential quality control/ quality assurance (QC/QA) concerns. The QC/QA concerns are specific to the effects of reheating WMA samples for subsequent compaction and volumetric and performance testing. The effects of moisture conditioning on WMA mixes were also investigated. Field trials of the most promising technologies were constructed and laboratory performance testing was completed.

The Iowa Department of Transportation (DOT) produced four field WMA mixes and four HMA control mixes, which were used in this research project. Each mix was produced for a different project at different plant locations. The WMA was produced first and the HMA control mixture was produced on the following day, unless weather delayed paving. The corresponding control mixes to each WMA mix differed only by the WMA additive. For each project, loose HMA and WMA mix was collected at the time of production and binder from the tank was collected for each mix. The WMA additives were terminally blended and no laboratory binder blending was performed. The field-sampled binder and mix was taken to Iowa State University (ISU) for subsequent asphalt binder testing and mix performance testing.

The details of each mix design are discussed in Chapter 4. The sample preparation includes both field-compacted samples and reheated laboratory-compacted samples. Mix samples are needed for dynamic modulus testing and indirect tensile testing (ITS). The dynamic modulus samples are 100mm diameter and 150mm in height. The ITS samples are 100mm in diameter and 62.5mm in height. Each field-produced mix has 10 field-compacted dynamic modulus samples, 10 field-compacted indirect tensile strength samples, as well as 10 laboratory-compacted dynamic modulus samples and 10 lab-compacted indirect tensile strength samples. Half of the lab-compacted samples and half of the field-compacted samples were moisture-conditioned and represent the experimental samples, whereas the unconditioned samples are the control samples. The experimental plan evaluates the effect moisture conditioning has on WMA mixtures and allows for comparison to HMA samples.

The samples that have undergone dynamic modulus testing are be used to develop master curves to determine if the mix properties change due to a laboratory reheating process to understand if there may be impacts on reheating WMA as part of the current Iowa DOT QC/QA process. The master curves can be compared to understand the effect of WMA technology on the stiffness of the asphalt mixtures. Figure 3.1 is a diagram which shows the different categories of mixtures produced and the samples procured for subsequent performance testing. For each field-produced mixture there was a WMA experimental mix and an HMA control mix. Table 3.1 shows the sample sizes for each mix. Each x represents the samples size for that category. Several of the field-compacted samples only had a samples size of six with three moisture-conditioned samples and three unconditioned samples. Field Mix 1 (FM1) did not have any field-compacted ITS samples because this mix was produced before the scope of this research was defined. Field Mix

4 only had six field-compacted samples of the WMA as indicated by the three “x”s within that row. In total, 284 samples were procured from the field-produced mixtures for dynamic modulus, flow number, and indirect tensile strength performance testing.

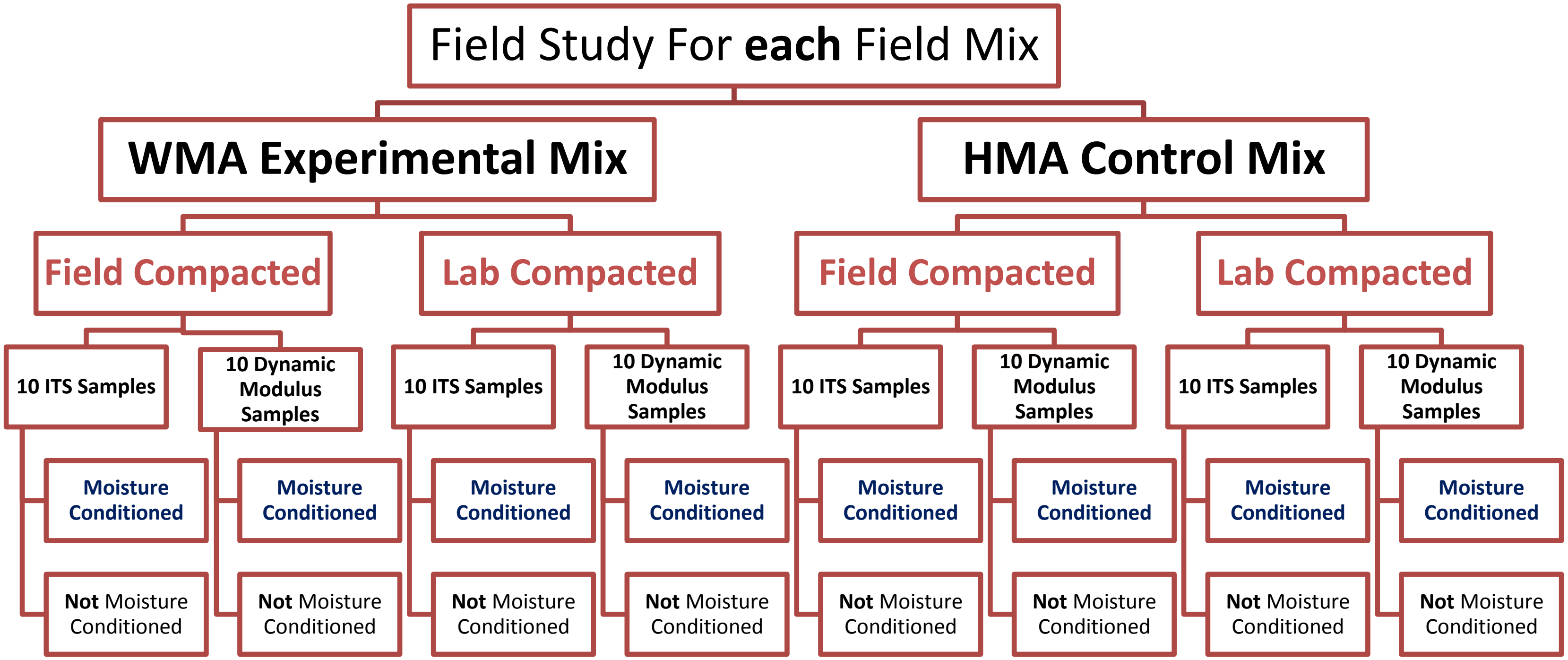


Figure 3.1. Diagram showing the categories of samples procured from each field mix

Table 3.1. Performance testing plan of warm-mix asphalt technologies and sample sizes

Mix	Unconditioned					Conditioned							
	E*			Fn	ITS Strength	E*			Fn	ITS Strength	E* Ratio	Fn Ratio	TSR
	4.4ºC	21 ºC	37 ºC			4.4	21	37					
FM1 HMA Field Compacted	xxx*	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
FM1 WMA (Evotherm 3G) Field Compacted	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
FM1 HMA Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM1 WMA (Evotherm 3G) Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM2 HMA Field Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM2 WMA (Revix) Field Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM2 HMA Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM2 WMA (Revix) Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM3 HMA Field Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM3 WMA (Sasobit) Field Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM3 HMA Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM3 WMA (Sasobit) Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM4 HMA Field Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM4 WMA (Double Barrel Green Foam) Field Compacted	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
FM4 HMA Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
FM4 WMA (Double Barrel Green Foam) Lab Compacted	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx

* “x” represents one sample and x within each cell represents sample size.

Types of Warm-Mix Additives

The types of warm-mix additives were limited to the additives that were used in the field-produced mixes. There were four different WMA technologies used and they include: Evotherm 3G, Revix, Sasobit and the Double Barrel Green foamed asphalt. As discussed in the literature review, the Evotherm 3G and Revix are chemical modifiers, the Sasobit is a wax additive and the Double Barrel Green system adds water to foam the asphalt. It is expected that the different additives will affect the HMA mixes differently in the performance testing results. Each field mix had the WMA additive terminally blended or foamed on site thus no laboratory binder blending was performed. The WMA mixes were compacted at 120°C and the HMA was compacted at 150°C. The binder grades used are as follows:

- Field Mix 1 / Evotherm 3G project used 58-28
- Field Mix 2 / Revix project used 64-28
- Field Mix 3 / Sasobit project used 64-22
- Field Mix 4 / Double Barrel Green used 64-22

Binder Testing

Binder testing on each warm mix binder and companion control binder was performed. The binder testing provides insight on the effects WMA technologies have on the binder properties. The tests and associated aging performed on the binder included the following: rotational viscometer testing (AASHTO, 2007), dynamic shear rheometer testing (AASHTO, 2007), rolling thin film oven testing (RTFO) (AASHTO, 2007), pressure aging vessel (PAV) (AASHTO, 2007), and bending beam rheometer (BBR) testing (AASHTO, 2007). The mixing and compaction temperatures determined by the rotational viscometer testing were not used in actual compaction because when the field mix was compacted, the tests on the binder had not been performed and the compaction temperature was kept the same for the field-compacted and the laboratory-compacted samples. The RTFO and PAV aged binders were aged according to AASHTO standards, T 240 and R 28, respectively.

Performance Testing

Performance testing will include indirect tensile strength (ITS), dynamic modulus testing and flow number testing. These are the main categories summarized in Figure 2.1 and Table 2.1 that will be compared for each of the four field mixes produced:

- HMA field-compacted, not moisture-conditioned
- HMA field-compacted, moisture-conditioned
- WMA field-compacted, not moisture-conditioned
- WMA field-compacted, moisture-conditioned
- HMA laboratory-compacted, not moisture-conditioned
- HMA laboratory-compacted, moisture-conditioned
- WMA laboratory-compacted, not moisture-conditioned
- WMA laboratory-compacted, moisture-conditioned

ITS testing will determine the peak loads and tensile strength ratios (TSR). The peak loads will help to compare the ultimate strengths of the control HMA mix with the ultimate strength of the corresponding experimental WMA mix. TSR ratios will help determine the effects of moisture conditioning on the mixes. The ITS test, as outlined in AASHTO T283, is a continuous load on the sample at the rate of 50mm/min (2in./min) until the sample reaches its peak load and the load is recorded. The TSR ratio is the ratio of the peak load of the moisture-conditioned sample divided by the peak load of the non-moisture-conditioned sample. A ratio above 0.80 for mixtures is deemed passing (AASHTO, 2007).

Dynamic Modulus

The purpose of dynamic modulus testing is to define the materials stress to strain relationship under continuous sinusoidal loading. The loadings are applied at various frequencies and temperatures to define the material property characteristics over a wide range of conditions. Dynamic modulus testing measures the stiffness of the asphalt under dynamic loading at various temperatures and frequencies thus it is used to determine which mixes may be more susceptible to performance issues including rutting, fatigue cracking and thermal cracking. The set up for this testing is based on NCHRP report 547. The test is performed at three temperatures (4, 21, 37°C) and nine frequencies (25, 15, 10, 5, 3, 1, 0.5, 0.3, 0.1 Hz) for each sample and yields 27 test results per sample. The dynamic modulus values (E*) are used to construct master curves which can be used to compare the various categories (Witczak, 2005). The dynamic modulus test was performed under strain controlled conditions. The target strain was 80 microstrain, which is considered to be well within the elastic region of the material. The strain response of the material was measured using 3 LVDTs that were positioned on mounted brackets at the beginning of each test. The brackets were attached using epoxy glue. The dynamic modulus test is considered to be a non-destructive test at low levels of strain in theory. Samples used in this research were compacted to the precise size needed for the dynamic modulus testing.

The dynamic modulus is expressed mathematically as the maximum peak recoverable axial strain (Witczak, 2005):

$$E^* = \frac{\sigma_o}{\varepsilon_o} \tag{3-1}$$

The complex modulus (or dynamic modulus, E*) when written in terms of the real and imaginary portion is expressed as:

$$E^* = E' + iE" = |E^*|cos\varphi + i|E^*|sin\varphi \tag{3-2}$$

$$\varphi = \frac{t_i}{t_p} \times (360) \tag{3-3}$$

where

$E*$ = complex modulus

E' = storage or elastic modulus

E'' = loss or viscous modulus

Φ = phase angle

t_i = time lag between a cycle of stress and strain (s)

t_p = time for stress cycle (s)

i = imaginary number

When a material is purely elastic, $\varphi=0$ and for a purely viscous material, $\varphi=90°$ (Witczak, 2005).

Master Curves

In order to compare the mixes, master curves were developed using the dynamic modulus data. The principle of time-temperature superposition is used and this allows for the E* values and phase angles, obtained during testing, to be shifted along the frequency axis. This helps characterize how a mix may perform at a frequency or temperature which was not tested. The data from the dynamic modulus testing is fitted to a sigmoid function. The shift factors are determined based on the data collected in the dynamic modulus testing and on the Williams-Landel-Ferry (WLF) equation (Williams, Landel, & Ferry, 1955):

$$log\alpha_t = \frac{C_1(T-T_s)}{C_2+T-T_s} \quad (3\text{-}4)$$

where

C_1 and C_2 are constants

T_s is the reference temperature

T is the temperature of each individual test

In general, modulus mater curves are modeled by the sigmoidal function expressed as:

$$log|E^*| = \delta + \frac{\alpha}{(1+e^{\beta-\gamma(log\, t_r)})} \quad (3\text{-}5)$$

where

t_r = reduced time of loading at reference temperature

δ = minimum value of E^*

$\delta + \alpha$ = maximum value of E^*

β, γ = parameters describing the shape of the sigmoidal function

Typically, the sigmoidal function used for developing master curves is based on reduced frequency instead of reduced time. For this study, the Witczak predictive equation presented in the same form as the previous equation is used and this will allow for a graphical representation of a mixture specific master curve. The equation is described as (Witczak, 2005):

$$log|E^{*}| = \delta + \frac{\alpha}{(1+e^{\beta-\gamma(\log(f_r)+\alpha_t)}} \qquad (3\text{-}6)$$

where

$log|E^{*}|$ = log of dynamic modulus

δ = minimum modulus value

f_r = reduced frequency

α = span of modulus values

α_r = shift factor according to temperature

β,γ = shape parameters

Flow Number

The same samples used in the dynamic modulus testing were then subjected to flow number testing. The flow number test is a destructive test which measures the point at which the asphalt material reaches tertiary flow. The testing procedure used in this study was devised from NCHRP Report 465 (Witzack et al., 2002) and NCHRP Report 513 (Bonaquist et al., 2003). A typical plot, shown in Figure 3.2, illustrates how accumulated permanent deformation increases with the number of applied load cycles. This figure also illustrates the three types of deformation that occur when performing the flow number test which are: primary, secondary, and tertiary flow. The flow number is defined as the number of loading cycles at the beginning of the tertiary zone. For this research the test is conducted at 37°C and at a frequency 1 Hz with a loading time of 0.1 second and a rest period of 0.9 second. The test is complete once 10,000 pulses have been reached or a strain of 10% has occurred. The deformation verses number of pulses is plotted and the strain rate vs. number of pulses is also plotted. The flow number is determined by the minimum strain rate and the corresponding pulse number.

An asphalt mixture cylindrical specimen with 100-mm diameter and 150-mm height are tested using a UTM 14P machine with a temperature controlled testing chamber. The test temperature used was 37 °C which was deemed representative of rutting temperatures in the state of Iowa. The measurements of the strains of the specimens were measured directly through machine actuators rather than affixed LVDTs due to the high deformations anticipated while conducting the tests.

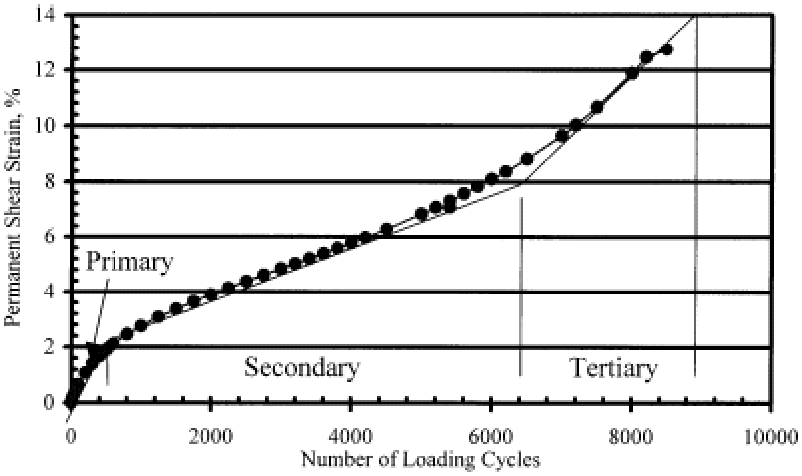


Figure 3.2. Permanent shear strain versus number of loading cycles: (Witczak, Kaloush, Pellinen, El-Aasyouny, & Von Quintus, 2002)

Statistical Analysis

A statistical analysis will be performed to determine if the differences between the means of the various categories can be considered statistically significant. The details of the type of comparison test used will be discussed in the statistical analysis section. Mean comparison tests will be used and all necessary assumptions will be addressed. Statistical analysis will help determine if the variables used in this research can be considered statistically significant and discussions will be presented regarding the implications of the findings of the statistical analysis. The main sections of the statistical analysis will be a detailed examination of the test data from ITS, dynamic modulus and the flow number testing. The major factors considered in this research are the effects of the WMA technology, the effect of moisture conditioning and the potential differences between field-compacted samples and reheated laboratory-compacted samples.

Completion of this experimental plan, will provide further insight into WMA technologies performance and assess how the technologies can be integrated into QC/QA procedures. The results will help state agencies make an informed decision on any potential adjustments that may be necessary in evaluating the quality of a WMA within the agencies QC/QA program. The research will also add to the growing database of tested WMA mixes regionally and nationally.

3.2 Experimental Plan for Laboratory-Produced Asphalt

The aim of this study is to identify WMA technologies that have high potential to succeed in Iowa pavements. Developed laboratory mixtures will be examined for performance and aging properties. A research plan was devised to answer a number of essential questions regarding WMA technology and its benefits in Iowa such as the performance of WMA and its effect on the performance grade selection of the asphalt binder. The main factors that are deemed important for answering the research questions are aggregate type, binder grade, use and percentage of recycled asphalt pavement (RAP) and specific WMA technology.

Materials

Four main types of aggregates are used in Iowa: limestone, quartzite, gravels and slag. Of these types, 12.5 mm nominal maximum aggregate size limestone and quartzite aggregates were selected for investigation in this study as limestone is the most common aggregate type and quartzite is important in pavements that require higher skid resistance.

The compatibility of using RAP with WMA technologies is investigated in this study through the preparation of three sets of mixtures; 0% RAP, 15% and 30% RAP to determine if higher amounts of RAP could be used with WMA.

Three WMA technologies that are predominantly the most successful in the US were selected for this project: Evotherm, Sasobit, and Advera. These technologies have different approaches in producing WMA and their usage in the experimental program is to be done based on the manufacturers' recommendations.

Sample Preparation and Testing

In summary the major factors identified are two aggregate types: limestone and quartzite, three levels of RAP additions (0%, 15%, and 30%) and three WMA technologies (Evotherm, Sasobit, and Advera) to be produced and evaluated in the laboratory. Hence, a partial factorial experimental plan consisting of 22 different laboratory mixtures are prepared as shown in Table 3.2 to be tested for moisture sensitivity (indirect tensile strength), flow number, and dynamic modulus test to evaluate the performance characteristics of WMA technologies compared to a set of control hot-mix asphalt. All the mixtures were tested for indirect tensile strength, flow number and dynamic modulus with the exception of mixtures no. 2, 5, 8 and 11 that were subjected to indirect tensile strength test only.

Aggregates were oven dried and preheated prior to mixing. The aggregates for the HMA control mixtures were preheated at 163 °C and blended with a PG 64-22 binder at 150°C and then aged for two hours at 140 °C.

For WMA mixtures prepared using Advera, the aggregates were heated for 4 hours at 120°C and then mixed with the preheated binder at the same temperature. Prior to preheating the binder, Advera powder was added to the amount of binder to be added to the aggregate at a dosage of 0.25% by weight of mix. The mix is then cured for four hours in the over at 110°C while being stirred once every hour.

Evotherm J1 was added to preheated PG 64-22 at 120°C at 0.5% by weight of binder for mixtures with 25% or less RAP and at 0.6% by weight of binder for mixtures with more than 25% RAP and then it was thoroughly mixed using a mechanical mixer according to the recommendations of the technology developer. The mixing and compaction temperatures for this set of mixtures were 120 and 110°C, respectively.

Sasobit mixtures were prepared by adding Sasobit to a preheated PG 64-22 binder at 120°C and dispersing it into the binder by a shear mixer operating at 700 rpm for five minutes. The binder blends were then used to produce mixtures that were cured and compacted at 110°C.

There are two specimen sizes prepared: specimens with a height of 150 mm and diameter of 100 mm for the dynamic modulus and flow number tests, and specimens with a height of 62.5 mm and a diameter of 100 mm for the indirect tensile strength test. Specimens were compacted to 7±1% air voids using a gyratory compacter.

Table 3.2. Preliminary experimental plan

		Aggregate Type					
		Limestone			Quartzite		
	Non-virgin AC %	0	15	30	0	15	30
PG 64-22	None	1	2	3	13		14
	Advera	4	5	6	15		16
	Evotherm	7	8	9	17		19
	Sasobit	10	11	12	20		21
PG 58-28	None			22			23

Moisture Conditioning

Air content data for compacted specimens was determined using the procedures of AASHTO T 166 and for each mix the specimens were sorted according to its air void in ascending order. Based on that sorting, odd ordered specimens were designated as non-moisture-conditioned and the even ordered ones were to be subjected to the moisture conditioning procedure stated in AASHTO T 283. Moisture-conditioned specimens are subjected to vacuum saturation and a freeze cycle followed by soaking in warm water. Both sets of specimens are then subjected to indirect strength testing. The tensile strength ratio (TSR) is calculated to two decimal places by dividing the average tensile strength of the dry set by the average strength of the corresponding moisture-conditioned set.

Dynamic Modulus and Flow Number

The laboratory-produced mixes were subjected to dynamic modulus and flow number testing. The details of these tests are explained section 3.1.

CHAPTER 4. FIELD MIX DETAILS AND SAMPLE PREPARATION

4.1 Field Mix Details

The purpose of dedicating a chapter to the field mix details and sample preparation is to provide information about the projects, investigate other factors which may have impacted mix performance and to discuss sample preparation. A job mix formula for each project is provided in Appendix A. The field mix details will discuss the level of traffic that the mix was designed for, the date that paving took place, the weather, and how each field mix was sampled. The sample preparation section will provide information on how samples were made as well as sample volumetrics and the methods used for moisture conditioning.

The Evotherm 3G WMA and control HMA for the first field project was produced on June 27 and 28, 2008, respectively. The job mix formula is provided in Appendix A. The design life for this mix is 1 million ESALs and is intended to be used as a surface course and includes 33% classified RAP. Six HMA and six WMA dynamic modulus samples were compacted in the field for this project. The scope of this research project had not yet been defined and this is the reason fewer field samples were made and field-compacted ITS samples were not created as did occur on ensuing projects. The weather for the days of production is shown in Table 4.1. There were 1.48 inches of precipitation recorded on June 27th. Both mixes were sampled from the top of the trucks just after loading.

The WMA Revix mix for the second field project was produced on Wednesday September 9, 2009 and the control HMA mix was produced on Thursday September 10, 2009. The job mix formula is provided in Appendix A. The weather data for production days is provided in Table 4.2. The weather for this project was favorable and no precipitation had delayed production of the control mix. The design life for this mix is 5,641,440 ESALs (10million ESAL design level) and the project location is on US 218, the Charles City Bypass. The intended use for this mixture was for the wearing surface and contained 17% RAP and a PG 64-28 binder. The sampling occurred just prior to the mix being augured into trucks.

Table 4.1. Weather data for Field Mix 1 production (NOAA, 2008)

Station: Ames 5SE Location: Ames, Iowa Production Date: June 27, 2008		
Precipitation	1.48	in.
Precipitation in the last 24 hours	0.23	in.
Temperature		
Max Temperature	73	°F
Min Temperature	64	°F

Station: Ames 5SE Location: Ames, Iowa Production Date: June 28, 2008		
Precipitation	0.52	in.
Precipitation in the last 24 hours	1.48	in.
Temperature		
Max Temperature	85	°F
Min Temperature	58	°F

Table 4.2. Weather data for Field Mix 2 production (NOAA, 2009)

Location: Charles City, Iowa Date: September 9, 2009		
Precipitation	0.00	in.
Precipitation in the last 24 hours	0.00	in.
Temperature		
Max Temperature	81	°F
Min Temperature	53	°F

Location: Charles City, Iowa Date: September 10, 2009		
Precipitation	0.00	in.
Precipitation in the last 24 hours	0.00	in.
Temperature		
Max Temperature	80	°F
Min Temperature	55	°F

Field Mix 3 (FM3) was produced a few miles west of Sheldon, Iowa. The Sasobit WMA mix was produced September 22, 2009 and the control HMA mix was produced on September 23, 2009. Table 4.3 provides weather data for this project. The ground was fairly wet from the precipitation that had occurred during the previous 24 hours prior to paving. The job mix formula is provided in Appendix A. The project location is IA 143 from Marcus North to IA 10. The design ESALs for this mix is three million and contained 20% RAP and a binder grade of PG 64-22. This mix was sampled using a bypass chute on the mix surge silo. This WMA mix contained high amounts of moisture due to the precipitation that had occurred in this area. The oven used for keeping the mixture warm for compaction had significant amounts of steam escaping each time the oven door was opened.

Table 4.3. Weather data for Field Mix 3 production (NOAA, 2009)

Location: Sheldon, Iowa Date: September 22, 2009		
Precipitation	0.01	in.
Precipitation in the last 24 hours	0.21	in.
Temperature		
Max Temperature	63	°F
Min Temperature	46	°F

Location: Sheldon, Iowa Date: September 23, 2009		
Precipitation	Trace	
Precipitation in the last 24 hours	0.01	in.
Temperature		
Max Temperature	68	°F
Min Temperature	46	°F

Field Mix 4 was produced in Johnston, Iowa. This project experienced rain delays and thus there was a period of a week and two days between the production of the Double Barrel Green foam WMA mix and the control HMA. The weather for each day of production is shown in Table 4.4. The WMA mix was produced on October 21, 2009 and the HMA control mix was produced on October 30, 2009 with the weather good for paving both days. However, wind gusts of up to 40 mph were experienced on October 30, 2009. The job mix formula is located in Appendix A. This is a surface course mix with a design life of 3 million ESALs and contains 20% RAP. Sampling for the HMA mix was taken from the top of several trucks. The trucks drove next to a high platform where the mix could be sampled. HMA was collected from at least 5 different trucks. Sampling for the WMA mix was performed by the contractor and was waiting in buckets when research personnel arrived to collect and compact the mix. The WMA production was delayed off and on all day due to the inclement (rainy) weather.

Table 4.4. Weather data for Field Mix 4 production (NOAA, 2009)

Station: Des Moines WSFO-JOHNST Location: Johnston, IA Production Date: October 21, 2009	
Precipitation	0.34 in.
Precipitation in the last 24 hours	0.01 in.
Temperature	
Max Temperature	67 °F
Min Temperature	45 °F

Station: Des Moines WSFO-JOHNST Location: Johnston, IA Date: October 30, 2009	
Precipitation	0.03 in.
Precipitation in the last 24 hours	1.80 in.
Temperature	
Max Temperature	62 °F
Min Temperature	39 °F

4.2 Sample Preparation

Loose mix was collected for four HMA/WMA field-produced mixes for a total of eight different mixes. Half of the samples were compacted in the field the other half was compacted in the laboratory after being reheated. All samples were compacted at target air voids of 7% based on the known G_{mm} values for each mix, provided by the contractor, and a fixed volume. The ITS samples are 100mm in diameter and 62.5mm tall. The dynamic modulus samples are 100mm in diameter and 150mm tall. All samples were compacted using a Pine Superpave gyratory compactor. Tables showing all of the volumetric data are located in Appendix B. The air voids were measured by weighing the samples dry, weighing the samples in water and weighing the samples saturated surface dry.

Moisture conditioning was performed in accordance with AASHTO T-283, Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage (AASHTO, 2007). First, the samples were ranked according to air void content and every other sample was moisture-conditioned. This step creates the control group of samples and the moisture-conditioned group, as well as ensures that the strength of the moisture-conditioned sample can be compared to the most-similar, non-moisture-conditioned sample. The next step is to compute the target weight range based on 70 to 80 percent saturation. The samples were placed in the vacuum container which is filled with potable water at room temperature so that the specimens have at least 25 mm of water above their surface. A vacuum pressure of 13 to 67 kPa was applied for a short time (approximately 5 to 10 minutes). Then the mass of the saturated specimens was measured. If the mass was below the target weight range, then the vacuum process is repeated. If the degree of saturation exceeded 80%, the sample was considered damaged and discarded. If target saturation was obtained, the specimen was covered tightly with a plastic film (Saran Wrap®). Each wrapped specimen was placed in a plastic bag containing 10±0.5mL of water and the bag sealed. Then the plastic bags containing the specimens were placed in a freezer set at -18 ±3°C for a minimum of

16 hours. When removed, the specimens are placed in a hot water bath at 60 ±1°C for 24 ±1hour. The specimens should have a minimum of 25mm of water above their surface. Finally, the specimens were placed in a water bath at 25 ±0.5°C for 2 hours ± 10 minutes and then the samples were tested for their indirect tensile strength.

CHAPTER 5. BINDER TESTING RESULTS

For each of the field mixes, binder was sampled and rheological testing was performed. The binder testing is useful in determining how the WMA additive affects the properties of the binder. As discussed in the literature review, some WMA additives may affect the binder grade and this testing helps to determine the extent of the differences between the HMA and WMA binders. The binder tests included DSR testing on the original binder, RTFO aged binder and PAV aged binder to determine the high and intermediate binder grade. BBR testing was performed on the PAV aged binder to determine low temperature binder grade and rotational viscometer testing was performed in order to compare the HMA mixing and compaction temperatures with those of the WMA. It should be noted that the rotational viscometer data may not fully quantify the effects of the WMA technologies (Bennert, Reinke, Mogawer, & Mooney, 2010). The rotational viscometer does give a binder viscosity comparison between the WMA additive and the HMA control binder. The results from the binder testing are to supplement and support the findings determined in the mix testing.

5.1 Field Mix 1 - Evotherm 3G

The binder for FM1 is a PG 58-28. The data from the rotational viscometer test is shown in Figure 5.1. The mixing temperature for the HMA ranges from 155°C to 161°C. The mixing range for the WMA is 131°C to 135°C. It is not known whether or not the base asphalt binder with the Evotherm 3G technology was the same asphalt binder without the WMA technology, thus the differences in mixing and compaction temperatures derived from viscosity testing may not be representative of the WMA technology. The HMA compaction temperature range is 143.5°C to 148.5°C and the WMA compaction range is 122°C to 126°C. The WMA reduced the mixing temperature by an average of 25°C but the mixing range was reduced from a range of 6°C to a range of 4°C as compared to the HMA binder range. The WMA reduced the compaction temperature by an average of 22°C and the compaction temperature range was only reduced by 1°C as compared to the HMA binder range.

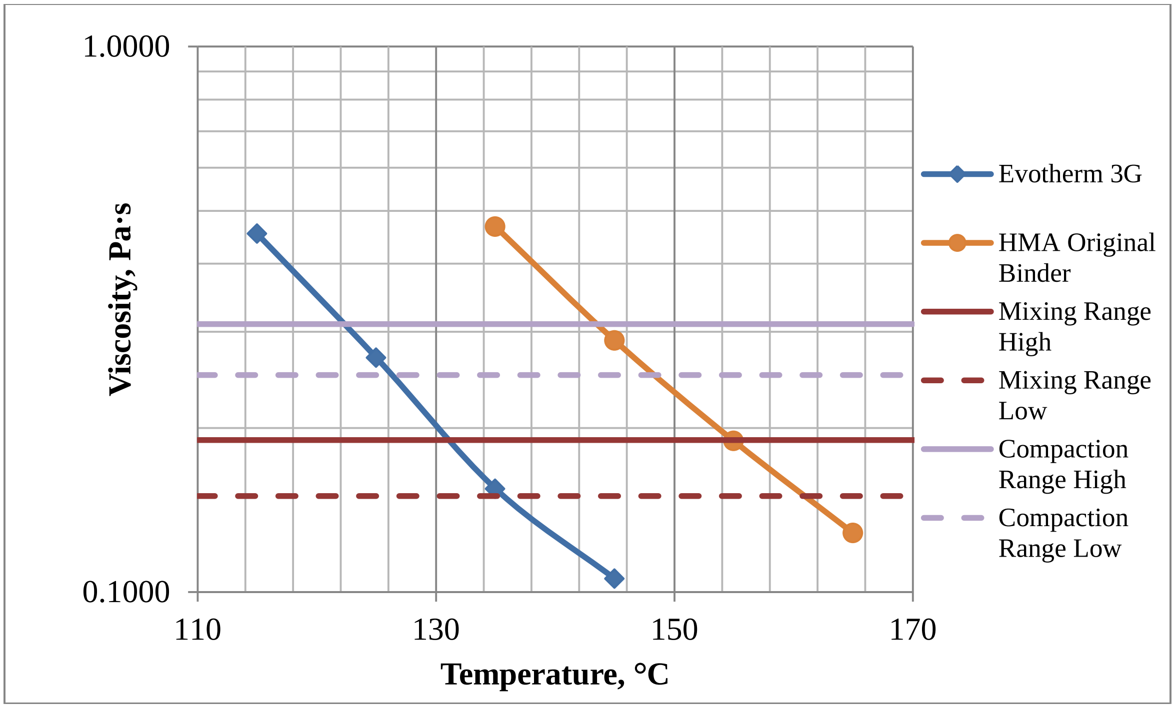


Figure 5.1. Rotational viscometer comparison of Evotherm 3G and control binder

Figure 5.2 compares average DSR continuous temperatures grades for the original, RTFO aged and PAV aged binders. The largest difference is between the HMA binder unaged and the WMA binder unaged with a continuous temperature grade difference of 7.7°C. It appears that as more aging takes place, there is a decrease in the difference in the rheological properties of the binder. Figure 5.1.3 the G*/sin(δ) of the original HMA/WMA binders and RTFO aged HMA/WMA binders. This figure shows the rheological properties over a range of temperatures in both a figure and table form. The G*/sin(δ) term is indicator for permanent deformation and is limited to 1.00 kPa for original binder and 2.20 kPa after RTFO aging. The trends of the G*/sin(δ) parameter continue through all of the temperatures tested. The permanent deformation may be more of a concern in the WMA mix however this mixture still passes the high temperature grading criteria for the PG 58 grade.

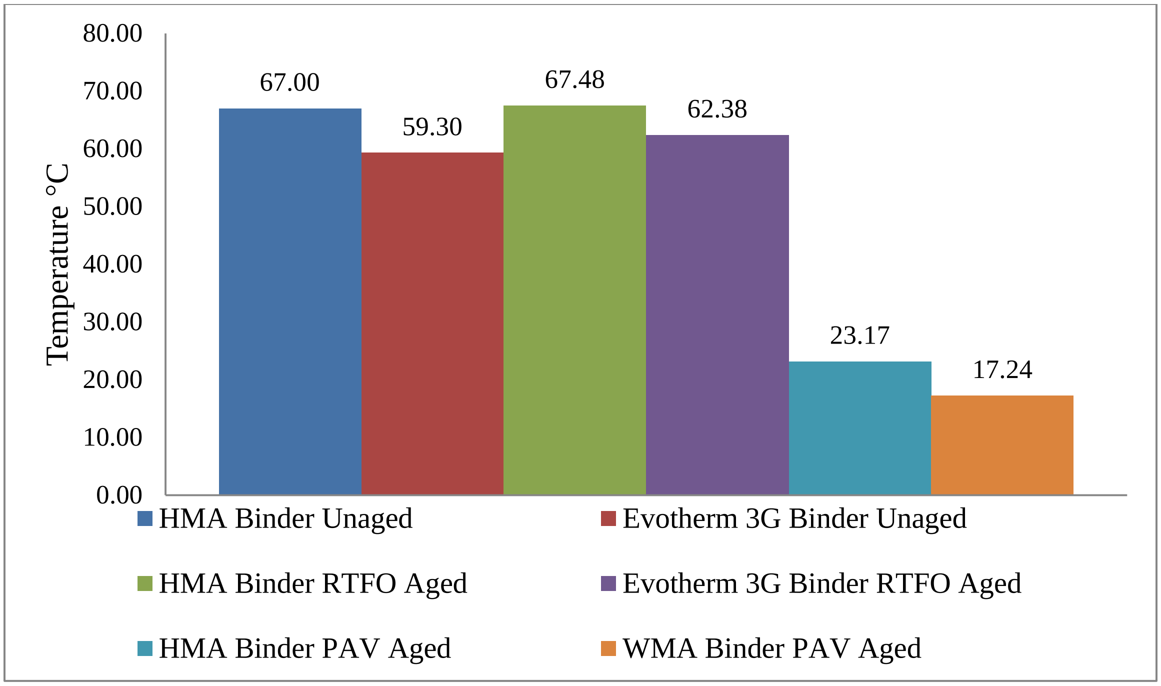
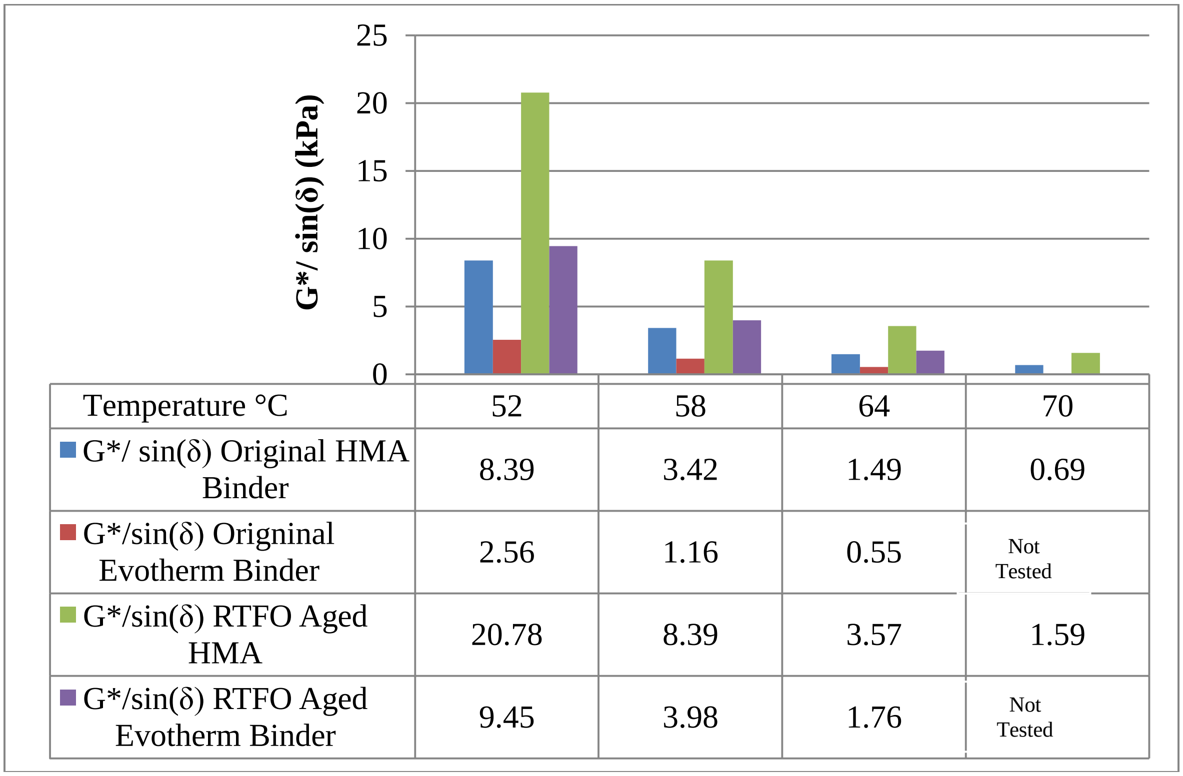
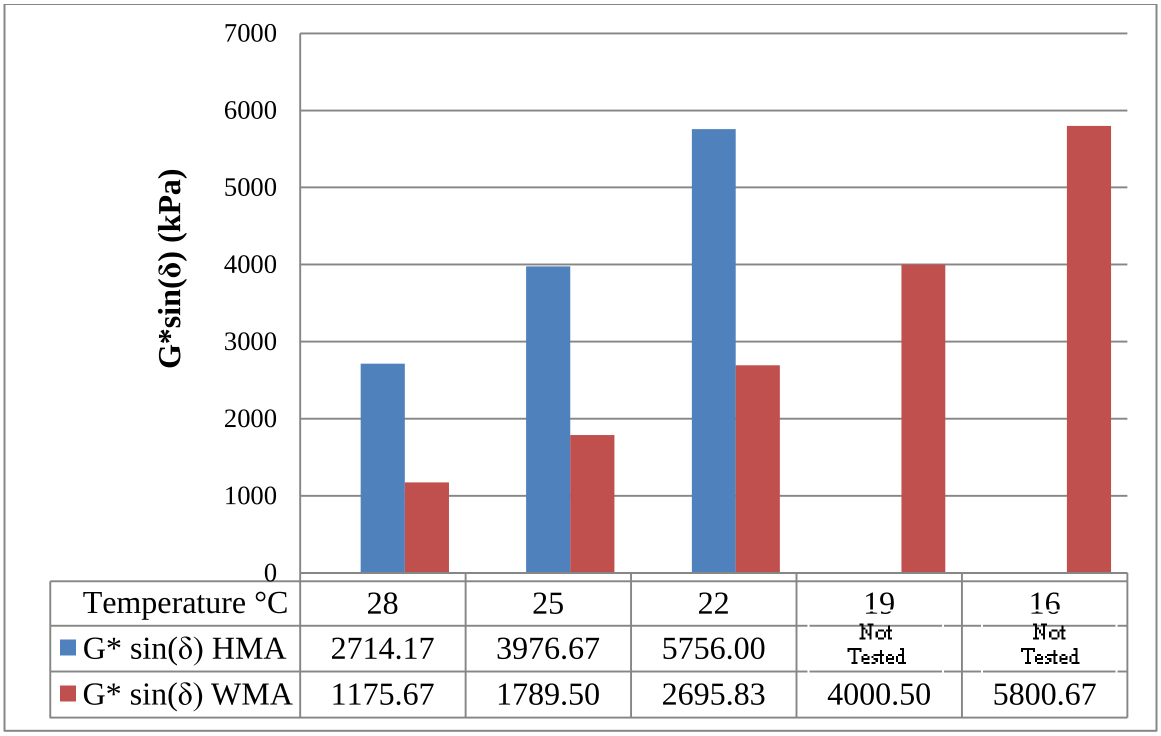


Figure 5.2 Comparison of failure temperatures for Evotherm 3G and control binders



Temperature °C	52	58	64	70
🟦 G*/ sin(δ) Original HMA Binder	8.39	3.42	1.49	0.69
🟥 G*/sin(δ) Orignial Evotherm Binder	2.56	1.16	0.55	Not Tested
🟩 G*/sin(δ) RTFO Aged HMA	20.78	8.39	3.57	1.59
🟪 G*/sin(δ) RTFO Aged Evotherm Binder	9.45	3.98	1.76	Not Tested

Figure 5.3. Comparison of G*/sin(δ) for original and RTFO aged binders



Temperature °C	28	25	22	19	16
🟦 G* sin(δ) HMA	2714.17	3976.67	5756.00	Not Tested	Not Tested
🟥 G* sin(δ) WMA	1175.67	1789.50	2695.83	4000.50	5800.67

Figure 5.4. Comparison of G*sin(δ) values for PAV aged Evotherm 3G and control binders

The DSR testing on the PAV aged material showed a large difference between the binders' rheological properties. Fatigue cracking is governed by limiting G*sin(δ) to values of less than 5000 kPa (Asphalt Institute, 2003). This testing would indicate that the WMA binder is less susceptible to fatigue cracking depending upon the pavement structure.

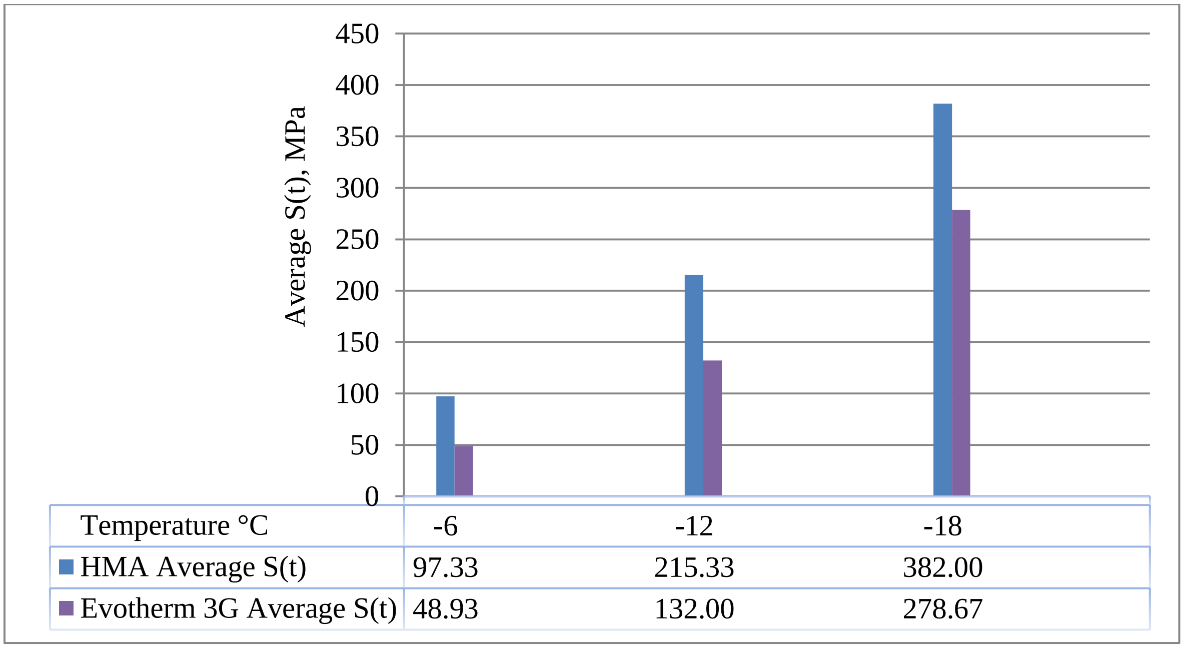
Mass loss was measured for RTFO aged binders. The average mass loss for the HMA binder was 0.75% and the average mass loss for the WMA binder was 1.3% and is above the 1% tolerance.

The bending beam rheometer data shows reduced stiffness in the Evotherm 3G modified binder. Table 5.1 provides all of the stiffness and m-value data compiled for each beam tested. Figures 5.5 and 5.6 show comparison of the Evotherm 3G and control binder stiffness and m-values, respectively. The Evotherm 3G showed a lower stiffness and a higher m-value at each temperature tested. From the BBR results, the low temperature binder grade of the Evotherm 3G is -28 and the HMA low binder grade is a -22. The stiffness for the HMA binder at -18°C exceeded the 300 MPa maximum for all three of the binder beams tested.

Table 5.1. BBR stiffness and m-value data for Evotherm 3G and control binders

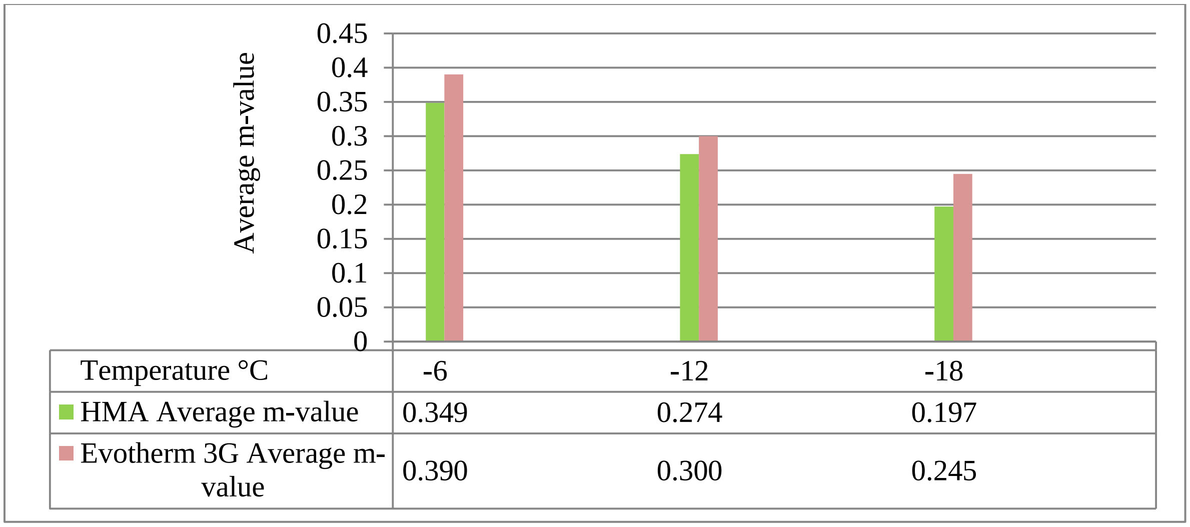
FM1 HMA Binder				
Temp (°C)	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**
-6	98.8	97.33	0.341	0.349
-6	96.9		0.352	
-6	96.3		0.353	
-12	225	215.33	0.272	0.274
-12	220		0.273	
-12	201		0.277	
-18	418	382.00	0.203	0.197
-18	395		0.182	
-18	333		0.207	

FM1 WMA Binder Evotherm 3G				
Temp (°C)	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**
-6	47	48.93	0.386	0.390
-6	45.7		0.390	
-6	54.1		0.395	
-12	113	132.00	0.305	0.300
-12	119		0.317	
-12	164		0.279	
-18	301	278.67	0.253	0.245
-18	264		0.247	
-18	271		0.235	



Temperature °C	-6	-12	-18
■ HMA Average S(t)	97.33	215.33	382.00
■ Evotherm 3G Average S(t)	48.93	132.00	278.67

Figure 5.5. Comparison of average stiffness values for Evotherm 3G and control binders



Temperature °C	-6	-12	-18
🟩 HMA Average m-value	0.349	0.274	0.197
🟥 Evotherm 3G Average m-value	0.390	0.300	0.245

Figure 5.6. Comparison of average m-values for Evotherm 3G and control binders

5.2 Field Mix 2 - Revix

The binder used in the FM2 project is a PG 64-28 and the warm mix technology is Revix. This is the next generation of the Evotherm 3G as discussed in the literature review. Figure 5.7 shows the data from the rotational viscometer testing. The mixing temperature range for the HMA is 163°C to 170°C. The mixing range for the Revix is 157°C to 164°C. The HMA compaction range is 151°C to 156°C and the compaction range for the WMA is 145°C to 150°C. The mixing and compaction ranges for the HMA and WMA are comparable and the range was not significantly reduced by the WMA additive. The Revix reduced the mixing temperature by an average of 6°C and the compaction temperature by an average of 6°C.

Figure 5.8 compares the average DSR failure temperatures for unaged, RTFO aged and PAV aged binders. The HMA and WMA binders are comparable with the average temperature differences being only 3.43°C for unaged, 2.04°C for RTFO aged and 0.59°C for PAV aged binders. Figure 5.9 compares the G*/sin(δ) values for the unaged and RTFO aged binders. The greatest difference between the G*/sin (δ) values occurred after RTFO aging at the lower temperatures.

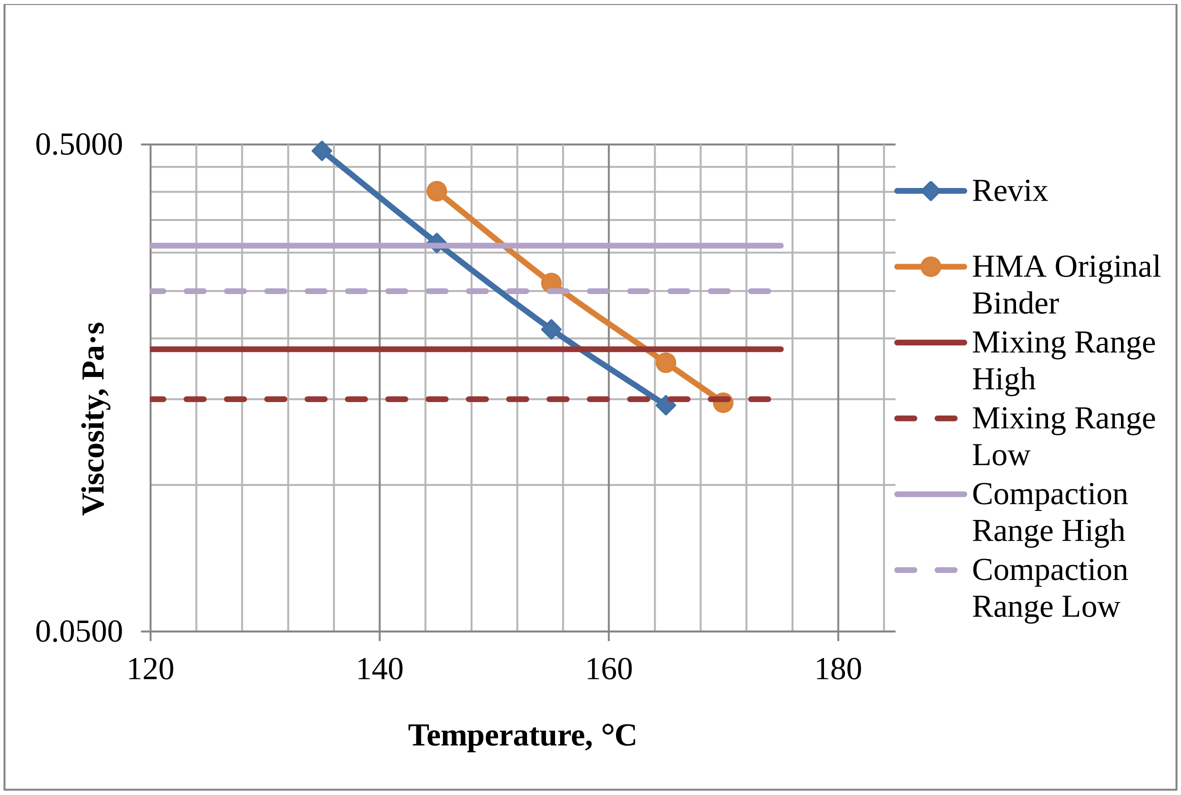


Figure 5.7. Rotational viscometer comparison of Revix and control binder

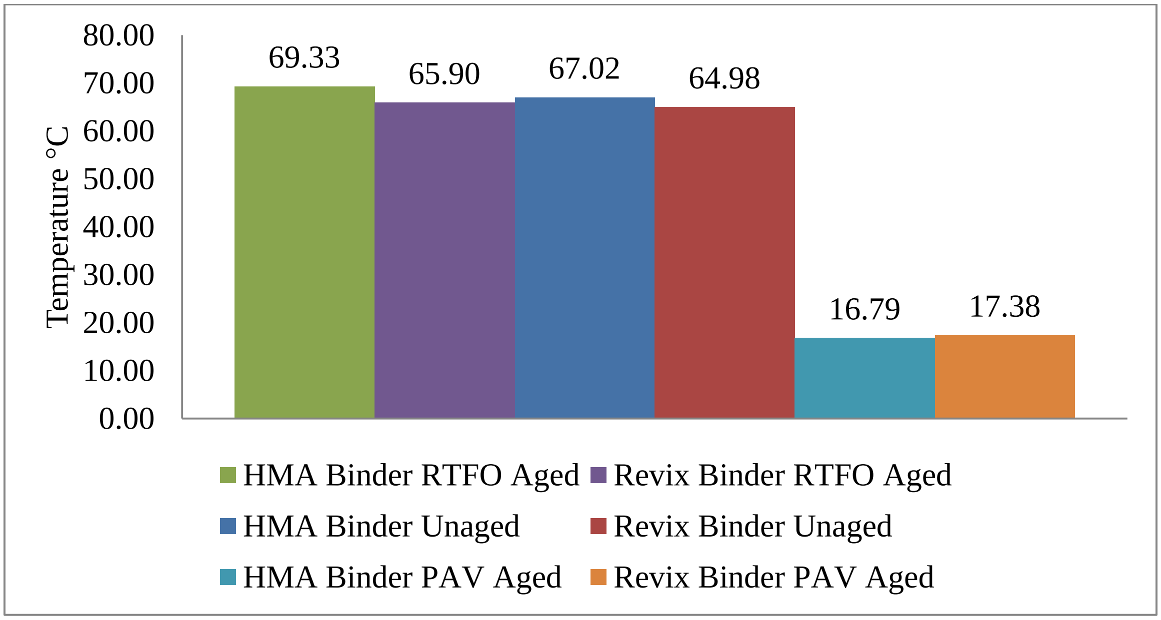
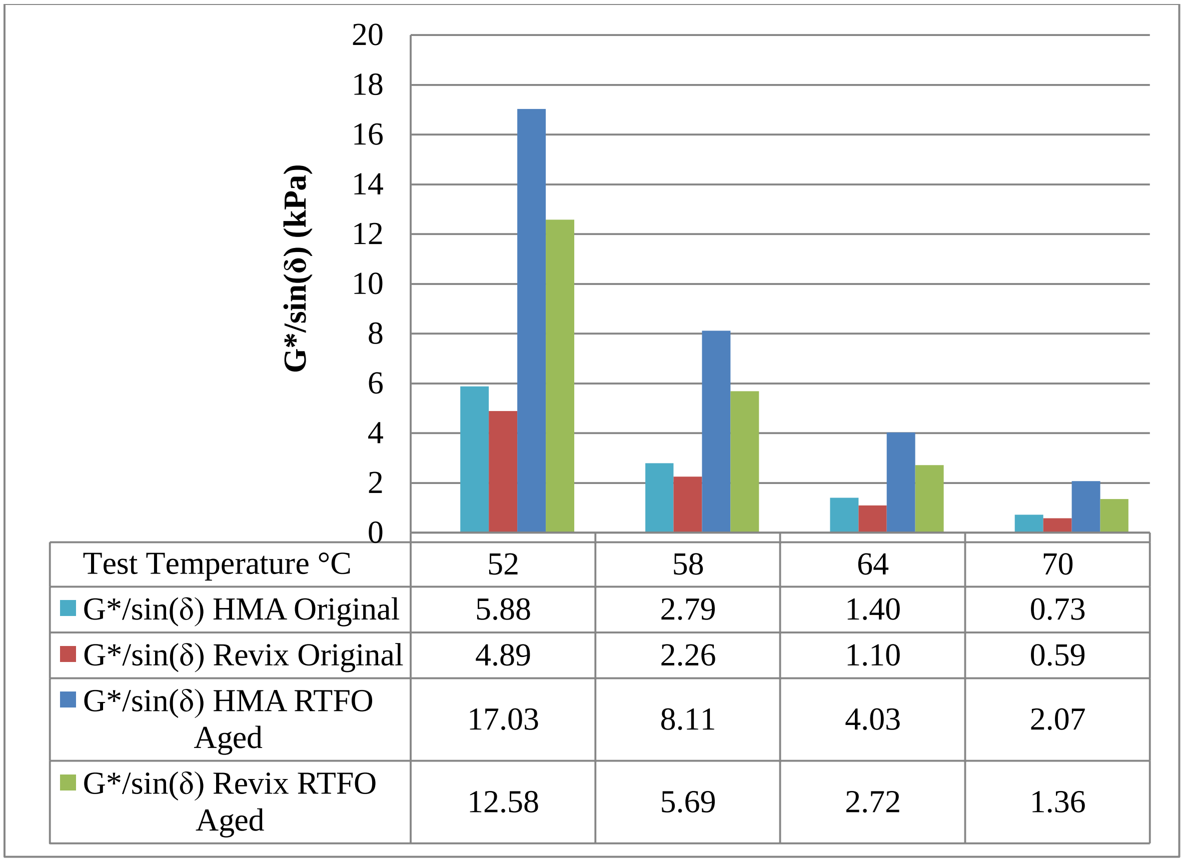
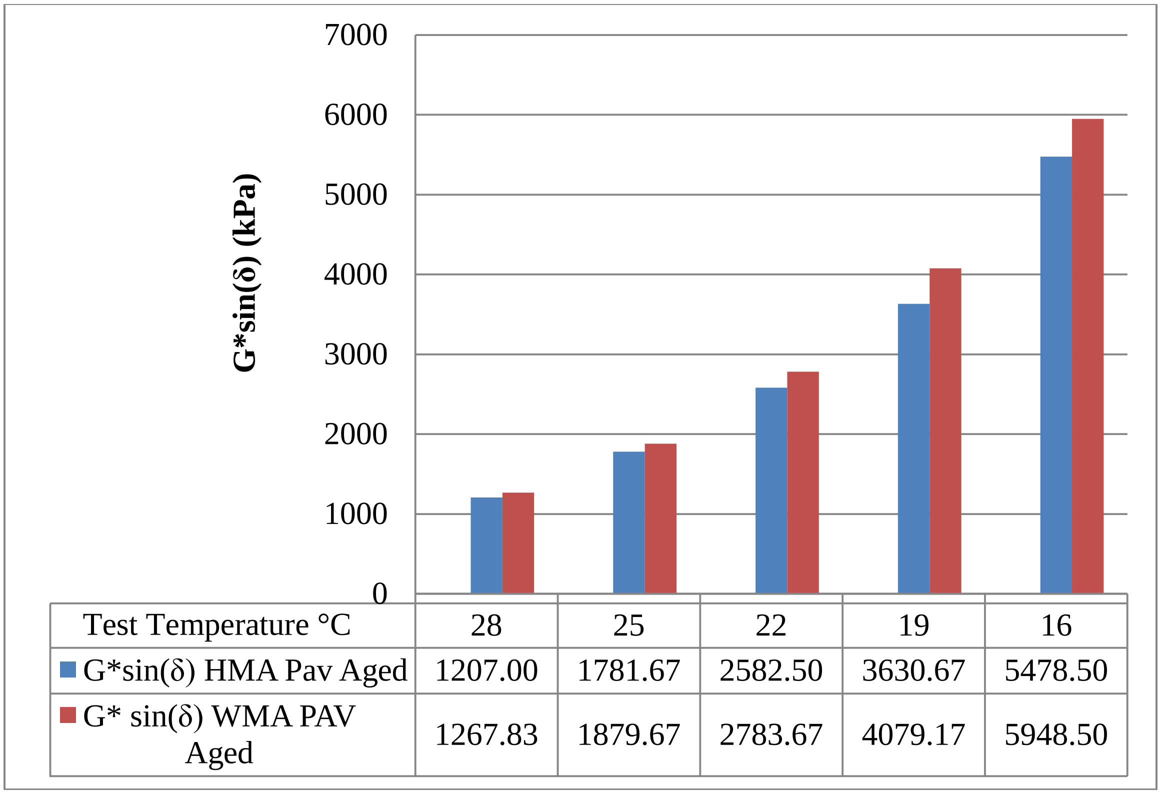


Figure 5.8. Comparison of failure temperatures for Revix and control binders



Test Temperature °C	52	58	64	70
🟦 G*/sin(δ) HMA Original	5.88	2.79	1.40	0.73
🟥 G*/sin(δ) Revix Original	4.89	2.26	1.10	0.59
🟦 G*/sin(δ) HMA RTFO Aged	17.03	8.11	4.03	2.07
🟩 G*/sin(δ) Revix RTFO Aged	12.58	5.69	2.72	1.36

Figure 5.9. Comparison of G*/sin(δ) for original and RTFO aged binders



Test Temperature °C	28	25	22	19	16
🟦 G*sin(δ) HMA Pav Aged	1207.00	1781.67	2582.50	3630.67	5478.50
🟥 G* sin(δ) WMA PAV Aged	1267.83	1879.67	2783.67	4079.17	5948.50

Figure 5.10. Comparison of G*sin(δ) values for PAV aged Evotherm 3G and control binders

Figure 5.10 shows the comparison of G*sin(δ) values. This test indicates the vulnerability to fatigue cracking. The differences are relatively small but with the WMA show a consistently higher G*sin(δ) values which would indicate a higher susceptibility to fatigue cracking depending upon the pavement structure.

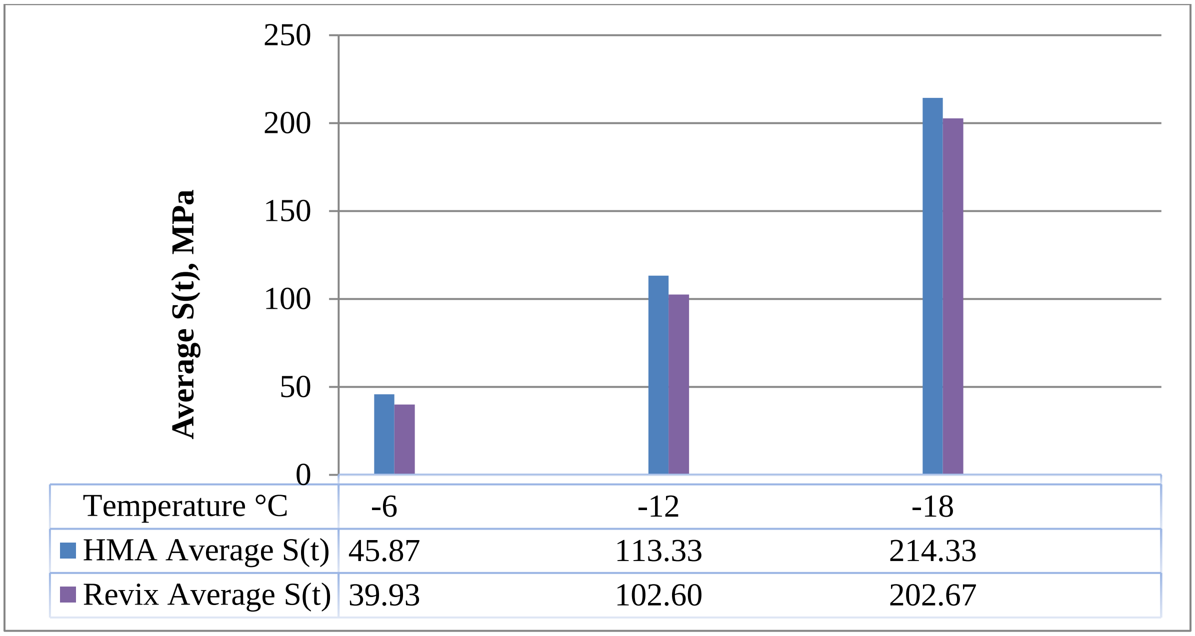
The mass loss during RTFO Aging was measured. The WMA had an average mass loss of 0.77% and average mass loss for HMA was 0.81%. Both binders were well within the acceptable range.

The bending beam rheometer data is shown in Table 5.2. Figures 5.11 and 5.12 show how the stiffness and m-value change as the temperature is reduced. The stiffness values are similar with the HMA being slightly higher. The HMA and WMA have the same low temperature grade of -22°C. The m-value at -18°C did not meet the 0.300 minimum requirements as shown in Figure 5.2.6.

Table 5.2. Bending beam rheometer stiffness and m-value data for Revix and control binders

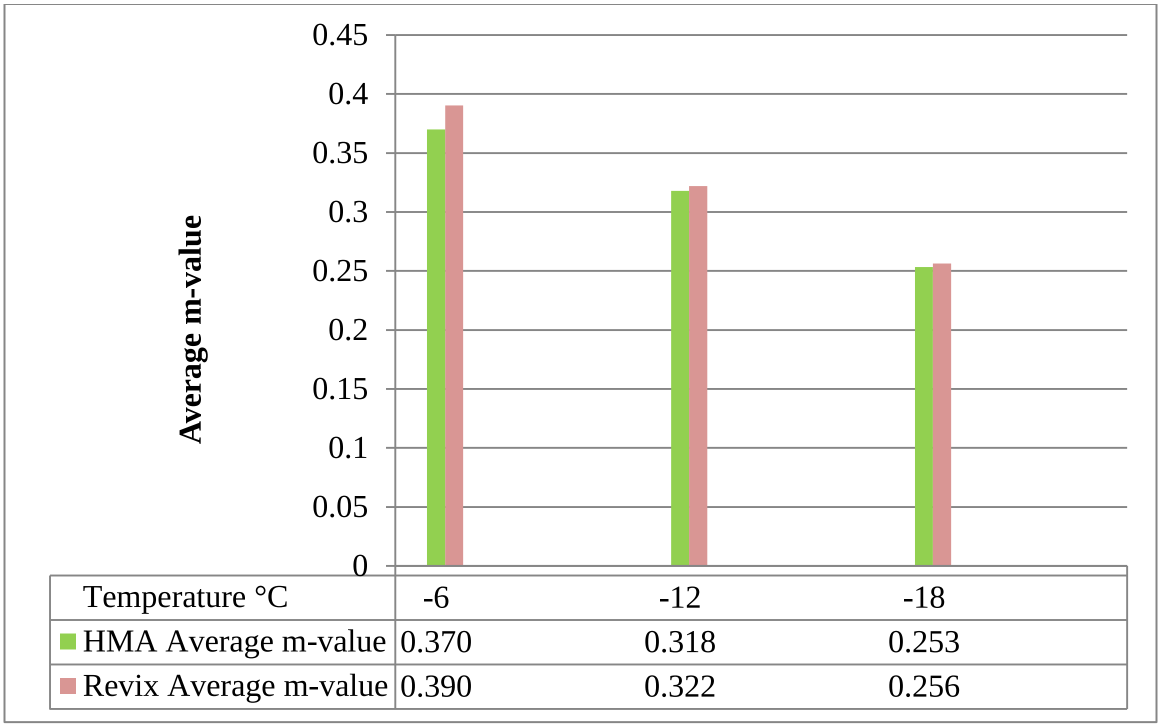
FM2 HMA Binder				
Temp (°C)	S(t)	Avg. S(t)	m-value	Avg. m
-6	44.6	45.87	0.363	0.370
-6	46.9		0.375	
-6	46.1		0.372	
-12	112	113.33	0.326	0.318
-12	111		0.311	
-12	117		0.317	
-18	215	214.33	0.264	0.253
-18	212		0.264	
-18	216		0.232	

FM2 WMA Binder Revix				
Temp (°C)	S(t)	Avg. S(t)	m-value	Avg. m
-6	38.8	39.93	0.390	0.390
-6	38.1		0.395	
-6	42.9		0.386	
-12	95.3	102.6	0.328	0.322
-12	98.5		0.317	
-12	114		0.321	
-18	196	202.67	0.269	0.256
-18	203		0.244	
-18	209		0.256	



Temperature °C	-6	-12	-18
■ HMA Average S(t)	45.87	113.33	214.33
■ Revix Average S(t)	39.93	102.60	202.67

Figure 5.11. Comparison of average stiffness values for Revix and control binders



Temperature °C	-6	-12	-18
🟩 HMA Average m-value	0.370	0.318	0.253
🟥 Revix Average m-value	0.390	0.322	0.256

Figure 5.12. Comparison of average m-values for Revix and control binders

5.3 Field Mix 3 - Sasobit

The binder for FM3 is a PG 64-22. The Sasobit wax was the WMA technology used on this project. The data from the rotational viscometer test comparing the WMA and HMA is shown in Figure 5.13. The mixing temperature for the HMA ranges from 153.5-160°C and WMA mixing range is from 146-153°C. The compaction range for the HMA is from 142-147°C and the Sasobit is from 135-140°C. The rotational viscometer tests show a 7°C decrease between the HMA and WMA binders for both the mixing and compaction range. The small difference in the viscosity between the HMA binder and the WMA binder supports findings by other researchers that this test is not sensitive differences in the binders; however, the DSR binder results show very similar values between the HMA and WMA binders.

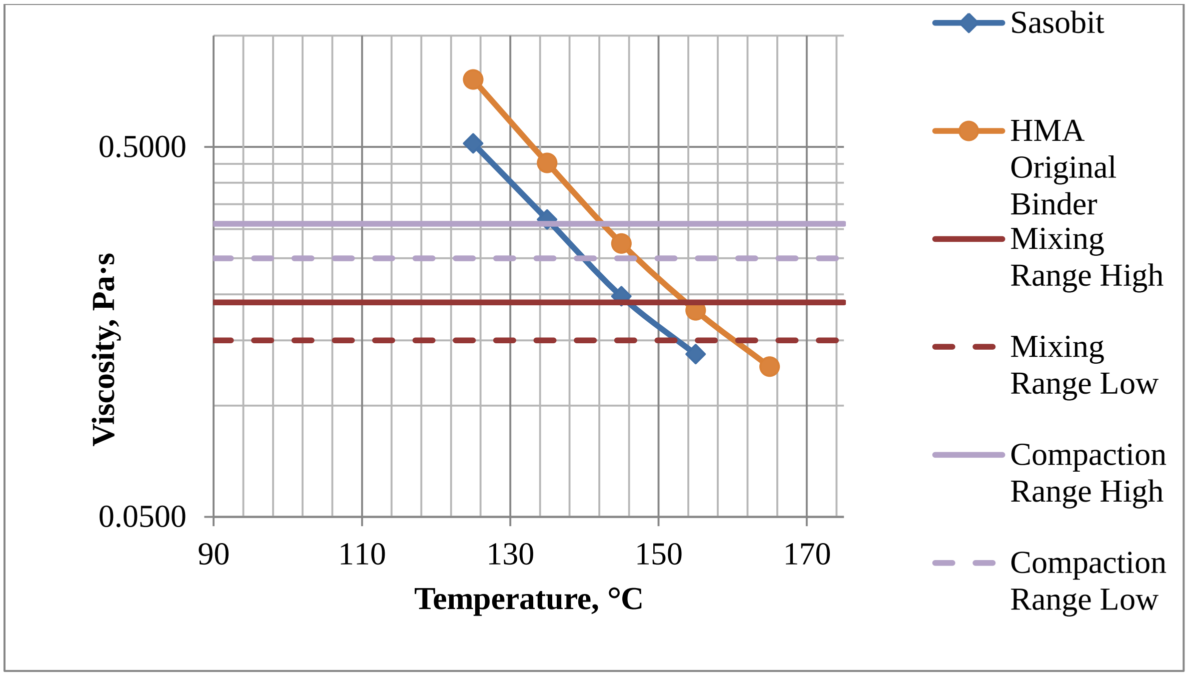


Figure 5.13. Rotational viscometer comparison of Sasobit and control binder

Figure 5.14 compares the average DSR failure temperatures for the unaged, RTFO aged and PAV aged binders. There is very little difference between the failure temperatures. The largest difference is 1.04°C. The G*/sin(δ) values shown in Figure 5.15 support the findings of the other tests by revealing only small differences between the values for the HMA and WMA binders. The PAV aged samples give similar G*sin(δ) values as shown in Figure 5.16.

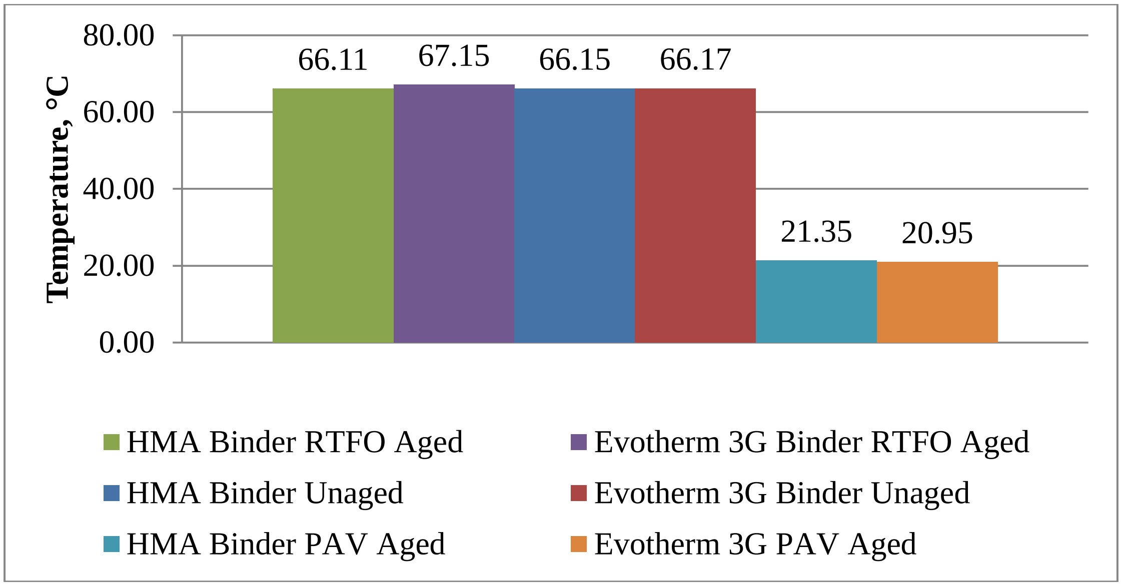
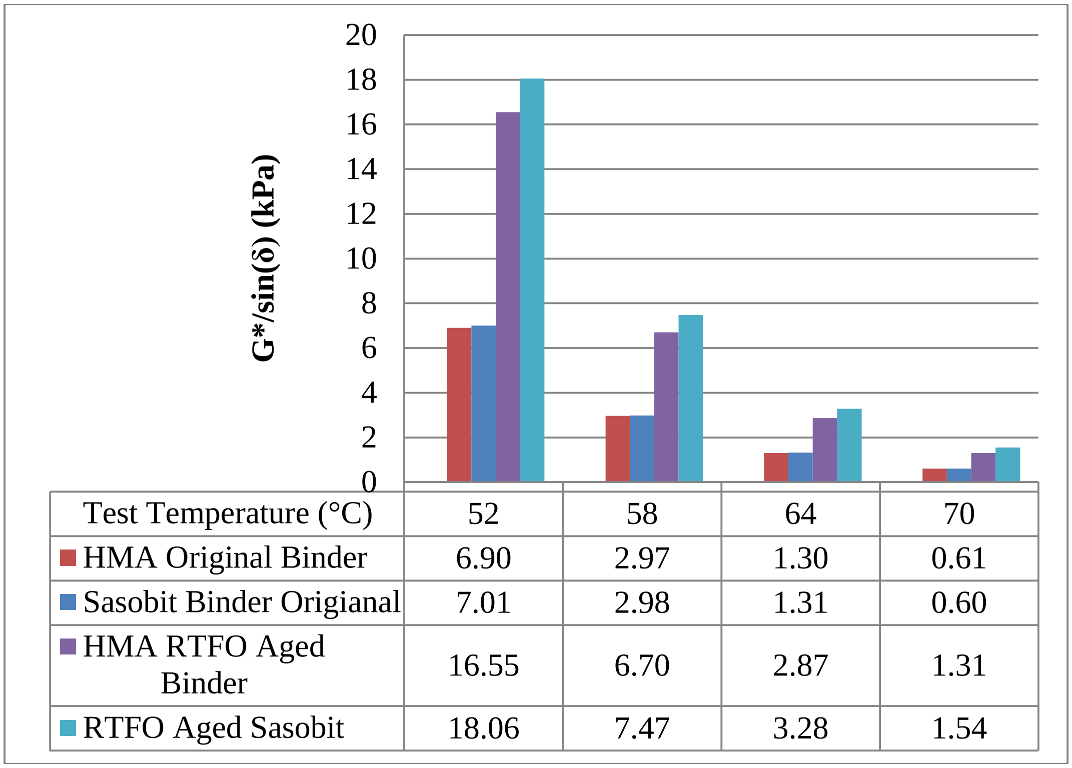
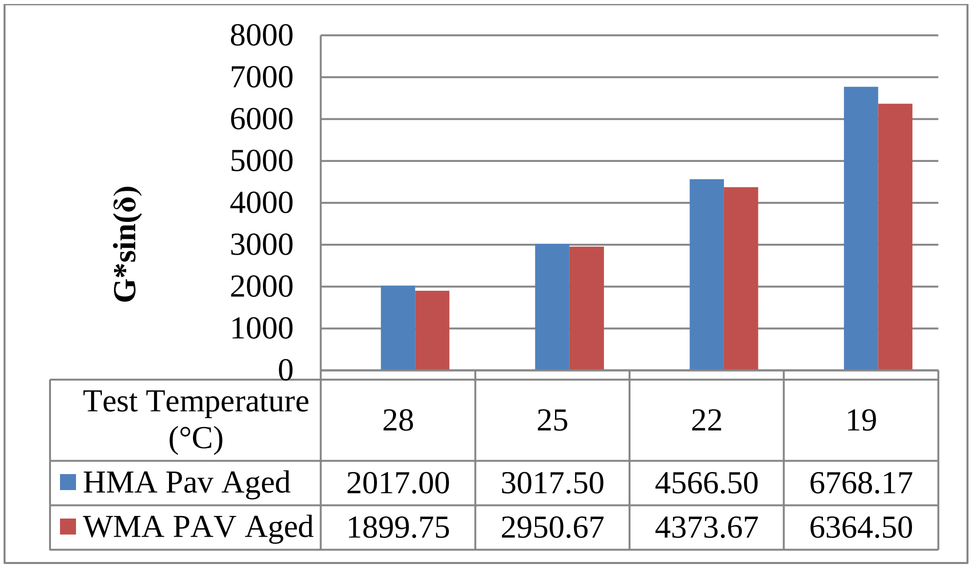


Figure 5.14. Comparison of failure temperatures for Sasobit and control binders



Test Temperature (°C)	52	58	64	70
🟥 HMA Original Binder	6.90	2.97	1.30	0.61
🟦 Sasobit Binder Origianal	7.01	2.98	1.31	0.60
🟪 HMA RTFO Aged Binder	16.55	6.70	2.87	1.31
🟦 RTFO Aged Sasobit	18.06	7.47	3.28	1.54

Figure 5.15. Comparison of G*/sin(δ) for original and RTFO aged binders



Test Temperature (°C)	28	25	22	19
🟦 HMA Pav Aged	2017.00	3017.50	4566.50	6768.17
🟥 WMA PAV Aged	1899.75	2950.67	4373.67	6364.50

Figure 5.16. Comparison of G*sin(δ) values for PAV aged Sasobit and control binders

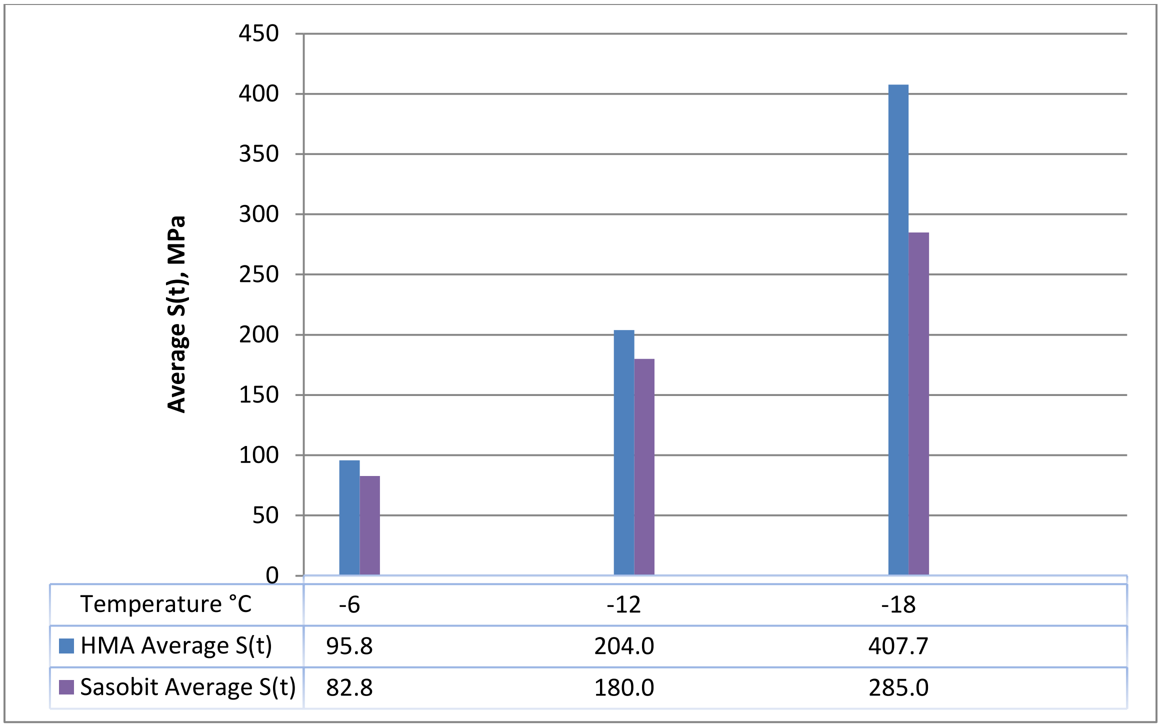
The mass loss was measured during the RTFO aging for WMA and the HMA binders. Each binder was under the 1% tolerance with the HMA binder losing 0.5% and the WMA losing 0.6% of mass. The mass loss is not a concern for the Sasobit WMA additive.

The complied data for the BBR is located in Table 5.3. Figures 5.17 and 5.18 are graphs of the stiffness and the m-value, respectively. The stiffness of the HMA tends to be higher than the Sasobit binder and the difference is more prominent as the temperature is decreased. The m-value of the Sasobit is consistently lower than the control binder; however, neither binder meets the 0.300 m-value requirement for the -12°C test temperature and thus do not meet the -22 PG binder grade and grade out to be a -18 binder grade.

Table 5.3. Beam rheometer stiffness and m-value data for Revix and control binders

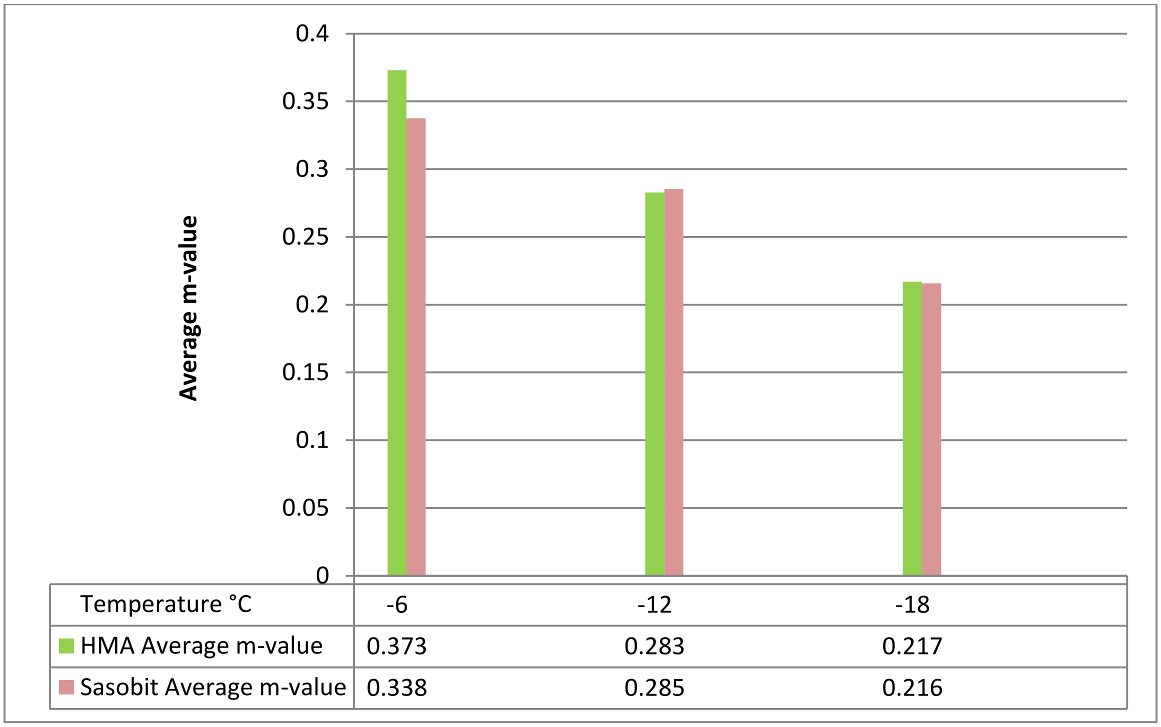
HMA Binder				
Temp (°C)	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**
-6	95.1	95.8	0.369	0.373
-6	99.3		0.381	
-6	92.9		0.369	
-12	199	204.0	0.277	0.283
-12	220		0.279	
-12	193		0.292	
-18	474	407.7	0.191	0.217
-18	367		0.227	
-18	382		0.233	

Sasobit WMA Binder				
Temp (°C)	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**
-6	83.8	82.8	0.340	0.338
-6	81.7		0.340	
-6	82.8		0.333	
-12	150	180.0	0.282	0.285
-12	200		0.291	
-12	190		0.283	
-18	314	285.0	0.222	0.216
-18	276		0.225	
-18	265		0.200	



Temperature °C	-6	-12	-18
■ HMA Average S(t)	95.8	204.0	407.7
■ Sasobit Average S(t)	82.8	180.0	285.0

Figure 5.17. Comparison of average stiffness values for Revix and control binders



Temperature °C	-6	-12	-18
■ HMA Average m-value	0.373	0.283	0.217
■ Sasobit Average m-value	0.338	0.285	0.216

Figure 5.18. Comparison of average m-values for Revix and control binders

Overall the binders used in FM3 showed very little difference in all of the testing. This is cause for concern because the rotational viscometer showed low mixing and compaction temperatures. The test results call into question the potential of the “control” binder being mixed with the WMA Sasobit binder that was produced on the preceding day. This binder displays variable stiffness properties as the temperature is lowered to below -12°C. This was not seen in the Evotherm 3G or Revix binders.

5.4 Field Mix 4 - Double Barrel Green Foaming

The double barrel green foaming technology was used for the fourth field mix. The base binder grade is PG 64-22. The data obtained from rotational viscometer results is shown in Figure 5.19. The mixing range for the HMA binder is 154 to 160°C. The mixing range for the foamed asphalt is 146.3 to 153°C. The compaction range is 142.5 to 147.5°C for the HMA binder and 135.5 to 140°C for the foamed binder. The overall difference is an average 7.25°C reduction in both the mixing and compaction temperature range. The DSR failure temperate comparing the HMA and foamed binders are shown in Figure 5.20. The comparison shows that the HMA and the foamed asphalt for the unaged, RTFO aged and PAV aged have very similar failure temperatures and this supports the similar values documented in the rotational viscometer testing. Figure 5.21 shows the G*/sin values for unaged and RTFO aged binders. The comparison shows that the $G^*/\sin(\delta)$ values for the HMA and the WMA are similar. The similarities continue in the PAV aged binder comparison shown in Figure 5.22. The $G^*\sin(\delta)$ are very similar throughout the testing temperatures.

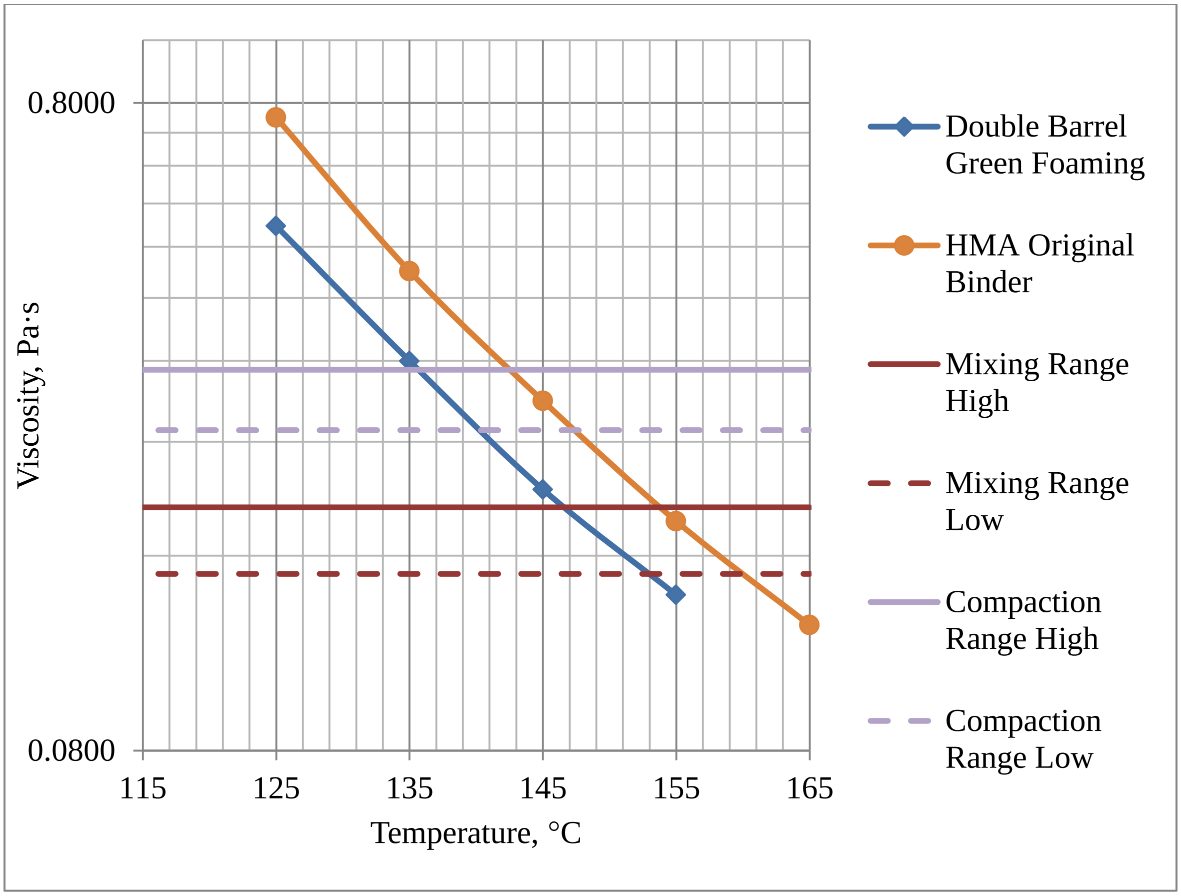


Figure 5.19. Rotational viscometer comparison of foamed and control binder

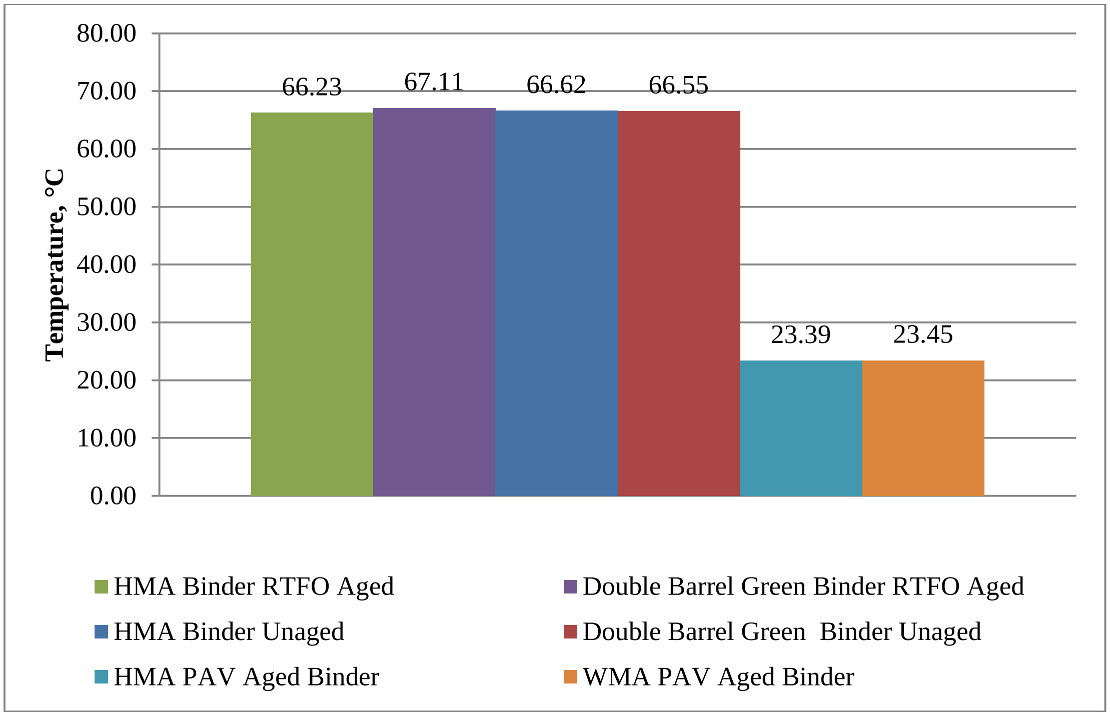
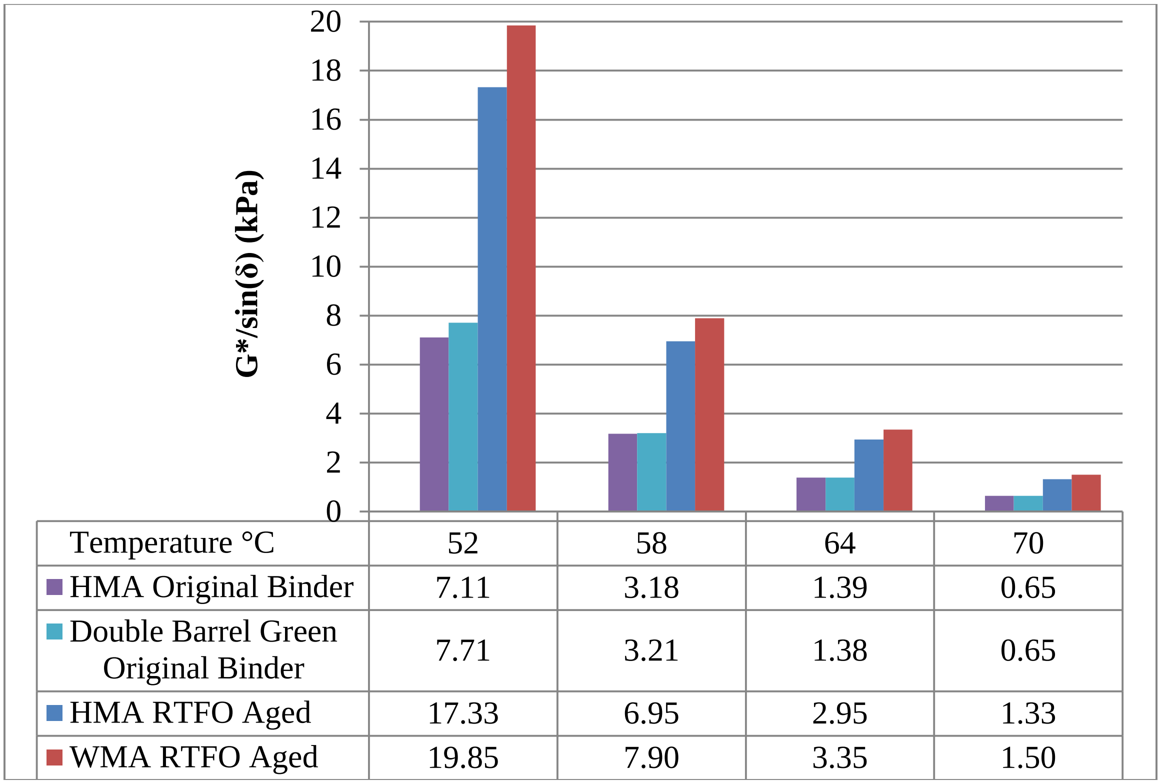
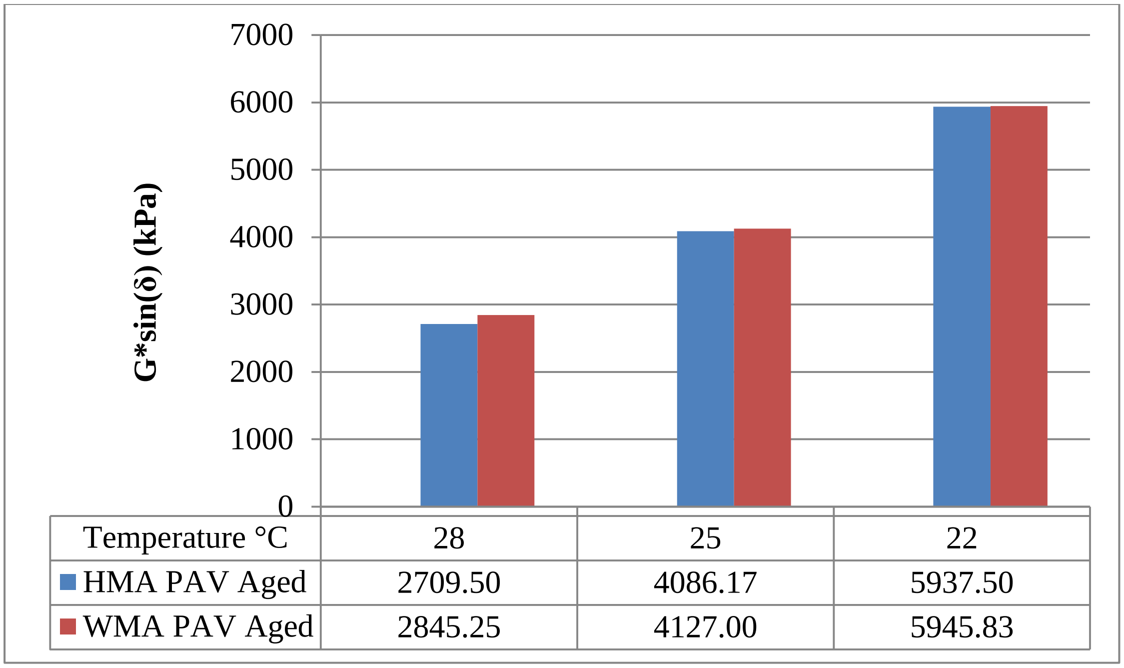


Figure 5.20. Comparison of failure temperatures for foamed and control binders



Temperature °C	52	58	64	70
🟪 HMA Original Binder	7.11	3.18	1.39	0.65
🟦 Double Barrel Green Original Binder	7.71	3.21	1.38	0.65
🟦 HMA RTFO Aged	17.33	6.95	2.95	1.33
🟥 WMA RTFO Aged	19.85	7.90	3.35	1.50

Figure 5.21. Comparison of G*/sin(δ) for original and RTFO aged binders



Temperature °C	28	25	22
🟦 HMA PAV Aged	2709.50	4086.17	5937.50
🟥 WMA PAV Aged	2845.25	4127.00	5945.83

Figure 5.22. Comparison of G*sin(δ) values for PAV aged foamed and control binders

The mass loss during RTFO aging was measured and both the HMA and WMA binders met the mass loss requirements of less than 1%. The mass loss for the WMA binder was 0.4% and the mass loss for the HMA binder was 0.2%.

Table 5.4 provides the stiffness and m-values for each BBR beam tested. Figures 5.23 and 5.24 compare the average stiffness and the m-values respectively. The stiffness of the HMA tends to be slightly higher than the WMA but this difference is less prevalent as the temperature is decreased. The m-value of the foamed asphalt is lower than the control binder; however, neither binder meets the 0.300 m-value minimum requirement during the -12°C test and thus the binders do not meet the -22 PG binder grade.

Table 5.4. Beam rheometer stiffness and m-value data for foamed and control binders

HMA Binder					Foamed WMA Binder				
Temp (°C)	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**	**Temp (°C)**	**S(t)**	**Avg. S(t)**	**m-value**	**Avg. m**
-6	96.9	96.5	0.336	0.334	-6	108	105.0	0.327	0.325
-6	89.6		0.329		-6	106		0.324	
-6	103		0.338		-6	101		0.325	
-12	236	257.3	0.266	0.250	-12	219	224.3	0.263	0.261
-12	237		0.273		-12	224		0.256	
-12	299		0.212		-12	230		0.264	
-18	378	380.7	0.211	0.205	-18	376	375.3	0.215	0.207
-18	350		0.207		-18	375		0.195	
-18	414		0.196		-18	375		0.210	

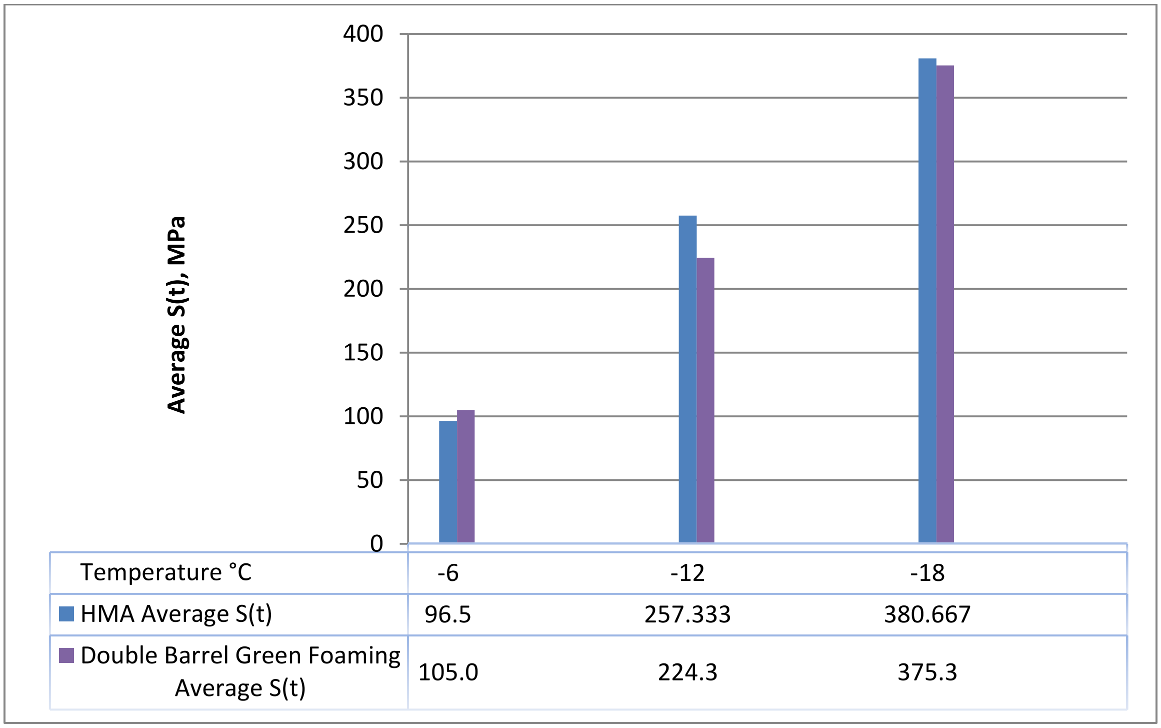
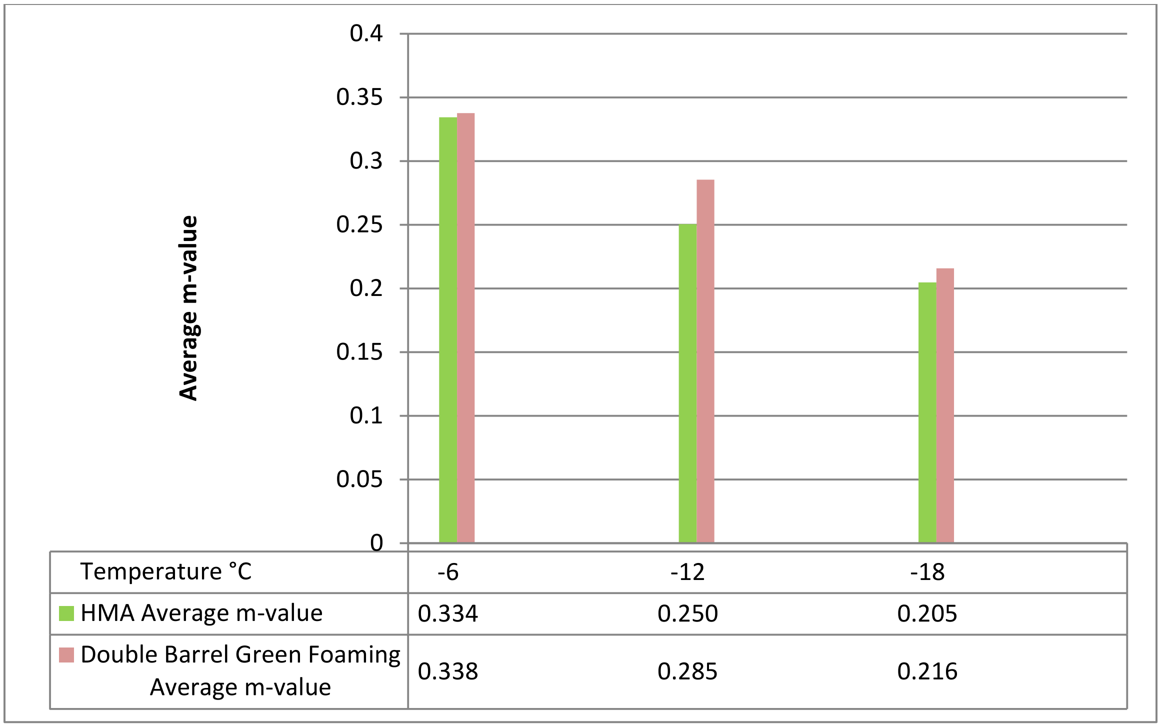


Figure 5.23. Comparison of average stiffness values for foamed and control binders



Temperature °C	-6	-12	-18
🟩 HMA Average m-value	0.334	0.250	0.205
🟥 Double Barrel Green Foaming Average m-value	0.338	0.285	0.216

Figure 5.24. Comparison of average m-values for foamed and control binders

CHAPTER 6. PERFORMANCE TESTING RESULTS

6.1 Indirect Tensile Strength Testing Results

Table 6.1 provides a summary of the TSR ratios obtained during ITS testing. These values are the overall average of 5 TSR ratios. A complete data chart for all of the ITS samples is shown in Appendix C. Figure 6.2 shows the average peak loads obtained during the ITS testing. The mix with the highest average peak load is Field Mix 1 HMA that was produced in the lab and moisture-conditioned. The lowest peak load was the FM3 field-produced Sasobit mix that was moisture-conditioned. This is the same mix that was produced during wet conditions and steam was observed when oven doors were opened. The HMA mixes had higher TSR values than the WMA mixes with the exception of the FM4 field-produced samples. There were some differences between the field and lab mix although a clear trend is not visible. The results of the ITS tests are discussed further in the statistical analysis chapter (Chapter 7). The statistical analysis addresses if the differences between the HMA versus WMA, laboratory- versus field-compacted and moisture-conditioned versus non-moisture-conditioned specimens are statistically significant.

Table 6.1. Tensile strength ratios

FM1 - Evotherm 3G	**Lab**	**Field**
Average TSR HMA	1.12	N/A
Average TSR WMA	1.03	N/A
FM2 - Floyd Co. - Revix	**Lab**	**Field**
Average TSR HMA	0.93	1.02
Average TSR WMA	0.88	0.87
FM3 - Marcus Sasobit	**Lab**	**Field**
Average TSR HMA	0.96	0.98
Average TSR WMA	0.91	0.81
FM4 - Johnston Foaming	**Lab**	**Field**
Average TSR HMA	0.92	0.87
Average TSR WMA	0.84	1.06

Table 6.2. Average peak load values

FM1 - Evotherm 3G	Lab		Field	
	MC	NMC	MC	NMC
Average Peak Load HMA	13,240	12,081	N/A	N/A
Average Peak Load WMA	10,483	10,136	N/A	N/A

FM2 - Floyd Co. Revix	Lab		Field	
	MC	NMC	MC	NMC
Average Peak Load HMA	7,365	7,938	7,439	7,297
Average Peak Load WMA	7,881	8,939	7,030	8,139

FM3 - Marcus Sasobit	Lab		Field	
	MC	NMC	MC	NMC
Average Peak Load HMA	10,419	10,898	9,939	10,233
Average Peak Load WMA	7,716	8,462	6,585	8,169

FM4 - Johnston Foaming	Lab		Field	
	MC	NMC	MC	NMC
Average Peak Load HMA	11,656	12,741	10,480	12,049
Average Peak Load WMA	10,325	12,272	11,068	10,478

MC = moisture-conditioned
NMC = not moisture-conditioned

6.2 Dynamic Modulus Testing Results

The dynamic modulus (E*) values for each field mix are located in Appendix D. The E* values shown are averages of a set of samples tested. The dynamic modulus values are simply the peak stress over the peak strain however obtaining those values from a large data file was completed in a timely manner by implementing the use of a macros which calculated the E* values according to NCHRP 547 recommendations (Witczak, 2005). The E* values were reviewed for potential outliers. The method for determining outliers included looking at both the coefficient of variation and the standard deviation. Most of the categories had a sample size of five except for three (Shown in Table 2.1 in the experimental plan section). In order to determine if an outlier was present in a set, first, the coefficient of variation had to be greater than 13%. If the coefficient of variation exceeded 13% the maximum or minimum value was excluded from the calculation of the average and a new average, standard deviation and coefficient of variation was calculated. If the potential outlier was greater than two standard devotions from the mean, the value was considered an outlier and discarded from the E* average that determines the master curve values.

Further discussion and comparison of E* values is provided in the statistical analysis section. The statistical analysis is needed in order to determine if the various factors impacted the E* values. The factors to be addressed are WMA versus HMA, laboratory-compacted versus field-compacted and moisture-conditioned versus not moisture-conditioned.

In general, the E* values increase as the temperature is decreased and the higher frequencies have higher associated E* values. Temperature and frequency are statistically significant factors that impact the E* values as will be shown in the statistical analysis section. Other factors investigated in this study include: type of mix (WMA/HMA), field/lab-compacted samples, and moisture/non-moisture-conditioned samples. The impact these factors on E* will be addressed in the statistical analysis.

6.3 Master Curves

The master curves provide an efficient way of comparing mixes based on the dynamic modulus over the entire range of testing temperatures and frequencies. The master curves were obtained from the average of the E* values and graphed using a sigmoidal function and regression techniques are used in order to find the best fit line. Five graphs are shown for each of the four field mixes. The five graphs compare the following for each field project:

- Comparison of field-compacted samples
    - HMA/WMA and Moisture-Conditioned/Non-Moisture-Conditioned
- Comparison of lab-compacted samples
    - HMA/WMA and Moisture-Conditioned/Non-Moisture-Conditioned
- Comparison of lab- versus field-compacted HMA
    - Lab/Field and Moisture-Conditioned/Non-Moisture-Conditioned
- Comparison of lab- versus field-compacted WMA
    - Lab/Field and Moisture-Conditioned/Non-Moisture-Conditioned
- Comparison of all mixes

The left side of the master curve indicates high temperature behavior and the right side indicates low temperature behavior. A higher line is desirable toward the left side of the graph indicating a higher stiffness at higher temperatures which is indicative of better rutting resistance. The lower E* values are desirable toward the right side of the graph indicating a better resistance to thermal cracking. The highest variability is observed on the left side of the graph indicating greater differences between mixes at higher temperatures.

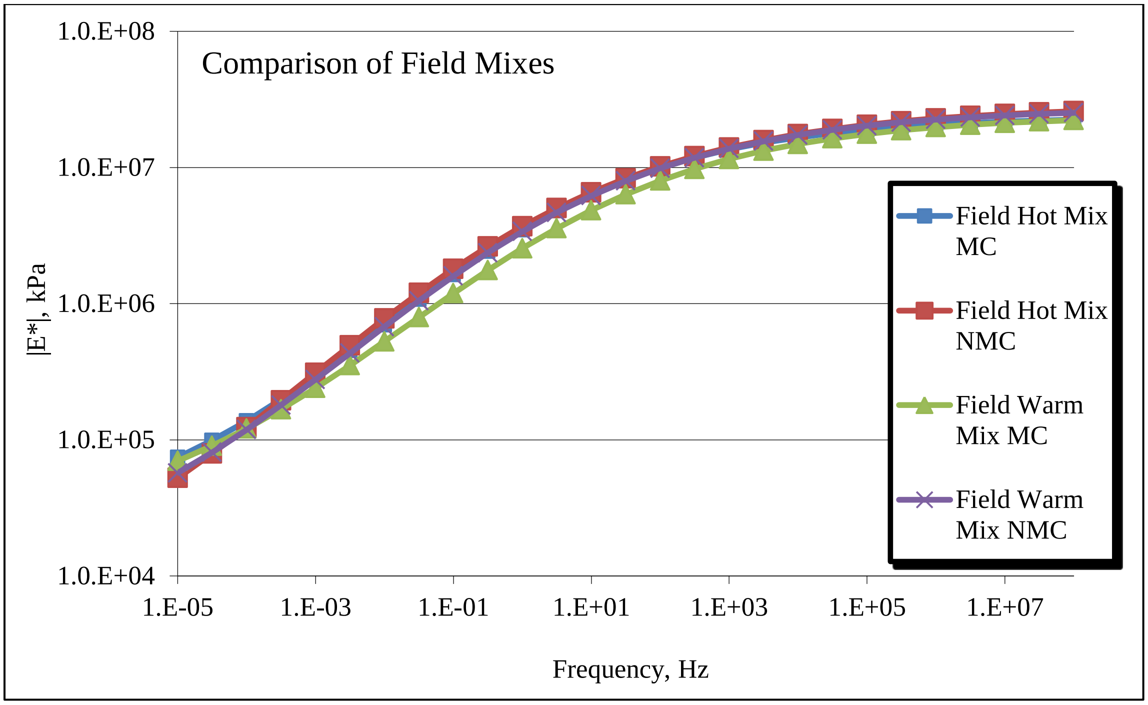


Figure 6.1. Field Mix 1 comparison of field-compacted mixes

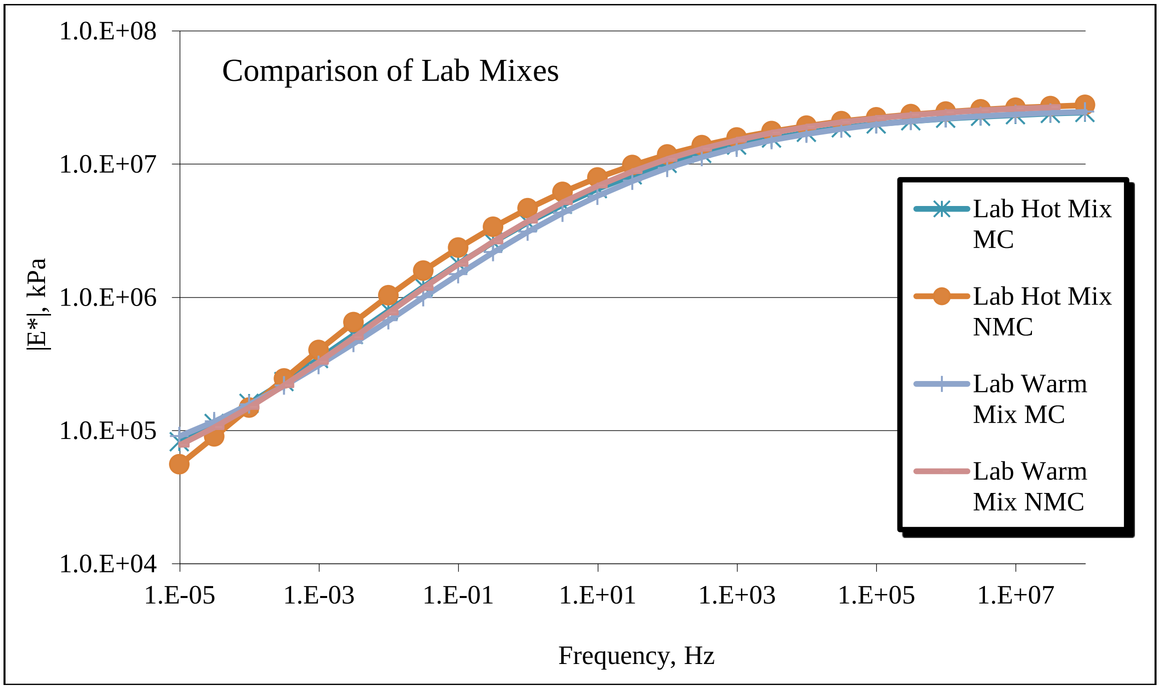


Figure 6.2. Field Mix 1 comparison of lab-compacted mixes

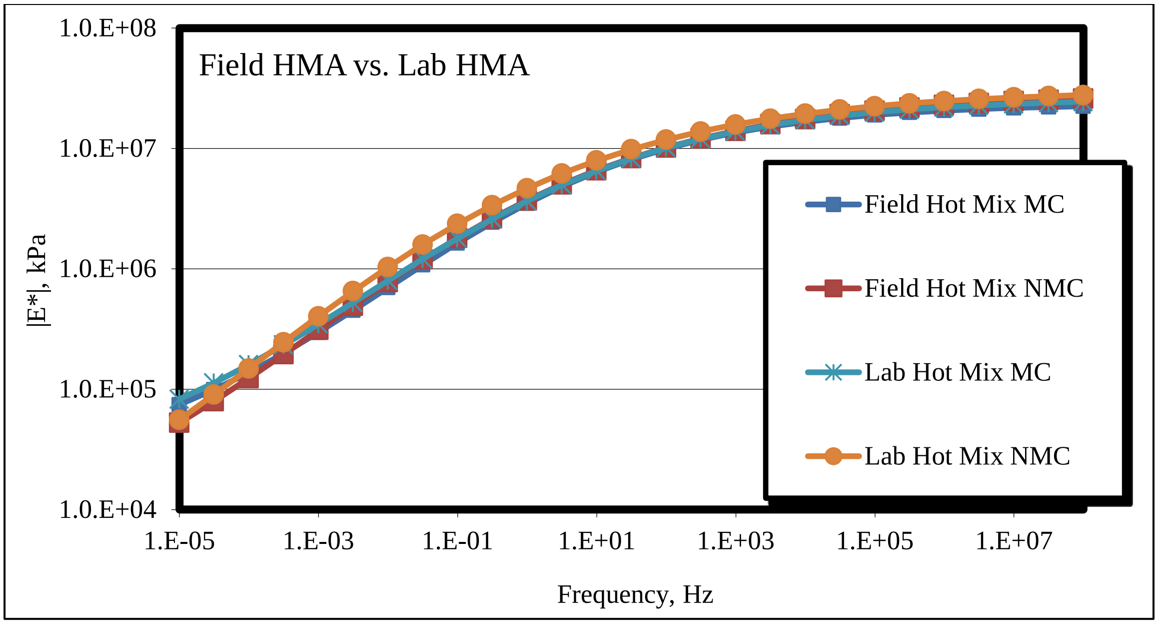


Figure 6.3. Field Mix 1 comparison of field-compacted HMA and laboratory-compacted HMA

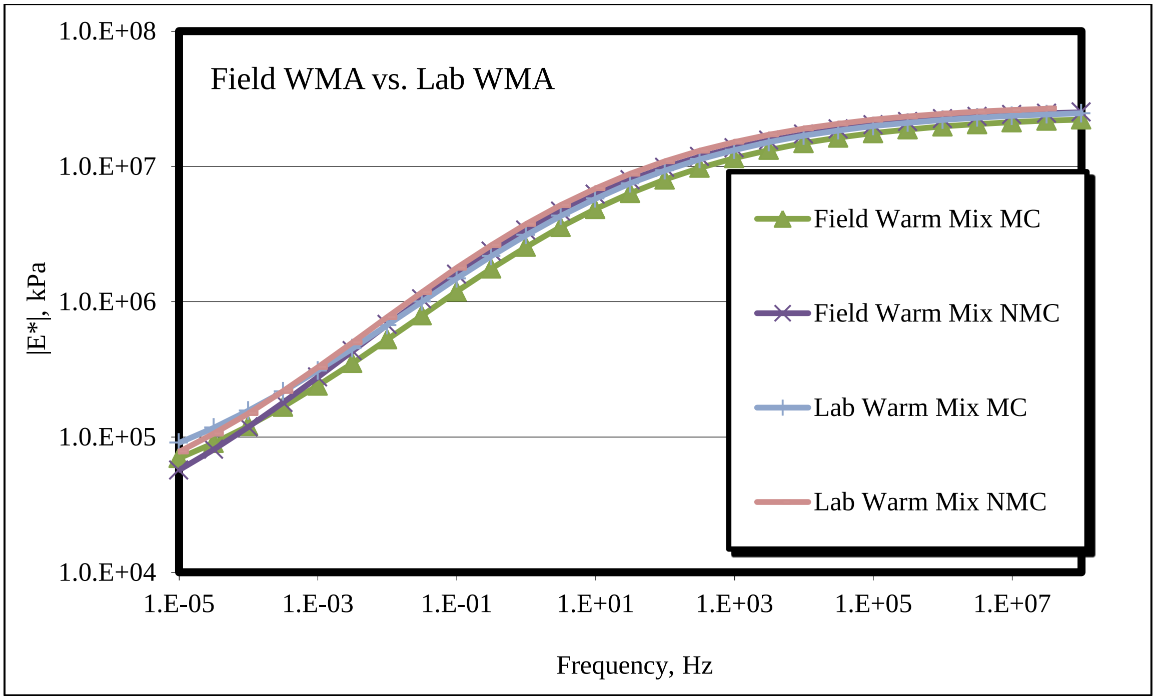


Figure 6.4. Field Mix 1 comparison of laboratory-compacted WMA and field-compacted WMA

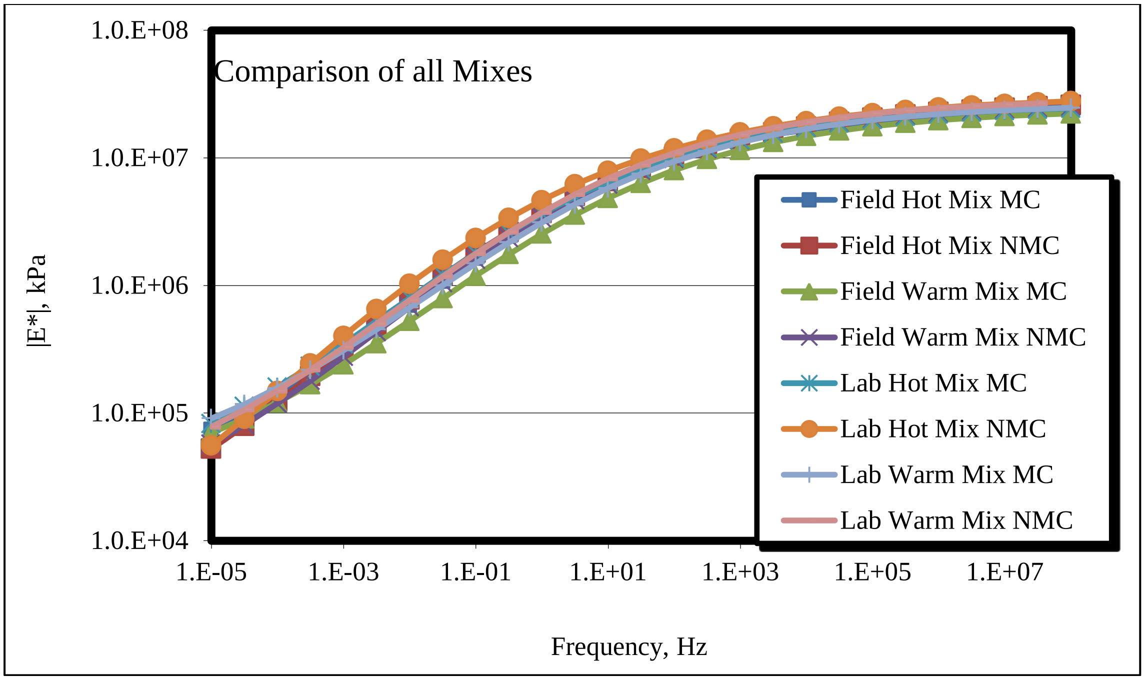


Figure 6.5. Field Mix 1 comparison of all mixes

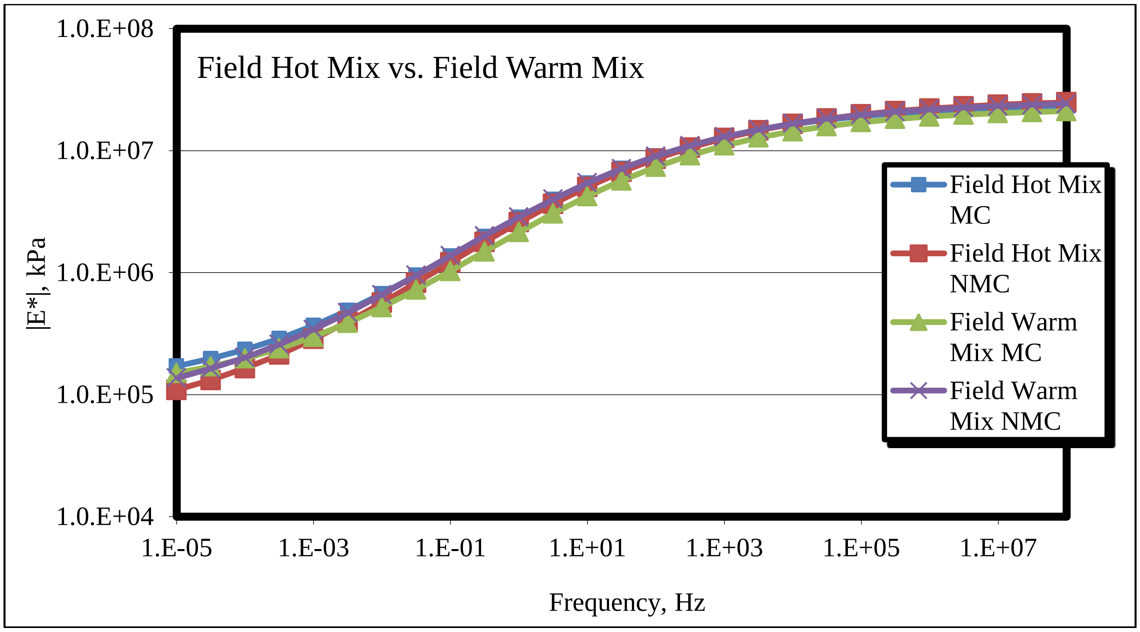


Figure 6.6. Field Mix 2 comparison of field-compacted mixes

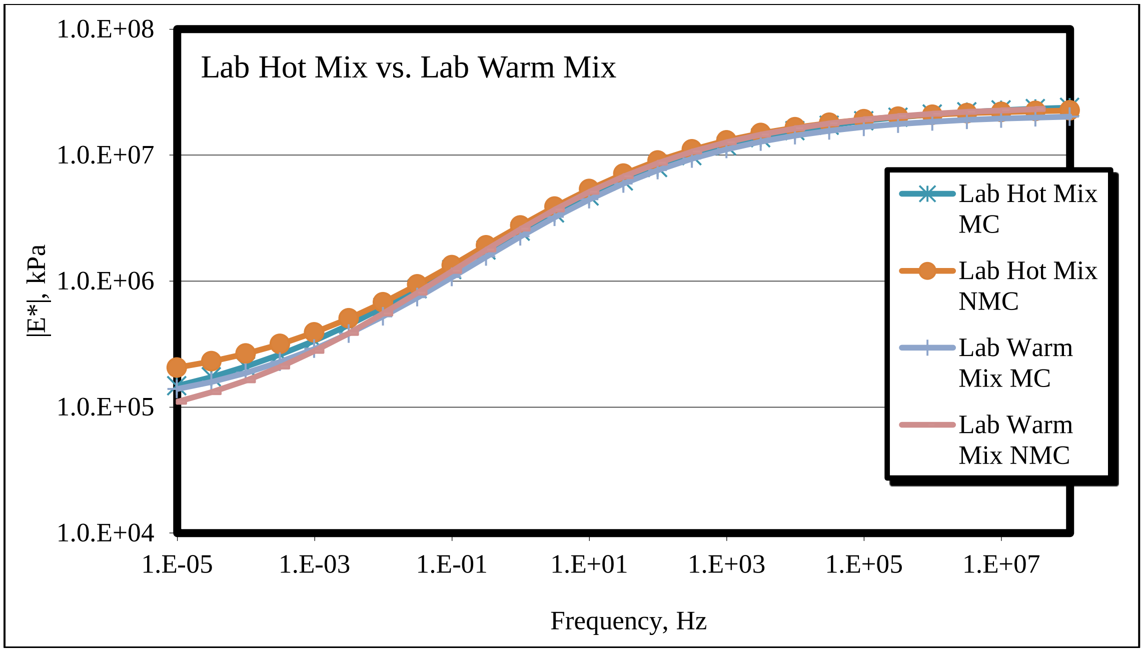


Figure 6.7. Field Mix 2 comparison of laboratory-compacted mixes

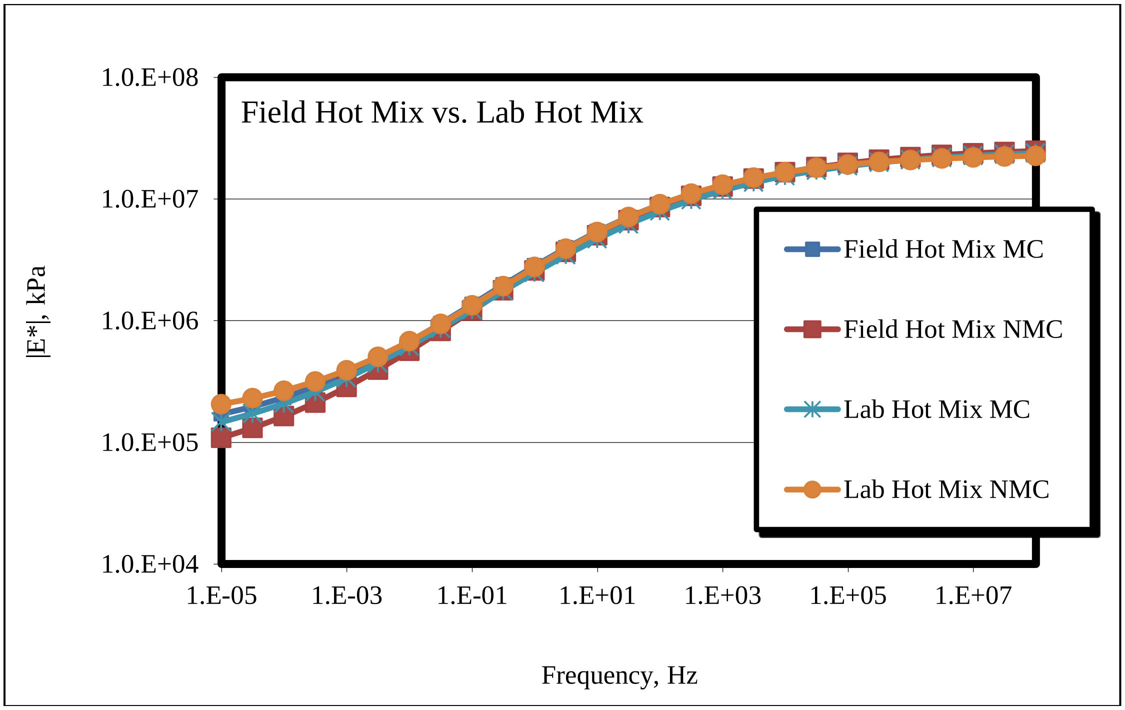


Figure 6.8. Field Mix 2 comparison of laboratory-compacted and field-compacted HMA

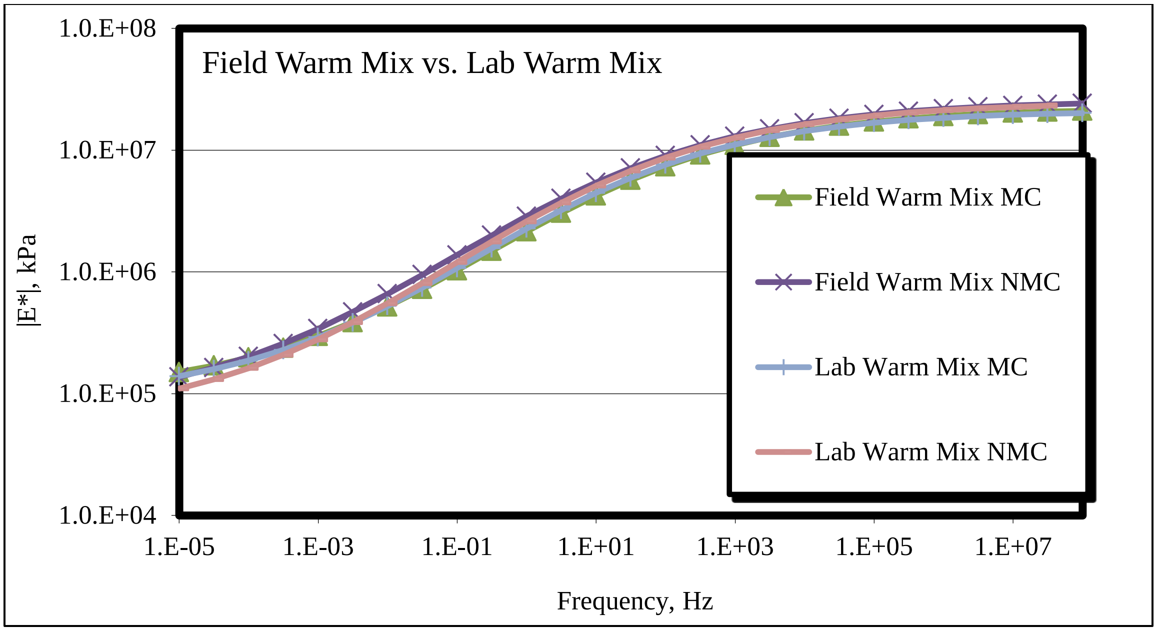


Figure 6.9. Field Mix 2 comparison of field-compacted and laboratory-compacted WMA

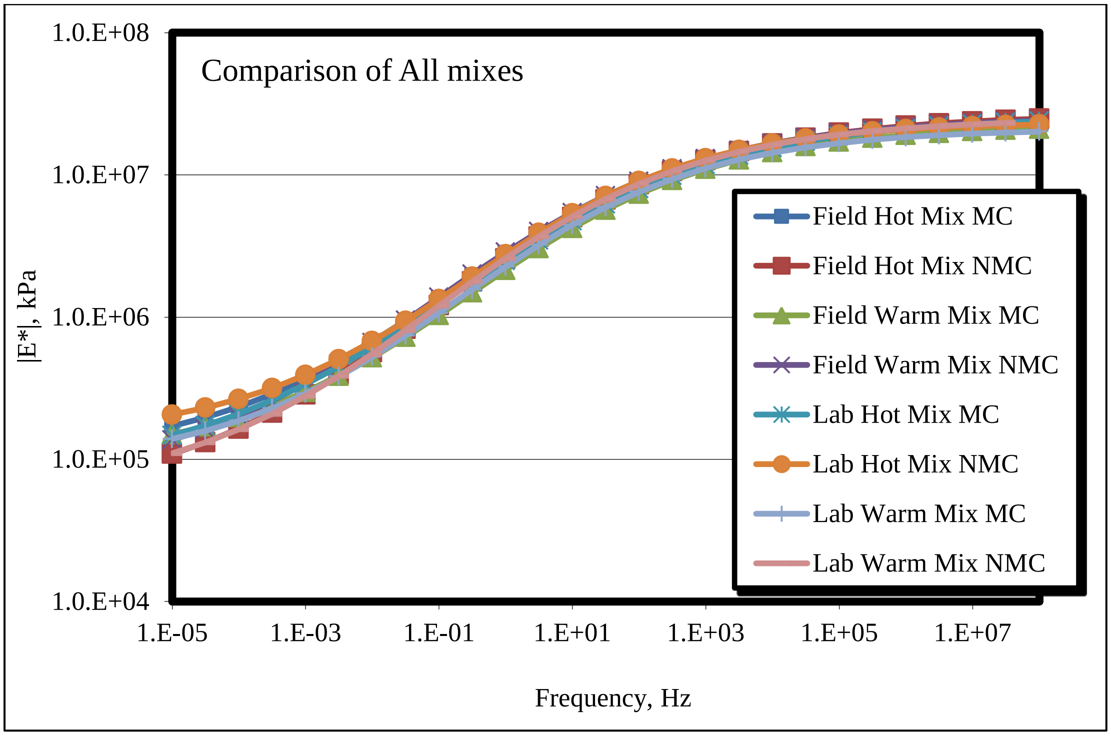


Figure 6.10. Field Mix 2 comparison of all mixes

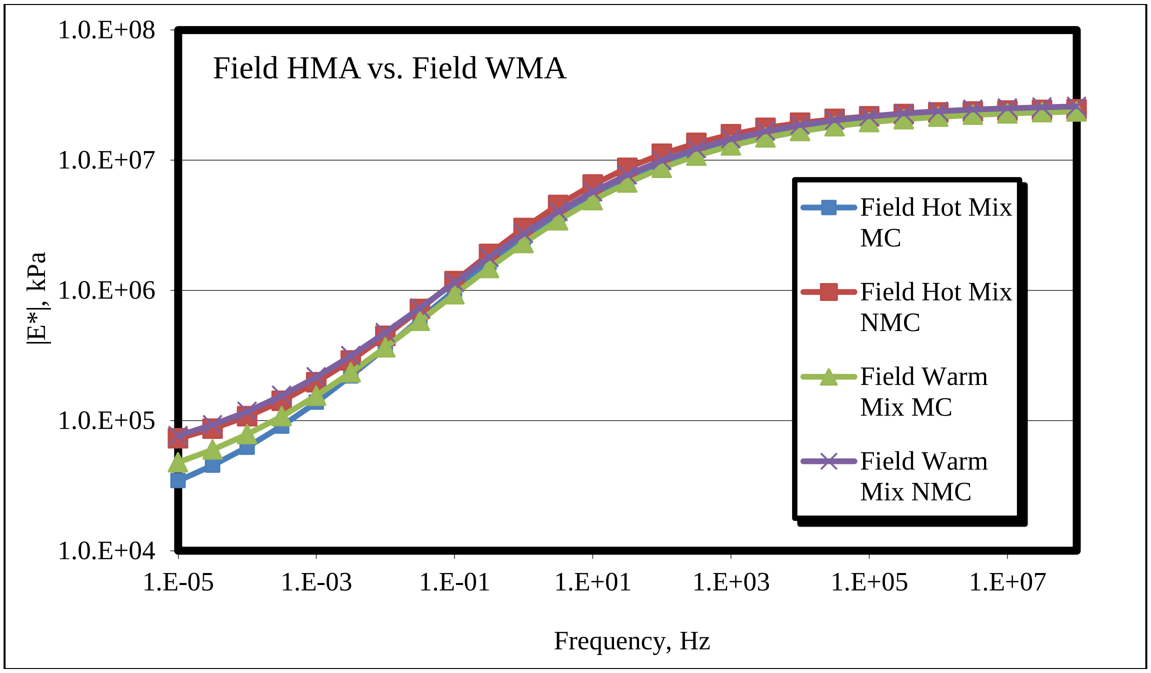


Figure 6.11. Field Mix 3 comparison of field-compacted mixes

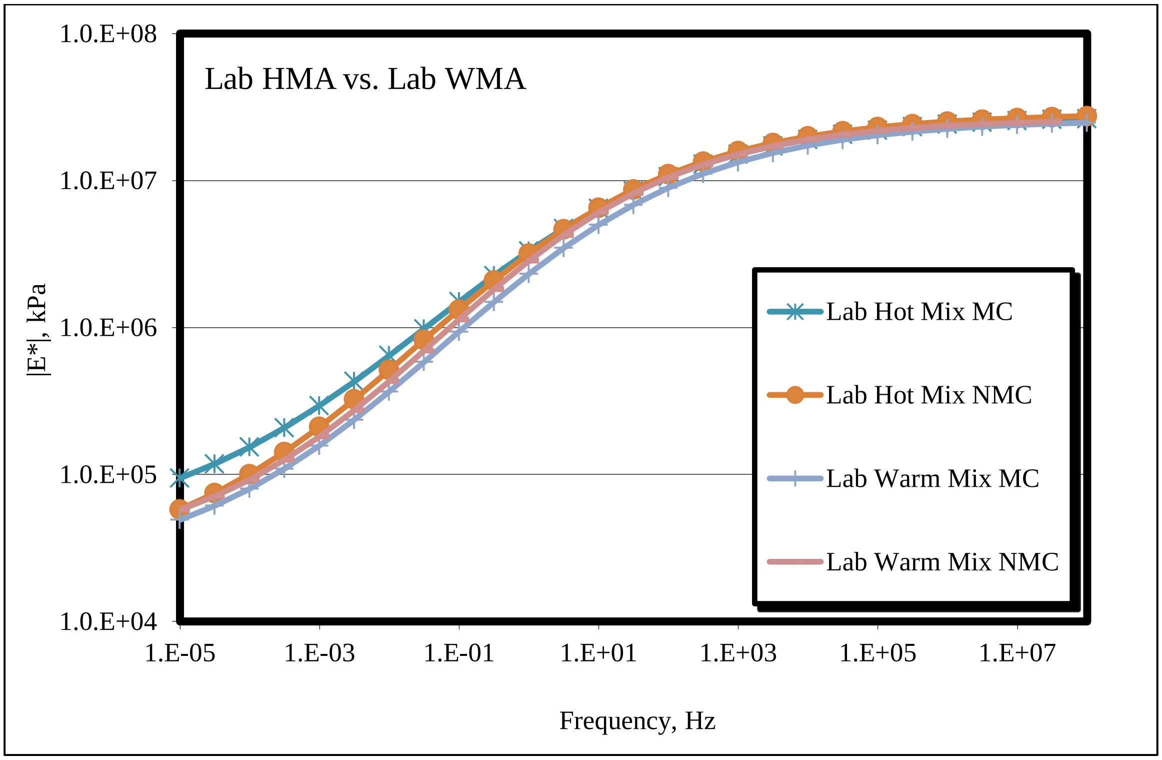


Figure 6.12. Field Mix 3 comparison of laboratory-compacted mixes

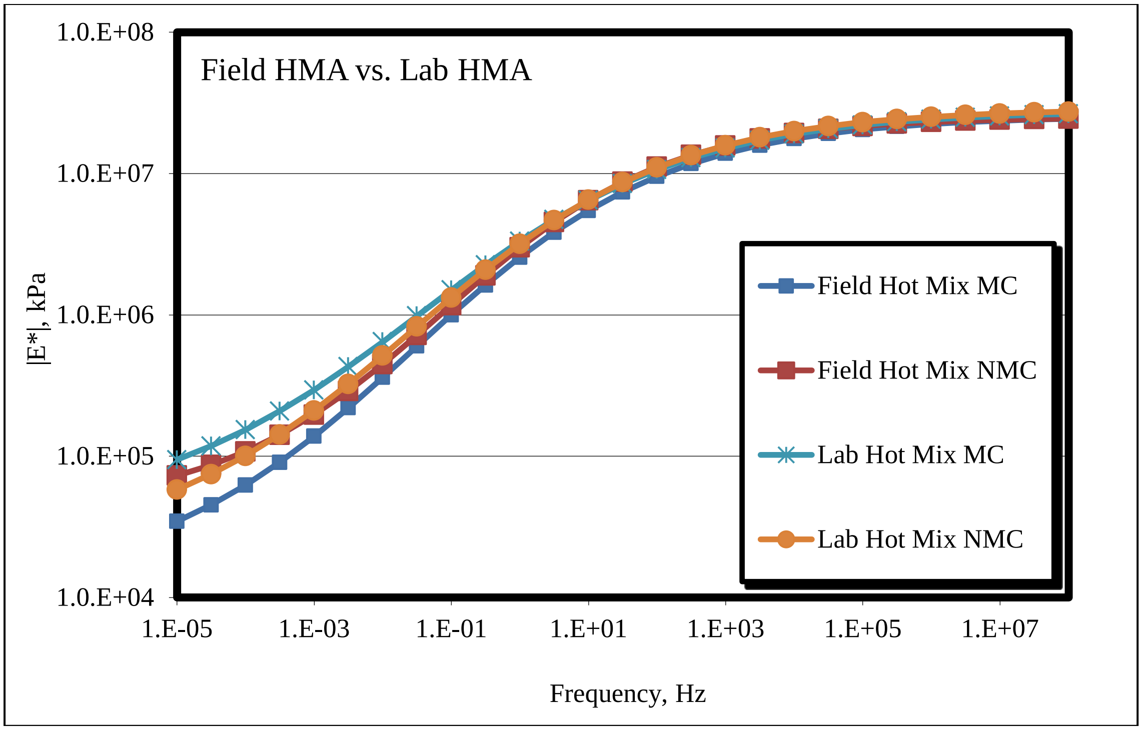


Figure 6.13. Field Mix 3 comparison of field-compacted and laboratory-compacted HMA

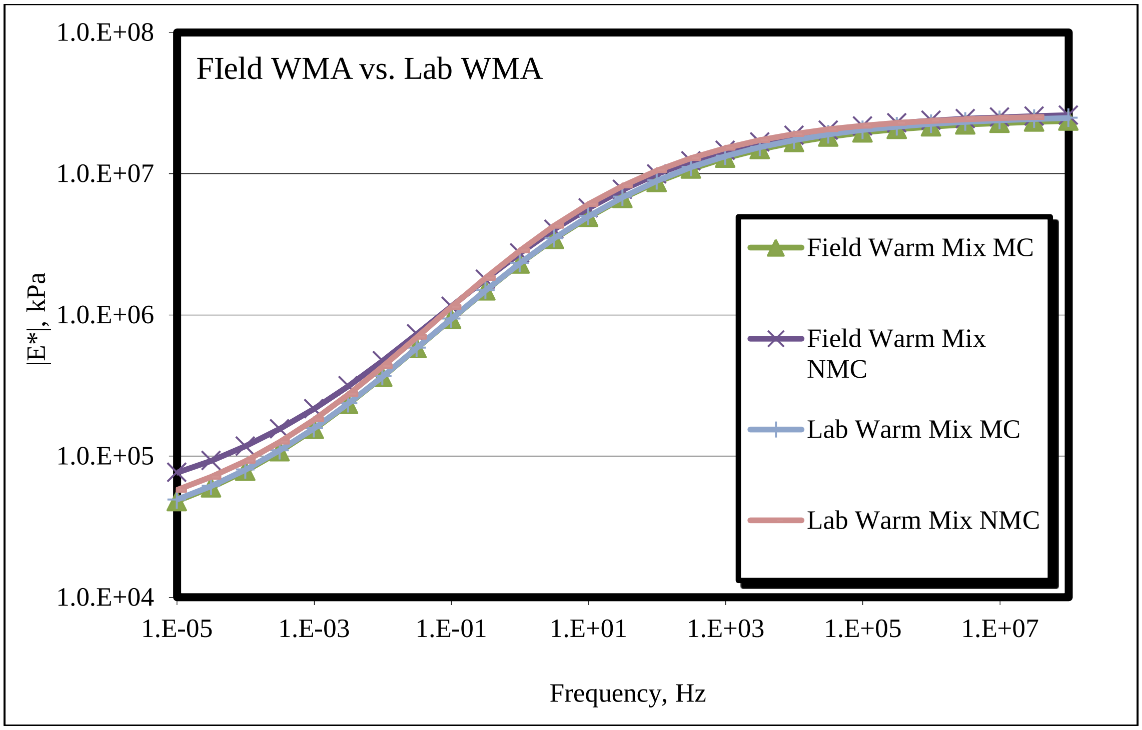


Figure 6.14. Field Mix 3 comparison of field-compacted and laboratory-compacted WMA

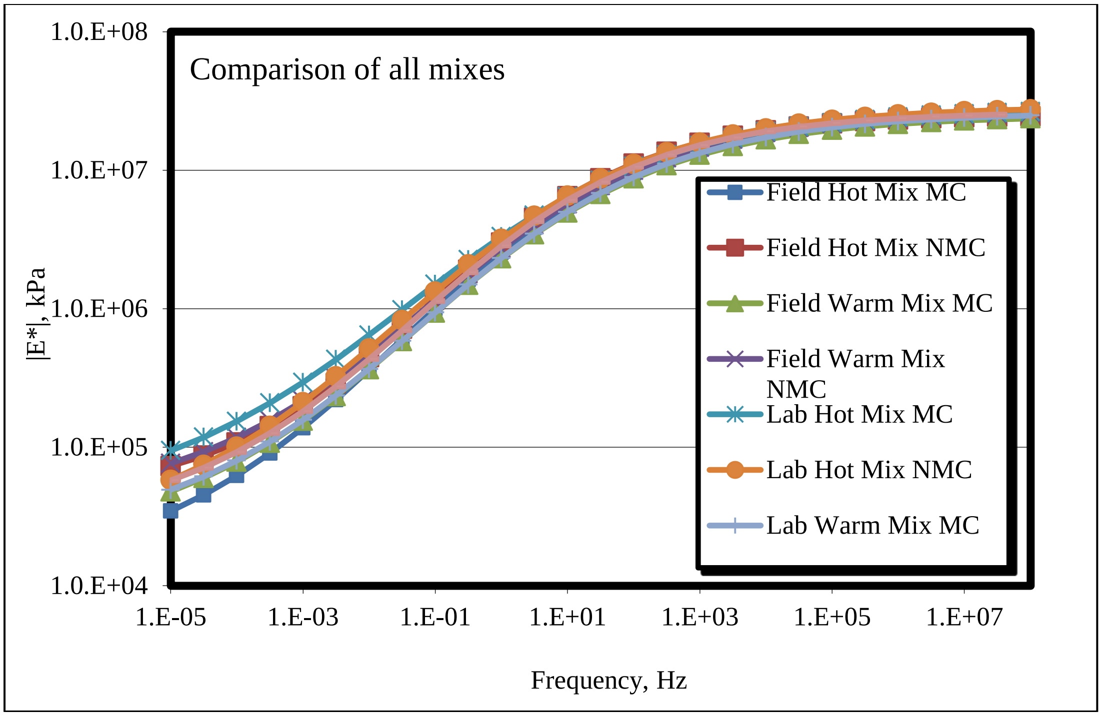


Figure 6.15. Field Mix 3 comparison of all mixes

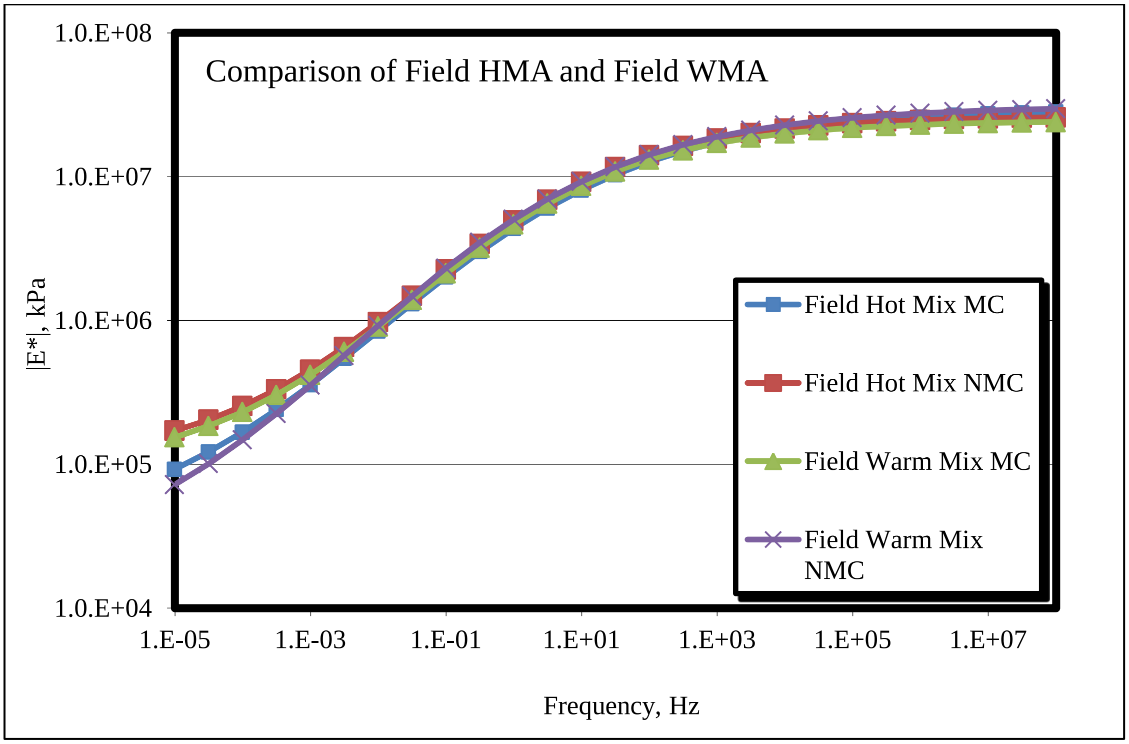


Figure 6.16. Field Mix 4 comparison of field-compacted HMA and WMA

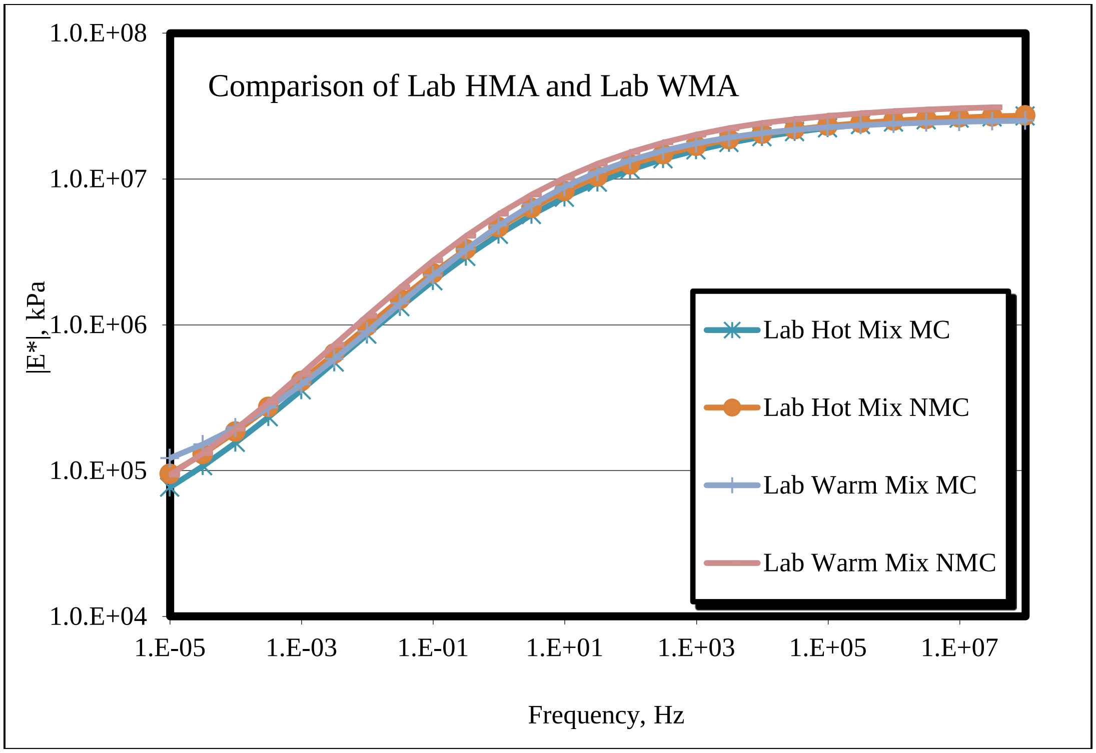


Figure 6.17. Field Mix 4 comparison of laboratory-compacted HMA and WMA

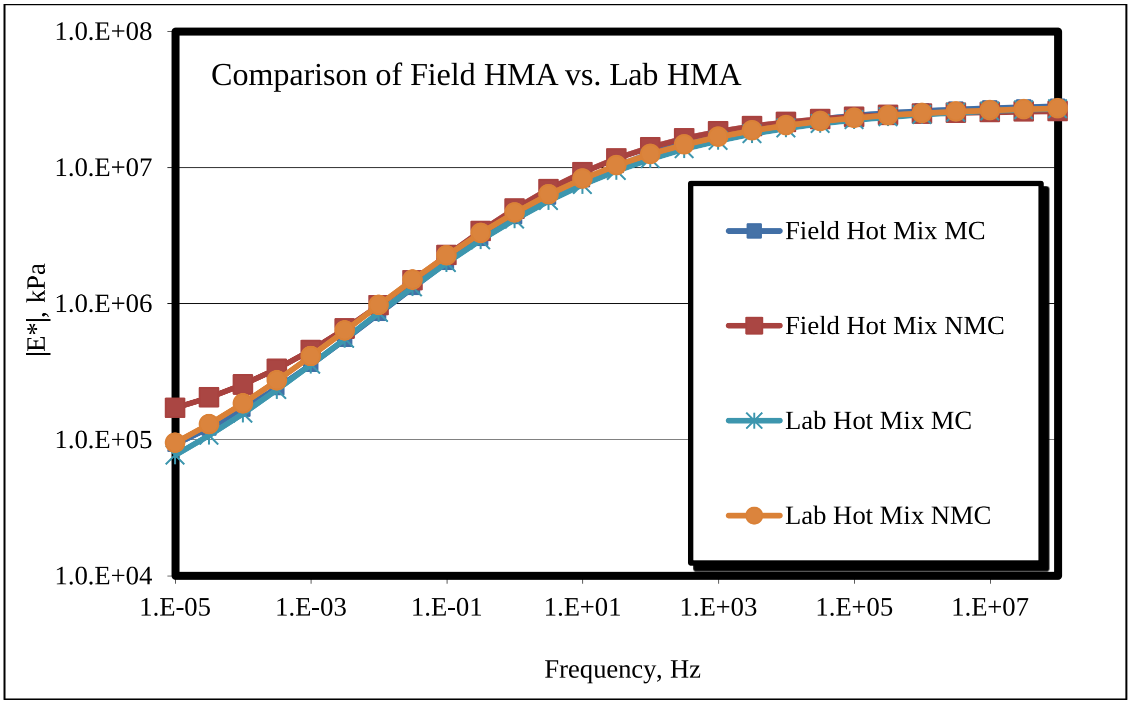


Figure 6.18. Field Mix 4 comparison of field-compacted and laboratory-compacted HMA

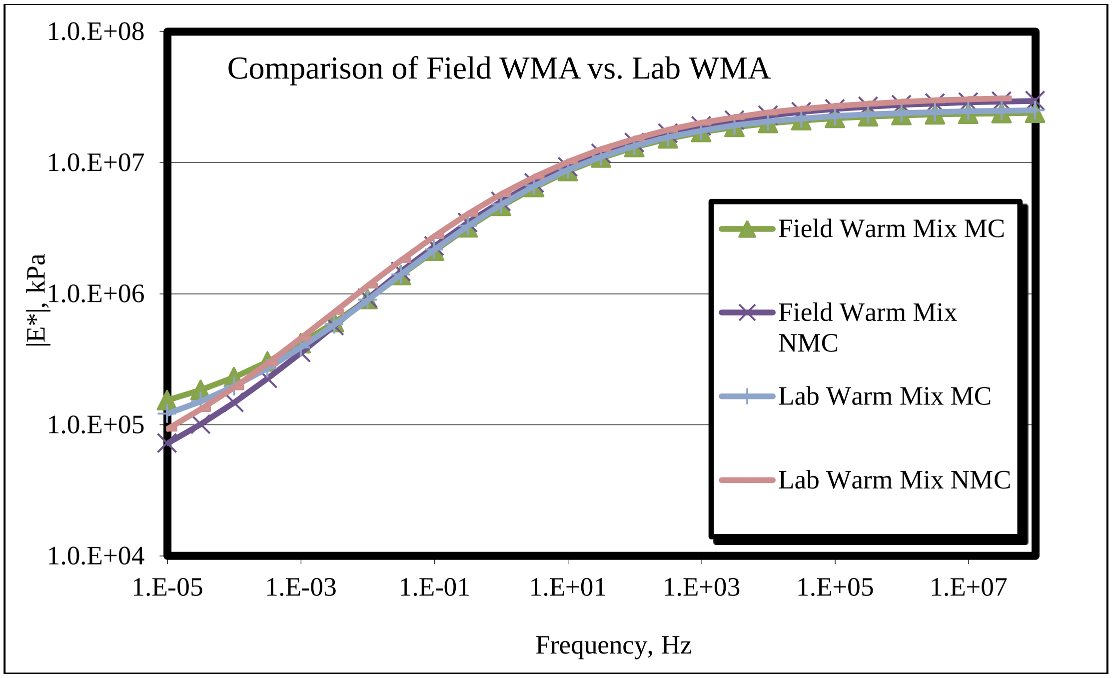


Figure 6.19. Field Mix 4 comparison of field-compacted and laboratory-compacted WMA

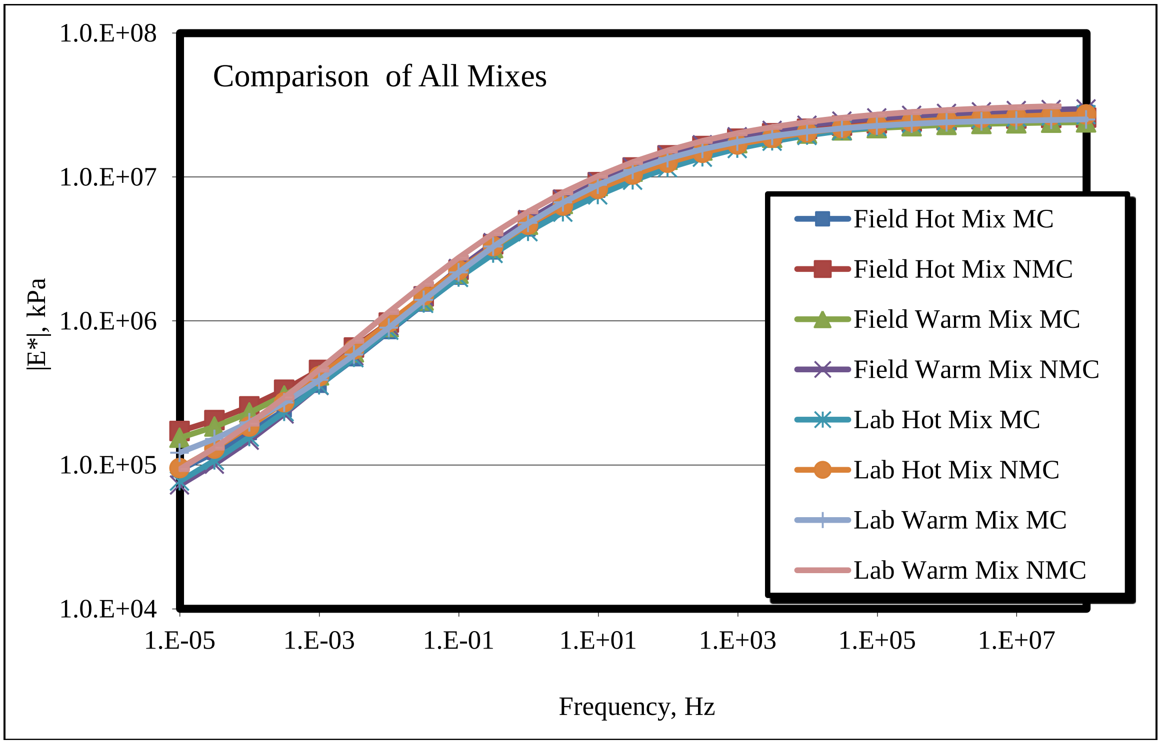


Figure 6.20. Field Mix 4 comparison of all mixes

6.4 Flow Number Results

All of the flow number averages are presented in the figures below. Each chart represents one of the four field produced mixes. The left side of the chart displays the flow number and the right side displays the number of cycles completed to reach three percent strain. The flow number and cycles to 3% strain for each sample are organized in tables in Appendix E.

6.4.1 Field Mix 1 - Flow Number Results

Figure 6.21 shows that the WMA values are consistently lower than the HMA values for this mix. The hot mix lab-compacted samples gave the highest cycles to 3% strain and the HMA lab-compacted, non-moisture-conditioned gave the highest flow number. The WMA values suggest the moisture conditioning had a strengthening effect on the WMA mix. One potential explanation for this is the 60°C hot water bath samples soak in for 24 hours may have stiffened the WMA binder or during the heating process, allowed for more binder absorption into the aggregate. An increase in the binder absorption may have strengthened the binder-aggregate bond. The WMA additive is likely not playing a factor in this because the increase in strength is also observed in several of the HMA mixes.

6.4.2 Field Mix 2 - Flow Number Results

The flow number data for FM2 shows very strong trends in all three of the categories tested as illustrated in Figure 6.22. The data gives evidence that the HMA values are higher than the WMA values, that the field-compacted samples are stronger than the laboratory-compacted samples, and that the moisture-conditioned samples display higher values than the non-moisture-conditioned samples. The HMA field-compacted samples that were moisture-conditioned gave the highest flow number and the highest number of cycles to 3% strain. The lowest values were the WMA lab-compacted, non-moisture-conditioned. The mix had the highest ESAL design out of all of the mixes tested but had the lowest averages in all of the flow number tested categories.

6.4.3 Field Mix 3 - Flow Number Results

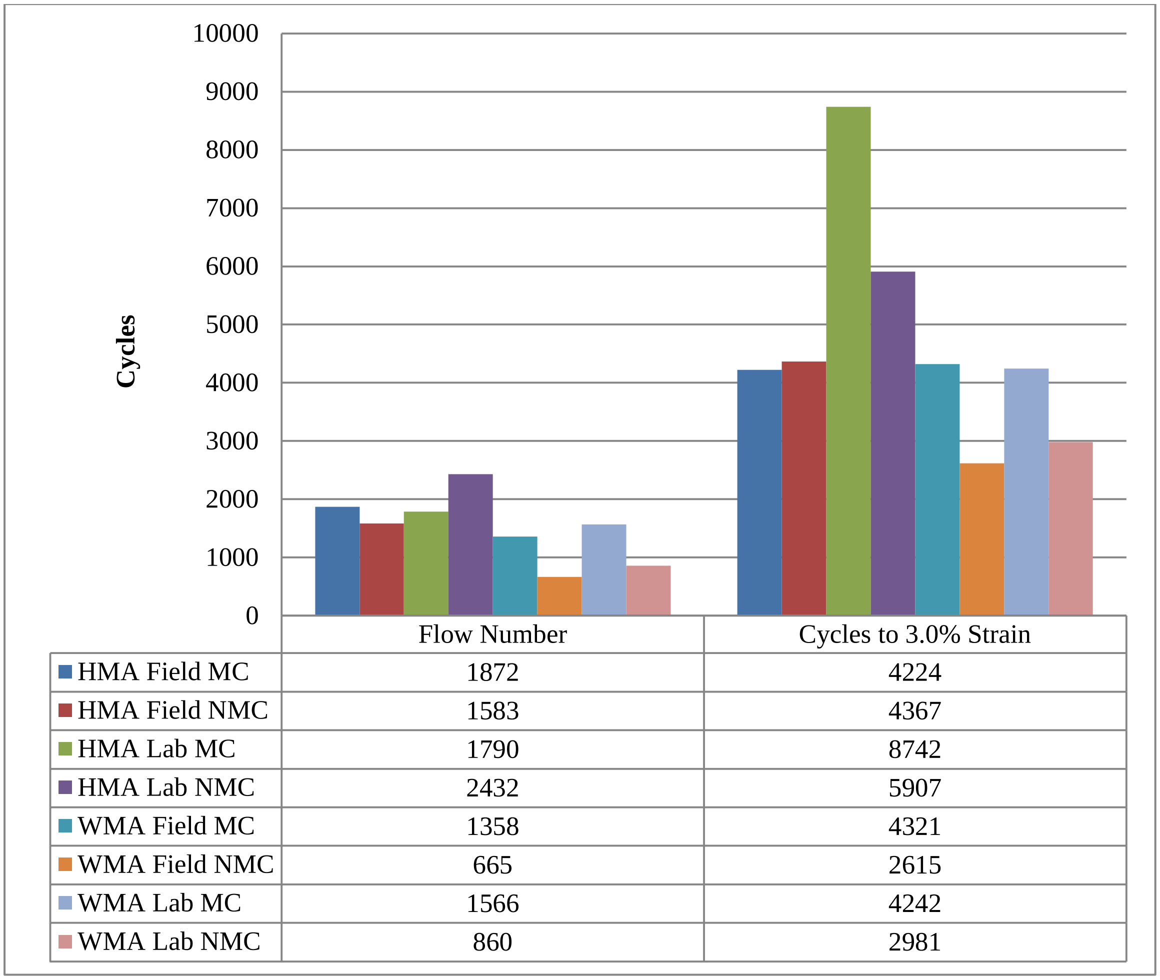
The Field Mix 3 test data in Figure 6.23 doesn’t show strong trends in the data except that the HMA lab-compacted samples displayed the highest flow number value and the highest number of cycles to 3% strain. The other samples show very similar flow number values around 500 cycles and show similar values for cycles to 3% strain approximately 1700 cycles.

6.4.4 Field Mix 4 - Flow Number Results

The general trends in the data indicate that the WMA values are higher than the HMA values for this mix as shown in Figure 6.24. The data showed that moisture conditioning improved the sample performance in most categories. The highest flow number value was the WMA field-compacted and moisture-conditioned category. The highest cycles to 3% strain was WMA laboratory-compacted and moisture-conditioned. The portion of the graph displaying the cycles to 3% strain indicate that moisture conditioning has a strengthening effect on this mix.

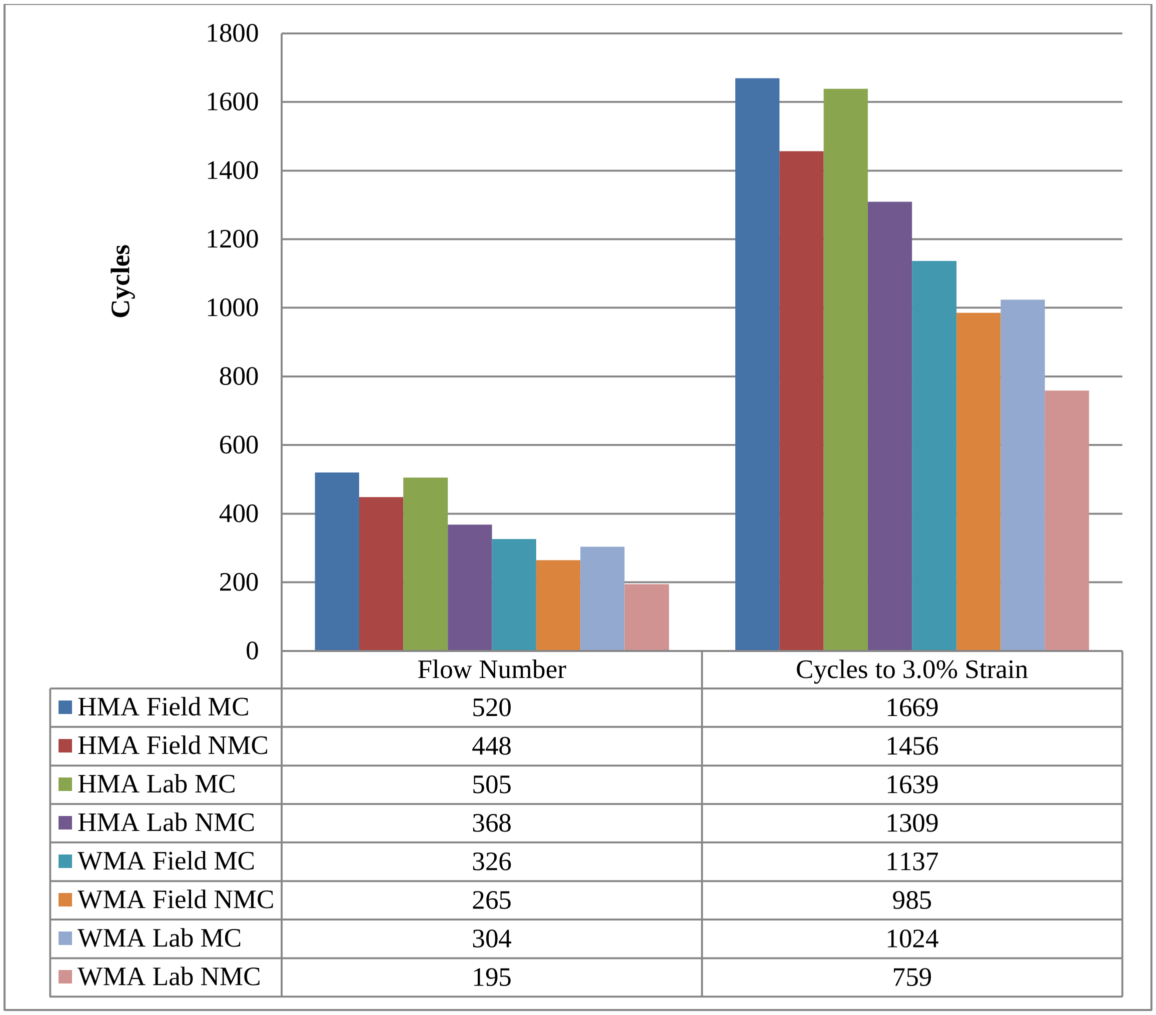
6.4.5 Overall Flow Number Comparison

Overall, the flow number values of the hot mix indicated a slightly higher performance than the warm mix, except in Field Mix 4. Field Mix 2, which had the highest ESAL design life, had the lowest-performing flow number values. The moisture conditioning had varying effect on the flow number and cycles to 3% strain.



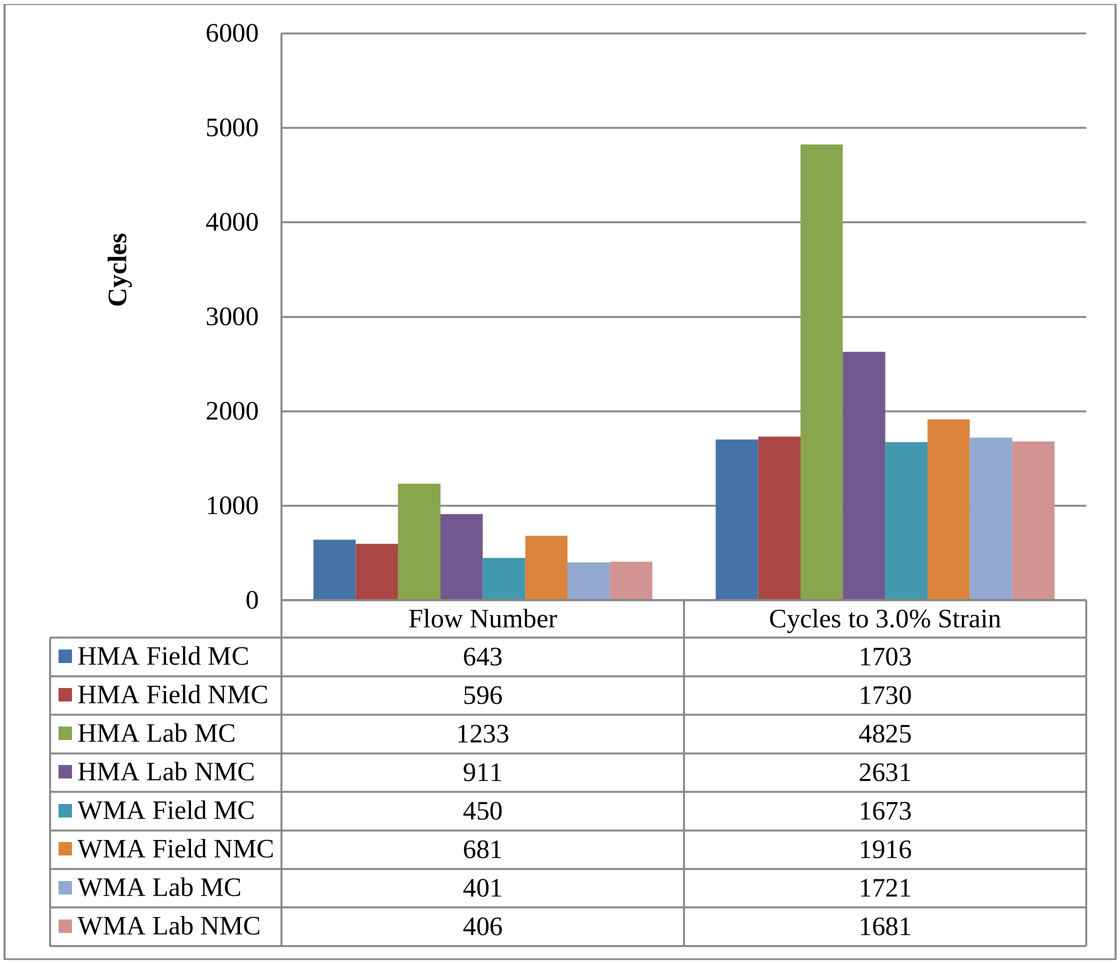
	Flow Number	Cycles to 3.0% Strain
🟦 HMA Field MC	1872	4224
🟥 HMA Field NMC	1583	4367
🟩 HMA Lab MC	1790	8742
🟪 HMA Lab NMC	2432	5907
🟦 WMA Field MC	1358	4321
🟧 WMA Field NMC	665	2615
🟦 WMA Lab MC	1566	4242
🟥 WMA Lab NMC	860	2981

Figure 6.21. Field Mix 1 flow number test data



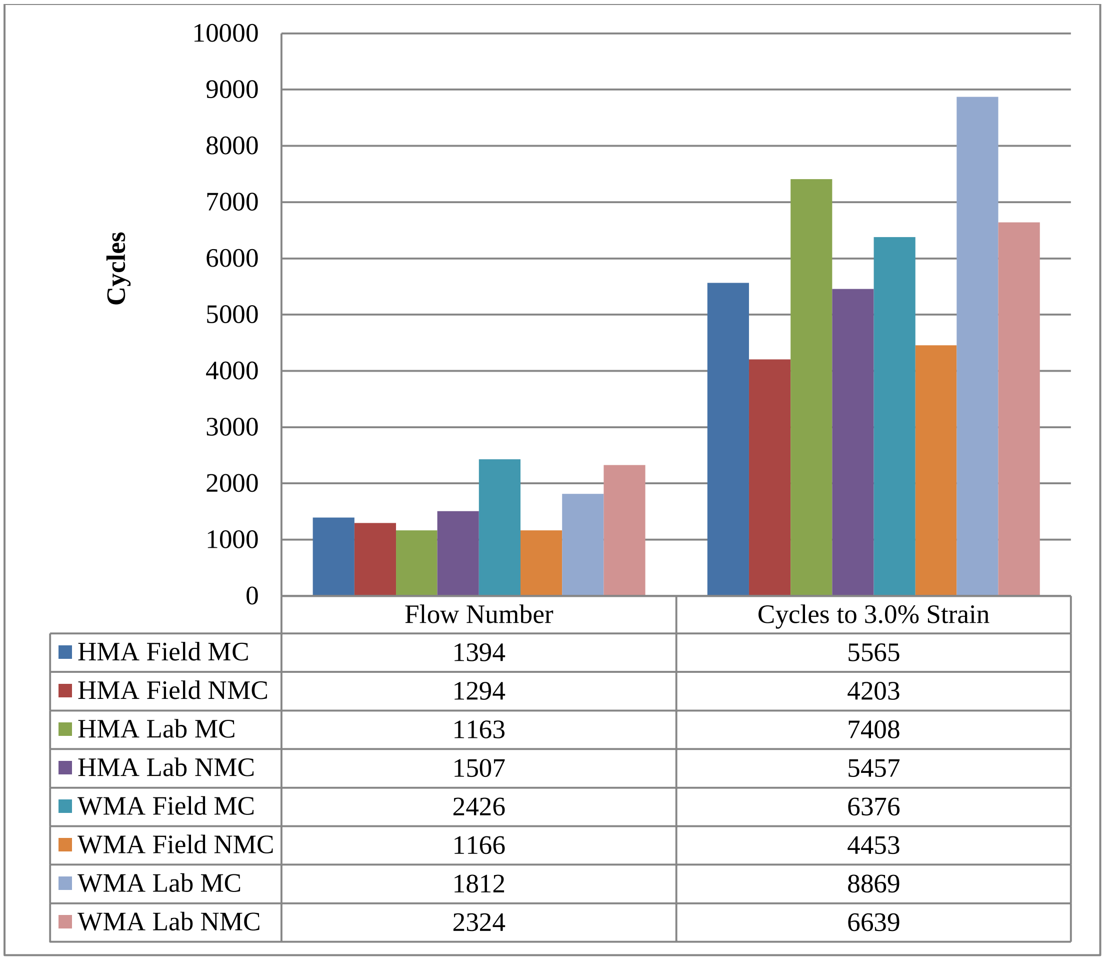
	Flow Number	Cycles to 3.0% Strain
HMA Field MC	520	1669
HMA Field NMC	448	1456
HMA Lab MC	505	1639
HMA Lab NMC	368	1309
WMA Field MC	326	1137
WMA Field NMC	265	985
WMA Lab MC	304	1024
WMA Lab NMC	195	759

Figure 6.22. Field Mix 2 flow number test data



	Flow Number	Cycles to 3.0% Strain
■ HMA Field MC	643	1703
■ HMA Field NMC	596	1730
■ HMA Lab MC	1233	4825
■ HMA Lab NMC	911	2631
■ WMA Field MC	450	1673
■ WMA Field NMC	681	1916
■ WMA Lab MC	401	1721
■ WMA Lab NMC	406	1681

Figure 6.23. Field Mix 3 flow number test data



	Flow Number	Cycles to 3.0% Strain
■ HMA Field MC	1394	5565
■ HMA Field NMC	1294	4203
■ HMA Lab MC	1163	7408
■ HMA Lab NMC	1507	5457
■ WMA Field MC	2426	6376
■ WMA Field NMC	1166	4453
■ WMA Lab MC	1812	8869
■ WMA Lab NMC	2324	6639

Figure 6.24. Field Mix 4 flow number test data

CHAPTER 7. STATISTICAL ANALYSIS FOR FIELD-PRODUCED MIXES

The methodology for the statistical analysis involves primarily testing the probability of a treatment effect within a population of tested samples or means comparison tests. The traditional method used to compare the treatment means is the analysis of variance, or ANOVA. The significance level used in the following analyses is $\alpha=0.05$. The ANOVA assumptions that must be satisfied are (Ramsey & Schafer, 2002):

- Errors are independent
- Errors have constant variance
- Errors are normally distributed
- Independence
- Equal variances
- Additive model

For this experiment, several factors were investigated and thus a higher order ANOVA was needed. The calculations were performed using the computer program SAS version 9.2 (SAS Institute Inc., 2008). For each set of samples tested, a statistical analysis was performed and a discussion for the ITS, dynamic modulus and flow number is provided in the subsequent sections.

Abbreviated versions of the SAS output for each analysis is in Appendix F. The purpose of the output is to provide validation of the assumptions listed above and to also provide a detailed analysis at how the categories within each mix compare. There are five main class variables; however, temperature and frequency are only used for the dynamic modulus testing. The following is a list of the class variables, the levels within each class variable, and the SAS coding abbreviations for the associated class variable:

- Mix type - HMA/WMA (SAS: mix)
- Compaction type - field/laboratory-compacted (SAS: comp)
- Moisture conditioning - non-moisture/moisture-conditioned samples (SAS: mcond)
- Testing frequency - 25, 15, 10, 5, 3, 1, 0.5, 0.3, 0.1 Hz (SAS: fre)
- Testing temperature - 4, 21, 37°C (SAS: temp)

7.1 Indirect Tensile Statistical Analysis

The ITS statistical analysis looks at both the peak loads and the TSR values for each mix. Abbreviated versions of each the SAS output for each mix can be found in Appendix F. The class variables for this analysis include: mix type, compaction type and moisture/non-moisture-conditioned.

7.1.1 Field Mix 1 ITS - Evotherm Technology

The statistical analysis included two class variables: the type of mix and the moisture conditioning. The compaction type was not a variable because this mix had no field-compacted ITS samples. Each class variable had two levels. The mix type included HMA and WMA and the moisture conditioning included the moisture-conditioned samples and the control non-moisture-conditioned samples. The abbreviated ANOVA table shown in Table 7.1 illustrates very strong evidence that the mix types are different. The moisture conditioning and the interaction of mix and moisture conditioning show no evidence of difference. The Duncan grouping was used to compare the mean peak load of the HMA and WMA the means are 12,660 N and 10,310 N, respectively. An abbreviated version of the statistical analysis output is provided on in Appendix F.

Table 7.1. Field Mix 1 ITS ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	27626601.8	27626601.8	13.86	0.0018
mcond	1	2832033.8	2832033.8	1.42	0.2506
mix*mcond	1	824180	824180	0.41	0.5293

A statistical analysis comparison of the TSR values was performed in order to understand the differences between the TSR ratios of the HMA and WMA. The average HMA and WMA TSR values are 1.12 and 1.04, respectively. The means test showed no statistical difference between the WMA and HMA groups for the TSR values.

7.1.2 Field Mix 2 ITS - Revix Technology

The three class variables taken into consideration for FM2 are the mix type, compaction type and moisture conditioning. The levels for the compaction class variable include field- and laboratory-compacted samples. The mix type and moisture conditioning levels remain the same. The ANOVA table for the ITS peak load, Table 7.2, shows statistical differences in mix, compaction type, moisture conditioning and for the interaction of mix and moisture conditioning. The ANOVA table is an abbreviated version of the statistical analysis output and the analysis can be viewed in its entirety in Appendix F. The average peak value of the HMA and the WMA is 7509 N and 7997 N, respectively. The Duncan grouping of all the mixes suggests that the WMA mix did not perform as well after moisture conditioning even though the WMA had the highest non-moisture-conditioned strength.

Table 7.2. Field Mix 2 ITS ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	2381440	2381440	8.61	0.0061
comp	1	3073593.6	3073593.6	11.12	0.0022
mix*comp	1	733326.4	733326.4	2.65	0.1132
mcond	1	4221100.9	4221100.9	15.27	0.0005
mix*mcond	1	1886164.9	1886164.9	6.82	0.0136
comp*mcond	1	275892.1	275892.1	1	0.3253
mix*comp*mcond	1	365956.9	365956.9	1.32	0.2585

Comparison the TSR ratios included the class variables of mix type and compaction type. The WMA and HMA are statistically different with an F-value of 10.83 and a p-value of 0.0046. The average HMA and WMA TSR values are 0.97 and 0.87, respectively. The ANOVA analysis shows a slight statistical difference for the interaction of the mix and compaction type with an F-value of 3.16 and a p value of 0.0946 but is not considered to be strong evidence.

7.1.3 Field Mix 3 ITS - Sasobit Technology

The class variables are the type of mix, compaction and moisture conditioning. The levels are the same as in the previous analyses. The ANOVA table, Table 7.3, shows that the statistically significant factors are the mix type, the compaction type, the moisture condition and the interaction of the mix and moisture conditioning. The HMA and WMA peak load averages are 10372.2 N and 7732.9 N, respectively. This data shows clear evidence of a difference between the two mixes. The Duncan and Tukey means tests also show the HMA and WMA being statistically different for all of the means tests. This is displayed in the statistical analysis output in Appendix F. The means comparison tests also show there is little evidence that within a mix, the field and laboratory compacting may not be a large factor in determining performance but when the average of the entire lab-compacted and field-compacted data sets are calculated there is then statistical difference. The interaction of the mix and the moisture conditioning suggests that the moisture conditioning affects the HMA and WMA differently. The field-compacted, moisture-conditioned WMA was the lowest performing set of samples and was statistically different from all of the other sample sets. The moisture-conditioned samples of the HMA were not statistically different from the controlled non-moisture-conditioned samples.

Table 7.3. Field Mix 3 ITS ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	69656405.63	69656405.63	275.95	<.0001
comp	1	4124850.62	4124850.62	16.34	0.0003
mix*comp	1	49210.22	49210.22	0.19	0.6618
mcond	1	6016329.22	6016329.22	23.83	<.0001
mix*mcond	1	1515934.22	1515934.22	6.01	0.0199
comp*mcond	1	266179.23	266179.23	1.05	0.3122
mix*comp*mcond	1	653569.23	653569.23	2.59	0.1174

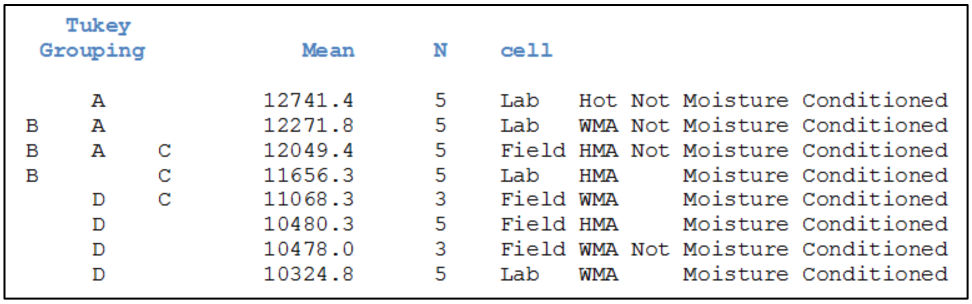
The TSR values show that the WMA and HMA are statistically different with an F-value of 10.50 and a p-value of 0.0051. The TSR means for HMA and WMA are 0.97 and 0.86, respectively. There is weak evidence for the interaction of the mix and compaction type to have a treatment effect. The p-value for the interaction is 0.0814.

7.1.4 Field Mix 4 ITS - Foaming Technology

The class variables for Field Mix 4 are mix type, compaction type and moisture conditioning. The levels are HMA/WMA, field/lab compaction and moisture/non-moisture conditioning. The FM4 ITS peak load ANOVA analysis, Table 7.4, has more statistically different factors listed than any of the other mixes tested. The Tukey grouping shown in Figure 7.1 displays the different class variables and the associated means. Different letters indicate which groups are statistically different when α=0.5. The means listed by each group help to indicate the differences between the various groups. The Tukey grouping shows that there are differences in the WMA field- and laboratory-compacted samples. The lab-compacted WMA non-moisture-conditioned has the highest peak load from the WMA groups. The lab-compacted WMA non-moisture-conditioned was statistically different from the field-compacted WMA non-moisture-conditioned group for this test. The non-moisture-conditioned samples for the HMA were not statistically different in terms of the field and laboratory compactions.

Table 7.4. Field Mix 4 ITS ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	3533448.1	3533448.1	17.7	0.0002
comp	1	5037843.93	5037843.93	25.24	<.0001
mix*comp	1	358213.93	358213.93	1.79	0.1911
mcond	1	12525700.69	12525700.69	62.76	<.0001
mix*mcond	1	244319.2	244319.2	1.22	0.278
comp*mcond	1	1438166.64	1438166.64	7.21	0.0121
mix*comp*mcond	1	4890200.65	4890200.65	24.5	<.0001

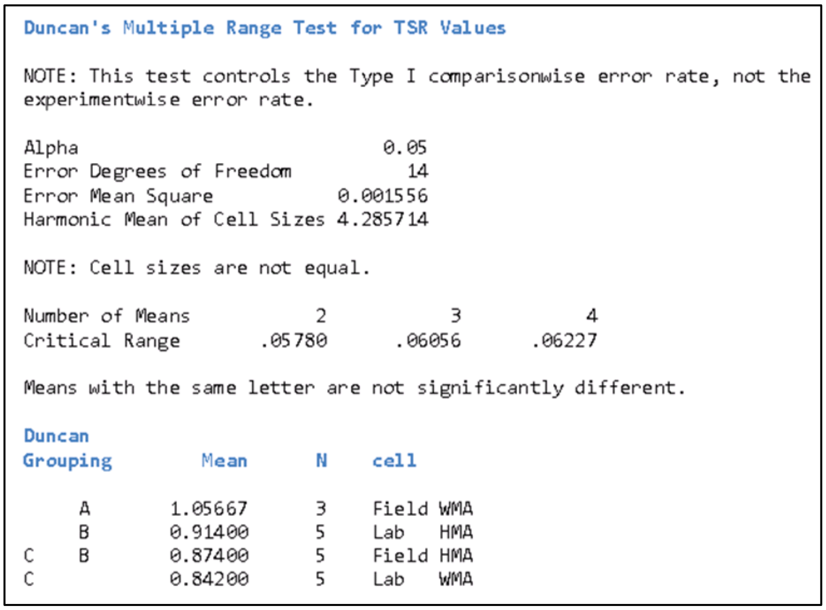


```
   Tukey
 Grouping             Mean      N    cell

     A             12741.4      5    Lab   Hot Not Moisture Conditioned
B    A             12271.8      5    Lab   WMA Not Moisture Conditioned
B    A    C        12049.4      5    Field HMA Not Moisture Conditioned
B         C        11656.3      5    Lab   HMA     Moisture Conditioned
     D    C        11068.3      3    Field WMA     Moisture Conditioned
     D             10480.3      5    Field HMA     Moisture Conditioned
     D             10478.0      3    Field WMA Not Moisture Conditioned
     D             10324.8      5    Lab   WMA     Moisture Conditioned
```

Figure 7.1. Tukey grouping of Field Mix 4 ITS results

The TSR statistical analysis shows the compaction and the interaction of the mix and compaction to be statistically different with p-values of 0.0025 and <0.0001, respectively. The interaction is statistically significant due to the variability within the compaction factor. The Duncan grouping of the four groups gives a good illustration of how the mixes rank in TSR values. The field-compacted WMA mix had the highest TSR values and is statistically different from the other mixes (α=0.05). Although the TSR value for WMA field-compacted is the highest, this did not have the overall highest peak load. The Duncan grouping is shown in Figure 7.2. This shows mixed results because the WMA had both the highest and lowest TSR ratios and the analysis indicates that the moisture conditioning process actually strengthened the samples. The opposite was seen in the HMA mix because there was no statistical difference between the lab and field compaction. It should be noted that the sample size for the field-compacted WMA had only three TSR values.



```
Duncan's Multiple Range Test for TSR Values

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                             0.05
Error Degrees of Freedom            14
Error Mean Square             0.001556
Harmonic Mean of Cell Sizes   4.285714

NOTE: Cell sizes are not equal.

Number of Means           2          3          4
Critical Range       .05780     .06056     .06227

Means with the same letter are not significantly different.

Duncan
Grouping        Mean      N    cell

    A        1.05667      3    Field WMA
    B        0.91400      5    Lab   HMA
C   B        0.87400      5    Field HMA
C            0.84200      5    Lab   WMA
```

Figure 7.2. Duncan grouping of Field Mix 4 ITS results

7.2 Dynamic Modulus Statistical Analysis

The dynamic modulus test data had five class variables that were accounted for in the analysis. In order for the constant variance assumption to be satisfied, a square root transformation was performed on the E* values. A summarized version of the SAS output for each mix is provided in Appendix F. The output includes information about the number of observations used and class levels, ANOVA tables which show the statistically significant class variables, Duncan Groupings for mean comparisons within a class variable, a residual plot and a normal probability plot. When analyzing the ANOVA tables it is helpful to remember the abbreviations used in the SAS coding and they are as follows: compaction is abbreviated as comp, the moisture conditioning is abbreviated as mcond, temperature is abbreviated as temp, and frequency is abbreviated as fre.

7.2.1 Field Mix 1 Dynamic Modulus - Evotherm

The ANOVA table, shown in Table 7.5, displays the significant factors and factor interactions for FM1. Each five individual factors are considered to be statistically significant. The important interactions are as follows: the mix*comp*mcond interaction, the mix*comp interaction and the mix*comp*temp. The mix *comp*mcond interaction implies that the combination of each of these factors influence the dynamic modulus response. The mix*comp*temp interaction implies that the different mixes and different compaction will impact the dynamic modulus response at the various temperatures.

The Duncan groupings show the average lab-compacted sample with a higher dynamic modulus than the field-compacted samples, the non-moisture-conditioned samples have a higher E* than the moisture-conditioned samples, and the HMA has a higher E* than the WMA samples.

Table 7.5. Field Mix 1 dynamic modulus ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	6076743.8	6076743.8	492.57	<.0001
comp	1	2399557.4	2399557.4	194.5	<.0001
mix*comp	1	76266.3	76266.3	6.18	0.0132
mcond	1	6062662.8	6062662.8	491.43	<.0001
mix*mcond	1	23343.8	23343.8	1.89	0.1694
comp*mcond	1	61417.7	61417.7	4.98	0.026
mix*comp*mcond	1	825077.8	825077.8	66.88	<.0001
temp	2	905842464	452921231.8	36713	<.0001
mix*temp	2	262660.4	131330.2	10.65	<.0001
comp*temp	2	647266.9	323633.5	26.23	<.0001
mix*comp*temp	2	135907.9	67954	5.51	0.0042
mcond*temp	2	700519	350259.5	28.39	<.0001
mix*mcond*temp	2	20754.4	10377.2	0.84	0.4317
comp*mcond*temp	2	17184.1	8592	0.7	0.4987
mix*comp*mcond*temp	2	40842.9	20421.5	1.66	0.1918
fre	8	149925935	18740741.9	1519.09	<.0001
mix*fre	8	16011.8	2001.5	0.16	0.9955
comp*fre	8	17616.1	2202	0.18	0.9938
mix*comp*fre	8	4795.8	599.5	0.05	0.9999
mcond*fre	8	128622.3	16077.8	1.3	0.2387
mix*mcond*fre	8	23013.3	2876.7	0.23	0.9847
comp*mcond*fre	8	2285.8	285.7	0.02	1
mix*comp*mcond*fre	8	15225.9	1903.2	0.15	0.9962
fre*temp	16	3556100.4	222256.3	18.02	<.0001
mix*fre*temp	16	301497.6	18843.6	1.53	0.0842
comp*fre*temp	16	17138.7	1071.2	0.09	1
mix*comp*fre*temp	16	13192.3	824.5	0.07	1
mcond*fre*temp	16	54418.9	3401.2	0.28	0.9979
mix*mcond*fre*temp	16	18918.8	1182.4	0.1	1
comp*mcond*fre*temp	16	11128.3	695.5	0.06	1
mix*com*mco*fre*temp	16	36029.5	2251.8	0.18	0.9999

7.2.2 Field Mix 2 Dynamic Modulus - Revix Technology

The statistically-significant factors are shown in Table 7.6. There are statistically-significant differences with all five of the class variables and several interactions that are statistically significant. The interaction of the mix and moisture conditioning implies that there is a treatment effect that is dependent upon each of the categories. This suggests that the mixes are impacted by the moisture conditioning differently. The four way interaction of the mix, compaction, moisture conditioning and temperature show all of these factors played a role in the affecting the dynamic modulus value.

Table 7.6. Field Mix 2 dynamic modulus ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	1015250.7	1015250.7	90.31	<.0001
comp	1	197722	197722	17.59	<.0001
mix*comp	1	8961.4	8961.4	0.8	0.3722
mcond	1	925236.4	925236.4	82.3	<.0001
mix*mcond	1	1051377.6	1051377.6	93.53	<.0001
comp*mcond	1	680	680	0.06	0.8058
mix*comp*mcond	1	597982	597982	53.19	<.0001
temp	2	920420241	460210120.5	40938	<.0001
mix*temp	2	191625	95812.5	8.52	0.0002
comp*temp	2	8363.8	4181.9	0.37	0.6895
mix*comp*temp	2	133609.7	66804.8	5.94	0.0027
mcond*temp	2	941204.7	470602.4	41.86	<.0001
mix*mcond*temp	2	267819.8	133909.9	11.91	<.0001
comp*mcond*temp	2	57717.3	28858.6	2.57	0.0773
mix*comp*mcond*temp	2	147992	73996	6.58	0.0015
fre	8	176316185	22039523.1	1960.52	<.0001
mix*fre	8	28472.6	3559.1	0.32	0.9599
comp*fre	8	7124.1	890.5	0.08	0.9997
mix*comp*fre	8	8192.7	1024.1	0.09	0.9994
mcond*fre	8	159435.8	19929.5	1.77	0.0788
mix*mcond*fre	8	15248.7	1906.1	0.17	0.9948
comp*mcond*fre	8	9857.1	1232.1	0.11	0.9989
mix*comp*mcond*fre	8	21757.3	2719.7	0.24	0.9828
fre*temp	16	9613237.4	600827.3	53.45	<.0001
mix*fre*temp	16	27494	1718.4	0.15	1
comp*fre*temp	16	36432.1	2277	0.2	0.9997
mix*comp*fre*temp	16	15860.3	991.3	0.09	1
mcond*fre*temp	16	72444.2	4527.8	0.4	0.9821
mix*mcond*fre*temp	16	9983.2	624	0.06	1
comp*mcond*fre*temp	16	39592.4	2474.5	0.22	0.9995
mix*com*mco*fre*temp	16	48039.1	3002.4	0.27	0.9983

The Duncan groupings for each class variable are provided in the SAS output. These groupings show the square root of the average for each category and serves as a check of the ANOVA table to assist in validating the statistical difference within a group and determining which group has better average performance. The differences may seem trivial however by taking the square of the mean given in the Duncan grouping and comparing the values of the raw data the differences are more apparent. The square root of the dynamic modulus mean for the field compaction is 2024 and the laboratory compaction is 1997. The non-moisture-conditioned samples have a higher dynamic modulus than the moisture-conditioned samples and the HMA have a higher average dynamic modulus than the WMA samples.

7.2.3 Field Mix 3 Dynamic Modulus - Sasobit Technology

Similar to FM1 and FM2, the FM3 ANOVA table displays each of the five class variables as statistically significant, shown in Table 7.7. The interactions assist in determining which combination of factors can impact the dynamic modulus values. The interaction of mix*comp shows that the type of mix and whether it was field- or lab-compacted will impact the dynamic modulus response. The type of mix and whether the samples were moisture-conditioned will impact the dynamic modulus. The interaction of the mix*comp*mcond shows the combination of all these factors will impact the dynamic modulus response of the sample. By knowing that the combination of these factors impact pavement response and by quantifying the difference in the response, this will help lead to the development of more accurate methods of predicting the pavement performance.

The Duncan grouping for FM3 is shown in Appendix F. The HMA dynamic modulus values are higher than the WMA, the laboratory-compacted samples show a higher dynamic modulus than the field-compacted samples and the non-moisture-conditioned samples have a higher dynamic modulus response than the moisture-conditioned samples.

Table 7.7. Field Mix 3 dynamic modulus ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	4891633	4891633	364.96	<.0001
comp	1	1550413	1550413	115.68	<.0001
mix*comp	1	922370	922370	68.82	<.0001
mcond	1	3612270	3612270	269.51	<.0001
mix*mcond	1	289625	289625	21.61	<.0001
comp*mcond	1	108601	108601	8.1	0.0045
mix*comp*mcond	1	532800	532800	39.75	<.0001
temp	2	1.261E+09	630356439	47030.8	<.0001
mix*temp	2	972755	486377	36.29	<.0001
comp*temp	2	181086	90543	6.76	0.0012
mix*comp*temp	2	77897	38949	2.91	0.0552
mcond*temp	2	1274327	637164	47.54	<.0001
mix*mcond*temp	2	44733	22366	1.67	0.1891
comp*mcond*temp	2	3914	1957	0.15	0.8642
mix*comp*mcond*temp	2	27986	13993	1.04	0.3525
fre	8	218858220	27357277	2041.12	<.0001
mix*fre	8	48593	6074	0.45	0.8888
comp*fre	8	10584	1323	0.1	0.9993
mix*comp*fre	8	10838	1355	0.1	0.9992
mcond*fre	8	107181	13398	1	0.4347
mix*mcond*fre	8	14517	1815	0.14	0.9976
comp*mcond*fre	8	21409	2676	0.2	0.9909
mix*comp*mcond*fre	8	7796	975	0.07	0.9998
fre*temp	16	11059319	691207	51.57	<.0001
mix*fre*temp	16	139260	8704	0.65	0.8443
comp*fre*temp	16	27549	1722	0.13	1
mix*comp*fre*temp	16	24491	1531	0.11	1
mcond*fre*temp	16	31232	1952	0.15	1
mix*mcond*fre*temp	16	28314	1770	0.13	1
comp*mcond*fre*temp	16	32693	2043	0.15	1
mix*com*mco*fre*temp	16	26047	1628	0.12	1

7.2.4 Field Mix 4 Dynamic Modulus - Double Barrel Green Foaming Technology

The dynamic modulus response of the FM4 samples was different from the other three field mixes tested especially in regards to the WMA having higher dynamic modulus values. One explanation of the difference is the nine day duration that elapsed between the production of the HMA mix and the WMA mix due to rain delays. Four of the five factors are statistically significant. The compaction type was not statistically significant and thus any of the interactions that are statistically significant and include compaction are a result of the variability in the other class variables. For example, the interaction of mix and compaction is statistically significant as a result of the variability in the mix (Ott, 2001).

Table 7.8. Field Mix 4 dynamic modulus ANOVA table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
mix	1	3249873	3249873	319.58	<.0001
comp	1	4709	4709	0.46	0.4964
mix*comp	1	1017906	1017906	100.1	<.0001
mcond	1	3356027	3356027	330.02	<.0001
mix*mcond	1	140236	140236	13.79	0.0002
comp*mcond	1	194105	194105	19.09	<.0001
mix*comp*mcond	1	133330	133330	13.11	0.0003
temp	2	1.22E+09	612000610	60182.6	<.0001
mix*temp	2	363814	181907	17.89	<.0001
comp*temp	2	77543	38771	3.81	0.0225
mix*comp*temp	2	122153	61076	6.01	0.0026
mcond*temp	2	703358	351679	34.58	<.0001
mix*mcond*temp	2	706170	353085	34.72	<.0001
comp*mcond*temp	2	129344	64672	6.36	0.0018
mix*comp*mcond*temp	2	51727	25864	2.54	0.0793
fre	8	2.12E+08	26508576	2606.79	<.0001
mix*fre	8	139377	17422	1.71	0.0917
comp*fre	8	43506	5438	0.53	0.8307
mix*comp*fre	8	96502	12063	1.19	0.3044
mcond*fre	8	95010	11876	1.17	0.3158
mix*mcond*fre	8	46777	5847	0.57	0.7989
comp*mcond*fre	8	6341	793	0.08	0.9997
mix*comp*mcond*fre	8	8705	1088	0.11	0.999
fre*temp	16	5143158	321447	31.61	<.0001
mix*fre*temp	16	132885	8305	0.82	0.6672
comp*fre*temp	16	79684	4980	0.49	0.9527
mix*comp*fre*temp	16	51941	3246	0.32	0.995
mcond*fre*temp	16	20197	1262	0.12	1
mix*mcond*fre*temp	16	42769	2673	0.26	0.9984
comp*mcond*fre*temp	16	10217	639	0.06	1
mix*com*mco*fre*temp	16	10269	642	0.06	1

The Duncan groupings show that the non-moisture-conditioned samples have a higher dynamic modulus response, the WMA has a higher dynamic modulus than the HMA and there was not a statistical difference in the compaction type. It may be advantageous to continue investigating the foaming technology because there was nine days between the production of the HMA and WMA mixes.

7.3 Flow Number

The statistical analysis for the flow number data includes an analysis of the flow numbers and of the number of cycles to three percent strain. SAS was used to perform the statistical analysis and the SAS output is located in Appendix F. The output includes ANOVA tables, Duncan groupings, residual plots, and normal probability plots. The flow number tests have three class variables and those are the mix type, the compaction type, and whether or not moisture-conditioned.

7.3.1 Field Mix 1 Flow Number Data Analysis - Evotherm Technology

The ANOVA table for the FM1 flow number shows that the mix class variable is statistically significant. The ANOVA table showing the cycles to three percent strain displays mix, compaction, and moisture conditioning as the statistically significant factors and the interaction of the mix and compaction as well as the interaction of mix, compaction and moisture conditioning as statistically significant. Both tables show the mix as having the highest statistical difference. The Duncan groupings for the SAS output show that the HMA has higher flow number and cycles to three percent strain. The average of the lab is higher than the field-compacted samples and the moisture-conditioned samples is, on average, higher than the non-moisture-conditioned samples.

7.3.2 Field Mix 2 Flow Number Data Analysis - Sasobit Technology

The ANOVA tables for FM2 flow number and cycles to three percent strain show the factors of the mix and the moisture conditioning are statistically significant. The HMA mix had higher average flow number and cycles to three percent strain when compared to the WMA mix and the moisture-conditioned samples had higher averages when compared to the non-moisture-conditioned samples. The Duncan and Tukey groupings list the categories of samples in order the mean values and show which groups are statistically different from each other. This is included in Appendix F. The groupings show that no particular group completely outranks the others but all of the HMA groups are all listed higher than the WMA groups.

7.3.3 Field Mix 3 Flow Number Data Analysis

The ANOVA table for the flow number data shows statistical differences in the mix category and for the interaction of mix and compaction type. The ANOVA table for the cycles to three percent strain similarly shows the mix class variable and the interaction of mix and compaction as statistically significant factors as well as the compaction type. The overall average of the lab-compacted mixes are higher than the field-compacted mixes. The average cycles for the HMA is higher than the WMA for both flow number and cycles to three percent strain.

7.3.4 Field Mix 4 Flow Number Data Analysis

The flow number ANOVA table for FM4 has the mix as the only statistically significant factor and the WMA has a higher average flow number than the HMA. The ANOVA table for 3% strain shows the mix, compaction type and moisture conditioning as significant factors. The lab-compacted samples averaged higher cycles as did the warm mix and the moisture-conditioned samples. All of the moisture-conditioned samples for Field Mix 4 had a higher average than the non-moisture-conditioned samples of the same group. For example, the moisture-conditioned, laboratory-compacted WMA samples had a higher average cycles to 3% strain than the non-moisture-conditioned, laboratory-compacted WMA samples.

7.4 Statistical Analysis Summary

The statistical analysis shows very strong evidence of differences in the HMA and WMA performance testing results. The first three field mixes performed similarly and show better performance testing data from the HMA mixes. The field mix which utilized the Double Barrel Green technology had better performance for the WMA mix, but this mix also had an added degree of variability due to weather delays, which postponed the production of the control mix by nine days.

The main objectives of this project was to compare HMA and WMA, evaluate the effects of moisture conditioning and evaluate whether field versus laboratory compaction had a significant impact on the mix performance. The statistical analysis shows evidence that each of these factors is statistically significant in at least one situation. All four field mixes tested had the interaction of mix*compaction*moisture-conditioning as being statistically significant in the dynamic modulus data. This shows that all three of these factors influence the material response in the dynamic modulus testing so in order to continue improving asphalt testing procedures and pavement design models, the samples produced for performance testing must resemble the material response of the actual pavement.

The overall analysis shows that there are differences in the material response of the HMA and WMA mixes during performance testing and also the factors of compaction and moisture conditioning play a role in determining the material response during performance testing.

CHAPTER 8. RESULTS AND ANALYSIS FOR LABORATORY-PRODUCED MIXES

8.1 Indirect Tensile Strength

This test was conducted on 176 specimens representing 22 mixtures. These specimens were classified into two subsets; control specimens and moisture-conditioned specimens. For each mixture, specimens were sorted in terms of their air void percent in ascending fashion with the first specimen assigned as a dry specimen and the following one as a moisture-conditioned specimen so that, for each mix, there are four dry specimens and four moisture-conditioned specimens. The results of the indirect tensile strength test are tabulated in Table 8.1.

From the TSR data shown above, it can be deduced that most mixtures were not susceptible to moisture. According to AASHTO T 283, a TSR of 0.7 is stipulated as the minimum ratio to regard a mix not susceptible to moisture. Based on this criterion, only mixtures prepared using Advera had TSRs lower than 0.7. This observation is also supported by Figures 8.1 through 8.5. In these figures, the trend observed is similar for all mix groups with the control mixture recording the highest TSR ratio as expected with the mixtures prepared Evotherm (green) and Sasobit (mauve) displaying slightly lower TSRs but still close to the 0.7 threshold. On the other hand, Advera mixtures were consistently showing TSR lower than 0.7 for all mixture groups regardless of the RAP content or the type of aggregate incorporated. An NCAT study stated that moisture susceptibility in WMA may be caused by the reduced aging of the binder, the presence of moisture and the insufficient dryness of the aggregates (Ghandi, 2008). Only the presence of moisture would qualify as a potential cause for the relatively lower TSR ratios of the Advera mixtures as the aggregates and the binder were subjected to similar conditions prior and during the mixing and compaction processes for all mixtures. Hence, the release of crystalline water from the synthetic zeolite which is necessary for improving the workability of the asphalt mix at lower temperature may be the cause of the increased moisture susceptibility of the Advera mixtures.

Table 8.1. Indirect tensile strength test results

Mix Group	Mix ID	WMA technology	Average dry indirect tensile strength	Average moisture conditioned tensile strength	Tensile Strength Ratio
Limestone 0% RAP	1	Control	11.03	7.97	0.74
	4	Advera	8.69	5.48	0.63
	7	Evotherm	11.19	8.07	0.72
	10	Sasobit	9.99	7.11	0.71
Limestone 15% RAP	2	Control	9.30	8.35	0.90
	5	Advera	12.66	6.24	0.49
	8	Evotherm	11.72	8.06	0.69
	11	Sasobit	11.87	9.20	0.77
Limestone 30% RAP	3	Control	11.56	9.95	0.86
	6	Advera	13.14	8.11	0.62
	9	Evotherm	11.98	10.11	0.84
	12	Sasobit	12.21	9.63	0.79
Quartzite 0% RAP	13	Control	8.81	6.22	0.75
	15	Advera	7.64	4.95	0.65
	17	Evotherm	7.74	7.65	0.99
	20	Sasobit	11.62	7.76	0.67
Quartzite 30% RAP	14	Control	12.17	9.53	0.78
	16	Advera	12.40	6.73	0.54
	19	Evotherm	10.69	8.89	0.85
	21	Sasobit	11.27	6.74	0.60

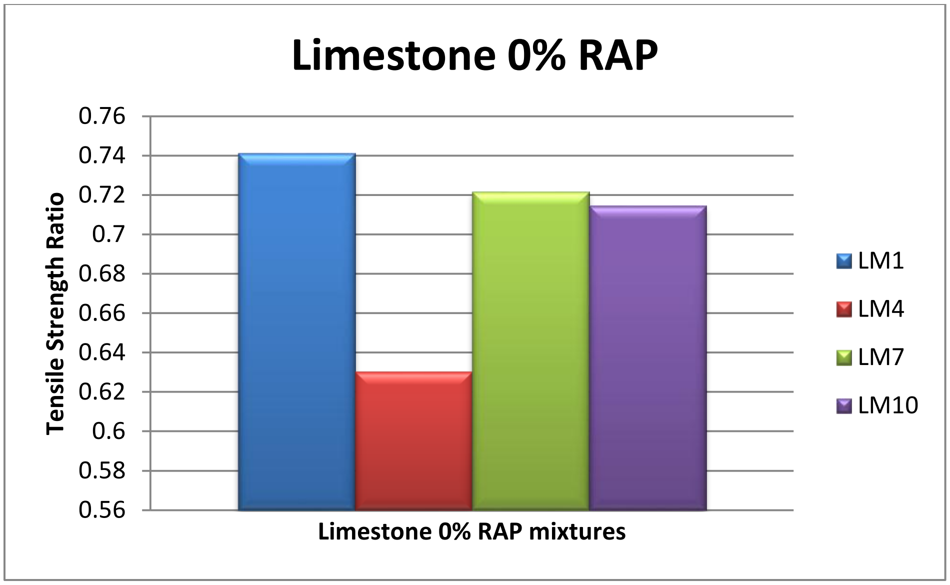


Figure 8.1. Tensile strength ratios for limestone 0% RAP mixtures

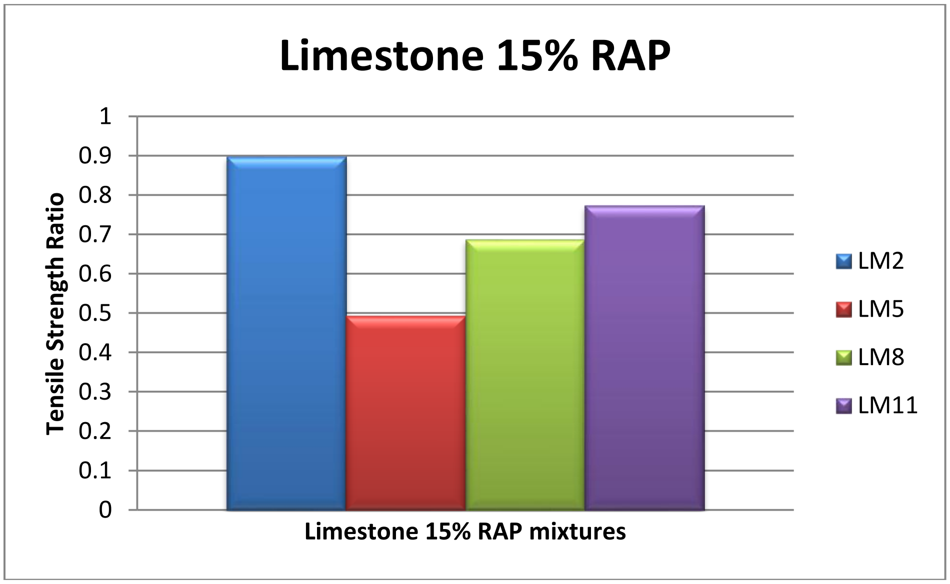


Figure 8.2. Tensile strength ratios for limestone 15% RAP mixtures

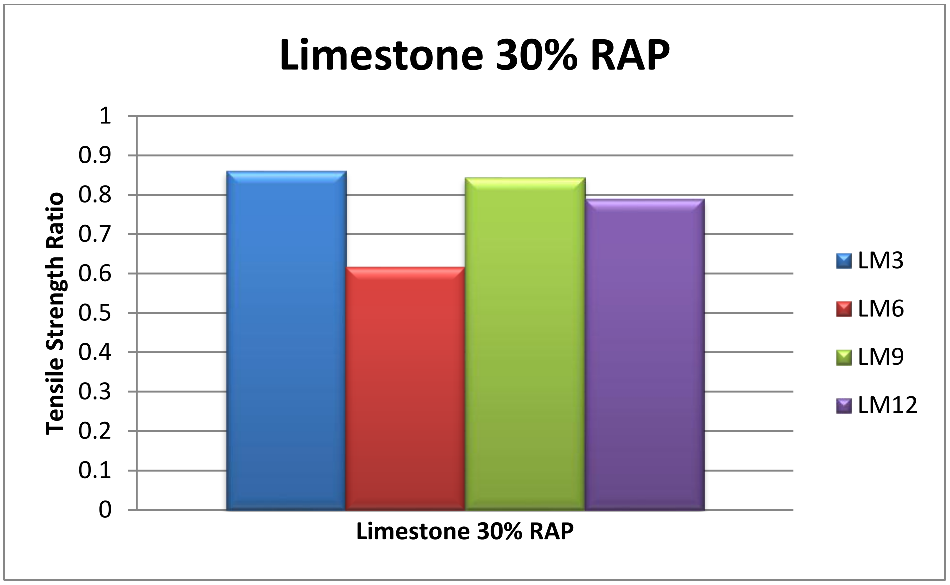


Figure 8.3. Tensile strength ratios for limestone 30% RAP mixtures

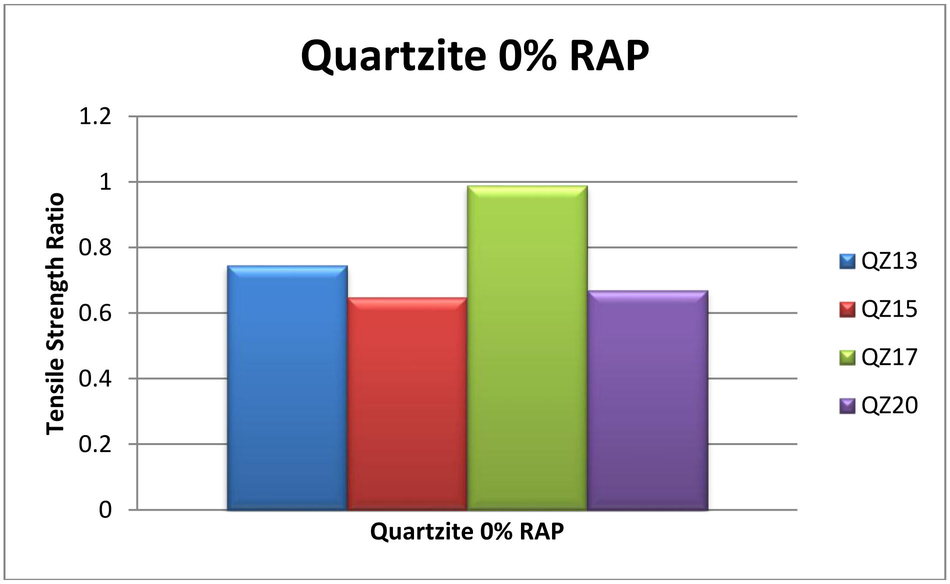


Figure 8.4. Tensile strength ratios for quartzite 0% RAP mixtures

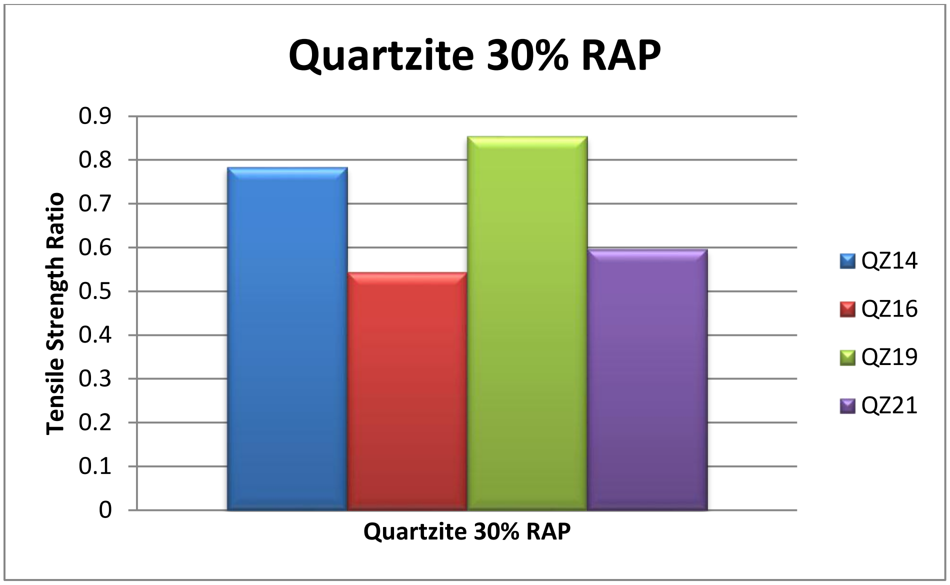


Figure 8.5. Tensile strength ratios for quartzite 30% RAP mixtures

8.2 Dynamic Modulus

In addition to specimens tested for the indirect tensile strength, the dynamic modulus test was conducted on 128 specimens representing 16 mixtures. The dynamic modulus test was conducted over the range of three temperatures; 4, 21 and 37°C and nine frequencies; 0.1, 0.3, 0.5,1,3,5,10,15 and 25 Hz in an attempt to characterize the performance of warm mix mixtures in various loading and climatic combinations. At a given test temperature, the asphalt mixture specimen is subjected to a sinusoidal compressive axial load at a given frequency of loading. The applied axial stress and the recoverable axial strain are used to calculate the dynamic modulus and phase angle for the specimen. For each mixture, the test was performed on eight replicates; four replicates that were subjected to moisture conditioning while the remaining four specimens act as the control for the moisture conditioning effect. The average dynamic modulus and phase angle of four replicates is calculated in addition to the standard deviation and the coefficient of variation for each mixture. The average values of the dynamic modulus and phase angle for the 16 asphalt mixtures investigated in this study are shown in Appendix H.

From the experimental data, it can be observed that the coefficient of variation for most mixtures is lower than 20 percent indicating that the repeatability of the test is satisfactory. In a plot of dynamic modulus against the frequency, the values of the dynamic modulus typically increase as the frequency increases. In the same way, dynamic modulus values increase in direct fashion with an increase in temperature as shown in Figure 8.6.

In Figure 8.6, it can be observed that the E* value increased with increase in temperature and frequency for asphalt mixtures prepared using limestone aggregates and were not subjected to moisture conditioning. The same chart shows the better performance of the asphalt mixture that did not incorporate a warm mix additive, LM1, for all three test temperatures. This behavior is more noticeable at medium and high frequency ranges and less evident at very low frequencies.

Moreover, the performance of the asphalt mix that was prepared using the Advera® additive, LM4 recorded higher E* values, specifically for specimens conditioned at 4C. For specimens conditioned at 21 and 37°C, the differences in the behavior of mixtures prepared using different WMA technologies are less evident especially between the Advera® and Sasobit® mixtures: LM4 and LM10 respectively. It can be observed that the difference in the dynamic modulus values of the four asphalt mixtures decreases with the increase in temperature.

Figure 8.7 plots the dynamic modulus behavior of mixtures prepared using limestone aggregate and were moisture-conditioned according to the procedures outlined in AASHTO T-283. The control mixture prepared without any WMA additives exhibit the highest dynamic modulus at different curing temperatures. However, at the 4°C test temperature the control, Evotherm® and Sasobit® mixtures display very similar behavior with the Advera® mixture, LM4 recording the lowest dynamic modulus especially at higher frequencies. For the 21 and 37°C test temperature, the control mixture LM1 recorded the highest dynamic modulus followed by the Sasobit® mixture LM10. Moreover, Evotherm® and Advera® mixtures: LM7 and LM4, show very similar trends.

In comparing Figures 8.6 and 8.7, it can be observed that the performance of the control mixture LM1 is superior to that of other mixtures for both the moisture-conditioned and non-moisture-conditioned sets. On the other hand, the performance of the Sasobit® mixture, LM4 is superior to other mixtures prepared with other WMA technologies upon exposure to moisture conditioning as shown in Figures 8.6 and 8.7.

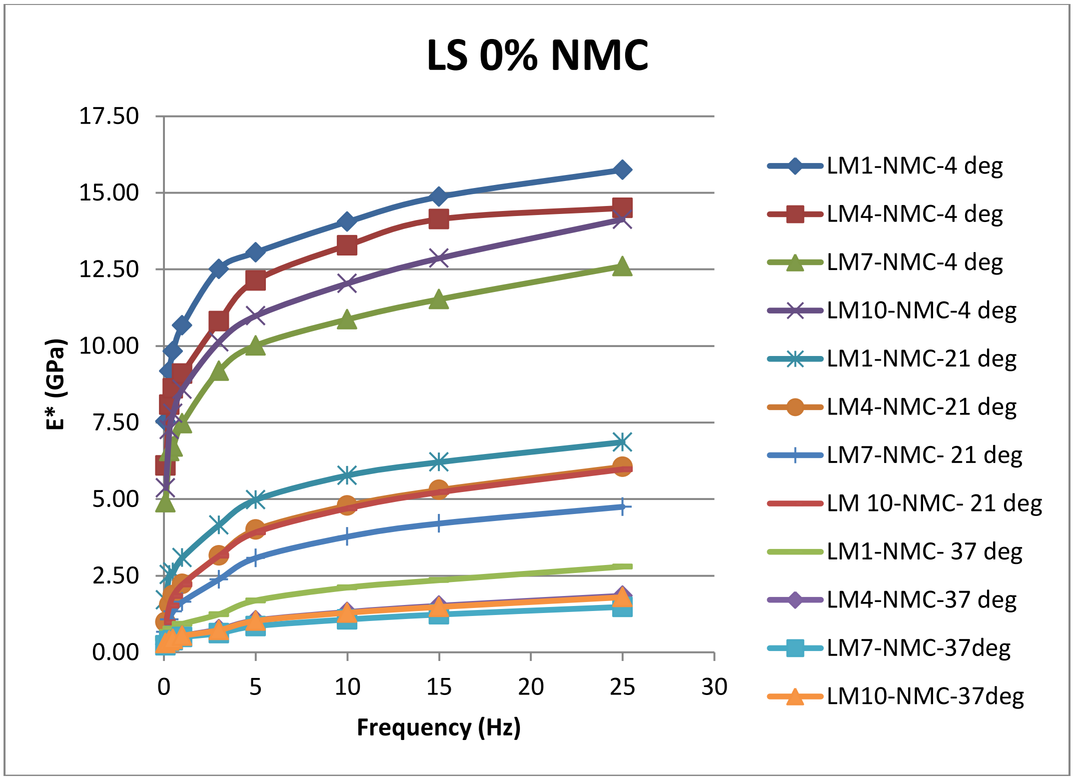


Figure 8.6. Limestone mixtures without RAP and *not* moisture-conditioned

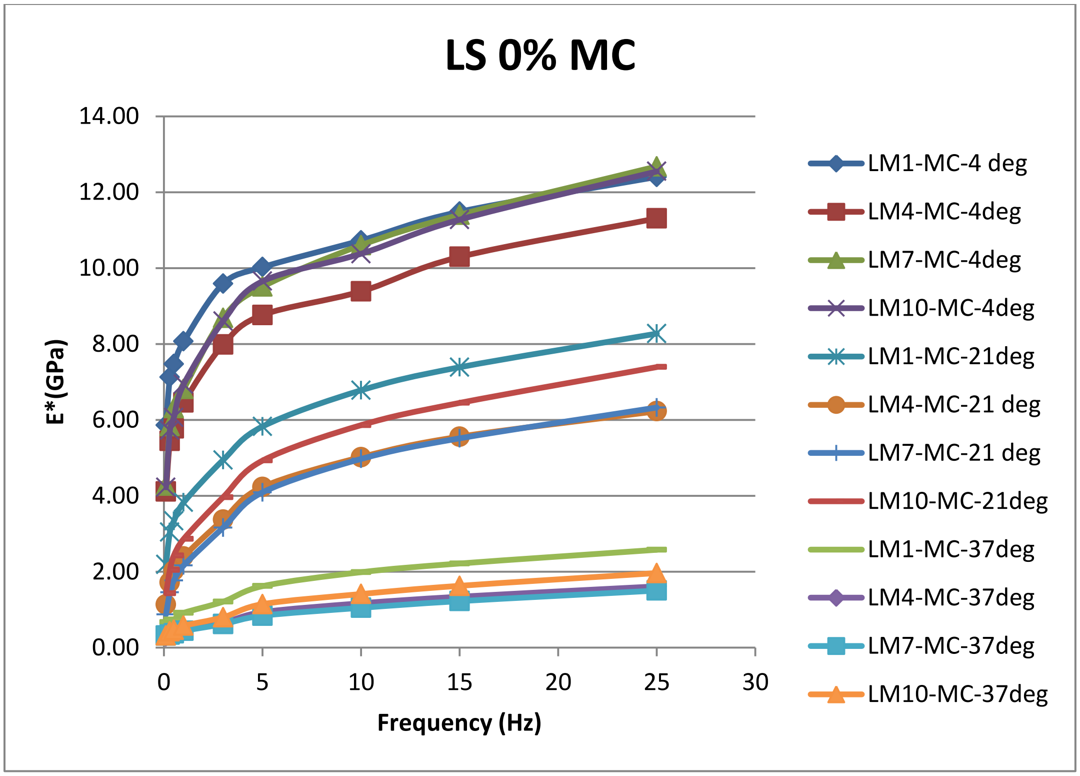


Figure 8.7. Limestone mixtures without RAP and moisture-conditioned

The behavior of mixtures prepared with limestone aggregate and incorporating 30% recycled asphalt pavement (RAP) is illustrated in Figure 8.8. The trend exhibited by the specimens of this subgroup is similar to that shown by LS 0% NMC sub group. The similarities lie in the fact that mostly the control mixture, LM 3 recorded the highest dynamic modulus at a given curing temperature and frequency. Moreover, another feature of similarity with LS 0% NMC subgroup is the superiority of the performance of the Advera® mixture, LM6 over mixtures comprising other WMA additives which is particularly evident in specimens cured at 21° and 37°C. Differences in dynamic modulus values among the different mixtures tested at the same temperature are more noticeable at higher test frequencies.

Alternatively, the dynamic modulus plot against frequency for limestone mixtures prepared with limestone aggregate and 30% recycled asphalt pavement (RAP) and was subjected to moisture conditioning, LS 30% MC is shown in Figure 8.9. The control mixture LM3 exhibits the highest dynamic modulus values for different curing temperatures and a wide frequency range. Asphalt mixture incorporating Evotherm®, LM9 has displayed the highest dynamic modulus among mixtures incorporating WMA technologies with the mix prepared with Sasobit®, LM12 is consistently registering the lowest values at a given test frequency.

For mixtures prepared with limestone aggregates, the control mixture prepared without the addition of any WMA additive consistently displayed higher dynamic modulus values than the other mixtures. When the mixtures were not subjected to moisture conditioning, the asphalt mixture prepared with Advera®, such as LM4 and LM6, represents the second-highest dynamic modulus values at different test temperatures. On the other hand, the trend of asphalt mixture including limestone aggregate and 0% recycled asphalt pavement that were moisture-conditioned was less consistent than the mixture containing the Sasobit®, which recorded the second-highest dynamic modulus for the LS 0% RAP MC subgroup. Conversely, for mixtures prepared with 30% recycled asphalt pavement that were subjected to moisture conditioning, the LS 30% RAP MC subgroup Evotherm® mixture displayed the second-highest dynamic modulus with the Sasobit® mixture having the lowest.

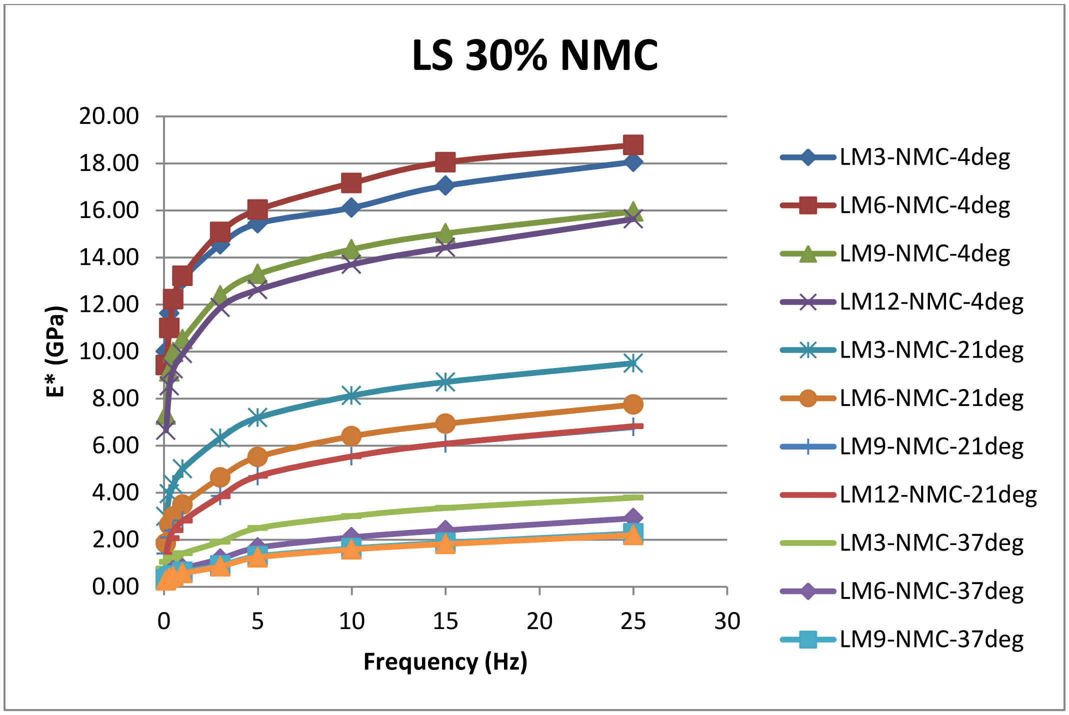


Figure 8.8. Limestone mixtures with 30% RAP and *not* moisture-conditioned

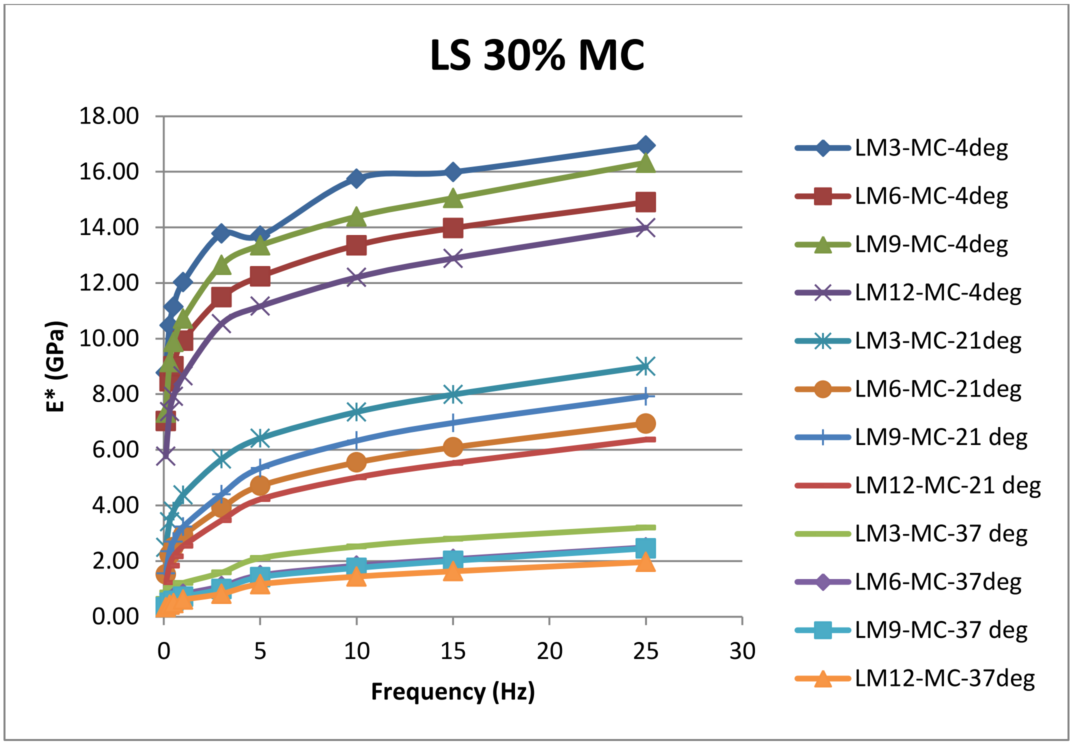


Figure 8.9. Limestone mixtures with 30% RAP and moisture-conditioned

The dynamic modulus test was conducted on 16 asphalt mixtures to investigate the suitability of the performance of three WMA technologies with respect to the incorporation of different aggregate types, recycled asphalt pavements (RAP) and susceptibility to moisture. The 16 mixtures are subdivided into four main groups; the first set incorporating limestone and no RAP, the LS 0% RAP group, the second set prepared using limestone and 30% RAP, LS 30% RAP, the third set prepared using quartzite without incorporating RAP and the final group was prepared with quartzite and 30% RAP.

For specimens prepared with quartzite aggregate without the inclusion of RAP and without subjecting the specimens to moisture conditioning, the dynamic modulus trend followed was similar to that observed in the LS 0% NMC group. The asphalt control mix that did not incorporate any WMA technologies QZ13 recorded the highest dynamic modulus at various curing temperatures followed by the Advera® specimens of QZ 15 as shown in Figure 8.10.

Alternatively, the QZ 0% MC specimens prepared with quartzite aggregate and were subjected to the moisture conditioning procedure stipulated in AASHTO T-283 are shown in Figure 8.11. The control mixture QZ13 registered the largest dynamic modulus values with the exception of the specimens tested at 4°C where the Evotherm® mix QZ 17 has higher dynamic modulus values. As the temperature increased, the dynamic modulus expectedly decreased at various frequencies and the variations between the E* values became smaller.

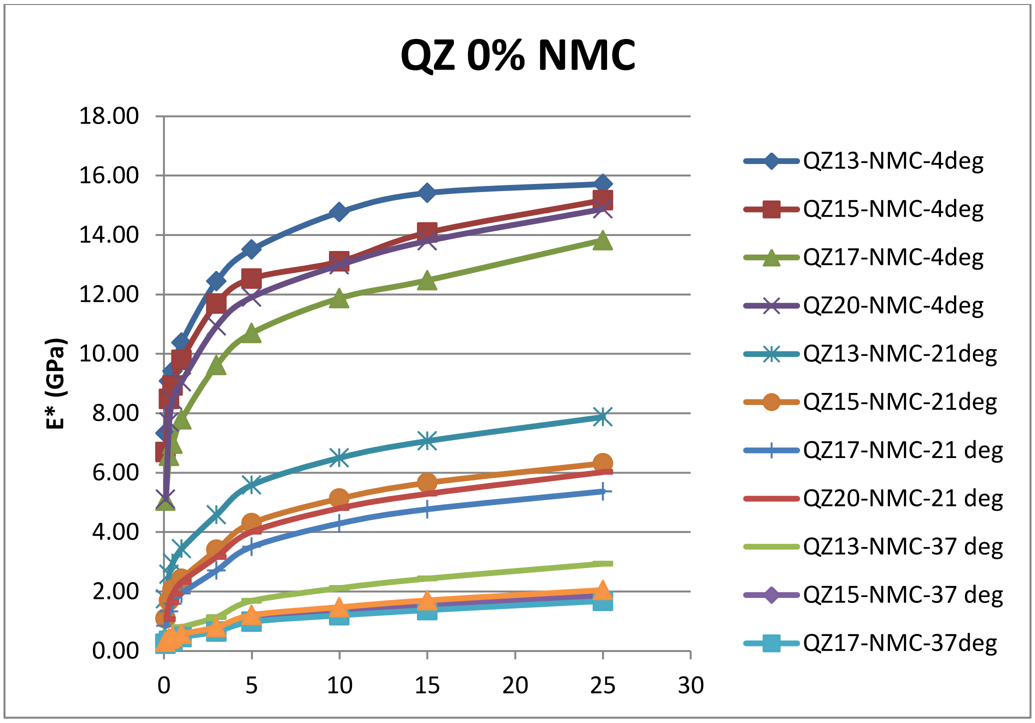


Figure 8.10. Quartzite mixtures with 0% RAP and *not* moisture-conditioned

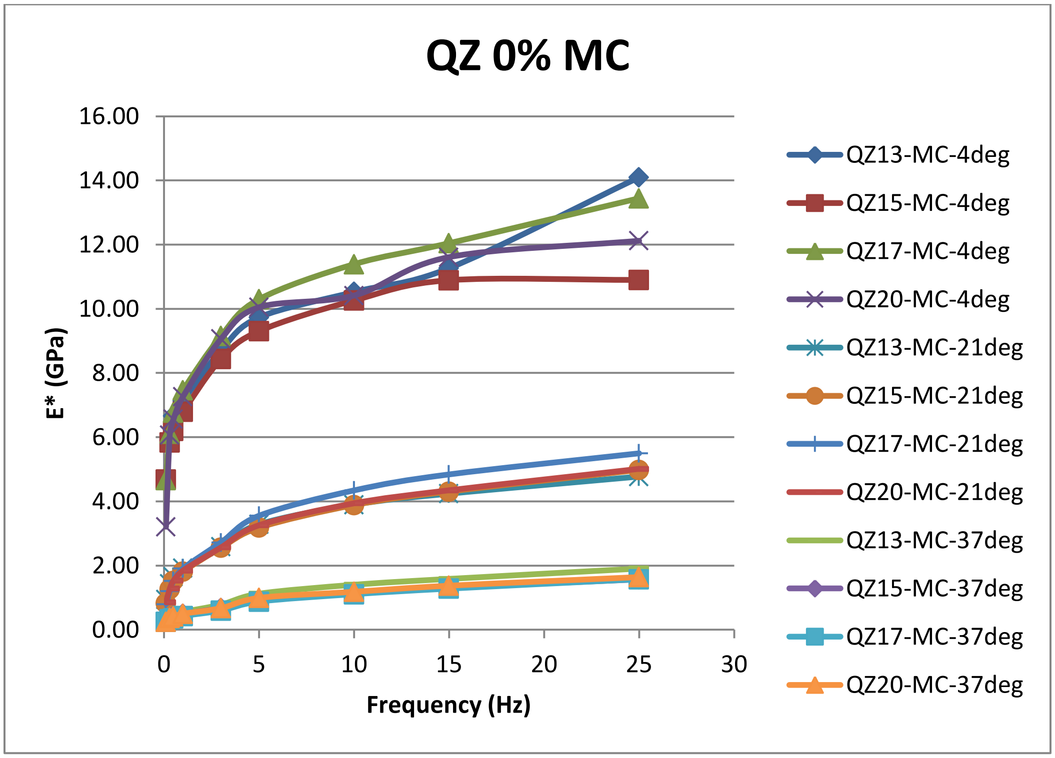


Figure 8.11. Quartzite mixtures with 0% RAP and moisture-conditioned

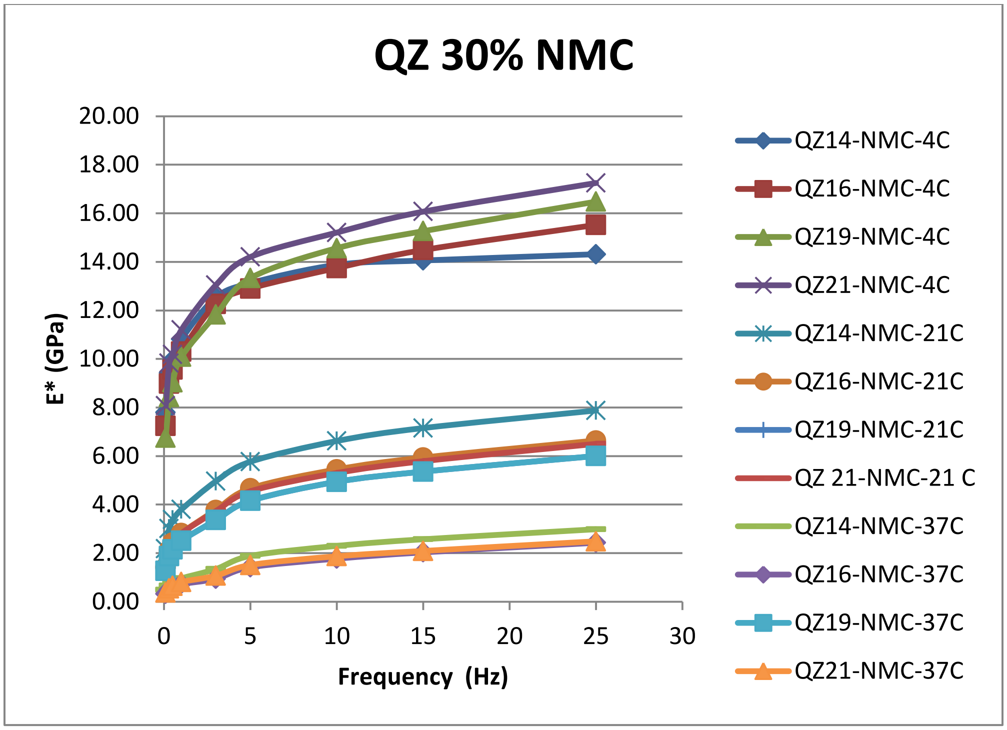


Figure 8.12. Quartzite mixtures with 30% RAP and *not* moisture-conditioned

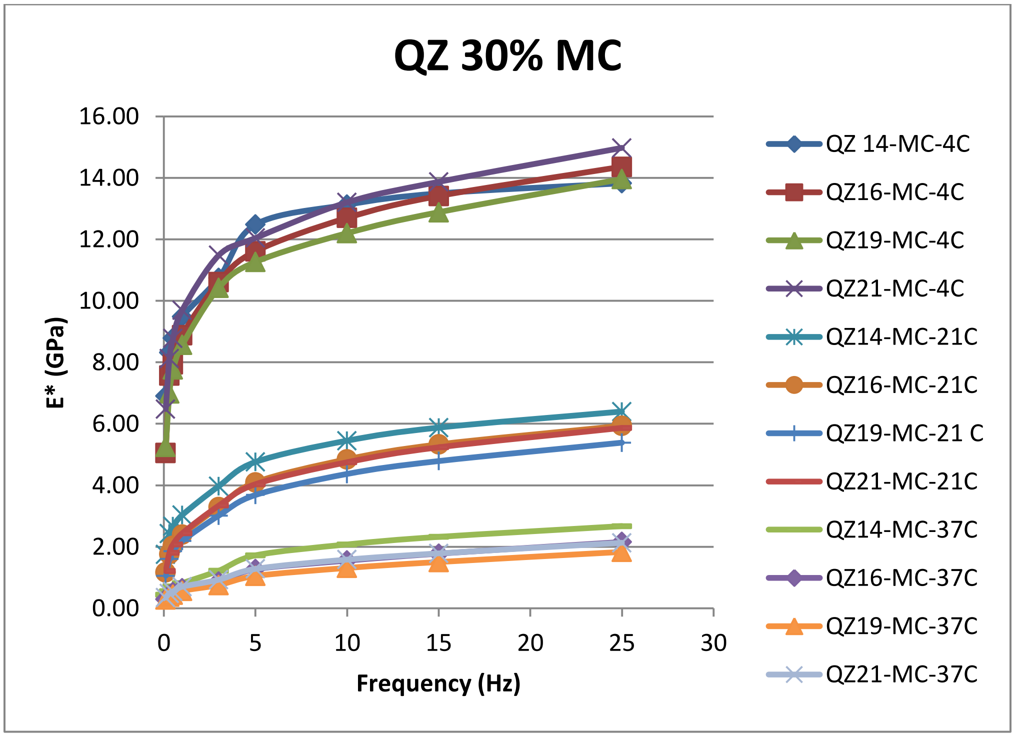


Figure 8.13. Quartzite mixtures with 30% RAP and moisture-conditioned

On the other hand, the dynamic modulus plot versus frequency of asphalt mixtures prepared with quartzite aggregates in addition to a 30% RAP and were not moisture conditioned, QZ 30% NMC is shown in Figure 8.12. With the exception of the specimens tested at 4°C, where the Sasobit® mixture QZ21 recorded the highest E* values, the control mix specimens, QZ 14 were the highest. In the same way, the specimens prepared with quartzite aggregates with the inclusion of 30% and were moisture conditioned, QZ 30% MC exhibit a similar trend to QZ 30% NMC specimens as illustrated in Figure 8.13.

8.3 Dynamic Modulus Master Curves

Master curves can be constructed for either the dynamic modulus or phase angle of asphalt mixtures using the time-temperature superposition principle based on the simple visco-elastic nature of the asphalt mixtures. Master curves are developed by shifting the dynamic modulus or the phase angle of the asphalt mixture along the frequency axis at a desired temperature or frequency forming a single curve that characterize the behavior of the mix at different temperatures and loading rates.

Typically, the dynamic modulus values at various temperatures are shifted at a reference temperature, usually 70°F (21°C) until the curves representing each temperature merge into a smooth single function. Master curves are generally modeled mathematically by a sigmoidal function shown as:

$$\text{Log } |E^*| = \frac{\delta+\alpha}{1+e^{\beta+\gamma(\log tr)}} \tag{8-1}$$

where

t_r = loading time at reference temperature

δ = minimum value of E*

$\delta+\alpha$ = maximum value of E*

β, γ = parameters describe the shape of the sigmoidal function

α = variable which is a function of gradation

The shift factors of the temperatures shifted to the reference temperature can be described by the following equation:

$$a(T) = t/t_r \tag{8-2}$$

where

a(T) = shift factor, as a function of temperature

t = loading time during test

t_r = loading time at reference temperature

In this study, the master curves were constructed by employing a non-linear curve fitting technique using Microsoft Excel Solver^{TM}. Using this approach, the parameters that give the best fit of data using the equations above were determined for various data sets by minimizing the sum of the squared difference between the predicted and observed values of E*. Master curves for all mixtures prepared in this study are shown in Appendix G. Figures 8.14 through 8.21 exhibit the trends shown by the master curves of the 16 mixtures investigated for their dynamic modulus behavior. The 16 mixtures are subdivided according to type of coarse aggregate incorporated, recycled asphalt pavement percentage and whether the samples were moisture conditioned.

In Figures 8.14 and 8.15, the master curves for the limestone asphalt mixtures prepared without the incorporation of RAP are shown. In Figure 8.12, at high frequencies, it can be observed that control mix LM1 exhibit higher E* values than LM4, LM7 and LM10 mixtures that incorporate Advera®, Evotherm® and Sasobit® WMA additives respectively. This trend changes slightly at the low frequencies as LM7 and LM10 have higher E* values than the control mix. Master curves of specimens of the same mixtures that were moisture conditioned are shown Figure 8.13. Mostly, the trend followed in this figure is similar to the non-moisture conditioned set illustrated in Figure 8.14 as the control mix LM1 recorded the highest E* values and LM7 incorporating Evotherm® was mostly showing the lowest E* values. The behavior of LM10 incorporating Sasobit® is a notable exception between the two sets as it was relatively the highest at high frequencies in the moisture conditioned set yet it had the lowest E* at low frequencies.

WMA additives have been reported to facilitate the incorporation of high percentages of RAP into asphalt mixtures. Hence, the effect of incorporating 30% RAP in asphalt mixtures prepared using limestone coarse aggregate is studied and the behavior of these mixtures is summarized in Figures 8.16 and 8.17 for non-moisture conditioned and moisture conditioned specimens, respectively. In the case of the non-moisture conditioned specimens, the control mix LM3 is consistently showing higher values of dynamic modulus compared to other mixtures incorporating WMA additives at different frequencies as shown in Figure 8.16. Moisture conditioned samples on the other hand reveal a different pattern as the master curve of the control mix LM3 is much closer to the master curves of LM6, LM9 and LM 12 incorporating Advera®, Evotherm® and Sasobit® respectively as shown in Figure 8.17.

For asphalt mixtures prepared with quartzite aggregate without including any RAP, the master curves of the four mixtures for the non-moisture and the moisture conditioned samples are illustrated in Figures 8.18 and 8.19, respectively. The trend displayed in those two figures are similar to that followed by the limestone group LS 0% RAP mixtures in Figures 8.14 and 8.15. Similarly, for the non-moisture conditioned mixtures shown in Figure 8.17, the control mix LM 13 displays higher E* values particularly at frequencies in the middle range. The moisture conditioned set, however, followed a different pattern as the master curves for all fours mixtures LM 13, LM15, LM 17 and LM 20, were very close to each other at high and mid frequencies.

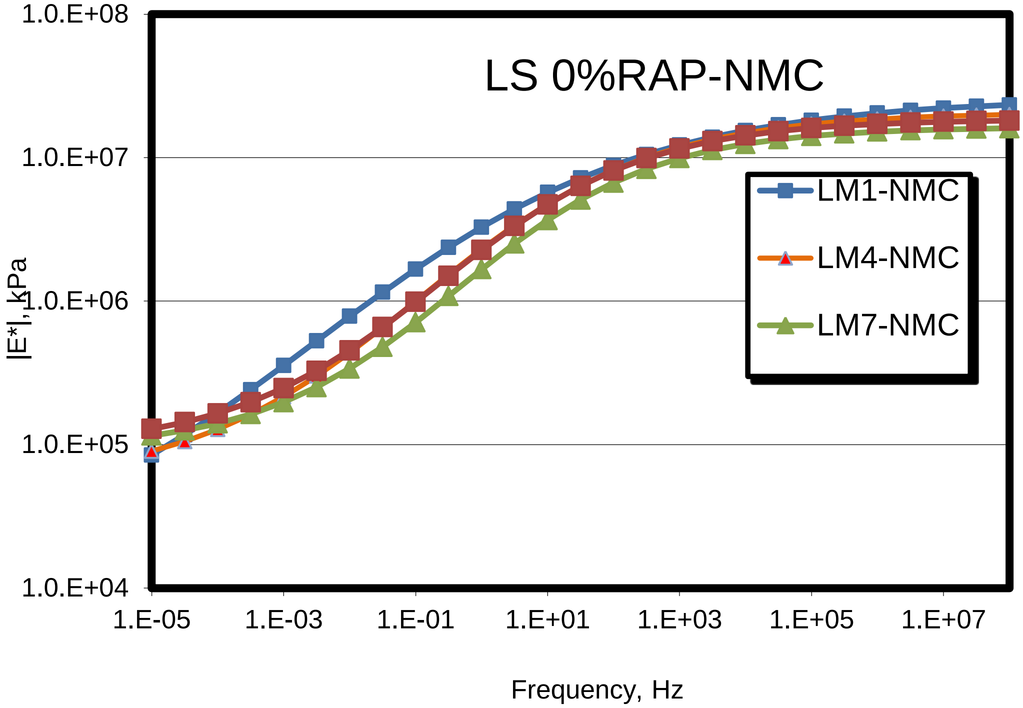


Figure 8.14. Master curves of non-moisture-conditioned limestone mixtures with 0% RAP

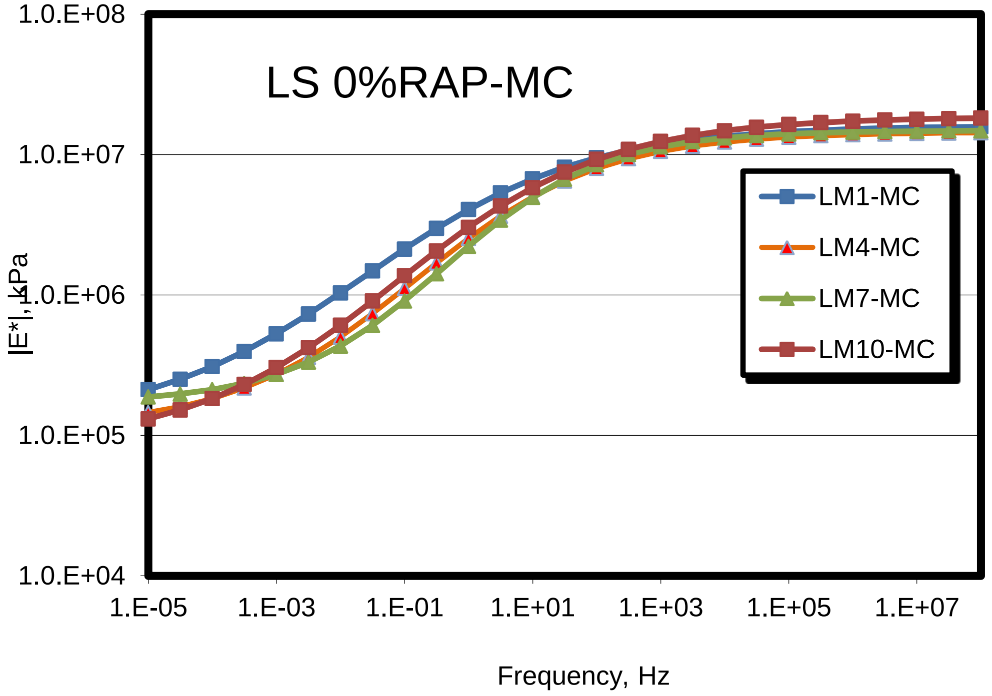


Figure 8.15. Master curves of moisture-conditioned limestone mixtures with 0% RAP

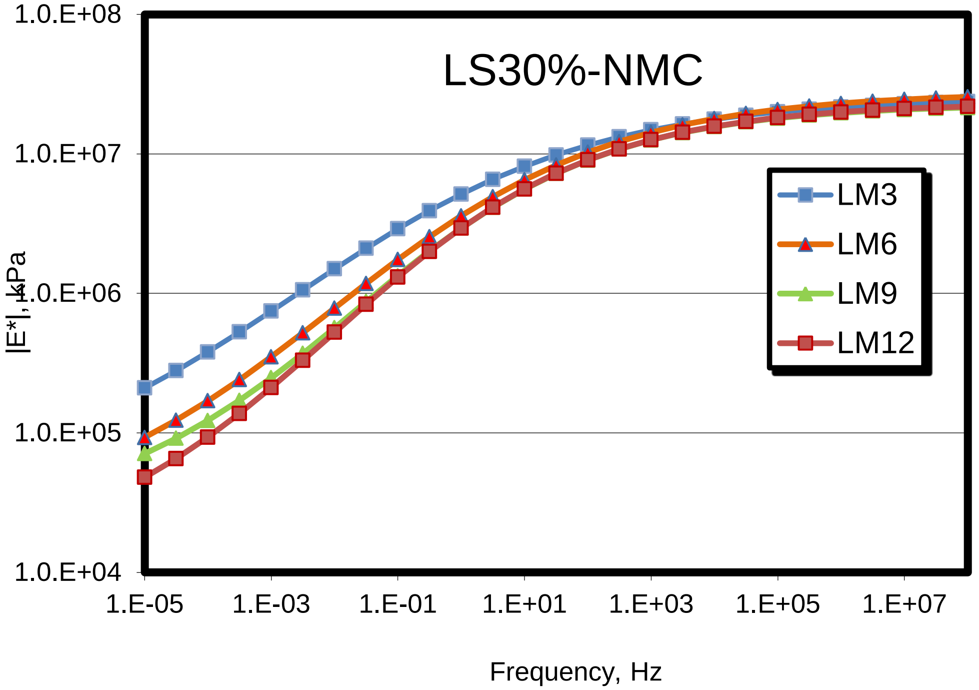


Figure 8.16. Master curves for non-moisture-conditioned limestone mixtures with 30% RAP

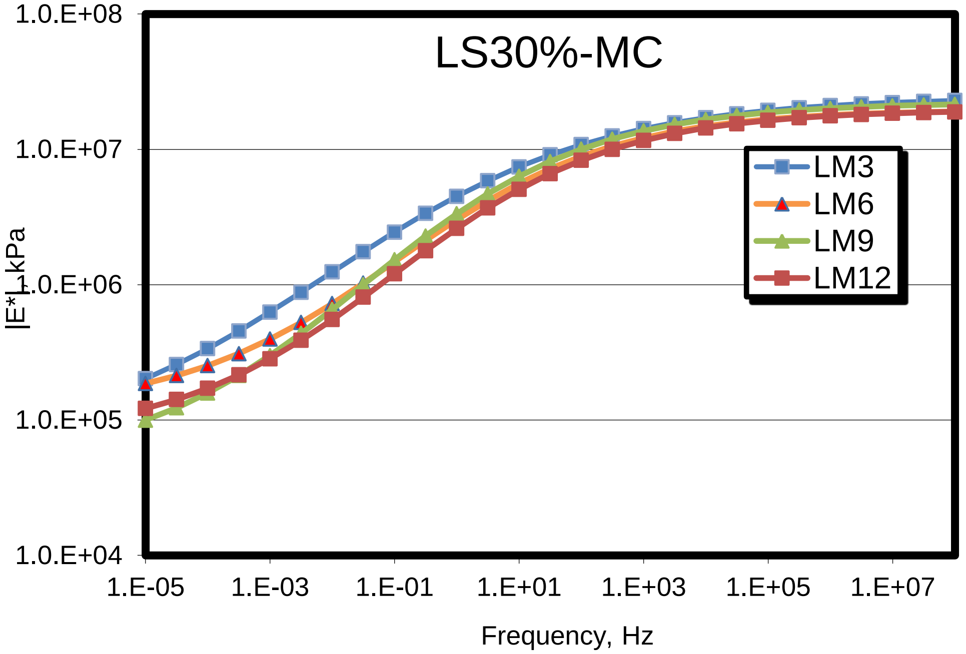


Figure 8.17. Master curves for moisture-conditioned limestone mixtures with 30% RAP

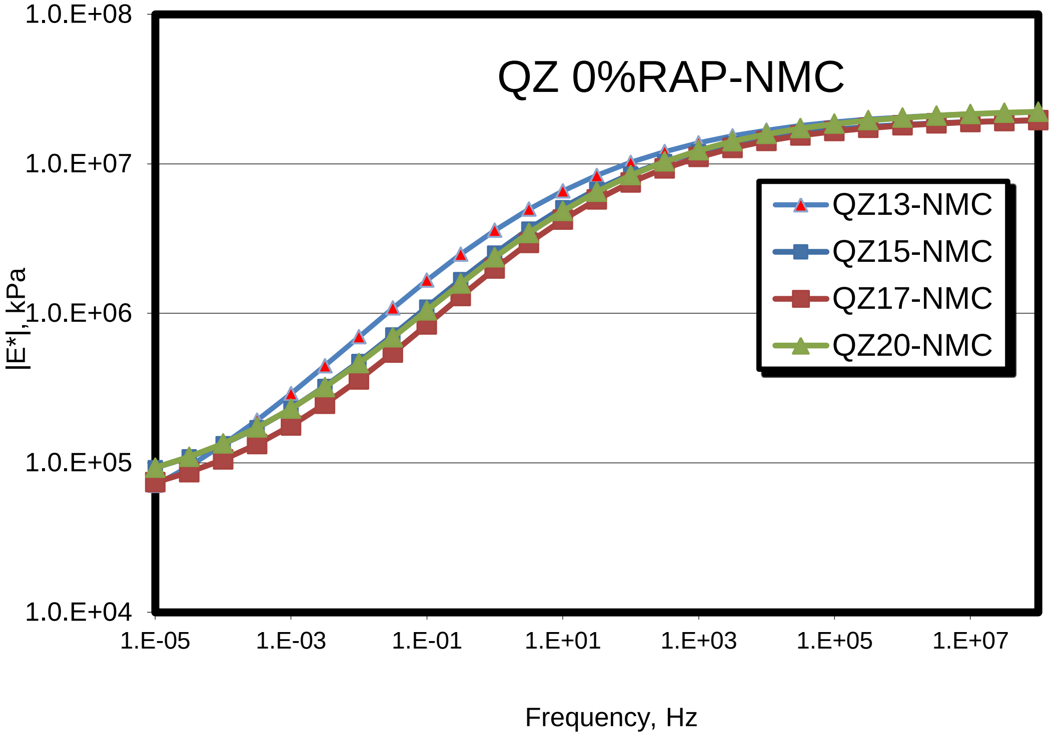


Figure 8.18. Master curves for non-moisture-conditioned quartzite mixtures with 0% RAP

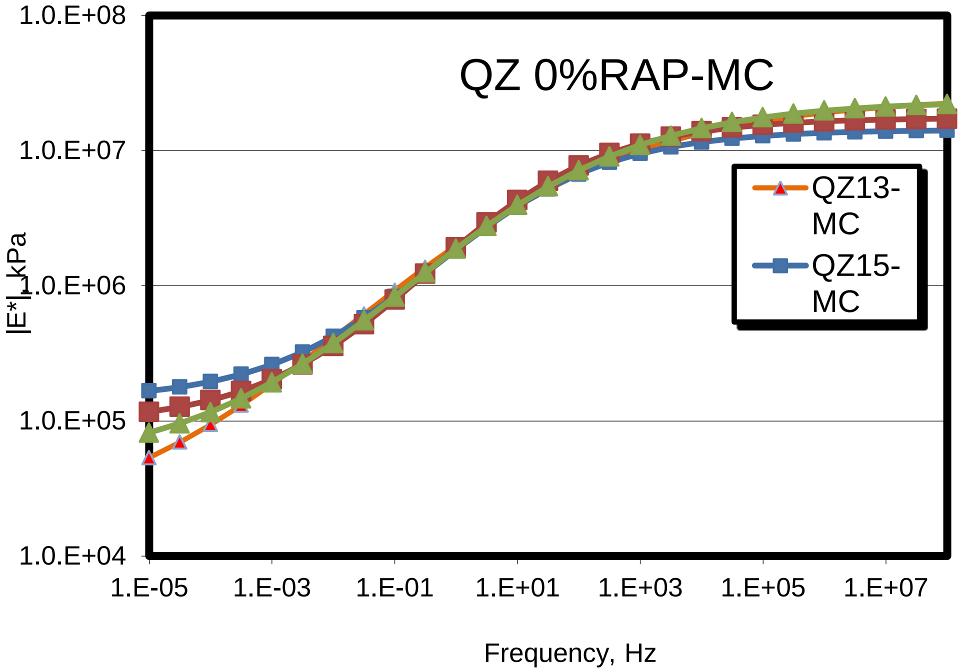


Figure 8.19 Master curves for moisture-conditioned quartzite mixtures with 0% RAP

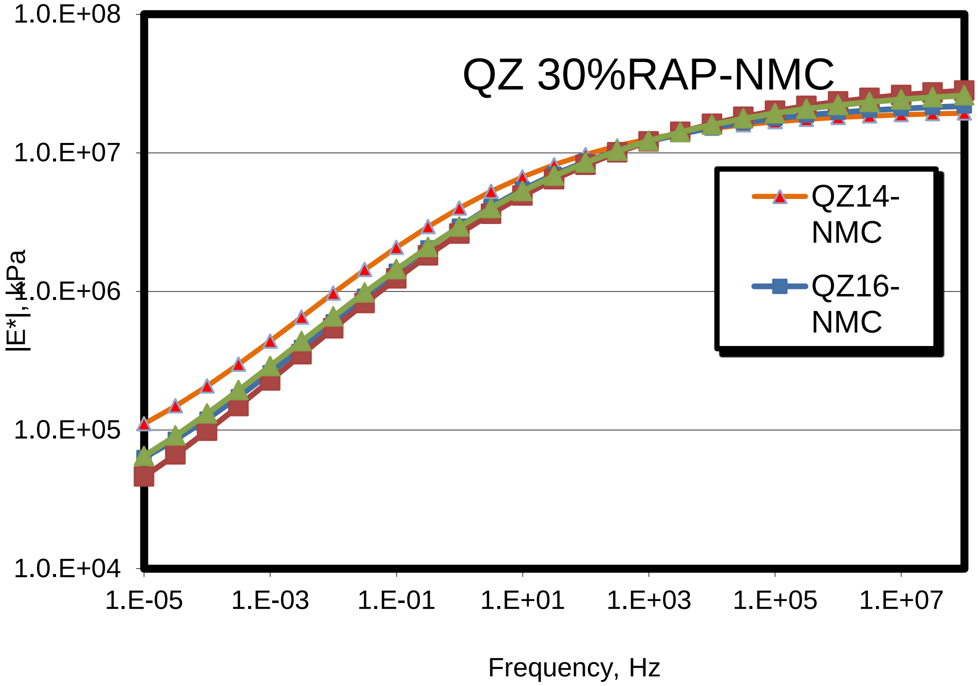


Figure 8.20. Master curves of non-moisture-conditioned quartzite mixtures with 30% RAP

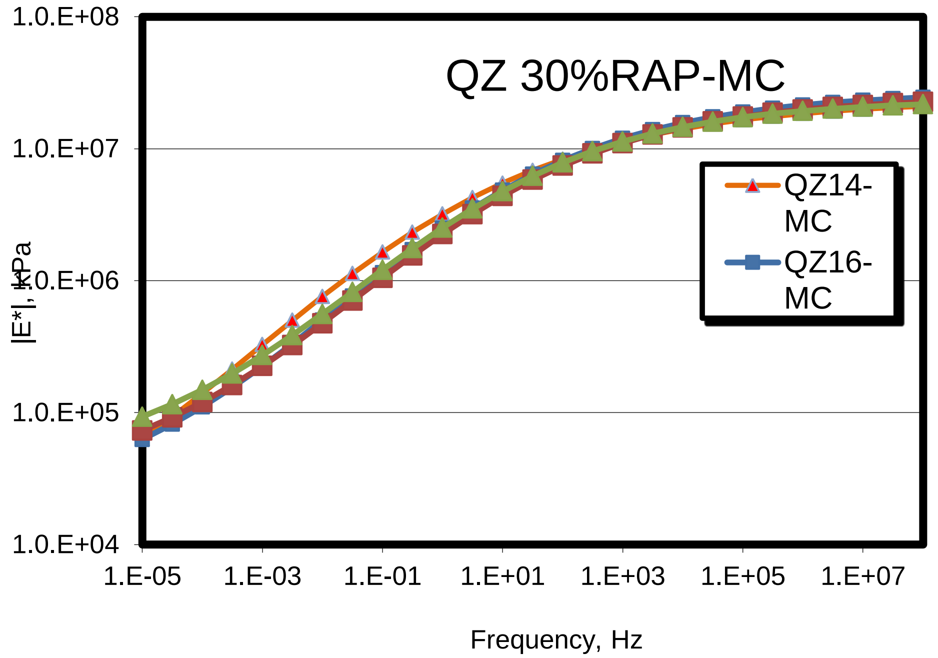


Figure 8.21. Master curves of moisture-conditioned quartzite mixtures with 30% RAP

8.4 Statistical Analysis

In order to examine the effect of different variables (factors) on the dynamic modulus values of the 16 mixtures under investigation, a statistical analysis is regarded as a viable aide towards that objective. The effect of aggregate type, RAP content, WMA technology and moisture conditioning are studied to identify the most significant factors.

Analysis of Variance

The dynamic modulus test data were analyzed using ANOVA as a whole. Hence, several factors were deemed significant in affecting the dynamic modulus results as shown in Table 8.2. It can be deduced from the table that the WMA technologies incorporated had a significant effect on the dynamic modulus data. Using the Tukey-Kramer multiple comparison technique to investigate the significance of each WMA technology compared to the control mix, it was observed that all three technologies are statistically significant compared to the control mix with respect to dynamic modulus test results. The Tukey-Kramer technique also revealed that the difference between Advera and Sasobit and Advera and Evotherm is statistically insignificant. On the other hand, the dynamic values of the Evotherm mixtures were significantly different from the mixtures incorporating Sasobit.

Table 8.2. ANOVA analysis of dynamic modulus data

Source	DF	Type I SS	Mean Square	F-statistic	Pr>F (p-value)
Model	16	5.1428509E16	1.343E15	3.2142818E15	<0.0001
Agg	1	41331257024	41331257024	0.01	0.9207
WMA	3	8.9366194E13	2.9788731E13	7.15	<0.0001
RAP	1	3.4224586E14	3.4224586E14	82.12	<0.0001
Moist	1	1.2735349E14	1.2735349E14	30.56	<0.0001
Temp	2	4.7354894E16	2.3677447E16	5680.93	<0.0001
Freq	8	3.514608E15	4.39326E14	105.41	<0.0001
Error	847	3.5301961E15	4.167882E12		
Total	863	5.4958705E16			

Linear and multiple regression models were constructed to select the most important variables that are necessary to predict the dynamic modulus value. The application of these models was preceded with a preliminary screening process using three different techniques: stepwise method, forward selection, and backward elimination. In the analysis, the aggregate type, WMA technology, moisture conditioning were regarded as categorical variables. On the other hand, RAP%, temperature and frequency were treated as quantitative variables.

The aggregate type variable was composed of two levels: 0 and 1 denoting limestone and quartzite, respectively. The WMA is represented with two variables, WMA1 and WMA2. For WMA1, Advera and Evotherm mixtures were denoted 1 and for mixtures without Advera and Evotherm denoted 0 as the multiple comparison test deemed the difference in the dynamic modulus values statistically insignificant. WMA2 was denoted 0 for non Sasobit mixtures and 1 for Sasobit mixtures. Lastly, for moisture conditioning, non-conditioned samples were denoted by 0 and conditioned samples were denoted by 1.

Linear Regression Model

The stepwise approach identified four variables as significant at 0.05: temperature, frequency, RAP content, and moisture conditioning (as compared to non-moisture conditioning). The Linear regression model output is shown in Table 8.3. Warm mix variable WMA1 is deemed significant with a p-value of 0.0015. On the other hand, WMA2 is deemed insignificant albeit at a p-value of 0.05. The forward selection technique identified the same variables as significant.

Table 8.3. Linear regression model output

Variable	Parameter Estimate	Standard Error	t-value	Pr>F
Intercept	-3737742	256944	-14.55	<.0001
RAP	41959	5699.74	7.36	<.0001
Moisture	-767854	170992	-4.49	<.0001
Temperature	542572	6345.14146	85.51	<.0001
Frequency	223347	10589	21.09	<.0001
WMA 1	-784096	209422	-3.74	**0.0002**
WMA 2	-474584	241819	-1.96	**0.05**

The optimum linear regression model was identified through a number of parameters: Cp, AIC and BIC using SAS^{TM} software package. Cp is a regression statistic criterion used to identify the best variables to fit a model from a pool of variables in regression analysis. According to Montgomery et al. (2003), the regression model with the lowest Cp or with Cp≈ p where p is the number of variables in the regression model, should be regarded as the best model. Applying such a concept, a linear regression model with five variables; temperature, frequency, RAP, moisture, WMA1 and WMA2 is selected as the most appropriate to model the dynamic modulus data in a linear regression model with the lowest Cp value of 6.0065 and the highest R^2 at 0.9015. This model is illustrated as this equation:

$$y = -3737742 + 41959x_2 - 784096x_3 - 474584x_4 - 767854x_5 + 542572x_6 + 223347x_7 \quad (8\text{-}3)$$

where

y = dynamic modulus in Pa

x_1 = aggregate type

x_2 = RAP content in percent

x_3 = with WMA technology (0 for Control and Sasobit, 1 for Advera and Evotherm)

x_4 = with WMA technology (0 for Control, Advera, and Evotherm, 1 for Sasobit)

x_5 = moisture conditioning status (1 for moisture conditioning and 0 for no moisture conditioning)

x_6 = test temperature of mixture, in °C

x_7 = dynamic test frequency in Hz

The outcome of this regression model is reasonable as temperature and frequency are expected to be influential factors in impacting the values of dynamic modulus. Moreover, the percentage of recycled asphalt pavement, RAP, content is expected to be a significant factor in affecting the performance of asphalt mixtures. The moisture conditioning procedure is regarded as a factor that affected the dynamic modulus values which is logical as illustrated by Figures 8.16 to 8.21

as the conditioning affected the dynamic modulus performance at various frequency ranges and temperatures. Finally, the incorporation of WMA is a significant factor.

A further analysis of the variables that were deemed significant is necessary to determine the trends followed with respect to the dynamic modulus values and to detect the presence of any interaction between these factors. In order to achieve this objective, a multiple regression analysis was conducted to capture the presence of any significant interactions.

Multiple Regression Model

A multiple regression model was developed to examine whether it would offer a better representation of the impact of different variables on the dynamic modulus values. The full model developed comprised all the aforementioned seven variables in addition to interactions of the variables and the second degree effects of the variables and with the exception of the aggregate variable as the previous regression analysis deemed this variable comprehensively insignificant. The interaction between temperature and WMA, RAP and WMA and WMA and Moisture were investigated with the significant variables listed in Table 8.4.

Table 8.4. Multiple regression analysis of dynamic modulus test

Variable	Parameter Estimate	Standard Error	Type II SS	F-value	Pr>F
Intercept	-2850495	317091	4.763692E14	80.81	<.0001
WMA1	-866670	363908	3.343453E13	5.67	0.0175
WMA2	-474584	233627	2.432488E13	4.13	0.0425
RAP	-35625	11488	5.668462E13	9.62	0.0020
Temperature	515018	10618	1.386905E16	2352.75	<.0001
Frequency	223347	10231	2.809524E15	476.61	<.0001
Moisture	-767854	165200	1.273535E14	21.60	<.0001
Temperature*RAP	2728.89961	408.67956	2.628336E14	44.59	<.0001
Temperature*WMA1	-26759	12260	2.807989E13	4.76	0.0293

From the table, it can be observed that there are many factors that impact the dynamic modulus of the asphalt mixtures investigated most notably as expected, temperature, frequency and moisture conditioning. Of more interest are the effect of warm-mix asphalt and the effect of interactions between temperature and RAP content, temperature and WMA1 having p-values of <0.0001 and 0.0293, respectively.

Flow Number (Fn) Test Results

This test was conducted on 128 specimens representing 16 different asphalt mixtures. The output of this test include cycles to failure, displacement and strain at failure in addition to displacement and strain at flow number.

Flow number trends followed by the mixtures investigated are shown in Figures 8.22 through 8.25 for asphalt mixtures LS0%, LS30%, QZ0% and LS30%.

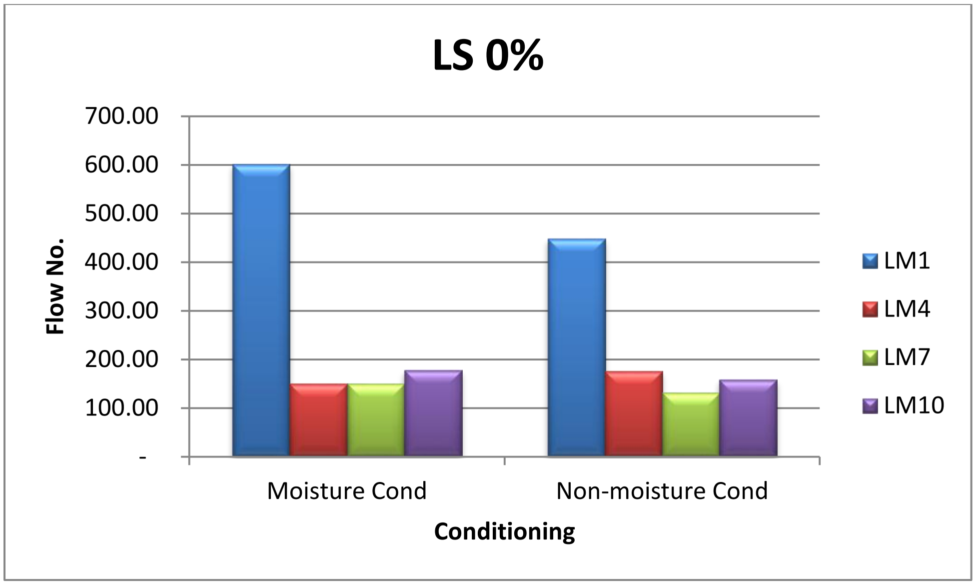


Figure 8.22 Flow number for LS 0% RAP mixtures

The control mixture LM1 exhibited in Figure 8.22 a significantly higher flow number than the following mixtures: LM4, LM7 and LM10 that incorporate Advera, Evotherm and Sasobit, respectively, indicating its superior resistance to permanent deformation. However, the incorporation of RAP at 30% increased the Fn considerably as observed in Figure 8.23 from 400-600 for LM1 to 3,000-3,500 for LM3. In the same way, Advera, Evotherm and Sasobit mixtures incurred an increase in its Fn albeit at much lower rate.

The same trend can be seen in the quartzite mixtures as specimens prepared with 0% RAP registered a significantly lower flow number than specimens with 30% RAP as shown in Figures 8.24 and 8.25, respectively. Moreover, the effect of moisture conditioning on flow number values is not clear as the data did not reveal any clear trend.

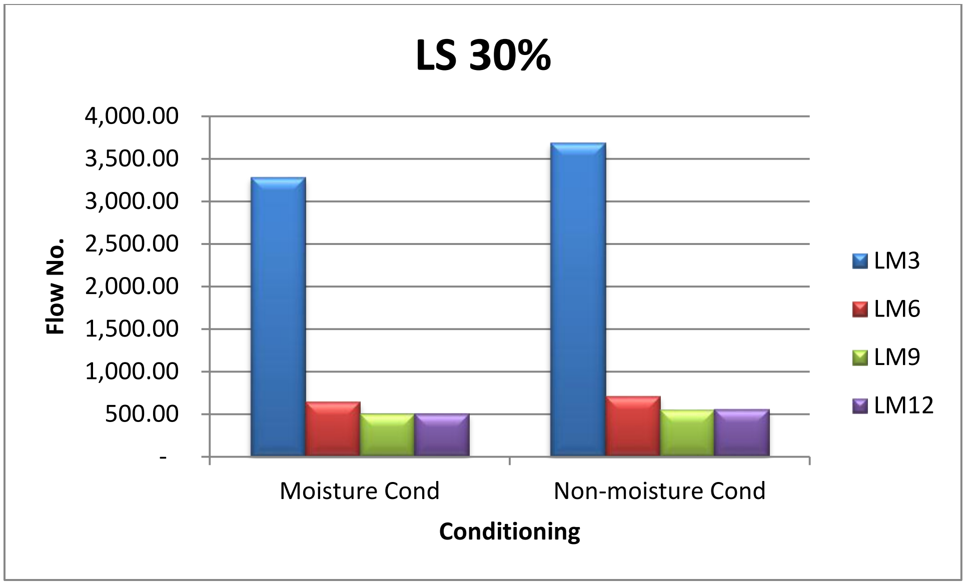


Figure 8.23 Flow number for LS 30% RAP mixtures

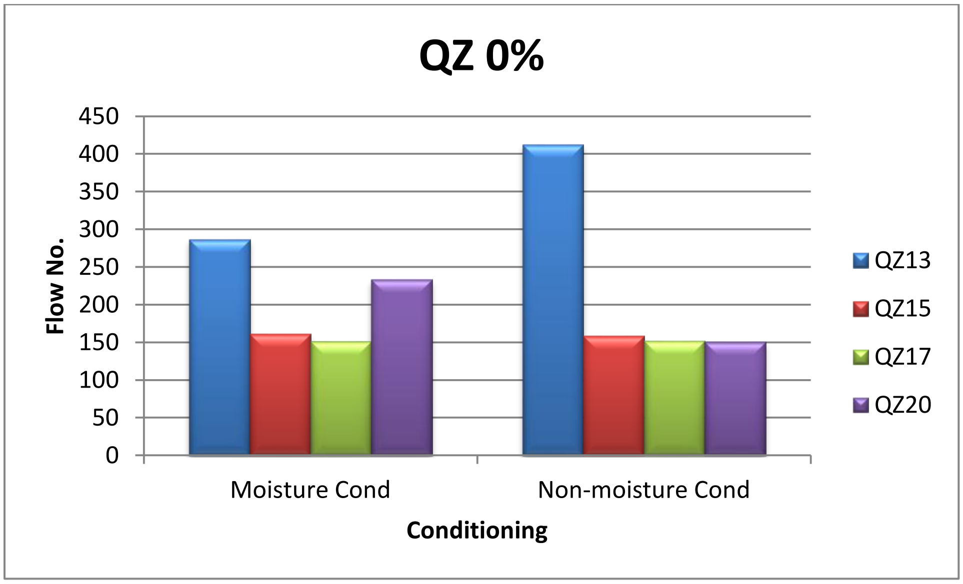


Figure 8.24. Flow number for QZ 0% RAP mixtures

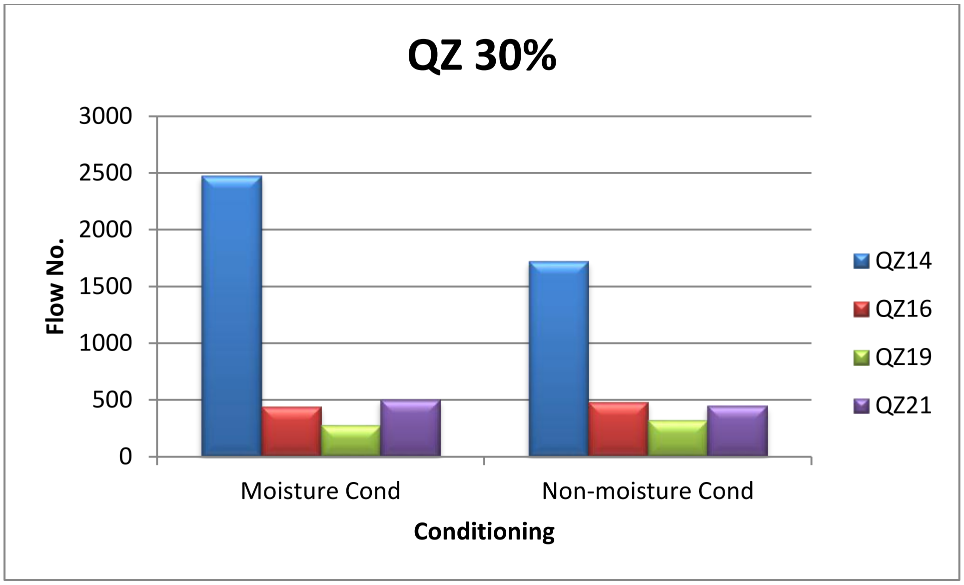


Figure 8.25. Flow number for QZ 30% RAP mixtures

Another parameter that helps in investigating the resistance of asphalt mixtures to permanent deformation is the strain incurred at flow number which indicates the magnitude of deformation that took place at the time at which the specimen is about to enter in the tertiary flow zone. The strain pattern followed by the investigated specimens is shown in Figures 8.26 to 8.29. The trends shown in these figures do not follow a regular pattern hence, a statistical analysis is thought to be effective in clarifying the strain behavior of the mixtures.

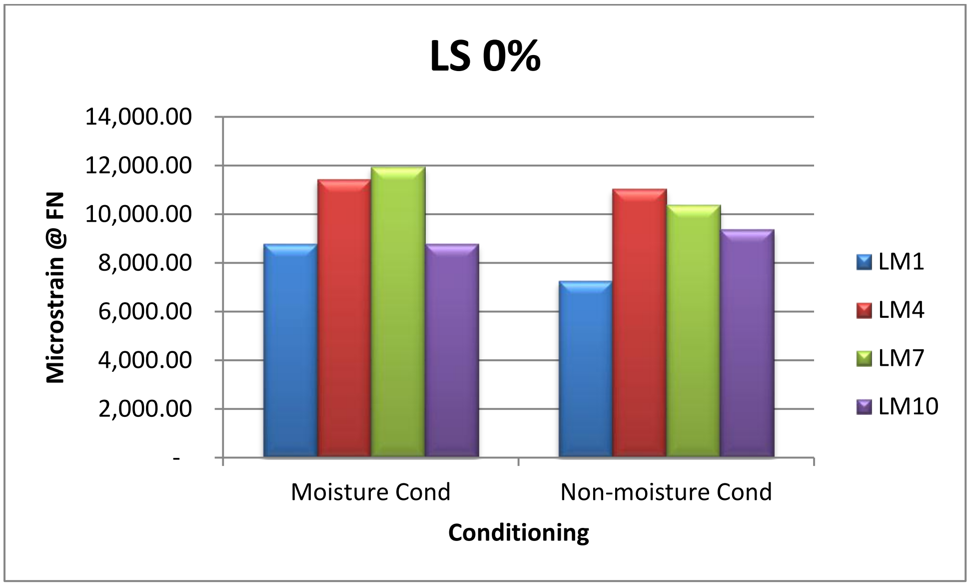


Figure 8.26. Microstrain at flow number for LS 0% RAP mixtures

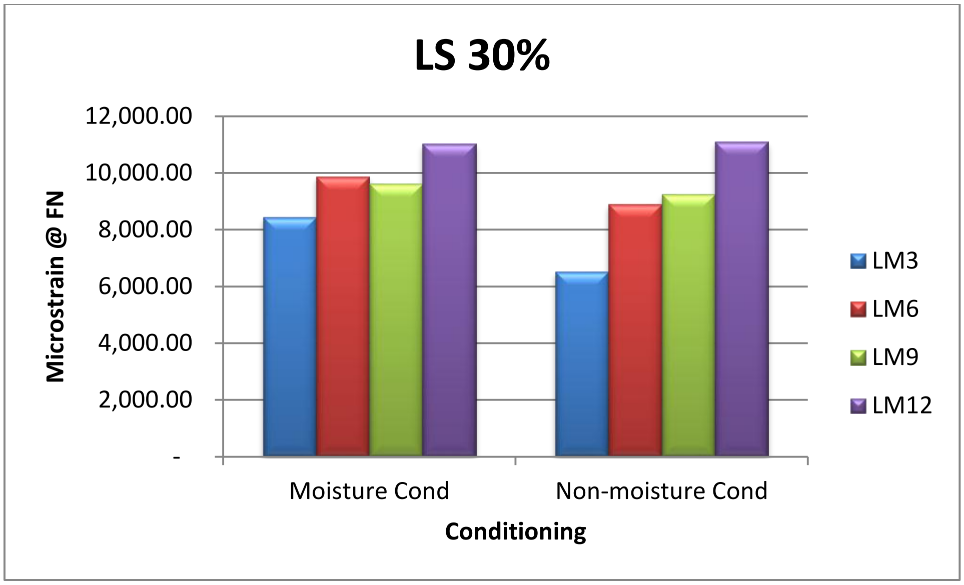


Figure 8.27. Microstrain at flow number for LS 30% RAP mixtures

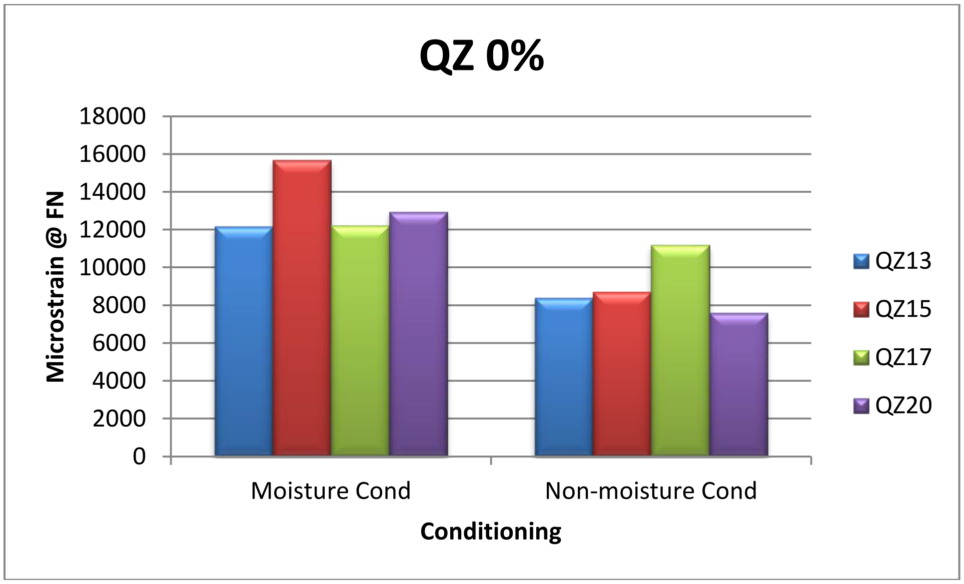


Figure 8.28. Microstrain at flow number for QZ 0% RAP mixtures

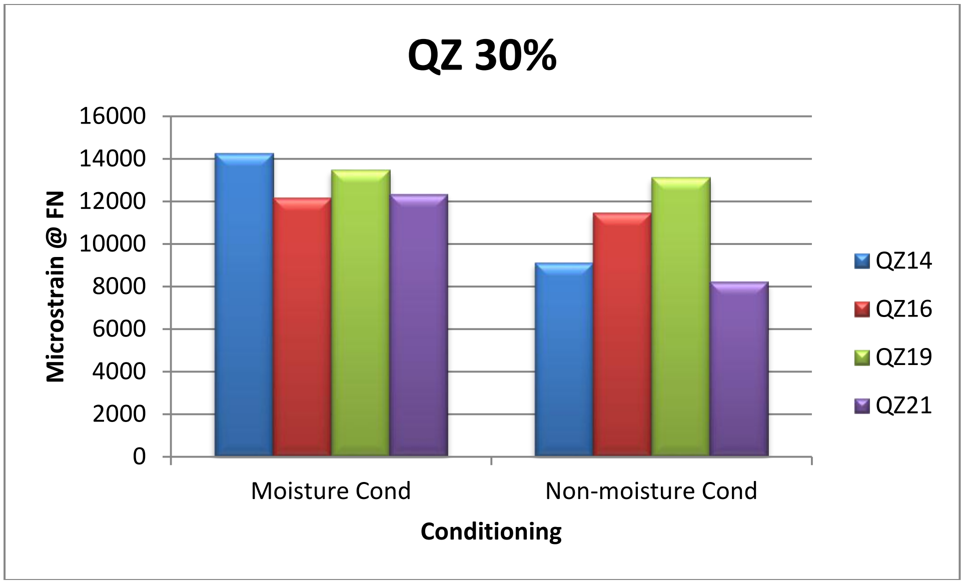


Figure 8.29. Microstrain at flow number for QZ 30% RAP mixtures

Plots of the main effects and the interaction of the factors under investigation on the flow number and strain are generated via MiniTab software package.

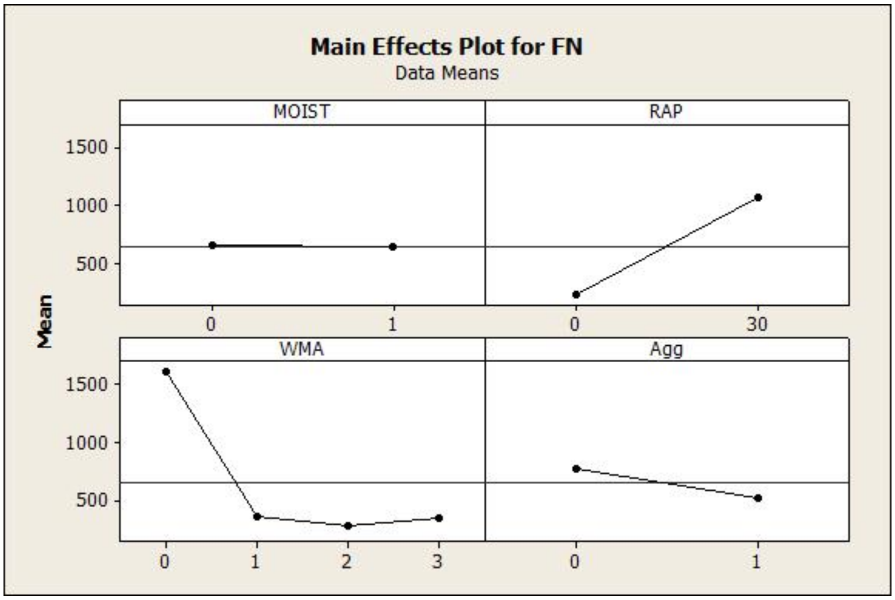


Figure 8.30. Main effect plots for flow number test

The plot illustrating the main effects on the flow number for the 16 mixtures investigated reveals the significant effect of warm-mix asphalt, RAP content, and, to a lesser degree, the aggregate type. A statistical analysis conducted using ANOVA gives a similar conclusion as shown in Table 8.5.

Table 8.5. ANOVA analysis for flow number test

Source	DF	Type I SS	Mean Square	F-statistic	Pr>F (p-value)
Model	12	22259356.20	1854946.35	18.42	<0.0001
Agg	1	515706.446	515706	5.12	0.0356
WMA	3	9941195.379	3313731.793	32.90	<0.0001
RAP	1	5635977.850	5635977.850	55.96	<0.0001
Moist	1	2354.581	2354.581	0.02	0.8801
Rap*WMA	3	6144238.455	2048079.485	20.33	<0.0001
Moist*WMA	3	19883	6627.829	0.07	0.9774
Error	19	1913677.41	100719.86		
Total	31	24173033.60			

Incorporating recycled asphalt pavement at 30% generally increased the flow number from around 500 cycles to above 1000 cycles possibly because of the increased stiffness added to the mix through the incorporation of the stiffer binder in the RAP. Using WMA, regardless of the technology used, lowered the flow number considerably and this raises concerns about the resistance of WMA mixtures to permanent deformation. A Tukey-Kramer multiple comparison analysis showed that all WMA technologies were significantly different from the control mixtures. Also, it proved that the differences among the flow numbers of WMA technologies were not significant. Finally, the quartzite mixtures had slightly lower flow numbers than the limestone mixtures. Figure 8.31 displays the interaction in between the factors and their effect on the flow number. The most notable interaction impacting the flow number is the one between WMA and RAP with the combination of control hot-mix asphalt and 30% RAP recording the highest flow number reinforcing the observation that RAP content is the most dominant factor in impacting flow number.

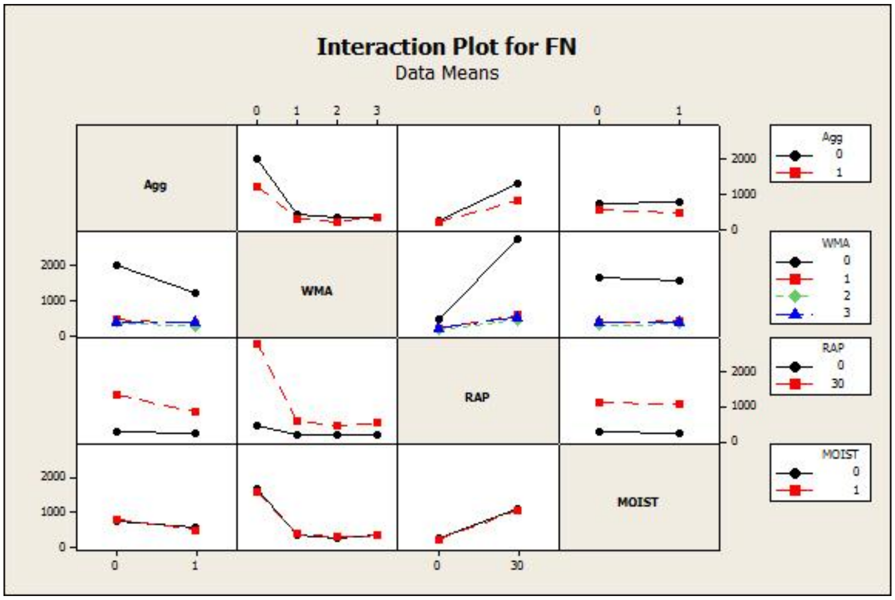


Figure 8.31. Interaction plot for flow number test variables

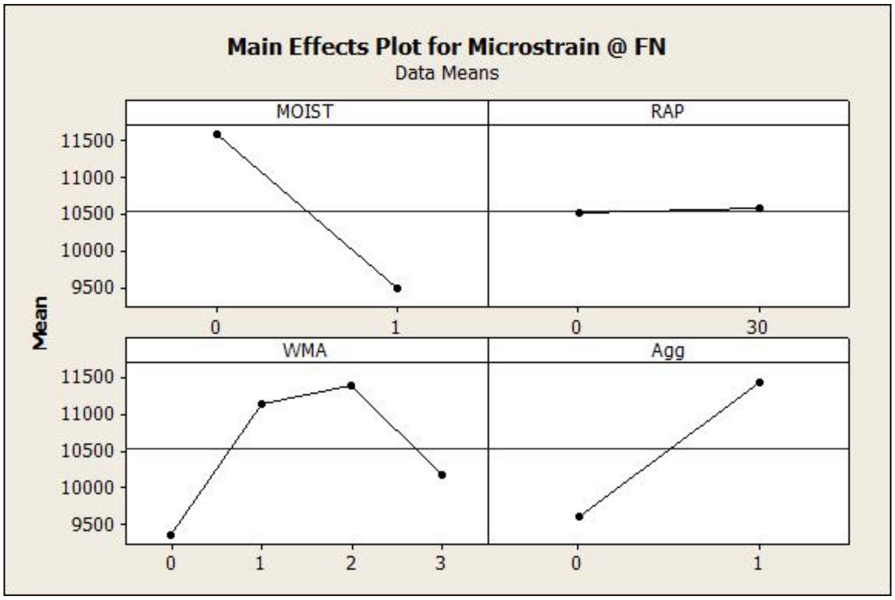


Figure 8.32. Main effects plot for microstrain at flow number

Figure 8.32 shows the main effects of the investigated factors on the strain induced in the specimen at flow number when tertiary flow is about to take place. Control mixtures predictably displayed lower strain at flow number than the three warm mix technologies with Evotherm and Advera recording the highest strain at about 11,500 microstrain. Moreover, the limestone mixtures registered lower strain values than the quartzite mixtures. In the same way, specimens that were moisture conditioned recorded significantly higher microstrain levels than non-moisture conditioned mixtures. Such an observation makes it really important to investigate the interaction between moisture conditioning and WMA to determine if WMA mixtures are more susceptible to moisture damage than mixtures without WMA.

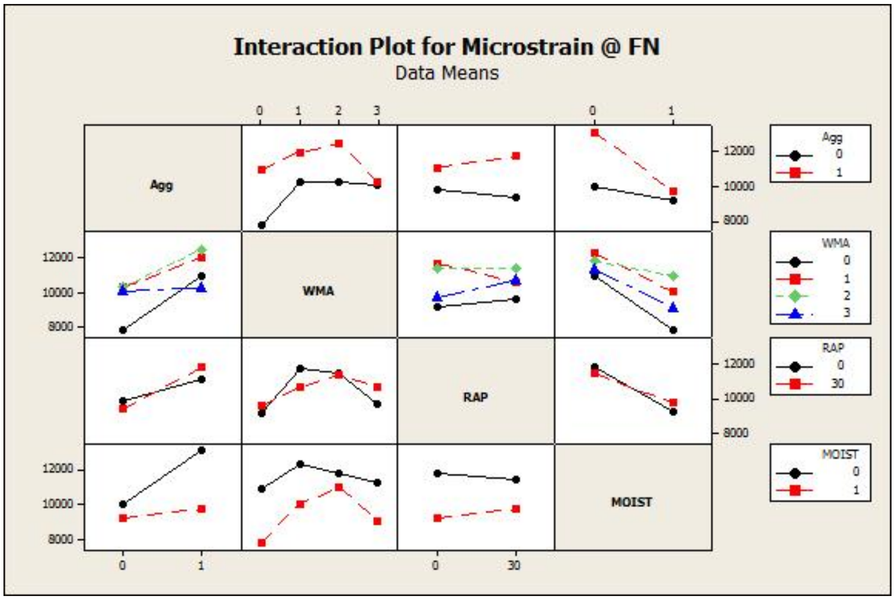


Figure 8.33. Interaction plot for variables affecting microstrain at flow number

In Figure 8.33, the interaction between moisture conditioning and warm mix additive reveal moisture conditioning increases the strain at flow number for all WMA mixes and the control mix as compared to the non-moisture conditioned mixes. It is important to note that Evotherm is the least affected warm mix additive by moisture conditioning as the magnitude of the strains were relatively close to the comparable control mixtures for the Evotherm mixtures regardless of the moisture conditioning status.

Another observable interaction is between aggregate type and moisture conditioning. The impact of moisture conditioning on the quartzite control mixture had considerable effect on the amount of strain incurred as compared to the control limestone mixture.

CHAPTER 9. DISCUSSION AND CONCLUSION

The purpose of the discussion is to summarize the statistical conclusions and to compare and contrast the differences between the HMA and WMA mixes within each field-produced mix. The discussion will also address certain limitations of the experiment and provide recommendations for future research. The conclusions summarize the discoveries made as a result of this research project and provide suggestions for continued research.

9.1 Field Mix 1 Discussion

The WMA technology for this mix was Evotherm 3G. The binder used was a PG 58-28 and the binder testing showed evidence of the reduction in the mixing and compaction temperature, but it is not known if this is due to the Evotherm 3G as it is not known whether the control asphalt binder was the same base asphalt binder used with the Evotherm 3G. The ITS test data showed that the mix was a statistically significant factor when comparing peak load and the HMA average peak load was greater than the peak load of the WMA samples. There was no statistical difference when comparing the TSR data. For this field mix, the field versus lab compaction was not tested using the ITS test. The dynamic modulus tests showed that the HMA and WMA were statistically different in their dynamic modulus response with HMA having a higher overall average. There was convincing evidence of a treatment effect for compaction type and moisture conditioning. The interaction of mix, compaction, and moisture conditioning suggests that there is a difference when a mix is compacted. Flow number testing showed the mix type as a statistically significant factor and the data measuring cycles to three percent strain show that mix, compaction, and moisture conditioning are statistically significant factors, as well as the three-way interaction of the mix, compaction, and moisture conditioning. By studying the results from these tests and the statistical evidence, the overall conclusion is that the HMA mix performed better than the Evotherm 3G mix in ITS peak load, the dynamic modulus test, and in the flow number test data.

9.2 Field Mix 2 Discussion

The WMA technology for this mix was Revix. The binder was a PG 64-28. The ITS test data shows that the mix, compaction type, and moisture conditioning were statistically significant factors, as well as the interaction of mix and moisture conditioning. The TSR data showed a statistical difference between the HMA and WMA mixes. The dynamic modulus data found all five class variables were statistically significant. There were several statistically significant three-way interactions and one four-way interaction. The Duncan grouping helped to show which groups had higher dynamic modulus values. The HMA had a higher average than the WMA, the field-compacted samples had a higher average than lab-compacted samples, and moisture-conditioned samples had a lower average than unconditioned samples. The flow number analysis showed the HMA had a higher average flow number and more cycles to three percent strain than the WMA. For this mix, there was little evidence to suggest that the WMA would perform as well as the traditional HMA mixes.

9.3 Field Mix 3 Discussion

The WMA technology used in this mix was Sasobit. The binder grade was a PG 64-22. The ITS showed that the mix, compaction type, moisture conditioning, and the interaction of mix and moisture conditioning were the statistically significant factors. The field-compacted moisture-conditioned WMA samples were the lowest performing samples and that particular sample set was statistically different from all other sample sets. The TSR values show that WMA and HMA are statistically different with the HMA average being the higher of the two. The dynamic modulus test data showed each of the five variables as statistically significant. The interaction of the mix, compaction, and moisture conditioning was statistically significant. Overall, HMA values were higher than WMA, lab-compacted values were higher than field-compacted, and non-moisture-conditioned samples were higher than moisture-conditioned samples. The flow number analysis shows statistical differences between HMA and WMA, as well as the interaction of mix and compaction type. When cycles to three percent strain were analyzed, the same factors were statistically different and compaction type was also found to be statistically significant. The average flow number and average cycles to three percent strain were higher for the HMA samples than the WMA samples.

9.4 Field Mix 4 Discussion

The WMA technology for Field Mix 4 was the Double Barrel Green foaming technology. The binder used was a PG 64-22. The ITS data showed the mix, compaction, and moisture conditioning, as well as the interaction of compaction, moisture conditioning, and the interaction of mix; compaction and moisture conditioning were statistically significant when peak load data were analyzed. The Tukey groupings helped to show the rankings of the mixes and showed that overall, the values were fairly comparable but, on average, moisture-conditioned samples had a lower peak load. The TSR analysis showed that the compaction was a statistically-significant factor. Dynamic modulus testing data showed that all class variables were statistically significant with the exception of compaction; however, the interaction of mix and compaction as well as the interaction of mix, compaction, and moisture conditioning were found to be statistically different. The performance for this mix was different than the other three mixes tested due to the Duncan groupings showing a higher average dynamic modulus response for the WMA mix. The flow number test results also confirmed that the WMA mix had higher averages than the HMA mix.

9.5 Discussion of Limitations

There are several limitations to this experiment. Each field mix had only one associated WMA technology and this limits the ability to compare WMA technologies. Field-produced mixes will entail higher variability than lab-produced mixes. A benefit to the field-produced mixes is that there are roadways in which the performance of the mix can be used as a benchmark to compare to the results of the performance testing. After performing the analysis, it seems as though the WMA technology may play a role in determining the performance of a mix, but the initial mix design will be a critical factor in the performance of a WMA mix. A poorly-designed HMA mix will have a poorly performing WMA mix. Field Mix 4, which had the Double Barrel Green foaming WMA technology, had a different trend than the other three field mixes tested. The WMA mix for Field Mix 4 performed superior to the HMA in the dynamic modulus and flow number testing; however, the control mix was produced nine days after the WMA mix. This extra variability may explain the difference in the trend and further research is needed on the comparison of the control HMA mix and foamed WMA mix.

9.6 Conclusions for Field-Produced Mixes

The overall findings of the field-produced mix experiment suggest a difference in the performance of HMA and WMA mixes. The binder results show that the mixing compaction temperatures are reduced and that the benefits of WMA mentioned in the literature review are realized. While the benefits of the technologies continue to drive the production of more WMA mixes, studying the performance testing results will help to show if there is a net benefit to using WMA. Three of the four field mixes indicate superior performance of the HMA mix in many aspects of the tests performed. There were mixed results for the foaming technology because the WMA mix did perform superior in dynamic modulus and flow number tests. The use of foaming should be further investigated under a higher degree of control. In this case, there was a nine-day elapse between the production of the WMA mix and the HMA mix due to weather delays. This may have caused a higher degree of variability between the two mixes. The dynamic modulus results show that the interaction of the mix, compaction type, and moisture conditioning are statistically significant in all four field mixes. This suggests that the combination of all three factors play a role in determining material response. The master curves do not display a high degree of overall variability but do show differences in mix responses at high temperatures.

Further investigation of WMA technologies will be beneficial to both contractors and owner agencies. There is evidence that the field versus laboratory compaction may impact the dynamic modulus response. Quality control and quality assurance programs may want to consider a change in how and when field-produced mixes are compacted. The field-produced sample may resemble the actual pavement response better than the reheated laboratory sample. There is also evidence that WMA mix may impact the mix response to moisture conditioning. The overall moisture conditioning response was variable with the moisture-conditioned samples performing better than unconditioned samples. This may be due to the immersion of the sample in the 60°C water bath for 24 hours, which may produce enough heat to allow for more asphalt absorption into the aggregate.

The experiment using field-produced mixes showed statistical differences between the control and WMA for all four field mixes tested. Three field mixes indicate higher overall performance than the HMA mix. Foaming was the only WMA technology in which WMA performed better in some instances. As WMA becomes produced in larger quantities and as WMA technologies begin to be used together, it is important to continue looking at the pavement performance data and performance testing results in order to adapt the QC/QA programs to evolving technologies. Further research will help to ensure that the short-term benefits of WMA that are realized during placement can be extended to long-term pavement performance and life cycle cost analysis.

9.7 Conclusions for Laboratory-Produced Mixes

In this study, a laboratory evaluation of WMA mixtures was conducted using three WMA technologies: Advera, Evotherm, and Sasobit. The conclusions drawn from this study include:

1. The WMA mixtures were produced at 120°C and compacted at 110°C compared to the control HMA mixtures produced and compacted at 150 and 140°C, respectively.
2. ITS testing conducted on 22 mixtures and the TSR indicated that the control mixtures have higher TSR values in comparison to the WMA mixtures with the Advera mixtures recording the lowest TSR values.
3. The relatively low TSR values of the Advera mixtures can likely be attributed to the release of crystallized water necessary for the improvement of the workability of the asphalt mixture.
4. Dynamic modulus tests conducted on 16 mixtures indicated that all WMA technologies have dynamic modulus values that were statistically significant compared to the control mixture values.
5. Dynamic modulus tests indicated that the differences in the dynamic modulus values of Evotherm and Sasobit mixtures are statistically significant.
6. Dynamic modulus tests showed that there is an interaction between temperature and rap content and such an interaction is statistically significant for the dynamic modulus.
7. Flow number tests indicated that aggregate type, RAP conten, and WMA technology are statistically significant variables.
8. RAP content increases the stiffness of the asphalt mixtures leading to a significant increase in flow number values.

9.8 Recommendations for Additional Research

HMA is evolving as new technologies are developed and higher percentages of recyclable materials are incorporated into mix designs. To maintain optimal sustainability in our roadways, future research must address the issue of how these technologies impact the long-term pavement performance. WMA is a tool that can help create more sustainable pavements by incorporating higher percentages of RAP and/or RAS in a mix. Research that incorporates performance testing is recommended because it provides quantifiable material properties that can be correlated to field performance. The following provides an outline of additional research recommendations that would enhance the community's understanding of recycled materials and WMA:

1. Continue the analysis of data within this study by incorporating the Mechanistic-Empirical Pavement Design Guide (M-E PDG) to investigate long-term pavement performance.

2. Conduct a field survey of the actual WMA pavement and compare with M-E PDG results over time.

3. Investigate the use of high percentage RAP/fractionated RAP and/or RAS used in conjunction with WMA. Conduct performance testing to evaluate differences in mixing and compaction temperatures and address potential moisture susceptibility concerns. The extent of blending of the recycled materials at reduced mixing temperatures is an area of concern.

4. Investigate how, using two WMA technologies in conjunction with each other, impacts mix properties (e.g. foaming using a WMA additive).

5. Reinvestigate field-produced foamed WMA and control HMA mixes under a more controlled setting, wherein production occurs on consecutive days. A plan that would address several of these concerns would be to produce a foamed WMA mix with a chemical modifier, such as Revix; on the following day, produce a foamed WMA mix; and, on the final day of paving, produce the control HMA mix. The samples procured from these mixes could undergo ITS, dynamic modulus, and flow number testing.

6. Beam fatigue testing on control HMA and WMA mixes with high percentages of RAP/fractionated RAP or RAS would help determine the flexural stiffness and fatigue life of the mixes.

7. Conduct low-temperature fracture testing on the paired field-produced HMA and WMA mixes to ensure low-temperature mix performance will be met.

8. Frequency sweeps on binders extracted from field-produced WMA mixes with varying amounts of RAP/fractionated RAP and/or RAS would establish binder master curves that would help characterize the binders over a large range of temperatures and frequencies.

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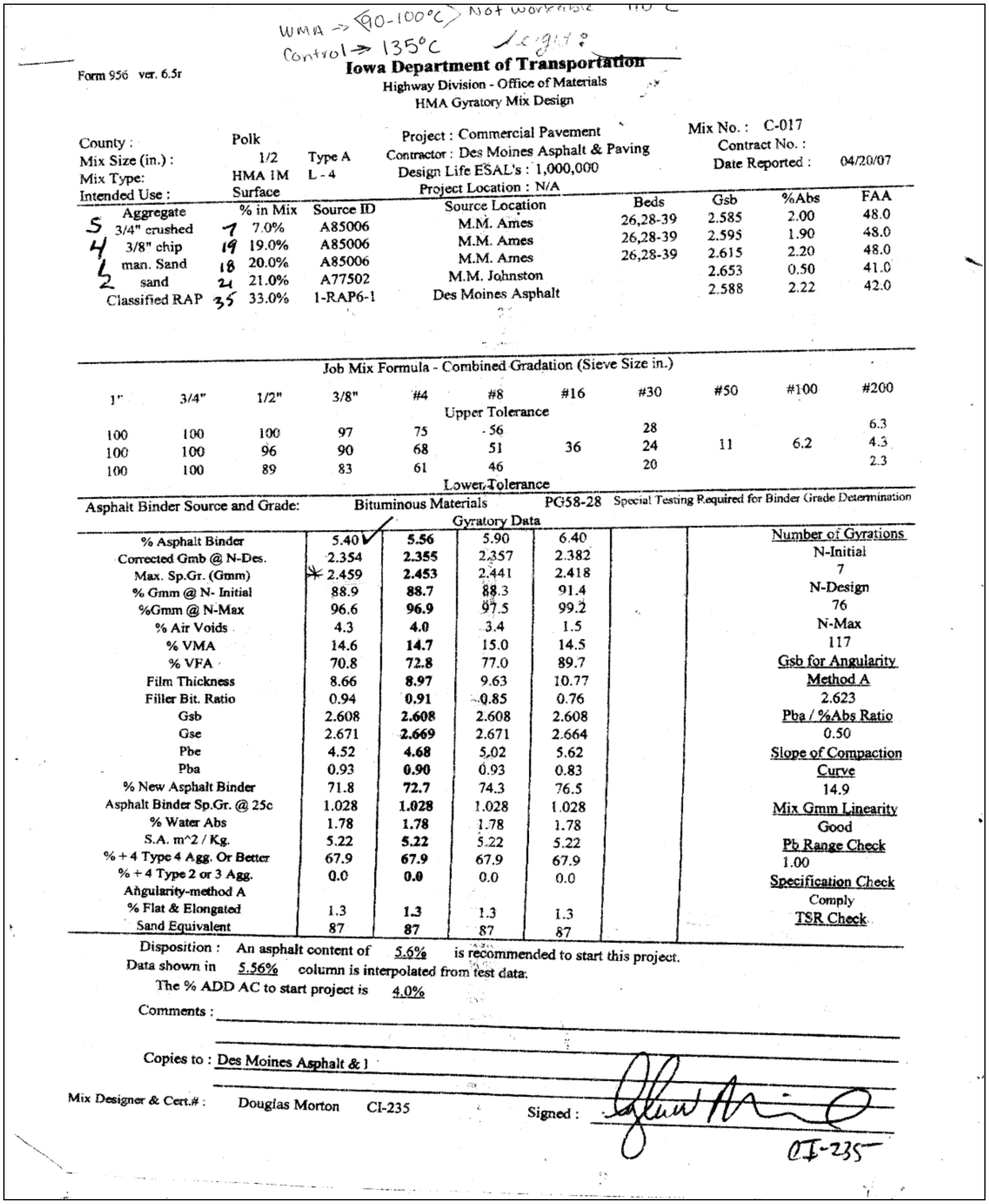
APPENDIX A. JOB MIX FORMULAS



WMA → 90-100°C Not workable
Control → 135°C

Form 956 ver. 6.5r

Iowa Department of Transportation
Highway Division - Office of Materials
HMA Gyratory Mix Design

County :	Polk		Project : Commercial Pavement	Mix No. : C-017
Mix Size (in.) :	1/2	Type A	Contractor : Des Moines Asphalt & Paving	Contract No. :
Mix Type:	HMA 1M	L - 4	Design Life ESAL's : 1,000,000	Date Reported : 04/20/07
Intended Use :	Surface		Project Location : N/A	

	Aggregate		% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
5	3/4" crushed	7	7.0%	A85006	M.M. Ames	26,28-39	2.585	2.00	48.0
4	3/8" chip	19	19.0%	A85006	M.M. Ames	26,28-39	2.595	1.90	48.0
L	man. Sand	18	20.0%	A85006	M.M. Ames	26,28-39	2.615	2.20	48.0
2	sand	21	21.0%	A77502	M.M. Johnston		2.653	0.50	41.0
	Classified RAP	35	33.0%	1-RAP6-1	Des Moines Asphalt		2.588	2.22	42.0

Job Mix Formula - Combined Gradation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	97	75	56		28			6.3
	100	100	96	90	68	51	36	24	11	6.2	4.3
Lower Tolerance	100	100	89	83	61	46		20			2.3

Asphalt Binder Source and Grade: Bituminous Materials PG58-28 Special Testing Required for Binder Grade Determination

Gyratory Data

% Asphalt Binder	5.40 ✓	**5.56**	5.90	6.40
Corrected Gmb @ N-Des.	2.354	**2.355**	2.357	2.382
Max. Sp.Gr. (Gmm)	* 2.459	**2.453**	2.441	2.418
% Gmm @ N- Initial	88.9	**88.7**	88.3	91.4
%Gmm @ N-Max	96.6	**96.9**	97.5	99.2
% Air Voids	4.3	**4.0**	3.4	1.5
% VMA	14.6	**14.7**	15.0	14.5
% VFA	70.8	**72.8**	77.0	89.7
Film Thickness	8.66	**8.97**	9.63	10.77
Filler Bit. Ratio	0.94	**0.91**	0.85	0.76
Gsb	2.608	**2.608**	2.608	2.608
Gse	2.671	**2.669**	2.671	2.664
Pbe	4.52	**4.68**	5.02	5.62
Pba	0.93	**0.90**	0.93	0.83
% New Asphalt Binder	71.8	**72.7**	74.3	76.5
Asphalt Binder Sp.Gr. @ 25c	1.028	**1.028**	1.028	1.028
% Water Abs	1.78	**1.78**	1.78	1.78
S.A. m^2 / Kg.	5.22	**5.22**	5.22	5.22
% + 4 Type 4 Agg. Or Better	67.9	**67.9**	67.9	67.9
% + 4 Type 2 or 3 Agg.	0.0	**0.0**	0.0	0.0
Angularity-method A				
% Flat & Elongated	1.3	**1.3**	1.3	1.3
Sand Equivalent	87	**87**	87	87

Number of Gyrations
N-Initial
7
N-Design
76
N-Max
117
Gsb for Angularity Method A
2.623
Pba / %Abs Ratio
0.50
Slope of Compaction Curve
14.9
Mix Gmm Linearity
Good
Pb Range Check
1.00
Specification Check
Comply
TSR Check

Disposition : An asphalt content of 5.6% is recommended to start this project.
Data shown in 5.56% column is interpolated from test data.
The % ADD AC to start project is 4.0%

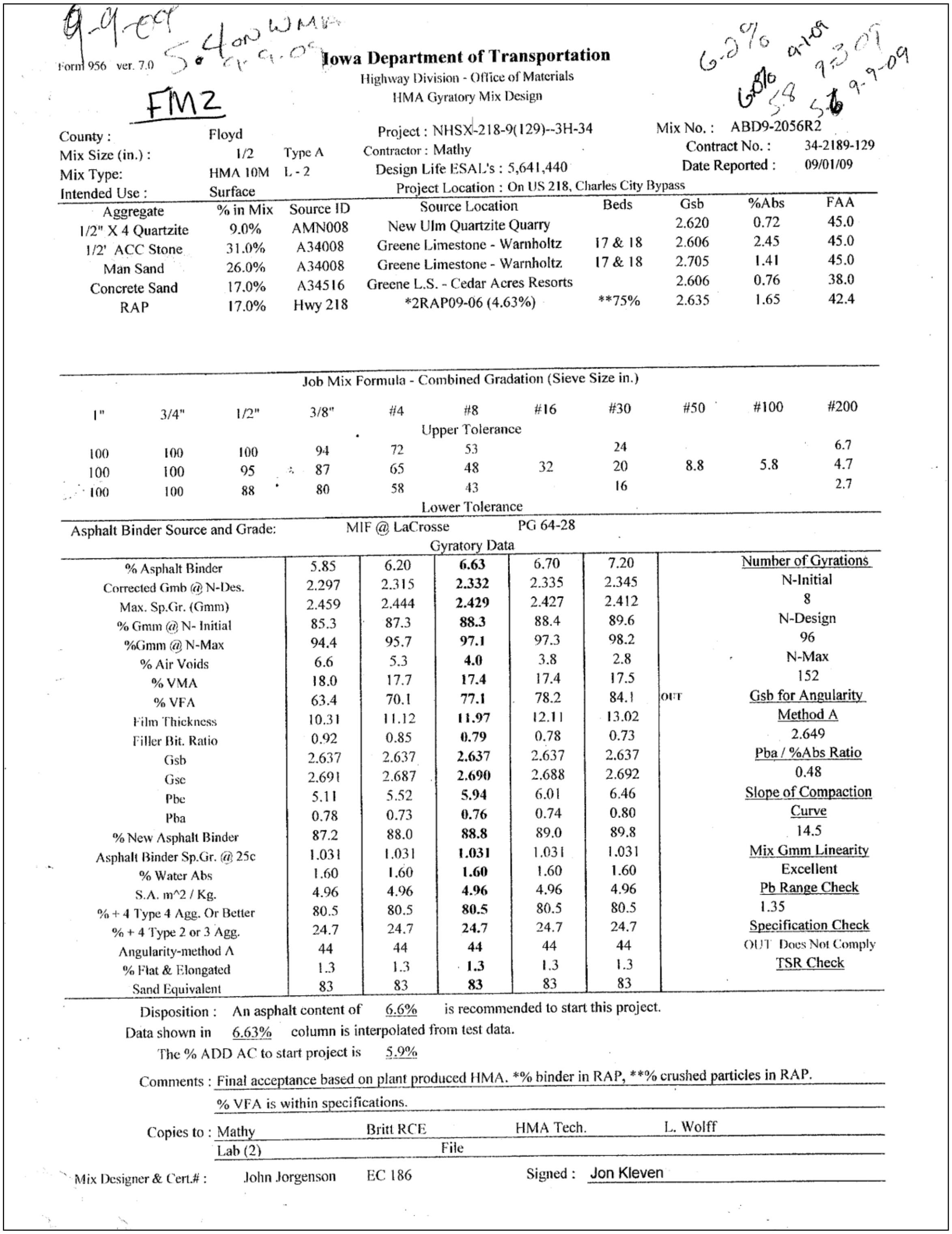
Comments :

Copies to : Des Moines Asphalt & I

Mix Designer & Cert.# : Douglas Morton CI-235 Signed :

CI-235

Figure A.1. Field Mix 1 job mix formula - WMA additive is Evotherm 3G



9-9-09

Form 956 ver. 7.0 5.4 on WMA 9-9-09

Iowa Department of Transportation
Highway Division - Office of Materials
HMA Gyratory Mix Design

6.2% 9-1-09
6.0% 9-3-09
5.8
5.6 9-9-09

FM2

County :	Floyd		Project : NHSX-218-9(129)--3H-34	Mix No. : ABD9-2056R2
Mix Size (in.) :	1/2	Type A	Contractor : Mathy	Contract No. : 34-2189-129
Mix Type:	HMA 10M	L - 2	Design Life ESAL's : 5,641,440	Date Reported : 09/01/09
Intended Use :	Surface		Project Location : On US 218, Charles City Bypass	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
1/2" X 4 Quartzite	9.0%	AMN008	New Ulm Quartzite Quarry		2.620	0.72	45.0
1/2' ACC Stone	31.0%	A34008	Greene Limestone - Warnholtz	17 & 18	2.606	2.45	45.0
Man Sand	26.0%	A34008	Greene Limestone - Warnholtz	17 & 18	2.705	1.41	45.0
Concrete Sand	17.0%	A34516	Greene L.S. - Cedar Acres Resorts		2.606	0.76	38.0
RAP	17.0%	Hwy 218	*2RAP09-06 (4.63%)	**75%	2.635	1.65	42.4

Job Mix Formula - Combined Gradation (Sieve Size in.)

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
					Upper Tolerance					
100	100	100	94	72	53		24			6.7
100	100	95	87	65	48	32	20	8.8	5.8	4.7
100	100	88	80	58	43		16			2.7
					Lower Tolerance					

Asphalt Binder Source and Grade: MIF @ LaCrosse PG 64-28

Gyratory Data

% Asphalt Binder	5.85	6.20	**6.63**	6.70	7.20	
Corrected Gmb @ N-Des.	2.297	2.315	**2.332**	2.335	2.345	
Max. Sp.Gr. (Gmm)	2.459	2.444	**2.429**	2.427	2.412	
% Gmm @ N- Initial	85.3	87.3	**88.3**	88.4	89.6	
%Gmm @ N-Max	94.4	95.7	**97.1**	97.3	98.2	
% Air Voids	6.6	5.3	**4.0**	3.8	2.8	
% VMA	18.0	17.7	**17.4**	17.4	17.5	
% VFA	63.4	70.1	**77.1**	78.2	84.1	OUT
Film Thickness	10.31	11.12	**11.97**	12.11	13.02	
Filler Bit. Ratio	0.92	0.85	**0.79**	0.78	0.73	
Gsb	2.637	2.637	**2.637**	2.637	2.637	
Gse	2.691	2.687	**2.690**	2.688	2.692	
Pbe	5.11	5.52	**5.94**	6.01	6.46	
Pba	0.78	0.73	**0.76**	0.74	0.80	
% New Asphalt Binder	87.2	88.0	**88.8**	89.0	89.8	
Asphalt Binder Sp.Gr. @ 25c	1.031	1.031	**1.031**	1.031	1.031	
% Water Abs	1.60	1.60	**1.60**	1.60	1.60	
S.A. m^2 / Kg.	4.96	4.96	**4.96**	4.96	4.96	
% + 4 Type 4 Agg. Or Better	80.5	80.5	**80.5**	80.5	80.5	
% + 4 Type 2 or 3 Agg.	24.7	24.7	**24.7**	24.7	24.7	
Angularity-method A	44	44	**44**	44	44	
% Flat & Elongated	1.3	1.3	**1.3**	1.3	1.3	
Sand Equivalent	83	83	**83**	83	83	

Number of Gyrations
N-Initial
8
N-Design
96
N-Max
152
Gsb for Angularity
Method A
2.649
Pba / %Abs Ratio
0.48
Slope of Compaction
Curve
14.5
Mix Gmm Linearity
Excellent
Pb Range Check
1.35
Specification Check
OUT Does Not Comply
TSR Check

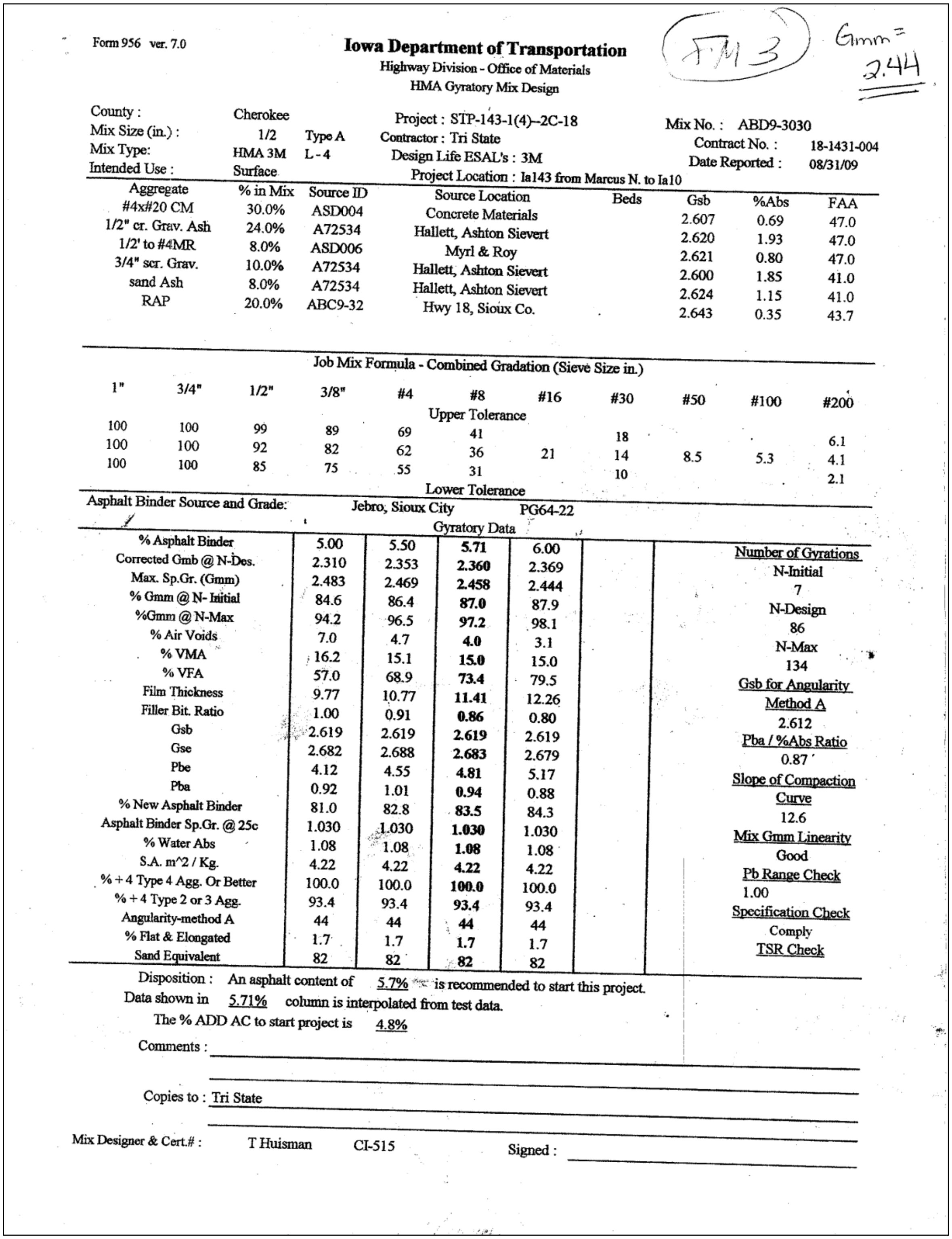
Disposition : An asphalt content of 6.6% is recommended to start this project.
Data shown in 6.63% column is interpolated from test data.
The % ADD AC to start project is 5.9%

Comments : Final acceptance based on plant produced HMA. *% binder in RAP, **% crushed particles in RAP.
% VFA is within specifications.

Copies to : Mathy Britt RCE HMA Tech. L. Wolff
Lab (2) File

Mix Designer & Cert.# : John Jorgenson EC 186 Signed : Jon Kleven

Figure A.2. Field Mix 2 job mix formula - WMA additive is Revix



Form 956 ver. 7.0

Iowa Department of Transportation
Highway Division - Office of Materials
HMA Gyratory Mix Design

FM 3

Gmm =
2.44

County :	Cherokee		Project : STP-143-1(4)--2C-18
Mix Size (in.) :	1/2	Type A	Contractor : Tri State
Mix Type:	HMA 3M	L - 4	Design Life ESAL's : 3M
Intended Use :	Surface		Project Location : Ia143 from Marcus N. to Ia10

Mix No. : ABD9-3030
Contract No. : 18-1431-004
Date Reported : 08/31/09

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
#4x#20 CM	30.0%	ASD004	Concrete Materials		2.607	0.69	47.0
1/2" cr. Grav. Ash	24.0%	A72534	Hallett, Ashton Sievert		2.620	1.93	47.0
1/2' to #4MR	8.0%	ASD006	Myrl & Roy		2.621	0.80	47.0
3/4" scr. Grav.	10.0%	A72534	Hallett, Ashton Sievert		2.600	1.85	41.0
sand Ash	8.0%	A72534	Hallett, Ashton Sievert		2.624	1.15	41.0
RAP	20.0%	ABC9-32	Hwy 18, Sioux Co.		2.643	0.35	43.7

Job Mix Formula - Combined Gradation (Sieve Size in.)

Upper Tolerance

1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
100	100	99	89	69	41		18			6.1
100	100	92	82	62	36	21	14	8.5	5.3	4.1
100	100	85	75	55	31		10			2.1

Lower Tolerance

Asphalt Binder Source and Grade: Jebro, Sioux City PG64-22

Gyratory Data

% Asphalt Binder	5.00	5.50	**5.71**	6.00		
Corrected Gmb @ N-Des.	2.310	2.353	**2.360**	2.369		
Max. Sp.Gr. (Gmm)	2.483	2.469	**2.458**	2.444		
% Gmm @ N- Initial	84.6	86.4	**87.0**	87.9		
%Gmm @ N-Max	94.2	96.5	**97.2**	98.1		
% Air Voids	7.0	4.7	**4.0**	3.1		
% VMA	16.2	15.1	**15.0**	15.0		
% VFA	57.0	68.9	**73.4**	79.5		
Film Thickness	9.77	10.77	**11.41**	12.26		
Filler Bit. Ratio	1.00	0.91	**0.86**	0.80		
Gsb	2.619	2.619	**2.619**	2.619		
Gse	2.682	2.688	**2.683**	2.679		
Pbe	4.12	4.55	**4.81**	5.17		
Pba	0.92	1.01	**0.94**	0.88		
% New Asphalt Binder	81.0	82.8	**83.5**	84.3		
Asphalt Binder Sp.Gr. @ 25c	1.030	1.030	**1.030**	1.030		
% Water Abs	1.08	1.08	**1.08**	1.08		
S.A. m^2 / Kg.	4.22	4.22	**4.22**	4.22		
% + 4 Type 4 Agg. Or Better	100.0	100.0	**100.0**	100.0		
% + 4 Type 2 or 3 Agg.	93.4	93.4	**93.4**	93.4		
Angularity-method A	44	44	**44**	44		
% Flat & Elongated	1.7	1.7	**1.7**	1.7		
Sand Equivalent	82	82	**82**	82		

Number of Gyrations
N-Initial
7
N-Design
86
N-Max
134
Gsb for Angularity Method A
2.612
Pba / %Abs Ratio
0.87
Slope of Compaction Curve
12.6
Mix Gmm Linearity
Good
Pb Range Check
1.00
Specification Check
Comply
TSR Check

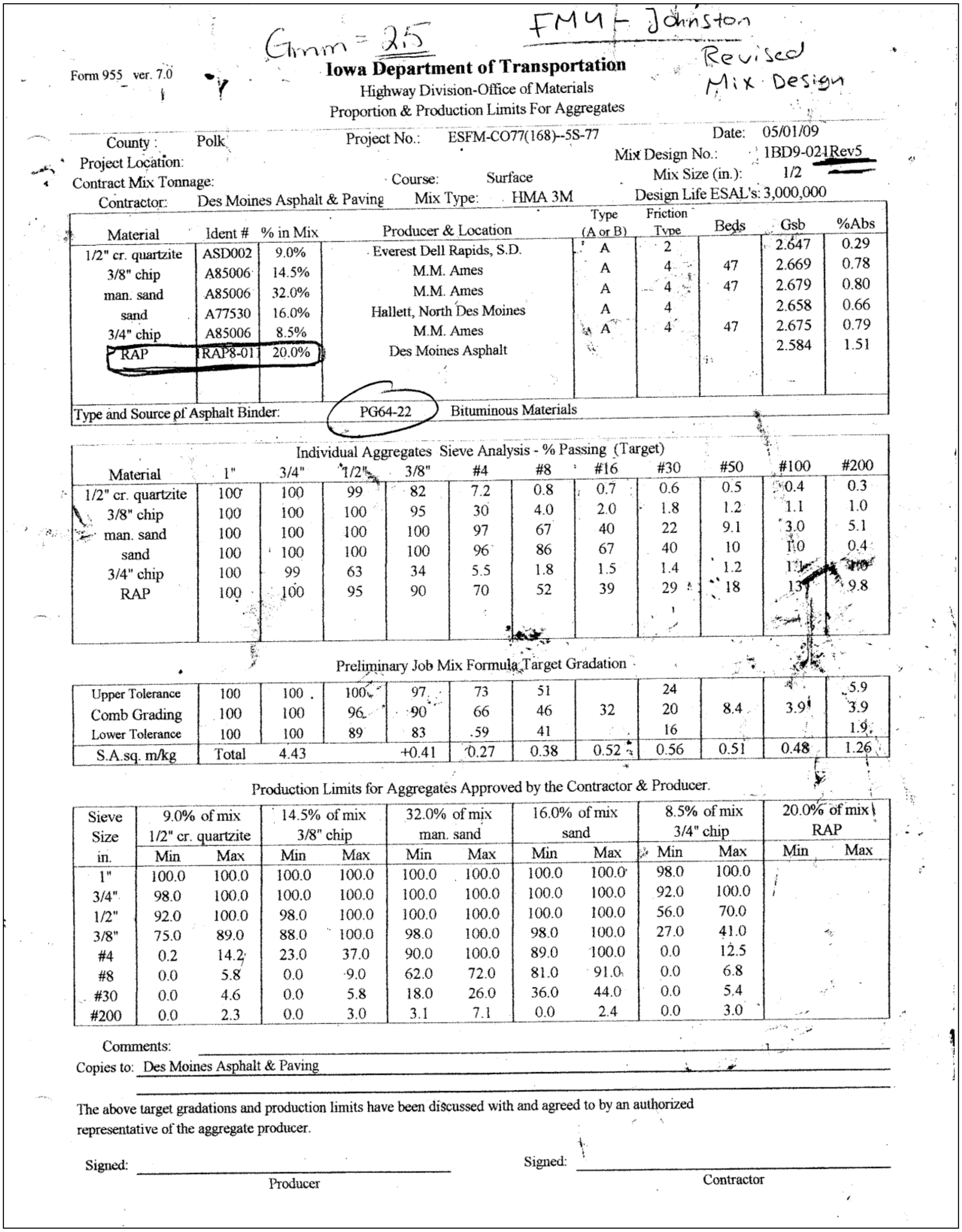
Disposition : An asphalt content of 5.7% is recommended to start this project.
Data shown in 5.71% column is interpolated from test data.
The % ADD AC to start project is 4.8%

Comments :

Copies to : Tri State

Mix Designer & Cert.# : T Huisman CI-515 Signed :

Figure A.3. Field Mix 3 job mix formula - WMA additive is Sasobit



Gmm = 2.5

FM4 - Johnston

Revised Mix Design

Form 955 ver. 7.0

Iowa Department of Transportation

Highway Division-Office of Materials

Proportion & Production Limits For Aggregates

County :	Polk	Project No.:	ESFM-CO77(168)--5S-77
Project Location:		Date:	05/01/09
		Mix Design No.:	1BD9-021Rev5
Contract Mix Tonnage:		Course:	Surface
		Mix Size (in.):	1/2
Contractor:	Des Moines Asphalt & Paving	Mix Type:	HMA 3M
		Design Life ESAL's:	3,000,000

Material	Ident #	% in Mix	Producer & Location	Type (A or B)	Friction Type	Beds	Gsb	%Abs
1/2" cr. quartzite	ASD002	9.0%	Everest Dell Rapids, S.D.	A	2		2.647	0.29
3/8" chip	A85006	14.5%	M.M. Ames	A	4	47	2.669	0.78
man. sand	A85006	32.0%	M.M. Ames	A	4	47	2.679	0.80
sand	A77530	16.0%	Hallett, North Des Moines	A	4		2.658	0.66
3/4" chip	A85006	8.5%	M.M. Ames	A	4	47	2.675	0.79
RAP	RAP8-011	20.0%	Des Moines Asphalt				2.584	1.51

Type and Source of Asphalt Binder: PG64-22 Bituminous Materials

Individual Aggregates Sieve Analysis - % Passing (Target)

Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1/2" cr. quartzite	100	100	99	82	7.2	0.8	0.7	0.6	0.5	0.4	0.3
3/8" chip	100	100	100	95	30	4.0	2.0	1.8	1.2	1.1	1.0
man. sand	100	100	100	100	97	67	40	22	9.1	3.0	5.1
sand	100	100	100	100	96	86	67	40	10	1.0	0.4
3/4" chip	100	99	63	34	5.5	1.8	1.5	1.4	1.2	1.1	[illegible]
RAP	100	100	95	90	70	52	39	29	18	13	9.8

Preliminary Job Mix Formula Target Gradation

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	97	73	51		24			5.9
Comb Grading	100	100	96	90	66	46	32	20	8.4	3.9	3.9
Lower Tolerance	100	100	89	83	59	41		16			1.9
S.A.sq. m/kg	Total	4.43		+0.41	0.27	0.38	0.52	0.56	0.51	0.48	1.26

Production Limits for Aggregates Approved by the Contractor & Producer.

Sieve Size in.	9.0% of mix 1/2" cr. quartzite		14.5% of mix 3/8" chip		32.0% of mix man. sand		16.0% of mix sand		8.5% of mix 3/4" chip		20.0% of mix RAP	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0		
3/4"	98.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	92.0	100.0		
1/2"	92.0	100.0	98.0	100.0	100.0	100.0	100.0	100.0	56.0	70.0		
3/8"	75.0	89.0	88.0	100.0	98.0	100.0	98.0	100.0	27.0	41.0		
#4	0.2	14.2	23.0	37.0	90.0	100.0	89.0	100.0	0.0	12.5		
#8	0.0	5.8	0.0	9.0	62.0	72.0	81.0	91.0	0.0	6.8		
#30	0.0	4.6	0.0	5.8	18.0	26.0	36.0	44.0	0.0	5.4		
#200	0.0	2.3	0.0	3.0	3.1	7.1	0.0	2.4	0.0	3.0		

Comments:

Copies to: Des Moines Asphalt & Paving

The above target gradations and production limits have been discussed with and agreed to by an authorized representative of the aggregate producer.

Signed: ______________________ Producer

Signed: ______________________ Contractor

Figure A.4. Field Mix 4 job mix formula - WMA is Double Barrel Green Foaming

APPENDIX B. VOLUMETRICS

Note: Highlighted blue lines indicate moisture-conditioned.

Table B.1. Field Mix 1 dynamic modulus lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM1: Dynamic Modulus Lab-Compacted Samples	HMA	1	2681.7	1529.7	2689.4	2.31	2.46	5.96%
		2	2685.9	1536.6	2695.4	2.32	2.46	5.74%
		3	2681.9	1537.9	2694.2	2.32	2.46	5.68%
		4	2680.8	1537.7	2694.4	2.32	2.46	5.75%
		5	2679.8	1531.7	2688.4	2.32	2.46	5.78%
		6	2680.9	1534.0	2689.0	2.32	2.46	5.61%
		7	2680.8	1531.9	2689.4	2.32	2.46	5.81%
		8	2678.8	1532.3	2688.8	2.32	2.46	5.80%
		9	2687.4	1537.3	2695.0	2.32	2.46	5.60%
		10	2680.9	1531.9	2689.9	2.32	2.46	5.85%
	WMA	1	2685.7	1538.3	2695.9	2.32	2.46	5.65%
		2	2682.8	1536.0	2694.2	2.32	2.46	5.80%
		3	2684.8	1539.0	2698.5	2.32	2.46	5.84%
		4	2684.9	1542.9	2701.7	2.32	2.46	5.78%
		5	2684.5	1537.3	2695.8	2.32	2.46	5.77%
		6	2683.1	1538.7	2696.3	2.32	2.46	5.74%
		7	2684	1540.2	2696.1	2.32	2.46	5.57%
		8	2684	1540.8	2698.3	2.32	2.46	5.70%
		9	2684.7	1540.3	2696.1	2.32	2.46	5.54%
		10	2684.3	1544.4	2699.8	2.32	2.46	5.52%

Table B.2. Field Mix 1 indirect tensile strength lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	$*G_{mm}$	Pa (Percent Air Voids)
FM1: ITS Lab-Compacted Samples	HMA	1	1120.0	644.3	1122.6	2.34	2.46	4.77%
		2	1119.5	644.7	1123.3	2.34	2.46	4.88%
		3	1125.1	649.8	1129.1	2.35	2.46	4.54%
		4	1119.1	645.7	1123.0	2.34	2.46	4.65%
		5	1118.8	643.0	1123.2	2.33	2.46	5.25%
		6	1118.6	642.6	1121.6	2.34	2.46	5.03%
		7	1118.3	643.1	1121.0	2.34	2.46	4.84%
		8	1119.6	643.0	1123.2	2.33	2.46	5.18%
		9	1119.0	643.2	1122.3	2.34	2.46	5.02%
		10	1117.8	640.6	1120.2	2.33	2.46	5.22%
	WMA	1	1122.0	643.2	1124.2	2.33	2.46	5.14%
		2	1123.4	646.3	1125.6	2.34	2.46	4.68%
		3	1121.3	644.6	1125.1	2.33	2.46	5.10%
		4	1122.5	646.3	1125.5	2.34	2.46	4.74%
		5	1122.4	647.1	1126.6	2.34	2.46	4.81%
		6	1122.9	646.7	1126.3	2.34	2.46	4.79%
		7	1121.2	645.5	1124.5	2.34	2.46	4.81%
		8	1121.6	646.6	1124.7	2.35	2.46	4.60%
		9	1126.3	650.0	1129.7	2.35	2.46	4.52%
		10	1124.8	647.9	1127.0	2.35	2.46	4.52%

Table B.3. Field Mix 1 dynamic modulus field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM1: Dynamic Modulus Field-Compacted Samples	HMA	1	2697.8	1538.4	2705.2	2.31	2.46	5.97%
		2	2698.2	1542.8	2707.6	2.32	2.46	5.80%
		3	2693.8	1532.8	2700.7	2.31	2.46	6.20%
		4	2692.4	1531.3	2698.5	2.31	2.46	6.19%
		5	2688.8	1527.3	2696.4	2.30	2.46	6.47%
		6	2690.9	1533.6	2701.3	2.30	2.46	6.29%
	WMA	1	2714.7	1551.5	2720.1	2.32	2.46	5.53%
		2	2692.0	1533.2	2698.7	2.31	2.46	6.07%
		3	2740.0	1573.7	2743.9	2.34	2.46	4.78%
		4	2695.1	1539.6	2707.8	2.31	2.46	6.18%
		5	2714.1	1550.4	2719.2	2.32	2.46	5.57%
		6	2692.9	1529.5	2703.1	2.29	2.46	6.69%

Table B.4. Field Mix 2 dynamic modulus lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	*G_{mm}	Pa (Percent Air Voids)
FM2: Dynamic Modulus Lab-Compacted Samples	HMA	1	2643.2	1499.3	2654.5	2.46	7.03%
		2	2646.7	1503.5	2656.3	2.46	6.71%
		3	2641.8	1493.8	2652.1	2.46	7.32%
		4	2640.9	1506.8	2658.6	2.46	6.83%
		5	2644.0	1506.3	2656.0	2.46	6.55%
		6	2641.0	1502.0	2651.9	2.46	6.68%
		7	2640.2	1496.8	2649.6	2.46	6.94%
		8	2639.1	1497.8	2652.2	2.46	7.11%
		9	2640.4	1502.1	2655.2	2.46	6.96%
		10	2647.0	1508.6	2662.0	2.46	6.75%
	WMA	1	2623.8	1484.3	2640.0	2.45	7.33%
		2	2628.7	1491.4	2645.9	2.45	7.06%
		3	2628.5	1490.9	2645.4	2.45	7.07%
		4	2629.2	1494.9	2648.6	2.45	6.98%
		5	2625.6	1489.8	2644.9	2.45	7.22%
		6	2627.7	1494.5	2647.8	2.45	7.00%
		7	2627.8	1499	2648.5	2.45	6.69%
		8	2627.2	1495.4	2648.2	2.45	6.98%
		9	2624.8	1492.6	2642.9	2.45	6.86%
		10	2629.1	1494.3	2648.2	2.45	7.00%

Table B.5. Field Mix 2 indirect tensile strength lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mm}	Pa (Percent Air Voids)
FM2: Indirect Tensile Strength Lab-Compacted Samples	HMA	1	1108.5	634.0	1112.2	2.46	5.77%
		2	1110.2	635.1	1113.1	2.46	5.59%
		3	1100.1	627.0	1103.3	2.46	6.11%
		4	1107.1	630.7	1110.2	2.46	6.14%
		5	1111.0	637.6	1114.0	2.46	5.20%
		6	1107.3	636.6	1110.5	2.46	5.02%
		7	1108.2	635.2	1111.2	2.46	5.36%
		8	1110.2	638.7	1113.1	2.46	4.87%
		9	1109.9	637.4	1113.3	2.46	5.19%
		10	1110.7	639.2	1115.6	2.46	5.23%
	WMA	1	1125.5	647.7	1127.5	2.45	4.25%
		2	1126.3	649.6	1128.7	2.45	4.05%
		3	1125.1	647.2	1126.9	2.45	4.27%
		4	1124.5	649.2	1127.5	2.45	4.04%
		5	1126.1	646.7	1125.7	2.45	4.04%
		6	1126.4	650.1	1128.1	2.45	3.82%
		7	1125.3	648.2	1126.5	2.45	3.97%
		8	1124.7	646.8	1126.4	2.45	4.28%
		9	1126.4	649.7	1128.5	2.45	3.98%
		10	1124.5	648.5	1127	2.45	4.08%

Table B.6. Field Mix 2 dynamic modulus field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	*G_{mm}	Pa (Percent Air Voids)
FM2: Dynamic Modulus Field-Compacted Samples	HMA	1	2634.9	1498.4	2647.1	2.46	6.76%
		2	2638.7	1502.6	2653.4	2.46	6.79%
		3	2647.0	1509.0	2659.8	2.46	6.50%
		4	2651.3	1515.6	2667.1	2.46	6.40%
		5	2639.2	1508.2	2657.2	2.46	6.63%
		6	2650.5	1513.0	2661.0	2.46	6.15%
		7	2642.2	1498.1	2647.8	2.46	6.58%
		8	2646.5	1509.2	2654.8	2.46	6.09%
		9	2646.5	1503.2	2653.9	2.46	6.51%
		10	2645.0	1508.5	2657.2	2.46	6.40%
	WMA	1	2645.5	1500.7	2661.0	2.45	6.94%
		2	2625.2	1486.5	2642.7	2.45	7.32%
		3	2632.7	1493.0	2649.5	2.45	7.08%
		4	2633.5	1494.0	2649.5	2.45	6.98%
		5	2625.6	1488.9	2644.4	2.45	7.25%
		6	2626.5	1496.1	2647.4	2.45	6.88%
		7	2631.4	1495	2648.3	2.45	6.87%
		8	2628.5	1491	2646.2	2.45	7.13%
		9	2627.5	1493.6	2647.4	2.45	7.05%
		10	2628.1	1491.9	2647.1	2.45	7.14%

Table B.7. Field Mix 2 indirect tensile strength field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	*G_{mm}	Pa (Percent Air Voids)
FM2: Indirect Tensile Strength Field-Compacted Samples	HMA	1	1109.3	638.3	1112.0	2.46	4.81%
		2	1110.9	636.7	1113.4	2.46	5.27%
		3	1111.1	637.9	1113.8	2.46	5.09%
		4	1111.4	639.8	1114.9	2.46	4.91%
		5	1108.6	637.3	1112.9	2.46	5.25%
		6	1109.4	640.7	1113.9	2.46	4.70%
		7	1113.0	640.8	1114.7	2.46	4.53%
		8	1108.4	636.4	1110.9	2.46	5.04%
		9	1108.8	636.1	1110.7	2.46	5.03%
		10	1110.3	637.8	1112.5	2.46	4.92%
	WMA	1	1128.5	645.7	1133.2	2.45	5.52%
		2	1126.1	647.9	1129.3	2.45	4.52%
		3	1128.4	645.3	1132.2	2.45	5.41%
		4	1128.5	648.5	1130.9	2.45	4.52%
		5	1126.2	649.0	1128.6	2.45	4.15%
		6	1125.0	646.8	1127.0	2.45	4.38%
		7	1121.7	645.3	1124.4	2.45	4.44%
		8	1125.5	647.8	1127.7	2.45	4.27%
		9	1128.7	652	1130.8	2.45	3.78%
		10	1125.8	649.1	1128.3	2.45	4.11%

Table B.8. Field Mix 3 dynamic modulus lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM3: Dynamic Modulus Lab-Compacted Samples	HMA	1	2621.2	1488.9	2638.2	2.28	2.44	6.53%
		2	2620.6	1486.9	2636.4	2.28	2.44	6.57%
		3	2618.5	1491.6	2642.7	2.27	2.44	6.77%
		4	2619.1	1490.5	2638.3	2.28	2.44	6.48%
		5	2620.7	1490.8	2638.9	2.28	2.44	6.45%
		6	2621.8	1488.7	2640.9	2.28	2.44	6.74%
		7	2619.2	1491.1	2639.2	2.28	2.44	6.50%
		8	2616.6	1483.1	2634.1	2.27	2.44	6.83%
		9	2622.5	1496.0	2641.0	2.29	2.44	6.13%
		10	2623.7	1491.9	2641.7	2.28	2.44	6.48%
	WMA	1	2618.2	1480.9	2633.4	2.27	2.44	6.90%
		2	2621.8	1484.5	2637.0	2.27	2.44	6.77%
		3	2619.2	1488.5	2636.3	2.28	2.44	6.48%
		4	2618.1	1485.3	2634.3	2.28	2.44	6.62%
		5	2619.7	1488.9	2637.3	2.28	2.44	6.51%
		6	2619.5	1489.2	2637.7	2.28	2.44	6.52%
		7	2617.8	1487.4	2634.6	2.28	2.44	6.48%
		8	2619.7	1488.7	2637.6	2.28	2.44	6.55%
		9	2619.3	1486.7	2636.1	2.28	2.44	6.60%
		10	2616.7	1487.4	2638.2	2.27	2.44	6.81%

Table B.9. Field Mix 3 indirect tensile strength lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM3: Indirect Tensile Strength Lab-Compacted Samples	HMA	1	1102.6	629.2	1105.7	2.31	2.44	5.17%
		2	1101.7	628.6	1104.8	2.31	2.44	5.18%
		3	1099.3	627.4	1103.1	2.31	2.44	5.29%
		4	1100.0	629.4	1103.8	2.32	2.44	4.97%
		5	1101.0	629.3	1104.3	2.32	2.44	5.00%
		6	1101.2	629.8	1105.0	2.32	2.44	5.03%
		7	1101.5	628.8	1105.5	2.31	2.44	5.30%
		8	1100.7	629.6	1104.7	2.32	2.44	5.05%
		9	1101.2	630.9	1105.0	2.32	2.44	4.81%
		10	1099.8	628.3	1103.1	2.32	2.44	5.07%
	WMA	1	1103.1	630.6	1105.8	2.32	2.44	4.86%
		2	1100.2	628.3	1104.4	2.31	2.44	5.29%
		3	1100.5	628.6	1104.5	2.31	2.44	5.23%
		4	1099.8	627.9	1104.1	2.31	2.44	5.35%
		5	1101.9	632.5	1107.8	2.32	2.44	4.99%
		6	1100.5	627.1	1104.1	2.31	2.44	5.45%
		7	1101.4	630	1106.4	2.31	2.44	5.25%
		8	1100.3	630.3	1106	2.31	2.44	5.20%
		9	1099.3	628.7	1103.5	2.32	2.44	5.11%
		10	1102.2	630	1106.8	2.31	2.44	5.26%

Table B.10. Field Mix 3 dynamic modulus field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM3: Dynamic Modulus Field-Compacted Samples	HMA	1	2606.1	1471.0	2620.1	2.27	2.44	7.05%
		2	2609.5	1477.8	2627.9	2.27	2.44	7.01%
		3	2605.3	1477.8	2628.6	2.26	2.44	7.22%
		4	2610.0	1480.0	2628.8	2.27	2.44	6.89%
		5	2607.9	1479.3	2630.1	2.27	2.44	7.12%
		6	2604.1	1474.1	2623.9	2.26	2.44	7.18%
		7	2622.5	1489.7	2639.5	2.28	2.44	6.52%
		8	2605.1	1482.1	2631.3	2.27	2.44	7.10%
		9	2607.2	1490.1	2636.1	2.28	2.44	6.76%
		10	2613.8	1492.3	2638.6	2.28	2.44	6.55%
	WMA	1	2617.8	1480.9	2629.8	2.28	2.44	6.62%
		2	2618.1	1482.6	2633.1	2.28	2.44	6.74%
		3	2605.6	1471.1	2620.4	2.27	2.44	7.09%
		4	2611.4	1484.7	2632.7	2.27	2.44	6.77%
		5	2606.2	1478.2	2625.3	2.27	2.44	6.89%
		6	2610.1	1480.7	2630.5	2.27	2.44	6.97%
		7	2610	1484.2	2630	2.28	2.44	6.64%
		8	2603	1475.8	2622.3	2.27	2.44	6.95%
		9	2611.8	1490.3	2636.5	2.28	2.44	6.61%
		10	2609.1	1488.1	2635.5	2.27	2.44	6.81%

Table B.11. Field Mix 3 indirect tensile field-compacted strength samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM3: Indirect Tensile Field-Compacted Strength Samples	**HMA**	1	1089.2	619.5	1095.2	2.29	2.44	6.16%
		2	1109.6	634.2	1113.5	2.32	2.44	5.12%
		3	1088.8	618.2	1095.5	2.28	2.44	6.51%
		4	1085.5	616.9	1093.0	2.28	2.44	6.56%
		5	1091.4	617.9	1099.9	2.26	2.44	7.20%
		6	1088.5	613.9	1098.5	2.25	2.44	7.94%
		7	1087.0	608.2	1097.0	2.22	2.44	8.86%
		8	1092.0	622.0	1097.5	2.30	2.44	5.88%
		9	1091.0	621.8	1095.8	2.30	2.44	5.67%
		10	1090.6	622.6	1096.0	2.30	2.44	5.58%
	WMA	1	1088.7	617.8	1093.8	2.29	2.44	6.26%
		2	1088.3	619.0	1094.9	2.29	2.44	6.28%
		3	1083.1	616.2	1088.2	2.29	2.44	5.95%
		4	1091.4	621.3	1096.4	2.30	2.44	5.85%
		5	1089.0	621.4	1095.1	2.30	2.44	5.78%
		6	1087.5	619.1	1094.5	2.29	2.44	6.25%
		7	1089.9	620.5	1096.5	2.29	2.44	6.16%
		8	1088.8	622.2	1094.7	2.30	2.44	5.56%
		9	1093.1	631.6	1101	2.33	2.44	4.56%
		10	1100.8	630.7	1105	2.32	2.44	4.88%

Table B.12. Field Mix 4 dynamic modulus lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM4: Dynamic Modulus Lab-Compacted Samples	HMA	1	2682.7	1532.6	2688.9	2.32	2.50	7.20%
		2	2683.9	1534.2	2690.0	2.32	2.50	7.12%
		3	2684.3	1534.6	2689.5	2.32	2.50	7.03%
		4	2682.7	1534.5	2689.2	2.32	2.50	7.07%
		5	2684.5	1535.6	2690.3	2.32	2.50	7.01%
		6	2685.0	1534.1	2690.4	2.32	2.50	7.12%
		7	2685.8	1537.6	2692.2	2.33	2.50	6.95%
		8	2684.5	1537.5	2692.1	2.33	2.50	7.00%
		9	2682.9	1534.7	2691.0	2.32	2.50	7.19%
		10	2683.9	1532.1	2689.3	2.32	2.50	7.23%
	WMA	1	2687.7	1541.2	2698.2	2.32	2.50	7.08%
		2	2686.7	1547.2	2701.6	2.33	2.50	6.91%
		3	2684.2	1542.2	2699.4	2.32	2.50	7.22%
		4	2689.5	1550.4	2703.5	2.33	2.50	6.70%
		5	2683.4	1547.1	2700.3	2.33	2.50	6.92%
		6	2686.0	1540.4	2696.1	2.32	2.50	7.03%
		7	2684.7	1548.6	2702	2.33	2.50	6.89%
		8	2683.9	1544.1	2696.7	2.33	2.50	6.86%
		9	2684.8	1541.7	2696	2.33	2.50	6.96%
		10	2683.9	1547.3	2700.2	2.33	2.50	6.88%

Table B.13. Field Mix 4 indirect tensile strength lab-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	$^*G_{mm}$	Pa (Percent Air Voids)
FM4: Indirect Tensile Strength Lab-Compacted Samples	HMA	1	1119.2	643.8	1120.8	2.35	2.50	6.15%
		2	1120.1	645.8	1120.9	2.36	2.50	5.70%
		3	1117.8	644.0	1119.3	2.35	2.50	5.93%
		4	1118.3	644.2	1119.7	2.35	2.50	5.93%
		5	1118.8	643.5	1119.9	2.35	2.50	6.06%
		6	1120.0	645.4	1121.5	2.35	2.50	5.90%
		7	1119.3	645.8	1120.8	2.36	2.50	5.74%
		8	1117.7	644.1	1120.0	2.35	2.50	6.06%
		9	1119.3	646.2	1121.0	2.36	2.50	5.70%
		10	1118.3	644.1	1120.3	2.35	2.50	6.06%
	WMA	1	1119.2	644.5	1122.6	2.34	2.50	6.36%
		2	1118.3	644.2	1120.8	2.35	2.50	6.14%
		3	1119.2	645.2	1121.6	2.35	2.50	6.03%
		4	1118.7	645.2	1122.0	2.35	2.50	6.15%
		5	1120.2	646.6	1123.7	2.35	2.50	6.08%
		6	1119.1	646.3	1122.9	2.35	2.50	6.08%
		7	1119.2	645.2	1122.8	2.34	2.50	6.26%
		8	1119	645.1	1121.9	2.35	2.50	6.12%
		9	1119.9	646.5	1122.6	2.35	2.50	5.91%
		10	1119.3	647	1122.7	2.35	2.50	5.88%

Table B.14. Field Mix 4 dynamic modulus field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM4: Dynamic Modulus Field-Compacted Samples	HMA	1	2686.9	1541.5	2698.5	2.32	2.50	7.11%
		2	2680.7	1538.9	2693.3	2.32	2.50	7.11%
		3	2681.4	1538.0	2693.7	2.32	2.50	7.19%
		4	2686.1	1542.6	2698.1	2.32	2.50	7.02%
		5	2685.6	1541.1	2695.7	2.33	2.50	6.96%
		6	2681.9	1535.1	2692.8	2.32	2.50	7.34%
		7	2683.9	1538.4	2693.1	2.32	2.50	7.03%
		8	2681.5	1536.0	2690.9	2.32	2.50	7.13%
		9	2684.3	1542.1	2696.3	2.33	2.50	6.97%
		10	2679.5	1536.7	2693.1	2.32	2.50	7.32%
	WMA	1	2685.7	1545.7	2702.4	2.32	2.50	7.13%
		2	2687.1	1550.8	2708.5	2.32	2.50	7.16%
		3	2687.6	1550.9	2709.1	2.32	2.50	7.18%
		4	2686.0	1545.5	2705.5	2.32	2.50	7.38%
		5	2686.5	1546.4	2705.3	2.32	2.50	7.27%
		6	2683.9	1548.9	2704.0	2.32	2.50	7.06%

Table B.15. Field Mix 4 indirect tensile strength field-compacted samples

		#	Dry Weight (g)	Weight in Water (g)	SSD Weight (g)	G_{mb}	*G_{mm}	Pa (Percent Air Voids)
FM4: Indirect Tensile Strength Field-Compacted Samples	HMA	1	1119.6	645.2	1123.6	2.34	2.50	6.39%
		2	1117.3	641.7	1119.8	2.34	2.50	6.52%
		3	1119.2	643.8	1123.0	2.34	2.50	6.58%
		4	1120.6	643.9	1123.3	2.34	2.50	6.50%
		5	1119.8	644.7	1122.1	2.35	2.50	6.18%
		6	1117.7	642.1	1120.4	2.34	2.50	6.53%
		7	1115.9	641.7	1119.1	2.34	2.50	6.50%
		8	1116.1	642.4	1119.7	2.34	2.50	6.47%
		9	1119.0	644.8	1122.3	2.34	2.50	6.26%
		10	1118.3	645.8	1123.7	2.34	2.50	6.40%
	WMA	1	1116.7	646.8	1121.6	2.35	2.50	5.92%
		2	1116.8	646.3	1121.1	2.35	2.50	5.91%
		3	1117.7	646.5	1122.6	2.35	2.50	6.10%
		4	1119.2	648.8	1123.2	2.36	2.50	5.63%
		5	1118.0	646.1	1124.1	2.34	2.50	6.44%
		6	1118.0	647.6	1123.5	2.35	2.50	6.03%

APPENDIX C. INDIRECT TENSILE STRENGTH AND TENSILE STRENGTH RATIO DATA

Table C.1. Field Mix 1 WMA indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM1 W9 L	FM1 W8 L	FM1W4 L	FM1 W5 L	FM1 W3 L	FM1 W10 L	FM1 W2 L	FM1 W6 L	FM1 W7 L	FM1 W1 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.3	62.3	62.3	62.4	62.5	62.39	62.37	62.27	62.45	62.42
Dry Mass in Air (A), g	1124.8	1121.6	1122.5	1122.4	1121.3	1124.8	1123.4	1122.9	1121.2	1122
SSD Mass (B), g	1127	1124.7	1125.5	1126.6	1125.1	1127	1125.6	1126.3	1124.5	1124.2
Submerged Mass (C), g	647.9	646.6	646.3	647.1	644.3	647.9	646.3	646.7	645.5	643.2
Volume (E=B-C), cm^3	479.1	478.1	479.2	479.5	480.8	479.1	479.3	479.6	479	481
Bulk specific Gravity (G_{mb} = A/E)	2.35	2.35	2.34	2.34	2.33	2.35	2.34	2.34	2.34	2.33
Maximum Specific Gravity (G_{mm})	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.56	4.64	4.78	4.85	5.20	4.52	4.68	4.79	4.81	5.14
Volume of Air Voids (Va = PaE/100), cm^3	21.86	22.17	22.90	23.24	24.99	21.68	22.45	22.95	23.04	24.72
Vacuum Saturation Conditions										
SSD Mass, g	1143.00	1139.30	1139.80	1140.70	1139.10	Not Applicable				
Volume of Absorbed Water, cm^3	16.70	17.70	17.30	18.30	17.80					
% Saturation	75.72	79.86	75.55	78.74	71.24					
Tensile Strength Calculations										
Failure Load, N	11,498	10,877	10,697	9,888	9,455	10,275	10,033	9,992	10,103	10,279
Dry Strength [2000P/πtD)], kPa (psi)						1,048	1,024	1,021	1,030	1,048
Wet Strength [2000P'/πt'D] (psi)	1,174	1,112	1,093	1,009	964					
TSR (S_2/S_1)	1.12	1.09	1.07	0.98	0.92					
Average Strength	10,483					10,136				
Average TSR	1.03									

Table C.2. Field Mix 1 HMA indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					Unconditioned Samples				
Sample Identification	FM1 H3 L	FM1 H1 L	FM1 H2 L	FM1 H6 L	FM1 H10 L	FM1 H4 L	FM1 H7 L	FM1 H9 L	FM1 H8 L	FM1 H5 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.5	62.4	62.4	62.4	62.4	62.4	62.3	62.4	62.4
Dry Mass in Air (A), g	1125.1	1120	1119.5	1118.6	1117.8	1119.1	1118.3	1119	1119.6	1118.8
SSD Mass (B), g	1129.1	1122.6	1123.3	1121.6	1120.2	1123	1121	1122.3	1123.2	1123.2
Submerged Mass (C), g	649.8	644.3	644.7	642.6	640.6	645.7	643.1	643.2	643	643
Volume (E=B-C), cm^3	479.3	478.3	478.6	479	479.6	477.3	477.9	479.1	480.2	480.2
Bulk specific Gravity (G_{mb} = A/E)	2.35	2.34	2.34	2.34	2.33	2.34	2.34	2.34	2.33	2.33
Maximum Specific Gravity (G_{mm})	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.58	4.81	4.91	5.07	5.26	4.65	4.84	5.02	5.18	5.25
Volume of Air Voids (Va = PaE/100), cm^3	21.94	23.02	23.52	24.28	25.21	22.20	23.12	24.04	24.89	25.22
Vacuum Saturation Conditions										
SSD Mass, g	1141.30	1137.30	1136.70	1137.90	1136.60	Not Applicable				
Volume of Absorbed Water, cm^3	16.20	17.30	17.20	19.30	18.80					
% Saturation	73.83	75.17	73.13	79.47	74.57					
Tensile Strength Calculations										
Failure Load, N	15,422	13,976	13,844	11,851	11,105	14,293	10,371	10,692	10,670	14,379
Dry Strength [2000P/πtD)], kPa (psi)						1,458	1,058	1,093	1,088	1,467
Wet Strength [2000P'/πt'D] (psi)	1572.05	1423.58	1412.93	1209.97	1132.54					
TSR (S_2/S_1)	1.08	1.35	1.29	1.11	0.77					
Average Strength	13239.60					12,081				
Average TSR	1.12									

Table C.3. Field Mix 2 WMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM2 W6 L	FM2 W4 L	FM2 W2 L	FM2 W8 L	FM2 W1 L	FM2 W7 L	FM2 W9 L	FM2 W5 L	FM2 W3 L	FM2 W10 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	100.00	100.00	100.00	100.00	100.00	62.2	62.5	62.5	62.5	62.5
Dry Mass in Air (A), g	1126.4	1124.5	1126.3	1124.7	1124.5	1125.3	1126.4	1125	1125.1	1124.5
SSD Mass (B), g	1128.1	1127.5	1128.7	1126.4	1127	1126.5	1128.5	1127	1126.9	1127
Submerged Mass (C), g	650.1	649.2	649.6	646.8	648.5	648.2	649.7	646.7	647.2	648.5
Volume (E=B-C), cm^3	478	478.3	479.1	479.6	478.5	478.3	478.8	480.3	479.7	478.5
Bulk specific Gravity (G_{mb} = A/E)	2.36	2.35	2.35	2.35	2.35	2.35	2.35	2.34	2.35	2.35
Maximum Specific Gravity (G_{mm})	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	3.82	4.04	4.05	4.28	4.08	3.97	3.98	4.40	4.27	4.08
Volume of Air Voids (Va = PaE/100), cm^3	18.24	19.32	19.39	20.54	19.52	18.99	19.04	21.12	20.48	19.52
Vacuum Saturation Conditions										
SSD Mass, g	1139.7	1139.9	1141.1	1140.2	1139.4	Not Applicable				
Volume of Absorbed Water, cm^3	13.3	15.4	14.8	15.5	14.9					
% Saturation	72.9	79.7	76.3	75.5	76.3					
Tensile Strength Calculations										
Failure Load, N	8559.00	7859.00	7450.00	8075.00	7460.00	9,399	9,478	8,774	8,170	8,876
Dry Strength [2000P/πtD)], kPa (psi)						962.71	965.78	894.14	832.46	904.05
Wet Strength [2000P'/πt'D] (psi)	871.16	801.02	757.76	822.12	759.18					
TSR (S_2/S_1)	0.90	0.83	0.85	0.99	0.84					
Average Strength	7881					8939				
Average TSR	0.88									

Table C.4. Field Mix 2 HMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM2 H8 L	FM2 H9 L	FM2 H10 L	FM2 H2 L	FM2 H3 L	FM2 H6 L	FM2 H5 L	FM2 H7 L	FM2 H1 L	FM2 H4 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	100.00	100.00	100.00	100.00	100.00	62.4	62.4	62.6	62.5	62.6
Dry Mass in Air (A), g	1110.2	1109.9	1110.7	1110.2	1100.1	1107.3	1111	1108.2	1108.5	1107.1
SSD Mass (B), g	1113.1	1113.3	1115.6	1113.1	1103.3	1110.5	1114	1111.2	1112.2	1110.2
Submerged Mass (C), g	638.7	637.4	639.2	635.1	627	636.6	637.3	635.2	634	630.7
Volume (E=B-C), cm^3	474.4	475.9	476.4	478	476.3	473.9	476.7	476	478.2	479.5
Bulk specific Gravity (G_{mb} = A/E)	2.34	2.33	2.33	2.32	2.31	2.34	2.33	2.33	2.32	2.31
Maximum Specific Gravity (G_{mm})	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.87	5.19	5.23	5.59	6.11	5.02	5.26	5.36	5.77	6.14
Volume of Air Voids (Va = PaE/100), cm^3	23.10	24.72	24.90	26.70	29.10	23.78	25.07	25.51	27.59	29.46
Vacuum Saturation Conditions										
SSD Mass, g	1128.10	1129.50	1129.40	1131.40	1123.10	Not Applicable				
Volume of Absorbed Water, cm^3	17.90	19.60	18.70	21.20	23.00					
% Saturation	77.49	79.28	75.11	79.40	79.02					
Tensile Strength Calculations										
Failure Load, N	7,753	7,436	7,707	7,034	6,894	8,382	8,508	7,887	7,784	7,127
Dry Strength [2000P/πtD)], kPa (psi)						855	867	803	793	725
Wet Strength [2000P'/πt'D] (psi)	789	756	785	713	702					
TSR (S_2/S_1)	0.92	0.87	0.98	0.90	0.97					
Average Strength	7365					7938				
Average TSR	0.93									

Table C.5. Field Mix 2 WMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					Unconditioned Samples				
Sample Identification	FM2 W9 F	FM2 W5 F	FM2 W6 F	FM2 W4 F	FM2 W3 F	FM2 W10 F	FM2 W8 F	FM2 W7 F	FM2 W2 F	FM2 W1 F
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.4	62.3	62.4	62.9	63.1	62.5	62.4	62.4	62.6	63.7
Dry Mass in Air (A), g	1128.7	1126.2	1125	1128.5	1128.4	1125.8	1125.5	1121.7	1126.1	1128.5
SSD Mass (B), g	1130.8	1128.6	1127	1130.9	1132.2	1128.3	1127.7	1124.4	1129.3	1133.2
Submerged Mass (C), g	652	649	646.8	648.5	645.3	649.1	647.8	645.3	647.9	645.7
Volume (E=B-C), cm^3	478.8	479.6	480.2	482.4	486.9	479.2	479.9	479.1	481.4	487.5
Bulk specific Gravity (G_{mb} = A/E)	2.36	2.35	2.34	2.34	2.32	2.35	2.35	2.34	2.34	2.31
Maximum Specific Gravity (G_{mm})	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	3.78	4.15	4.38	4.52	5.41	4.11	4.27	4.44	4.52	5.52
Volume of Air Voids (Va = PaE/100), cm^3	18.11	19.93	21.02	21.79	26.33	19.69	20.51	21.26	21.77	26.89
Vacuum Saturation Conditions										
SSD Mass, g	1142.20	1141.50	1141.50	1145.60	1148.70	Not Applicable				
Volume of Absorbed Water, cm^3	13.50	15.30	16.50	17.10	20.30					
% Saturation	74.56	76.78	78.51	78.48	77.10					
Tensile Strength Calculations										
Failure Load, N	7704.00	7617.00	6945.00	6243.00	6642.00	8,720	8,489	7,986	8,228	7,274
Dry Strength [2000P/πtD)], kPa (psi)						888.54	865.98	815.10	836.89	727.16
Wet Strength [2000P'/πt'D] (psi)	786.02	777.81	708.21	631.93	670.26					
TSR (S_2/S_1)	0.88	0.90	0.87	0.76	0.92					
Average Strength	7030					8139				
Average TSR	0.87									

Table C.6. Field Mix 2 HMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					Unconditioned Samples				
Sample Identification	FM2 H7 F	FM2 H1 F	FM2 H10 F	FM2 H8 F	FM2 H5 F	FM2 H6 F	FM2 H4 F	FM2 H9 F	FM2 H3 F	FM2 H2 F
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.4	62.5	62.4	62.6	62.52	62.46	62.41	62.40	62.42
Dry Mass in Air (A), g	1113	1109.3	1110.3	1108.4	1108.6	1109.4	1111.4	1108.8	1111.1	1110.9
SSD Mass (B), g	1114.7	1112	1112.5	1110.9	1112.9	1113.9	1114.9	1110.7	1113.8	1113.4
Submerged Mass (C), g	640.8	638.3	637.8	636.4	637.3	640.7	639.8	636.1	637.9	636.7
Volume (E=B-C), cm^3	473.9	473.7	474.7	474.5	475.6	473.2	475.1	474.6	475.9	476.7
Bulk specific Gravity (G_{mb} = A/E)	2.35	2.34	2.34	2.34	2.33	2.34	2.34	2.34	2.33	2.33
Maximum Specific Gravity (G_{mm})	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46	2.46
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.53	4.81	4.92	5.04	5.25	4.70	4.91	5.03	5.09	5.27
Volume of Air Voids (Va = PaE/100), cm^3	21.46	22.77	23.36	23.93	24.95	22.22	23.31	23.87	24.23	25.11
Vacuum Saturation Conditions										
SSD Mass, g	1129.20	1127.10	1128.60	1127.50	1128.30	Not Applicable				
Volume of Absorbed Water, cm^3	16.20	17.80	18.30	19.10	19.70					
% Saturation	75.49	78.19	78.34	79.81	78.96					
Tensile Strength Calculations										
Failure Load, N	8119.00	6362.00	7721.00	7485.00	7506.00	7,422	7,242	7,853	7,022	6,944
Dry Strength [2000P/πtD)], kPa (psi)						755.76	738.14	801.01	716.36	708.22
Wet Strength [2000P'/πt'D] (psi)	826.77	648.62	786.37	763.35	763.78					
TSR (S_2/S_1)	1.09	0.88	0.98	1.07	1.08					
Average Strength	7439					7297				
Average TSR	1.02									

Table C.7. Field Mix 3 WMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM3 W1 L	FM3 W9 L	FM3 W3 L	FM3 W10 L	FM3 W4 L	FM3 W5 L	FM3 W8 L	FM3 W7 L	FM3 W2 L	FM3 W6 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.5	62.6	62.5	62.6	62.5	62.5	62.5	62.4	62.5
Dry Mass in Air (A), g	1103.1	1099.3	1100.5	1102.2	1099.8	1101.9	1100.3	1101.4	1100.2	1100.5
SSD Mass (B), g	1105.8	1103.5	1104.5	1106.8	1104.1	1107.8	1106	1106.4	1104.4	1104.1
Submerged Mass (C), g	630.6	628.7	628.6	630	627.9	632.5	630.3	630	628.3	627.1
Volume (E=B-C), cm^3	475.2	474.8	475.9	476.8	476.2	475.3	475.7	476.4	476.1	477
Bulk specific Gravity (G_{mb} = A/E)	2.32	2.32	2.31	2.31	2.31	2.32	2.31	2.31	2.31	2.31
Maximum Specific Gravity (G_{mm})	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.86	5.11	5.23	5.26	5.35	4.99	5.20	5.25	5.29	5.45
Volume of Air Voids (Va = PaE/100), cm^3	23.11	24.27	24.88	25.08	25.46	23.70	24.76	25.01	25.20	25.98
Vacuum Saturation Conditions										
SSD Mass, g	1120.70	1117.10	1119.90	1122.10	1119.70	Not Applicable				
Volume of Absorbed Water, cm^3	17.60	17.80	19.40	19.90	19.90					
% Saturation	76.16	73.35	77.99	79.35	78.15					
Tensile Strength Calculations										
Failure Load, N	7500	7820	8246	7300	7714	8,118	8,659	8,466	8,318	8,750
Dry Strength [2000P/πtD)], kPa (psi)						827.25	882.56	862.62	848.71	891.03
Wet Strength [2000P'/πt'D] (psi)	764.23	796.67	839.08	743.37	784.70					
TSR (S_2/S_1)	0.92	0.90	0.97	0.88	0.88					
Average Strength	7716					8,462				
Average TSR	0.91									

Table C.8. Field Mix 3 WMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM3 H9 L	FM3 H5 L	FM3 H8 L	FM3 H1 L	FM3 H3 L	FM3 H4 L	FM3 H6 L	FM3 H10 L	FM3 H2 L	FM3 H7 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.4	62.5	62.5	62.5	100.00	100.00	100.00	100.00	100.00
Dry Mass in Air (A), g	1101.2	1101	1100.7	1102.6	1101.5	1100	1101.2	1099.8	1101.7	1101.5
SSD Mass (B), g	1105	1104.3	1104.7	1105.7	1105.5	1103.8	1105	1103.1	1104.8	1105.5
Submerged Mass (C), g	630.9	629.3	629.6	629.2	628.8	629.4	629.8	628.3	628.6	628.8
Volume (E=B-C), cm^3	474.1	475	475.1	476.5	476.7	474.4	475.2	474.8	476.2	476.7
Bulk specific Gravity ($G_{mb} = A/E$)	2.32	2.32	2.32	2.31	2.31	2.32	2.32	2.32	2.31	2.31
Maximum Specific Gravity (G_{mm})	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44
% Air Voids [$Pa = 100 (G_{mm}-G_{mb})/G_{mm}$]	4.81	5.00	5.05	5.17	5.30	4.97	5.03	5.07	5.18	5.30
Volume of Air Voids ($Va = PaE/100$), cm^3	22.79	23.77	23.99	24.61	25.27	23.58	23.89	24.06	24.68	25.27
Vacuum Saturation Conditions										
SSD Mass, g	1118.60	1119.10	1118.20	1121.70	1121.30	Not Applicable				
Volume of Absorbed Water, cm^3	17.40	18.10	17.50	19.10	19.80					
% Saturation	76.35	76.14	72.94	77.60	78.37					
Tensile Strength Calculations										
Failure Load, N	10,160	10,580	10,470	10,628	10,256	10,610	10,892	11,408	10,604	10,974
Dry Strength [2000P/πtD)], kPa (psi)						1,081	1,110	1,163	1,080	1,119
Wet Strength [2000P'/πt'D] (psi)	1,035	1,079	1,066	1,082	1,045					
TSR (S_2/S_1)	0.96	0.97	0.92	1.00	0.93					
Average Strength	10,419					10,898				
Average TSR	0.96									

Table C.9. Field Mix 3 WMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					Unconditioned Samples				
Sample Identification	FM3 W9 F	FM3 W8 F	FM3 W4 F	FM3 W7 F	FM3 W1 F	FM3 W10 F	FM3 W5 F	FM3 W3 F	FM3 W6 F	FM3 W2 F
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.6	62.6	62.5	62.6	62.4	62.3	62.4	62.5	62.5
Dry Mass in Air (A), g	1093.1	1088.8	1091.4	1089.9	1088.7	1100.8	1089	1083.1	1087.5	1088.3
SSD Mass (B), g	1101	1094.7	1096.4	1096.5	1093.8	1105	1095.1	1088.2	1094.5	1094.9
Submerged Mass (C), g	631.6	622.2	621.3	620.5	617.8	630.7	621.4	616.2	619.1	619
Volume (E=B-C), cm^3	469.4	472.5	475.1	476	476	474.3	473.7	472	475.4	475.9
Bulk specific Gravity (G_{mb} = A/E)	2.33	2.30	2.30	2.29	2.29	2.32	2.30	2.29	2.29	2.29
Maximum Specific Gravity (G_{mm})	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	4.56	5.56	5.85	6.16	6.26	4.88	5.78	5.95	6.25	6.28
Volume of Air Voids (Va = PaE/100), cm^3	21.41	26.27	27.80	29.32	29.81	23.15	27.39	28.11	29.70	29.88
Vacuum Saturation Conditions										
SSD Mass, g	1109.90	1107.80	1113.60	1113.10	1111.50	Not Applicable				
Volume of Absorbed Water, cm^3	16.80	19.00	22.20	23.20	22.80					
% Saturation	78.47	72.32	79.84	79.13	76.48					
Tensile Strength Calculations										
Failure Load, N	6434.00	7494.00	6323.00	5876.00	6797.00	8,193	7,429	8,668	7,660	8,893
Dry Strength [2000P/πtD)], kPa (psi)						836.00	758.61	884.00	780.45	906.17
Wet Strength [2000P'/πt'D] (psi)	655.15	761.55	643.51	598.27	691.23					
TSR (S_2/S_1)	0.78	1.00	0.73	0.77	0.76					
Average Strength	6585					8169				
Average TSR	0.81									

Table C.10. Field Mix 3 HMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM3 H2 F	FM3 H9 F	FM3 H1 F	FM3 H4 F	FM3 H6 F	FM3 H10 F	FM3 H8 F	FM3 H3 F	FM3 H5 F	FM3 H7 F
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.5	62.5	62.5	62.5	64.4	100.00	100.00	100.00	100.00	100.00
Dry Mass in Air (A), g	1109.6	1091	1089.2	1085.5	1088.5	1090.6	1092	1088.8	1091.4	1087
SSD Mass (B), g	1113.5	1095.8	1095.2	1093	1098.5	1096	1097.5	1095.5	1099.9	1097
Submerged Mass (C), g	634.2	621.8	619.5	616.9	613.9	622.6	622	618.2	617.9	608.2
Volume (E=B-C), cm^3	479.3	474	475.7	476.1	484.6	473.4	475.5	477.3	482	488.8
Bulk specific Gravity (G_{mb} = A/E)	2.32	2.30	2.29	2.28	2.25	2.30	2.30	2.28	2.26	2.22
Maximum Specific Gravity (G_{mm})	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44	2.44
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	5.12	5.67	6.16	6.56	7.94	5.58	5.88	6.51	7.20	8.86
Volume of Air Voids (Va = PaE/100), cm^3	24.55	26.87	29.31	31.22	38.49	26.43	27.96	31.07	34.70	43.31
Vacuum Saturation Conditions										
SSD Mass, g	1128.10	1112.00	1112.30	1110.10	1119.10	Not Applicable				
Volume of Absorbed Water, cm^3	18.50	21.00	23.10	24.60	30.60					
% Saturation	75.37	78.16	78.82	78.79	79.49					
Tensile Strength Calculations										
Failure Load, N	9,549	9,719	9,761	11,274	9,393	10,490	10,468	10,708	10,265	9,234
Dry Strength [2000P/πtD)], kPa (psi)						1,069	1,067	1,092	1,032	900
Wet Strength [2000P'/πt'D] (psi)	972	990	994	1,149	929					
TSR (S_2/S_1)	0.91	0.93	0.91	1.11	1.03					
Average Strength	9939					10233				
Average TSR	0.98									

Table C.11. Field Mix 4 WMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					Unconditioned Samples				
Sample Identification	FM4 W10 L	FM4 W3 L	FM4 W5 L	FM4 W2 L	FM4 W7 L	FM4 W9 L	FM4 W6 L	FM4 W8 L	FM4 W4 L	FM4 W1 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.4	62.5	62.5	62.5	62.5	62.3	62.3	62.4	62.4	62.4
Dry Mass in Air (A), g	1119.3	1119.2	1120.2	1118.3	1119.2	1119.9	1119.1	1119.0	1118.7	1119.2
SSD Mass (B), g	1122.7	1121.6	1123.7	1120.8	1122.8	1122.6	1122.9	1121.9	1122	1122.6
Submerged Mass (C), g	647	645.2	646.6	644.2	645.2	646.5	646.3	645.1	645.2	644.5
Volume (E=B-C), cm^3	475.7	476.4	477.1	476.6	477.6	476.1	476.6	476.8	476.8	478.1
Bulk specific Gravity (G_{mb} = A/E)	2.35	2.35	2.35	2.35	2.34	2.35	2.35	2.35	2.35	2.34
Maximum Specific Gravity (G_{mm})	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	5.88	6.03	6.08	6.14	6.26	5.91	6.08	6.12	6.15	6.36
Volume of Air Voids (Va = PaE/100), cm^3	27.98	28.72	29.02	29.28	29.92	28.14	28.96	29.20	29.32	30.42
Vacuum Saturation Conditions										
SSD Mass, g	1142.10	1141.80	1141.30	1141.80	1142.60	Not Applicable				
Volume of Absorbed Water, cm^3	22.20	22.70	22.30	23.10	23.40					
% Saturation	79.34	79.04	76.84	78.89	78.21					
Tensile Strength Calculations										
Failure Load, N	9856.00	9917.00	11188.00	10755.00	9908.00	12,042	12,250	12,154	12,943	11,970
Dry Strength [2000P/πtD)], kPa (psi)						1229.67	1251.38	1240.18	1319.91	1220.43
Wet Strength [2000P'/πt'D] (psi)	1005.00	1010.95	1138.99	1095.79	1009.28					
TSR (S_2/S_1)	0.82	0.81	0.92	0.83	0.83					
Average Strength	10324.80					12,272				
Average TSR	0.84									

Table C.12. Field Mix 4 HMA lab-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM4 H2 L	FM4 H7 L	FM4 H4 L	FM4 H8 L	FM4 H10 L	FM4 H9 L	FM4 H6 L	FM4 H3 L	FM4 H5 L	FM4 H1 L
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.4	62.4	62.3	62.3	62.3	62.28	62.57	62.30	62.32	62.49
Dry Mass in Air (A), g	1120.1	1119.3	1118.3	1117.7	1118.3	1119.3	1120	1117.8	1118.8	1119.2
SSD Mass (B), g	1120.9	1120.8	1119.7	1120	1120.3	1121	1121.5	1119.3	1119.9	1120.8
Submerged Mass (C), g	645.8	645.8	644.2	644.1	644.1	646.2	645.4	644	643.5	643.8
Volume (E=B-C), cm^3	475.1	475	475.5	475.9	476.2	474.8	476.1	475.3	476.4	477
Bulk specific Gravity (G_{mb} = A/E)	2.36	2.36	2.35	2.35	2.35	2.36	2.35	2.35	2.35	2.35
Maximum Specific Gravity (G_{mm})	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
% Air Voids [$P_a = 100 (G_{mm}-G_{mb})/G_{mm}$]	5.70	5.74	5.93	6.06	6.06	5.70	5.90	5.93	6.06	6.15
Volume of Air Voids (Va = PaE/100), cm^3	27.06	27.28	28.18	28.82	28.88	27.08	28.10	28.18	28.88	29.32
Vacuum Saturation Conditions										
SSD Mass, g	1138.40	1139.30	1137.90	1140.20	1140.70	Not Applicable				
Volume of Absorbed Water, cm^3	19.10	19.30	20.10	21.40	21.50					
% Saturation	70.58	70.75	71.33	74.25	74.45					
Tensile Strength Calculations										
Failure Load, N	11,787	12,130	11,493	11,509	11,362	12,860	12,659	12,886	12,810	12,492
Dry Strength [2000P/πtD)], kPa (psi)						1,315	1,288	1,317	1,309	1,273
Wet Strength [2000P'/πt'D] (psi)	1,202	1,238	1,175	1,176	1,162					
TSR (S_2/S_1)	0.91	0.96	0.89	0.90	0.91					
Average Strength	11,656					12,741				
Average TSR	0.92									

Table C.13. Field Mix 4 WMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples			**Unconditioned Samples**		
Sample Identification	FM4 W4 F	FM4 W1 F	FM4 W3 F	FM4 W2 F	FM4 W6 F	FM4 W5 F
Diameter (D), mm	100	100	100	100	100	100
Thickness (t), mm	62.5	62.4	62.4	62.5	62.3	62.4
Dry Mass in Air (A), g	1119.2	1116.7	1117.7	1116.8	1118	1118
SSD Mass (B), g	1123.2	1121.6	1122.6	1121.1	1123.5	1124.1
Submerged Mass (C), g	648.8	646.8	646.5	646.3	647.6	646.1
Volume (E=B-C), cm^3	474.4	474.8	476.1	474.8	475.9	478
Bulk specific Gravity (G_{mb} = A/E)	2.36	2.35	2.35	2.35	2.35	2.34
Maximum Specific Gravity (G_{mm})	2.50	2.50	2.50	2.50	2.50	2.50
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	5.63	5.92	6.10	5.91	6.03	6.44
Volume of Air Voids (Va = PaE/100), cm^3	26.72	28.12	29.02	28.08	28.70	30.80
Vacuum Saturation Conditions						
SSD Mass, g	1137.50	1140.20	1139.80	Not Applicable		
Volume of Absorbed Water, cm^3	20.70	22.20	21.80			
% Saturation	77.47	78.95	75.12			
Tensile Strength Calculations						
Failure Load, N	11215.33	11068.33	10921.33	10,270	10,366	10,798
Dry Strength [2000P/πtD)], kPa (psi)				1046.82	1058.64	1100.99
Wet Strength [2000P'/πt'D] (psi)	1142.08	1129.52	1114.22			
TSR (S_2/S_1)	1.09	1.07	1.01			
Average Strength	11068.33			10,478		
Average TSR	1.06					

Table C.14. Field Mix 4 HMA field-compacted indirect tensile strength and tensile strength ratio data

	Moisture-Conditioned Samples					**Unconditioned Samples**				
Sample Identification	FM4 H5 F	FM4 H1 F	FM4 H8 F	FM4 H7 F	FM4 H6 F	FM4 H9 F	FM4 H10 F	FM4 H4 F	FM4 H2 F	FM4 H3 F
Diameter (D), mm	100	100	100	100	100	100	100	100	100	100
Thickness (t), mm	62.6	62.5	62.5	62.6	62.5	62.47	62.41	62.50	62.45	62.55
Dry Mass in Air (A), g	1119.8	1119.6	1116.1	1115.9	1117.7	1119	1118.3	1120.6	1117.3	1119.2
SSD Mass (B), g	1122.1	1123.6	1119.7	1119.1	1120.4	1122.3	1123.7	1123.3	1119.8	1123
Submerged Mass (C), g	644.7	645.2	642.4	641.7	642.1	644.8	645.8	643.9	641.7	643.8
Volume (E=B-C), cm^3	477.4	478.4	477.3	477.4	478.3	477.5	477.9	479.4	478.1	479.2
Bulk specific Gravity (G_{mb} = A/E)	2.35	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34
Maximum Specific Gravity (G_{mm})	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
% Air Voids [Pa = 100 (G_{mm}-G_{mb})/G_{mm}]	6.18	6.39	6.47	6.50	6.53	6.26	6.40	6.50	6.52	6.58
Volume of Air Voids (Va = PaE/100), cm^3	29.48	30.56	30.86	31.04	31.22	29.90	30.58	31.16	31.18	31.52
Vacuum Saturation Conditions										
SSD Mass, g	1140.20	1140.50	1142.70	1141.80	1141.30	Not Applicable				
Volume of Absorbed Water, cm^3	21.20	22.20	22.10	24.50	22.10					
% Saturation	71.91	72.64	71.61	78.93	70.79					
Tensile Strength Calculations										
Failure Load, N	10,774	10,627	10,480	10,333	10,186	12,412	13,154	12,029	11,633	11,019
Dry Strength [2000P/πtD)], kPa (psi)						1,265	1,342	1,225	1,186	1,121
Wet Strength [2000P'/πt'D] (psi)	1,096	1,082	1,067	1,052	1,038					
TSR (S_2/S_1)	0.87	0.81	0.87	0.89	0.93					
Average Strength	10,480					12,049				
Average TSR	0.87									

APPENDIX D. DYNAMIC MODULUS VALUES

Table D.1. Field Mix 1 dynamic modulus values (kPa)

Mix	Temp °C	Moisture Conditioned	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Hot Mix Field	**4**	**Y**	**1.72E+07**	**1.59E+07**	**1.52E+07**	**1.42E+07**	**1.33E+07**	**1.16E+07**	**1.08E+07**	**1.01E+07**	**8.33E+06**
Hot Mix Field	**21**	**Y**	**7.82E+06**	**6.89E+06**	**6.37E+06**	**5.48E+06**	**4.55E+06**	**3.29E+06**	**2.82E+06**	**2.51E+06**	**1.69E+06**
Hot Mix Field	**37**	**Y**	**2.79E+06**	**2.38E+06**	**2.07E+06**	**1.64E+06**	**1.21E+06**	**8.48E+05**	**6.36E+05**	**5.33E+05**	**3.85E+05**
Hot Mix Field	**4**	**N**	**1.80E+07**	**1.72E+07**	**1.59E+07**	**1.50E+07**	**1.43E+07**	**1.23E+07**	**1.12E+07**	**1.06E+07**	**8.65E+06**
Hot Mix Field	**21**	**N**	**7.89E+06**	**7.06E+06**	**6.48E+06**	**5.58E+06**	**4.68E+06**	**3.57E+06**	**3.09E+06**	**2.70E+06**	**1.87E+06**
Hot Mix Field	**37**	**N**	**2.97E+06**	**2.47E+06**	**2.16E+06**	**1.72E+06**	**1.27E+06**	**8.81E+05**	**6.60E+05**	**5.52E+05**	**3.97E+05**
Warm Mix Field	**4**	**Y**	**1.46E+07**	**1.35E+07**	**1.27E+07**	**1.15E+07**	**1.06E+07**	**8.93E+06**	**7.95E+06**	**7.52E+06**	**5.96E+06**
Warm Mix Field	**21**	**Y**	**6.02E+06**	**5.34E+06**	**4.81E+06**	**4.10E+06**	**3.33E+06**	**2.49E+06**	**2.11E+06**	**1.77E+06**	**1.21E+06**
Warm Mix Field	**37**	**Y**	**1.95E+06**	**1.63E+06**	**1.43E+06**	**1.14E+06**	**8.33E+05**	**6.16E+05**	**4.55E+05**	**3.89E+05**	**2.95E+05**
Warm Mix Field	**4**	**N**	**1.75E+07**	**1.59E+07**	**1.62E+07**	**1.48E+07**	**1.38E+07**	**1.18E+07**	**1.08E+07**	**1.00E+07**	**8.12E+06**
Warm Mix Field	**21**	**N**	**7.62E+06**	**6.83E+06**	**6.25E+06**	**5.32E+06**	**4.05E+06**	**3.28E+06**	**2.79E+06**	**2.39E+06**	**1.70E+06**
Warm Mix Field	**37**	**N**	**2.64E+06**	**2.20E+06**	**1.92E+06**	**1.54E+06**	**1.09E+06**	**7.65E+05**	**5.74E+05**	**4.81E+05**	**3.49E+05**
Hot Mix Lab	**4**	**Y**	**1.72E+07**	**1.63E+07**	**1.55E+07**	**1.43E+07**	**1.36E+07**	**1.16E+07**	**1.07E+07**	**9.96E+06**	**8.19E+06**
Hot Mix Lab	**21**	**Y**	**7.74E+06**	**7.12E+06**	**6.55E+06**	**5.64E+06**	**4.66E+06**	**3.57E+06**	**2.98E+06**	**2.67E+06**	**1.83E+06**
Hot Mix Lab	**37**	**Y**	**2.63E+06**	**2.21E+06**	**1.95E+06**	**1.56E+06**	**1.15E+06**	**8.27E+05**	**6.30E+05**	**5.31E+05**	**3.87E+05**
Hot Mix Lab	**4**	**N**	**1.96E+07**	**1.83E+07**	**1.76E+07**	**1.66E+07**	**1.61E+07**	**1.38E+07**	**1.28E+07**	**1.19E+07**	**9.71E+06**
Hot Mix Lab	**21**	**N**	**9.24E+06**	**8.50E+06**	**7.80E+06**	**6.82E+06**	**5.84E+06**	**4.51E+06**	**3.91E+06**	**3.46E+06**	**2.46E+06**
Hot Mix Lab	**37**	**N**	**3.41E+06**	**2.84E+06**	**2.48E+06**	**1.97E+06**	**1.45E+06**	**1.02E+06**	**7.66E+05**	**6.33E+05**	**4.39E+05**
Warm Mix Lab	**4**	**Y**	**1.71E+07**	**1.53E+07**	**1.47E+07**	**1.36E+07**	**1.28E+07**	**1.06E+07**	**9.69E+06**	**9.11E+06**	**7.24E+06**
Warm Mix Lab	**21**	**Y**	**7.18E+06**	**6.37E+06**	**5.76E+06**	**4.89E+06**	**3.97E+06**	**3.01E+06**	**2.58E+06**	**2.21E+06**	**1.54E+06**
Warm Mix Lab	**37**	**Y**	**2.22E+06**	**1.85E+06**	**1.62E+06**	**1.30E+06**	**9.61E+05**	**6.93E+05**	**5.34E+05**	**4.57E+05**	**3.48E+05**
Warm Mix Lab	**4**	**N**	**1.83E+07**	**1.72E+07**	**1.65E+07**	**1.51E+07**	**1.42E+07**	**1.19E+07**	**1.09E+07**	**1.01E+07**	**8.03E+06**
Warm Mix Lab	**21**	**N**	**8.38E+06**	**7.52E+06**	**6.87E+06**	**5.84E+06**	**4.82E+06**	**3.63E+06**	**3.08E+06**	**2.65E+06**	**1.86E+06**
Warm Mix Lab	**37**	**N**	**2.76E+06**	**2.27E+06**	**1.97E+06**	**1.55E+06**	**1.15E+06**	**8.13E+05**	**6.16E+05**	**5.16E+05**	**3.76E+05**

Table D.2. Field Mix 2 dynamic modulus values (kPa)

Mix	Temp °C	Moisture Conditioned	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Hot Mix Field	4	Y	1.59E+07	1.45E+07	1.35E+07	1.23E+07	1.14E+07	9.35E+06	8.54E+06	7.80E+06	6.22E+06
Hot Mix Field	21	Y	6.80E+06	5.97E+06	5.40E+06	4.57E+06	3.72E+06	2.76E+06	2.32E+06	1.95E+06	1.42E+06
Hot Mix Field	37	Y	2.12E+06	1.75E+06	1.52E+06	1.24E+06	8.92E+05	6.77E+05	5.99E+05	5.20E+05	4.08E+05
Hot Mix Field	4	N	1.59E+07	1.43E+07	1.34E+07	1.21E+07	1.10E+07	9.10E+06	8.29E+06	7.52E+06	5.89E+06
Hot Mix Field	21	N	6.46E+06	5.57E+06	5.05E+06	4.21E+06	3.47E+06	2.53E+06	2.08E+06	1.77E+06	1.24E+06
Hot Mix Field	37	N	2.12E+06	1.75E+06	1.52E+06	1.25E+06	8.91E+05	6.78E+05	5.52E+05	4.93E+05	3.42E+05
Warm Mix Field	4	Y	1.43E+07	1.28E+07	1.20E+07	1.09E+07	9.95E+06	8.26E+06	7.26E+06	6.76E+06	5.28E+06
Warm Mix Field	21	Y	5.32E+06	4.67E+06	4.21E+06	3.54E+06	2.89E+06	2.12E+06	1.82E+06	1.45E+06	1.04E+06
Warm Mix Field	37	Y	1.94E+06	1.61E+06	1.39E+06	1.15E+06	8.31E+05	6.29E+05	5.43E+05	4.94E+05	3.75E+05
Warm Mix Field	4	N	1.64E+07	1.47E+07	1.39E+07	1.26E+07	1.14E+07	9.71E+06	8.88E+06	8.07E+06	6.42E+06
Warm Mix Field	21	N	6.88E+06	6.02E+06	5.41E+06	4.54E+06	3.70E+06	2.72E+06	2.30E+06	1.94E+06	1.53E+06
Warm Mix Field	37	N	2.17E+06	1.79E+06	1.56E+06	1.28E+06	9.11E+05	6.67E+05	5.40E+05	5.02E+05	3.96E+05
Hot Mix Lab	4	Y	1.55E+07	1.38E+07	1.29E+07	1.18E+07	1.07E+07	8.92E+06	8.15E+06	7.42E+06	5.88E+06
Hot Mix Lab	21	Y	5.78E+06	5.26E+06	4.81E+06	4.06E+06	3.31E+06	2.42E+06	2.04E+06	1.74E+06	1.25E+06
Hot Mix Lab	37	Y	2.08E+06	1.75E+06	1.56E+06	1.27E+06	9.45E+05	7.34E+05	6.16E+05	5.53E+05	4.01E+05
Hot Mix Lab	4	N	1.64E+07	1.49E+07	1.39E+07	1.26E+07	1.18E+07	9.64E+06	8.84E+06	8.03E+06	6.38E+06
Hot Mix Lab	21	N	6.67E+06	5.89E+06	5.30E+06	4.51E+06	3.65E+06	2.74E+06	2.27E+06	1.94E+06	1.36E+06
Hot Mix Lab	37	N	2.01E+06	1.65E+06	1.46E+06	1.18E+06	8.44E+05	6.63E+05	5.46E+05	5.46E+05	4.32E+05
Warm Mix Lab	4	Y	1.40E+07	1.26E+07	1.19E+07	1.08E+07	9.97E+06	8.19E+06	7.42E+06	6.76E+06	5.34E+06
Warm Mix Lab	21	Y	5.64E+06	4.98E+06	4.46E+06	3.73E+06	3.01E+06	2.19E+06	1.84E+06	1.57E+06	1.10E+06
Warm Mix Lab	37	Y	2.01E+06	1.69E+06	1.47E+06	1.21E+06	8.53E+05	6.60E+05	5.50E+05	4.87E+05	3.68E+05
Warm Mix Lab	4	N	1.53E+07	1.39E+07	1.30E+07	1.18E+07	1.09E+07	8.98E+06	8.08E+06	7.37E+06	5.76E+06
Warm Mix Lab	21	N	6.74E+06	5.78E+06	5.15E+06	4.27E+06	3.45E+06	2.50E+06	2.04E+06	1.76E+06	1.23E+06
Warm Mix Lab	37	N	1.86E+06	1.52E+06	1.39E+06	1.12E+06	8.13E+05	5.88E+05	5.02E+05	4.73E+05	2.87E+05

Table D.3. Field Mix 3 dynamic modulus values (kPa)

Mix	Temp °C	Moisture Conditioned	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Hot Mix Field	**4**	**Y**	**1.78E+07**	**1.60E+07**	**1.49E+07**	**1.38E+07**	**1.30E+07**	**1.07E+07**	**9.76E+06**	**8.96E+06**	**6.77E+06**
Hot Mix Field	**21**	**Y**	**6.98E+06**	**6.06E+06**	**5.39E+06**	**4.48E+06**	**3.54E+06**	**2.50E+06**	**2.07E+06**	**1.65E+06**	**1.00E+06**
Hot Mix Field	**37**	**Y**	**2.02E+06**	**1.62E+06**	**1.36E+06**	**1.03E+06**	**7.06E+05**	**4.72E+05**	**3.44E+05**	**2.78E+05**	**1.89E+05**
Hot Mix Field	**4**	**N**	**1.90E+07**	**1.83E+07**	**1.72E+07**	**1.57E+07**	**1.48E+07**	**1.21E+07**	**1.10E+07**	**1.03E+07**	**7.95E+06**
Hot Mix Field	**21**	**N**	**8.03E+06**	**7.07E+06**	**6.32E+06**	**5.25E+06**	**4.19E+06**	**2.97E+06**	**2.42E+06**	**1.93E+06**	**1.20E+06**
Hot Mix Field	**37**	**N**	**2.30E+06**	**1.82E+06**	**1.51E+06**	**1.15E+06**	**8.12E+05**	**5.07E+05**	**3.60E+05**	**3.56E+05**	**2.57E+05**
Warm Mix Field	**4**	**Y**	**1.67E+07**	**1.48E+07**	**1.40E+07**	**1.27E+07**	**1.19E+07**	**9.78E+06**	**8.65E+06**	**8.11E+06**	**6.09E+06**
Warm Mix Field	**21**	**Y**	**6.30E+06**	**5.48E+06**	**4.89E+06**	**4.06E+06**	**3.22E+06**	**2.27E+06**	**1.86E+06**	**1.49E+06**	**9.29E+05**
Warm Mix Field	**37**	**Y**	**2.06E+06**	**1.67E+06**	**1.40E+06**	**1.10E+06**	**7.82E+05**	**5.44E+05**	**3.85E+05**	**3.36E+05**	**2.28E+05**
Warm Mix Field	**4**	**N**	**1.85E+07**	**1.68E+07**	**1.55E+07**	**1.43E+07**	**1.33E+07**	**1.10E+07**	**9.76E+06**	**9.22E+06**	**6.94E+06**
Warm Mix Field	**21**	**N**	**7.30E+06**	**6.36E+06**	**5.63E+06**	**4.69E+06**	**3.79E+06**	**2.69E+06**	**2.20E+06**	**1.79E+06**	**1.14E+06**
Warm Mix Field	**37**	**N**	**2.14E+06**	**1.72E+06**	**1.47E+06**	**1.15E+06**	**8.42E+05**	**5.76E+05**	**4.81E+05**	**3.53E+05**	**2.75E+05**
Hot Mix Lab	**4**	**Y**	**1.90E+07**	**1.77E+07**	**1.67E+07**	**1.54E+07**	**1.47E+07**	**1.22E+07**	**1.12E+07**	**1.04E+07**	**8.14E+06**
Hot Mix Lab	**21**	**Y**	**8.00E+06**	**7.12E+06**	**6.43E+06**	**5.44E+06**	**4.17E+06**	**2.74E+06**	**2.68E+06**	**2.38E+06**	**1.26E+06**
Hot Mix Lab	**37**	**Y**	**2.57E+06**	**2.01E+06**	**1.71E+06**	**1.33E+06**	**9.79E+05**	**6.89E+05**	**6.06E+05**	**4.82E+05**	**4.05E+05**
Hot Mix Lab	**4**	**N**	**1.99E+07**	**1.87E+07**	**1.75E+07**	**1.58E+07**	**1.53E+07**	**1.26E+07**	**1.16E+07**	**1.07E+07**	**8.40E+06**
Hot Mix Lab	**21**	**N**	**8.28E+06**	**7.33E+06**	**6.61E+06**	**5.59E+06**	**4.17E+06**	**2.74E+06**	**2.68E+06**	**2.38E+06**	**1.26E+06**
Hot Mix Lab	**37**	**N**	**2.54E+06**	**2.05E+06**	**1.73E+06**	**1.30E+06**	**9.46E+05**	**6.47E+05**	**4.89E+05**	**4.26E+05**	**2.66E+05**
Warm Mix Lab	**4**	**Y**	**1.72E+07**	**1.56E+07**	**1.45E+07**	**1.30E+07**	**1.22E+07**	**9.84E+06**	**8.83E+06**	**8.20E+06**	**6.13E+06**
Warm Mix Lab	**21**	**Y**	**6.28E+06**	**5.50E+06**	**4.96E+06**	**4.12E+06**	**3.22E+06**	**2.36E+06**	**1.79E+06**	**1.57E+06**	**9.26E+05**
Warm Mix Lab	**37**	**Y**	**1.85E+06**	**1.49E+06**	**1.26E+06**	**9.69E+05**	**6.99E+05**	**4.55E+05**	**3.41E+05**	**2.86E+05**	**2.15E+05**
Warm Mix Lab	**4**	**N**	**1.94E+07**	**1.78E+07**	**1.67E+07**	**1.53E+07**	**1.51E+07**	**1.19E+07**	**1.10E+07**	**9.82E+06**	**7.87E+06**
Warm Mix Lab	**21**	**N**	**7.51E+06**	**6.55E+06**	**5.81E+06**	**4.92E+06**	**4.00E+06**	**2.85E+06**	**2.42E+06**	**1.85E+06**	**1.12E+06**
Warm Mix Lab	**37**	**N**	**2.18E+06**	**1.74E+06**	**1.47E+06**	**1.13E+06**	**7.48E+05**	**5.01E+05**	**3.70E+05**	**3.09E+05**	**2.46E+05**

Table D.4. Field Mix 4 dynamic modulus values (kPa)

Mix	Temp °C	Moisture Conditioned	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
Hot Mix Field	4	Y	2.06E+07	2.01E+07	1.90E+07	1.75E+07	1.61E+07	1.41E+07	1.27E+07	1.22E+07	9.77E+06
Hot Mix Field	21	Y	1.00E+07	8.80E+06	8.00E+06	6.73E+06	5.54E+06	4.04E+06	3.52E+06	3.29E+06	2.08E+06
Hot Mix Field	37	Y	3.24E+06	2.68E+06	2.31E+06	1.81E+06	1.35E+06	8.72E+05	6.72E+05	5.65E+05	4.34E+05
Hot Mix Field	4	N	2.10E+07	2.00E+07	1.89E+07	1.74E+07	1.64E+07	1.43E+07	1.29E+07	1.24E+07	9.99E+06
Hot Mix Field	21	N	1.12E+07	9.93E+06	9.07E+06	7.80E+06	6.51E+06	4.94E+06	3.90E+06	3.58E+06	2.30E+06
Hot Mix Field	37	N	3.66E+06	2.97E+06	2.54E+06	1.98E+06	1.50E+06	1.02E+06	8.12E+05	6.90E+05	5.23E+05
Warm Mix Field	4	Y	2.02E+07	1.93E+07	1.77E+07	1.71E+07	1.67E+07	1.43E+07	1.32E+07	1.24E+07	1.01E+07
Warm Mix Field	21	Y	1.03E+07	9.22E+06	8.39E+06	7.24E+06	6.12E+06	4.61E+06	3.95E+06	3.22E+06	2.17E+06
Warm Mix Field	37	Y	3.65E+06	3.01E+06	2.57E+06	2.01E+06	1.49E+06	1.01E+06	7.86E+05	6.68E+05	5.22E+05
Warm Mix Field	4	N	2.25E+07	2.16E+07	2.04E+07	1.90E+07	1.81E+07	1.49E+07	1.43E+07	1.33E+07	1.09E+07
Warm Mix Field	21	N	1.12E+07	9.96E+06	8.95E+06	5.17E+06	6.57E+06	4.91E+06	4.14E+06	3.61E+06	2.42E+06
Warm Mix Field	37	N	3.69E+06	3.01E+06	2.56E+06	1.96E+06	1.38E+06	8.92E+05	7.15E+05	5.86E+05	4.07E+05
Hot Mix Lab	4	Y	1.95E+07	1.85E+07	1.75E+07	1.62E+07	1.56E+07	1.33E+07	1.23E+07	1.14E+07	9.41E+06
Hot Mix Lab	21	Y	9.15E+06	8.06E+06	7.36E+06	6.36E+06	5.27E+06	4.00E+06	3.43E+06	3.05E+06	2.08E+06
Hot Mix Lab	37	Y	3.19E+06	2.67E+06	2.34E+06	1.84E+06	1.34E+06	9.27E+05	7.18E+05	5.97E+05	4.32E+05
Hot Mix Lab	4	N	2.06E+07	1.96E+07	1.84E+07	1.74E+07	1.69E+07	1.44E+07	1.34E+07	1.24E+07	1.02E+07
Hot Mix Lab	21	N	9.85E+06	8.79E+06	8.05E+06	6.98E+06	6.00E+06	4.54E+06	3.90E+06	3.41E+06	2.34E+06
Hot Mix Lab	37	N	3.57E+06	2.98E+06	2.57E+06	2.02E+06	1.49E+06	1.00E+06	7.83E+05	6.78E+05	4.90E+05
Warm Mix Lab	4	Y	2.05E+07	1.97E+07	1.79E+07	1.66E+07	1.67E+07	1.36E+07	1.33E+07	1.24E+07	1.00E+07
Warm Mix Lab	4	N	2.40E+07	2.29E+07	2.15E+07	1.93E+07	1.96E+07	1.62E+07	1.55E+07	1.45E+07	1.17E+07
Warm Mix Lab	21	Y	1.09E+07	9.53E+06	8.71E+06	7.45E+06	6.30E+06	4.73E+06	3.72E+06	3.43E+06	2.24E+06
Warm Mix Lab	21	N	1.23E+07	1.08E+07	9.93E+06	8.64E+06	7.30E+06	5.55E+06	4.61E+06	4.39E+06	2.85E+06
Warm Mix Lab	37	Y	3.82E+06	3.19E+06	2.75E+06	2.15E+06	1.59E+06	1.07E+06	8.23E+05	6.87E+05	4.98E+05
Warm Mix Lab	37	N	4.19E+06	3.47E+06	2.96E+06	2.30E+06	1.70E+06	1.14E+06	8.73E+05	7.19E+05	5.17E+05

APPENDIX E. FLOW NUMBER RESULTS

Note: Blue means moisture-conditioned sample and 10,000 cycles is the maximum.

Table E.1. Field Mix 1 flow number values

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
HMA	1	1208	4495	1393	10000**
HMA	2	XX	XX	1833	10000**
HMA	3	2551	4596	1263	7941
HMA	4	1114	2744	2338	5610
HMA	5	2428	5863	1483	8282
HMA	6	1193	3851	1573	10000**
HMA	7	--	--	2143	9202
HMA	8	--	--	1979	3813
HMA	9	--	--	2078	6402
HMA	10	--	--	4503	5770
Average MC		1872	4224	1790	8742
Average NMC		1583	4367	2432	5907

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
WMA	1	1453	5999	XX	XX
WMA	2	1723	3393	883	2827
WMA	3	738	3671	963	5190
WMA	4	698	2282	1628	4235
WMA	5	898	3572	503	2481
WMA	6	558	1892	1918	4396
WMA	7	--	--	628	2181
WMA	8	--	--	1108	2919
WMA	9	--	--	1753	3148
WMA	10	--	--	1178	4499
Average MC		1358	4321	1566	4242
Average NMC		665	2615	860	2981

Table E.2. Field Mix 2 flow number values

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
HMA	1	313	1013	403	1223
HMA	2	423	1257	468	1700
HMA	3	408	1007	308	1352
HMA	4	323	1176	443	1521
HMA	5	503	1233	498	1499
HMA	6	263	1298	358	1377
HMA	7	523	1659	338	1053
HMA	8	848	2768	523	1658
HMA	9	823	2543	593	1815
HMA	10	413	1674	433	1542
Average MC		520	1669	505	1639
Average NMC		448	1456	368	1309

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
WMA	1	338	1250	218	828
WMA	2	308	1146	308	1181
WMA	3	293	983	213	755
WMA	4	278	809	123	749
WMA	5	323	986	303	936
WMA	6	233	1071	148	645
WMA	7	408	1340	333	1050
WMA	8	303	1094	262	939
WMA	9	258	1015	273	818
WMA	10	213	918	313	1013
Average MC		326	1137	304	1024
Average NMC		265	985	195	759

Table E.3. Field Mix 3 flow number values

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
HMA	1	498	1919	1018	2485
HMA	2	748	1763	1023	4014
HMA	3	533	1511	1463	4241
HMA	4	753	1971	803	2984
HMA	5	458	1452	1328	2335
HMA	6	578	1516	643	2764
HMA	7	713	2163	673	1627
HMA	8	603	1766	763	2586
HMA	9	573	1307	1578	9798
HMA	10	738	1798	1428	4445
Average MC		643	1703	1233	4825
Average NMC		596	1730	911	2631

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
WMA	1	718	2005	248	1284
WMA	2	573	1622	378	1402
WMA	3	498	1769	363	1605
WMA	4	488	1810	403	1698
WMA	5	458	1742	446	1787
WMA	6	528	1555	403	1654
WMA	7	513	1773	533	2188
WMA	8	1278	2702	453	1885
WMA	9	263	1484	468	1879
WMA	10	338	1481	338	1630
Average MC		450	1673	401	1721
Average NMC		681	1916	406	1681

Table E.4. Field Mix 4 flow number values

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
HMA	1	1023	5250	1728	5587
HMA	2	728	3475	1768	3530
HMA	3	1713	3935	1148	4075
HMA	4	1423	6147	1103	7621
HMA	5	1358	6114	1118	8160
HMA	6	1548	4227	1028	6808
HMA	7	1053	4594	838	8862
HMA	8	973	4932	2283	5866
HMA	9	1428	4783	1053	6837
HMA	10	2193	5381	1283	6978
Average MC		1394	5565	1163	7408
Average NMC		1294	4203	1507	5457

		Field		Lab	
		Flow Number	Cycles to 3.0%	Flow Number	Cycles to 3.0%
WMA	1	1908	4829	1433	7695
WMA	2	1218	6507	1718	8320
WMA	3	978	4473	3293	4735
WMA	4	613	4056	2383	8328
WMA	5	2913	6543	1568	4823
WMA	6	3148	6079	1393	7345
WMA	7	--	--	2573	7429
WMA	8	--	--	2793	8862
WMA	9	--	--	1838	10000*
WMA	10	--	--	1688	10000*
Average MC		2426	6376	1812	8869
Average NMC		2426	6376	2324	6639

APPENDIX F. SAS OUTPUT DATA

F.1. Field Mix 1 ITS Statistical Analysis - Peak Loads

```
                                       Class Level Information

Class         Levels    Values
mix                2    HMA WMA
mcond              2    Moisture Conditioned(MC) Not Moisture ConditionedNMC)

Number of Observations Read          20
Number of Observations Used          20
                                THREE-WAY ANOVA FOR FM1 ITS Samples
The GLM Procedure
Dependent Variable: Peak Load
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      3   31282815.60   10427605.20     5.23  0.0104
Error                     16   31887540.40    1992971.28
Corrected Total           19   63170356.00

R-Square     Coeff Var      Root MSE      Peak Load Mean
0.495214      12.29191      1411.726      11485.00

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   27626601.80   27626601.80    13.86  0.0018
mcond                      1    2832033.80    2832033.80     1.42  0.2506
mix*mcond                  1     824180.00     824180.00     0.41  0.5293

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   27626601.80   27626601.80    13.86  0.0018
mcond                      1    2832033.80    2832033.80     1.42  0.2506
mix*mcond                  1     824180.00     824180.00     0.41  0.5293

Duncan's Multiple Range Test for Peak Load
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       16
Error Mean Square         1992971

Number of Means         2
Critical Range       1338
Means with the same letter are not significantly different.

Duncan Grouping
           Mean       N    mcond
A       11861.3      10    MC
A       11108.7      10    NMC

Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       16
Error Mean Square         1992971

Number of Means         2
Critical Range       1338

Means with the same letter are not significantly different.
```

```
Duncan Grouping
           Mean      N    mix
A       12660.3     10    HMA
B       10309.7     10     WMA

                                  RESIDUAL x PREDICTED VALUE PLOT
      Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

     resid |
           |
      4000 -
           |
           |
           |
           |                             B
      2000 -                                            A
           |
           |        A
           |                                            B
           |        B
         0 -    E
           |        A
           |
           |        A                    A              A
           |                             B
     -2000 -                                            A
           |
           |
           |
           |
     -4000 -
           |
           Š--|------------|------------|------------|------------|--
            10000        11000        12000        13000        14000

                                     predict



                             Normal Probability Plot

    2250+                                    *  * +++*
        |                                     ++++
        |                                 +*++
     750+                             ++**
        |                         +****
        |                            ***
    -750+                  +++*
        |              *+*+**
        |          +*++
   -2250+      *+++
        +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
```

Tukey's Studentized Range (HSD) Test for Peak Load

```
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  16
Error Mean Square                    1992971
Critical Value of Studentized Range  4.04609
Minimum Significant Difference        2554.5

Means with the same letter are not significantly different.

Tukey Grouping
                Mean      N    cell
     A       13239.6      5    HMA     Moisture Conditioned
B    A       12081.0      5    HMA Not Moisture Conditioned
B            10483.0      5    WMA     Moisture Conditioned
B            10136.4      5    WMA Not Moisture Conditioned
```

F.2. Field Mix 2 ITS Statistical Analysis - Peak Loads

```
                                       Class Level Information

Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          40
Number of Observations Used          40

                               THREE-WAY ANOVA FOR FM2 ITS Samples
Dependent Variable: Peak Load
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      7   12937474.80    1848210.69     6.68  <.0001
Error                     32    8847578.80     276486.84
Corrected Total           39   21785053.60

R-Square     Coeff Var      Root MSE       Peak Load Mean
0.593869      6.781801      525.8202      7753.400

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   2381440.000   2381440.000     8.61  0.0061
comp                       1   3073593.600   3073593.600    11.12  0.0022
mix*comp                   1    733326.400    733326.400     2.65  0.1132
mcond                      1   4221100.900   4221100.900    15.27  0.0005
mix*mcond                  1   1886164.900   1886164.900     6.82  0.0136
comp*mcond                 1    275892.100    275892.100     1.00  0.3253
mix*comp*mcond             1    365956.900    365956.900     1.32  0.2585

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   2381440.000   2381440.000     8.61  0.0061
comp                       1   3073593.600   3073593.600    11.12  0.0022
mix*comp                   1    733326.400    733326.400     2.65  0.1132
mcond                      1   4221100.900   4221100.900    15.27  0.0005
mix*mcond                  1   1886164.900   1886164.900     6.82  0.0136
comp*mcond                 1    275892.100    275892.100     1.00  0.3253
mix*comp*mcond             1    365956.900    365956.900     1.32  0.2585


Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.01
Error Degrees of Freedom       32
Error Mean Square        276486.8

Number of Means          2
Critical Range       455.4

Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N    comp
A        8030.6     20    lab compacted
B        7476.2     20    field compacted
```

Duncan's Multiple Range Test for Peak Load

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square        276486.8

Number of Means          2
Critical Range       338.7

Means with the same letter are not significantly different.
```

Duncan Grouping

```
           Mean      N    mcond
A        8078.3     20    Not Moisture Conditioned
B        7428.6     20    Moisture Conditioned
```

RESIDUAL x PREDICTED VALUE PLOT

```
Legend: A = 1 obs, B = 2 obs, etc.

     resid |
           |
      1000 -
           |
           |
           |   B         A           AA     A
       500 -          A               A                         B
           |           B                    A
           |             A           A
           |          AA A                  A
         0 -          A  A           AA
           |   A                      A     A                   B
           |          A
           |   A      AA             B
      -500 -           A
           |
           |   A                      A                         A
           |                                A
     -1000 -
           |             A
           |
           |
     -1500 -
           |
           Š--|------------|------------|------------|------------|--
            7000         7500         8000         8500         9000

                                     predict
```

Normal Probability Plot

```
     650+                                      ++* *    *
        |                                  *****
        |                                **++
        |                              **++
        |                             *++
        |                            *+
        |                         ***
        |                      ****
        |                    ***
        |                   *+
        |                 ***
        |              ***
        |             ++
        |           ++
        |         ++ **
        |       +* *
        |     ++
   -1050+  +*+
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
```

Duncan's Multiple Range Test for Peak Load

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square        276486.8

Number of Means       2       3       4       5       6       7       8
Critical Range    677.4   712.0   734.4   750.5   762.7   772.2   779.9

Means with the same letter are not significantly different.

  Duncan
 Grouping            Mean      N    cell
     A             8939.4      5    Lab   WMA NMC
     B             8139.4      5    Field WMA NMC
C    B             7937.6      5    Lab   HMA NMC
C    B             7880.6      5    Lab   WMA MC
C    B    D        7438.6      5    Field HMA MC
C         D        7364.8      5    Lab   HMA MC
C         D        7296.6      5    Field HMA NMC
          D        7030.2      5    Field WMA MC
```

Tukey's Studentized Range (HSD) Test for Peak Load

```
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  32
Error Mean Square                   276486.8
Critical Value of Studentized Range  4.58106
Minimum Significant Difference        1077.3

Means with the same letter are not significantly different.
   Tukey
 Grouping            Mean      N    cell
     A             8939.4      5    Lab___WMA_NMC
     A
B    A             8139.4      5    Field_WMA_NMC
B    A    C        7937.6      5    Lab___HMA_NMC
B    A    C        7880.6      5    Lab___WMA_MC
B         C        7438.6      5    Field_HMA_MC
B         C        7364.8      5    Lab___HMA_MC
B         C        7296.6      5    Field_HMA_NMC
          C        7030.2      5    Field_WMA_MC
```

F.3. Field Mix 3 ITS Statistical Analysis Output - Peak Loads

```
                                         Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          40
Number of Observations Used          40

                                   THREE-WAY ANOVA FOR FM3 ITS Samples

Dependent Variable: Peak Load
                                    Sum of
Source                    DF       Squares    Mean Square  F Value  Pr > F
Model                      7   82282478.38    11754639.77    46.57  <.0001
Error                     32    8077649.60      252426.55
Corrected Total           39   90360127.98

R-Square      Coeff Var       Root MSE       Peak Load Mean
0.910606       5.550061       502.4207      9052.525

Source                    DF     Type I SS    Mean Square  F Value  Pr > F
mix                        1   69656405.63    69656405.63   275.95  <.0001
comp                       1    4124850.62     4124850.62    16.34  0.0003
mix*comp                   1      49210.22       49210.22     0.19  0.6618
mcond                      1    6016329.22     6016329.22    23.83  <.0001
mix*mcond                  1    1515934.22     1515934.22     6.01  0.0199
comp*mcond                 1     266179.23      266179.23     1.05  0.3122
mix*comp*mcond             1     653569.23      653569.23     2.59  0.1174


Source                    DF   Type III SS    Mean Square  F Value  Pr > F
mix                        1   69656405.63    69656405.63   275.95  <.0001
comp                       1    4124850.62     4124850.62    16.34  0.0003
mix*comp                   1      49210.22       49210.22     0.19  0.6618
mcond                      1    6016329.22     6016329.22    23.83  <.0001
mix*mcond                  1    1515934.22     1515934.22     6.01  0.0199
comp*mcond                 1     266179.23      266179.23     1.05  0.3122
mix*comp*mcond             1     653569.23      653569.23     2.59  0.1174

Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                            0.01
Error Degrees of Freedom           32
Error Mean Square            252426.5

Number of Means            2
Critical Range         435.1

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N     comp
A        9373.7     20     lab compacted
B        8731.4     20     field compacted
```

```
Duncan's Multiple Range Test for Peak Load
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square        252426.5
Number of Means          2
Critical Range       323.6

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    mcond
A        9440.4     20    Not Moisture Conditioning
B        8664.7     20    Moisture Conditioning
```

```
                                  RESIDUAL x PREDICTED VALUE PLOT

       Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
 2000 -
      |
      |
      |
      |
      |                                                    A
      |
 1000 -
      |         A
      |                             A
      |                       A                                         A
      |                             A                          A
      |                                 A                      B
      |         A             A         A                        B      A
    0 -                       A     A   A                      A A      A
      |         A                       A                  A     A
      |         A             A         A                  A     A      B
      |                       A                            A
      |                             A                      A
      |         A                   A
      |
-1000 -                                                        A
      |
      Š-|------------|------------|------------|------------|------------|-
      6000         7000         8000         9000         10000       11000

                                     Predict
```

```
                                       Normal Probability Plot
    1300+                                               *
        |                                               ++++
        |                                          *++++
        |                                       +*++
        |                                  +****
        |                              +****
     100+                         ******
        |                     +****
        |               *******
        |            ***++
        |        *+*+
        |   *++++
   -1100+++++
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.


Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square        252426.5


Number of Means        2        3        4        5        6        7        8
Critical Range    647.3    680.3    701.8    717.1    728.7    737.9    745.2


Means with the same letter are not significantly different.


Duncan
Grouping
                Mean      N    cell
     A       10897.6      5    lab   HMA Not Moisture Conditioned
B    A       10418.8      5    lab   HMA     Moisture Conditioned
B    A       10233.0      5    field HMA Not Moisture Conditioned
B             9939.2      5    field HMA     Moisture Conditioned
     C        8462.2      5    lab   WMA Not Moisture Conditioned
D    C        8168.6      5    field WMA Not Moisture Conditioned
D             7716.0      5    lab   WMA     Moisture Conditioned
     E        6584.8      5    field WMA     Moisture Conditioned
```

```
                      Tukey's Studentized Range (HSD) Test for Peak Load

NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  32
Error Mean Square                   252426.5
Critical Value of Studentized Range  4.58106
Minimum Significant Difference        1029.3

Means with the same letter are not significantly different.
Tukey
Grouping
           Mean      N    cell

A       10897.6      5    lab   HMA Not Moisture Conditioned
A       10418.8      5    lab   HMA     Moisture Conditioned
A       10233.0      5    field HMA Not Moisture Conditioned
A        9939.2      5    field HMA     Moisture Conditioned
B        8462.2      5    lab   WMA Not Moisture Conditioned
B        8168.6      5    field WMA Not Moisture Conditioned
B        7716.0      5    lab   WMA     Moisture Conditioned
C        6584.8      5    field WMA     Moisture Conditioned
```

F.4. Field Mix 4 ITS Statistical Analysis Output – Peak Loads

```
                                       Class Level Information

Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned


Number of Observations Read          36
Number of Observations Used          36
                               THREE-WAY ANOVA FOR FM4 ITS Samples
Dependent Variable: Peak Load
                                    Sum of
Source                    DF       Squares    Mean Square   F Value   Pr > F
Model                      7   28027893.14     4003984.73     20.06   <.0001
Error                     28    5588258.07      199580.65
Corrected Total           35   33616151.21

R-Square     Coeff Var      Root MSE      Peak Load Mean
0.833763      3.901140      446.7445      11451.64

Source                    DF     Type I SS    Mean Square   F Value   Pr > F
mix                        1    3533448.10     3533448.10     17.70   0.0002
comp                       1    5037843.93     5037843.93     25.24   <.0001
mix*comp                   1     358213.93      358213.93      1.79   0.1911
mcond                      1   12525700.69    12525700.69     62.76   <.0001
mix*mcond                  1     244319.20      244319.20      1.22   0.2780
comp*mcond                 1    1438166.64     1438166.64      7.21   0.0121
mix*comp*mcond             1    4890200.65     4890200.65     24.50   <.0001

Source                    DF   Type III SS    Mean Square   F Value   Pr > F
mix                        1   4153688.373    4153688.373     20.81   <.0001
comp                       1   4562459.798    4562459.798     22.86   <.0001
mix*comp                   1    358213.928     358213.928      1.79   0.1911
mcond                      1   8618120.558    8618120.558     43.18   <.0001
mix*mcond                  1    901850.545     901850.545      4.52   0.0425
comp*mcond                 1   2258549.335    2258549.335     11.32   0.0022
mix*comp*mcond             1   4890200.648    4890200.648     24.50   <.0001

Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.01
Error Degrees of Freedom          28
Error Mean Square           199580.6
Harmonic Mean of Cell Sizes 17.77778

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       414.1

Means with the same letter are not significantly different.

Duncan Grouping
           Mean       N     comp
A       11748.6      20     Clab
B       11080.5      16     Cfield
```

Duncan's Multiple Range Test for Peak Load

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       28
Error Mean Square        199580.6

Number of Means          2
Critical Range       305.0

Means with the same letter are not significantly different.
Duncan Grouping
           Mean       N    mcond
A       12041.5      18    NMC
B       10861.8      18    MC
```

RESIDUAL x PREDICTED VALUE PLOT

```
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
 2000 -
      |
      |
      |
      |
      |
      |                                             A
 1000 -
      |       A
      |                                                  A
      |
      |       A                            A        A
      |           B
      |           A            A           A                       B
    0 -           A            A                    A    A         A
      |           C            A           B             A         A
      |           A                        A             B         A
      |       C                                     A
      |
      |
      |
-1000 -                                             A
      |
      Š|----------|----------|----------|----------|----------|----------|
     10000      10500      11000      11500      12000      12500     13000

                                     Predict
```

Normal Probability Plot

```
    1100+                                              *
        |                                         *   +++++
        |                                        *+++++
        |                                    *+*++
        |                               ++***
        |                         ++******
        |                    *******
        |               ******
        |        * *+*+*
        |     +++++
        |+++++
   -1100+    *
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Peak Load

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                            0.05
Error Degrees of Freedom           28
Error Mean Square            199580.6
Harmonic Mean of Cell Sizes 4.285714

NOTE: Cell sizes are not equal.

Number of Means       2       3       4       5       6       7       8
Critical Range    625.1   656.9   677.4   692.0   702.9   711.5   718.4

Means with the same letter are not significantly different.

Duncan
Grouping
                Mean      N    cell
     A       12741.4      5    lab   HMA Not Moisture Conditioned
B    A       12271.8      5    lab   WMA Not Moisture Conditioned
B            12049.4      5    field HMA Not Moisture Conditioned
B    C       11656.3      5    lab   HMA     Moisture Conditioned
D    C       11068.3      3    field WMA     Moisture Conditioned
D    E       10480.3      5    field HMA     Moisture Conditioned
D    E       10478.0      3    field WMA Not Moisture Conditioned
     E       10324.8      5    lab   WMA     Moisture Conditioned
```

F.5. Field Mix 1 Dynamic Modulus Statistical Analysis Output

```
                                   Class Level Information

                      Class         Levels    Values
                      mix                2    MHMA MWMA
                      comp               2    Cfield Clab
                      mcond              2    iNMC iiMC
                      fre                9    fa fb fc fd fe ff fg fi fj
                      temp               3    tx ty tz

                            Number of Observations Read         864
                            Number of Observations Used         864

                         Five-WAY ANOVA FOR FM3 Dynamic Modulus Samples
Dependent Variable: SQRT(E*)
                                                   Sum of
       Source                      DF             Squares     Mean Square    F Value    Pr > F
       Model                      215          1077334599         5010859     406.17    <.0001
       Error                      648             7994242           12337
       Corrected Total            863          1085328841

                      R-Square     Coeff Var      Root MSE     SQRT(E*) Mean
                      0.992634      4.913300      111.0711          2260.622

       Source                      DF           Type I SS     Mean Square    F Value    Pr > F
       mix                          1           6076743.8       6076743.8     492.57    <.0001
       comp                         1           2399557.4       2399557.4     194.50    <.0001
       mix*comp                     1             76266.3         76266.3       6.18    0.0132
       mcond                        1           6062662.8       6062662.8     491.43    <.0001
       mix*mcond                    1             23343.8         23343.8       1.89    0.1694
       comp*mcond                   1             61417.7         61417.7       4.98    0.0260
       mix*comp*mcond               1            825077.8        825077.8      66.88    <.0001
       temp                         2         905842463.6     452921231.8    36713.0    <.0001
       mix*temp                     2            262660.4        131330.2      10.65    <.0001
       comp*temp                    2            647266.9        323633.5      26.23    <.0001
       mix*comp*temp                2            135907.9         67954.0       5.51    0.0042
       mcond*temp                   2            700519.0        350259.5      28.39    <.0001
       mix*mcond*temp               2             20754.4         10377.2       0.84    0.4317
       comp*mcond*temp              2             17184.1          8592.0       0.70    0.4987
       mix*comp*mcond*temp          2             40842.9         20421.5       1.66    0.1918
       fre                          8         149925934.9      18740741.9    1519.09    <.0001
       mix*fre                      8             16011.8          2001.5       0.16    0.9955
       comp*fre                     8             17616.1          2202.0       0.18    0.9938
       mix*comp*fre                 8              4795.8           599.5       0.05    0.9999
       mcond*fre                    8            128622.3         16077.8       1.30    0.2387
       mix*mcond*fre                8             23013.3          2876.7       0.23    0.9847
       comp*mcond*fre               8              2285.8           285.7       0.02    1.0000
       mix*comp*mcond*fre           8             15225.9          1903.2       0.15    0.9962
       fre*temp                    16           3556100.4        222256.3      18.02    <.0001
       mix*fre*temp                16            301497.6         18843.6       1.53    0.0842
       comp*fre*temp               16             17138.7          1071.2       0.09    1.0000
       mix*comp*fre*temp           16             13192.3           824.5       0.07    1.0000
       mcond*fre*temp              16             54418.9          3401.2       0.28    0.9979
       mix*mcond*fre*temp          16             18918.8          1182.4       0.10    1.0000
       comp*mcond*fre*temp         16             11128.3           695.5       0.06    1.0000
       mix*com*mco*fre*temp        16             36029.5          2251.8       0.18    0.9999
```

```
Dependent Variable: SQRT(E*)

       Source                    DF     Type III SS     Mean Square    F Value    Pr > F
       mix                        1       6031291.3       6031291.3     488.89    <.0001
       comp                       1       2399557.4       2399557.4     194.50    <.0001
       mix*comp                   1         76266.3         76266.3       6.18    0.0132
       mcond                      1       5392168.9       5392168.9     437.08    <.0001
       mix*mcond                  1        140639.8        140639.8      11.40    0.0008
       comp*mcond                 1         61417.7         61417.7       4.98    0.0260
       mix*comp*mcond             1        825077.8        825077.8      66.88    <.0001
       temp                       2     838922895.3     419461447.7    34000.8    <.0001
       mix*temp                   2        332840.2        166420.1      13.49    <.0001
       comp*temp                  2        647266.9        323633.5      26.23    <.0001
       mix*comp*temp              2        135907.9         67954.0       5.51    0.0042
       mcond*temp                 2        629330.5        314665.3      25.51    <.0001
       mix*mcond*temp             2         30886.8         15443.4       1.25    0.2867
       comp*mcond*temp            2         17184.1          8592.0       0.70    0.4987
       mix*comp*mcond*temp        2         40842.9         20421.5       1.66    0.1918
       fre                        8     139958134.5      17494766.8    1418.10    <.0001
       mix*fre                    8         13441.8          1680.2       0.14    0.9976
       comp*fre                   8         17616.1          2202.0       0.18    0.9938
       mix*comp*fre               8          4795.8           599.5       0.05    0.9999
       mcond*fre                  8        115659.4         14457.4       1.17    0.3136
       mix*mcond*fre              8         26843.1          3355.4       0.27    0.9749
       comp*mcond*fre             8          2285.8           285.7       0.02    1.0000
       mix*comp*mcond*fre         8         15225.9          1903.2       0.15    0.9962
       fre*temp                  16       3264448.1        204028.0      16.54    <.0001
       mix*fre*temp              16        283568.7         17723.0       1.44    0.1184
       comp*fre*temp             16         17138.7          1071.2       0.09    1.0000
       mix*comp*fre*temp         16         13192.3           824.5       0.07    1.0000
       mcond*fre*temp            16         45124.7          2820.3       0.23    0.9993
       mix*mcond*fre*temp        16         17919.4          1120.0       0.09    1.0000
       comp*mcond*fre*temp       16         11128.3           695.5       0.06    1.0000
       mix*com*mco*fre*temp      16         36029.5          2251.8       0.18    0.9999

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                           0.01
Error Degrees of Freedom         648
Error Mean Square           12336.79
Harmonic Mean of Cell Sizes      405

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       20.16

Means with the same letter are not significantly different.

Duncan Grouping
          Mean      N    comp
A      2301.443    540    lab
B      2192.586    324    field

Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      648
Error Mean Square        12336.79
Number of Means          2
Critical Range       14.84

Means with the same letter are not significantly different.
Duncan Grouping          Mean      N    mcond
A      2344.389    432    Not Moisture Conditioned
B      2176.854    432        Moisture Conditioned
```

```
Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         648
Error Mean Square           12336.79
Harmonic Mean of Cell Sizes      405

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       15.33

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    comp
A      2301.443    540    lab
B      2192.586    324    field

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      648
Error Mean Square        12336.79

Number of Means          2
Critical Range       14.84

Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N    mix
A      2344.486    432    MHMA
B      2176.757    432    MWMA

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      648
Error Mean Square        12336.79

Number of Means         2         3         4         5         6         7         8         9
Critical Range      31.48     33.14     34.26     35.08     35.72     36.24     36.68     37.06

Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N    fre
A       2868.96     96    fa
B       2722.94     96    fb
C       2621.50     96    fc
D       2459.92     96    fd
E       2296.13     96    fe
F       2050.56     96    ff
G       1915.25     96    fg
H       1819.74     96    fi
I       1590.60     96    fj
```

Duncan's Multiple Range Test for SQRT(E*)

```
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                          0.05
Error Degrees of Freedom        648
Error Mean Square          12336.79

Number of Means           2           3
Critical Range        18.18       19.14

Means with the same letter are not significantly different.

Duncan Grouping
         Mean      N    temp
A      3583.493    288    tx
B      2109.236    288    ty
C      1089.135    288    tz
```

RESIDUAL x PREDICTED VALUE PLOT

```
Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
  400 -
      |
      |
      |                                                                                    A
      |                                                         A A   A     A  A  A  A A A    B
  200 -                                                  A      A A      A  A  A     B  AA
      |                         A          A    A A AAA A AA  AA     AA   A     BAAA  A D AA
      |                    A BABA CA A   A    A   A   A BACA AA A  B GA DA A AB CACBB A B  B
      |   A A A A AABA ACAEB BBAECBB BBAA   B   AA A B  AAB CA A BBA B   AA B CABA A CCAC A
      |   BBCDDCCCAC CDADCAGFCDBFFBCCADDBAA FDA BDCA EBBDBBABA BAACA CA AA  CAAACAAAABA BA A
    0 -  CHJLHLEFF DGDBEGEBJECEBCFCBCBAD  AA D  A DA A F ABD D     A B  AB    A A AA    AB A
      |   BBDDABA  A AA AAAB AC CB BAA B BA BBA CACCADBBCCCB B AA  A B  AB  C B  BA  AAA   A
      |     A CAABAAAA  A AC  BCACABA BAAA  AAB  AA  A AAA AA  C  D  A  A  B  AA       ABA    A
      |         A   AAAAAAA BA AA A  A AA  AB   AAA AAA B A A   ABA  B  BA  A BBBA   A   A
      |                 A AA BA BAAA  A           A  AA     A   A  B A  A   AAA  AA BBBAB  A  A
 -200 -                         A A  A                  A AA A       B   A      B  A  A C A   A
      |                                                         A     A   A          A     B
      |                                                  AA   A   A  A      A  AA B  A  AA
      |                                                               A
      |                                                                            A
 -400 -
      |
      Š-|----------|----------|----------|----------|----------|----------|----------|----------|-
       500       1000       1500       2000       2500       3000       3500       4000       4500

                                                 predict
```

```
                   Normal Probability Plot
 275+                                                  *
    |                                              *****
    |                                         +*****
    |                                    *******
    |                               ******
    |                       *********
    |                  ******+
    |              *****+
    |          +****
    |     +******
    |+++++**
    |*****
    |*
-375+*
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

F.6. Field Mix 2 Dynamic Modulus Statistical Analysis Output

```
                                      Class Level Information
Class          Levels     Values      (Coding Translation)
mix                 2     MHMA MWMA (HMA WMA)
comp                2     Cfield Clab (field lab)
mcond               2     iNMC iiMC (Not Moisture Conditioned / Moisture conditioned)
fre                 9     fa fb fc fd fe ff fg fi fj (Frequencies: 25, 15, 10, 5, 3, 1, 0.5, 0.3, 0.1 Hz.)
temp                3     tx ty tz (4, 21, 37 C)

Number of Observations Read        1080
Number of Observations Used        1080

                        Five-WAY ANOVA FOR FM4 Dynamic Modulus Samples

Dependent Variable: SQRT(E*)
                                          Sum of
Source                       DF          Squares     Mean Square    F Value    Pr > F
Model                       215       1112395139         5173931     460.25    <.0001
Error                       864          9712782           11242
Corrected Total            1079       1122107921

R-Square      Coeff Var      Root MSE      SQRT(E*) Mean
0.991344       5.274478      106.0266      2010.182

Source                       DF        Type I SS     Mean Square    F Value    Pr > F
mix                           1        1015250.7       1015250.7      90.31    <.0001
comp                          1         197722.0        197722.0      17.59    <.0001
mix*comp                      1           8961.4          8961.4       0.80    0.3722
mcond                         1         925236.4        925236.4      82.30    <.0001
mix*mcond                     1        1051377.6       1051377.6      93.53    <.0001
comp*mcond                    1            680.0           680.0       0.06    0.8058
mix*comp*mcond                1         597982.0        597982.0      53.19    <.0001
temp                          2      920420241.0     460210120.5    40938.0    <.0001
mix*temp                      2         191625.0         95812.5       8.52    0.0002
comp*temp                     2           8363.8          4181.9       0.37    0.6895
mix*comp*temp                 2         133609.7         66804.8       5.94    0.0027
mcond*temp                    2         941204.7        470602.4      41.86    <.0001
mix*mcond*temp                2         267819.8        133909.9      11.91    <.0001
comp*mcond*temp               2          57717.3         28858.6       2.57    0.0773
mix*comp*mcond*temp           2         147992.0         73996.0       6.58    0.0015
fre                           8      176316184.6      22039523.1    1960.52    <.0001
mix*fre                       8          28472.6          3559.1       0.32    0.9599
comp*fre                      8           7124.1           890.5       0.08    0.9997
mix*comp*fre                  8           8192.7          1024.1       0.09    0.9994
mcond*fre                     8         159435.8         19929.5       1.77    0.0788
mix*mcond*fre                 8          15248.7          1906.1       0.17    0.9948
comp*mcond*fre                8           9857.1          1232.1       0.11    0.9989
mix*comp*mcond*fre            8          21757.3          2719.7       0.24    0.9828
fre*temp                     16        9613237.4        600827.3      53.45    <.0001
mix*fre*temp                 16          27494.0          1718.4       0.15    1.0000
comp*fre*temp                16          36432.1          2277.0       0.20    0.9997
mix*comp*fre*temp            16          15860.3           991.3       0.09    1.0000
mcond*fre*temp               16          72444.2          4527.8       0.40    0.9821
mix*mcond*fre*temp           16           9983.2           624.0       0.06    1.0000
comp*mcond*fre*temp          16          39592.4          2474.5       0.22    0.9995
mix*com*mco*fre*temp         16          48039.1          3002.4       0.27    0.9983
```

```
Dependent Variable: SQRT(E*)

Source                      DF     Type III SS     Mean Square    F Value    Pr > F
mix                          1       1015250.7       1015250.7      90.31    <.0001
comp                         1        197722.0        197722.0      17.59    <.0001
mix*comp                     1          8961.4          8961.4       0.80    0.3722
mcond                        1        925236.4        925236.4      82.30    <.0001
mix*mcond                    1       1051377.6       1051377.6      93.53    <.0001
comp*mcond                   1           680.0           680.0       0.06    0.8058
mix*comp*mcond               1        597982.0        597982.0      53.19    <.0001
temp                         2     920420241.0     460210120.5    40938.0    <.0001
mix*temp                     2        191625.0         95812.5       8.52    0.0002
comp*temp                    2          8363.8          4181.9       0.37    0.6895
mix*comp*temp                2        133609.6         66804.8       5.94    0.0027
mcond*temp                   2        941204.7        470602.4      41.86    <.0001
mix*mcond*temp               2        267819.8        133909.9      11.91    <.0001
comp*mcond*temp              2         57717.3         28858.6       2.57    0.0773
mix*comp*mcond*temp          2        147992.0         73996.0       6.58    0.0015
fre                          8     176316184.6      22039523.1    1960.52    <.0001
mix*fre                      8         28472.6          3559.1       0.32    0.9599
comp*fre                     8          7124.1           890.5       0.08    0.9997
mix*comp*fre                 8          8192.7          1024.1       0.09    0.9994
mcond*fre                    8        159435.8         19929.5       1.77    0.0788
mix*mcond*fre                8         15248.7          1906.1       0.17    0.9948
comp*mcond*fre               8          9857.1          1232.1       0.11    0.9989
mix*comp*mcond*fre           8         21757.3          2719.7       0.24    0.9828
fre*temp                    16       9613237.4        600827.3      53.45    <.0001
mix*fre*temp                16         27494.0          1718.4       0.15    1.0000
comp*fre*temp               16         36432.1          2277.0       0.20    0.9997
mix*comp*fre*temp           16         15860.3           991.3       0.09    1.0000
mcond*fre*temp              16         72444.2          4527.8       0.40    0.9821
mix*mcond*fre*temp          16          9983.2           624.0       0.06    1.0000
comp*mcond*fre*temp         16         39592.4          2474.5       0.22    0.9995
mix*com*mco*fre*temp        16         48039.1          3002.4       0.27    0.9983

Duncan's Multiple Range Test for SQRT(E*)

Alpha                           0.01
Error Degrees of Freedom         864
Error Mean Square           11241.65

Number of Means          2
Critical Range       16.66

Means with the same letter are not significantly different.

Duncan Grouping
          Mean      N    comp
A      2023.713    540   field
B      1996.652    540   lab

Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         864
Error Mean Square           11241.65

Number of Means          2
Critical Range       12.66
Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N    mcond
A      2039.452    540    Not Moisture Conditioned
B      1980.913    540        Moisture Conditioned
```

```
Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        11241.65

Number of Means          2
Critical Range       12.66

Means with the same letter are not significantly different.

Duncan Grouping
          Mean      N    comp
A      2023.713    540    field
B      1996.652    540    lab

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        11241.65

Number of Means          2
Critical Range       12.66

Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N    mix
A      2040.843    540    HMA
B      1979.522    540    WMA

Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        11241.65
Number of Means         2         3         4         5         6         7         8         9
Critical Range      26.87     28.29     29.24     29.94     30.49     30.94     31.31     31.63
Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    fre
A       2622.46    120    fa
B       2461.68    120    fb
C       2352.83    120    fc
D       2195.11    120    fd
E       2025.22    120    fe
F       1797.14    120    ff
G       1677.28    120    fg
H       1580.67    120    fi
I       1379.27    120    fj
```

Duncan's Multiple Range Test for SQRT(E*)

```
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        11241.65
Number of Means          2          3
Critical Range       15.51      16.33

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    temp
A      3223.533    360    tx
B      1820.875    360    ty
C       986.139    360    tz
```

RESIDUAL x PREDICTED VALUE PLOT

```
Legend: A = 1 obs, B = 2 obs, etc.
resid |
      |
  500 -
      |
      |
      |                        A                                                A
      |                                                     A  A      A  A   A       A
  250 -                                           A      A                        A
      |                    A                     A   A                 A   A   B A A  C
      |           A  AAA AB C AB      AA  A   A AAA  BA  A CB C  CA  A  AA B   BA  A B
      |  CCAA   A   AB B AA BBA A A    C   ACAA D CC BE AB C A E AA  BE BAACDB DBB ABAA
      |  AADGICE DBABIFGFGKDLCFCBCAA ACB ABACABBFAGADBDC ECBEBCBCAB  AAEDCBAC CD CA  AA
    0 -  BFHKXLIHKLCDMJHNHPDMICCEADC CHG CGBCFBEHCHC CEACEACDA BAAB  BCACCAAC  ABAA  B
      |  ADDEGDF EDABBGDDEHEIEGBA D  ABD AD DBBCEBE  AD  B  D AA AB  BB BC CD AGB AAB B
      |  B C  A   A ABAAAB AE AB A A   B   AA A DACB  D AA  B  B  A    AAA   A      AA
      |     A   A      B AA  AAAA     AA  A A A BAAAAABA A AA A AAA  B A  AA  A AB
      |  AA                                          C   AAC AB  B    AA A CA  C A   AB
 -250 -                                                         A      A B      B  A   A
      |                                           A
      |              A                                   A  A  A      A
      |                   A    A                                          A   A     A
      |                     A                                                   A
 -500 -                                                                              A
      |
      Š-|----------|----------|----------|----------|----------|----------|----------|----------|-
       500        1000       1500       2000       2500       3000       3500       4000       4500
                                                  predict
```

Normal Probability Plot

```
      375+                                                  *
         |                                                  *
         |                                                 **
         |                                               **++
         |                                         ++****
         |                                    ++*****
         |                               +*******
         |                        *********
         |                *********
         |            *****+++
         |          ***++
         |    ++*****
         |+++****
         |   *
         |   *
         |***
         |*
     -475+*
          +----+----+----+----+----+----+----+----+----+----+
              -2        -1         0        +1        +2
```

F.7. Field Mix 3 Statistical Analysis Output

```
                                       Class Level Information
Class         Levels    Values      (Coding Translation)
mix                2    MHMA MWMA (HMA WMA)
comp               2    Cfield Clab (field lab)
mcond              2    iNMC iiMC (Not Moisture Conditioned / Moisture conditioned)
fre                9    fa fb fc fd fe ff fg fi fj (Frequencies: 25, 15, 10, 5, 3, 1, 0.5, 0.3, 0.1 Hz.)
temp               3    tx ty tz (4, 21, 37 C)

Number of Observations Read        1080
Number of Observations Used        1080

                        Five-WAY ANOVA FOR FM3 Dynamic Modulus Samples
Dependent Variable: SQRT(E*)
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                    215    1505651330       7003029   522.49  <.0001
Error                    864      11580244         13403
Corrected Total         1079    1517231574

R-Square     Coeff Var      Root MSE       SQRT(E*) Mean
0.992368      5.385027      115.7716      2149.880

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1       4891633       4891633   364.96  <.0001
comp                       1       1550413       1550413   115.68  <.0001
mix*comp                   1        922370        922370    68.82  <.0001
mcond                      1       3612270       3612270   269.51  <.0001
mix*mcond                  1        289625        289625    21.61  <.0001
comp*mcond                 1        108601        108601     8.10  0.0045
mix*comp*mcond             1        532800        532800    39.75  <.0001
temp                       2    1260712878     630356439  47030.8  <.0001
mix*temp                   2        972755        486377    36.29  <.0001
comp*temp                  2        181086         90543     6.76  0.0012
mix*comp*temp              2         77897         38949     2.91  0.0552
mcond*temp                 2       1274327        637164    47.54  <.0001
mix*mcond*temp             2         44733         22366     1.67  0.1891
comp*mcond*temp            2          3914          1957     0.15  0.8642
mix*comp*mcond*temp        2         27986         13993     1.04  0.3525
fre                        8     218858220      27357277  2041.12  <.0001
mix*fre                    8         48593          6074     0.45  0.8888
comp*fre                   8         10584          1323     0.10  0.9993
mix*comp*fre               8         10838          1355     0.10  0.9992
mcond*fre                  8        107181         13398     1.00  0.4347
mix*mcond*fre              8         14517          1815     0.14  0.9976
comp*mcond*fre             8         21409          2676     0.20  0.9909
mix*comp*mcond*fre         8          7796           975     0.07  0.9998
fre*temp                  16      11059319        691207    51.57  <.0001
mix*fre*temp              16        139260          8704     0.65  0.8443
comp*fre*temp             16         27549          1722     0.13  1.0000
mix*comp*fre*temp         16         24491          1531     0.11  1.0000
mcond*fre*temp            16         31232          1952     0.15  1.0000
mix*mcond*fre*temp        16         28314          1770     0.13  1.0000
comp*mcond*fre*temp       16         32693          2043     0.15  1.0000
mix*com*mco*fre*temp      16         26047          1628     0.12  1.0000
```

```
Dependent Variable: SQRT(E*)

Source                     DF    Type III SS    Mean Square  F Value  Pr > F
mix                         1        4891633        4891633   364.96  <.0001
comp                        1        1550413        1550413   115.68  <.0001
mix*comp                    1         922370         922370    68.82  <.0001
mcond                       1        3612270        3612270   269.51  <.0001
mix*mcond                   1         289625         289625    21.61  <.0001
comp*mcond                  1         108601         108601     8.10  0.0045
mix*comp*mcond              1         532800         532800    39.75  <.0001
temp                        2     1260712878      630356439  47030.8  <.0001
mix*temp                    2         972755         486377    36.29  <.0001
comp*temp                   2         181086          90543     6.76  0.0012
mix*comp*temp               2          77897          38949     2.91  0.0552
mcond*temp                  2        1274327         637164    47.54  <.0001
mix*mcond*temp              2          44733          22366     1.67  0.1891
comp*mcond*temp             2           3914           1957     0.15  0.8642
mix*comp*mcond*temp         2          27986          13993     1.04  0.3525
fre                         8      218858220       27357277  2041.12  <.0001
mix*fre                     8          48593           6074     0.45  0.8888
comp*fre                    8          10584           1323     0.10  0.9993
mix*comp*fre                8          10838           1355     0.10  0.9992
mcond*fre                   8         107181          13398     1.00  0.4347
mix*mcond*fre               8          14517           1815     0.14  0.9976
comp*mcond*fre              8          21409           2676     0.20  0.9909
mix*comp*mcond*fre          8           7796            975     0.07  0.9998
fre*temp                   16       11059319         691207    51.57  <.0001
mix*fre*temp               16         139260           8704     0.65  0.8443
comp*fre*temp              16          27549           1722     0.13  1.0000
mix*comp*fre*temp          16          24491           1531     0.11  1.0000
mcond*fre*temp             16          31232           1952     0.15  1.0000
mix*mcond*fre*temp         16          28314           1770     0.13  1.0000
comp*mcond*fre*temp        16          32693           2043     0.15  1.0000
mix*com*mco*fre*temp       16          26047           1628     0.12  1.0000

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                            0.01
Error Degrees of Freedom          864
Error Mean Square            13403.06


Number of Means          2
Critical Range       18.19

Means with the same letter are not significantly different.

Duncan Grouping
           Mean       N    comp
A      2187.769     540    lab
B      2111.991     540    field

Duncan's Multiple Range Test for SQRT(E*)

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                            0.05
Error Degrees of Freedom          864
Error Mean Square            13403.06

Number of Means          2
Critical Range       13.83

Means with the same letter are not significantly different.
```

```
Duncan Grouping
           Mean      N    mcond
A      2207.713    540    Not Moisture Conditioned
B      2092.046    540        Moisture Conditioned

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        13403.06

Number of Means          2
Critical Range       13.83

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    comp
A      2187.769    540    lab
B      2111.991    540    field

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        13403.06

Number of Means          2
Critical Range       13.83
Means with the same letter are not significantly different.

Duncan Grouping
          Mean      N     mix
A      2217.180    540    HMA
B      2082.580    540    WMA

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        13403.06
Number of Means      2      3      4      5      6      7      8      9
Critical Range   29.33  30.88  31.92  32.69  33.29  33.78  34.19  34.54

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    fre
A       2819.68    120    fa
B       2653.62    120    fb
C       2530.79    120    fc
D       2354.12    120    fd
E       2184.64    120    fe
F       1917.73    120    ff
G       1780.73    120    fg
H       1681.61    120    fi
I       1426.02    120    fj
```

Duncan's Multiple Range Test for SQRT(E*)

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom      864
Error Mean Square        13403.06

Number of Means          2          3
Critical Range       16.94      17.83
Means with the same letter are not significantly different.
```

Duncan Grouping

```
          Mean      N    temp
A      3569.967    360    tx
B      1928.206    360    ty
C       951.467    360    tz
```

RESIDUAL x PREDICTED VALUE PLOT

```
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
  500 -
      |
      |                                                     A
      |                                                A    A
      |                                        A AA     AA A  BA
  250 -                                  AA       A  B   AAA   A A
      |                 A A A  A   A  BA BAAABBA BB BAAA  CB B    A
      |        AB A A AA AABABAB  C  CA BA C E   CA  DB  C ABD  ABA
      |       AEBBAAABA EBDCBCABAB CCAFBCGBD B C CBDAA B CBDABCABB
      |        FNEFDEGMKHJJJIFEACACCBBBDAE DAFB  AE BDAC BADBAB CC
    0 -       BJNJMJEJFFFLEKEDCABABACBCDCBDCACBC AAB AA   CDBAAADB
      |       BPRFGDGJJJIKEIDECCC BC BE BHCF E B DD  BACBCAE BBCBAA
      |        BEBBA ADBEDHCECACA EBAEABACC BGAD HEDDEBBADFB FC AAA
      |             A   A  AABAB   B  DACCA  DC   A ABBBAABCD  BBB
      |                   AAB    A  A AA B B A   AA  A A AABAA A  A
 -250 -                                  A A   A     A        A
      |                                          AA
      |                                    A         A     A A
      |                                                  A    A  A
      |                                                     A
 -500 -
      |
     Š-|------------|------------|------------|------------|------------|-
        0          1000         2000         3000         4000         5000

                                     predict
```

```
                         Normal Probability Plot
  425+                                                  *
     |
     |                                                  *
     |                                               ****
     |                                            ****++
     |                                       ******
     |                                   +****
     |                              *******
     |                         ******
  -25+                    ******
     |              *******
     |         ******+
     |     *****+
     | +****
     |+ *
     |**
     |*
     |*
 -475+*
      +----+----+----+----+----+----+----+----+----+----+
          -2        -1         0        +1        +2
```

F.8. Field Mix 4 Dynamic Modulus Statistical Analysis Output

```
                                    Class Level Information
Class         Levels    Values     (Coding Translation)
mix                2    MHMA MWMA (HMA WMA)
comp               2    Cfield Clab (field lab)
mcond              2    iNMC iiMC (Not Moisture Conditioned / Moisture conditioned)
fre                9    fa fb fc fd fe ff fg fi fj (Frequencies: 25, 15, 10, 5, 3, 1, 0.5, 0.3, 0.1 Hz.)
temp               3    tx ty tz (4, 21, 37 C)

Number of Observations Read         971
Number of Observations Used         971
                        Five-WAY ANOVA FOR FM4 Dynamic Modulus Samples
Dependent Variable: SQRT(E*)
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                    215    1452247463       6754639   664.23  <.0001
Error                    755       7677637         10169
Corrected Total          970    1459925101

R-Square     Coeff Var      Root MSE      SQRT(E*) Mean
0.994741      3.939880      100.8417      2559.513

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1       3249873       3249873   319.58  <.0001
comp                       1          4709          4709     0.46  0.4964
mix*comp                   1       1017906       1017906   100.10  <.0001
mcond                      1       3356027       3356027   330.02  <.0001
mix*mcond                  1        140236        140236    13.79  0.0002
comp*mcond                 1        194105        194105    19.09  <.0001
mix*comp*mcond             1        133330        133330    13.11  0.0003
temp                       2    1224001219     612000610  60182.6  <.0001
mix*temp                   2        363814        181907    17.89  <.0001
comp*temp                  2         77543         38771     3.81  0.0225
mix*comp*temp              2        122153         61076     6.01  0.0026
mcond*temp                 2        703358        351679    34.58  <.0001
mix*mcond*temp             2        706170        353085    34.72  <.0001
comp*mcond*temp            2        129344         64672     6.36  0.0018
mix*comp*mcond*temp        2         51727         25864     2.54  0.0793
fre                        8     212068612      26508576  2606.79  <.0001
mix*fre                    8        139377         17422     1.71  0.0917
comp*fre                   8         43506          5438     0.53  0.8307
mix*comp*fre               8         96502         12063     1.19  0.3044
mcond*fre                  8         95010         11876     1.17  0.3158
mix*mcond*fre              8         46777          5847     0.57  0.7989
comp*mcond*fre             8          6341           793     0.08  0.9997
mix*comp*mcond*fre         8          8705          1088     0.11  0.9990
fre*temp                  16       5143158        321447    31.61  <.0001
mix*fre*temp              16        132885          8305     0.82  0.6672
comp*fre*temp             16         79684          4980     0.49  0.9527
mix*comp*fre*temp         16         51941          3246     0.32  0.9950
mcond*fre*temp            16         20197          1262     0.12  1.0000
mix*mcond*fre*temp        16         42769          2673     0.26  0.9984
comp*mcond*fre*temp       16         10217           639     0.06  1.0000
mix*com*mco*fre*temp      16         10269           642     0.06  1.0000
```

```
The GLM Procedure

Dependent Variable: SQRT(E*)
Source                     DF    Type III SS    Mean Square   F Value   Pr > F
mix                         1        2635974        2635974    259.22   <.0001
comp                        1          41692          41692      4.10   0.0432
mix*comp                    1         997454         997454     98.09   <.0001
mcond                       1        2982445        2982445    293.29   <.0001
mix*mcond                   1          71464          71464      7.03   0.0082
comp*mcond                  1         231014         231014     22.72   <.0001
mix*comp*mcond              1         127489         127489     12.54   0.0004
temp                        2     1169909935      584954967   57523.0   <.0001
mix*temp                    2         354636         177318     17.44   <.0001
comp*temp                   2          58967          29483      2.90   0.0557
mix*comp*temp               2         110115          55058      5.41   0.0046
mcond*temp                  2         765389         382695     37.63   <.0001
mix*mcond*temp              2         640590         320295     31.50   <.0001
comp*mcond*temp             2         113561          56780      5.58   0.0039
mix*comp*mcond*temp         2          44485          22243      2.19   0.1129
fre                         8      202465629       25308204   2488.75   <.0001
mix*fre                     8         119486          14936      1.47   0.1648
comp*fre                    8          30374           3797      0.37   0.9348
mix*comp*fre                8          97108          12139      1.19   0.2998
mcond*fre                   8         112449          14056      1.38   0.2005
mix*mcond*fre               8          53304           6663      0.66   0.7312
comp*mcond*fre              8           7847            981      0.10   0.9993
mix*comp*mcond*fre          8           9142           1143      0.11   0.9988
fre*temp                   16        4910161         306885     30.18   <.0001
mix*fre*temp               16         116241           7265      0.71   0.7809
comp*fre*temp              16          69991           4374      0.43   0.9749
mix*comp*fre*temp          16          52124           3258      0.32   0.9949
mcond*fre*temp             16          18253           1141      0.11   1.0000
mix*mcond*fre*temp         16          45565           2848      0.28   0.9977
comp*mcond*fre*temp        16          10892            681      0.07   1.0000
mix*com*mco*fre*temp       16          10269            642      0.06   1.0000
```

Duncan's Multiple Range Test for SQRT(E*)

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                              0.05
Error Degrees of Freedom            755
Error Mean Square              10169.06
Harmonic Mean of Cell Sizes    485.4995

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       12.71

Means with the same letter are not significantly different.

Duncan Grouping
          Mean       N    mcond
A      2618.348    485     Not Moisture Conditioned
B      2500.798    486         Moisture Conditioned
```

```
Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         755
Error Mean Square           10169.06
Harmonic Mean of Cell Sizes 479.3821
NOTE: Cell sizes are not equal.
Number of Means          2
Critical Range       12.79

Means with the same letter are not significantly different.

Duncan Grouping
           Mean      N     comp
A      2568.000    540     lab
B      2548.879    431     field

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         755
Error Mean Square           10169.06
Harmonic Mean of Cell Sizes 479.3821

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       12.79

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mix
A      2624.269    431    WMA
B      2507.828    540    HMA

Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         755
Error Mean Square           10169.06
Harmonic Mean of Cell Sizes  107.888
NOTE: Cell sizes are not equal.
Number of Means      2      3      4      5      6      7      8      9
Critical Range   26.95  28.38  29.33  30.03  30.59  31.03  31.41  31.73

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    fre
A       3246.09    108    fa
B       3091.35    108    fb
C       2955.25    108    fc
D       2768.61    107    fd
E       2603.51    108    fe
F       2313.26    108    ff
G       2173.44    108    fg
H       2080.70    108    fi
I       1805.33    108    fj
```

```
Duncan's Multiple Range Test for SQRT(E*)
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom         755
Error Mean Square           10169.06
Harmonic Mean of Cell Sizes  323.666

NOTE: Cell sizes are not equal.

Number of Means          2          3
Critical Range       15.56      16.38
Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    temp
A      3989.380    324    tx
B      2440.449    323    ty
C      1248.343    324    tz
```

```
                                  RESIDUAL x PREDICTED VALUE PLOT

Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
  400 -
      |
      |
      |                          BA           A     A          A
  200 -                     A     AAA    A A   BAA A        BAA BA A
      |                     B A C B BA AAAAAAA  AC  A CC CAABDDBAHCBA
      |          AAAA A  A BAABDBAA   AAAAAC BCBAFACB GADC AACBB A BB A B
      |         BHCKHF EFBFAIJGEFGGBCBBBACACBDAGAH DAAEDBCBBDC CADDCB D
    0 -          ODPJKBCGCJGIHEGGJIBDAACCEDCABBEAIAADBEDAACBAED AGBCC A A
      |         AHDLFFBEECDDFDGGCKCDDC   DACBCCDBJ DCBDD F BAAF BGECC   A
      |          AAAA    AA HCCCGAEABA B BBAAB BBEAAA FDAC ABBCA BDA
      |                    A     BA B  ABA C ABD C AA   AABA  B CC AB B A
 -200 -                           A   A       A AA A  CAAA   BA  B B
      |
      |                                             A        B A
      |                                                     A
 -400 -                                                     A    A
      |
      |                                                        A
      |
 -600 -
      |
      Š-|------------|------------|------------|------------|------------|-
        0          1000         2000         3000         4000         5000

                                     predict
```

```
                                   Normal Probability Plot
 225+                                                ***
    |                                          *******
    |                                     *****
    |                               +******
    |                         *******
    |                   *******
    |             *******
-125+        ******
    |  *******
    |+**
    |**
    |*
    |*
    |*
-475+*
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

F.9. Field Mix 1 Flow Number Statistical Analysis Output

```
                                    Class Level Information
Class          Levels    Values
mix                 2    HMA WMA
comp                2    field lab
mcond               2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          30
Number of Observations Used          30

                                THREE-WAY ANOVA FOR FM1 Flow Number
Dependent Variable: Flow Number
                                    Sum of
Source                    DF       Squares    Mean Square  F Value  Pr > F
Model                      1    5166750.00     5166750.00    10.75  0.0028
Error                     28   13453562.67      480484.38
Corrected Total           29   18620312.67

R-Square     Coeff Var      Root MSE      Flow Number Mean
0.277479      45.49353      693.1698      1523.667

Source                    DF      Type I SS    Mean Square  F Value  Pr > F
mix                        1    5166750.000    5166750.000    10.75  0.0028

Source                    DF    Type III SS    Mean Square  F Value  Pr > F
mix                        1    5166750.000    5166750.000    10.75  0.0028

Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                          0.05
Error Degrees of Freedom         28
Error Mean Square          480484.4

Number of Means          2
Critical Range       518.5

Means with the same letter are not significantly different.
Duncan Grouping
          Mean       N    mix
A        1938.7     15     MHMA
B        1108.7     15     MWMA
```

RESIDUAL x PREDICTED VALUE PLOT

```
Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
 3000 -
      |
      |                                               A
      |
      |
 2000 -
      |
      |
      |
      |
 1000 -
      |  A
      |  C                                            A
      |  A                                            B
      |                                               B
    0 -  B                                            A
      |  C                                            A
      |  C                                            B
      |  B                                            B
      |                                               C
-1000 -
      |
      Š--|--------------------------------------------|--
      1108.67                                    1938.67

                            Predict
```

Normal Probability Plot

```
2750+                                             *
    |
    |                                                +++
    |                                        ++++++++
    |                                 +**+*+* *
    |                         ++*******
    |                  *********
-750+     *   * *+*+***
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          22
Error Mean Square             436564
Harmonic Mean of Cell Sizes 3.404255

NOTE: Cell sizes are not equal.

Number of Means       2       3       4       5       6       7       8
Critical Range     1050    1103    1136    1160    1178    1191    1202

Means with the same letter are not significantly different.
  Duncan
 Grouping            Mean     N    cell
     A             2432.2     5    lab   HMA Npt Moisture Conditioned
B    A             1872.0     2    field HMA _    Moisture Conditioned
B    A    C        1685.0     5    lab_  HMA_    Moisture Conditioned
B    A    C        1583.3     3    field HMA Not Moisture Conditioned
B    A    C        1565.5     4    lab_  WMA_    Moisture Conditioned
B    A    C        1358.0     3    field WMA     Moisture Conditioned
B         C         860.0     5    lab   WMA Not Moisture Conditioned
          C         664.7     3    field WMA Not Moisture Conditioned
```

```
Tukey's Studentized Range (HSD) Test for Flow Number

NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  22
Error Mean Square                     436564
Critical Value of Studentized Range  4.72167
Minimum Significant Difference        1690.9
Harmonic Mean of Cell Sizes         3.404255

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey
Grouping
                Mean      N    cell
     A        2432.2      5    lab   HMA Not Moisture Conditioned
B    A        1872.0      2    field_HMA_    Moisture Conditioned
B    A        1685.0      5    lab   HMA     Moisture Conditioned
B    A        1583.3      3    field HMA Not Moisture Conditioned
B    A        1565.5      4    lab   WMA     Moisture Conditioned
B    A        1358.0      3    field WMA     Moisture Conditioned
B    A         860.0      5    lab   WMA Not Moisture Conditioned
B              664.7      3    field_WMA Not Moisture Conditioned
```

F.10. Field Mix 1 Cycles to 3% Strain Statistical Analysis

```
                                       Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          30
Number of Observations Used          30

                          THREE-WAY ANOVA FOR FM1 Cycles to 3% Strain

The GLM Procedure
Dependent Variable: Cycles to 3% Strain
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      7   148821627.3    21260232.5    16.98  <.0001
Error                     22    27540764.1     1251852.9
Corrected Total           29   176362391.5

R-Square     Coeff Var      Root MSE      Cycles to 3% Strain Mean
0.843840      22.20347      1118.862      5039.133

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   70429105.20   70429105.20    56.26  <.0001
comp                       1   19205001.23   19205001.23    15.34  0.0007
mix*comp                   1   19162240.65   19162240.65    15.31  0.0007
mcond                      1   26855690.77   26855690.77    21.45  0.0001
mix*comp*mcond             3   13169589.49    4389863.16     3.51  0.0323

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   41333128.24   41333128.24    33.02  <.0001
comp                       1   21328776.20   21328776.20    17.04  0.0004
mix*comp                   1   18231863.56   18231863.56    14.56  0.0009
mcond                      1   17392768.61   17392768.61    13.89  0.0012
mix*comp*mcond             3   13169589.49    4389863.16     3.51  0.0323
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          22
Error Mean Square            1251853
Harmonic Mean of Cell Sizes 13.93333

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       879.1

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    comp
A        5727.1     19    lab
B        3850.8     11    field

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          22
Error Mean Square            1251853
Harmonic Mean of Cell Sizes 14.93333

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       849.2

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mcond
A        6127.4     14    Moisture Conditioned
B        4086.9     16    Not Moisture Conditioned

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       22
Error Mean Square         1251853

Number of Means          2
Critical Range       847.3

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    mix
A        6571.3     15    HMA
B        3506.9     15    WMA
```

RESIDUAL x PREDICTED VALUE PLOT

```
   Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
 2000 -                           A
      |
      |        A        A
      |                 A
      |
 1000 -      A
      |                A
      |                                                   C
      |                A          A
      |                AA
    0 -        A       A
      |        A                  B                       A
      |      A         A
      |        A
      |      A A        A
-1000 -                AA
      |                                                   A
      |
      |                 A
      |
-2000 -                           A
      |
      Š--|------------|------------|------------|------------|--
       2000         4000         6000         8000         10000

                                Predict
```

Normal Probability Plot

```
 2250+                                             *+++++
     |                                       * *++++
     |                                   *+*+++
  750+                               ****+
     |                         +*****
     |                    ******
 -750+               *****
     |          +*+*+
     |     ++++*
-2250++++++*
      +----+----+----+----+----+----+----+----+----+----+
          -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          22
Error Mean Square            1251853
Harmonic Mean of Cell Sizes 3.404255
NOTE: Cell sizes are not equal.
Number of Means       2       3       4       5       6       7       8
Critical Range     1779    1867    1924    1964    1994    2017    2035

Means with the same letter are not significantly different.
Duncan
Grouping
                Mean      N    cell
     A        9496.8      5    lab   HMA     Moisture Conditioned
     B        5907.2      5    lab   HMA_Not Moisture Conditioned
C    B        4367.3      3    field_HMA Not Moisture Conditioned
C    B        4321.3      3    field WMA     Moisture Conditioned
C    B        4224.0      2    field HMA     Moisture Conditioned
C    B        4222.0      4    lab   WMA     Moisture Conditioned
C             2981.4      5    lab   WMA Not Moisture Conditioned
C             2615.0      3    field WMA_Not Moisture Conditioned

Tukey's Studentized Range (HSD) Test for Cycles to 3% Strain
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                       0.05
Error Degrees of Freedom                      22
Error Mean Square                        1251853
Critical Value of Studentized Range  4.72167
Minimum Significant Difference        2863.3
Harmonic Mean of Cell Sizes         3.404255
NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.

Tukey
Grouping
                Mean      N    cell
     A        9496.8      5    lab   HMA     Moisture Conditioned
     B        5907.2      5    lab   HMA Not Moisture Conditioned
C    B        4367.3      3    field HMA Not Moisture Conditioned
C    B        4321.3      3    field WMA_    Moisture Conditioned
C    B        4224.0      2    field HMA_    Moisture Conditioned
C    B        4222.0      4    lab   WMA     Moisture Conditioned
C             2981.4      5    lab   WMA Not Moisture Conditioned
C             2615.0      3    field WMA Not Moisture Conditioned
```

F.11. Field Mix 2 Flow Number Statistical Analysis Output

```
                                       Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          40
Number of Observations Used          40

                               THREE-WAY ANOVA FOR FM2 Flow Number
Dependent Variable: Flow Number
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      2   442369.3000   221184.6500    18.40  <.0001
Error                     37   444857.8000    12023.1838
Corrected Total           39   887227.1000

R-Square     Coeff Var      Root MSE       Flow Number Mean
0.498598      29.93047      109.6503      366.3500

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   352688.4000   352688.4000    29.33  <.0001
mcond                      1    89680.9000    89680.9000     7.46  0.0096

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   352688.4000   352688.4000    29.33  <.0001
mcond                      1    89680.9000    89680.9000     7.46  0.0096

Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       37
Error Mean Square        12023.18

Number of Means          2
Critical Range       70.26

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mcond
A        413.70     20    Moisture Conditioned
B        319.00     20    Not Moisture Conditioned

Duncan's Multiple Range Test for Flow Number

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       37
Error Mean Square        12023.18

Number of Means          2
Critical Range       70.26

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mix
A        460.25     20    HMA
B        272.45     20    WMA
```

RESIDUAL x PREDICTED VALUE PLOT

```
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
  400 -                                        A
      |
      |                                                         A
      |
      |
      |
      |
  200 -
      |
      |
      |
      |       A                A                                A
      |       C
      |                        A               A                B
    0 -       D                D               C                B
      |                        B                                A
      |                        B               A                A
      |       A                                B                A
      |       A                                A
      |                                        A
      |
 -200 -                                                         A
      |
      Š--|--------|--------|--------|--------|--------|--------|--------|--
        200      250      300      350      400      450      500      550

                                     predict
```

Normal Probability Plot

```
  425+                                               *
     |
     |                                          *
     |                                                 ++
     |                                            +++++
     |                                        ++++
  125+                                   +++++
     |                              +++++**** *
     |                         +++*******
     |                    ********
     |             *******+
     |        * *+*+++
 -175+   *   ++++
      +----+----+----+----+----+----+----+----+----+----+
          -2        -1         0        +1        +2
```

Duncan's Multiple Range Test for Flow Number

```
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square         12932.9

Number of Means       2       3       4       5       6       7       8
Critical Range    146.5   154.0   158.8   162.3   165.0   167.0   168.7

Means with the same letter are not significantly different.

  Duncan
 Grouping            Mean      N    cell

     A             520.00      5    field HMA     Moisture Conditioned
     A
     A             505.00      5    lab   HMA     Moisture Conditioned
     A
B    A             448.00      5    field HMA Not Moisture Conditioned
B    A
B    A    C        368.00      5    lab   HMA Not Moisture Conditioned
B         C
B    D    C        326.00      5    field WMA     Moisture Conditioned
B    D    C
B    D    C        303.80      5    lab   WMA     Moisture Conditioned
     D    C
     D    C        265.00      5    field WMA Not Moisture Conditioned
     D
     D             195.00      5    lab   WMA Not Moisture Conditioned
```

Tukey's Studentized Range (HSD) Test for Flow Number

```
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  32
Error Mean Square                    12932.9
Critical Value of Studentized Range  4.58106
Minimum Significant Difference        232.99
Means with the same letter are not significantly different.

   Tukey
 Grouping            Mean      N    cell
     A             520.00      5    field HMA     Moisture Conditioned
     A             505.00      5    lab   HMA     Moisture Conditioned
B    A             448.00      5    field HMA Not Moisture Conditioned
B    A    C        368.00      5    lab   HMA Not Moisture Conditioned
B    A    C        326.00      5    field WMA     Moisture Conditioned
B    A    C        303.80      5    lab   WMA     Moisture Conditioned
B         C        265.00      5    field WMA Not Moisture Conditioned
          C        195.00      5    lab   WMA Not Moisture Conditioned
```

F.12. Field Mix 2 Cycles to 3% Strain Statistical Analysis Output

```
                                        Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Co9nditioned

Number of Observations Read          40
Number of Observations Used          40

                            THREE-WAY ANOVA FOR FM2 Cycles to 3% Strain
The GLM Procedure
Dependent Variable: Cycles to 3% Strain
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      2   3513285.000   1756642.500    16.22  <.0001
Error                     37   4007180.100    108302.165
Corrected Total           39   7520465.100

R-Square     Coeff Var      Root MSE       Cycles to 3% Strain Mean
0.467163      26.38337      329.0929      1247.350

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   2938724.100   2938724.100    27.13  <.0001
mcond                      1    574560.900    574560.900     5.31  0.0270

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   2938724.100   2938724.100    27.13  <.0001
mcond                      1    574560.900    574560.900     5.31  0.0270

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       37
Error Mean Square        108302.2

Number of Means          2
Critical Range       210.9

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    mcond
A        1367.2     20    Moisture Conditioned
B        1127.5     20    Not Moisture Conditioned

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       37
Error Mean Square        108302.2

Number of Means          2
Critical Range       210.9

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N     mix
A        1518.4     20     HMA
B         976.3     20     WMA
```

RESIDUAL x PREDICTED VALUE PLOT

```
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
 1500 -
      |
      |
      |                                        A              A
 1000 -
      |
      |
      |
  500 -
      |
      |     B              A
      |     A              B                   A              A
    0 -     D              B                   B              D
      |     B              E                   C              B
      |     A                                  A
      |                                        B              A
 -500 -      ,                                                       A
      |
      |
-1000 -
      |
      Š-|------------|------------|------------|------------|------------|------------|-
       800         1000         1200         1400         1600         1800

                                     predict
```

Normal Probability Plot

```
1150+                                          *    *
    |
    |
    |                                                 +
    |                                              +++
    |                                           +++
    |                                        +++
    |                                     +++
    |                                  +++
 250+                                +++  ** *
    |                             +++ ****
    |                         +++*****
    |                      +******
    |               ********
    |             ** +++
    |          * *+++
    |        * +++
    |       +++
-650+   *+++
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square          118151

Number of Means        2       3       4       5       6       7       8
Critical Range     442.8   465.4   480.1   490.6   498.6   504.8   509.9

Means with the same letter are not significantly different.

Duncan
Grouping
                Mean      N    cell
     A        1669.4      5    field HMA     Moisture Conditioned
     A        1638.6      5    lab   HMA     Moisture Conditioned
B    A        1456.2      5    field HMA Not Moisture Conditioned
B    A        1309.4      5    lab   HMA Not Moisture Conditioned
B    C        1137.0      5    field WMA     Moisture Conditioned
B    C        1023.8      5    lab   WMA     Moisture Conditioned
B    C         985.4      5    field WMA Not Moisture Conditioned
     C         759.0      5    lab   WMA Not Moisture Conditioned

Tukey's Studentized Range (HSD) Test for Cycles to 3% Strain
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                     0.05
Error Degrees of Freedom                    32
Error Mean Square                       118151
Critical Value of Studentized Range    4.58106
Minimum Significant Difference          704.21

Means with the same letter are not significantly different.
Tukey
Grouping
                Mean      N    cell
     A        1669.4      5    field HMA     Moisture Conditioned
     A        1638.6      5    lab   HMA     Moisture Conditioned
B    A        1456.2      5    field HMA Not Moisture Conditioned
B    A        1309.4      5    lab   HMA Not Moisture Conditioned
B    A        1137.0      5    field WMA     Moisture Conditioned
B    A        1023.8      5    lab   WMA     Moisture Conditioned
B    A         985.4      5    field WMA Not Moisture Conditioned
B              759.0      5    lab   WMA Not Moisture Conditioned
```

F.13. Field Mix 3 Flow Number Statistical Analysis Output

```
                                      Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          40
Number of Observations Used          40

                               THREE-WAY ANOVA FOR FM3 Flow Number

Dependent Variable: Flow Number
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      3   2461063.675    820354.558    14.89  <.0001
Error                     36   1983653.100     55101.475
Corrected Total           39   4444716.775

R-Square     Coeff Var      Root MSE      Flow Number Mean
0.553705      35.29482      234.7370      665.0750

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   1305738.225   1305738.225    23.70  <.0001
mix*comp                   2   1155325.450    577662.725    10.48  0.0003

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   1305738.225   1305738.225    23.70  <.0001
mix*comp                   2   1155325.450    577662.725    10.48  0.0003

Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          36
Error Mean Square           55101.47

Number of Means          2
Critical Range       150.5

Means with the same letter are not significantly different.
Duncan Grouping
          Mean       N    mix
A       845.75      20     HMA
B       484.40      20     WMA
```

```
                             RESIDUAL x PREDICTED VALUE PLOT
   Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid ,
 1000 ˆ
      ,
      ,
      ,
      ,             A
      ,
      ,
  500 ˆ                                              A
      ,
      ,                                              B
      ,                                              A
      ,
      ,  A          A  C
      ,  C             A
    0 ˆ  C          A  A
      ,  B          D  C                             B
      ,  A          A  B
      ,             A
      ,             A                                B
      ,
      ,                                              B
 -500 ˆ
      ,
      Šƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒƒƒƒƒƒƒƒƒƒƒˆƒƒ
        400          600          800         1000         1200

                                Predict
```

```
                   Normal Probability Plot
 750+                                               *
    |
    |                                          *     +++
    |                                           +++++
    |                                      *+*++
    |                                  +++*+
 150+                              ++*****
    |                         +++****
    |                   **********
    |               ****++
    |            +**++
    |        *+*+*
-450+   *++++
     +----+----+----+----+----+----+----+----+----+----+
         -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square        49545.16

Number of Means       2       3       4       5       6       7       8
Critical Range    286.8   301.4   310.9   317.7   322.9   326.9   330.2

Means with the same letter are not significantly different.

Duncan
Grouping
                Mean      N    cell
     A        1233.0      5    lab   HMA     Moisture Conditioned
     B         911.0      5    lab   HMA Not Moisture Conditioned
C    B         681.0      5    field WMA Not Moisture Conditioned
C    B         643.0      5    field HMA     Moisture Conditioned
C              596.0      5    field HMA Not Moisture Conditioned
C              450.0      5    field WMA     Moisture Conditioned
C              406.0      5    lab   WMA Not Moisture Conditioned
C              400.6      5    lab   WMA     Moisture Conditioned

Tukey's Studentized Range (HSD) Test for Flow Number
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  32
Error Mean Square                   49545.16
Critical Value of Studentized Range  4.58106
Minimum Significant Difference        456.02

Means with the same letter are not significantly different.
Tukey
Grouping
                Mean      N    cell
     A        1233.0      5    lab   HMA     Moisture Conditioned
B    A         911.0      5    lab   HMA Not Moisture Conditioned
B    C         681.0      5    field WMA Not Moisture Conditioned
B    C         643.0      5    field HMA     Moisture Conditioned
B    C         596.0      5    field HMA Not Moisture Conditioned
     C         450.0      5    field WMA     Moisture Conditioned
     C         406.0      5    lab   WMA Not Moisture Conditioned
     C         400.6      5    lab   WMA     Moisture Conditioned
```

F.14. Field Mix 3 Cycles to 3% Strain Statistical Analysis Output

```
                                                 Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          40
Number of Observations Used          40

                                       THREE-WAY ANOVA FOR FM3 Cycles to 3% Strain

Dependent Variable: Cycles to 3% Stain
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      3   29766479.00    9922159.67     7.04  0.0008
Error                     36   50770777.00    1410299.36
Corrected Total           39   80537256.00

R-Square     Coeff Var      Root MSE      Cycles to 3% Strain Mean
0.369599      53.13469      1187.560      2235.000

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1    9496502.50    9496502.50     6.73  0.0136
comp                       1    9198728.10    9198728.10     6.52  0.0150
mix*comp                   1   11071248.40   11071248.40     7.85  0.0081

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1    9496502.50    9496502.50     6.73  0.0136
comp                       1    9198728.10    9198728.10     6.52  0.0150
mix*comp                   1   11071248.40   11071248.40     7.85  0.0081

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                          0.05
Error Degrees of Freedom         36
Error Mean Square           1410299

Number of Means          2
Critical Range       761.6

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    comp
A        2714.6     20    lab
B        1755.5     20    field

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                          0.05
Error Degrees of Freedom         36
Error Mean Square           1410299

Number of Means          2
Critical Range       761.6

Means with the same letter are not significantly different.
Duncan Grouping
         Mean      N    mix
A        2722.3     20    HMA
B        1747.8     20    WMA
```

```
                                      RESIDUAL x PREDICTED VALUE PLOT
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
 6000 -                                                           A
      |
      |
      |
      |
 4000 -
      |
      |
      |
      |
 2000 -
      |
      |
      |         A                                                 A
      |      AC A                                                 B
    0 -      GC E
      |      BD C
      |                                                           B
      |                                                           C
      |
-2000 -                                                           A
      |
      Š-|------------|------------|------------|------------|------------|-
      1500         2000         2500         3000         3500         4000

                                     predict
```

```
                       Normal Probability Plot
    6250+                                               *
        |
        |
        |
        |
        |
        |
        |                                               ++++
        |                                           ++++
        |                                       ++++
        |                                  +++++
        |                              ++++    * * *
        |                         ++***********
        |               *************
        |             **  ++++
        |        * * *++++
        |        ++++
   -2250+   *++++
         +----+----+----+----+----+----+----+----+----+----+
             -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square         1205659

Number of Means       2       3       4       5       6       7       8
Critical Range     1415    1487    1534    1567    1593    1613    1629

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    cell
A        4825.0      5    lab   HMA     Moisture Conditioned
B        2630.8      5    lab   HMA Not Moisture Conditioned
B        1915.8      5    field WMA Not Moisture Conditioned
B        1730.2      5    field HMA Not Moisture Conditioned
B        1721.0      5    lab   WMA     Moisture Conditioned
B        1703.0      5    field HMA     Moisture Conditioned
B        1681.4      5    lab   WMA Not Moisture Conditioned
B        1672.8      5    field WMA     Moisture Conditioned

Tukey's Studentized Range (HSD) Test for Cycles to 3% Strain

NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ

Alpha                                   0.05
Error Degrees of Freedom                  32
Error Mean Square                    1205659
Critical Value of Studentized Range  4.58106
Minimum Significant Difference        2249.5

Means with the same letter are not significantly different.
Tukey
Grouping
                Mean      N    cell
     A        4825.0      5    lab   HMA     Moisture Conditioned
B    A        2630.8      5    lab   HMA Not Moisture Conditioned
B             1915.8      5    field WMA Not Moisture Conditioned
B             1730.2      5    field HMA Not Moisture Conditioned
B             1721.0      5    lab   WMA     Moisture Conditioned
B             1703.0      5    field HMA     Moisture Conditioned
B             1681.4      5    lab   WMA Not Moisture Conditioned
B             1672.8      5    field WMA     Moisture Conditioned
```

F.15. Field Mix 4 Flow Number Statistical Analysis Output

```
                                        Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          36
Number of Observations Used          36

                                  THREE-WAY ANOVA FOR FM4 Flow Number
Dependent Variable: Flow Number
                                   Sum of
Source                    DF      Squares    Mean Square  F Value  Pr > F
Model                      1   3490301.25     3490301.25     9.13  0.0047
Error                     34  12994048.75      382177.90
Corrected Total           35  16484350.00

R-Square     Coeff Var      Root MSE      Flow Number Mean
0.211734      38.20800      618.2054      1618.000

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   3490301.250   3490301.250     9.13  0.0047

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1   3490301.250   3490301.250     9.13  0.0047

Duncan's Multiple Range Test for Flow Number

NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                            0.05
Error Degrees of Freedom           34
Error Mean Square            382177.9
Harmonic Mean of Cell Sizes 17.77778

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       421.4

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mix
A        1966.1     16    WMA
B        1339.5     20    HMA
```

```
Duncan's Multiple Range Test for Flow Number
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          28
Error Mean Square           334260.1
Harmonic Mean of Cell Sizes 4.285714

NOTE: Cell sizes are not equal.

Number of Means       2       3       4       5       6       7       8
Critical Range    809.0   850.1   876.6   895.5   909.7   920.8   929.7
Means with the same letter are not significantly different.
  Duncan
 Grouping            Mean      N    cell
     A             2426.3      3    field WMA     Moisture Conditioned
B    A             2324.0      5    lab   WMA Not Moisture Conditioned
B    A    C        1812.0      5    lab   WMA     Moisture Conditioned
B         C        1507.0      5    lab   HMA Not Moisture Conditioned
          C        1394.0      5    field HMA     Moisture Conditioned
          C        1294.0      5    field HMA Not Moisture Conditioned
          C        1166.3      3    field WMA Not Moisture Conditioned
          C        1163.0      5    lab   HMA     Moisture Conditioned
```

F.16. Field Mix 4 Cycles to 3% Strain Statistical Analysis Output

```
                                       Class Level Information
Class         Levels    Values
mix                2    HMA WMA
comp               2    field lab
mcond              2    Moisture Conditioned Not Moisture Conditioned

Number of Observations Read          36
Number of Observations Used          36

                          THREE-WAY ANOVA FOR FM4 Cycles to 3% Strain
Dependent Variable: Cycles to 3% Strain
                                    Sum of
Source                    DF       Squares   Mean Square  F Value  Pr > F
Model                      3    75506545.7    25168848.6    20.68  <.0001
Error                     32    38953412.8     1217294.2
Corrected Total           35   114459958.6

R-Square     Coeff Var      Root MSE      Cycles to 3% Strain Mean
0.659677      17.79645      1103.311     6199.611

Source                    DF     Type I SS   Mean Square  F Value  Pr > F
mix                        1   13195542.76   13195542.76    10.84  0.0024
comp                       1   31170882.86   31170882.86    25.61  <.0001
mcond                      1   31140120.11   31140120.11    25.58  <.0001

Source                    DF   Type III SS   Mean Square  F Value  Pr > F
mix                        1    8445938.44    8445938.44     6.94  0.0129
comp                       1   31170882.86   31170882.86    25.61  <.0001
mcond                      1   31140120.11   31140120.11    25.58  <.0001

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          32
Error Mean Square            1217294
Harmonic Mean of Cell Sizes 17.77778

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       753.8

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    comp
A        7093.1     20    lab
B        5082.8     16    field
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                        0.05
Error Degrees of Freedom       32
Error Mean Square         1217294

Number of Means          2
Critical Range       749.1

Means with the same letter are not significantly different.
Duncan Grouping
          Mean      N    mcond
A        7129.7     18    Moisture Conditioned
B        5269.6     18    Not Moisture Conditioned

Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          32
Error Mean Square            1217294
Harmonic Mean of Cell Sizes 17.77778

NOTE: Cell sizes are not equal.

Number of Means          2
Critical Range       753.8

Means with the same letter are not significantly different.
Duncan Grouping
           Mean      N    mix
A        6876.5     16    WMA
B        5658.1     20    HMA
```

```
                                  RESIDUAL x PREDICTED VALUE PLOT
        Plot of resid*predict. Legend: A = 1 obs, B = 2 obs, etc.

resid |
      |
 4000 |
      |
      |
      |
      |                                        A
 2000 -
      |                                                             B
      |                             B                    A
      |         B                              B         A
      |         A                   B
    0 -         A         A         A          B         A          B
      |         A         A         B          A
      |                   A         A                    A          A
      |
      |                             A
-2000 -                             A          B         A
      |
      |
      |
      |
-4000 -
      |
      Š|----------|----------|----------|----------|----------|----------|-
     3000       4000       5000       6000       7000       8000       9000

                                     predict
```

```
                     Normal Probability Plot
 2250+                                            ++*++
     |                                        ++++
     |                                   **+*+* *
  750+                              *****
     |                         *****
     |                    ******
 -750+               *****+
     |           +++++
     |       +*+* * *
-2250+  ++*++
      +----+----+----+----+----+----+----+----+----+----+
          -2        -1         0        +1        +2
```

```
Duncan's Multiple Range Test for Cycles to 3% Strain
NOTE: This test controls the Type I comparisonwise error rate, not the
experimentwise error rate.

Alpha                           0.05
Error Degrees of Freedom          28
Error Mean Square            1308058
Harmonic Mean of Cell Sizes 4.285714

NOTE: Cell sizes are not equal.

Number of Means       2       3       4       5       6       7       8
Critical Range     1600    1682    1734    1771    1800    1822    1839

Means with the same letter are not significantly different.

Duncan
Grouping
                Mean      N    cell
     A        8868.6      5    lab WMA Moisture Conditioned
B    A        7407.6      5    lab HMA Moisture Conditioned
B    C        6638.8      5    lab WMA Not Moisture Conditioned
B    C        6376.3      3    field WMA Moisture Conditioned
D    C        5564.8      5    field HMA Moisture Conditioned
D    C        5457.2      5    lab HMA Not Moisture Conditioned
D             4452.7      3    field WMA Not Moisture Conditioned
D             4202.8      5    field HMA Not Moisture Conditioned
```

```
Tukey's Studentized Range (HSD) Test for Cycles to 3% Strain
NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.

Alpha                                   0.05
Error Degrees of Freedom                  28
Error Mean Square                    1308058
Critical Value of Studentized Range  4.62479
Minimum Significant Difference          2555
Harmonic Mean of Cell Sizes         4.285714

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

   Tukey
 Grouping            Mean      N    cell
     A             8868.6      5    lab   WMA     Moisture Conditioned
B    A             7407.6      5    lab   HMA     Moisture Conditioned
B    A    C        6638.8      5    lab   WMA Not Moisture Conditioned
B    A    C        6376.3      3    field WMA     Moisture Conditioned
B         C        5564.8      5    field HMA     Moisture Conditioned
B         C        5457.2      5    lab   HMA Not Moisture Conditioned
          C        4452.7      3    field WMA Not Moisture Conditioned
          C        4202.8      5    field HMA Not Moisture Conditioned
```

APPENDIX G. MASTER CURVES FOR LABORATORY-PRODUCED MIXES

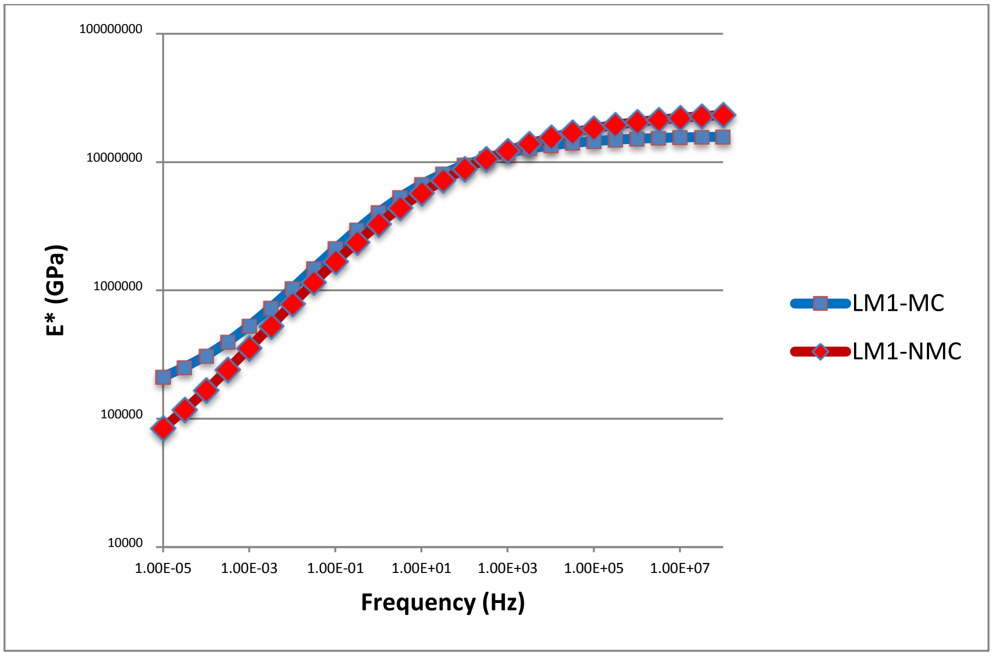


Figure G.1. Master curves for limestone mixture LM1

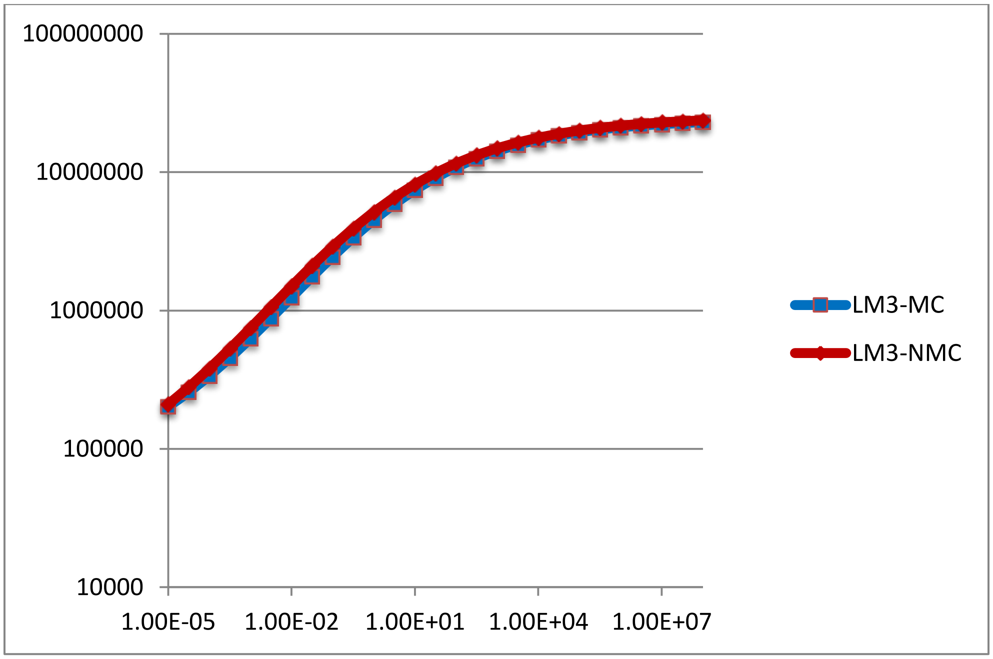


Figure G.2. Master curves for limestone mixture LM3

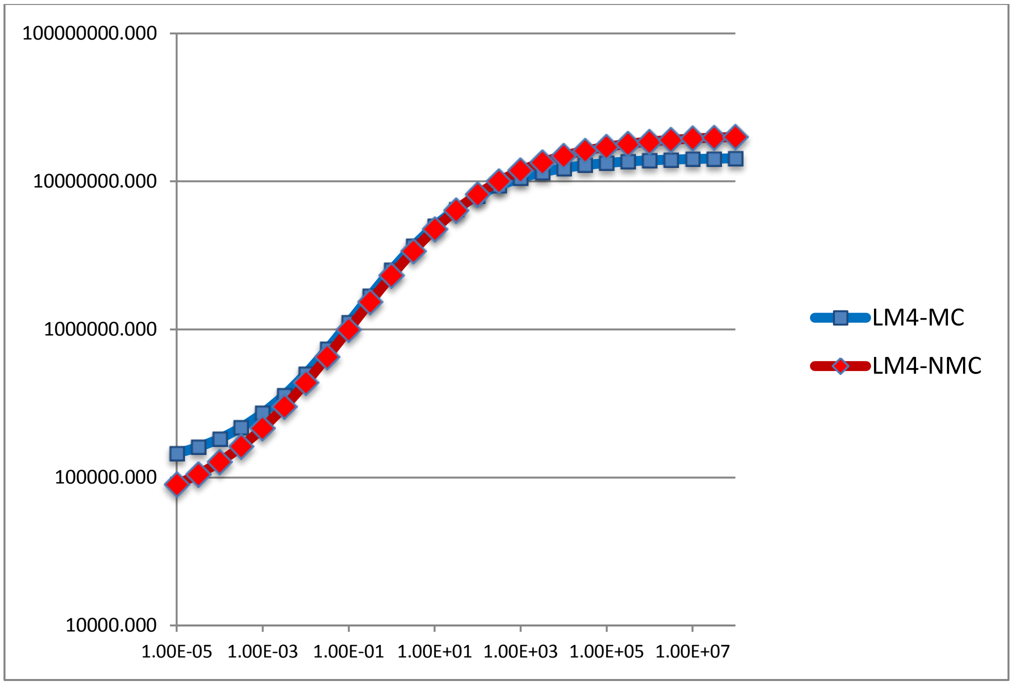


Figure G.3. Master curves for limestone mixture LM4

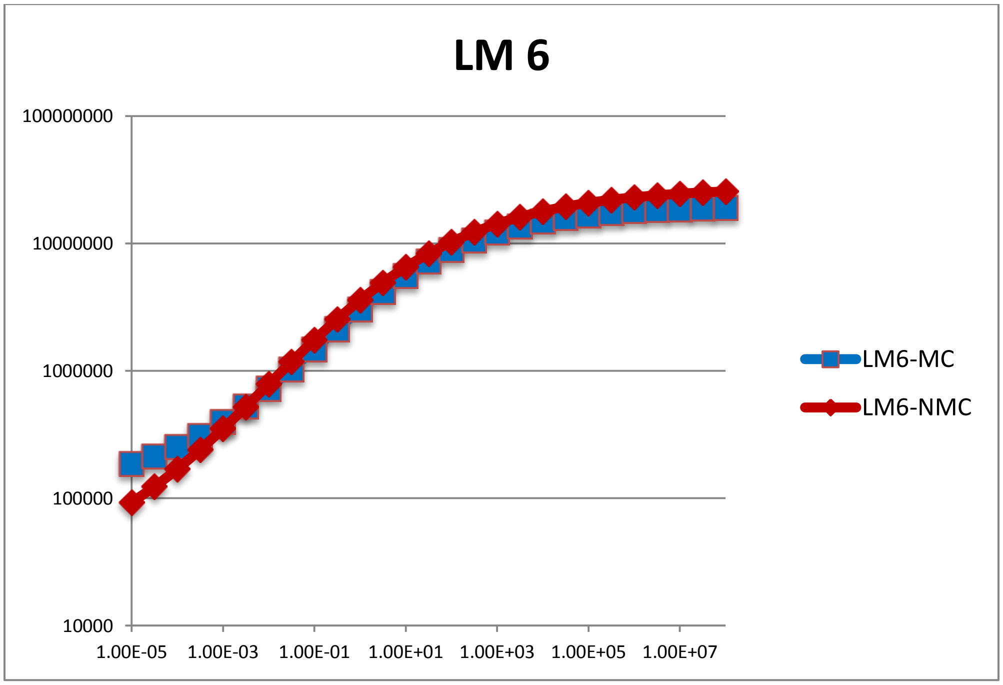


Figure G.4. Master curves for limestone mixture LM6

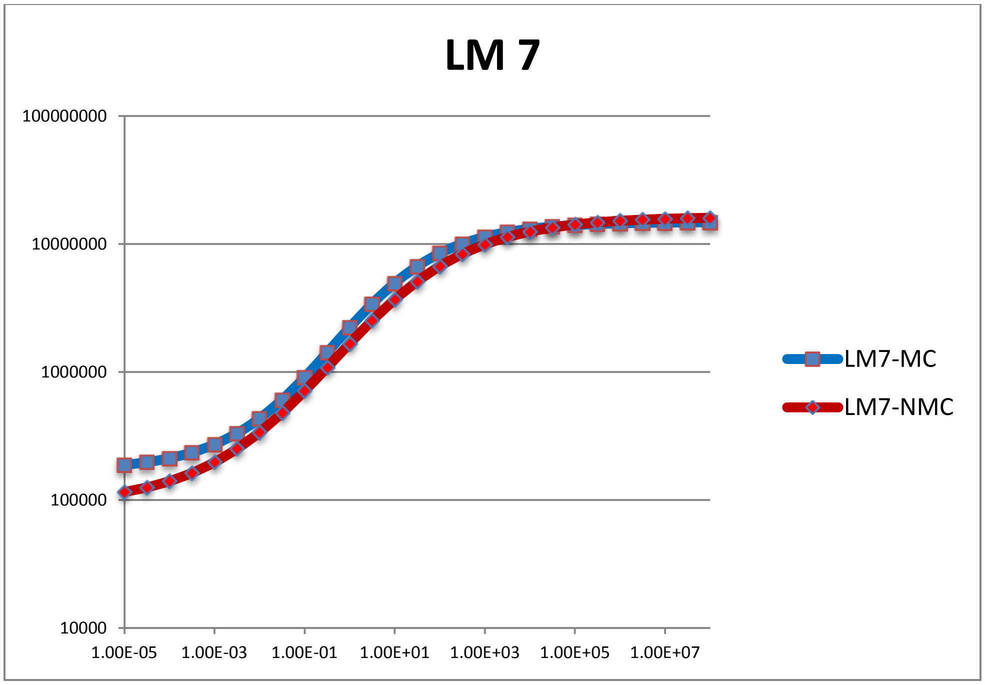


Figure G.5. Master curves for limestone mixture LM7

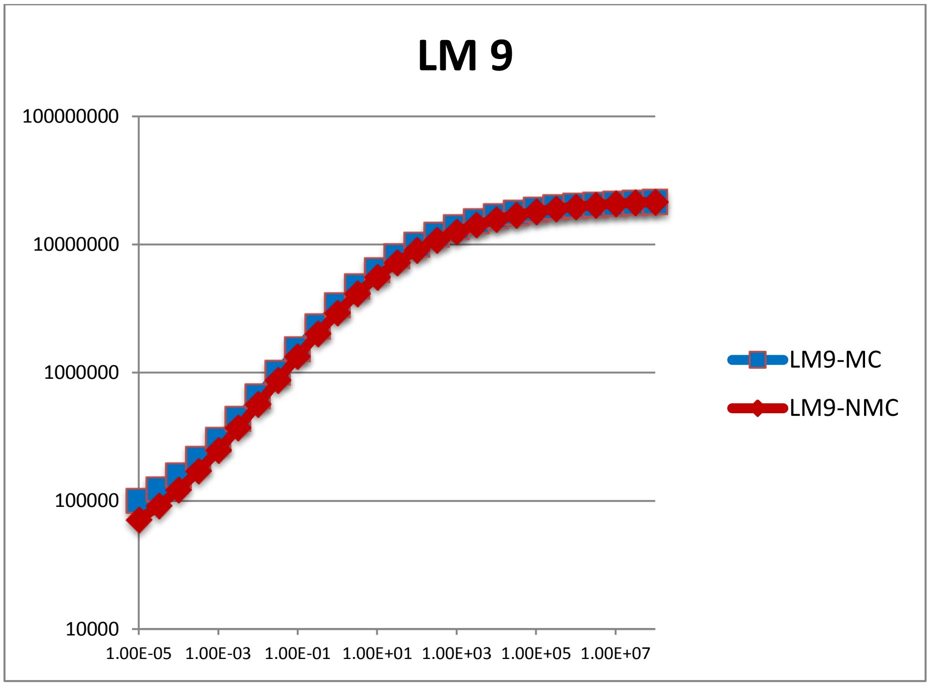


Figure G.6. Master curves for limestone mixture LM9

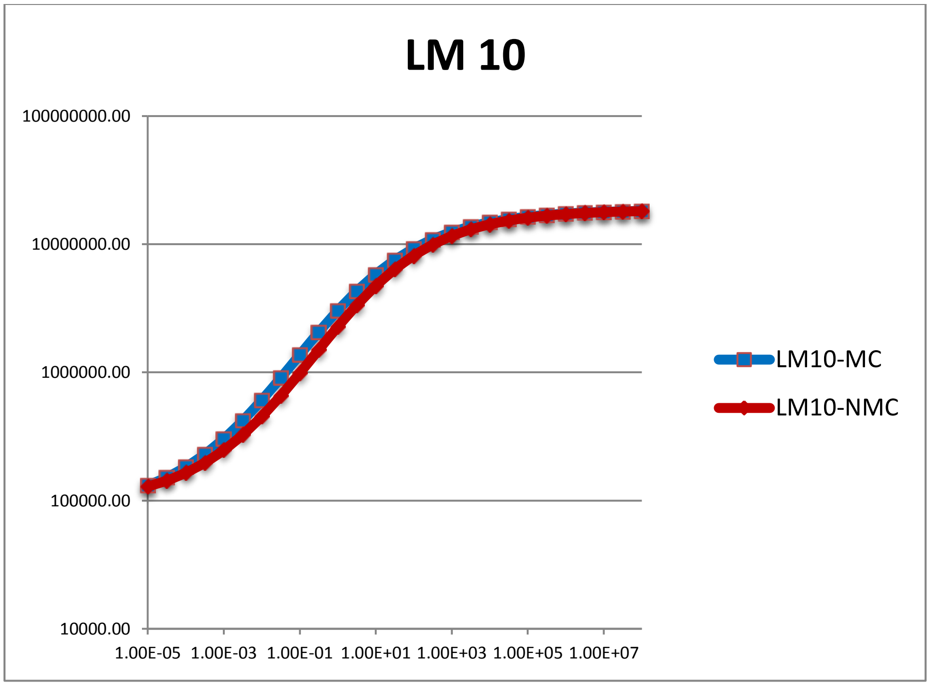


Figure G.7. Master curves for limestone mixture LM10

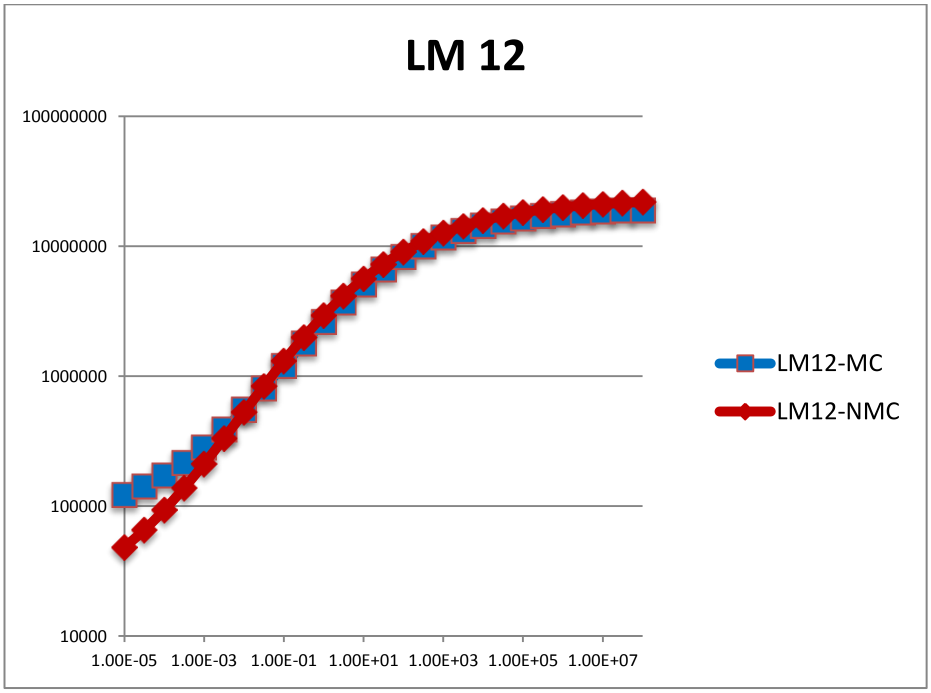


Figure G.8. Master curves for limestone mixture LM12

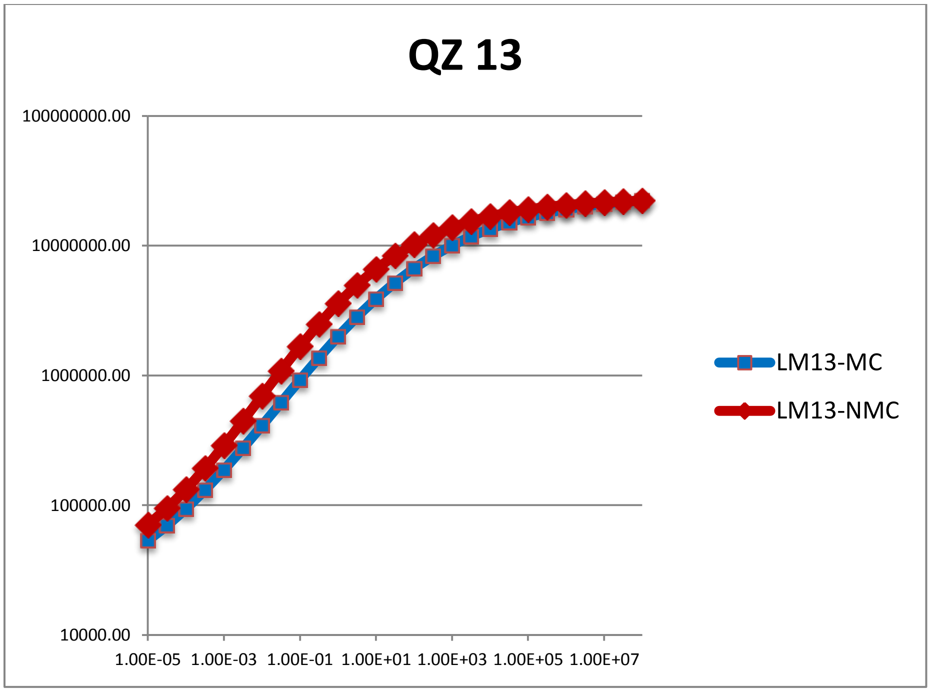


Figure G.9. Master curves for quartzite mixture QZ13

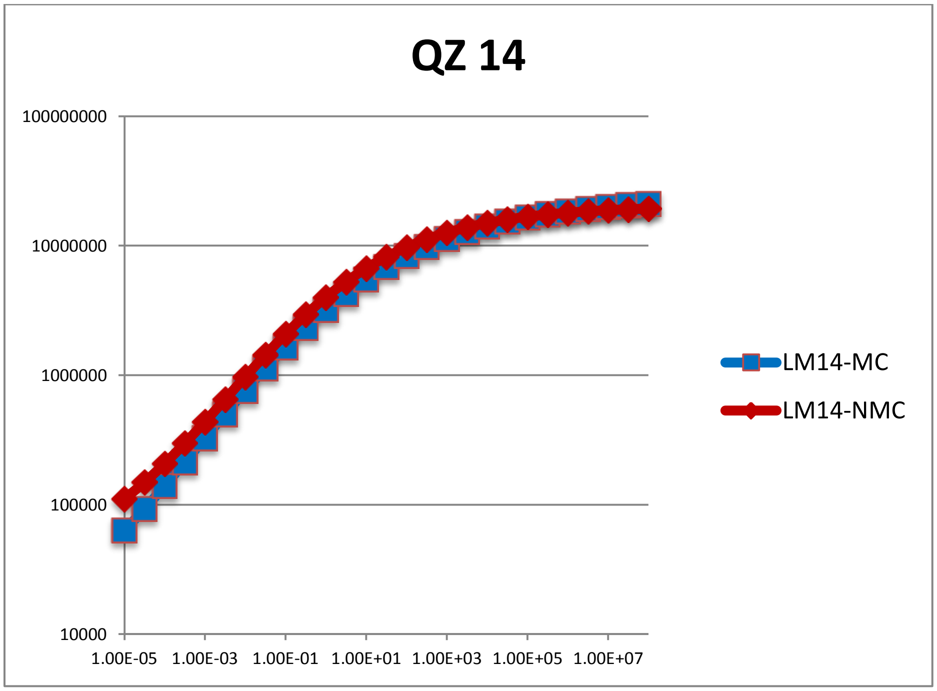


Figure G.10. Master curves for quartzite mixture QZ14

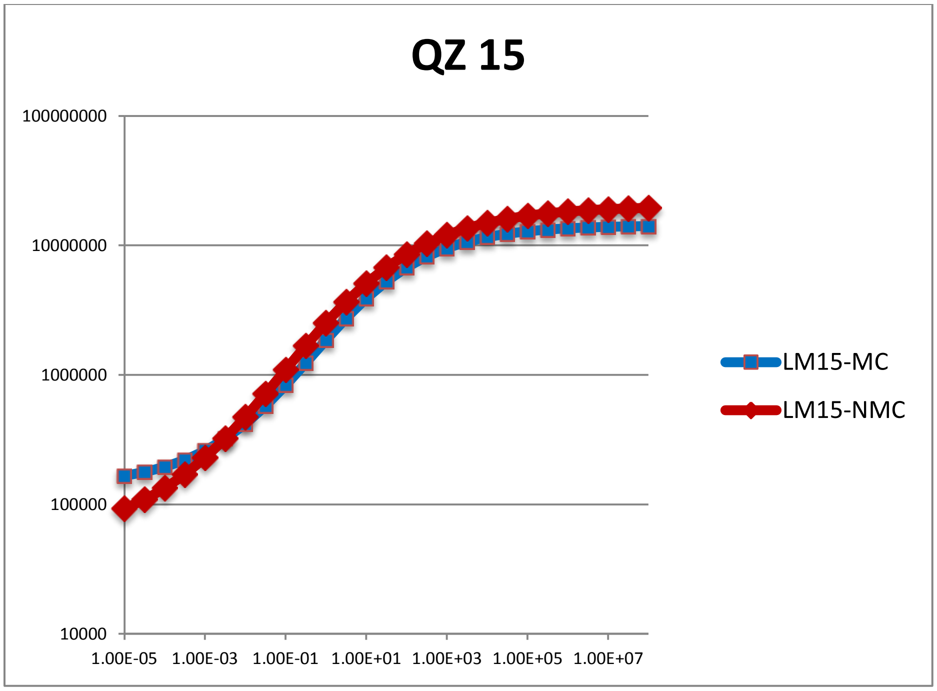


Figure G.11. Master curves for quartzite mixture QZ15

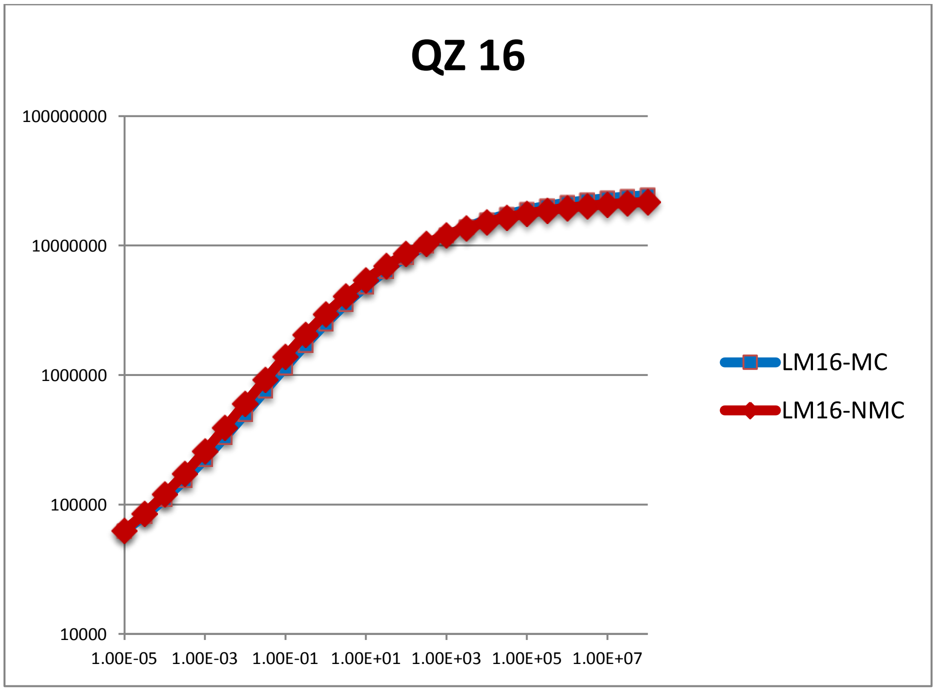


Figure G.12. Master curves for quartzite mixture QZ16

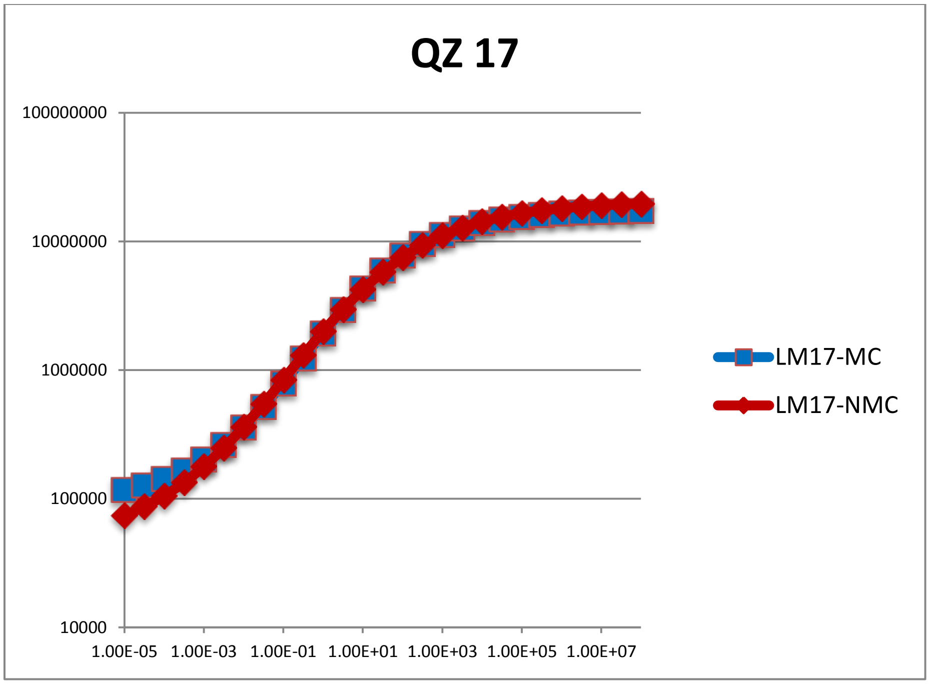


Figure G.13. Master curves for quartzite mixture QZ17

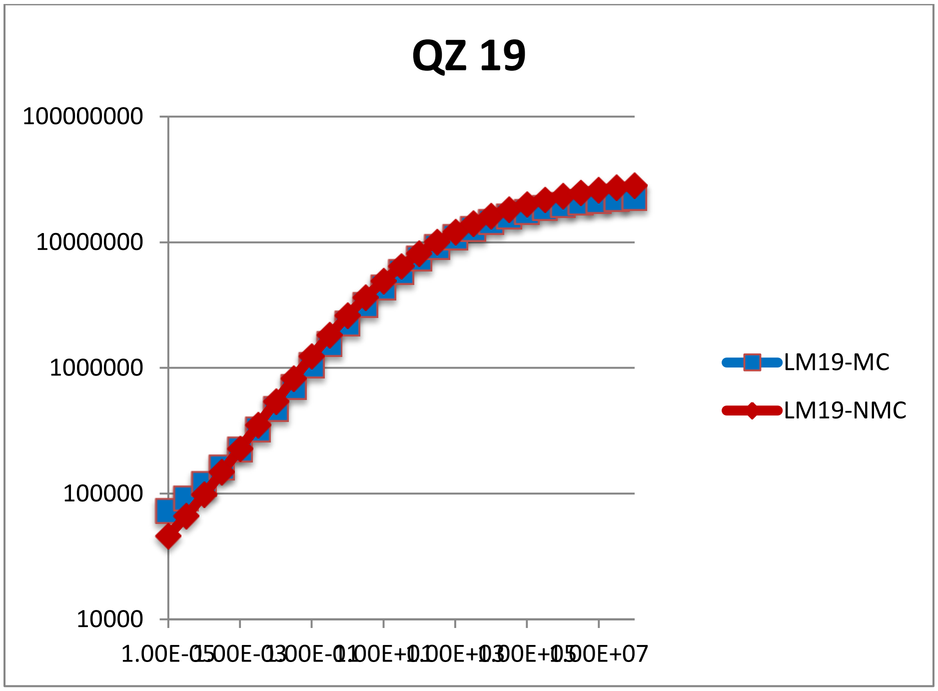


Figure G.14. Master curves for quartzite mixture QZ19

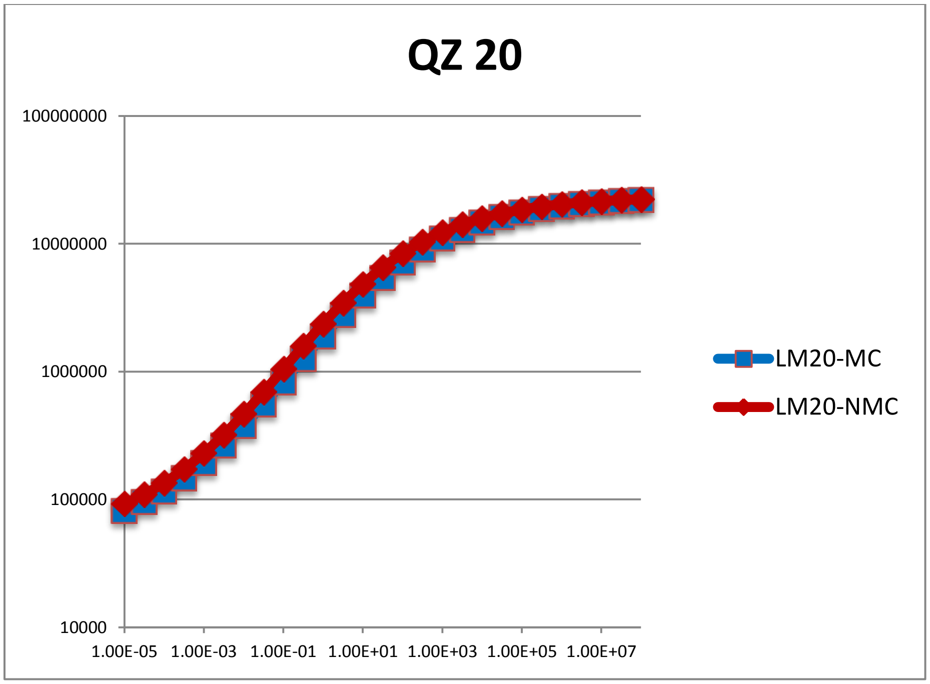


Figure G.15. Master curves for quartzite mixture QZ20

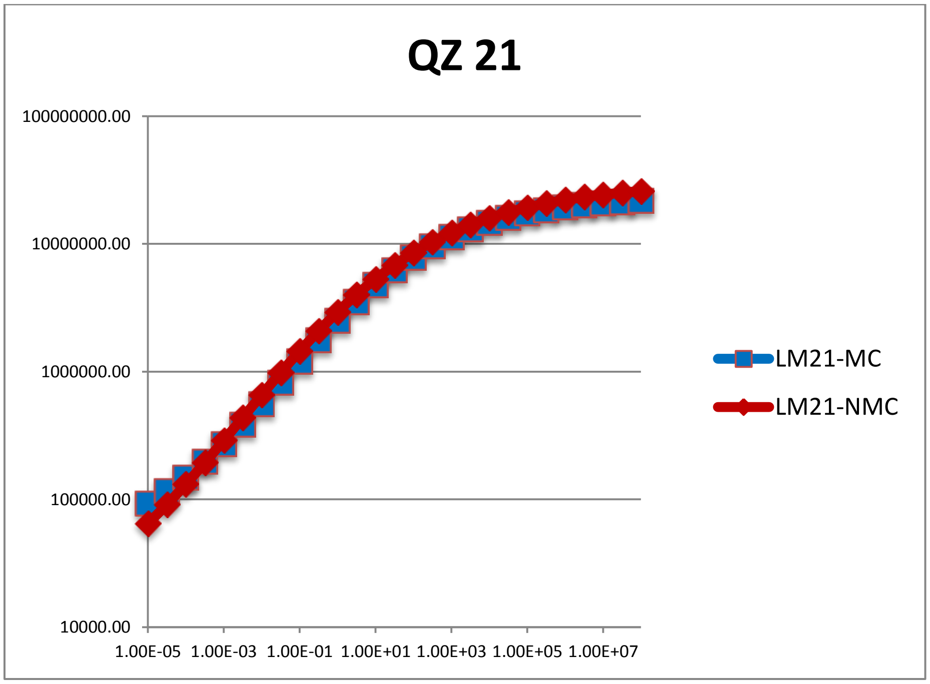


Figure G.16. Master curves for quartzite mixture QZ21

APPENDIX H. DYNAMIC MODULUS DATA FOR LABORATORY-PRODUCED MIXES

Table H.1. Dynamic modulus data for LM1 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	15.75	1.13	7.17	5.900	0.615	10.43
	15	14.87	1.01	6.79	8.046	0.589	7.32
	10	14.05	0.94	6.66	8.985	0.424	4.72
	5	13.05	0.87	6.69	10.377	0.528	5.09
	3	12.51	1.22	9.74	10.886	0.553	5.08
	1	10.67	0.93	8.73	12.094	1.651	13.65
	0.5	9.82	0.78	7.96	12.788	1.092	8.54
	0.3	9.18	0.88	9.63	13.893	5.146	37.04
	0.1	7.54	0.71	9.48	17.864	3.990	22.33
21	25	6.86	0.42	6.09	15.269	0.818	5.36
	15	6.21	0.35	5.62	17.323	0.544	3.14
	10	5.77	0.28	4.85	18.213	0.739	4.06
	5	4.98	0.27	5.49	20.756	0.633	3.05
	3	4.15	0.30	7.17	24.182	1.602	6.63
	1	3.09	0.31	10.17	24.841	3.096	12.46
	0.5	2.61	0.35	13.30	27.784	0.930	3.35
	0.3	2.54	0.28	10.97	31.183	2.473	7.93
	0.1	1.71	0.16	9.44	34.916	5.497	15.74
37	25	2.80	0.41	14.50	23.570	0.647	2.75
	15	2.36	0.35	14.98	24.619	0.710	2.88
	10	2.12	0.31	14.83	25.281	0.513	2.03
	5	1.69	0.25	14.59	26.938	0.549	2.04
	3	1.24	0.20	16.37	30.808	1.192	3.87
	1	0.93	0.12	13.20	31.799	1.469	4.62
	0.5	0.77	0.12	15.81	35.971	2.341	6.51
	0.3	0.66	0.11	16.33	37.375	1.118	2.99
	0.1	0.45	0.05	11.70	39.147	0.526	1.34

Table H.2. Dynamic modulus data for LM1 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.40	1.40	11.26964	7.507	1.677	22.33
	15	11.49	1.28	11.167675	8.302	0.416	5.02
	10	10.73	1.23	11.459212	10.434	1.488	14.26
	5	10.03	1.15	11.501122	11.777	0.959	8.14
	3	9.59	1.22	12.731061	13.486	1.682	12.47
	1	8.07	0.98	12.126287	14.700	2.623	17.84
	0.5	7.48	1.06	14.246793	15.107	1.576	10.43
	0.3	7.13	0.88	12.317356	18.304	4.051	22.13
	0.1	5.86	0.77	13.162407	20.411	4.233	20.74
21	25	8.27	0.23	2.79	15.403	1.491	9.68
	15	7.39	0.28	3.85	17.320	1.560	9.01
	10	6.78	0.28	4.17	18.339	1.252	6.83
	5	5.83	0.30	5.21	26.830	12.910	48.12
	3	4.95	0.29	5.96	25.397	3.849	15.15
	1	3.83	0.26	6.83	26.424	2.351	8.90
	0.5	3.34	0.25	7.58	27.482	2.039	7.42
	0.3	3.05	0.21	6.84	28.120	6.667	23.71
	0.1	2.19	0.17	7.76	37.212	9.392	25.24
37	25	2.58	0.17	6.48	23.443	0.612	2.61
	15	2.22	0.16	7.35	24.340	0.483	1.98
	10	1.99	0.16	8.13	24.448	0.842	3.45
	5	1.62	0.13	7.84	25.766	0.461	1.79
	3	1.21	0.09	7.57	28.503	1.255	4.40
	1	0.92	0.08	8.22	30.416	0.367	1.21
	0.5	0.74	0.08	10.19	31.750	0.504	1.59
	0.3	0.67	0.09	13.33	35.930	1.224	3.41
	0.1	0.50	0.07	13.27	36.984	1.210	3.27

Table H.3. Dynamic modulus data for LM3 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	18.06	1.74	9.6372629	4.197	1.338	31.88
	15	17.05	1.62	9.5065387	6.218	0.472	7.59
	10	16.11	1.42	8.7846922	7.005	0.490	6.99
	5	15.44	1.40	9.04796	8.328	0.146	1.75
	3	14.54	1.25	8.5734046	9.067	0.637	7.02
	1	13.07	1.64	12.560549	10.542	1.339	12.70
	0.5	12.05	1.24	10.331507	11.127	1.385	12.44
	0.3	11.63	1.01	8.7136861	11.855	1.246	10.51
	0.1	10.00	1.13	11.29301	15.366	3.858	25.11
21	25	9.50	0.52	5.49	3.784	0.226	5.96
	15	8.70	0.46	5.33	3.346	0.172	5.14
	10	8.12	0.44	5.43	3.001	0.155	5.15
	5	7.19	0.36	5.03	2.489	0.112	4.52
	3	6.32	0.41	6.50	1.910	0.092	4.79
	1	5.02	0.30	5.94	1.418	0.077	5.43
	0.5	4.35	0.25	5.69	1.228	0.097	7.89
	0.3	3.96	0.21	5.19	1.055	0.082	7.79
	0.1	2.98	0.15	5.09	0.764	0.082	10.67
37	25	3.78	0.23	5.96	21.064	0.490	2.33
	15	3.35	0.17	5.14	22.476	0.474	2.11
	10	3.00	0.15	5.15	23.420	0.316	1.35
	5	2.49	0.11	4.52	25.271	0.292	1.15
	3	1.91	0.09	4.79	28.463	1.070	3.76
	1	1.42	0.08	5.43	30.343	1.705	5.62
	0.5	1.23	0.10	7.89	33.824	2.769	8.19
	0.3	1.06	0.08	7.79	36.423	0.820	2.25
	0.1	0.76	0.08	10.67	37.294	1.101	2.95

Table H.4. Dynamic modulus data for LM3 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	16.94	1.60	9.4606874	3.348	1.201	35.88
	15	15.99	1.44	8.9918584	6.888	0.360	5.23
	10	11.93	7.71	64.664786	17.525	17.450	99.57
	5	10.72	5.98	55.828128	18.697	15.995	85.55
	3	13.78	0.93	6.7243223	9.635	0.500	5.19
	1	12.03	1.02	8.4907148	10.895	1.075	9.87
	0.5	11.14	0.85	7.6177435	11.875	0.554	4.67
	0.3	10.48	0.83	7.9400831	12.792	0.308	2.41
	0.1	8.78	0.79	8.9638386	16.797	3.229	19.22
21	25	9.00	1.22	13.57	13.547	0.473	3.49
	15	7.99	1.09	13.65	15.917	0.666	4.18
	10	7.36	0.97	13.24	17.220	0.623	3.62
	5	6.41	0.84	13.09	19.480	0.783	4.02
	3	5.66	0.83	14.73	21.230	0.893	4.21
	1	4.38	0.67	15.23	23.715	0.461	1.94
	0.5	3.79	0.52	13.83	26.013	1.227	4.72
	0.3	3.41	0.45	13.10	27.404	1.279	4.67
	0.1	2.49	0.34	13.73	33.381	2.034	6.09
37	25	3.20	0.37	11.40	22.941	1.190	5.19
	15	2.80	0.32	11.47	23.837	0.916	3.84
	10	2.52	0.28	10.91	24.422	0.637	2.61
	5	2.11	0.23	10.80	26.033	0.387	1.49
	3	1.58	0.16	9.99	29.556	1.276	4.32
	1	1.21	0.12	10.27	30.644	2.094	6.83
	0.5	1.03	0.10	9.66	34.141	0.615	1.80
	0.3	0.86	0.07	8.69	38.521	2.762	7.17
	0.1	0.64	0.07	11.12	40.575	1.250	3.08

Table H.5. Dynamic modulus data for LM4 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.20	0.85	5.9982556	6.111	2.561	41.91
	15	13.00	0.60	4.6533188	9.466	0.793	8.37
	10	12.17	0.45	3.6615573	10.553	0.349	3.31
	5	11.10	0.50	4.4871565	11.916	0.311	2.61
	3	9.54	0.75	7.8511787	13.426	0.334	2.49
	1	8.11	0.34	4.1982847	16.231	0.311	1.92
	0.5	7.87	0.33	4.1928257	17.170	0.471	2.75
	0.3	7.31	0.46	6.3459883	18.900	1.143	6.05
	0.1	5.23	0.88	16.886582	27.720	3.123	11.27
21	25	5.99	0.35	5.76	19.206	0.930	4.84
	15	5.23	0.16	3.15	20.899	0.948	4.54
	10	4.72	0.12	2.49	22.676	0.960	4.23
	5	3.94	0.12	2.99	25.527	0.982	3.85
	3	3.08	0.14	4.66	29.910	0.677	2.26
	1	2.15	0.09	4.01	31.748	1.103	3.47
	0.5	1.79	0.10	5.38	36.397	3.397	9.33
	0.3	1.47	0.09	5.92	37.578	1.784	4.75
	0.1	0.92	0.06	7.01	37.199	2.126	5.72
37	25	1.65	0.24	14.56	28.898	0.521	1.80
	15	1.52	0.20	13.08	28.793	0.299	1.04
	10	1.32	0.15	11.42	28.775	0.337	1.17
	5	1.05	0.12	11.02	28.378	0.888	3.13
	3	0.75	0.09	11.61	32.230	1.112	3.45
	1	0.54	0.05	9.68	28.287	3.572	12.63
	0.5	0.44	0.04	8.73	33.961	2.153	6.34
	0.3	0.39	0.05	13.55	37.587	2.497	6.64
	0.1	0.26	0.04	15.82	39.346	2.163	5.50

Table H.6. Dynamic modulus data for LM4 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	11.31	1.18	10.473123	8.648	1.173	13.57
	15	10.29	0.77	7.4825583	9.688	1.031	10.65
	10	9.39	0.29	3.069087	11.661	0.352	3.02
	5	8.76	0.65	7.4022577	13.595	0.444	3.27
	3	7.98	0.80	9.9642119	15.150	0.747	4.93
	1	6.46	0.69	10.626724	16.720	1.376	8.23
	0.5	5.77	0.66	11.363654	17.803	0.538	3.02
	0.3	5.45	0.51	9.269163	20.950	0.770	3.67
	0.1	4.11	0.49	11.862298	27.488	3.438	12.51
21	25	6.23	0.18	2.87	19.483	0.742	3.81
	15	5.56	0.12	2.10	21.372	0.347	1.63
	10	5.02	0.15	3.02	22.816	0.295	1.29
	5	4.24	0.12	2.79	25.346	0.348	1.37
	3	3.37	0.14	4.08	28.148	0.656	2.33
	1	2.40	0.11	4.57	30.496	0.186	0.61
	0.5	2.03	0.10	5.14	34.873	1.163	3.33
	0.3	1.72	0.06	3.78	36.716	0.954	2.60
	0.1	1.14	0.03	2.75	39.383	2.041	5.18
37	25	1.62	0.09	5.75	28.474	0.261	0.92
	15	1.34	0.06	4.57	27.994	0.496	1.77
	10	1.17	0.05	4.52	28.036	0.790	2.82
	5	0.94	0.06	5.94	28.343	0.337	1.19
	3	0.66	0.05	7.33	33.767	2.285	6.77
	1	0.48	0.04	8.52	31.307	3.567	11.39
	0.5	0.40	0.03	8.81	35.055	4.049	11.55
	0.3	0.35	0.03	7.43	36.459	0.371	1.02
	0.1	0.30	0.03	10.38	34.032	1.744	5.13

Table H.7. Dynamic modulus data for LM6 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	18.77	1.61	8.5724717	5.332	0.960	18.01
	15	18.05	1.31	7.2683535	7.393	0.313	4.24
	10	17.16	1.37	7.9778151	8.132	0.217	2.67
	5	16.02	1.23	7.6491128	9.431	0.417	4.42
	3	15.07	1.50	9.9209903	10.046	0.292	2.91
	1	13.21	0.89	6.7480374	12.249	0.921	7.52
	0.5	12.22	0.86	7.0755137	12.613	0.582	4.61
	0.3	11.53	0.98	8.4781184	13.654	1.392	10.20
	0.1	9.42	0.65	6.8962364	18.109	2.863	15.81
21	25	7.74	0.36	4.63	16.344	0.901	5.51
	15	6.92	0.30	4.29	18.073	1.062	5.88
	10	6.39	0.29	4.54	19.470	0.974	5.00
	5	5.52	0.28	5.01	22.060	1.005	4.56
	3	4.64	0.21	4.53	24.231	1.203	4.97
	1	3.49	0.19	5.42	27.591	0.793	2.88
	0.5	2.99	0.12	4.08	30.039	1.184	3.94
	0.3	2.62	0.11	4.12	33.238	1.725	5.19
	0.1	1.83	0.09	4.85	36.487	1.097	3.01
37	25	2.91	0.26	8.82	25.829	0.716	2.77
	15	2.40	0.21	8.56	27.513	1.055	3.84
	10	2.10	0.18	8.62	28.111	0.539	1.92
	5	1.66	0.16	9.41	29.385	0.597	2.03
	3	1.18	0.11	9.62	33.365	1.499	4.49
	1	0.84	0.14	17.08	35.029	1.378	3.93
	0.5	0.69	0.14	19.92	36.019	1.761	4.89
	0.3	0.57	0.10	18.00	37.686	2.516	6.68
	0.1	0.44	0.12	26.25	37.107	4.047	10.91

Table H.8. Dynamic modulus data for LM6 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.45	1.12	7.78	5.79	1.03	17.88
	15	13.47	1.20	8.89	8.21	0.56	6.82
	10	12.88	1.12	8.73	9.15	0.43	4.70
	5	11.82	1.00	8.49	10.83	0.33	3.00
	3	11.02	1.15	10.46	12.07	0.83	6.88
	1	9.55	0.90	9.38	12.33	0.29	2.35
	0.5	8.70	0.62	7.10	14.41	1.33	9.26
	0.3	8.10	0.78	9.67	16.14	2.27	14.09
	0.1	6.73	0.71	10.57	20.99	3.35	15.96
21	25	6.38	1.16	18.25	17.57	1.18	6.72
	15	5.57	1.06	19.00	18.88	0.58	3.05
	10	5.18	0.76	14.66	20.53	0.90	4.38
	5	4.38	0.68	15.53	22.74	0.83	3.64
	3	3.56	0.72	20.29	25.47	1.90	7.46
	1	2.67	0.53	19.72	28.16	0.48	1.72
	0.5	2.38	0.29	12.08	29.67	2.18	7.36
	0.3	2.03	0.40	19.77	33.58	2.34	6.96
	0.1	1.47	0.14	9.82	37.28	1.64	4.39
37	25	2.42	0.16	6.51	25.67	1.23	4.80
	15	2.02	0.11	5.61	26.71	0.85	3.17
	10	1.78	0.12	6.87	26.97	1.12	4.14
	5	1.45	0.08	5.51	28.30	1.43	5.04
	3	1.07	0.06	6.06	32.50	2.37	7.31
	1	0.79	0.07	8.42	32.58	1.18	3.61
	0.5	0.67	0.06	9.59	36.40	2.42	6.64
	0.3	0.56	0.05	9.59	40.95	1.84	4.49
	0.1	0.44	0.08	17.69	40.84	0.97	2.37

Table H.9. Dynamic modulus data for LM7 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.61	1.15	9.1243375	8.271	0.480	5.81
	15	11.52	0.91	7.8659067	9.955	0.539	5.42
	10	10.87	0.92	8.5105682	11.038	0.313	2.84
	5	10.02	0.81	8.0979065	13.092	0.266	2.03
	3	9.19	0.75	8.1510235	14.656	0.249	1.70
	1	7.47	0.54	7.2483992	15.083	1.420	9.41
	0.5	7.07	0.54	7.5740618	15.542	1.173	7.54
	0.3	6.57	0.39	5.958186	23.958	2.586	10.79
	0.1	4.90	0.29	5.9217408	28.903	3.973	13.75
21	25	4.75	0.41	8.55	21.818	0.748	3.43
	15	4.21	0.30	7.21	23.475	0.199	0.85
	10	3.78	0.26	6.78	25.121	0.104	0.42
	5	3.08	0.19	6.20	28.094	0.109	0.39
	3	2.38	0.13	5.43	30.671	1.748	5.70
	1	1.65	0.09	5.36	32.718	2.924	8.94
	0.5	1.33	0.06	4.33	34.544	3.630	10.51
	0.3	1.08	0.04	3.73	38.427	1.062	2.76
	0.1	0.66	0.01	1.61	36.920	3.757	10.18
37	25	1.48	0.01	0.99	**28.880**	**0.909**	**3.15**
	15	1.24	0.02	1.93	**28.871**	**0.443**	**1.53**
	10	1.07	0.04	3.47	**29.013**	**0.570**	**1.97**
	5	0.86	0.03	3.28	**27.682**	**0.663**	**2.40**
	3	0.63	0.01	2.39	**31.299**	**1.452**	**4.64**
	1	0.50	0.02	4.89	**29.602**	**2.511**	**8.48**
	0.5	0.40	0.02	4.00	**32.850**	**1.371**	**4.17**
	0.3	0.37	0.03	7.27	**36.433**	**1.910**	**5.24**
	0.1	0.23	0.00	1.18	**36.441**	**1.028**	**2.82**

Table H.10. Dynamic modulus data for LM7 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.68	1.13	8.8962011	8.869	0.884	9.97
	15	11.40	0.83	7.2509064	10.659	0.301	2.83
	10	10.61	0.79	7.4641046	11.742	0.649	5.53
	5	9.51	0.66	6.9288439	13.774	0.832	6.04
	3	8.69	0.79	9.041002	17.299	3.648	21.08
	1	6.82	0.67	9.8179501	17.777	1.196	6.73
	0.5	6.31	0.67	10.693961	19.689	2.285	11.60
	0.3	5.84	0.58	9.9363659	21.255	1.306	6.14
	0.1	4.27	0.33	7.6643415	32.129	6.101	18.99
21	25	6.33	1.05	16.53	21.556	0.212	0.98
	15	5.52	0.87	15.84	23.103	0.215	0.93
	10	4.97	0.84	16.96	24.672	0.323	1.31
	5	4.09	0.69	16.76	27.382	0.390	1.43
	3	3.16	0.56	17.81	30.311	0.999	3.30
	1	2.17	0.34	15.64	34.295	1.748	5.10
	0.5	1.77	0.28	15.71	36.693	0.820	2.23
	0.3	1.46	0.24	16.42	40.168	2.848	7.09
	0.1	0.88	0.15	17.35	41.054	0.719	1.75
37	25	1.51	0.10	6.42	29.305	1.202	4.10
	15	1.23	0.07	5.65	29.682	0.865	2.91
	10	1.05	0.05	5.06	29.136	0.720	2.47
	5	0.84	0.05	6.06	28.209	0.590	2.09
	3	0.62	0.03	4.92	31.373	2.700	8.61
	1	0.45	0.06	13.58	28.404	4.108	14.46
	0.5	0.37	0.06	16.21	32.021	2.533	7.91
	0.3	0.34	0.04	12.47	34.555	3.606	10.44
	0.1	0.28	0.11	39.17	36.137	3.377	9.34

Table H.11. Dynamic modulus data for LM9 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	15.94	1.64	10.31	6.679	0.919	13.76
	15	15.02	1.32	8.82	8.027	0.289	3.60
	10	14.34	1.15	7.98	9.222	0.085	0.93
	5	13.29	0.97	7.32	10.834	0.290	2.68
	3	12.38	0.89	7.20	11.633	0.464	3.99
	1	10.52	0.81	7.65	12.295	0.722	5.87
	0.5	9.97	0.97	9.76	13.109	0.630	4.80
	0.3	9.15	0.84	9.23	18.325	1.988	10.85
	0.1	7.31	0.45	6.19	21.363	1.140	5.34
21	25	6.79	0.05	0.74	17.905	0.430	2.40
	15	6.08	0.05	0.83	19.641	0.299	1.52
	10	5.54	0.02	0.41	21.102	0.312	1.48
	5	4.70	0.04	0.84	23.637	0.284	1.20
	3	3.85	0.05	1.18	25.580	0.506	1.98
	1	2.80	0.04	1.35	29.833	0.701	2.35
	0.5	2.38	0.05	2.13	32.091	0.543	1.69
	0.3	2.08	0.06	2.93	35.165	1.168	3.32
	0.1	1.40	0.02	1.68	38.021	0.914	2.40
37	25	2.26	0.11	4.87	26.292	1.093	4.16
	15	1.87	0.09	4.67	27.519	0.264	0.96
	10	1.63	0.07	4.12	28.206	0.793	2.81
	5	1.29	0.05	4.11	28.916	0.331	1.15
	3	0.90	0.05	6.10	31.754	1.558	4.91
	1	0.63	0.07	11.32	33.831	1.728	5.11
	0.5	0.48	0.05	11.40	34.709	1.457	4.20
	0.3	0.40	0.05	11.33	36.057	4.208	11.67
	0.1	0.32	0.06	19.65	34.474	5.373	15.59

Table H.12. Dynamic modulus data for LM9 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	16.33	1.18	7.2086969	6.107	0.756	12.38
	15	15.06	0.86	5.7200056	8.431	0.461	5.46
	10	14.39	0.61	4.2528626	9.488	0.596	6.29
	5	13.35	0.54	4.0321902	11.072	0.645	5.82
	3	12.65	0.77	6.096154	11.852	0.864	7.29
	1	10.71	0.49	4.5512623	12.207	1.330	10.90
	0.5	9.87	0.44	4.4598664	14.472	2.221	15.35
	0.3	9.15	0.45	4.8768766	15.741	1.325	8.42
	0.1	7.33	0.28	3.7760435	20.864	1.418	6.80
21	25	7.92	1.59	20.11	17.642	0.648	3.67
	15	6.97	1.34	19.24	19.711	0.821	4.17
	10	6.33	1.26	19.92	21.114	0.782	3.70
	5	5.34	1.09	20.39	23.828	1.017	4.27
	3	4.40	0.92	20.93	27.549	2.167	7.87
	1	3.23	0.72	22.20	30.101	1.249	4.15
	0.5	2.70	0.57	21.00	32.415	0.804	2.48
	0.3	2.35	0.55	23.39	35.152	1.531	4.35
	0.1	1.56	0.37	23.71	36.093	1.818	5.04
37	25	2.45	0.10	4.10	26.846	1.010	3.76
	15	2.01	0.09	4.62	27.347	0.481	1.76
	10	1.75	0.07	4.20	27.477	0.794	2.89
	5	1.42	0.02	1.52	28.396	0.465	1.64
	3	0.99	0.05	5.45	32.900	0.377	1.15
	1	0.71	0.03	4.76	32.278	1.280	3.96
	0.5	0.57	0.05	8.13	36.618	0.724	1.98
	0.3	0.49	0.06	12.31	39.729	3.165	7.97
	0.1	0.34	0.05	13.85	39.763	3.397	8.54

Table H.13. Dynamic modulus data for LM10 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.13	1.25	8.81	8.169	0.513	6.28
	15	12.86	1.03	8.00	9.829	0.434	4.42
	10	12.04	1.03	8.56	10.742	0.424	3.95
	5	10.98	0.89	8.09	12.470	0.509	4.08
	3	10.13	0.81	7.96	13.490	0.440	3.26
	1	8.58	0.80	9.30	16.006	0.649	4.06
	0.5	7.80	0.87	11.21	16.696	0.639	3.83
	0.3	7.27	0.67	9.26	19.074	3.945	20.68
	0.1	5.36	0.49	9.19	26.872	3.351	12.47
21	25	5.98	0.33	5.52	19.214	0.564	2.94
	15	5.23	0.30	5.76	21.012	0.570	2.71
	10	4.70	0.26	5.43	22.773	0.688	3.02
	5	3.92	0.24	6.07	25.584	0.674	2.64
	3	3.15	0.23	7.35	29.414	1.484	5.04
	1	2.22	0.15	6.99	32.093	1.274	3.97
	0.5	1.84	0.12	6.35	34.520	0.779	2.26
	0.3	1.52	0.11	6.91	37.231	1.484	3.99
	0.1	0.98	0.08	8.16	37.250	1.240	3.33
37	25	1.80	0.10	5.35	27.732	0.965	3.48
	15	1.48	0.05	3.49	28.604	0.962	3.36
	10	1.29	0.05	4.21	28.718	0.870	3.03
	5	1.03	0.06	5.55	28.948	0.685	2.36
	3	0.72	0.04	6.02	32.409	1.054	3.25
	1	0.54	0.06	11.88	32.132	2.574	8.01
	0.5	0.44	0.07	14.84	34.830	1.660	4.77
	0.3	0.38	0.06	15.90	36.513	2.001	5.48
	0.1	0.30	0.06	18.71	37.648	2.623	6.97

Table H.14. Dynamic modulus data for LM10 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.14	1.15	9.4464723	8.094	0.557	6.88
	15	11.17	0.65	5.8576152	9.941	0.095	0.95
	10	10.38	0.93	8.9806069	60.317	76.601	127.00
	5	7.03	4.64	66.014675	13.726	0.906	6.60
	3	8.45	0.80	9.4304066	15.706	0.744	4.74
	1	6.76	0.75	11.146259	15.830	0.792	5.00
	0.5	6.00	0.91	15.137339	19.476	2.416	12.40
	0.3	5.52	0.74	13.385715	21.507	2.375	11.04
	0.1	4.15	0.60	14.555203	30.047	7.404	24.64
21	25	7.14	0.79	11.00	19.744	2.063	10.45
	15	6.19	0.78	12.57	21.410	1.755	8.20
	10	5.59	0.78	13.90	22.957	1.624	7.07
	5	4.67	0.71	15.30	25.345	1.542	6.09
	3	3.74	0.61	16.19	28.637	1.221	4.26
	1	2.69	0.47	17.33	31.423	2.313	7.36
	0.5	2.27	0.41	17.86	34.397	2.094	6.09
	0.3	1.91	0.34	17.78	38.590	2.311	5.99
	0.1	1.31	0.30	22.86	38.595	1.852	4.80
37	25	1.81	0.36	19.79	27.158	1.475	5.43
	15	1.50	0.31	20.99	27.211	0.525	1.93
	10	1.30	0.27	20.67	27.313	0.783	2.87
	5	1.06	0.22	20.65	27.035	0.957	3.54
	3	0.73	0.16	21.79	30.130	1.506	5.00
	1	0.54	0.10	18.13	31.151	1.516	4.87
	0.5	0.43	0.10	23.18	32.262	1.341	4.16
	0.3	0.40	0.08	19.03	37.743	2.227	5.90
	0.1	0.31	0.04	14.14	37.266	2.021	5.42

Table H.15. Dynamic modulus data for LM12 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	15.63	2.00	12.80	7.279	0.185	2.54
	15	14.42	1.92	13.29	8.754	0.381	4.35
	10	13.70	1.62	11.84	9.952	0.331	3.33
	5	12.62	1.41	11.16	11.627	0.735	6.32
	3	11.86	1.54	13.02	12.391	0.675	5.45
	1	9.91	1.19	12.04	14.307	0.343	2.40
	0.5	9.26	1.22	13.22	16.155	0.953	5.90
	0.3	8.53	1.19	13.94	17.637	1.046	5.93
	0.1	6.64	0.85	12.72	24.219	1.044	4.31
21	25	6.83	0.91	13.30	17.872	1.424	7.97
	15	6.08	0.79	12.94	19.714	0.933	4.73
	10	5.54	0.76	13.74	21.158	1.176	5.56
	5	4.70	0.68	14.43	23.955	1.060	4.43
	3	3.83	0.59	15.39	26.328	1.763	6.70
	1	2.81	0.42	14.94	30.707	0.626	2.04
	0.5	2.40	0.40	16.70	32.708	0.890	2.72
	0.3	2.06	0.33	16.08	38.764	2.177	5.62
	0.1	1.35	0.20	15.12	39.597	1.411	3.56
37	25	2.20	0.21	9.45	27.421	0.473	1.72
	15	1.81	0.15	8.09	27.871	0.292	1.05
	10	1.59	0.13	7.91	28.445	0.144	0.51
	5	1.25	0.09	7.04	29.285	0.228	0.78
	3	0.86	0.04	4.83	32.398	0.508	1.57
	1	0.57	0.02	4.01	34.118	1.751	5.13
	0.5	0.44	0.02	4.08	35.249	0.567	1.61
	0.3	0.37	0.01	3.83	34.478	1.040	3.02
	0.1	0.27	0.01	5.48	31.281	1.375	4.39

Table H.16. Dynamic modulus data for LM12 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	13.99	1.71	12.19301	7.195	0.964	13.40
	15	12.88	1.52	11.832201	9.203	0.203	2.20
	10	12.20	1.43	11.679502	10.493	0.485	4.62
	5	11.16	1.24	11.068644	12.345	0.387	3.13
	3	10.53	1.47	13.987994	13.535	1.589	11.74
	1	8.65	1.14	13.194487	14.002	1.195	8.53
	0.5	7.92	1.06	13.334667	15.474	1.465	9.47
	0.3	7.36	1.02	13.803684	19.678	2.390	12.15
	0.1	5.76	0.91	15.759989	21.807	1.962	9.00
21	25	6.37	0.22	3.43	18.357	0.481	2.62
	15	5.52	0.18	3.30	20.063	0.321	1.60
	10	5.00	0.14	2.87	21.352	0.327	1.53
	5	4.22	0.11	2.67	24.083	0.511	2.12
	3	3.47	0.13	3.89	27.497	1.926	7.00
	1	2.54	0.09	3.63	29.474	1.134	3.85
	0.5	2.16	0.07	3.04	33.860	2.885	8.52
	0.3	1.84	0.10	5.71	36.822	1.460	3.97
	0.1	1.21	0.16	12.96	38.255	1.636	4.28
37	25	1.97	0.41	20.90	27.359	0.596	2.18
	15	1.63	0.33	20.12	26.971	0.465	1.72
	10	1.44	0.27	19.05	26.839	0.322	1.20
	5	1.17	0.22	18.50	27.157	0.830	3.06
	3	0.82	0.15	18.05	30.804	1.204	3.91
	1	0.61	0.12	19.91	30.398	3.259	10.72
	0.5	0.49	0.06	12.69	34.079	2.246	6.59
	0.3	0.42	0.06	14.19	37.535	2.656	7.08
	0.1	0.29	0.10	33.14	41.620	6.213	14.93

Table H.17. Dynamic modulus data for QZ13 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.79	2.27	15.36	6.616	1.379	20.84
	15	15.41	1.46	9.50	8.505	0.673	7.91
	10	14.77	1.50	10.16	9.919	0.246	2.48
	5	13.51	1.13	8.33	11.561	0.254	2.20
	3	12.44	1.56	12.53	13.220	0.676	5.11
	1	10.38	1.35	13.04	13.679	1.158	8.47
	0.5	9.41	1.09	11.56	15.137	0.909	6.01
	0.3	9.08	1.24	13.62	17.460	1.210	6.93
	0.1	7.33	0.91	12.36	22.217	4.556	20.51
21	25	7.87	0.52	6.59	16.525	0.720	4.36
	15	7.06	0.41	5.76	18.430	0.545	2.96
	10	6.50	0.36	5.48	19.601	0.388	1.98
	5	5.58	0.29	5.28	22.365	0.448	2.00
	3	4.58	0.30	6.50	25.993	1.280	4.92
	1	3.44	0.23	6.81	27.478	1.092	3.98
	0.5	2.95	0.18	6.08	32.840	3.101	9.44
	0.3	2.57	0.15	5.80	33.773	2.003	5.93
	0.1	1.75	0.08	4.55	35.880	0.494	1.38
37	25	2.93	0.27	9.22	25.235	0.462	1.83
	15	2.43	0.22	9.17	26.667	0.275	1.03
	10	2.11	0.18	8.55	27.157	0.375	1.38
	5	1.69	0.13	7.50	27.962	0.789	2.82
	3	1.14	0.10	8.87	33.150	3.058	9.22
	1	0.80	0.12	14.58	35.055	1.251	3.57
	0.5	0.61	0.07	12.13	35.189	1.090	3.10
	0.3	0.52	0.06	11.82	37.031	2.672	7.21
	0.1	0.38	0.06	16.82	34.732	3.676	10.58

Table H.18. Dynamic modulus data for QZ13 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	11.20	2.24	20.01354	10.450	5.660	54.16
	15	11.27	1.63	14.465427	10.886	1.059	9.73
	10	7.98	5.20	65.225265	32.987	43.380	131.51
	5	9.73	1.22	12.524885	13.760	1.043	7.58
	3	8.71	1.29	14.862983	16.011	1.280	7.99
	1	7.13	1.13	15.850724	15.642	0.696	4.45
	0.5	6.67	1.19	17.903779	17.225	4.215	24.47
	0.3	5.49	1.11	20.234697	17.639	4.837	27.42
	0.1	4.73	0.87	18.474116	26.089	2.470	9.47
21	25	4.77	0.49	10.18	21.020	1.681	7.99
	15	4.24	0.51	11.99	22.164	1.239	5.59
	10	3.90	0.49	12.52	23.445	1.083	4.62
	5	3.29	0.43	13.12	25.667	1.055	4.11
	3	2.59	0.41	15.85	28.690	0.842	2.93
	1	1.92	0.29	15.26	31.499	2.010	6.38
	0.5	1.65	0.27	16.22	34.297	0.699	2.04
	0.3	1.43	0.23	16.10	37.009	2.100	5.67
	0.1	0.94	0.17	17.51	39.409	0.568	1.44
37	25	1.91	0.20	10.25	27.704	0.929	3.35
	15	1.58	0.17	10.44	27.363	0.200	0.73
	10	1.40	0.15	10.43	27.397	0.600	2.19
	5	1.12	0.11	9.52	27.587	0.231	0.84
	3	0.78	0.06	7.63	31.517	1.087	3.45
	1	0.55	0.04	7.14	30.026	3.149	10.49
	0.5	0.43	0.05	11.13	32.684	1.392	4.26
	0.3	0.36	0.06	17.34	34.716	3.292	9.48
	0.1	0.27	0.07	25.94	34.378	6.973	20.28

Table H.19. Dynamic modulus data for QZ14 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.87	1.02	7.93	9.996	17.512	175.19
	15	15.10	2.29	15.19	6.998	2.159	30.85
	10	14.81	2.04	13.77	8.635	1.285	14.88
	5	13.96	1.71	12.22	9.701	0.732	7.55
	3	13.26	1.47	11.12	10.618	1.239	11.67
	1	11.62	1.62	13.92	11.468	0.944	8.23
	0.5	10.83	1.75	16.19	12.090	1.315	10.88
	0.3	10.21	1.60	15.67	15.053	2.721	18.07
	0.1	8.47	1.44	17.03	17.276	3.548	20.54
21	25	7.95	0.56	7.06	13.727	0.599	4.36
	15	7.22	0.41	5.74	16.139	0.204	1.26
	10	6.72	0.39	5.74	17.374	0.143	0.83
	5	5.89	0.37	6.35	19.749	0.163	0.83
	3	5.10	0.39	7.61	22.192	0.621	2.80
	1	3.95	0.37	9.42	24.777	1.063	4.29
	0.5	3.53	0.36	10.11	26.647	1.538	5.77
	0.3	3.17	0.36	11.37	30.259	1.469	4.86
	0.1	2.32	0.31	13.40	32.107	1.483	4.62
37	25	2.99	0.16	5.40	23.264	1.901	8.17
	15	2.57	0.12	4.55	24.096	1.150	4.77
	10	2.30	0.13	5.64	24.760	0.966	3.90
	5	1.89	0.11	5.90	26.106	0.783	3.00
	3	1.35	0.07	5.13	30.334	1.975	6.51
	1	0.85	0.20	23.07	32.130	2.116	6.59
	0.5	0.80	0.03	4.29	34.567	1.363	3.94
	0.3	0.66	0.01	1.42	36.309	3.073	8.46
	0.1	0.40	0.15	37.85	37.113	4.378	11.80

Table H.20. Dynamic modulus for QZ14 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.27	2.72	22.124918	8.079	2.629	32.54
	15	13.49	0.76	5.6123141	7.826	0.723	9.24
	10	13.13	0.71	5.394295	8.920	0.797	8.93
	5	12.48	0.76	6.0798416	10.285	0.392	3.81
	3	10.74	0.87	8.065932	11.171	1.394	12.48
	1	9.49	0.70	7.4037586	12.199	0.753	6.18
	0.5	8.79	0.73	8.2697186	12.913	1.041	8.06
	0.3	8.32	0.63	7.6149864	15.541	2.060	13.26
	0.1	6.90	0.71	10.30337	18.901	2.672	14.14
21	25	6.40	0.36	5.64	16.200	1.393	8.60
	15	5.88	0.28	4.81	17.608	1.249	7.10
	10	5.45	0.29	5.35	18.621	1.032	5.54
	5	4.76	0.28	5.83	21.180	1.081	5.10
	3	3.97	0.26	6.43	23.841	1.576	6.61
	1	3.03	0.23	7.54	25.860	1.456	5.63
	0.5	2.67	0.18	6.90	28.919	1.686	5.83
	0.3	2.42	0.19	7.88	31.186	1.627	5.22
	0.1	1.75	0.12	7.02	34.474	0.720	2.09
37	25	2.67	0.22	8.30	25.570	0.868	3.39
	15	2.32	0.21	8.84	24.748	0.795	3.21
	10	2.08	0.18	8.46	25.105	0.684	2.73
	5	1.72	0.15	8.84	26.074	0.245	0.94
	3	1.22	0.08	6.63	30.277	2.042	6.74
	1	0.82	0.13	16.05	31.014	2.032	6.55
	0.5	0.63	0.15	23.31	35.739	4.349	12.17
	0.3	0.55	0.08	14.93	37.044	5.641	15.23
	0.1	0.37	0.12	32.40	35.560	4.710	13.25

Table H.21. Dynamic modulus data for QZ15 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	15.17	2.57	16.918715	7.136	1.415	19.83
	15	14.08	2.30	16.3149	8.294	0.987	11.90
	10	13.11	1.00	7.6284254	9.113	1.421	15.60
	5	12.53	1.65	13.127249	11.424	0.585	5.12
	3	11.69	1.75	14.928104	12.889	0.631	4.89
	1	9.79	1.47	14.983667	14.374	1.063	7.39
	0.5	8.93	1.11	12.418644	15.865	1.347	8.49
	0.3	8.48	1.00	11.77877	17.525	1.406	8.03
	0.1	6.69	0.64	9.5137301	23.276	1.953	8.39
21	25	6.31	0.21	3.26	18.342	0.515	2.81
	15	5.66	0.24	4.26	21.215	0.721	3.40
	10	5.13	0.20	3.93	22.267	0.843	3.79
	5	4.30	0.21	4.97	25.155	0.832	3.31
	3	3.40	0.10	2.91	29.430	1.369	4.65
	1	2.43	0.14	5.60	31.904	0.557	1.75
	0.5	2.07	0.12	5.78	34.197	0.624	1.83
	0.3	1.69	0.12	7.10	38.661	1.154	2.98
	0.1	1.09	0.06	5.60	38.451	1.508	3.92
37	25	1.86	0.15	8.11	27.962	0.863	3.09
	15	1.52	0.12	7.87	27.825	0.506	1.82
	10	1.32	0.08	6.26	27.699	0.390	1.41
	5	1.07	0.08	7.18	27.568	0.377	1.37
	3	0.72	0.05	7.62	33.564	3.052	9.09
	1	0.54	0.06	11.48	32.267	1.772	5.49
	0.5	0.45	0.07	14.74	35.408	2.559	7.23
	0.3	0.37	0.01	3.49	37.581	2.361	6.28
	0.1	0.26	0.02	9.33	39.110	4.565	11.67

Table H.22. Dynamic modulus data for QZ15 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	11.71	1.81	15.43	7.136	1.415	19.83
	15	11.34	1.12	9.88	8.294	0.987	11.90
	10	10.71	1.08	10.11	9.113	1.421	15.60
	5	9.71	0.96	9.91	11.424	0.585	5.12
	3	8.79	0.93	10.55	12.889	0.631	4.89
	1	7.12	0.80	11.22	14.374	1.063	7.39
	0.5	6.49	0.77	11.80	15.865	1.347	8.49
	0.3	6.07	0.70	11.51	17.525	1.406	8.03
	0.1	3.82	1.24	32.40	23.276	1.953	8.39
21	25	4.55	0.93	20.47	18.342	0.515	2.81
	15	3.94	0.79	20.10	21.215	0.721	3.40
	10	3.57	0.68	19.12	22.267	0.843	3.79
	5	2.92	0.58	19.72	25.155	0.832	3.31
	3	2.31	0.52	22.64	29.430	1.369	4.65
	1	1.67	0.31	18.85	31.904	0.557	1.75
	0.5	1.25	0.56	45.16	34.197	0.624	1.83
	0.3	1.16	0.23	19.48	38.661	1.154	2.98
	0.1	0.76	0.14	18.80	38.451	1.508	3.92
37	25	1.57	0.24	15.41	27.962	0.863	3.09
	15	1.32	0.18	13.87	27.825	0.506	1.82
	10	1.13	0.14	12.68	27.699	0.390	1.41
	5	0.93	0.11	11.32	27.568	0.377	1.37
	3	0.67	0.09	13.96	33.564	3.052	9.09
	1	0.51	0.04	8.78	32.267	1.772	5.49
	0.5	0.42	0.03	6.89	35.408	2.559	7.23
	0.3	0.37	0.02	5.99	37.581	2.361	6.28
	0.1	0.29	0.07	25.25	39.110	4.565	11.67

Table H.23. Dynamic modulus data for QZ16 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.53909	2.080992	14.31308	4.945	2.605	52.68
	15	14.48793	0.675419	4.661942	8.795	1.048	11.91
	10	13.74647	0.455796	3.315728	9.692	0.424	4.38
	5	12.90286	0.405695	3.144224	11.238	0.704	6.27
	3	12.26133	0.668447	5.451668	11.876	0.779	6.56
	1	10.30453	0.25943	2.517634	13.477	0.575	4.26
	0.5	9.564007	0.13772	1.439978	15.194	1.764	11.61
	0.3	8.978916	0.246195	2.741919	16.074	2.084	12.97
	0.1	7.236857	0.275357	3.804924	20.512	2.158	10.52
21	25	6.64	0.41	6.13	16.816	0.591	3.51
	15	5.94	0.30	5.01	18.837	0.572	3.04
	10	5.45	0.25	4.53	20.337	0.425	2.09
	5	4.67	0.19	4.11	22.955	0.413	1.80
	3	3.78	0.18	4.72	25.486	1.101	4.32
	1	2.83	0.08	2.76	28.861	1.117	3.87
	0.5	2.43	0.06	2.33	31.287	0.992	3.17
	0.3	2.12	0.04	1.66	35.283	1.358	3.85
	0.1	1.42	0.03	2.27	37.195	0.406	1.09
37	25	2.43	0.26	10.62	26.075	1.163	4.46
	15	2.03	0.20	10.04	27.807	0.103	0.37
	10	1.77	0.19	10.58	28.480	0.499	1.75
	5	1.42	0.14	9.87	28.962	1.079	3.73
	3	0.95	0.10	10.83	35.151	3.038	8.64
	1	0.73	0.09	12.69	34.940	2.337	6.69
	0.5	0.59	0.08	14.20	39.026	1.962	5.03
	0.3	0.49	0.04	7.29	41.716	1.896	4.54
	0.1	0.32	0.03	10.30	41.537	0.327	0.79

Table H.24. Dynamic modulus data for QZ16 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.07	1.32	9.3626369	7.216	1.507	20.88
	15	13.41	1.41	10.530006	9.326	1.386	14.86
	10	12.70	1.48	11.660946	10.579	1.262	11.93
	5	11.61	1.44	12.434843	12.322	1.362	11.06
	3	10.61	1.57	14.766649	12.695	2.001	15.76
	1	8.88	1.36	15.266364	14.635	2.031	13.88
	0.5	7.93	1.41	17.808433	14.672	1.448	9.87
	0.3	7.57	1.16	15.274981	19.069	2.751	14.43
	0.1	5.05	0.98	19.412906	29.377	12.849	43.74
21	25	5.94	0.59	9.89	17.895	1.751	9.78
	15	5.33	0.53	9.98	19.900	0.151	0.76
	10	4.85	0.49	10.12	21.192	0.318	1.50
	5	4.10	0.41	10.08	23.856	0.409	1.71
	3	3.30	0.32	9.73	27.169	1.401	5.16
	1	2.40	0.25	10.31	29.706	0.781	2.63
	0.5	2.04	0.20	9.85	33.424	1.467	4.39
	0.3	1.77	0.20	11.29	36.286	2.038	5.62
	0.1	1.17	0.11	9.65	37.318	1.953	5.23
37	25	2.16	0.21	9.58	26.721	0.661	2.47
	15	1.78	0.16	8.91	27.068	0.463	1.71
	10	1.55	0.14	8.91	27.723	0.439	1.58
	5	1.27	0.12	9.41	28.615	0.600	2.10
	3	0.87	0.09	10.48	32.709	0.714	2.18
	1	0.65	0.06	9.66	32.889	1.740	5.29
	0.5	0.52	0.06	11.52	36.762	2.300	6.26
	0.3	0.43	0.07	15.47	40.795	3.555	8.71
	0.1	0.30	0.07	23.93	42.327	4.698	11.10

Table H.25. Dynamic modulus data for QZ 17 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	13.83	1.25	9.02	8.583	0.845	9.84
	15	12.48	0.89	7.11	9.986	1.759	17.62
	10	11.87	0.94	7.95	11.629	1.157	9.95
	5	10.70	0.84	7.90	13.748	1.235	8.98
	3	9.62	1.00	10.43	15.312	1.684	11.00
	1	7.78	0.97	12.40	16.385	0.906	5.53
	0.5	6.98	0.82	11.75	18.541	1.264	6.82
	0.3	6.57	0.73	11.15	20.950	1.538	7.34
	0.1	5.06	0.63	12.48	29.159	3.604	12.36
21	25	5.37	0.24	4.52	20.342	1.317	6.47
	15	4.77	0.26	5.39	22.467	0.886	3.95
	10	4.29	0.20	4.74	23.968	0.689	2.87
	5	3.50	0.17	4.94	26.636	0.881	3.31
	3	2.71	0.18	6.59	30.168	2.012	6.67
	1	1.94	0.12	6.20	33.048	2.036	6.16
	0.5	1.59	0.15	9.47	36.225	0.860	2.38
	0.3	1.33	0.13	10.12	38.314	0.399	1.04
	0.1	0.84	0.08	9.90	39.707	1.504	3.79
37	25	1.68	0.19	11.04	28.552	0.990	3.47
	15	1.37	0.15	10.73	28.090	0.390	1.39
	10	1.20	0.12	9.72	27.314	0.310	1.13
	5	0.98	0.10	10.35	27.178	0.301	1.11
	3	0.65	0.09	13.88	31.235	1.069	3.42
	1	0.46	0.06	13.95	31.001	1.190	3.84
	0.5	0.35	0.02	6.88	34.726	0.704	2.03
	0.3	0.34	0.03	7.79	38.018	2.815	7.40
	0.1	0.23	0.02	8.67	37.256	3.174	8.52

Table H.26. Dynamic modulus data for QZ17 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	13.51	1.99	14.707213	9.151	1.310	14.32
	15	12.00	1.44	11.987341	11.271	0.896	7.95
	10	11.28	0.96	8.5077393	12.347	0.796	6.44
	5	10.14	0.69	6.8486716	14.069	0.491	3.49
	3	9.01	1.08	11.980372	17.618	3.148	17.87
	1	7.30	0.91	12.492328	16.931	1.572	9.28
	0.5	6.59	0.61	9.2445728	19.615	2.787	14.21
	0.3	5.89	0.81	13.674721	23.625	1.123	4.75
	0.1	4.47	0.62	13.882162	36.571	13.779	37.68
21	25	5.60	0.75	13.38	21.677	0.641	2.96
	15	4.90	0.73	14.88	23.715	1.146	4.83
	10	4.36	0.69	15.92	25.492	1.088	4.27
	5	3.55	0.63	17.83	28.316	1.165	4.11
	3	2.72	0.48	17.77	33.647	1.105	3.28
	1	1.88	0.35	18.78	34.774	0.115	0.33
	0.5	1.49	0.35	23.18	40.287	2.104	5.22
	0.3	1.15	0.31	26.70	40.788	0.232	0.57
	0.1	0.56	0.39	69.65	36.273	6.741	18.59
37	25	1.44	0.13	8.69	28.799	0.304	1.06
	15	1.18	0.10	8.20	28.589	0.573	2.01
	10	1.02	0.09	8.89	28.322	0.369	1.30
	5	0.81	0.08	9.41	27.161	0.416	1.53
	3	0.53	0.06	11.50	31.000	1.342	4.33
	1	0.37	0.04	10.84	30.041	1.491	4.96
	0.5	0.32	0.05	16.94	32.086	0.331	1.03
	0.3	0.28	0.07	27.06	34.156	3.415	10.00
	0.1	0.24	0.02	10.20	35.496	1.983	5.59

Table H.27. Dynamic modulus data for QZ19 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	16.09534	1.299332	8.072723	6.881	0.375	5.45
	15	15.26457	0.868547	5.689951	8.603	0.233	2.70
	10	14.564	0.721297	4.952601	9.859	0.404	4.10
	5	13.33528	0.699964	5.248963	11.513	0.617	5.36
	3	11.82305	0.809535	6.84709	12.655	0.594	4.70
	1	10.08764	0.543315	5.385947	13.276	0.907	6.83
	0.5	9.035665	0.427974	4.736495	14.321	1.580	11.03
	0.3	8.428996	0.410764	4.873228	19.700	1.912	9.71
	0.1	6.755406	0.461601	6.833064	22.527	0.869	3.86
21	25	6.00	0.84	14.04	19.014	1.881	9.89
	15	5.36	0.77	14.38	20.748	1.456	7.02
	10	4.94	0.71	14.47	21.823	1.527	7.00
	5	4.16	0.61	14.79	24.637	1.426	5.79
	3	3.36	0.54	16.10	27.305	2.124	7.78
	1	2.51	0.39	15.69	30.465	1.531	5.03
	0.5	2.16	0.35	16.30	33.495	1.544	4.61
	0.3	1.88	0.33	17.75	36.586	0.660	1.80
	0.1	1.27	0.23	18.10	39.120	1.297	3.31
37	25	2.04	0.20	9.81	26.898	0.965	3.59
	15	1.71	0.14	8.15	27.790	0.540	1.94
	10	1.49	0.13	8.80	27.666	0.601	2.17
	5	1.20	0.09	7.92	28.206	0.328	1.16
	3	0.81	0.04	4.74	33.522	3.321	9.91
	1	0.60	0.06	9.91	33.677	1.247	3.70
	0.5	0.47	0.06	13.63	36.722	2.429	6.61
	0.3	0.40	0.05	13.11	41.776	1.002	2.40
	0.1	0.24	0.09	38.23	41.230	1.415	3.43

Table H.28. Dynamic modulus data for QZ19 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	13.96	0.74	5.309335	7.374318	1.315377	17.83727
	15	12.88	0.57	4.3864101	9.725886	0.466274	4.794152
	10	12.20	0.45	3.6686146	10.97863	0.732717	6.674026
	5	11.27	0.61	5.3718096	12.6688	0.976416	7.707251
	3	10.43	0.54	5.1630793	14.0739	1.082452	7.691205
	1	8.57	0.48	5.5575954	15.2755	0.750838	4.915307
	0.5	7.77	0.44	5.7134278	16.2747	1.457761	8.957221
	0.3	6.99	0.69	9.8100501	19.34215	1.617363	8.361857
	0.1	5.25	0.76	14.526816	23.79037	1.205039	5.065238
21	25	5.39	0.30	5.52	18.8654	1.482495	7.858275
	15	4.79	0.22	4.60	20.52567	0.83872	4.086202
	10	4.37	0.16	3.60	22.22353	1.045607	4.704955
	5	3.68	0.12	3.20	24.78234	0.99066	3.997446
	3	3.02	0.12	3.93	27.58294	1.056872	3.831617
	1	2.19	0.07	3.12	29.69417	1.302472	4.38629
	0.5	1.86	0.04	1.96	33.71552	0.375061	1.112427
	0.3	1.61	0.06	3.74	35.72197	0.846173	2.368774
	0.1	1.06	0.08	7.56	38.42208	0.699935	1.8217
37	25	1.83	0.16	8.88	28.346	1.038	3.66
	15	1.50	0.12	7.65	28.782	1.560	5.42
	10	1.31	0.11	8.38	28.808	1.615	5.61
	5	1.05	0.09	8.89	28.724	1.744	6.07
	3	0.76	0.06	7.43	33.268	0.923	2.77
	1	0.57	0.04	7.19	29.419	3.209	10.91
	0.5	0.44	0.01	2.98	33.208	1.535	4.62
	0.3	0.38	0.02	6.53	36.130	4.616	12.78
	0.1	0.28	0.06	20.74	39.365	7.144	18.15

Table H.29. Dynamic modulus data for LM20 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	6.019654	0.563569	9.362158	7.793	2.118	27.18
	15	5.288252	0.459124	8.681964	9.551	0.661	6.92
	10	4.803489	0.366953	7.639309	10.540	0.208	1.97
	5	4.011713	0.269704	6.722914	12.472	0.334	2.68
	3	3.160072	0.170111	5.383126	14.004	0.625	4.47
	1	2.319352	0.166505	7.178956	15.144	1.082	7.14
	0.5	1.917303	0.129338	6.745839	16.623	0.286	1.72
	0.3	1.637392	0.122667	7.491623	19.284	1.004	5.20
	0.1	1.069271	0.124115	11.60748	26.340	4.855	18.43
21	25	6.02	0.56	9.36	19.612	0.631	3.22
	15	5.29	0.46	8.68	21.109	0.443	2.10
	10	4.80	0.37	7.64	22.546	0.660	2.93
	5	4.01	0.27	6.72	25.303	0.529	2.09
	3	3.16	0.17	5.38	29.095	1.873	6.44
	1	2.32	0.17	7.18	32.128	0.788	2.45
	0.5	1.92	0.13	6.75	35.496	2.633	7.42
	0.3	1.64	0.12	7.49	39.378	1.089	2.77
	0.1	1.07	0.12	11.61	39.118	1.900	4.86
37	25	2.05	0.17	8.42	28.295	1.062	3.75
	15	1.70	0.16	9.24	27.718	0.557	2.01
	10	1.47	0.15	9.89	28.154	0.855	3.04
	5	1.20	0.11	9.31	28.320	0.965	3.41
	3	0.80	0.09	11.70	33.563	2.722	8.11
	1	0.58	0.08	13.24	32.529	2.273	6.99
	0.5	0.48	0.10	20.03	36.820	3.223	8.75
	0.3	0.41	0.08	19.58	40.828	2.857	7.00
	0.1	0.26	0.10	38.58	40.820	2.214	5.42

Table H.30. Dynamic modulus data for LM20 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	12.12002	1.217294	10.04366	7.886095	2.11131	26.77256
	15	11.61164	1.57186	13.53693	10.77871	0.576474	5.348266
	10	7.860769	5.159652	65.63801	11.17086	1.596944	14.29563
	5	10.04864	1.254509	12.48437	13.90918	0.718306	5.164263
	3	9.064108	1.377801	15.20063	15.88087	1.471314	9.264698
	1	7.265818	1.09084	15.01331	17.34757	0.588827	3.394292
	0.5	6.565079	0.926509	14.11269	19.33839	1.955459	10.1118
	0.3	6.068906	0.931979	15.35662	22.51343	3.990922	17.72685
	0.1	3.208407	0.783042	24.40593	32.79503	4.941635	15.06824
21	25	5.01	0.32	6.46	20.05697	1.270077	6.332349
	15	4.34	0.32	7.42	21.92405	0.833832	3.803273
	10	3.94	0.28	7.16	23.30411	0.704488	3.023022
	5	3.26	0.24	7.22	25.63435	0.652352	2.544836
	3	2.56	0.24	9.53	29.54329	1.458854	4.93802
	1	1.84	0.14	7.52	31.5289	0.869676	2.758346
	0.5	1.53	0.11	7.16	34.32642	0.71954	2.096169
	0.3	1.28	0.10	7.59	37.11771	1.492995	4.022324
	0.1	0.85	0.09	10.20	38.09433	1.243108	3.263237
37	25	1.64	0.11	6.90	27.054	0.910	3.36
	15	1.37	0.09	6.84	27.840	0.737	2.65
	10	1.18	0.07	5.84	27.244	0.932	3.42
	5	0.99	0.06	6.48	27.173	1.034	3.81
	3	0.67	0.04	6.64	31.701	2.106	6.64
	1	0.50	0.01	2.05	30.127	1.575	5.23
	0.5	0.41	0.02	5.50	34.912	1.100	3.15
	0.3	0.36	0.01	3.53	39.257	1.779	4.53
	0.1	0.24	0.04	15.00	39.792	2.698	6.78

Table H.31. Dynamic modulus data for QZ21 *not* moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	17.24911	1.105182	6.40718	5.821	0.887	15.24
	15	16.06903	0.795735	4.951979	8.185	0.741	9.06
	10	15.20677	0.763704	5.02213	9.490	0.466	4.91
	5	14.20191	0.506274	3.564831	10.973	0.714	6.50
	3	13.04594	0.628885	4.820539	12.112	1.182	9.76
	1	11.19276	0.6705	5.990474	11.784	1.457	12.37
	0.5	10.18254	0.717504	7.046418	13.454	1.599	11.88
	0.3	9.820296	0.691428	7.040805	16.477	1.541	9.36
	0.1	8.069187	0.638297	7.910305	19.183	0.630	3.29
21	25	6.50	0.59	9.11	17.147	2.081	12.14
	15	5.79	0.46	8.02	19.235	0.881	4.58
	10	5.30	0.39	7.39	20.469	0.810	3.96
	5	4.55	0.32	7.02	22.972	0.892	3.88
	3	3.73	0.30	8.10	26.355	0.860	3.26
	1	2.82	0.21	7.32	27.949	0.272	0.97
	0.5	2.45	0.16	6.71	32.416	2.780	8.58
	0.3	2.17	0.13	6.00	35.304	1.160	3.29
	0.1	1.44	0.09	6.10	37.425	1.918	5.12
37	25	2.49	0.31	12.27	26.144	0.930	3.56
	15	2.09	0.27	13.01	26.779	0.898	3.35
	10	1.87	0.25	13.37	26.992	0.887	3.29
	5	1.51	0.18	11.99	27.840	0.659	2.37
	3	1.07	0.14	12.83	32.784	0.663	2.02
	1	0.82	0.10	11.91	31.987	1.504	4.70
	0.5	0.65	0.10	16.04	36.509	1.587	4.35
	0.3	0.55	0.07	13.41	40.980	2.387	5.82
	0.1	0.38	0.08	20.12	40.428	1.306	3.23

Table H.32. Dynamic modulus data for QZ21 moisture-conditioned

Temperature	Frequency	E* (GPa)			Phase Angle (Degree)		
°C	Hz	Mean	SD	CoV	Mean	SD	CoV
4	25	14.97443	0.706369	4.717172	7.463369	1.051531	14.08922
	15	13.6477	0.598178	4.382993	8.785564	0.362351	4.124396
	10	13.20164	0.397061	3.007664	9.752456	0.491196	5.036642
	5	12.0427	0.376922	3.129878	11.34622	0.522836	4.608022
	3	11.48438	0.405176	3.528059	12.31785	0.909087	7.380238
	1	9.697998	0.330605	3.408999	14.30826	0.79117	5.529467
	0.5	8.78256	0.282071	3.21172	15.36558	0.952687	6.20014
	0.3	8.122812	0.312761	3.850405	18.35434	1.962419	10.69186
	0.1	6.480443	0.121498	1.874848	21.95507	1.346589	6.133385
21	25	5.87	0.35	5.91	17.519	1.461375	8.341656
	15	5.24	0.35	6.77	19.36277	0.893887	4.616523
	10	4.75	0.34	7.08	20.8488	0.7088	3.399714
	5	4.04	0.31	7.58	23.38393	0.784394	3.354416
	3	3.34	0.32	9.52	26.85098	0.894465	3.33122
	1	2.44	0.22	8.94	29.06388	0.85023	2.925385
	0.5	2.08	0.20	9.84	32.13032	1.68823	5.254322
	0.3	1.81	0.20	11.20	36.02823	0.826815	2.294908
	0.1	1.21	0.12	10.21	36.93112	0.577753	1.564408
37	25	2.13	0.30	14.32	26.231	0.936	3.57
	15	1.78	0.22	12.37	26.867	0.821	3.05
	10	1.58	0.20	12.45	26.761	1.285	4.80
	5	1.28	0.14	11.32	27.769	1.178	4.24
	3	0.93	0.10	11.01	32.536	1.667	5.12
	1	0.70	0.11	15.90	30.286	2.414	7.97
	0.5	0.54	0.09	16.91	36.499	1.917	5.25
	0.3	0.49	0.10	20.38	39.534	2.548	6.45
	0.1	0.35	0.09	24.70	40.641	2.205	5.42