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Characterization of Warm Mix Asphalt (WMA) performance in different asphalt applications

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Characterization of Warm Mix Asphalt (WMA) performance in different asphalt applications

by

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ABSTRACT

With the prices of crude oil increasing and reserves of natural nonrenewable resources dwindling over time, the needs for adopting greener and more sustainable approaches in various construction activities are stronger. The asphalt production industry has been keen during the last few decades to reduce the impact of its activities on the environment especially regions adjacent to its operating activities and on natural resources. Thus, recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) are increasingly being used in the production of asphalt mixtures. Moreover, different techniques to produce and place asphalt mixtures at lower temperatures than the typical hot mix asphalt (HMA) temperatures are recently being used. These techniques are currently known as warm mix asphalt (WMA) technologies.

The performance of three commonly used warm mix technologies: Advera, Evotherm J1 and Sasobit were examined in comparison to a control HMA mixture with respect to dynamic modulus and permanent deformation (flow number). Each mixture was developed using a PG 64-22 binder and two types of aggregates: limestone or quartzite. In addition, this study will look into whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA.

Warm mix asphalt mixtures prepared at 120°C and compacted at 110°C showed no concerns regarding workability or compactability even in mixtures incorporating 30% RAP. Dynamic modulus and flow number tests were conducted to assess the stiffness and permanent deformation resistance, respectively. The performance tests data suggested that there is a significant difference in the performance of HMA mixtures and the three WMA technologies investigated. Dynamic modulus data of WMA mixtures were consistently lower compared to HMA, with the difference in E* values decreasing with increasing temperature. The incorporation of RAP increased the dynamic modulus of all mixtures but HMA mixture was still higher than WMA mixtures. The impact of RAP incorporation decreased as temperature increased. Finally, the rutting resistance of WMA mixtures was considerably lower compared to HMA mixes even after incorporation of RAP. Thus, WMA technologies suitability for hot regions needs to further investigated.

MEPDG design runs were performed to assess the performance of lab produced asphalt mixtures incorporating WMA and RAP and compare it to the performance of corresponding control mixtures. MEPDG output agreed with laboratory test results specifically for rutting prediction and terminal IRI values. The statistical analysis of variance indicated that the Evotherm™ mixtures performance was generally different from the control mixtures regardless of type of aggregates used.

Finally, the rheological behavior of two binders: a base binder and a polymer modified binders incorporating two types of warm mix asphalt (WMA) additives were studied through an extensive testing scheme. The warm mix additives used were an organic wax and an oily chemical additive. Tests performed comprise basic rheological tests such as rotational viscometer, viscous flow, creep, temperature and frequency sweeps. The output data of these tests were used to construct Viscosity-Temperature Susceptibility (VTS) curves and master curves to study the behavior of the binders tested. The performance of the unmodified WMA binders was similar to the control binder at the midrange and high test temperatures. On the other hand, the modified binder incorporating the waxy WMA additive exhibited stiffer behavior indicating the presence of more advanced polymer networks within the binder structure. Moreover, the wax additive had an anti-oxidizing effect on the aging rate of the binder using pressure aging vessel (PAV).

CHAPTER 1: INTRODUCTION

The rise in the prices of energy resources and the steadily increasing depletion of nonrenewable natural resources that are considered input raw materials for plenty of industries were cause for a rethink about adopting more sustainable approaches in utilizing these natural resources. Persistent warnings regarding the adverse effects of the excessive emission of greenhouse gases most notably, carbon dioxide led to intensive efforts on a global scale to address these concerns culminating with the ratification of the Kyoto protocol by the European Union in which they pledged to lower the carbon dioxide emissions by 15% by 2010. These newly imposed environmental restrictions spurred the asphalt industry bodies in European countries to look into new approaches and techniques that lower emissions and energy consumption. The production of hot mix asphalt (HMA) raises a number of environmental concerns because of the emission of gases such as CO_2, SO_2 and NO_x into the atmosphere and the health risks encountered by workers of asphalt plants.

1.1. What is Warm Mix Asphalt (WMA)?

One of the approaches identified to lower emissions of asphalt mixing plants was to lower the production temperature of the asphalt mixtures. As a result, several European companies began to investigate practical techniques and methodologies to achieve that objective through the reduction of the mixing temperatures. These efforts resulted in the emergence of several innovative techniques that became collectively known as warm mix asphalt (WMA). This family of technologies can be classified into 1) water-based technologies, 2) water bearing additive technologies, 3) organic additive technologies, and 4) chemical additive technologies.

In addition to its obvious benefits regarding the cleaner/environmental production of asphalt, other benefits provided by the WMA technologies acted as additional drivers that increased the interest in trying and using these technologies such as the lower viscosity of the binders which in turn improved the compactability of mixtures, lower susceptibility to oxidative hardening as the asphalt was exposed to lower mixing temperatures which meant the binders have undergone less aging and finally the perceived lesser aging meant that there is higher potential for accommodating higher contents of recycled/reclaimed asphalt pavement (RAP).

After being introduced to the WMA technologies developed in Europe since the mid 1990s, governmental agencies and asphalt industry bodies in the United States focused on establishing frameworks through which the suitability of applying WMA techniques in the United States is investigated. Hence, several research studies tried to investigate the characteristics of WMA mixtures and their potential drawbacks such as susceptibility to moisture and its fatigue and rutting performance.

1.2. Problem Statement

The benefits acquired through the utilization of WMA technologies will only be useful if the performance of pavements constructed using WMA mixtures is comparable to the performance of conventional HMA pavements in terms of pavement durability, function-ability and quality. As WMA techniques are deemed merely past their embryonic phases, there is a concern regarding its resistance to moisture susceptibility as there is a worry that the lower production temperature will not lead to the drying of the aggregates used in the asphalt mix affecting the binder adhesion to the aggregate surface adversely as a result. In addition, another concern is that WMA mixtures are less stiff than conventional HMA mixtures due to its reduced aging as the binder was exposed to lower temperatures during production which could make WMA pavements more vulnerable to rutting problems. Moreover, the ability of WMA mixtures to incorporate higher RAP content while being investigated in previous research, the impact of higher RAP incorporation needs further verification. With the number of projects using WMA mixtures still small, the ability of pavement performance evaluating software packages such as the Mechanistic Empirical Pavement Design Guide (MEPDG) to predict the performance of WMA mixtures and whether these predictions are comparable to the output test data from performance tests conducted on these mixtures needs investigation.

Little research has been conducted on the rheological behavior of WMA binders and their characteristics at critical temperature ranges for the rutting and fatigue performance of WMA mixtures. Moreover, the effect of using WMA additives on polymer modified binders needs investigation because the use of WMA additives could help reheating polymer modified mixtures at lower temperatures which could lead to energy savings.

1.3. Objectives

The objectives of this dissertation are as follow: first, to study the performance of asphalt mixtures prepared with three WMA technologies, Advera, Evotherm and Sasobit in comparison with a control HMA mixture by conducting dynamic modulus and repeated loading (flow number tests). Secondly, this work looked into whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA. Thirdly, the performance of pavements using the asphalt mixtures prepared in this work is predicted by the MEPDG software using the test data acquired from laboratory testing. The performance of the pavement sections was assessed based on the amount of alligator cracking and permanent deformation predicted by the software.

Fourthly, the basic characteristics of a PG 64-22 binder incorporating Evotherm and Sasobit are studied by carrying out Superpave binder testing procedures on the binders in its original form, rolling thin film (RTFO) aged and pressure aging vessel (PAV) aged states. These tests were conducted using rotational viscometer, dynamic shear rheometer (DSR) and bending beam rheometer (BBR). Fifthly, the basic rheological properties of SBS polymer modified WMA binders were measured and the effect of polymer modification on the characteristics of the binders was analyzed. Sixthly, additional rheological procedures such as viscous flow, creep, frequency and temperature sweeps were performed to further investigate the behavior of WMA binders and polymer modified WMA binders. Finally, the rate of aging of the binders in the high temperature range 46-76°C was studied by comparing the percent increase in complex modulus values of RTFO aged binders to the values of PAV aged binders. This could give an indication about the impact of WMA additives and styrene butadiene styrene polymers on the trends of aging progression in pavements after placement and compaction.

1.4. Dissertation Organization

This dissertation follows a journal paper format and is divided into six chapters including three papers. Each paper appears as a chapter including its related literature review and background, analysis, observations, conclusions and recommendations. The first chapter is a general introduction that provides a brief account about the emergence of WMA technologies and its potential benefits and concerns regarding its application. In this chapter, a problem statement regarding the key research questions concerning the topic of this dissertation is provided along with the research objectives this work attempts to achieve. A brief outline of the methodologies used to achieve these objectives was briefly outlined. Chapter 2 discusses the emergence of WMA technologies and previous research conducted on WMA binders and mixtures in laboratories or field projects. The major findings of past studies on the performance of binders and mixtures incorporating various WMA additives are presented. Chapter 3 titled *An Evaluation of Warm Mix Asphalt Additives and Reclaimed Asphalt Pavement (RAP) on Performance Properties* discusses the mechanical performance of WMA mixtures prepared with three different WMA technologies and 30 % RAP content. The mechanical performance of these mixtures was assessed using dynamic modulus test data and flow number test. Chapter 4 titled *Performance Evaluation of Lab Warm Mix Asphalt Mixes incorporating RAP using the MEPDG* looks into the ability of the MEPDG software to estimate the performance of pavements made using WMA mixtures through predicting pavement distresses such as fatigue cracking and permanent deformation in the asphalt layer based on dynamic modulus test data of the mixtures that were input into the software. Major findings included identifying which WMA mixtures gave comparable performance to conventional control HMA mixtures. These findings were reached with the help of statistical analysis of the output data generated from the software runs. Chapter 5 is a paper titled *Evaluation of the Rheological Properties of Polymer Modified Warm Mix Asphalt Binders* and discusses the rheological behavior of different unmodified and polymer modified binders incorporating two WMA additives. The rheological behavior of the binders was investigated by conducting basic Superpave binder testing in addition to frequency and temperature sweeps at a wide range of test temperatures within which critical fatigue and permanent deformation typical critical temperatures lie. The findings of this chapter included which of the two WMA binder groups is more susceptible to permanent deformation problems and the impact of polymer modification was quantified through qualitative and quantitative analysis of the complex modulus and phase angles of the binders tested. Moreover, the impact of the Sasobit and Evotherm additives on the aging trend of RTFO aged binders was analyzed with Sasobit identified to have an antioxidant effect on the rate of aging. Finally, Chapter 6 provides a summary, conclusions and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

Warm Mix Asphalt (WMA) additives and technologies allow asphalt to be mixed and placed with mineral aggregates at relatively lower temperatures, 20 to 55°C (35 to 100°F) lower than typical HMA (Mallick et al., 2009; D'Angelo, et al., 2008). These technologies facilitate reduction in the asphalt binder's viscosity enabling the coating of aggregates particles completely at lower temperatures. The incorporation of WMA also tends to improve compaction reducing the permeability and binder hardening caused by aging, improving the performance of the asphalt mix in terms of cracking resistance and susceptibility to moisture.

The evolution of WMA technologies in Europe was driven by a number of identified benefits acquired through the adoption of these technologies. The most notable benefits reported are the reduction in harmful emissions and energy consumption. Moreover, improvements in compaction enable the extension of the pavement season and longer haul distances.

The concept of lowering production temperatures of asphalt mixtures is not a new one. Professor Ladis Csanyi of Iowa State University identified the potential of using foamed bitumen as a soil binder in 1956. In this process, the introduction of saturated steam at about 40 psi into heated asphalt cement using a specially developed nozzle led to the production of controlled foam. Improved coating and mixing with cold, wet aggregates or soils was possible due to the reduced viscosity and the increased surface energy of the foamed asphalt (Lee, 1980). It was reported that foamed asphalt could be used in preparing mixes for stabilized bases and pavement surfaces of low traffic roads.

Patent rights of the Csanyi process were attained by Mobil of Australia in 1968 that modified the process by substituting steam with 1-2% cold water and a more extensive mixing process. The Mobil process, also known as Foamix, comprised the introduction of cold water under controlled flow and pressure into the heated asphalt binder in a specially developed foaming chamber. Consequently, the foamed asphalt is discharged into the cold, moist aggregate using spray bar nozzles (Lee, 1980).

Chevron developed mixture and thickness design methodologies in their Bitumuls Mix Manuals for paving mixtures stabilized with emulsified asphalts in the 1970s. Moreover, agencies like, the Federal Highway Administration (FHWA) and Asphalt Emulsion Manufacturers Association (AMEA) published similar guidelines in 1979 and 1981, respectively (Button, et al., 2007). In 1994, Button reported that Maccarone and his team investigated cold-mixed asphalt-based foamed bitumen and reached the conclusion that the use of cold mixtures on roads was becoming more acceptable due to its energy efficiency and lesser emissions.

In 1995, Shell developed a warm-mix technique that used a two-component process that was widely tested in Norway, the United Kingdom and the Netherlands which culminated in the development of WAM-Foam. Moreover, Sasobit, a long chained hydrocarbon additive started to be marketed in Europe as a compaction aid for asphalt mixtures by Sasol Wax International.

2.1 WMA Technologies Classification

WMA technologies can be classified differently, either according to degree of temperature reduction or by type. If classified by type, WMA technologies can be classified into two major types, technologies that rely on water or those that comprise a form of chemical additive to force the temperature reduction.

2.1.1 Water-based WMA Technologies

WMA technologies that rely on water can be further classified into:

- foaming processes such as Astec Double Green System, or
- foaming techniques that rely on the introduction of foaming additives such as Advera or Aspha-min.

Wielinski et al. (2009) and Middleton et al. (2009) described the foaming process as a procedure where a given volume of water is added to the hot binder, with the water turning into steam at atmospheric pressure and leading to the expansion of the binder. Hence, the viscosity of the foamed binder is significantly reduced.

WAM-Foam is the most commonly used process in Europe followed by LEA, low energy asphalt process. In the United States, the Double Barrel Green technology produced by Astec is the most prevalent (Anderson, et al., 2008). The Double Barrel Green process utilizes a chamber where water is injected via nozzles and the asphalt binder is foamed in a single stage procedure that foams all the binder. On the other hand, the LEA process makes use of a small amount of a coating and adhesion additive incorporated into the asphalt binder prior to mixing. Consequently, coarse aggregate is heated to normal mixing temperatures at

290 °F and mixed with asphalt binder at the temperature deemed appropriate for the binder grade. Wet fine aggregate with 3-4% moisture is then added to the coated coarse aggregates at ambient temperature and mixed so that the moisture in the fine aggregates initiates the foaming of the asphalt binder. The foaming of the binder causes the increase of its volume and surface area enabling the rapid coating of the aggregates (Button, et al., 2007; Anderson, et al., 2008). Figure 2.1 below illustrates the phases of the LEA process.

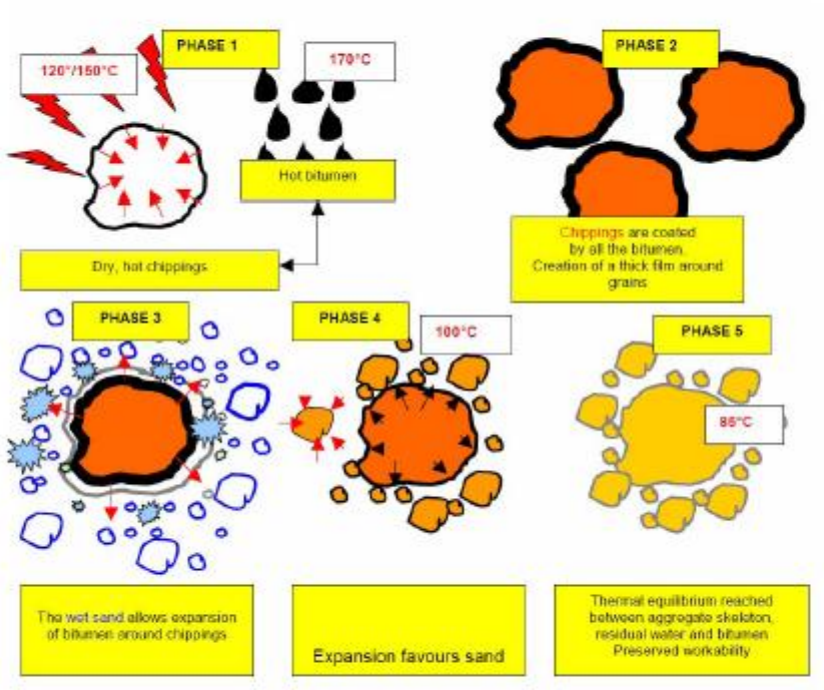


Figure2.3 LEA Process Phases (Button et al., 2007)

WAM Foam is a two staged process developed through a joint venture between Shell International and Kolo-Veidekke of Norway. The process begins with the introduction of the soft binder which is mixed with the aggregate in the first stage at temperatures ranging from 210 °F to 250 °F until full coating of the aggregates. The second stage consists of foaming a very hard binder into the pre-coated aggregate mixture with the aid of a small amount of cold water to induce foaming and improve the coating. The combination of a soft binder and foaming of the hard binder interact to lower the collective viscosity of the mixture providing the necessary workability which enables the placement and compaction of the mixture at temperatures ranging from 175°F to 195°F (Button, et al., 2007). It was reported that decreased production temperatures using WAM-Foam process can lead to plant fuel savings up to 30 percent given the appropriate selection of the soft and hard binder components.

2.1.2 Water Bearing Additive Technologies

Another group of WMA technologies that comprise foaming is the water bearing additives technologies group that rely on inducing foaming mechanisms in the asphalt binder using water bearing additives. The most notable examples of water bearing additives are Aspha-min and Advera which are available in the form of a very fine white powder. The former is manufactured in Germany by Eurovia while the latter is processed in the United States by PQ Corporation.

Aspha-min and Advera are both synthetic zeolites that are formed of alumin-silicates and alkali metals and nearly one fifth of its weight comprises crystalline water which is released as the temperature rises above 100°C upon the introduction of the additive to the mixture simultaneously with the binder. Consequently, the water released triggers a foaming effect that increases the volume of the asphalt binder and reducing its viscosity in the process. This gradual slow release of water from zeolite offers an extended period of workability for the asphalt mixture enabling the rapid coating of the aggregates at temperatures lower than those used in producing conventional HMA mixtures (Anderson, et al., 2008). Aspha-min is typically added at 0.3 percent by weight of the total mix.

2.1.3 Organic-based WMA Technologies

In addition to foaming based WMA technologies, another common group of WMA products is the organic based additives such as Sasobit, Sasoflex and Asphaltan B. Sasobit is a long chained synthetic wax (chain lengths ranging between 40 to 115 carbon atoms) that is produced using the Fischer-Tropsch (F-T) process. The greater length of chains assists in preserving the wax in solution and help in reducing the asphalt binder viscosity at conventional production and compaction temperatures. This is possible because Sasobit incorporates an organic additive that chemically alters the temperature-viscosity curve of the binder as this additive melts at approximately 210°F (100°C) as shown in Figure 2.2. At temperatures below its melting point, Sasobit forms crystalline structures within the binder that improves stability of the pavement during service (Anderson et al, 2008; Gandhi, 2008; Hurley and Prowell, 2005). According to the manufacturers, Sasobit incorporation at 3-4 percent by weight of binder enhances the ability to reduce mixing temperatures by 20 to 40°C (Damm et al., 2004). Furthermore, Sasobit permits the incorporation of Styrene Butadiene Styrene (SBS) polymer modifier using a specific cross-linking agent known as Sasoflex.

Asphaltan-B is a Montan (lignite) wax that is extracted from lignite coal deposits using toluene solvents. It is characterized by its higher molecular weight hydrocarbons and was manufactured specifically for fine grained HMA used for pavement surfacing (Corrigan et al, 2006). Asphaltan-B is recommended to be added at 2 to 4 percent by weight of binder and it can be incorporated either at the mixing plant or to the binder at an asphalt terminal.

Like Sasobit, this wax melts around 100 °C and improves the compactability and rutting resistance of asphalt mixtures (Button et al., 2007).

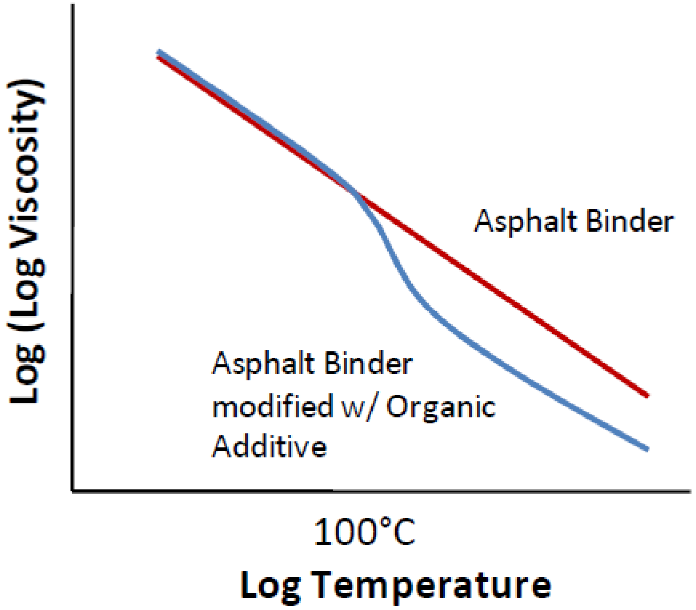


Figure 4.2 Temperature-viscosity relationships with the addition of organic additive (Anderson, et al., 2008)

2.1.4 Chemical Additive-based Technologies

Evotherm (Dispersed Asphalt Technology) DAT

Evotherm is a chemical package that includes cationic emulsification agents and additives that enhance the coating of aggregates and mixture workability in addition to adhesion (anti-stripping) agents. Moreover, Evotherm has 70% of its content as binder and it can lower the mixing temperature to 200°F. Upon mixing, steam droplets are liberated and a thin film of water between the aggregate and asphalt droplets forms improving the workability of the mix in the process as the water film exerts up to 10 MPa of capillary pressure. Takamura (2005) reported that the cationic emulsifiers present in the Evotherm emulsion adsorb to the aggregate surface due to its positively charged nature and promoting strong asphalt adhesion.

According to Hurley (2006), Evotherm could be stored at 180°F in silos with no plant modifications required for its use. During processing, the Evotherm emulsion is used instead of the conventional asphalt binder as it can be mixed with aggregate in the HMA plant. According to MeadWestvaco, the Evotherm emulsion manufacturer, field testing has shown that 100°F reduction in the mixing temperatures can be achieved which in turn can be advantageous in lowering energy consumption and CO_2, SO_2 and NO_x emissions.

Evotherm 3G (REVIX)

Another generation of chemical additives is known as Evotherm 3G and REVIX which was developed by Mathy Technology in cooperation with several companies. This additive enables the reduction of internal friction between the asphalt binder, aggregate and also between the coated aggregate particles during production and construction phases. This WMA product is marketed as Evotherm 3G (Anderson et al., 2008).

2.2 Benefits of utilizing WMA

The major driving force for the development of WMA is the benefits acquired through its implementation. The European practice study group dispatched by the FHWA identified several advantages of WMA usage (Anderson et al., 2008).

Environmental Benefits

There are a number of environmental advantages reported when using WMA technologies such as lower energy consumption, reduced emissions and better working conditions (Anderson et al., 2008).

2.2.1 Lower Energy Consumption

Hossain et al. (2009) reported that based on the WMA technique used and conditions, the energy consumption range is 20 to 75% of HMA while D’Angelo et al. indicated that burner fuel savings range from 20 to 35% (D’Angelo et al., 2008; Hossain et al., 2009). For processes such as low-energy asphalt concrete (LEAB) and low energy asphalt (LEA), fuel savings could reach more than 50%. Previous studies showed that the WAM-Foam WMA plant processing can be implemented with 40% lower energy consumption than HMA. Moreover, a 30% in energy consumption reduction was reported in measurements conducted for Eurovia when using Aspha-Min because of a 54 to 63°F decrease mix temperature (Button et al., 2007). Hossain pointed out that the true economic gain from the reduced energy consumption relies on the type of energy and its cost at the time. With continuous surges in the prices of energy sources, the non-renewable sources specifically, WMA could turn into an economically attractive alternative to HMA in the near future (Hossain et al., 2009).

2.2.2 Reduced Emissions

Another notable benefit of WMA usage instead of HMA in road pavements is the reduced emissions produced from the asphalt producing plants. The FHWA study team reported that Europeans asphalt suppliers presented data that indicated reduction in plant emissions while producing WMA compared to HMA. Table 2.1 below illustrates reported reductions in plant emissions in the European countries investigated in the FHWA study tour (D'Angelo et al., 2008).

Based on processing conditions and production temperature, WMA plant emissions were reported to represent 30 to 98% of HMA emissions (Hossain et al., 2009). A considerable reduction in fume emissions was reported between HMA produced at 165°C and WAM-Foam prepared at 115°C, from 0.2-0.5 mg/m3 range to below 0.05 mg/m3 . Button et al. reported that a production temperature reduction of 47°F using Aspha-Min resulted in a 75% reduction in fume emissions (Button et al., 2007).

Table 2.1 Emission Reduction in plants with WMA (%) (D'Angelo et al., 2008)

Emission	Norway	Italy	Netherlands	France
CO_2	31.5	30-40	15-30	23
SO_2	NA	35	NA	18
VOC	NA	50	NA	19
CO	28.5	10-30	NA	NA
NO_x	61.5	60-70	NA	18*
Dust	54	NA	NA	NA

The significance of this advantage depends on the environmental conditions and the strictness of environmental regulations at a given location. For example, using WMA technologies will be advantageous in countries participating in the Kyoto Protocol as it will help in abiding with the tighter emission regulations.

Paving Benefits

Although the driving factors for WMA development were mostly related to its favorable impact on the environment and fuel economy, there are several paving benefits that could be gained from adopting WMA technologies. These benefits are related to the effects of the WMA process or additive on the asphalt binder. The main effects of WMA are reducing the viscosity and the oxidative hardening of the asphalt binder (Hossain et al., 2009).

2.2.3 Lower Viscosity

Generally, most WMA technologies have the ability to reduce the binder viscosity. Several advantages are gained from the lower viscosity as the workability of the asphalt mixture is improved. Better compaction can be achieved and a lower number of roller passes are needed to reach the targeted density. Moreover, the incorporation of WMA allows for better workability at lower temperatures. Hence, WMA can help extend the paving season and enable hauling the asphalt mix for longer distances and preserve sufficient workability for placement and compaction (D'Angelo et al., 2008; Hossain et al., 2009).

NCAT researchers examined the impact of Sasobit on the binder viscosity in 2005. In their research, A Sasobit dosage of 2.5% was added to a PG 58-28 binder to produce a PG 64-22 modified binder in the process. Upon comparing the modified Sasobit PG 64-22 binder to the base unmodified PG64-22 binder, it was found that the compaction temperature needed for the WMA modified binder was approximately 18°C lower than that of the corresponding unmodified binder (Hurley et al., 2005). Kanitpong et al. (2008) reported similar observations in their study of viscosity effects of Sasobit on asphalt binders. It was noted that adding a 3% Sasobit to a polymer-modified asphalt binder decreased its viscosity. Wasiuddin et al. (2007) reported similar findings regarding the effect of Sasobit. Moreover, they noticed that Aspha-min did not exhibit any significant change in viscosity when added to a PG 64-22 binder.

D’Angelo et al. (2008) reported that in several projects in Germany, the paving was completed with different WMA technologies at low ambient temperatures ranging between -3 and 4°C. Base and SMA surface courses were placed using Aspha-min. The mixing temperature behind the paver ranged from 102 to 139°C with better density achieved with WMA compared to HMA with fewer roller passes. The researchers noted that the actual production temperatures for WMA mixtures during cool weather depends on the nature of WMA technology used, the surrounding conditions and the haul distance.

Furthermore, the lower rate of cooling of WMA, due to less difference between ambient and mix temperatures, and the reduced viscosity of WMA at lower temperatures, may allow longer haul distances. Kolo Veidekke stored WAM-Foam for 2 days in a silo and was still able to place and compact the mix. It was also reported that a Sasobit mix was hauled for 9 hours in Australia and it was workable enough to be unloaded (D’Angelo et al., 2008; Button et al., 2007).

2.2.4 Oxidative Hardening

Oxidation of the asphalt binder starts during its mixing with hot aggregates and continues throughout the pavement life. Age hardening takes place due to oxidation resulting in the stiffening and the hardening of the binder with the temperature of the asphalt oxidation reaction a significant factor that determines the rate of formation and the type of oxidized species formed (Hossain et al., 2009). Hence, theoretically, using WMA technologies can possibly reduce the susceptibility of an asphalt mixture to aging and cracking as the mix is not exposed to the elevated production and placement temperatures which can lead to a longer pavement service life.

2.2.5 Potential for using higher percentage of (RAP)

The use of recycled asphalt pavement (RAP) in HMA pavements has become more popular due to a number of factors, most notably, the scarcity of space available in landfills, decrease in the amount of high quality virgin aggregate and the increasing prices of oil (Loria et al, 2011).More than half of state DOTs allow high RAP (more than 25% RAP) to be used in asphalt mixtures but the incorporation of high RAP content has been relatively low in comparison to the available supply of RAP. An explanation for this is the concerns regarding RAP mixtures resistance to fatigue and cracking (Copeland et al., 2010). Typically, a lower grade binder is utilized to offset the extra stiffness of the RAP mixture.

Incorporating WMA technologies can be beneficial with mixtures with high RAP proportions because of its lower viscosity, which will facilitate compaction, and the reduced aging of the binder that will substitute for the increased aging of the RAP binder. D’Angelo, et al. (2008) reported the use of Aspha-Min and Sasobit in pavements containing high RAP content in Germany. Copeland, et al. (2010) investigated the performance of two high RAP mixtures (45% RAP): one an HMA control mix and the other is a WMA mixture. The performances of the two mixtures were studied in terms of its binder and mixture characteristics. The control mix was mixed at 155 °C and compacted at 149°C while the water injection WMA mix was mixed at 133 °C and compacted at 127°C. It was concluded that the high RAP-WMA mix had a lower performance grade than the high RAP-HMA mix indicating that the binder in the WMA mix is softer. Moreover, the results of the dynamic modulus displayed similar behavior for both mixes except that the RAP-WMA mix |E*| values are a little lower than the RAP-HMA mix. The same way, flow number results show that the flow number, Fn, value of the RAP-WMA mix is lower than the control mix.

2.3 Recent Warm Mix Research

2.3.1 United States

2.3.1.1 NAPA Study Tour, 2002

The National Asphalt Pavement Association (NAPA) sent out 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).

2.3.1.2 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 the 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). 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 (Kuennen, 2004).

2.3.1.3 NCAT WMA Research Program

Following the 2002 NAPA study tour, a jointly funded research program was begun in 2004 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 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, 2007).

2.3.1.4 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).

2.3.1.5 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, 2007).

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 project 09-43 and 09-47 (Corrigan, 2007).

2.3.1.6 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 development of 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 (Bonaquist, 2011). Consequently, the design method should be validated using data and materials acquired from completed field projects.

2.3.1.7 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, 2007). The project included multiple WMA technologies where 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 (Anderson, et al., 2008).

2.3.1.8 2007 FHWA European Scan Tour

Through the International Technology Scanning Program of the FHWA, 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, the 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 2.2 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. 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).

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.

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 2-5 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 5 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 (D'Angelo et al., 2008).

Table 2.2 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.

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.

2.3.1.9 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 and 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; and Brown, 2007, 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; and 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 has 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 in 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 and 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; EPA, 2008).

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).

2.3.2. 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, 2009); Hansen, 2006; and 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 of around 30°C. In June 2003, a larger runway in the same airport was paved with SMA that incorporated Sasobit® (Sasol wax, 2009).

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, 2009).

2.3.3. 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 laid in 2006 using Aspha-min®. The first was a demonstration project; 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).

2.3.4. United Kingdom

While the condition of the M6 motorway near Birmingham, United Kingdom was deteriorating alarmingly fast, 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 1 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 hot mix asphalt. 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, 2009).

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).

2.3.5. 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).

2.4. Properties of Warm Mix Binders & Mixtures

2.4.1. Binder Grade Selection

Previous research noted that aging taking place during the production (mixing) phase of HMA is strongly impacted by its production temperature. Hence, a minimum production temperature is required to avoid the increase in the high temperature grade of the binder. The minimum production temperature is determined by both the aging index of the asphalt binder and the binder grade as shown in Table 2.3 below. The aging index of the binder is the ratio of G*/sinδ after RTFO aging to G*/sinδ of the original binder. As shown in the table, the higher the aging index and the greater the performance grade of the binder, the greater the production temperature of WMA need to be to avoid increasing the binder grade (Anderson et al., 2008).

Table 2.3: Minimum WMA production temperature (Anderson et al., 2008)

	Aging Index											
PG	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**	**2.4**	**2.6**	**2.8**	**3.0**	**3.2**	**3.4**	**3.6**
52	<215	<215	<215	<215	<215	<215	220	220	225	225	230	230
58	<215	<215	<215	220	225	230	235	235	240	240	245	245
64	<215	<215	220	230	235	235	240	245	245	250	250	250
70	<215	220	230	240	245	245	250	255	255	260	260	260
76	<215	225	235	245	250	255	260	260	265	265	265	270
82	<215	235	245	250	255	260	265	265	270	270	275	275

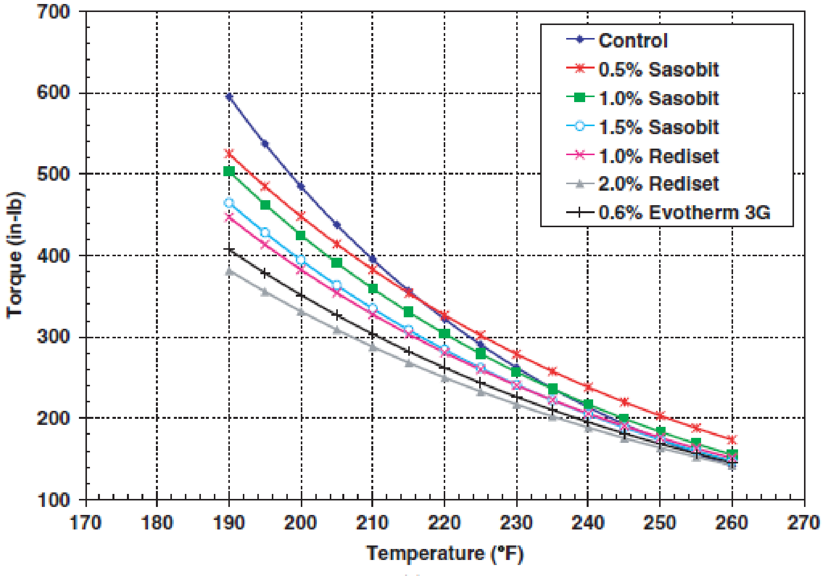
2.4.2. Workability & Compactability

With conventional binder and mixture tests for determining the mixing and compaction temperatures deemed insensitive for WMA mixtures, Bennert et.al (2010) investigated different approaches for evaluating the workability of asphalt material modified with WMA additives. They evaluated potential binder and mixture tests that would enable the ranking of the workability and compactability of binders incorporating warm mix additives and WMA mixtures. Three binder workability tests: rotational viscosity (AASHTO T316), NCHRP project 9-39 procedure and a lubricity test were conducted to evaluate their suitability for classifying the workability properties of a binder (PG-76-22) modified with different dosages of three WMA additives: Evotherm 3G, Rediset and Sasobit.

In the rotational viscosity test, a rotational viscometer was used to identify the temperature ranges for mixing and compacting the asphalt binders. On the other hand, the dynamic shear rheometer (DSR) was used to perform the NCHRP9-39 procedure to identify the production and the placement temperatures based on the viscoelastic behavior of the binders acquired through conducting a frequency sweep procedure at three to five temperatures. Consequently, the master curve constructed from the frequency sweep output data is used to determine the temperatures by using simple regression models. Finally, the third binder test used was the lubricity test in which the asphalt sample is brought sequentially into four test gaps at a given temperature at which a steady shear test is carried out.

The mixing and compaction temperatures calculated using the rotational viscosity test did not look reasonable as they were higher than 300 °F and 287°F, respectively. The same observation was noted for the results of the NCHRP 9-39 procedure. On the other hand, the lubricity test showed that the workability of WMA binders is higher compared to that of the control binder. Hence, the lubricity test provided the most reasonable ranking compared to the other two binder tests used in that study.

Moreover, three mix testing techniques were used to assess the workability properties of asphalt mixtures incorporating each of the studied WMA binders: asphalt workability device (AWD), Marshall compaction device and the gyratory compaction procedure. The AWD measures the resulting torque exerted to rotate a loose asphalt mixture at a constant speed in a bucket at a given temperature. Consequently, a torque versus temperature curve is developed from which the workability of mixtures can be classified with mixtures exerting lower torques at a given temperature is deemed more workable. The results of the AWD test showed that the control mixture exhibited the highest torque values with the torque of the mixtures incorporating WMA additives decreasing with when the dosage of the additives increased as shown in Figure 2.3 below.



(a)

Figure 2.5 AWD torque vs. temperature curve for 260 °F starting temperature (Bennert et al., 2010).

The Marshall compaction procedure was used in assessing the workability of different mixtures by measuring the compacted density after the samples are subjected to the same number of compactive blows at different temperatures. Mixtures with higher workability would have higher densities at a given temperature. The results showed that the control PG 76-22 would have the highest air void % compared to the mixtures incorporating WMA when the same compactive effort was applied. It was observed that asphalt mixtures incorporating 1.5% Sasobit and 2% Rediset would have the lowest air voids indicating superior workability and compactability at temperatures well below the typical HMA production temperature.

The gyratory compactor test was used to evaluate the workability and compactability of WMA mixtures in two ways. In the first approach, the compactor was used to compact different mixtures to 100 gyrations at different temperatures. Consequently, the densities of the compacted samples were measured. The second testing approach using the gyratory compactor was to compact asphalt mixture specimens to a standard density of approximately 7% air voids. The rate of compaction in (mm/gyrations) was calculated using the initial, the predetermined final specimen height of 77mm and the number of gyrations recorded. Higher compaction rates would exhibit specimens that were compacted quicker which indicate they are more compactable and workable compared to their counterparts with lower compaction rates. Results reported showed that an unexpected trend was observed with the compaction rate lower at 260°F compared to the compaction rate at 215°F. A possible explanation for this phenomenon offered by Bennert and his team is that the extra aging and stiffening the asphalt undergone at 260°F could have necessitated greater compactive effort compared to that needed at 215°F (Bennert et al., 2010).

2.4.3. Evaluation of production, lay down and compaction of warm mix

The Texas Department of Transportation conducted a WMA field trial using Evotherm emulsion in which the production and placement characteristics of warm mix were studied and compared to the behavior of a control HMA mixture. The WMA mixture was produced at 220°F and was compacted after three different curing modes: no curing, curing for 2 hours at 200 °F and curing for 240°F. On the other hand, the conventional control mixture was produced and compacted at 320 and300°F, respectively. Lab compacted field mixed samples were tested to measure density, susceptibility to moisture and resistance to cracking. The reheated WMA samples were lab compacted at 240°F and 300°F to 93% density with the control mix samples compacted at 300°F. Moreover, cores were extracted from the road after one month of service and also after one year. The Hamburg Wheel Tracker test was conducted to measure the rutting potential and the moisture susceptibility of asphalt. Additionally, the TTI overlay and X-ray chromatography tests were conducted to assess the reflection cracking potential and the air void distribution with core depth, respectively (Estakhri et al. 2009).

The research team did not observe any problems during the lay down and compaction phases of both the warm mix and the control mix pavement sections. However, all WMA samples failed the Hamburg test criteria as the rutting depth exceeded 12.5 mm after 20,000 passes with the warm mix samples lab compacted at 300°F performing slightly better than the samples compacted at 240°F. Moreover, WMA core samples extracted at one month failed the Hamburg test while the one year old samples met the test requirements. The overlay test results were inconsistent and the lab compacted test samples for both the WMA and HMA exhibited poor results. Finally, the X-ray chromatography results showed that the air void distribution is more uniform in warm mix compared to the cores of the HMA mix (Estakhri et al. 2009).

In 2008, Granite Construction researchers conducted two demonstration projects to study the characteristics of sections paved with the Astec Double Barrel Green foaming technology and compare it to the performance of control HMA sections. Both the WMA and the HMA mixtures incorporated 15 % RAP content and were produced using PG 70-10 binders at 275 and 330°F plant discharge temperatures, respectively. Conventional testing of mixture properties was conducted in addition to the Asphalt Pavement Analyzer (APA) test and Tensile Strength Ratio (TSR) tests to evaluate the rutting resistance and the moisture sensitivity of the mixtures investigated in the study, respectively.

Results had shown that it is possible to design WMA mixtures using conventional methods of design such as Hveem and Marshall. It was reported that the produced HMA and WMA mixtures satisfied the volumetric and stability criteria of the design methods. While, satisfying the APA minimum requirements, the WMA mixtures exhibited lower stiffness compared to the control mixtures; hence, the WMA APA rut depths were higher than the conventional HMA mixtures. A possible explanation could be the lower production temperature of the WMA which relatively reduced the binder stiffness during production affecting the mixture stiffness in the process. The TSR test results were significantly lower than the acceptable range stipulated by AASHTO and the WMA mixtures had TSR were

10% lower than those of HMA mixtures indicating poor resistance to moisture and the possible need to use anti-strip agents. (Wielinski et al., 2009).

A low volume gravel road in southeast Alaska was constructed using Sasobit warm mix technology in 2008. The Sasobit pellets were added 1.5% by weight of a PG 58-28 polymer modified binder altering its performance grade to PG 70-22. The production temperatures for the WMA and HMA mixtures were 265 and 315°F, respectively. It was reported that fuel consumption of the plant was lower during the production of the warm mix compared to the consumption of the HMA production. In addition, lower fumes were visually noticed during production but no quantification of the fumes emitted from both the HMA and WMA mixtures was conducted (Saboundjian et al., 2011).

Due to the lower production temperature of the WMA section, the main properties that were of concern were the stiffness of the produced mixture, its resistance to rutting and its moisture susceptibility. Hence, dynamic modulus, flow number and TSR tests were conducted to address the aforementioned mixture characteristics. The dynamic modulus test conducted at four temperatures 40°F, 70°F, 100°F and 129°F showed that at a given temperature, the WMA mixture exhibited higher stiffness compared to the HMA mix. This observation was attributed to the presence of Sasobit which probably stiffened the binder making the mix more resistant to rutting. The same way, the flow number test results showed that the WMA mixture exhibited higher Fn values in comparison to the control mixture confirming that the addition of the Sasobit WMA additive improved the mixture’s resistance to rutting. Moreover, the TSR test conducted according to AASHTO T283 showed that there were no significant difference in the performance of the WMA and the HMA mixtures in terms of tensile strength ratio. Finally, a field survey was performed at project completion to determine whether there were any pavement distresses. Hence, the wearing course modulus and the pavement smoothness were measured to determine any variations in the performances of the WMA and HMA pavements. The survey showed there were no significant discrepancies between the two pavements (Saboundjian et al., 2011).

2.4.4. Warm Mix aging performance

A laboratory study was conducted at Clemson University to investigate the aging behavior of WMA mixtures. Samples for three mixtures: a control, Aspha-min and Sasobit were prepared and indirect tensile strength (ITS), resilient modulus and APA tests were performed to evaluate the moisture susceptibility, stiffness and rutting potential, respectively. Moreover, the HMA control samples were mixed at 150°C and then compacted at 145°C. On the other hand, the WMA samples were mixed and compacted at 120 and 115°C, respectively. In order to study the effect of aging on the characteristics of the WMA mixtures in comparison to HMA mixes, an aging procedure was performed to mimic the aging of compacted asphalt mixtures during 7-10 years of service according to AASHTO R30. Consequently, the performance of the aged mixtures was compared to the behavior of the unaged samples (Gandhi et al., 2010).

Results of the tests conducted showed that unaged mixtures incorporating Aspha-min exhibited lower modulus of resilience (M_r) compared to the control mixtures at 25 and 40°C. On the other hand, the unaged WMA exhibited higher TSR values indicating there are no serious concerns regarding moisture susceptibility. In addition, the incorporation of Sasobit, improved the rutting resistance of the mixes compared to both the aged and non aged mixes.

For the tests conducted in this study, the results of the aged samples did not exhibit significant differences compared to their unaged counterparts with the exception that the M_r values of the aged WMA mixtures were significantly higher. In summary, it was concluded that the presence of the WMA additives did not compromise the characteristics of the asphalt mixtures as it aged (Gandhi et al., 2010).

2.4.5. Moisture susceptibility of WMA mixtures

As warm mix asphalts are produced at lower production temperatures, moisture susceptibility is a concern as aggregates used in the mixtures may not be as dry as those used in conventional HMA mixes. Hence, extensive research work has focused on investigating the moisture susceptibility potential of mixtures incorporating different WMA additives. As mentioned above, no problems with the moisture susceptibility were reported in some of these studies (Gandhi et al, 2010) and (Saboundjian, et al., 2011) while other researchers observed some problems related to susceptibility to moisture (Wielinski et al. 2009).

A study was conducted to investigate moisture damage in WMA mixtures incorporating moist aggregates. Two moisture contents, 0% and 0.5%, and two WMA additives in Aspha-min and Sasobit were used this study. The performance of these mixtures was evaluated by performing indirect tensile strength test, tensile strength ratio and deformation and toughness tests. The researchers defined toughness as the area under the indirect tensile stress deformation curve with a maximum deformation of double that incurred at maximum tensile strength as illustrated in the Figure 2.4 below.

It was concluded from the experiments performed that the dry indirect tensile strength of mixtures and its deformation resistance containing moist aggregate were lower compared to other mixtures. However, the addition of hydrated lime at 1 and 2 % improved the ITS of these mixtures. Moreover, the incorporation of WMA additives did not have statistically significant differences between them in ITS values under the same testing conditions (Xiao et al., 2009).

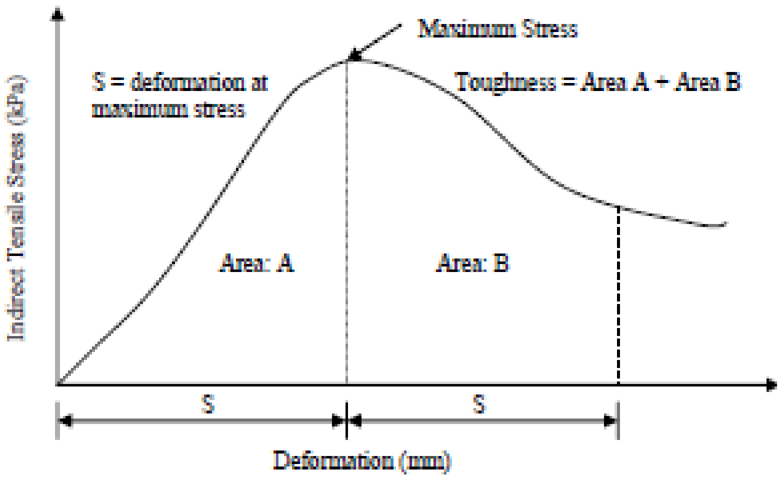


Figure 2.4 Definition of toughness (Xiao et al., 2009)

Another study was conducted to investigate the moisture susceptibility of four WMA technologies using the Hamburg wheel tracking device and bitumen bond strength (BBS) test. The setup for the bond strength test relied on a modified version of the PATTI equipment used by Youtcheff and Aurilio to assess the moisture sensitivity of the asphalt binder. Figure 2.5 below illustrates a modified version of the PATTI device. The pull-off tensile strength of the binder is calculated through measuring maximum pressure needed to apply upward pulling force on the binder at failure (Mogawer et al., 2011).

The WMA technologies used in this research were Advera, Evotherm, Sasobit and Sonne Warmix. Advera is a moisture based additive while Evotherm is a chemical additive. Sasobit and Sonne Warmix are organic wax based additives. The objective of the study is to investigate the impact of aging time and temperature on the moisture susceptibility of WMA mixtures. Moreover, the effect of adding hydrated lime and liquid anti-stripping agent on mixtures that previously failed the moisture susceptibility test was also studied (Mogawer et al., 2011).

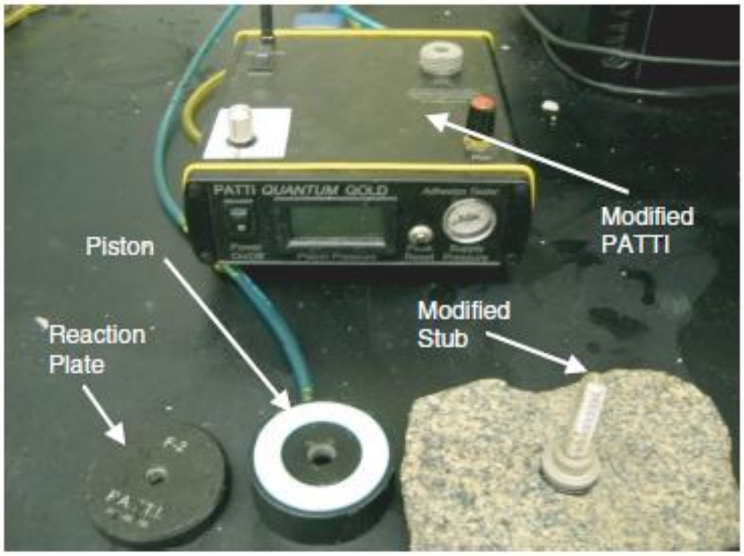


Figure 2.5 Modified Binder Bond Strength Test Setup (Mogawer et al., 2011)

Results of the Hamburg wheel-tracking device showed that moisture susceptibility of various mixtures decreased significantly upon the increase in the aging time or temperature. Moreover, the addition of anti-strip agents and hydrated lime both improved the moisture resistance of the mixtures investigated with Advera the most improved mixture by hydrated lime. The authors recommended that WMA mixtures should be cured for a minimum period of 4 hours at their relatively lower placement temperature prior to testing in the Hamburg wheel-tracking device. The bitumen bond strength test results showed that the additional stiffness of the Sasobit mixture made its binder much harder to pull away from the aggregate surface in a dry state compared to the other mixtures. Finally, it was concluded that higher stiffness binders were the most difficult to peel off the aggregates for both HMA and WMA mixtures (Mogawer et al., 2011).

2.4.6. Rheological properties of WMA binders

Researchers at Clemson University studied the rheological behavior of asphalt binders modified by two warm mix technologies: Aspha-min and Sasobit. Binders from five different sources were used in this study with Aspha-min incorporated at 0.3 % by weight of mix and Sasobit added at 1.5% by weight of binder at 120°C. The rheological attributes of the WMA binders were investigated by conducting a number of testing procedures: viscous flow, frequency sweeps, creep, creep recovery tests at 60°C and temperature sweeps ranging from 25 to 80°C (Biro et al., 2009).

The results of the experiments conducted showed that all virgin asphalts exhibited Newtonian flow behavior at 60°C. Moreover, it was reported that the incorporation of Aspha-min did not affect the flow behavior of the binders tested. On the other hand, Sasobit altered the behavior into a shear thinning behavior. Viscosity of the WMA binders increased at 60°C. For the Aspha-min binders, this observation was attributed to the filling effect of the additive powder. In contrast, the viscosity of the Sasobit binders increased due to the recrystalization of the organic hydrocarbon at mid-range temperatures that are lower than its melting point increasing the viscosity and the stiffness of the binder in the process. The addition of the WMA additives increased the stiffness of the binders in the frequency range between 0.01 to 100 Hz with the increase more evident in the binders incorporating Sasobit.

The compliance results showed that the Sasobit binders are more resistant to rutting as they exhibited lower compliance values compared to virgin binders and the Aspha-min binders (Biro et al., 2009).

Another study investigated the rheological characteristics of WMA binders that contain aged binders in terms of shear stress loading and the ensuing strain response. The long term aged binders were aged in the rolling thin film oven at 163 °C for 85 minutes and then in the pressure aging vessel at 100°C for 20 hours. The binders tested were 85% virgin binders and 15% long term aged binders with two WMA additives used in this study: Aspha-min and Sasobit. Moreover, the tested binders were tested using the dynamic shear rheometer for viscous flow, creep compliance and frequency and temperature sweeps.

Results showed that the binders tested exhibited Newtonian flow behavior with the exception of the Sasobit binder showing a shear thinning behavior. In addition, the creep compliance tests showed that the WMA aged binders illustrated a lower compliance compared to the control ones indicating a lower rutting potential. Moreover, the frequency sweep test showed that the Sasobit binders exhibit higher complex modulus and lower phase angles (Kim et al., 2011) as shown in Figure 2.6.

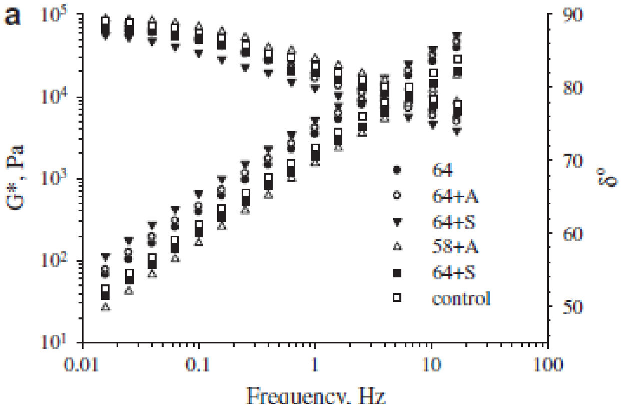


Figure 2.6 Frequency dependence curve (Kim et al., 2011)

2.4.7. Effect of WMA on polymer modified binders

Airey (2004) defined asphalt as an organic material extracted from crude oil that can be divided into two major fractional groups: the Asphaltenes which possess a considerably higher molecular mass and the maltenes which comprise fractions of bitumen with the lowest molecular weight: saturates, aromatics and resins. Polymers are used to enhance one or two aspects of the asphalt performance with the objective not to affect adversely other binder properties. Polymers used to modify bitumen performance can be classified into two broad classes known as plastomers and elastomers that differ in their mechanism of enhancement. Plastomers alters asphalt by forming strong, rigid, three dimensional networks to counter deformation in the binder induced by pavement distresses. On the other hand, elastomers resist deformation by making use of their significantly high elastic response to stretch and to regain their previous shape (Airey, 2004). Three different characteristics were identified as crucial in determining the effectiveness of any polymer as a modifier: compatibility of solvency parameters between polymer and binder, the ability of the polymer to form network structures in the binder and the thermoplastic nature of the polymer network whose ability to reform its characteristics after heating cycles is crucial for the performance of polymer modified asphalt.

Common polymer types that are used in modifying asphalts such ethylene vinyl acetate (EVA) and styrene butadiene styrene (SBS) possess the aforementioned characteristics that enable them to form networks that disintegrate by heating allowing the easy processing and handling of the modified asphalt and have the ability to reform these networks after cooling down (Airey,2004). When a polymer is mixed with bitumen, the polymer tends to absorb the aromatic oil fractions present in the maltenes and expand in volume so that at high temperatures, the binder and polymer coexist as a single phase. On the other hand, at ambient temperatures, the different molecular characteristics of the polymer and the binder form two separate phases. According to Airey (2004), the distribution and layout of these heterogeneous phases have a profound effect on the behavior of polymer modified binders.

A laboratory experimental examination of polymer modified WMA binders was conducted to study the impact of the WMA additives on the rheological properties of polymer modified binders. Two WMA additives, Aspha-min and Sasobit were incorporated into three different PG 76-22 polymer modified binders. The modified binders were studied through the performance of Superpave binder tests: rotational viscosity, dynamic shear rheometer and bending beam rheometer test procedures. It was found out that the addition of WMA additives increased the high temperature of the performance grade according to the dynamic shear rheometer test. In addition, it was observed that the Sasobit additive reduced the rotational viscosity of the binder compared to the control SBS binder while the Aspha-min additive caused an increase in viscosity. Moreover, fatigue cracking parameter, G*Sinδ at 25 °C showed that polymer modified binders with WMA additives are less resistant to fatigue cracking than control polymer modified binders. Finally, it was noted that addition of Sasobit decreased the reduction to low temperature cracking compared to other binders as reflected by the stiffness and m-value of the BBR test at -12°C (Kim et al., 2010).

CHAPTER 3: AN EVALUATION OF WARM MIX ASPHALT ADDITIVES AND RECLAIMED ASPHALT PAVEMENT (RAP) ON PERFORMANCE PROPERTIES

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A paper accepted for presentation at the *Transportation Research Board* Annual Meeting

3.1. Abstract

The consumption of natural resources and climatic changes are regarded as key factors in the deterioration and disruption of ecosystems. Hence, the asphalt paving industry is trying to address these issues over the last few years. Two features of the efforts directed towards sustainability have been in the use of warm mix asphalt technologies and reclaimed asphalt pavement (RAP) in road applications.

The performance of three commonly used warm mix technologies: Advera, Evotherm J1 and Sasobit were examined in comparison to a control HMA mixture with respect to dynamic modulus and permanent deformation (flow number). Each mixture was developed using a PG 64-22 binder and two types of aggregates: limestone or quartzite. In addition, this study will look into whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA.

Warm mix asphalt mixtures prepared at 120°C and compacted at 110°C showed no concerns regarding workability or compactability even in mixtures incorporating 30% RAP. Dynamic modulus and flow number tests were conducted to assess the stiffness and permanent deformation resistance, respectively.

The performance tests data suggested that there is a significant difference in the performance of HMA mixtures and the three WMA technologies investigated. Dynamic

modulus data of WMA mixtures were consistently lower compared to HMA, with the difference in E* values decreasing with increasing temperature. The incorporation of RAP increased the dynamic modulus of all mixtures but HMA mixture was still higher than WMA mixtures. The impact of RAP incorporation decreased as temperature increased. Finally, the rutting resistance of WMA mixtures was considerably lower compared to HMA mixes even after incorporation of RAP. Thus, WMA technologies suitability for hot regions needs to further investigated.

3.2. Introduction

The consumption of natural resources and climatic changes are regarded as key factors in the deterioration and disruption of ecosystems. Numerous industrial, agricultural and transportation activities are deemed major contributors to such decline in the natural ecosystems. Hence, the asphalt paving industry is trying to address these issues over the last few years. Two features of the efforts directed towards sustainability have been in the use of warm mix asphalt technologies and reclaimed asphalt pavement (RAP) in road applications.

3.2.1 Background

WMA refers to asphalt mixtures generally produced at temperatures in the range of 200° F to 275° F. Hot mix asphalt (HMA) is typically produced in the temperature range of 285 °F to 340 °F while cold asphalt temperatures are manufactured at ambient temperatures in the range of 68°F to 120°F (Hurley and Prowell 2006). Producing warm mix asphalt with comparable strength and durability to HMA can have extensive implications for producers and suppliers of asphalt. Using WMA technologies offers a number of advantages such as reduction in fuel consumption and plant emissions produced, in addition to longer paving seasons, reduced binder aging, and longer haul distances (D'Angelo et al., 2008). Three common WMA technologies are zeolites, waxes derived from Fischer-Tropsch, and other chemical additives.

Advera is fine powdered synthetic zeolite, a sodium silicate hydrate, with water forming approximately 20% of its weight. Zeolites are typified by their ability to gain or lose water by heating without losing their structure. When Advera is added to the mix simultaneously with the binder, its water content is released, at temperatures higher than 85°F causing the foaming of the asphalt binder which improves the workability of the binder temporarily and allows it to coat the aggregate properly at lower temperatures (PQ Corporation, 2010).

Sasobit is a wax based material produced through the Fischer-Tropsch process and is characterized by long chemical chains (40 to 115 carbon atoms). The structure and properties of Sasobit particularly its low melting point, 210°F (99°C), allow its ingredients to alter the temperature-viscosity curve of the binder causing a reduction in the viscosity of binder. Sasobit forms a lattice structure inside the asphalt binder, at temperatures below its melting point which improves the stability of asphalt mixtures (Sasol Wax, 2010).

Evotherm J1 is a chemical additive with low viscosity at room temperature that blends with liquid binder and enables asphalt mixture production at temperatures higher than 220°F (104 °C) through the improved coating and workability provided by its chemical constituents. (MeadWestvaco, 2010).

The effect of the reduced aging of WMA binders on fatigue cracking resistance of asphalt mixtures was studied by (Haggag et al., 2011). Three WMA technologies: Advera, Evotherm G3 and Sasobit, were investigated using a PG 64-22 virgin binder. Uniaxial direct tension-compression test was used in evaluating the fatigue characteristics of all mixtures. It was indicated that there was no notable difference between the HMA control mixtures and the corresponding WMA mixtures with the exception of Advera zeolite.

Reclaimed Asphalt Pavement (RAP) use has become more attractive recently due to increase in the prices of virgin asphalt binders over the last few years. The incorporation of RAP has several advantages, most notably, the preservation of natural and economic resources, thus it is considered an environmentally friendly practice (Tao et al., 2009).

Numerous studies have reported the inclusion of RAP into HMA pavements and it was reported that when adequately designed, RAP mixtures gave comparable performance to conventional mixtures. (Kim et al., 2011). However, the inclusion of a significant RAP content in HMA mixtures presents challenges in the mix design and construction stages due to its stiffer and aged binders. Hence, problems often arise due to workability and compactability problems and the scarce availability of an adequate mix design guidelines for very high RAP content mixtures.

Due to their ability to reduce the viscosity of asphalt at lower production temperatures, WMA technologies were used in preparing asphalt mixtures with high RAP content. For example, in Maryland, two demonstration projects were conducted with the investigated mixtures incorporating RAP content ranging of 25% to 45% using Sasobit (Tao et al., 2009). It was observed that Sasobit mixtures aided in achieving improved workability and compaction compared to HMA mixtures containing the same amount of RAP. A laboratory study has shown that the incorporation of Sasobit and Advera zeolite at temperatures as low as 110°C improves the workability of a 100% RAP HMA.

Thin-lift asphalt overlays incorporating high percentages of RAP, 15%, 30%, and 50%, and WMA technology, Sasobit, in mixtures prepared using PG 64-28 and PG52-34 binders. The mixtures were investigated for stiffness and workability (Mogawer, et al. 2009). Dynamic modulus data confirmed that blending had taken place between RAP binder and virgin binder. On the other hand, workability results indicated that the higher RAP contents lowered the workability of the mixtures.

3.2.2. Objective

This study aims to examine the performance of three commonly used warm mix technologies: Advera, Evotherm J1 and Sasobit in comparison to a control HMA mixture with respect to dynamic modulus, permanent deformation (flow number). In addition, this study will look into whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA.

3.3. Experimental Plan

The scope of this work comprised preparation of asphalt mixtures samples with different WMA additives and RAP combinations and test and assess the performance of these samples in comparison to corresponding control mixtures. Three different techniques of warm mix were selected for this study: Advera, a chemical powder made of synthetic zeolite by PQ Corporation, Evotherm J1, a chemically developed fluid by MeadWestvaco, Inc and Sasobit, a long chained hydrocarbon pellets procured from Sasol Wax Americas, Inc. A performance grade (PG) 64-22 binder was chosen to be used in the preparation of all three warm mixtures as it is a commonly used grade in the Midwest and other parts of the United States.

The aggregates for the HMA control mixtures were preheated at 163 °C and blended with the PG 64-22 binder at 150°C and then aged for two hours at 140 °C. All three warm mix asphalt binders were prepared based on the recommendations of the warm mix additives' manufacturers. Technique 1 involved the addition of Advera powder to the binder at a dosage of 0.25% by weight of mix. The binder was stirred to enable the dispersing of the powder in the binder. The second technique for warm mix asphalt binder preparation was conducted by adding Evotherm J1 fluid at a concentration of 0.5% or 0.6%, by weight of binder, depending on reclaimed asphalt pavement (RAP) content. The binder was stirred using a mechanical stirrer for better blending of the Evotherm J1 fluid into the binder. Technique 3 involved the addition of Sasobit particles at a concentration of 1.5% by weight of the binder. The Sasobit was dispersed into the binder by a shear mixer operating at 700 rpm for five minutes based on recommendations of previous studies (Gandhi, 2008). All warm mix asphalt additives were added to binders preheated at 120 °C. The warm mix binders were subsequently mixed with aggregates and RAP at 120 °C. This mixing temperature was selected based on previous studies in which WMA mixtures were prepared at 125 °C. Subsequently, mixtures were cured and compacted at 110 °C with the Advera mixtures cured for four hours and, stirred every hour, prior to compaction.

Two performance tests were performed on the mixtures: dynamic modulus and flow number tests. Specimens were prepared to a height of 150mm and diameter of 100 mm for the dynamic modulus and flow number tests. All specimens were compacted to 7±1% air voids using a gyratory compacter.

In addition to warm mix asphalt technology, the effect of two other variables is investigated: aggregate type and the reclaimed asphalt pavement (RAP) content. Thus, mixtures studied comprised two different aggregates with nominal maximum aggregate size of 12.5 mm: limestone, a common aggregate type used in the Midwest and quartzite which is often used in pavements that require higher skid resistance. The possibility of using high RAP content in WMA mixtures is also studied through preparing two sets of mixtures at 0% RAP and 30% RAP. Figure 3.1 lays out the eight limestone asphalt mixtures prepared for this study with eight equivalent mixtures prepared using quartzite aggregates. Thus 16 different mixtures were prepared in this work.

Dynamic modulus test is conducted in this study to capture the stress to strain relationship of warm mix asphalt under sinusoidal loading so that it can be compared to the corresponding hot mix asphalt mixture. The test is conducted, in strain controlled conditions, at various temperatures and frequencies that represent the different conditions to which an asphalt pavement is exposed. 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) on each specimen.

Flow number is a destructive test and was performed on the same specimens used in dynamic modulus testing, to measure the point at which the asphalt mixture tested reaches the tertiary flow phase, characterizing the permanent deformation properties of the asphalt mix in the process. Specimens were tested at 37 °C and at a frequency of 1 Hz with a loading time of 0.1 second and a rest period of 0.9 seconds. The test was stopped once

10,000 load cycles were reached or a strain of 10% has occurred (Witczak, et al. 2002). Flow number is determined by the minimum strain rate and the corresponding load cycle. The test was conducted using a UTM 14P machine with a temperature controlled testing chamber.

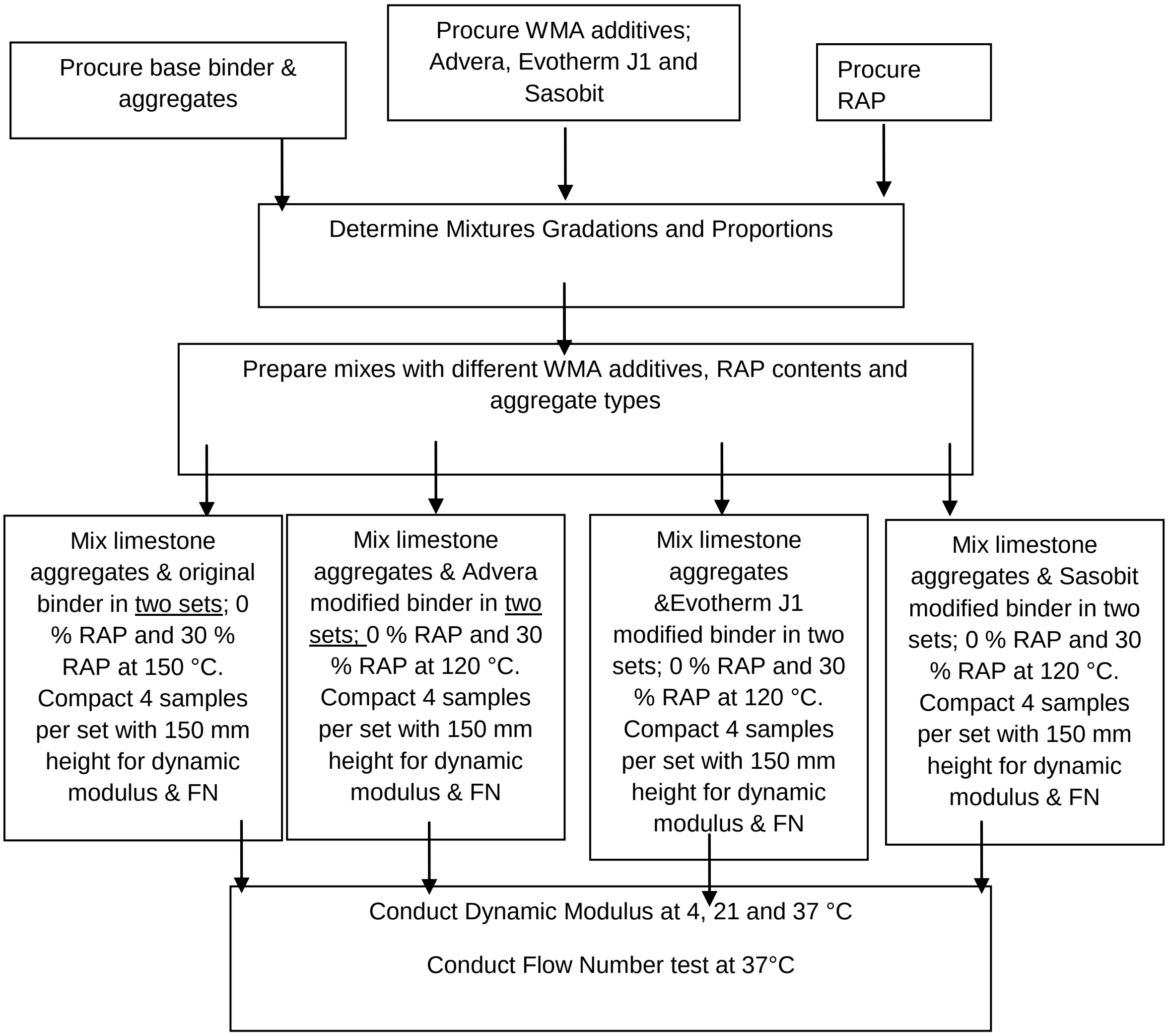

Figure 3.1 Study experimental plan

A temperature of 37 °C was chosen as it is deemed representative of rutting temperatures in the Midwest. The strain readings of the specimens were measured directly through machine actuators rather than LVDTs because of high deformations anticipated during the test.

3.4. Results and Discussion

3.4.1. Dynamic Modulus

The dynamic modulus trends for each mix are shown in Figures 3.2 through 3.5. The values used in these charts are the averages of moduli of four samples per asphalt mixture at a given frequency and temperature. The dynamic modulus is the ratio of peak stress to peak strain was calculated using the programming features in electronic spreadsheets to facilitate a time-efficient derivation of the E* values based on the recommendations in the National Cooperative Highway Research Program (NCHRP) 547 Report (Witczak, 2005). As expected, the general trend observed for all mixtures is that E* values for a given mix increases with an increase in the frequency at which the test is conducted. On the contrary, E* values for a given mixture decreased with the increase in test temperature.

For the mixtures prepared with limestone aggregate and with no RAP, the control mix E* moduli have been consistently higher than the WMA mixtures at all frequency levels at 4,21 and 37 °C as shown in Figure 3.2. The Advera mix has the highest E* values among the WMA mixtures followed by the Sasobit mixture with the Evotherm mix exhibiting the lowest E* values. It was observed from Figure 3.2 also that the difference in the E* values between different mixtures decreases with increase in temperature as the E* curves at 37°C are much closer to each other than the corresponding curves at either 4°C or 21°C. For the set of mixtures prepared with quartzite aggregate and without RAP, the trends exhibited in Figure 3.4 were similar to the abovementioned limestone set with the control mix consistently recording the highest values of E* with the Evotherm mixture displaying the lowest E* values. For mixtures incorporating a 30 % RAP content, the control mixtures prepared with limestone aggregates again has shown in Figure 3.3 the highest E* except in the 4°C setting.

A statistical analysis was conducted to further validate these observations. Hence, an analysis of variance (ANOVA) was conducted to examine which factors of variability are significant in affecting the dynamic modulus values. The factors examined are aggregate type, WMA technology, RAP content, test temperature and test frequency. Moreover, the interactions between RAP and WMA, RAP and temperature and RAP and frequency were also studied. The ANOVA was run through Minitab software package with its results shown in Table 3.1 below.

In Table 3.1, it is evident that temperature and frequency are statistically significant sources of variability as expected. Moreover, the WMA technology, RAP content and the interactions between WMA and RAP, and RAP and temperature are also significant. Tukey and Bonferroni multiple comparison techniques were used to identify which WMA technologies were statistically different from each other. Both statistical techniques gave similar results as the differences in E* moduli for control mixtures, Advera and Sasobit were statistically significant according to Bonferroni. However, the Tukey method which is considered more conservative, deemed that the variations among the E* values of all four mix types statistically significant.

In case of RAP content, the statistical significance of the difference in E* can be attributed to the higher stiffness of mixtures incorporating RAP due to aging. The mean of the E* of all mixtures with no RAP is 5.03 GPa which is lower than the corresponding mean of mixtures with 30% RAP content at 6.08 GPa.

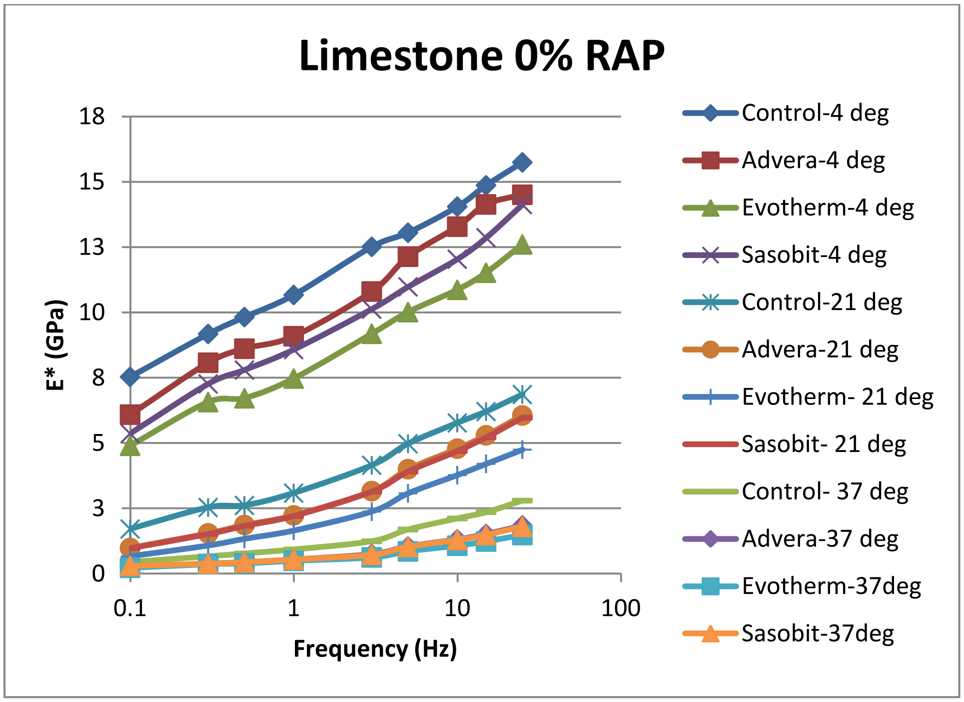

Figure 3.2 Dynamic modulus results for limestone mixtures with 0% RAP

The trends of interactions between different factors are illustrated in a Minitab output in Figure 3.6. In the interaction between WMA and RAP, it can be observed that the differences in E* in between different WMA technologies were greater at 0%RAP than the differences in between the corresponding mixtures incorporating 30% RAP however the impact of this interaction was not significant statistically. On the other hand, while samples incorporating 30% RAP consistently exhibited higher E* values than their 0%RAP counterparts, such a gap in E* values gets larger as the test temperature decreases as shown

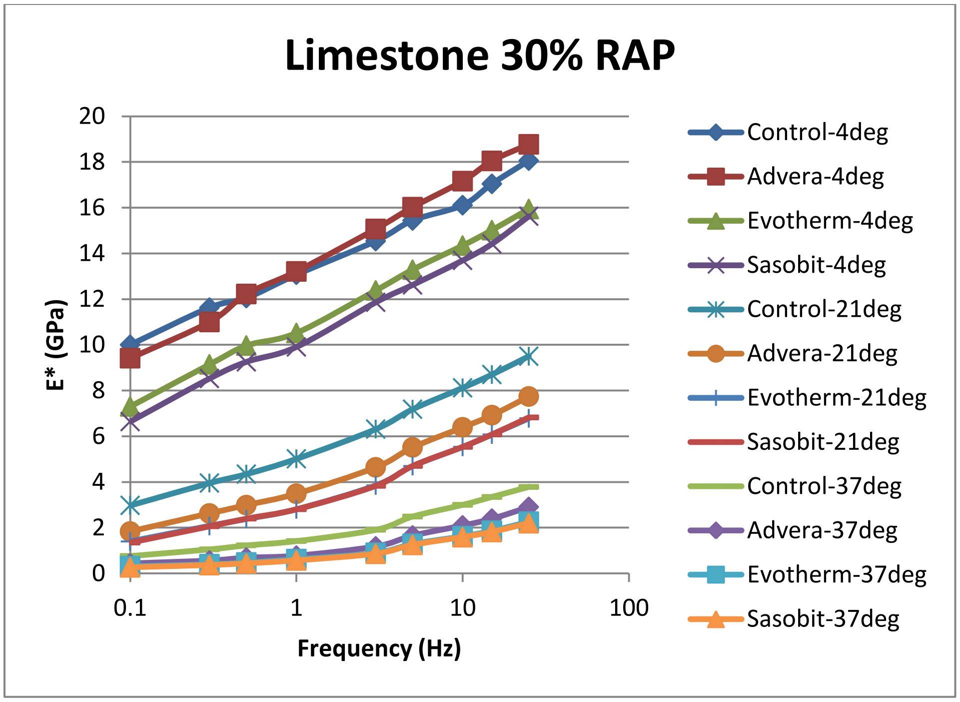

Figure 3.3 Dynamic modulus results for limestone mixtures with 30% RAP

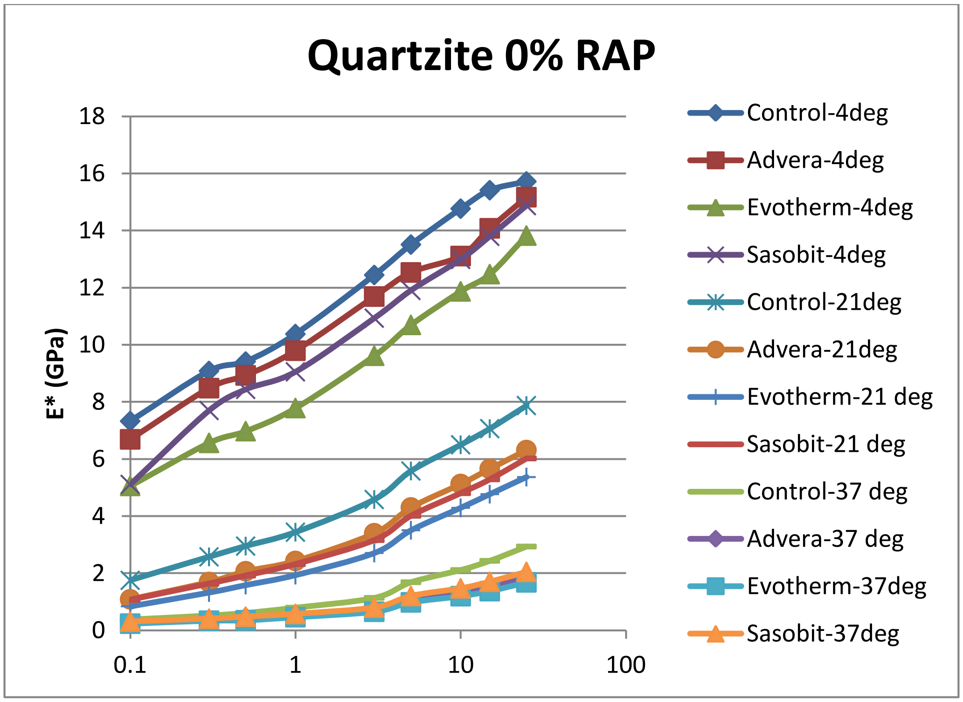

Figure 3.4 Dynamic modulus results for quartzite mixtures with 0% RAP

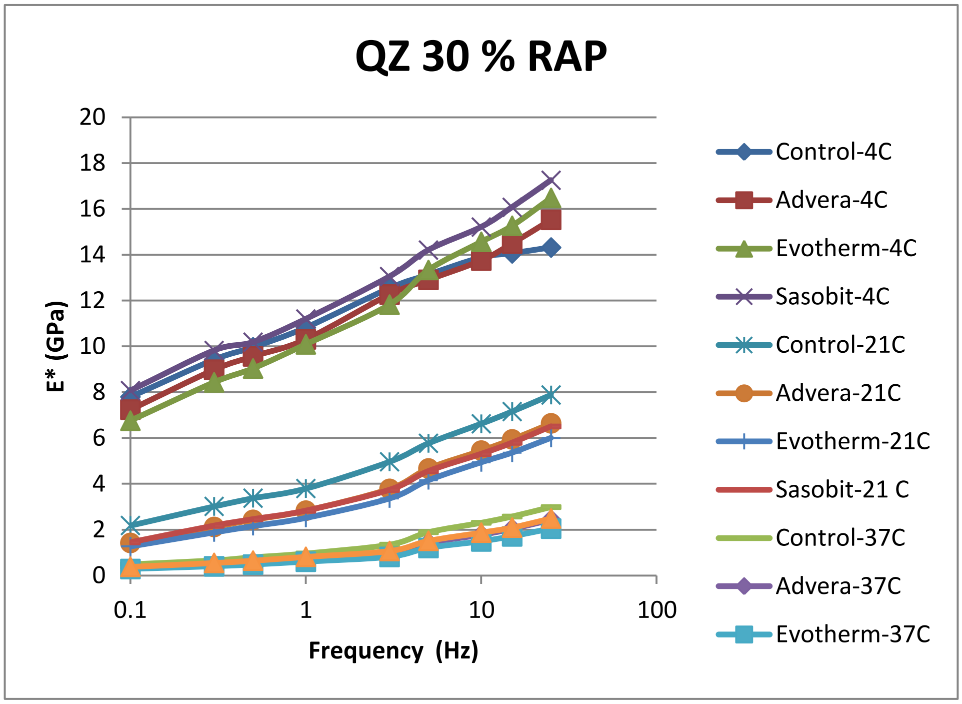

Figure 3.5 Dynamic modulus results for quartzite mixtures with 30% RAP

Table 3.1 Analysis of variance of dynamic modulus test results

Source	DF	Sum of Squares	Mean Squares	F-value	P-value	Status
Aggregate	1	3.65	3.65	3.09	0.08	Not-significant
WMA	3	131.86	43.95	37.26	0.0001	Significant
RAP	1	119.82	119.82	101.56	0.0001	Significant
Temperature	2	8308.36	4154.18	3521.09	0.0001	Significant
Frequency	8	1282.54	160.32	135.89	0.0001	Significant
WMA*RAP	3	3.97	1.32	1.12	0.340	Not-significant
RAP*Temp	2	48.50	24.25	20.55	0.0001	Significant
RAP*Freq	8	1.48	0.18	0.16	0.996	Not-significant
WMA*Temp	6	27.49	4.58	3.88	0.001	Significant
WMA*Freq	24	1.85	0.08	0.07	1.0	Not-significant
Error	373	440.07	1.18			
Total	431	10369.57				

in the figure which may explain why the interaction between RAP content and temperature was statistically significant. This was further investigated by conducting a multiple comparison among the combinations of the RAP and test temperature interactions which showed that there is a statistical difference between 0% and 30% RAP samples at a given temperature with the exception of the samples tested at 37 °C.

In investigating the interaction between the mix type and the test temperature, it was observed that at the 4 °C test temperature, there was no statistical difference between the E* values of the control and Advera samples. However, those two sets were different from the Evotherm and Sasobit sets who were similar to each other. At 21°C the control set is statistically different from all other sets, which had no significant difference relative to each other which may raise concerns regarding the performance of warm mix pavements constructed with technologies investigated in this study at mid range temperatures. In contrast, at 37 °C, the variability in the E* values was statistically insignificant in between all four groups of mixtures which comes in agreement with previous work conducted by Mohammad et al. (2008). In that study, it was observed that the difference in dynamic moduli decreased as temperature increased between conventional and Sasobit modified mixture.

3.4.2. Flow Number (FN)

This test was conducted on 64 specimens representing the 16 asphalt mixtures investigated in this study. The output of this test include cycles to failure, displacement and strain at failure in addition to displacement and strain at flow number. Figures 3.7 and 3.8 illustrate the FN values for limestone and quartzite mixtures, respectively. It can be deduced from the figures that the control mixtures exhibited higher flow numbers compared to the three WMA technologies investigated.

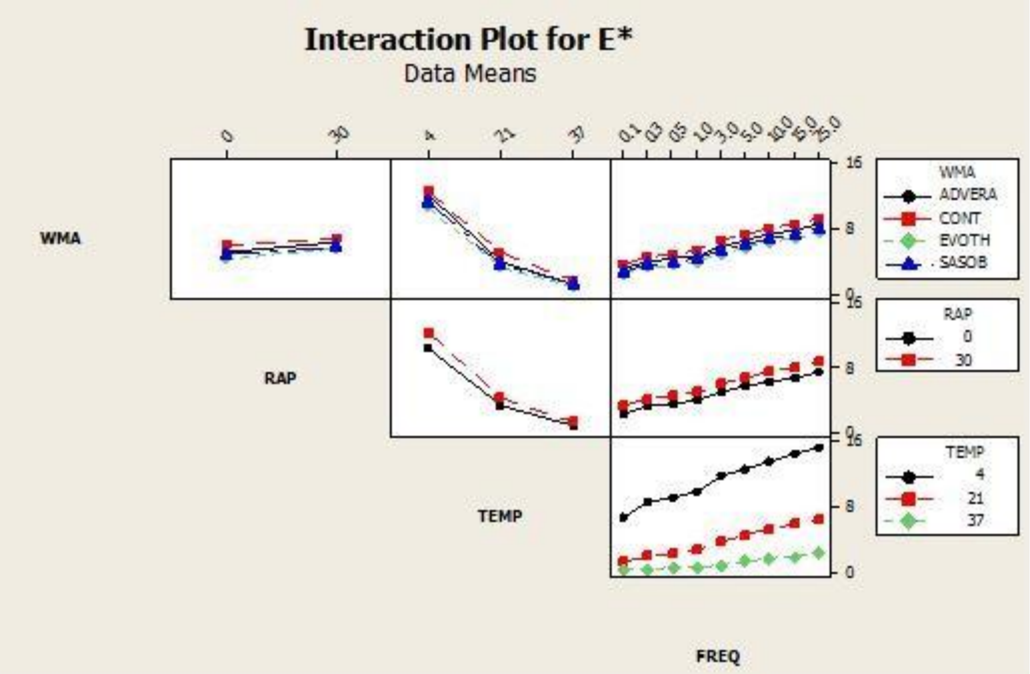

Figure 3.6 Interaction plot for dynamic modulus tests

Moreover, the incorporation of RAP increased the FN considerably, more than 3,500 for the 30% RAP control compared to less than 500 for the 0% RAP control which is expected possibly by the presence of the relatively more aged constituents of RAP that may have caused the increase in the rutting resistance. However, while the trends shown are logical, the flow number test is known for its variability which may have had an impact on the results.

A statistical analysis was performed to identify the significant factors affecting the flow number results obtained in this study. An analysis of variance (ANOVA) showed that RAP content and mix type were statistically significant factors as shown in Table 3.2. Multiple comparisons were conducted to identify the sources of variability within the significant factors. Using Tukey's pairwise comparison among levels of WMA had identified that the FN of control mixtures are statistically different from the FN of the WMA technologies studied which in turn, were statistically similar to each other. On the other hand, even though the interaction between RAP content and mix type was marginally insignificant at a p-value of 0.057, a multiple comparison was done to test the presence of statistical significance among the different combinations of this interaction. The FN of the specimens produced with HMA and incorporating 30% RAP was deemed significant compared to the other combinations.

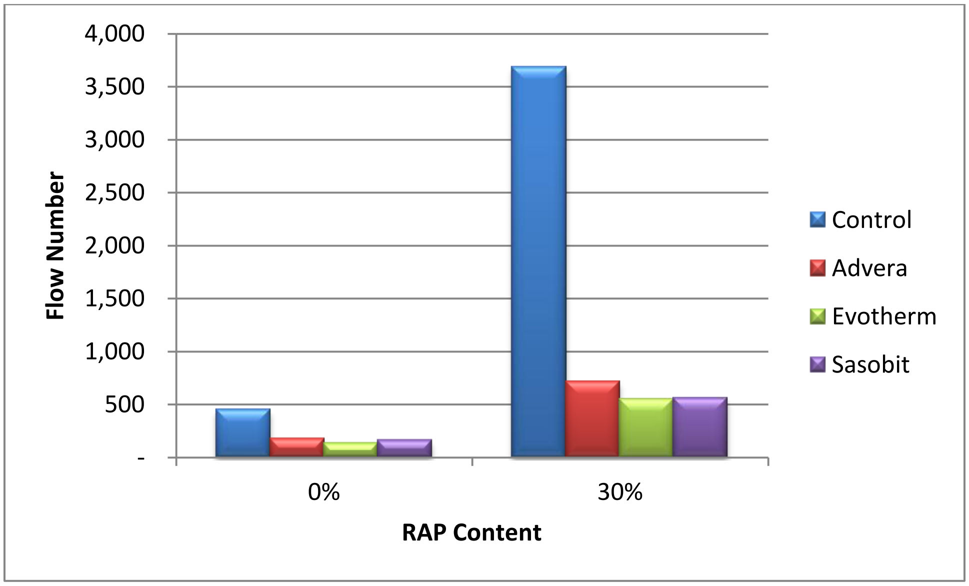

Figure 3.7 Flow number test results for limestone mixtures

This raises concern regarding WMA technologies effectiveness in producing mixtures with high RAP content with comparable rutting resistance to conventional HMA mixes.

A graphical representation of the trends of different factors investigated and their interactions with respect to FN is shown in Figure 3.9. The observations noticed through the analysis of variance and multiple comparisons are confirmed by the trends shown in the interaction plot. Moreover, it was observed that limestone mixtures incorporating 30% RAP have a greater resistance to permanent deformation than the quartzite equivalent.

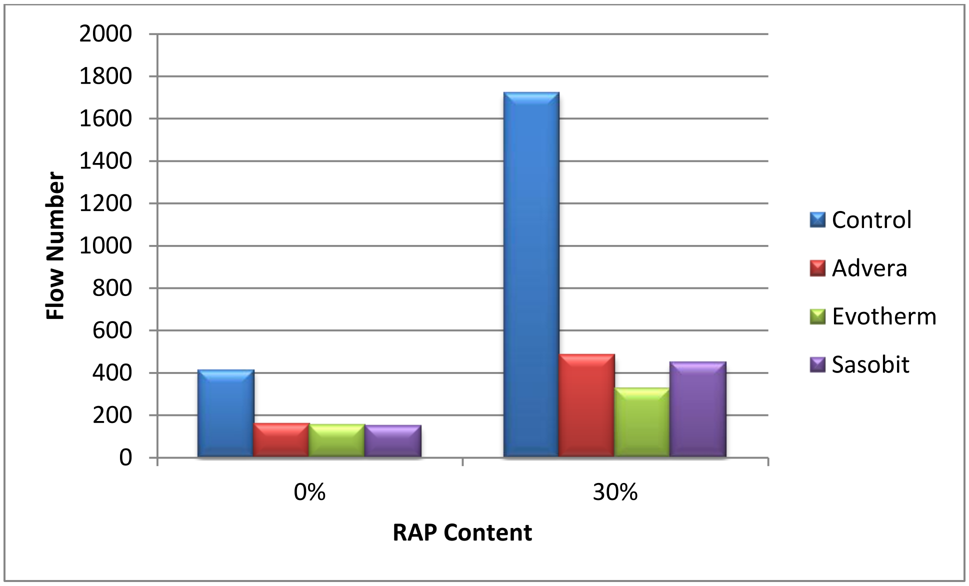

Figure 3.8 Flow number test results for quartzite mixtures

Table 3.2 Analysis of variance of flow number results

Source	DF	SS	MS	F-value	P-Value	Status
Agg	1	415783	415873	1.85	0.216	Not-significant
RAP	1	2807230	2807230	12.48	0.01	Significant
WMA	3	4581971	1527324	6.79	0.018	Significant
RAP*WMA	3	2759601	919867	4.09	0.057	Not-significant
Error	7	1574344	224906			
Total	15					

3.4.3. Discussion

This study confirmed the possibility of producing WMA mixtures at 120°C and compacted at 110°C using Advera, Evotherm and Sasobit additives. However, the dynamic moduli of WMA mixes were consistently lower than those of the HMA mix. Moreover, the difference in the E* between the HMA mixture and the WMA mixes, particularly Evotherm and Sasobit were largest at 4 °C. Hence, the use of these WMA mixtures in cold climates may be advantageous as their stiffness is lower than HMA which make them more resistant to low-temperature cracking. The fact that E* of WMA mixtures is also lower than HMA at 21°C may make them more resistant to fatigue cracking.

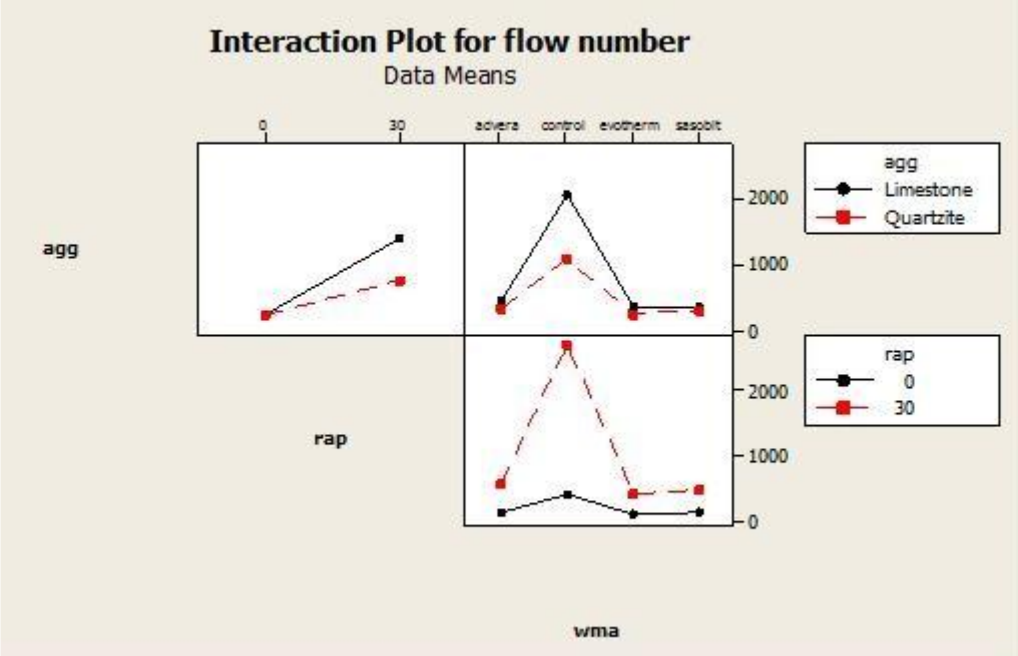

Figure 3.9 Interaction plot for flow number results

The incorporation of RAP improved the E* of various mixtures due to the increased stiffness of the aged binder present in RAP indicating that a degree of blending took place between the aged binder in RAP and the virgin binder. On the other hand, the impact of RAP incorporation on the increase of E* decreased as test temperature increased.

HMA specimens showed a greater resistance to permanent deformation compared to the specimens of WMA additives investigated in this study which comes in agreement with the relatively lower dynamic moduli of WMA mixtures at 37°C. RAP also has an appreciable impact on the mixtures resistance to permanent deformation which increased considerably through the incorporation of RAP. However, the impact of RAP use was more appreciable in the HMA samples than WMA additives' samples which raise concerns regarding the rutting of mixtures incorporating WMA. The influence of RAP inclusion was higher in mixtures incorporating limestone than those incorporating quartzite. Additional work examining the low temperature fracture performance of the tested combinations provided in this paper needs to be done to fully understand the performance expectations of the WMA technologies as compared to typical HMA mixtures.

3.5. Conclusions

Some conclusions that can be deduced from this work include:

- Preparing WMA asphalt mixtures using Advera or Evotherm J1 or Sasobit at 120°C is feasible with no concerns regarding workability or compactability even in mixtures where 30% RAP was incorporated.
- The findings of this study suggest that there is a difference in the performance of HMA mixtures and the three WMA technologies investigated.
- The dynamic moduli of WMA mixtures were consistently lower compared to the corresponding HMA mixture at all test temperatures with Evotherm recording lowest stiffness.
- The differences in E* values between control mixture and other WMA mixtures decreased with increasing test temperatures.
- The fact that E* of WMA was significantly lower, at low and mid range temperatures, makes WMA mixes more suitable for use in cold climates due to its lower stiffness at lower temperatures. Hence, the pavement's resistance to low temperature and fatigue cracking would be higher.

- Incorporation of RAP increased the dynamic moduli of all mixtures with control RAP mixtures still exhibiting higher E* than WMA RAP mixes.
- The effect of RAP incorporation on the increase in dynamic moduli values, decreased as test temperatures increased.
- The rutting resistance of WMA mixtures is a concern as it was considerably lower compared to HMA mixes based on flow number test.
- While RAP inclusion improved the flow number of WMA mixtures, its performance was still much lower compared to HMA mixtures. Thus, the suitability of the studied WMA technologies for application in hot regions needs to be further studied.

3.6. Acknowledgments

The authors appreciate the assistance of Iowa DOT in this investigation of WMA and help of John Hinrichson with laboratory testing and Scott Schram at the Iowa DOT. Special thanks also go to Annette Smith of PQ Corporation.

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CHAPTER 4: PERFORMANCE EVALUATION OF LAB WARM MIX ASPHALT MIXES INCORPORATING RAP USING MEPDG

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A paper submitted to the *Construction Buildings and Materials Journal*

4.1. Abstract

The consumption of natural resources and climatic changes are regarded as key factors in the deterioration and disruption of ecosystems. Hence, the asphalt paving industry is trying to address these issues over the last few years. Two features of the efforts directed towards sustainability have been in the use of warm mix asphalt technologies and reclaimed asphalt pavement (RAP) in road applications.

While the emergence of WMA technologies has increased the drive towards using higher RAP percentages into asphalt pavements, national and state agencies efforts are hindered by the scarcity of information available on the field performance of mixtures prepared with WMA and high RAP content. Hence, until the development of a well-documented database of the performance of field mixtures containing high RAP and WMA, the mechanistic-empirical pavement design guide (MEPDG) may serve as a verification tool by estimating pavement performance through models that use measured material properties, climatic and traffic data.

Asphalt mixtures samples with three different WMA additives and RAP (0% and 30%) combinations were prepared and tested for dynamic modulus and flow number tests to assess its moisture susceptibility, resistance to fatigue and rutting. MEPDG design runs were performed to assess the performance of lab produced asphalt mixtures incorporating WMA and RAP and compare it to the performance of corresponding control mixtures.

Dynamic moduli and flow number results of mixtures incorporating WMA were consistently lower than those of corresponding HMA mixtures. While the inclusion of RAP improved the flow number of WMA mixtures, its performance was still much lower compared to the control HMA mixtures. MEPDG output agreed with laboratory test results specifically for rutting prediction and terminal IRI values. Finally, statistical analysis of variance indicated that the Evotherm™ mixtures performance was generally different from the control mixtures regardless of type of aggregates used.

Keywords: warm mix asphalt; reclaimed asphalt pavements; mechanistic-empirical pavement design guide; dynamic modulus; flow number

4.2. Introduction

With the prices of crude oil rising, quality aggregate sources scarce along with calls for adopting greener and more sustainable approaches in construction activities, the urge to reduce the consumption of energy in asphalt production is significantly increasing for economic and environmental merits. Hence, the use of reclaimed asphalt pavements (RAP) and warm mix asphalts (WMA) have increased dramatically in recent years due to potential cost savings and possible lower impact on the environment (McDaniel et al., 2001) and (Bonaquist, 2011).

WMA refers to asphalt mixtures generally produced at temperatures in the range of 200° F to 275° F while hot mix asphalt (HMA) is typically produced in the temperature range of 285 °F to 340 °F (Hurley et al., 2006). WMA additives introduced to the mix allow the production and compaction at significantly lower temperatures by lowering the binder viscosity which in turn improves the mixture workability. Three common WMA technologies are zeolites, waxes derived from Fischer-Tropsch, and other chemical additives. Hence, producing warm mix asphalt with comparable strength and durability to HMA can have extensive implications for producers and suppliers of asphalt. Using WMA technologies offers a number of advantages such as reduction in fuel consumption and plant emissions produced as the plant temperature required to produce the mix is significantly lower, in addition to longer paving seasons, reduced binder aging, and longer haul distances (D'Angelo et al., 2008). The lower production temperatures of WMA compared to HMA can allow for the incorporation of higher percentages of RAP as the risk of RAP being further aged and stiffened is evaded(Copeland et al., 2010).

As a result, the emergence of WMA technologies has increased the drive towards using higher RAP percentages into asphalt pavements. Copeland et al. reported that by 2010, only eleven states have experience working with WMA incorporating high RAP which reflects the scarcity of information available on the performance and experiences of State Departments of Transportation (DOTs) working with high RAP and WMA mixtures.

Until the development of a well-documented database of the performance of field mixtures containing high RAP and WMA, the mechanistic-empirical pavement design guide (MEPDG) may serve as a verification tool by estimating pavement performance through models that use measured material properties, climatic and traffic data.

4.2.1. Mechanistic-Empirical Pavement Design Guide

The MEPDG adopts a hierarchical approach in which the designer can use three different levels of analysis of the studied pavement structure based on the information available. The hierarchical approach is applied in terms of three levels of inputs in which traffic, materials and environmental/climatic information are fed to the software. Level 1 inputs offer the highest level of accuracy and hence its material inputs require laboratory or field testing such as dynamic modulus test of HMA specimens and it needs more time and resources than other levels of analysis (NCHRP, 2004). Level 2 offers an intermediary level of accuracy and its inputs are acquired either from an organization's database, correlations or through a limited testing plan. For example, dynamic modulus can be estimated from aggregates, binder and mix properties whereas traffic volume and classification data are site specific. Level 3 inputs provide the lowest accuracy level and it is used when there is a real lack of data or the least consequences of early failures.

4.2.2. Objective

The main objective of this work was to evaluate the predicted performance of asphalt mixtures incorporating three warm mix additives and RAP using the MEPDG and compare it to a control mixture. The performance of the pavement sections was assessed based on the amount of alligator cracking and permanent deformation predicted by the software.

4.3. Experimental Plan

The scope of this work comprised preparation of asphalt mixtures samples with different WMA additives and RAP (0% and 30%) combinations and to test and assess the performance of these mixtures in comparison to corresponding control mixtures. Three different techniques of warm mix were selected for this study: Advera, a chemical powder made of synthetic zeolite by PQ Corporation, Evotherm™ J1, a chemically developed fluid by MeadWestvaco, Inc and Sasobit, a long chained hydrocarbon pellet procured from Sasol Wax Americas, Inc. A performance grade (PG) 64-22 binder was chosen to be used in the preparation of all three warm mixtures as it is a commonly used grade in the Midwest and other parts of the United States.

The aggregates for the HMA control mixtures were preheated at 163 °C and blended with the PG 64-22 binder at 150°C and then aged for two hours at 140 °C. All three warm mix asphalt binders were prepared based on the recommendations of the warm mix additives' manufacturers. Technique 1 involved the addition of Advera powder to the binder at a dosage of 0.25% by weight of mix. The binder was stirred to enable the dispersing of the powder in the binder. The second technique for warm mix asphalt binder preparation was conducted by adding Evotherm™ J1 fluid at a concentration of 0.5% or 0.6%, by weight of binder, depending on RAP content. For RAP content lower than 25%, a 0.5% of Evotherm™ is recommended while a dosage of 0.6% is recommended for RAP contents higher than 25%. The binder was stirred using a mechanical stirrer for better blending of the Evotherm™ J1 fluid into the binder. Technique 3 involved the addition of Sasobit particles at a concentration of 1.5% by weight of the binder. The Sasobit was dispersed into the binder by a shear mixer operating at 700 rpm for five minutes based on recommendations of previous studies (Gandhi 2008). All warm mix asphalt additives were added to binders preheated at 120 °C. The warm mix binders were subsequently mixed with aggregates and RAP at 120 °C. This mixing temperature was selected based on previous studies in which WMA mixtures were prepared at 125 °C. Subsequently, mixtures were cured and compacted at 110 °C with the Advera mixtures cured for four hours and, stirred every hour, prior to compaction.

Three performance tests were performed on the mixtures: indirect tensile strength, dynamic modulus and flow number tests to assess the moisture susceptibility, cracking and rutting resistance, respectively. Specimens were prepared to a height of 150mm and diameter of 100 mm for the dynamic modulus and flow number tests. All specimens were compacted to 7±1% air voids using a gyratory compacter.

Simulations Using MEPDG

The second part of the analysis consists of MEPDG design runs performed to assess the performance of lab produced asphalt mixtures incorporating WMA and RAP and compare it to the performance of a corresponding control mix. Version 1.0 of the MEPDG software was used to address the objectives of this research.

Design Inputs

An input file was created and used as a template for the runs conducted with the design life of the pavement section chosen to be 20 years. The construction of the pavement was selected to take place in summer months with the opening of the pavement taking place at end of September. All design input were kept constant except for traffic level, AC layer properties, and pavement structure depending on the traffic level.

Traffic

Three levels of traffic volume were studied for different roads, low, medium and high. Table 4.1 shows the parameters used for each traffic level. The average annual daily truck traffic (AADTT) and the traffic growth values were assumed for each traffic level with the rest of parameters left at their default level 3 values.

Table 4.1 Input data at different traffic volume levels

Parameter	Low Traffic	Medium Traffic	High Traffic
AADTT	80	696	2000
Traffic Growth	2%	1.2%	1.37%

Climate

For all MEPDG runs, the default climatic database of Des Moines, Iowa was used in this study given its central location within the State of Iowa and the Midwest of the United States.

AC Layer

For each mix assessed, dynamic modulus values of tests conducted in the lab at five temperatures and 6 frequencies are input into the software. Table 4.2 illustrates an example of dynamic modulus data entered into an Evotherm ™ –Quartzite 0% RAP mixture. Moreover, complex modulus and phase angle of binder are entered into the program to fully characterize the binder used.

Table 4.2 Asphalt mix input data for Evotherm Quartzite 0% RAP mixture

Temperature °F	Mixture E* (psi)					
	0.1	**1**	**5**	**10**	**15**	**25**
10	1425181	1867421	2090010	2164666	2203047	2246313
40	675648.2	1081994	1493751	1651940	1746973	1950005
70	115140	276549	515156	629713	701857	797180
100	36368	62182	127359	160710	185798	228259
130	17892	22833	29961	34785	38333	43781

The properties of the crushed stone base and the subgrade were left at the third level of detail with resilient modulus values of 30,000 and 11,500 psi, respectively.

Structure

The asphalt pavement structure used comprised three structural layers: the asphalt cement (AC) layer, a crushed stone base layer and subgrade. Only the thickness of the AC layer varied with the increase in the traffic volume. Table 4.3 shows the thicknesses of the different of the pavement structures used for different traffic volumes.

Table 4.3 Pavement structure cross-sections for different traffic volumes

Layer	Low Volume Traffic	Medium Volume Traffic	High Volume Traffic
AC Layer	6’’ PG 64-22	10’’ PG 64-22	15’’ PG 64-22
Base	4’’ Crushed Stone	4’’ Crushed Stone	4’’ Crushed Stone
Subgrade	A-7-6	A-7-6	A-7-6

4.4. Results and Analysis

4.4.1. Dynamic Modulus

The dynamic modulus test data output were used to construct master curves of the mixtures tested. Figure 4.1 below illustrates the master curves of the control, Advera, Evotherm™ and Sasobit, respectively, asphalt mixtures prepared with limestone aggregates and were not subjected to moisture conditioning (NMC). It can be observed that control mixture displayed higher dynamic modulus values, E* compared to WMA mixtures with Evotherm™ exhibiting the lowest E*.

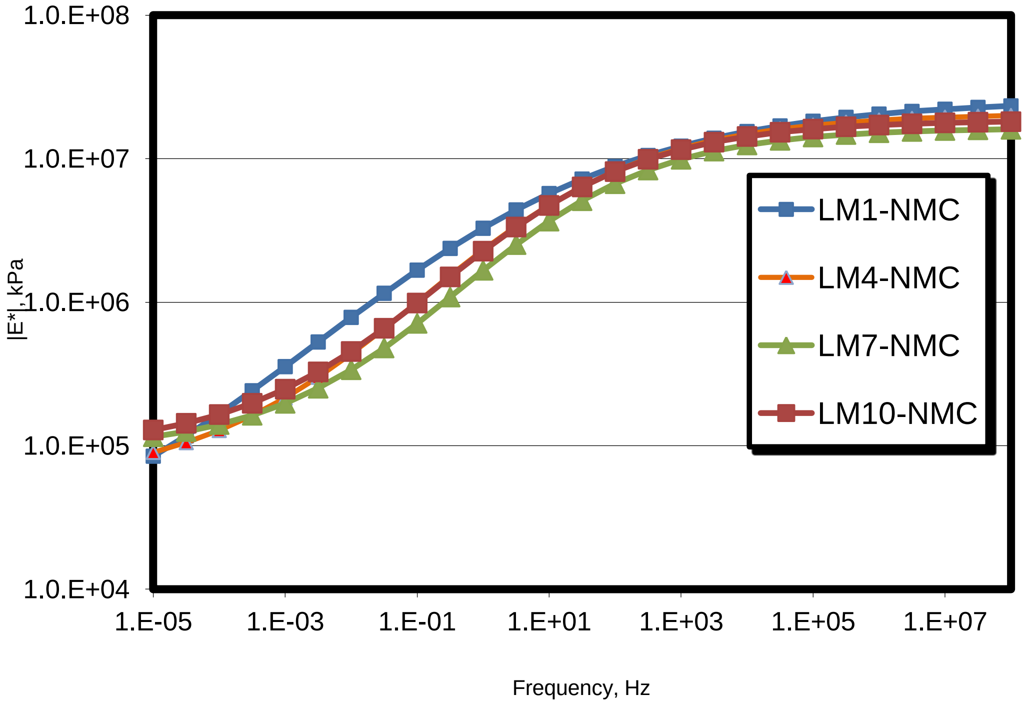
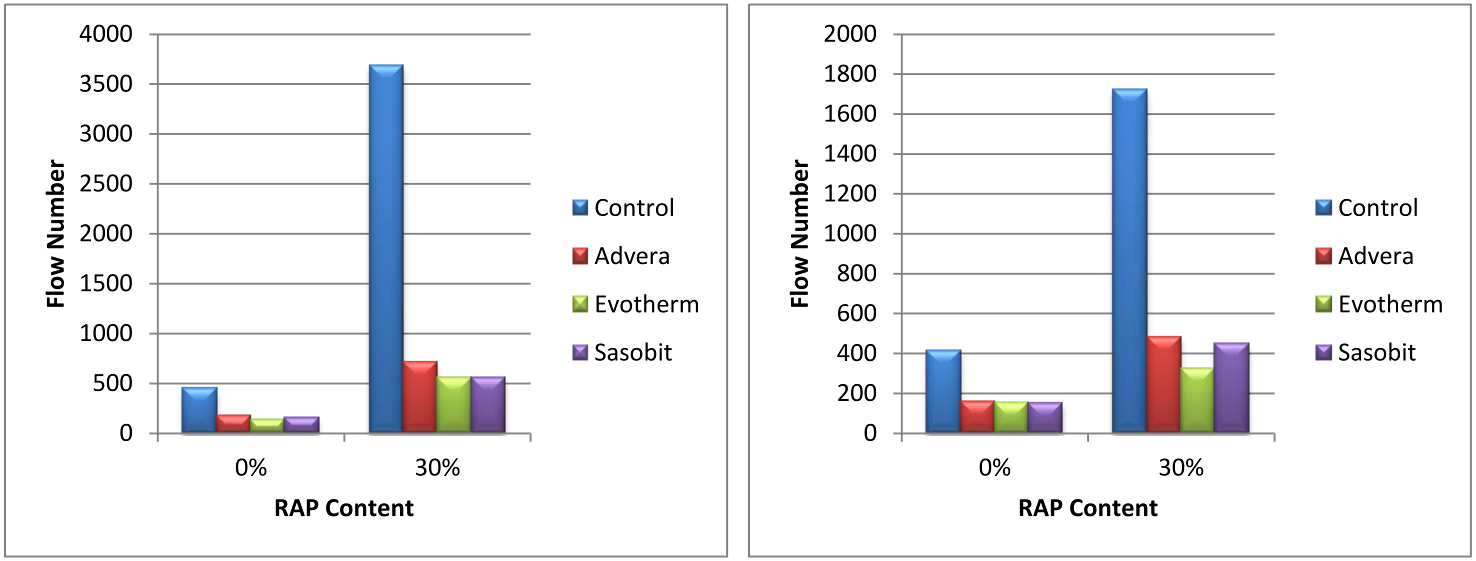


Figure 4.1 Master curves of non-moistured limestone mixtures without RAP

4.4.2. Repeated Load Permanent Deformation Test

The main outcome of this test is the flow number, which is the cycle number where the tertiary flow begins according to NCHRP Report 465(Witczak et al. 2002). Figure 4.2 below illustrates flow number for the asphalt mixtures incorporating different WMA additives, RAP content and aggregates. Control mixtures consistently displayed higher flow number compared to WMA incorporating mixes. Moreover, control mixtures with 30 % RAP exhibited significantly higher flow numbers exceeding 3500 and 1600 for limestone and quartzite mixtures respectively.



a)

b)

Figure 4.2 Flow Number results for (a) Limestone mixtures (b) Quartzite mix

The superior flow number of control mixtures compared to WMA mixtures raises concern regarding the rutting resistance of WMA technologies. An explanation for such an observation could be the reduced aging experienced by WMA mixtures due to their relatively lower production and compaction temperatures. The significant superiority of control mixtures incorporating 30 % RAP could be attributed to the higher aging of the mixtures due to higher production and compaction temperatures and the presence of high percentage of RAP. However, it is important to note that the flow number test is known for its variability. Hence, conclusions reached from its results should be used with caution particularly when trying to differentiate the different WMA technologies used in this study.

4.4.3. MEPDG Runs Output

The design guide relies on input data concerning traffic, climate, structure and material properties of the investigated road section to estimate the primary distresses resulting from the accumulation of damage in the pavement structure during a specific period of time. Typical distresses estimated by the design guide are permanent deformation in all rut-susceptible layers, alligator (fatigue) cracking and the International Roughness Index (IRI) as an indicator of pavement smoothness and overall quality.

The MEPDG runs were conducted at a reliability of 90 percent meaning that 90 out of 100 designed projects would exhibit values lower than the maximum limit criteria for a given distress.

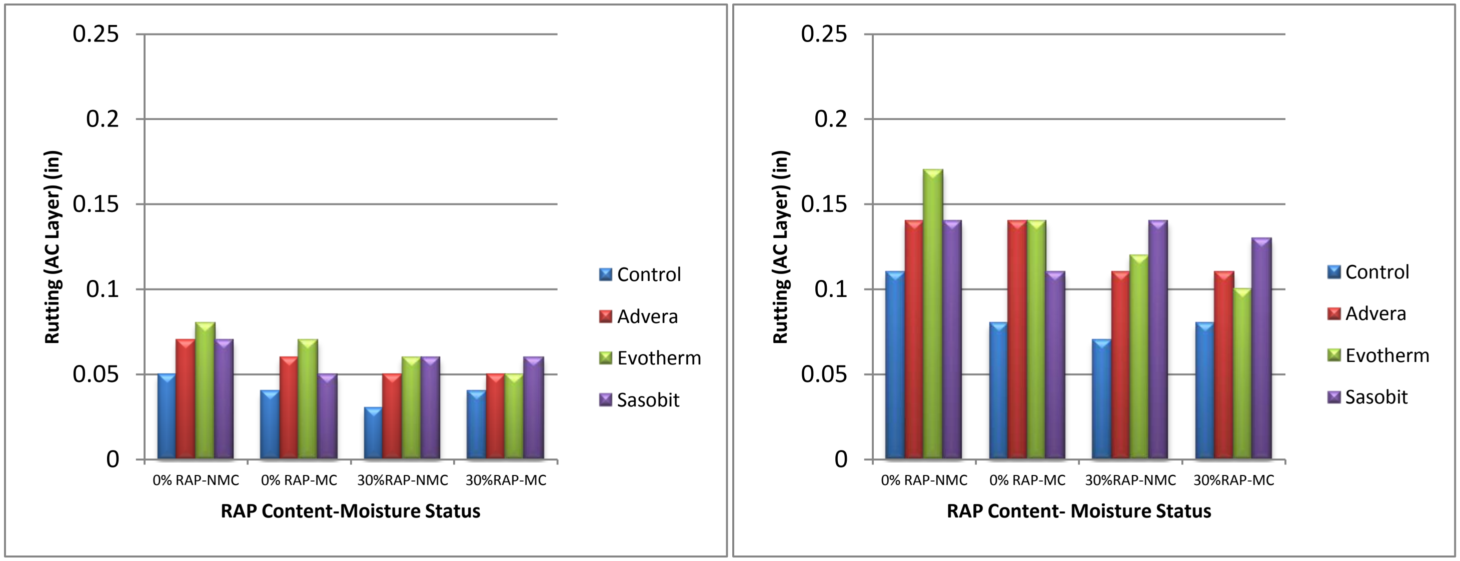
Rutting in AC Layer

The estimated permanent deformation taking place in the asphalt concrete layer is shown below in Figures 4.3 and 4.4 for the limestone and quartzite mixtures, respectively for different levels of traffic. The control limestone mixtures exhibited the lowest rut depth regardless of RAP content, moisture conditioning and traffic level. The limestone mixtures with 0 percent RAP incorporating Sasobit, displayed slightly better resistance to rutting in the asphalt layer compared to other corresponding WMA mixtures. On the other hand, Sasobit limestone mixtures registered the highest amount of rutting among mixtures with 30 percent RAP content.

The control mixtures prepared with the quartzite aggregates showed the best resistance to rutting in the asphalt layer as displayed in Figure 4.4 for the medium and high traffic levels. Sasobit mixtures exhibited lower rutting depths than Advera and Evotherm™ mixtures. It is important to note all limestone and quartzite mixtures had predicted rutting depths lower than maximum limit at 90 percent reliability which is set at 0.2.

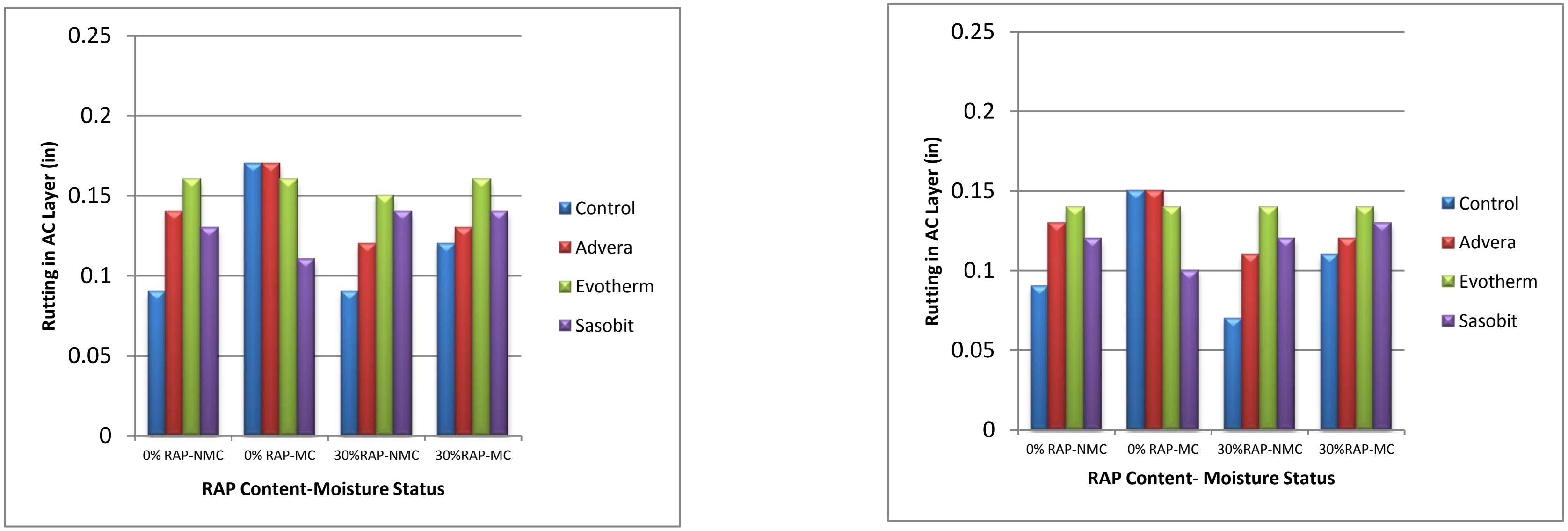
AC Layer Rutting vs. Flow Number

The estimated asphalt layer rut depths for various mixtures were charted against their corresponding flow number test results as shown in Figure 4.5 below for the low traffic level. It can be deduced from the figure that there is good correlation between the flow number and the rut depth estimated in the asphalt layer with an R^2 equal to 0.71. Hence, the results using the design guide seem reasonable.



(a) Low traffic **(b) Medium traffic**

Figure 4.3 Rutting (AC layer) in limestone pavements



(a) Medium traffic

(b) High traffic

Figure 4.4 Rutting (AC layer) in quartzite pavements

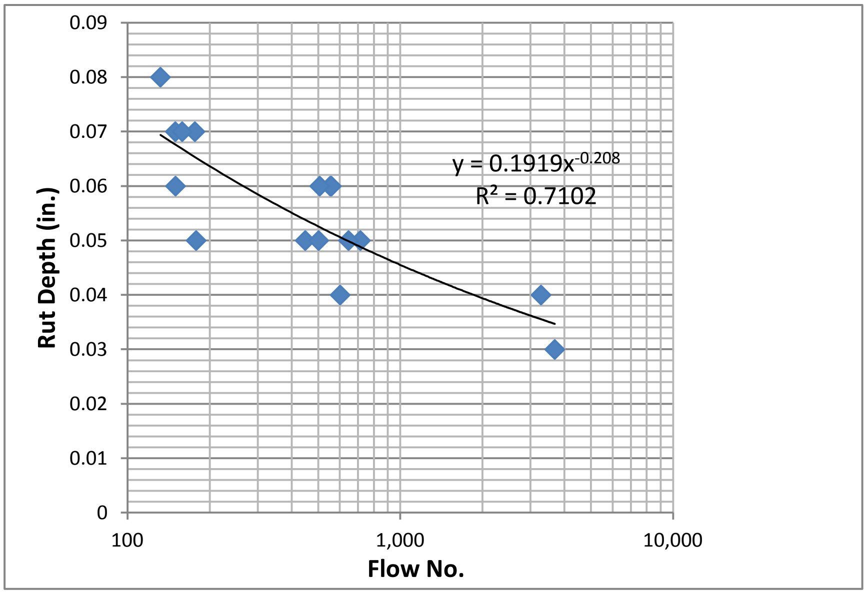
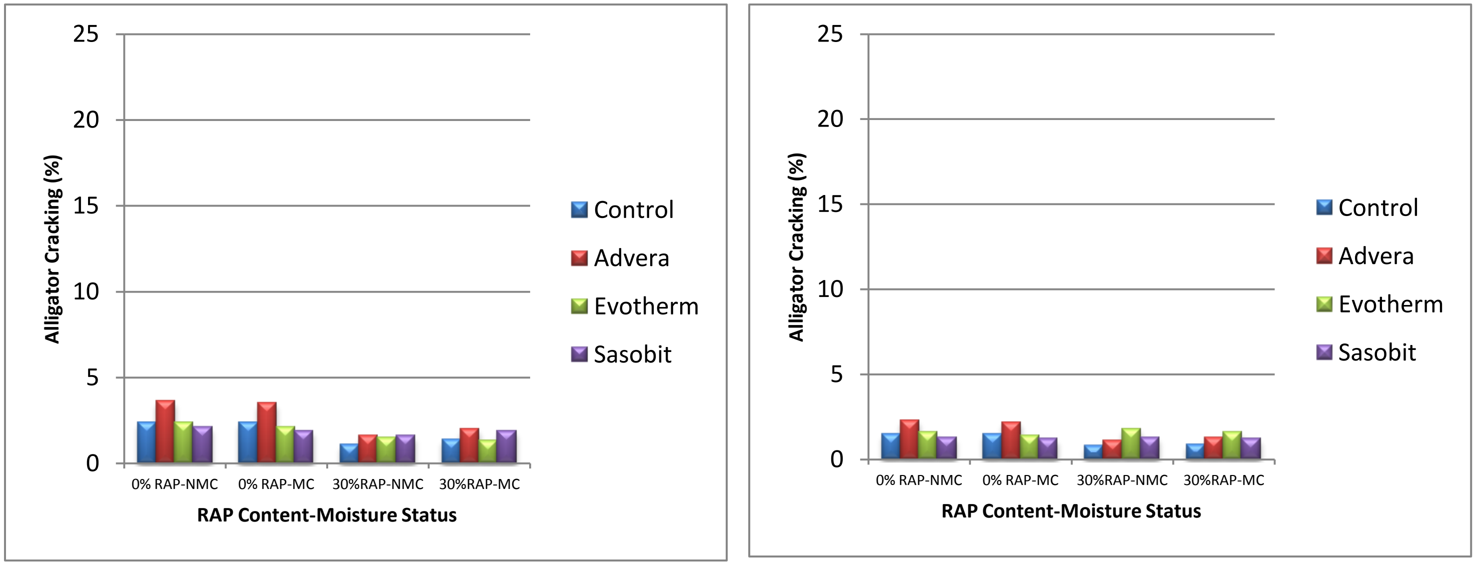


Figure 4.5 AC layer rutting vs. flow no. at low traffic level

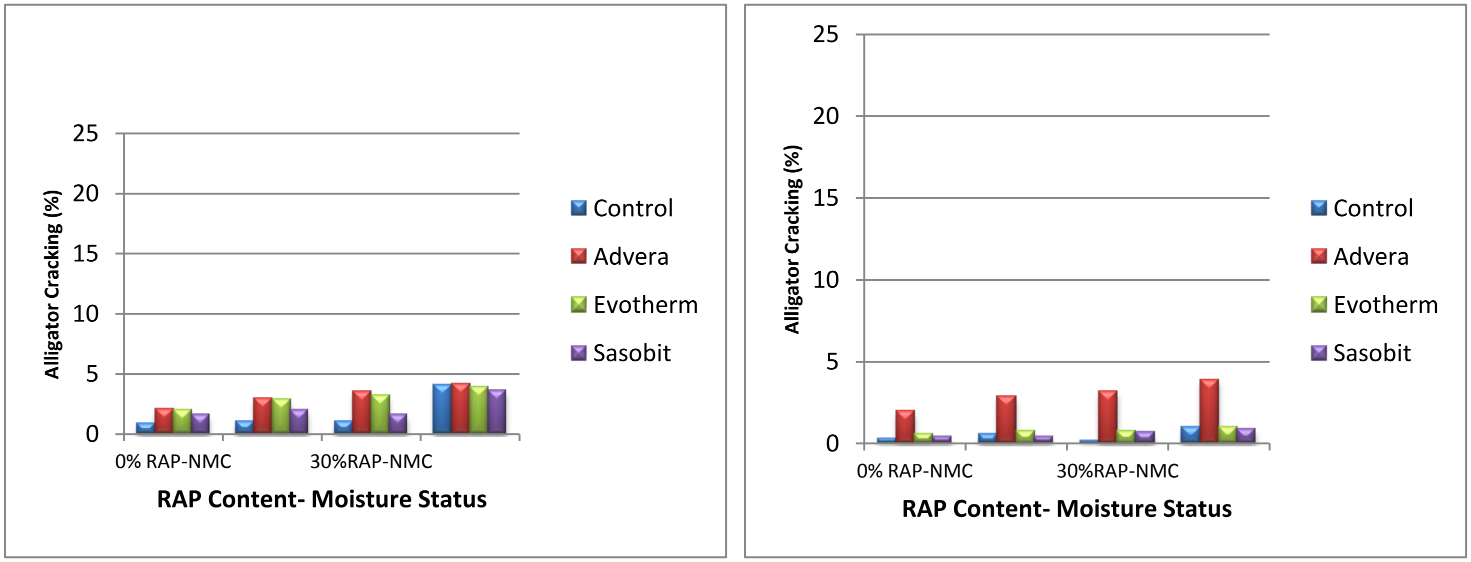
Alligator Cracking

Bottom-up fatigue cracking is one of the critical distresses in flexible pavements as it allows water infiltration into lower pavement layers, increasing the likelihood of pavement structural failure. Figures 4.6 and 4.7 illustrate the estimated percentage of alligator cracking in the limestone and quartzite mixtures, respectively. All investigated mixtures registered a significantly lower alligator cracking (lower than 5 percent) than the maximum acceptable criterion of 25 percent. However, the Advera mixtures showed a relatively higher amount of cracking compared to control and other WMA mixtures.



(a)Low traffic **(b) Medium traffic**

Figure 4.6 Alligator cracking (%) in limestone pavements



(a)Low traffic **(b) High traffic**

Figure 4.7 Alligator cracking (%) in quartzite pavements

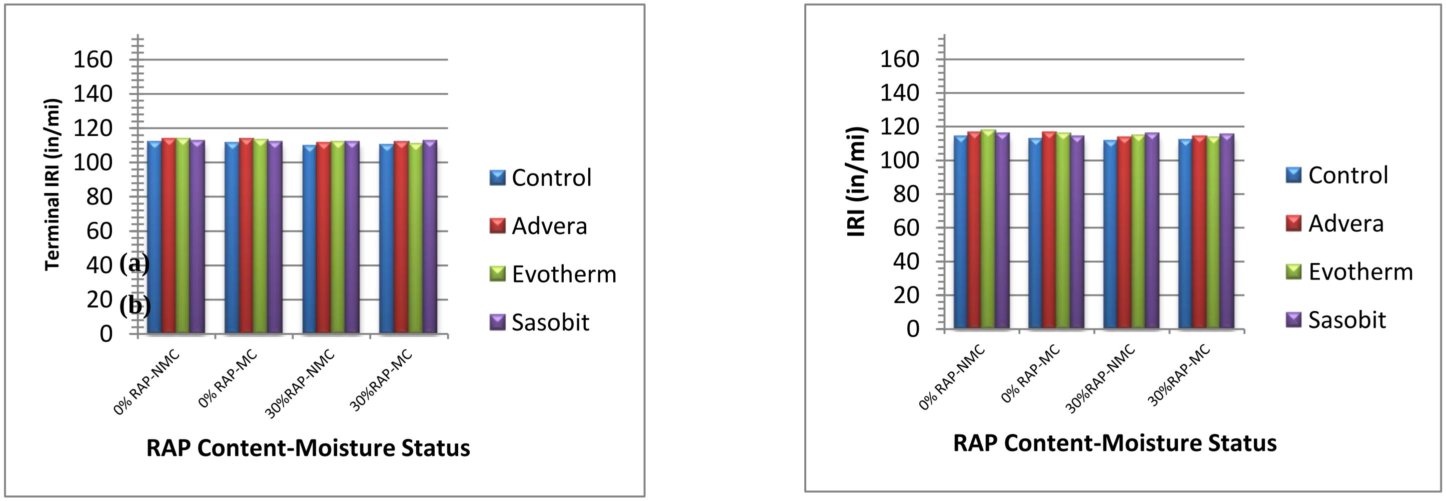
Terminal IRI

The international roughness index (IRI) is an indicator of the overall quality of the pavement and all distresses contributing to pavement condition. At a reliability of 90 percent, the maximum acceptable IRI limit is 172 in/mile. Figure 4.8 below shows the terminal IRI values for different limestone mixtures at various traffic levels. From this figure, it is clear that the IRI lies in between 100 and 120 in/mile for all the limestone mixtures. Hence, it can be deduced from these observations that the incorporation of WMA additives and also the addition of RAP did not affect the overall quality of the pavements significantly. Another possibility, the differences between various mixtures was not fully captured by modeling techniques used in estimating the IRI in the design guide.

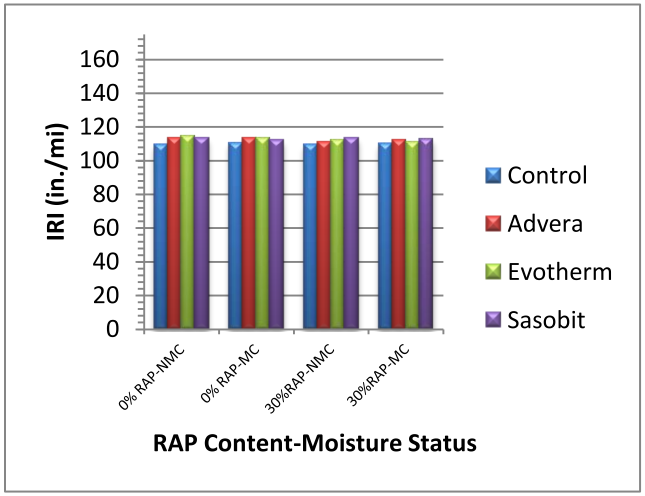
4.4.4 Statistical Analysis

As the variability in the quantitative values of distresses estimated using the design guide may not be too significant to be observed easily, especially given most of the values are well below the maximum design reliability criteria, conducting a statistical analysis is a feasible means to quantify the variability and identify its sources. A two-way Analysis of

Variance (ANOVA) was conducted to identify the significant factors affecting the predicted performance of the pavement. Moreover, in the case of significant factors, the Tukey multiple comparison technique was used to identify which levels of significant factors display variability. Table 4.4 below lists the outcome of ANOVA conducted to identify



(a)Low traffic **(b) Medium traffic**



(c) High traffic

Figure 4.8 Terminal IRI in limestone pavements

whether the incorporation of WMA additives and the addition of RAP affected pavement distresses estimated at 95 percent reliability.

Table 4.4 Results of two-way ANOVA of factors affecting pavement distresses

Source of Variation	Alligator Cracking	Rutting in AC Layer	Rutting in Total Pavement	Terminal IRI
Limestone	**Significant**			
WMA	No	Yes	Yes	Yes
RAP (%)	Yes	No	Yes	Yes
Interaction	No	No	No	No
Quartzite	**Significant**			
WMA	No	No	Yes	Yes
RAP(%)	Yes	No	No	No
Interaction	No	No	No	No

In Table 4.4 above, the RAP content was a significant source of variability in the percentage of alligator cracking predicted for both the limestone and quartzite mixtures. There was no consistent trend, as the 30% RAP mixtures with limestone exhibited a lower amount of alligator cracking than their corresponding 0% RAP mixtures. However, the quartzite mixes displayed the opposite with the 0% RAP having a mean of 1.29 percent with 30% RAP having a mean of 2.05 percent of alligator cracking. The trend followed by the limestone mixtures makes more sense as it is expected that the addition of RAP would stiffen the mixtures and makes them more resistant to fatigue cracking and hence, the 30% RAP group is expected to show lower amount of alligator cracking given the appropriate layer thickness.

For rutting in the asphalt layer, the WMA addition was a significant factor in the limestone mixtures but not in the quartzite mixtures confirming the observations exhibited by the flow number tests. The Tukey multiple comparison technique showed that there is a significant difference in the estimated rutting depth between the control and Evotherm™ J1 mixtures.

For rutting in the total structure of the pavement, both WMA and RAP content were significant factors in the limestone mixtures while the WMA was the only significant factor affecting permanent deformation in the pavement structure for quartzite mixtures. In the case of the limestone mixtures, the control mix was deemed significantly different from all the other mixtures containing WMA additives by the Tukey multiple comparison test. On the other hand, the control mixtures were significantly different compared to only the Evotherm™ mixtures in the group of mixes incorporating the quartzite aggregates. The observation that the rutting in the total pavement seemed more impacted by the incorporation of WMA additives and RAP compared to rutting in the asphalt layer is interesting. This is because, it was expected that the addition of the WMA additives and RAP would have a stronger direct effect on the asphalt layer compared to the entire pavement structure.

The analysis of variance of the IRI output showed that WMA and RAP variables are significant factors affecting the estimated overall quality of the limestone mixtures investigated. The Tukey method confirmed that the IRI values of the control mixtures are significantly different from those of mixtures containing WMA additives. Such an observation, agrees with the dynamic modulus test results that displayed generally stiffer master curves in the limestone control mixtures compared to their corresponding WMA mixtures counterparts. For the quartzite mixtures, only the WMA incorporation was the significant factor due to the statistical difference between the control and the Evotherm™ mixtures.

4.5. Conclusions and Recommendations

Based on the work conducted in this research using the materials, laboratory methods, assumptions and equipment previously discussed, the following conclusions are reached:

- The dynamic moduli of WMA mixtures were consistently lower compared to the corresponding HMA mixture at all test temperatures with the Evotherm™ J1 recording lowest stiffness.
- The rutting resistance of WMA mixtures is a concern as it was considerably lower compared to HMA mixes based on flow number test.
- While the inclusion of RAP improved the flow number of WMA mixtures, its performance was still much lower compared to the control HMA mixtures.
- MEPDG performance evaluation of the different mixtures through the estimation of pavement distresses agreed with laboratory test results specifically for rutting prediction and terminal IRI values which agreed with results of flow number and dynamic modulus tests, respectively.
- Statistical analysis of variance indicated that the Evotherm™ mixtures performance was generally different from the control mixtures regardless of type of aggregates used.
- It is well known that the flow number test is variable and difficult to assess. It is recommended to evaluate the permanent deformation resistance of mixtures

incorporating WMA and RAP using other testing procedures such as Hamburg Wheel Track Test or Asphalt Pavement Analyzer to validate the results observed.

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CHAPTER 5: EVALUATION OF THE RHEOLOGICAL PROPERTIES OF POLYMER MODIFIED WARM MIX ASPHALT BINDERS

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A paper to be submitted to the *Applied Rheology International Journal*

5.1. Abstract

The rheological behavior of two binders: a base binder and a polymer modified binders incorporating two types of warm mix asphalt (WMA) additives were studied through an extensive testing scheme. The warm mix additives used were an organic wax and an oily chemical additive. Tests performed comprise basic rheological tests such as rotational viscometer, viscous flow, creep, temperature and frequency sweeps. The output data of these tests were used to construct Viscosity-Temperature Susceptibility (VTS) curves and master curves to study the behavior of the binders tested. The performance of the unmodified WMA binders was similar to the control binder at the midrange and high test temperatures. On the other hand, the modified binder incorporating the waxy WMA additive exhibited stiffer behavior indicating the presence of more advanced polymer networks within the binder structure. Moreover, the wax additive had an anti-oxidizing effect on the aging of the binder using pressure aging vessel (PAV).

KEYWORDS: warm mix asphalt- polymer modified binders-complex shear modulus-rheology- master curve

5.2. Introduction

Intensive efforts on the global scale have been directed towards the reduction of carbon dioxide (CO_2) and other greenhouse gases culminating with the issuance of the Kyoto

Protocol designated to reduce the concentrations of greenhouse gases. The protocol's objective is to reduce the generation of CO_2 of 1990 levels by 5.2 percent between 2008 and 2012. Correspondingly, the European Union set the target of cutting CO_2 emissions by 15 percent by 2010 (D'Angelo, et al., 2008). This legislation has facilitated the asphalt pavement industries in several European countries to implement procedures and techniques that foster a reduction in emissions and resource consumption which were identified by the German Bitumen Forum established in 1997 as the most viable approaches to meet the newly targeted cuts in CO_2 emissions (Ruhl et al., 2003).

Intensive research efforts in that direction have resulted in the innovation of several technologies and additives, generically known as warm mix asphalt (WMA) by European companies. WMA technologies enable the production of asphalt mixtures at temperatures in the range of 200° F to 275° F. Hot mix asphalt (HMA) is typically produced in the temperature range of 285 °F to 340 °F while cold in-place recycling asphalt temperatures occur at ambient temperatures in the range of 68°F to 120°F (Hurley and Prowell 2006). Producing warm mix asphalt with comparable strength and durability to HMA can have extensive implications for producers and suppliers of asphalt. Using WMA technologies offers a number of advantages such as reduction in fuel consumption and plant emissions produced, in addition to longer paving seasons, reduced binder aging, and longer haul distances (D'Angelo, et al., 2008). Three common WMA technologies are synthetic zeolites, waxes derived from Fischer-Tropsch, and other chemical additives.

Synthetic zeolites are fine powdered sodium silicate hydrate, with water forming approximately 20% of its weight. Zeolites are typified by their ability to gain or lose water by heating without losing their structure. When zeolites are added to the mix simultaneously with the binder, its water content is released, at temperatures higher than 85°F causing the foaming of the asphalt binder which improves the workability of the binder temporarily and allows it to coat the aggregate properly at lower temperatures (PQ Corporation, 2010).

Another well known WMA additive is a wax based material produced through the Fischer-Tropsch process and is characterized by long chemical chains (40 to 115 carbon atoms). The structure and properties of this wax particularly its low melting point, 210°F, allow it to alter the temperature-viscosity curve of the binder causing a reduction in the viscosity of binder. The Fischer-Tropsch wax forms a lattice structure inside the asphalt binder, at temperatures below its melting point which improves the stability of asphalt mixtures (Sasol Wax, 2010).

An oily fluid that is similar to tallow oil is extracted from forest based plants is also used as a warm mix additive. this chemical additive with low viscosity at room temperature blends with liquid binder and enables asphalt mixture production at temperatures higher than 220°F through the improved coating and workability provided by its chemical constituents (MeadWestvaco, 2010).

The incorporation of polymers into asphalt was reported to enhance performance as polymer modified mixtures displayed greater resistance to rutting, thermal cracking and lower fatigue damage (Yildrim, 2007). However, polymer modified binders are typically mixed and compacted at relatively higher temperatures compared to conventional binders due to their higher viscosity characteristics. Hence, more energy is used in the production and placement of polymer modified mixes and consequently greater emissions are produced in the process (Kim et al.2010). Incorporating warm mix additives into polymer modified (PM) mixtures could be a possible viable approach that enables the mixing and production of the PM mixtures at lower temperatures without compromising the quality or the properties of the mixtures produced. For this reason, this research investigates the effect of WMA additives on the properties of polymer modified binders.

This study presents an assessment of the performance characteristics of two warm mix technologies, a waxy hydrocarbon produced by the Fischer-Tropsch chemical process and a forest based oily chemical additive were incorporated to a virgin binder with a PG (64-22) and a polymer modified binder PG (70-22). Selected rheological tests were conducted at different states of the binders: original form, rolling thin-film (RTFO) aged form mimicking the aging effect of the mixing and placement phases during construction and (Pressure Aging Vessel) PAV aged form simulating the in-service aging conditions of the material. Rheological tests conducted include rotational viscometer testing (RV) at 135°C and the dynamic shear rheometer (DSR) test.

The rheology of polymer modified bitumen is reported to vary from that of unmodified bitumen. A polymer modified bitumen can be regarded as a bituminous rich phase with a polymer phase finely dispersed. According to Mutri et al. (2010), the moderate miscibility of phases causes the segregation of the polymer phase within the bitumen phase which in turn affects the rheology of polymer modified binders and makes them more complex than unmodified binders. Hence, additional rheological procedures were performed to investigate the effect of polymer modification on the performance of polymer modified warm mix asphalt such as the viscous flow, creep, frequency and temperature sweep test. In addition, the Viscosity-Temperature relationship of all binders tested was studied to check whether there are any discrepancies in the rheological response of the binders over the temperature range of the frequency sweeps. Moreover, master curves of the complex modulus, G* are constructed versus reduced frequency to illustrate the impact of variables investigated in this study, WMA additives and polymer modification, on the performance of asphalt binders.

5.3. Experimental Program

A virgin PG (64-22) binder was procured for investigating the effect of two warm mix additives on the performance characteristics of the binder. Moreover, the binder was modified through the addition of a 3% Styrene-Butadiene-Styrene (SBS) polymer and the effect of incorporating WMA additives to the polymer modified binder of a PG (70-22) was also studied. Two commercially available warm mix additives were used: a long chained aliphatic hydrocarbon that is generated during the Fischer-Tropsch process which will be referred to as (F-T) wax and a chemical additive which includes surfactants that enhance binder aggregate adhesion in addition to improving workability that will be referred to as (F-P) additive. Figure 5.1 below illustrates the different components of the experimental procedures carried out in this work.

The viscosity of three 11 gram samples of each binder was measured using a rotational viscometer at 135°C with a S27 spindle. Dynamic shear rheometer (DSR) was used to determine the high performance grade of the binders using its original, RTFO and PAV aged residues. Moreover, low temperature properties were studied using Bending beam rheometer (BBR) on PAV aged binders.

Additional testing procedures were conducted using the DSR comprised of frequency sweeps, viscosity curves and creep tests. The output of this testing was used to construct master curves of the tested binders. Viscosity and creep curves were tested at 60°C, a temperature critical for the rutting resistance performance of the tested binders using 25 mm parallel plates with a 1mm gap. The frequency sweep procedure was carried out at different temperatures 13,21,29,37,46,58,70 and 76°C at frequencies ranging between 0.1 to 25 Hz. Sweeps at temperatures ranging between 13 and 37°C were performed using 8mm parallel plates with 2 mm gap while the frequency sweeps at temperatures between 46 and 76 °C were conducted using 25 mm parallel plates with 1 mm gap. DSR test data were used to investigate the viscosity temperature susceptibility (VTS) of the binders. Binders with similar values of the temperature susceptibility parameter VTS are anticipated to perform similarly in terms of their rheological response to variations in temperatures. Typically the VTS is computed using equation (1) below:

$$\mathrm{VTS}\ (T_1\text{-}T_2) = \frac{\log(\log V_2) - \log(\log\ (V_1)}{\log T_1 - logT_2} \qquad (1)$$

where T_1 and T_2= temperature in (K), V_1 and V_2 = viscosity in centipoises at T_1 and T_2

However, VTS can be estimated using DSR testing through the following relationship illustrated in equation (2) outlined by Mutri et al. (2010):

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \qquad (2)$$

where η= bitumen viscosity (cP), G*= bitumen complex shear modulus at 10 rad/s, δ= phase angle (degrees) for a plot of viscosity versus temperature, the VTS value is equal to the slope of the line.

Master curves are graphical representations resulting from applying the time-temperature superposition (TTSP) principle which assumes that time (frequencies) and temperatures have comparable effect on a material's rheological behavior. Thus, frequency sweep data at different temperatures are shifted along the frequency axis with respect to a determined reference temperature using shift factors for each temperature. Hence, a single curve illustrating the change in the behavior of a rheological parameter, in this case, the shear complex modulus, G* with frequency is formed. The advantage of master curves is that exhibits the behavior of the tested material over a wider range of frequency or temperature domains than the range allowed through experimental testing using the rheometer (Peralta et al. 2010).

In addition, it is important to note that the applicability of the TTSP principle and the method of shifting curves to construct master curves is dependent on the assumption that asphalt is a simple thermo-rheological material and that the linear viscoelastic region applies for the whole temperature range tested. Hence, Lesueur et al. (1996) argued that the TTSP only applies for low temperatures and that it fails at high temperatures. As a result, they reasoned that using master curves of G' and G'' plots versus frequency at high temperatures would erroneously imply that TTSP still applies where it clearly does not. They recommended the use of Black diagrams to check the applicability of applying the TTSP principles at the temperatures range under investigation. Black diagrams are plots of G* versus phase angle in which the rheological properties of binders are illustrated through a single curve irrespective of temperature and frequencies. In the case, the curve resembles approximately a single curve, this is an indication that the time-temperature superposition is applicable for the test conditions and parameters and that the binder tested is thermo-rheologically simple. In other cases, the TTSP is not applicable, usually; when the binder tested comprise other phases such as polymers or paraffins. .

5.4. Results and Discussion

5.4.1. Viscosity

The rotational viscosity test is stipulated in the standard binder testing procedures to assess whether the flow properties of the asphalt binder ensure proper pumpability and handling at the mixing plant (Asphalt Institute, 2003). The Control unmodified binder displayed higher viscosity compared to unmodified binders incorporating (F-T) wax and (F-P) additive as shown in Figure 5.2.

The reduction in the viscosity of the F-T unmodified binder could be attributed to F-T's long chained arrangement of the carbon atoms (Gandhi, 2008, Hurley et al., 2006). On the other hand, according to the manufacturer of the chemical warm mix additive, it incorporates additives and agents that enhance workability and coating which might explain the observed reduction in viscosity.

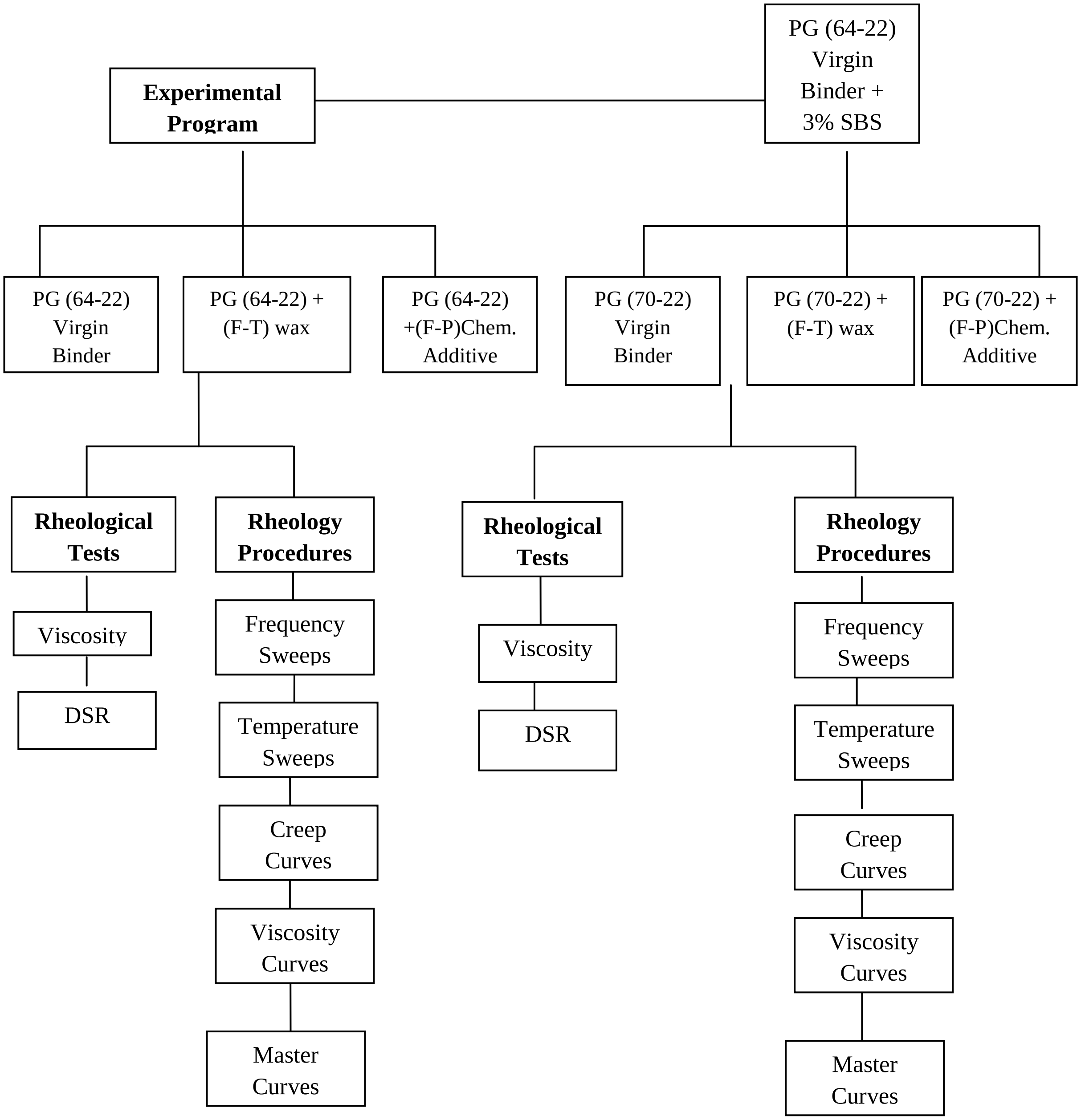


Figure 5.1 Experimental program layout.

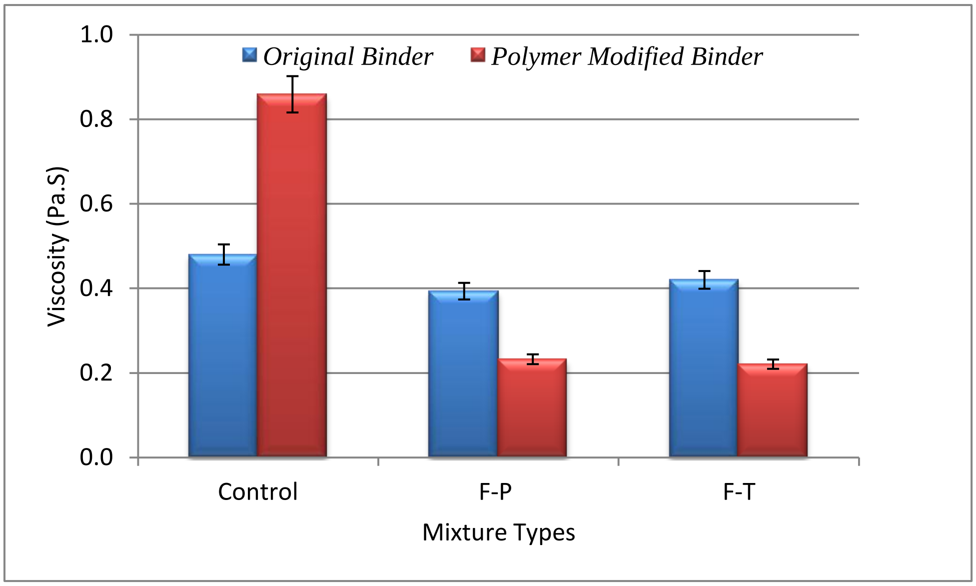


Figure 5.2 Viscosity at 135C of original and polymer modified WMA binders

The polymer modified control binder expectedly exhibited a higher viscosity at 0.8 Pa.s compared to 0.48 Pa.s for the unmodified control binder as the SBS interacts with the asphaltenes and resin components of the asphalt binder (Kim, 2010). However, the SBS modified WMA binders displayed significantly lower viscosities in comparison to their unmodified counterparts indicating that an interaction might have taken place between the warm mix additives and the SBS polymers incorporated causing this sharp decrease in viscosity. This behavior could be beneficial in lowering the temperatures at which polymer modified binders need to be mixed as the lower viscosity would enable mixing with aggregate at lower temperatures.

5.4.2 High Temperature Grade

A plot of the DSR test temperatures with the corresponding complex shear modulus values is shown in Figure 5.3 below. For the unmodified group of binders, the binder incorporating the F-T wax additive displayed the highest complex moduli values at test temperatures. On the other hand, the control and the F-P binders had a very similar behavior across all test temperatures.

Modifying the binders with SBS block copolymers expectedly led to an increase in the complex moduli of all binders with the F-T binder again exhibiting a superior performance. Such superiority could be attributed to the formation of a critical network between the binder and the polymer phases resulting in an increase in the complex modulus, G*. Moreover, an interaction possibly has taken place between F-T wax and the polymer leading to a significant increase in the complex modulus values. Hence, the F-T polymer modified binder is the least susceptible to rutting while the F-P binders performance were similar to their corresponding control ones.

5.4.3. Fatigue Cracking

Table 5.1 below shows the temperatures at which the binders investigated met the criteria for fatigue cracking in asphalt binders. The temperature at which a maximum value of 5000 kPa for $G^*\sin\delta$ is recorded determines the limiting temperature with respect to fatigue cracking. It can be observed that F-T binder is the most susceptible to fatigue cracking as the fatigue cracking criteria are met at a higher temperature compared to other binders. Moreover, the impact of the polymer modification is evident as it increased the minimum temperature at which the criteria were met within each WMA binder group.

Table 5.1 Minimum temperature for fatigue cracking (°C)

Binder Modification	Control	F-T binder	F-P binder
Unmodified	23.43	24.36	22.90
Modified	23.81	25.74	23.11

5.4.4. Low Temperature Properties

Table 5.2 shows the m-value and the stiffness parameter S at -12 °C acquired using the bending beam rheometer which illustrates the behavior of the binders at low temperatures. It could be observed that all binders passed the specifications criteria with the exception of the polymer modified F-T binder who failed both the m-value and the stiffness tests.

Table 5.2 Low temperature properties at -12 °C

Binder Property	Control	Control modified	F-T binder	F-T modified	F-P binder	F-P modified
m-value at -12 °C	0.32	0.303	0.3	0.278	0.325	0.307
Stiffness at -12 °C (MPa)	194	204	220	235	177	191

5.4.5. Flow

Asphalt materials are expected to behave as Newtonian fluids at temperatures greater than 60 °C (Asphalt Institute, 2003). Newtonian fluids are characterized by a linear relationship between the shear stress applied and the resulting shear strain rate. That is the viscosity of the asphalt binder is constant with increasing shear rate. Figure 5.4 below illustrates the viscous flow properties of RTFO and PAV aged unmodified asphalt binders at 60°C.

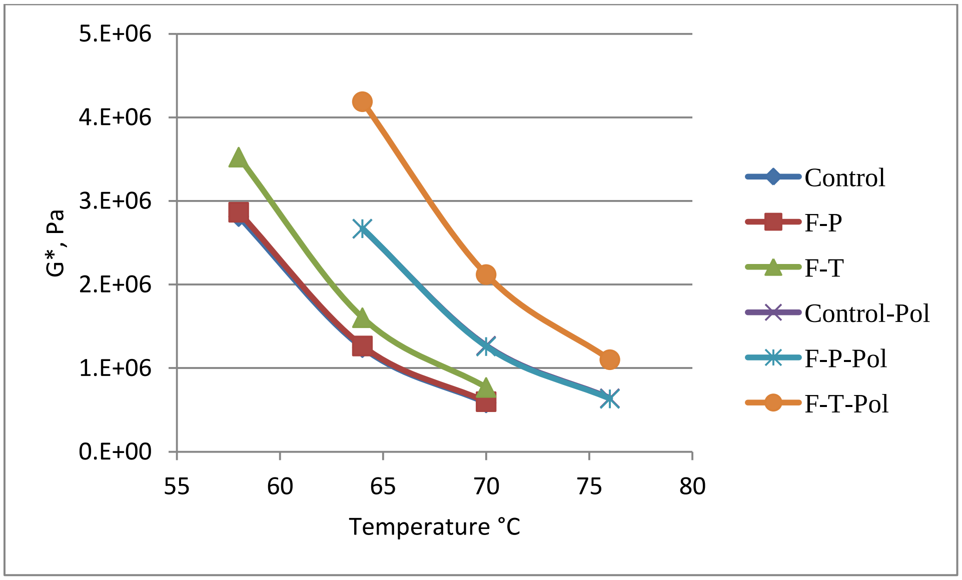


Figure 5.3 Temperature vs. complex modulus plot of unmodified and polymer WMA binders.

For the RTFO aged binders, control and F-T binders had very similar trends exhibiting a shear thinning (pseudo-plastic) behavior as the viscosity started to dip slightly as the shear rate increased. At the test beginning, the viscosity was nearly 1000 Pa.s decreasing gradually until reaching 900 and 800 Pa.s for control and F-T binders, respectively. The flow curve for the RTFO aged F-P binder was significantly lower than the control and F-T curves indicating a lower resistance to rutting at 60°C and also followed a shear thinning trend.

The PAV aged unmodified binders expectedly shown greater viscosities than their RTFO aged counterparts with the differences between the control and the warm mix binders is significantly smaller in magnitude. Similarly, pseudo-plastic trends were observed for the PAV aged binders curves.

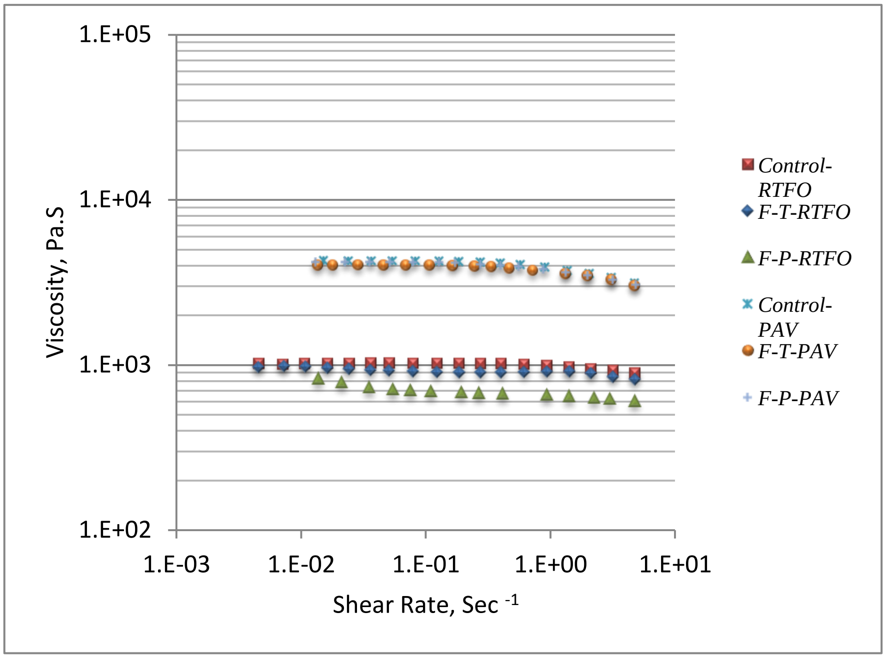


Figure 5.4 Viscous flow curves for RTFO and PAV aged unmodified binders

Similarly, the flow curves of polymer modified binders exhibited shear thinning trends for RTFO and PAV aged samples as observed in Figure 5.5. However, unlike the unmodified flow curves, the F-T polymer modified binder displayed higher flow curves compared to the control and F-P binders for both the RTFO and the PAV aged samples indicating a superior resistance to permanent deformation which agrees with the high temperature grade results discussed above. Additionally, the F-P curve for the PAV aged binders was much lower than the F-T and control curves.

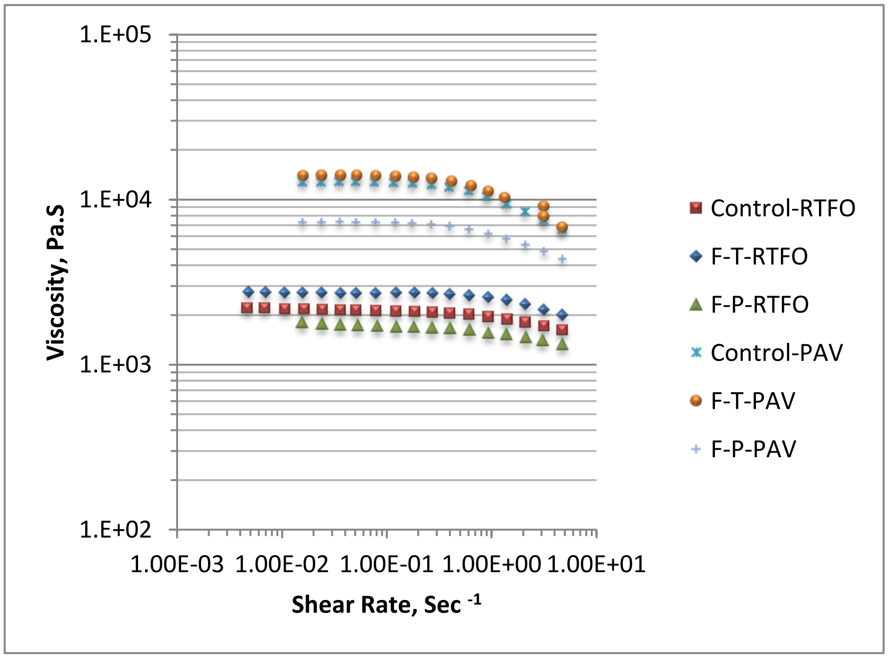


Figure 5.5 Viscous flow curves for RTFO and PAV aged polymer modified binders

5.4.6. Creep

The creep test was conducted on the studied binders by applying a 10 Pa stress for 35 seconds at 60°C and measuring the resulting strain during the test duration. Creep compliance is calculated by dividing the strain over stress. The more creep a material exhibits at higher temperatures (e.g. 60 °C) the greater its susceptibility to rutting. Figure 5.6 below shows that the F-T binder had the lowest compliance while the creep compliance of the F-P binder was the highest. Thus, the F-T binder exhibited the lowest susceptibility to rutting as its waxy constituents recrystallize at midrange temperatures improving the stiffness as a result. The creep curves for the SBS modified binders showed a similar trend as the F-P binder had the highest compliance and F-T the lowest as displayed in Figure 5.7.

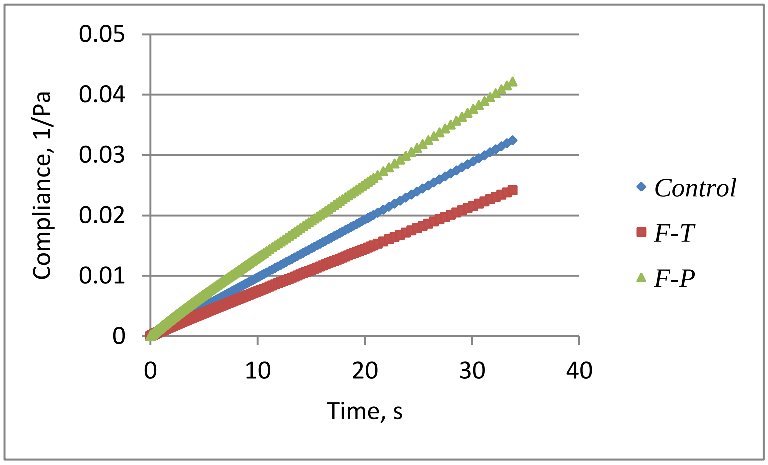


Figure 5.6 Creep curves for RTFO aged unmodified WMA binders

5.4.7. Temperature Sweep

A temperature sweep test was conducted to chart the dependence of the binders' rheological properties i.e. its complex modulus, G* and phase angle, δ on temperature. For the unmodified WMA binders, it can be observed that the control binder had the highest complex modulus in the temperature range tested. The F-T and F-P binders performed similarly as shown in Figure 5.8. The trend followed for the phase angle curves for the binders was similar to the complex modulus observations.

The temperature sweeps of the polymer modified WMA binders showed a different trend to their unmodified counterparts. It was noted that the F-T binder had a higher complex modulus, G* compared to the control and F-P polymer modified binders. This observation was more evident at the lower temperature range suggesting the presence of an interaction between the F-T wax additive and the SBS polymer that increased the stiffness of the binder.

Moreover, the phase angle curves of the F-P polymer modified binder were the highest over the whole tested temperature range as shown in Figure 5.9 with the phase angle of the F-T binder indicating a slightly better elastic behavior than the control binder.

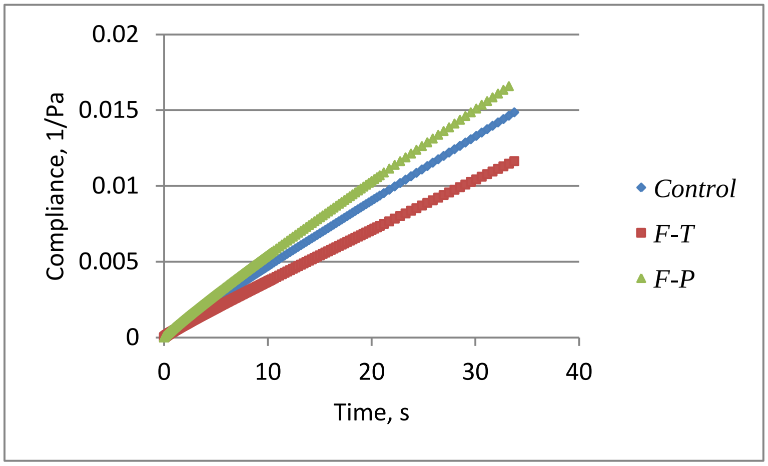


Figure 5.7 Creep curves for RTFO aged polymer modified WMA binders

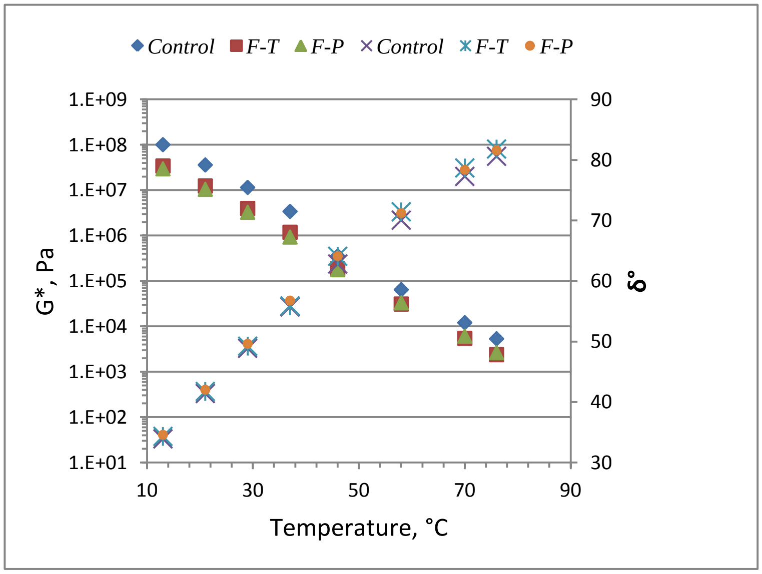


Figure 5.8 Temperature sweeps of unmodified WMA binders

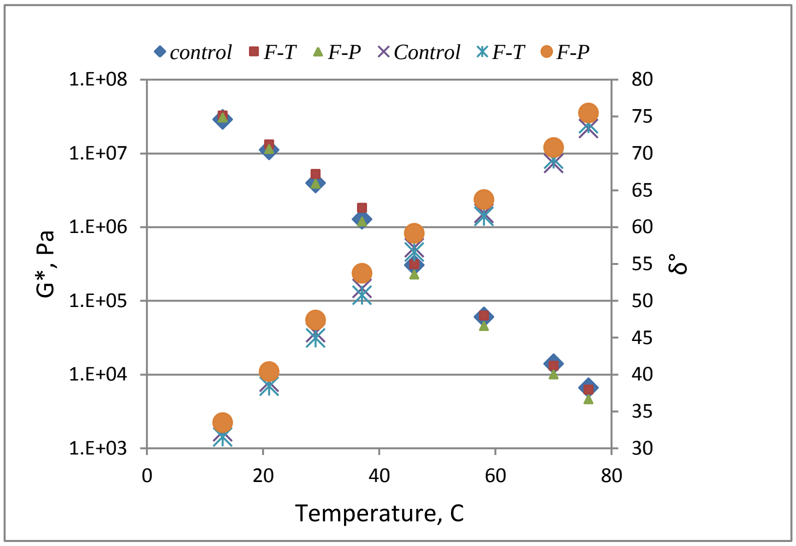


Figure 5.9 Temperature sweeps of polymer modified WMA binders

5.4.8. Frequency Sweeps

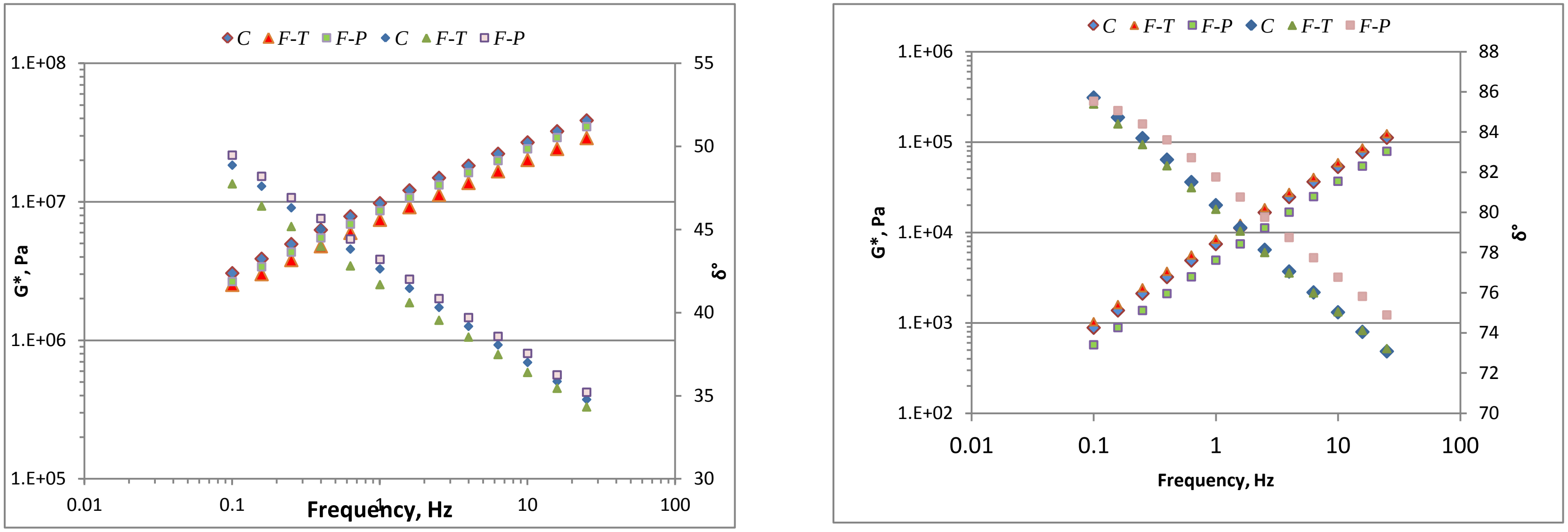
Frequency sweep tests were conducted between 0.1 and 25 Hz at eight different temperatures ranging between 13 and 76°C. The frequency dependence test was conducted on PAV aged binders for the sweeps at temperatures 13 to 37°C because the fatigue cracking properties are of interest at this temperature range. Hence, conducting the test on PAV aged binders is more conservative as they are more aged and also because fatigue is a material property that is more critical at later stages of binder life which is better simulated by PAV aging. On the other hand, the test was carried out on RTFO aged binders for the sweeps at temperatures between 46 and 76°C. That is because the primary property investigated at this temperature range is the rutting performance of the material and hence, it is more critical to assess the rutting resistance of RTFO aged materials as they are more susceptible to rutting compared to the more aged PAV binders.

Figure 5.10 below shows the frequency dependence of unmodified WMA binders at 21°C and 58°C. For PAV aged binders at 21°C, the control binder displayed a slightly stiffer performance than F-P and F-T binders. Moreover, it can be observed that the F-T binder had the lower phase angles especially at lower frequencies which indicate a higher elastic performance compared to the control and F-P binders. As for the RTFO aged binders at 58°C, the F-T and control binders exhibited higher G* values compared to F-P binder indicating their higher resistance to permanent deformation. A similar conclusion can be drawn from the higher phase angles of the F-P binders.

The frequency sweeps carried out using polymer modified WMA binders showed a different trend to the unmodified ones. Figure 5.11 below shows the frequency dependence of PAV and RTFO aged binders at 21 and 58 °C, respectively. For the PAV aged binders, the F-T polymer modified binder showed higher G* value compared to the control and F-P modified binders especially at low frequencies. The same trend noted for phase angles as the F-T binders had lower phase angles indicating higher elasticity. Airey (2004) reported that phase angles are better indicators of the impact of polymer modification as they are more sensitive the binder structure than G*. Hence, the lower phase angles are indicative of a relatively more advance polymer network formation in the F-T binder. On the other hand, the control and F-T binders exhibited higher G* than F-P modified binder. The higher phase angles of F-P binder indicates that rutting resistance could be a concern. An analysis of variance (ANOVA) was conducted on the complex modulus values for both RTFO and PAV aged tested samples tested using Minitab statistical software at an α=0.05. The impact of several factors: WMA type, polymer modification, temperature and frequency along with

WMA type interaction with the three other factors were investigated. Table 5.3 below shows the outcome of the ANOVA test conducted in which all investigated factors were deemed statistically significant in affecting the complex modulus values for the RTFO aged binders at high temperatures.

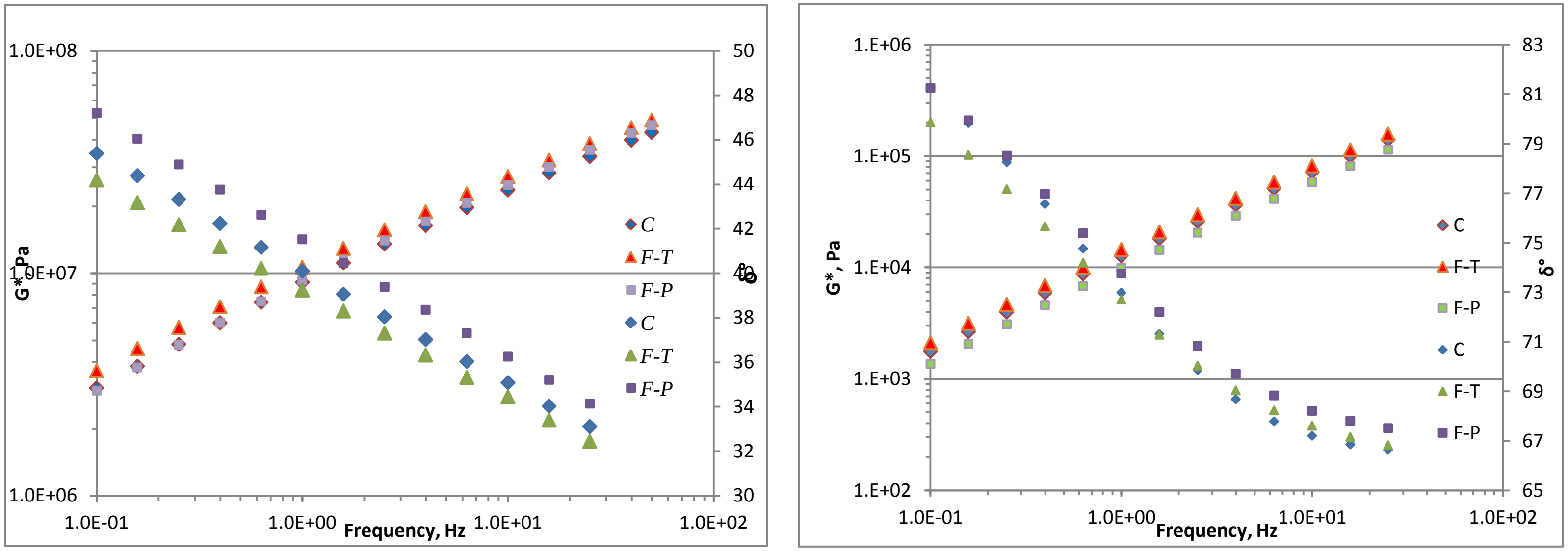
Moreover, interactions between the type of warm mix additive incorporated and the presence of polymer and temperature were found significant as the p-values were lower than 0.05. On the other hand, the ANOVA output for the PAV aged materials regarding variability in the complex modulus values of PAV aged material at temperatures ranging between 13 and 37°C shows that WMA type and polymer modification are not significant factors affecting the complex modulus values while the interaction between both factors is statistically significant. These observations indicate that the performance of the binders with WMA additives is similar to the control binders at mid range temperatures.



a)

b)

Figure 5.10 Frequency dependence of unmodified WMA binders: a) PAV aged at 13 °C b) RTFO aged at 58 °C



a)

b)

Figure 5.11 Frequency dependence of polymer modified WMA binders: a) PAV aged at 21 °C b) RTFO aged at 58 °C

5.4.9. Viscosity-Temperature Susceptibility (VTS)

The VTS curves for the binders tested in this work are shown in Figures 5.12 and 5.13 for unmodified and polymer modified WMA binders, respectively. It can be deduced from the figures that within the same group, the binders exhibit VTS curves with similar slopes indicating a similarity in their rheological response in this case the viscosity to changes in test temperature.

5.4.10. Master curves

Prior to constructing the master curves, the data output from the frequency sweeps were first checked for applicability for shifting using the time-temperature superposition principle. This was done through constructing the black diagrams for all the binders tested. Figures 5.13 and 5.14 show the black diagrams for the unmodified and SBS modified WMA binders. By observing the aforementioned figures, it can be noted that graphical representation of the G* versus the phase angle for all binders tested resemble roughly a single curve for each binder which is an indication of the suitability of applying the TTS principle for the temperature range in question.

Consequently, the master curves for the six binders investigated in this work can be developed by using the TTSP concept to shift curves of G* versus frequency for different temperatures with respect to a reference temperature which is selected at 46°C. Figures 5.16 to Figure 5.18 presents a representation of master curves of G* and tan δ.

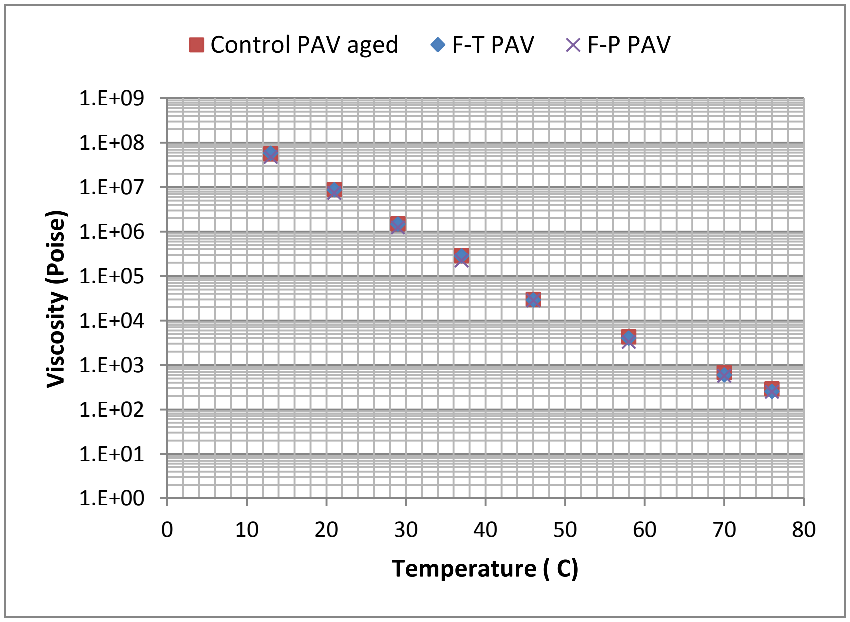


Figure 5.12 VTS curve for unmodified WMA binders

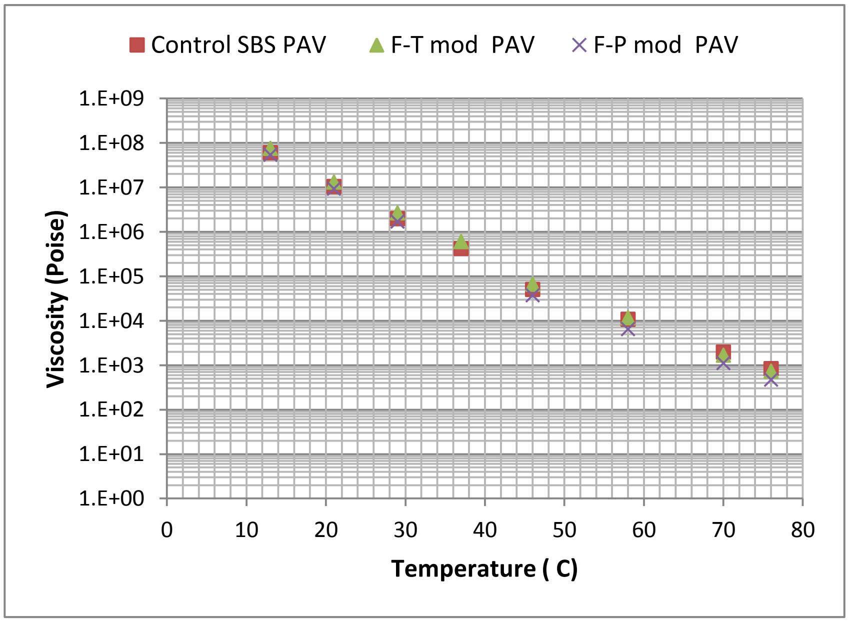


Figure 5.13 VTS curve for SBS modified WMA binders

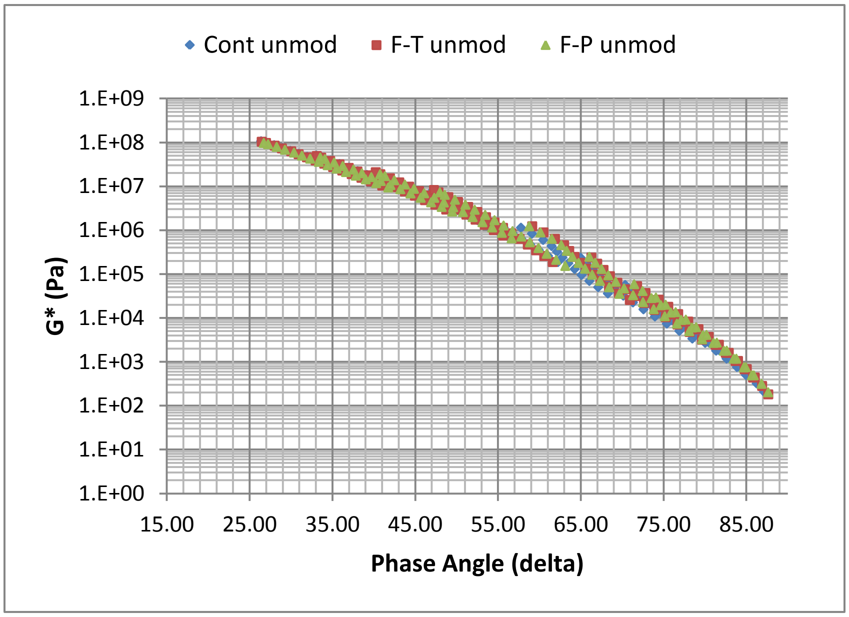


Figure 5.14 Black diagrams for unmodified WMA binders

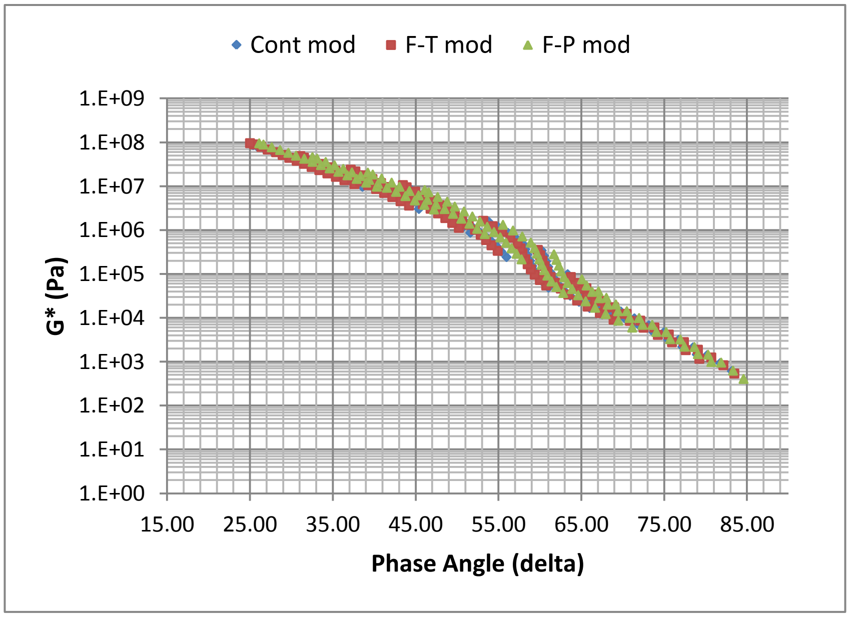


Figure 5.15 Black diagrams for SBS modified WMA binders

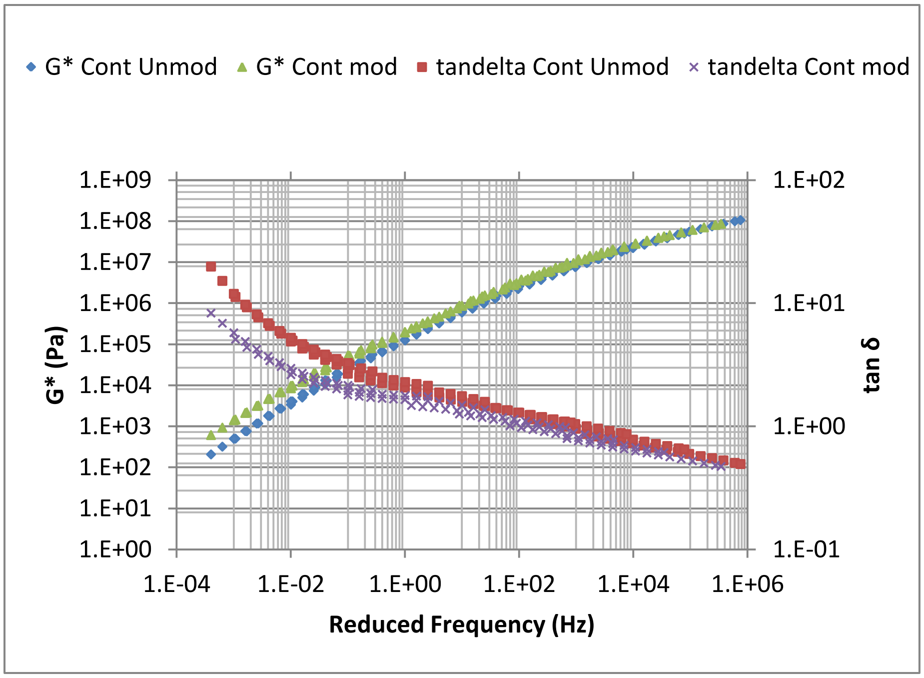


Figure 5.16 Master curves for control binders

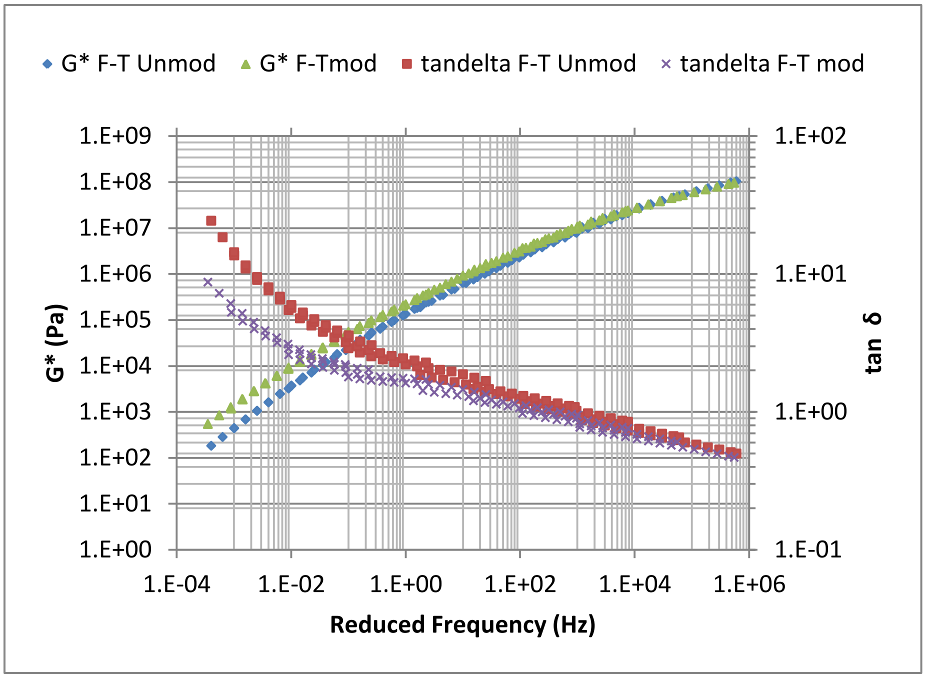


Figure 5.17 Master curves for F-T binders

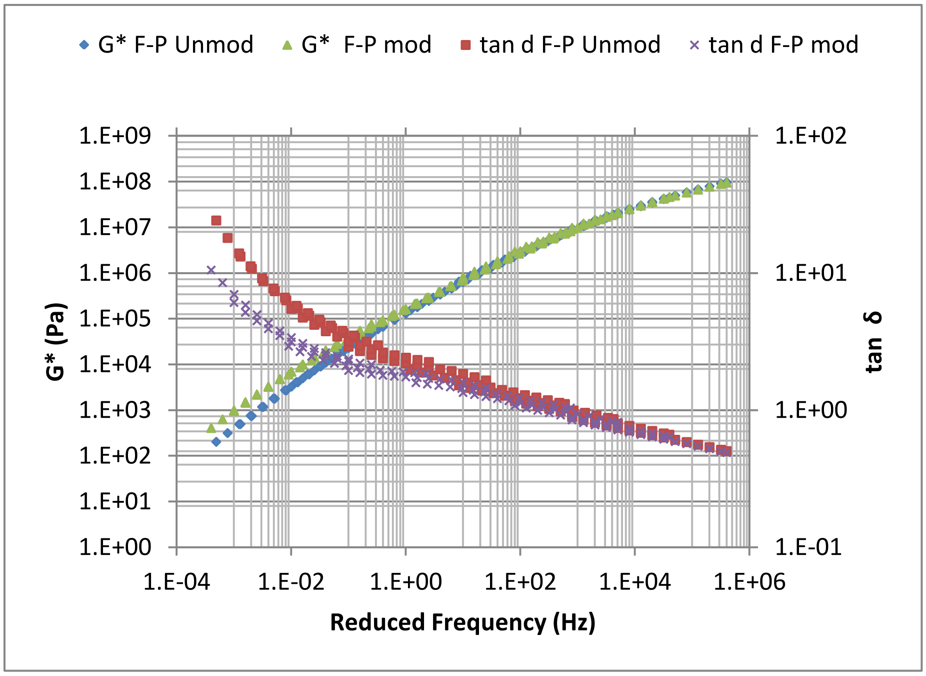


Figure 5.18 Master curves for F-P binders

From the previous figures, it was noticed that master curves for all the binders followed a similar trend as the G* decreased with the decrease in reduced frequency. Another observation noted is that the differences in behavior between unmodified and modified binders were more evident in low frequency/ high temperature region. These differences were more obvious in the tan delta curves with the tan delta curves of unmodified binders noticeably higher than the polymer modified tan delta curves. This observation makes sense as polymer modified binders are expected to exhibit stiffer behavior compared to the unmodified ones, hence the delta values are expected to be higher for the base binders. An additional observation is the G* master curves were converging into an asymptotic value of 1 GPa towards its high end.   Figure 5.19 illustrates master curves for both the unmodified and modified binders investigated. Again, the differences between the binders are more obvious in the low frequency/high temperature region. The control and F-T binder exhibited a similar trend at high temperatures as their G* values were comparable. However, the F-P binders exhibited a relatively lower G* values compared to the other two binders indicating its resistance to permanent deformation is possibly lower. On the other hand, differences between binders were insignificant at high frequency/ low temperatures.

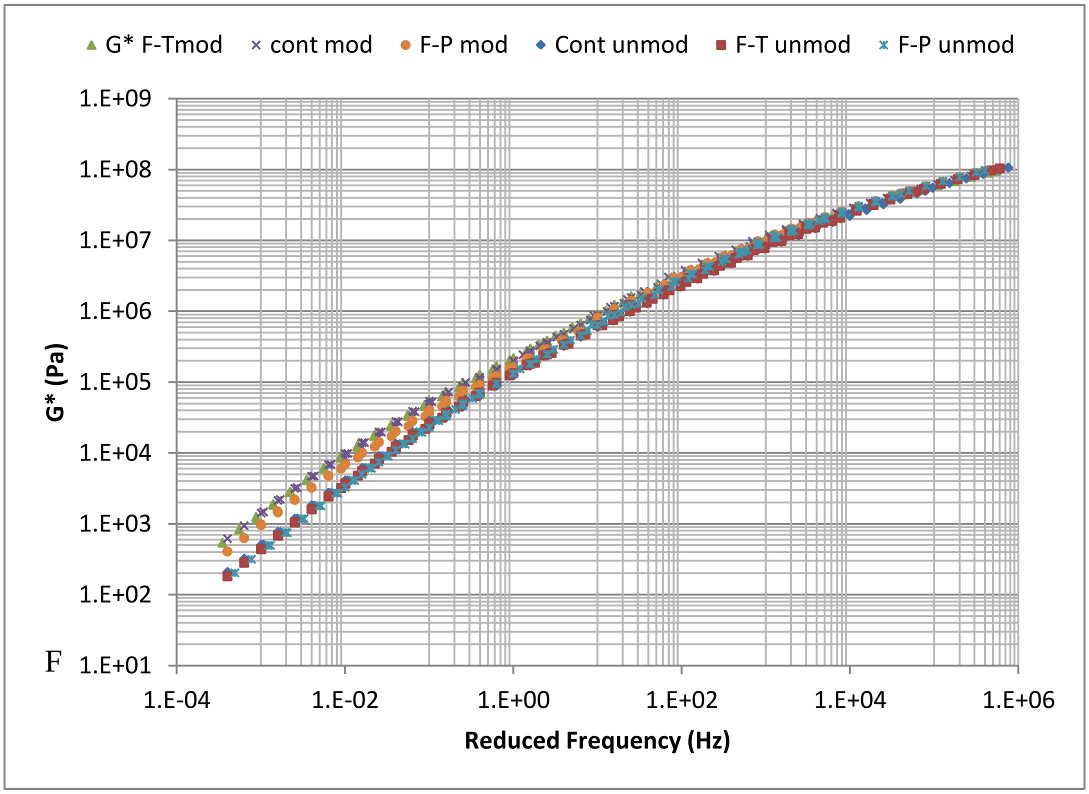


Figure 5.19 Master curves for unmodified and modified WMA binders

Table 5.3 ANOVA test for RTFO and PAV aged complex modulus.

	RTFO G*		PAV G*	
Source	P-value	Significant	P-value	Significant
WMA	0.0001	Yes	0.727	No
Polymer Modification	0.0001	Yes	0.340	No
Temperature	0.0001	Yes	0.0001	Yes
Frequency	0.0001	Yes	0.0001	Yes
WMA*Polymer	0.0001	Yes	0.001	Yes
WMA*Temperature	0.0001	Yes	0.936	No
WMA*Frequency	0.39	No	1.000	No

5.4.11. Rate of Complex Modulus Aging

The rate at which the binders investigated in this work age in the high temperature range 46-76°C was studied by comparing the percent increase in the RTFO aged complex modulus values upon aging the binders in the Pressure Aging Vessel (PAV). It was noticed that as the frequency increased, the percent increase of the complex modulus decreased with the binder incorporating F-T wax having a lower percent increase in modulus values than the control and F-P binders, an average of 151% compared to 208 and 213%, respectively. In the same manner described previously, conducting an ANOVA to identify the factors affecting the percent change in the complex modulus showed that WMA type, polymer modification and frequency were statistically significant. As a result, a pairwise comparison was performed to investigate which WMA additives were statistically different. The F-T binders displayed the lowest percent change in the complex modulus value compared to the control and F-P binders who were not statistically different with regard to each other.

Table 5.4 Multiple comparisons of binders complex modulus percent increase.

Unmodified + polymer modified binders			Unmodified binders only			Polymer modified binders only		
	Mean	**Group**		**Mean**	**Group**		**Mean**	**Group**
Control	208%	A	Control	182%	A	Control	237%	A
F-T	152%	B	F-T	119%	B	F-T	185%	B
F-P	213%	A	F-P	250%	C	F-P	175%	B

However, these observations could have been affected by the presence of confounding variables in which two opposing trends for two variables cancel each other affecting the final statistical observations. Hence, an analysis of variance was conducted on the unmodified binder data only to identify which factors are affecting the variability of the percent change in G*. The factors investigated and found significant were WMA type, temperature and frequency. Upon carrying a pairwise comparison, all three levels of the WMA type factor were deemed statistically different compared to each other as shown in Table 5.4. The F-P binder had the highest mean percent change of G* at 250% while the F-T binder had the lowest mean percent change of G* at 118.5 %. This could be an indication that the F-T wax warm mix additive acts as an antioxidant that regresses the aging of the binder through oxidation taking place in the pressure aging vessel causing such a notable lower rate of increase in the complex modulus values compared to the rates of the control and F-P binders.

The same way, the polymer modified binders were analyzed separately to determine which factors were statistically significant using ANOVA. The results showed again that WMA type, temperature and frequency were significant factors. Pairwise comparison showed that the control binder had the highest percent change in the value of the complex modulus with an average of 237% while the F-T and F-P binders had percentages of 185 and 175%, respectively. These observations confirmed the presence of a confounding statistical effect regarding the impact of polymer modification as the F-P binder exhibited the highest percent increase in G* value when unmodified but upon the addition of the SBS polymer, it recorded the lowest rate of increase in the complex modulus values. This observation was not obvious in the original ANOVA analysis due to the confounding statistical impact of polymer modification on the whole data set. An explanation for such change in the behavior of the F-P binder could be that the polymer acted as an antioxidant while interacting with the F-P additive.

5.5 Conclusions and Recommendations

The flow, creep and other rheological characteristics of two binders: an unmodified PG 64-22 and a polymer modified PG 70-22 binders with two different WMA additives were investigated. Moreover, the percent increase in the complex modulus values of different RTFO aged binders upon aging them using PAV oven was studied. Based on the materials used and procedures followed in this work, the following can be concluded:

- For unmodified binders, the incorporation of the WMA additives: the Fisher-Tropsch wax and the chemical additive lowered the viscosity of the binders at 135°C.

- The addition of WMA additives to the SBS polymer modified binders caused a sharp reduction in viscosity indicating the possibility of mixing polymer modified binders at lower mixing temperatures due to an interaction between the SBS network and the WMA additives.
- The high temperature binder grade of polymer modified binder increased significantly with the addition of the wax WMA additive indicating the presence of a combining effect between the SBS polymers and the recrystalization of the wax in the binder causing the observed increase in the stiffness of the binder.
- All binders exhibited a shear-thinning behavior at 60°C with the unmodified binder incorporating the chemical additive looking more susceptible to rutting than other investigated binders.
- F-T unmodified binders are stiffer than the control and chemical additive binders for the high temperature ranges indicating a superior resistance to permanent deformation according to creep and frequency sweeps. The midrange temperatures performance of the WMA unmodified binders indicate there are no concerns regarding their fatigue cracking resistance.
- However, for modified binders, the wax binder lower phase angles are indicative of higher degree of polymer network formation in the binder. On the other hand, rutting could be a concern for modified binder incorporating chemical WMA additive as shown by its higher phase angles.
- The Fisher-Tropsch wax added to the unmodified binder behave as an antioxidant reducing the rate at which aging taking place in the PAV oven while the chemical additive has the reverse effect on the aging rate.

- The addition of the SBS polymer significantly alters the aging behavior of binders incorporating wax and chemical WMA additives as it inhibits the antioxidant effect of the former leading to increase in the rate of aging. It has the opposite effect on binders with forest plant chemical additive as it critically weaken the effect of the additive in lowering the rate of aging of the binder in the PAV as reflected by the investigated values of the complex shear modulus.
- Conducting a study that investigates the volumetric and performance characteristics of polymer modified WMA mixtures is recommended.
- To study the binder properties at significantly lower and higher temperatures using suitable rheological equipment such as differential scanning calorimetry (DSC) to capture the rheological behavior of the binders at a wider temperature range.

5.6. References

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CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1. Summary

With the prices of crude oil increasing and reserves of natural nonrenewable resources dwindling over time, the needs for adopting greener and more sustainable approaches in various construction activities are stronger. The asphalt production industry has been keen during the last few decades to reduce the impact of its activities on the environment especially regions adjacent to its operating activities and on natural resources. Moreover, increasingly stringent governmental regulations targeting the reduction of carbon dioxide and other greenhouse gas production have placed additional pressure on the asphalt industry to adopt greener approaches in its production activities. Hence, the asphalt industries in Europe, the United States and other regions in the world started to study the feasibility of using materials, procedures and techniques that foster a reduction in emissions and resources consumption. Thus, recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) are increasingly being used in the production of asphalt mixtures. Moreover, different techniques to produce and place asphalt mixtures at lower temperatures than the typical hot mix asphalt (HMA) temperatures are recently being used. These techniques are currently known as warm mix asphalt (WMA) technologies. This family of technologies can be classified into: 1) water-based technologies, 2) water bearing additive technologies, 3) organic additive technologies, and 4) chemical additive technologies.

The major force driving the development of WMA techniques first in Europe and later in the United States is the benefits gained through its implementation. Several environmental benefits such as lower energy consumption needed for the heating up of the asphalt binder and reduced emissions from the asphalt plants were reported by developers of these technologies and some of the contractors who worked with them on trial projects. In addition, a number of paving benefits was also reported such as lower viscosity of binder, lower susceptibility to oxidative hardening and a higher potential for using higher content of RAP.

After being introduced to the WMA technologies developed in Europe since the mid 1990s, governmental agencies and asphalt industry bodies in the United States focused on establishing frameworks through which the suitability of using WMA techniques in the United States is investigated. Hence, several research studies tried to investigate the characteristics of WMA mixtures and its potential drawbacks such as susceptibility to moisture and its fatigue and rutting performance.

The objectives of this dissertation were as follows: first, to study the performance of asphalt mixtures prepared with three WMA technologies, Advera, Evotherm and Sasobit, in comparison with a control HMA mixture by conducting dynamic modulus and repeated loading (flow number tests). Secondly, this work looked into whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA. Thirdly, the performance of pavements using the asphalt mixtures prepared in this work is predicted by the MEPDG software using the test data acquired from laboratory testing. The performance of the pavement sections was assessed based on the amount of alligator cracking and permanent deformation predicted by the software. Fourthly, the basic characteristics of a PG 64-22 binder incorporating Evotherm and Sasobit are studied by carrying out Superpave binder testing procedure on the binders in its original form, rolling thin film (RTFO) aged and pressure aging vessel (PAV) aged. These tests were conducted using rotational viscometer, dynamic shear rheometer (DSR) and bending beam rheometer (BBR) test equipment. Fifthly, the basic rheological properties of SBS polymer modified WMA binders were measured and the effect of polymer modification on the characteristics of the binders was analyzed. Sixthly, additional rheological procedures such as viscous flow, creep, frequency and temperature sweeps were performed to further investigate the behavior of WMA binders and polymer modified WMA binders. Finally, the rate of aging of the binders in the high temperature range 46-76°C was studied by comparing the percent increase in complex modulus values of RTFO aged binders to the values of PAV aged binders.

6.2. Conclusions

Twelve WMA mixtures were mixed and compacted at 120°C and 110°C, respectively using Advera, Evotherm and Sasobit additives and two coarse aggregate types: limestone and quartzite. Limestone was selected because it is a commonly used aggregate type in the Midwest while quartzite was utilized as it is often needed in pavements requiring higher skid resistance. Also the chemistry of the limestone and quartzite aggregates are different with the limestone comprised of calcium and quartzite silica. In addition, the potential for incorporating higher percentages of RAP was analyzed by preparing half of the mixtures with 30% RAP content so that its performance can be compared to equivalent mixtures that do not contain any RAP.

6.2.1. Performance Tests of WMA Mixtures

Two performance tests: dynamic modulus and flow number were conducted to characterize the stress-strain relationship and permanent deformation properties, respectively. The properties of the WMA mixtures were compared to the characteristics of four control HMA mixes produced and compacted at typical HMA temperatures. The dynamic modulus test data showed that WMA mixtures had lower dynamic modulus |E*| values compared to the values of control HMA mixes. This observation could be attributed to the lower aging of WMA mixtures as they were exposed to lower production and compaction temperatures compared to the HMA control mixtures. Moreover, the differences in dynamic modulus values between control HMA mixtures and the WMA mixtures decreased as the test temperature increased. As a result, the largest differences in |E*| values between WMA, Evotherm and Sasobit in particular, and the HMA mixtures were observed at 4°C. Thus, the lower |E*| values of the WMA mixes at low and mid range temperatures may deem these mixtures more suitable for use in cold climates due to its lower stiffness at lower temperatures which could make the pavements more resistant to low temperature and fatigue cracking.

The incorporating of RAP into the mixtures prepared in this dissertation led to increasing of the dynamic modulus values of all mixtures in comparison with the corresponding mixtures that did not have any RAP content. A reasonable cause for such an increase is the higher stiffness of the aged binder present in the RAP. Moreover, control

HMA mixtures with RAP recorded higher |E*| compared to their equivalent WMA mixtures. The impact of RAP incorporation on the increase in dynamic moduli values decreased as the test temperature increased. On the other hand, the rutting resistance of WMA mixtures is a concern as it was significantly lower than that of HMA mixtures based on flow number test results, possibly, due to the lower aging undergone by the WMA mixtures as they were exposed to lower mixing and compaction temperatures. The RAP inclusion generally improved the permanent deformation resistance of all mixtures; however, its impact was more evident in the performance of HMA mixtures than in the WMA mixtures. Hence, the suitability of the studied WMA technologies for use in pavements located in hot climate regions needs to be further investigated.

6.2.2. Performance Prediction of Pavements with WMA using MEPDG

The test data acquired by conducting the dynamic modulus test on specimens of twelve WMA mixtures and four HMA mixtures were used as input data into the MEPDG software. This software package was used to estimate the performance of pavements designs made from the lab produced WMA and HMA mixtures. All the design inputs used were default values suggested by the software except for climatic region, traffic level, asphalt layer properties and pavement structure which is dependent on the traffic level.

For the climatic input data, a climatic database of Des Moines, Iowa was used given its central location within the State of Iowa and the Midwest of the United States. Moreover, three levels of traffic levels were studied for different roads, low, medium and high with the average annual daily truck traffic and traffic growth values reasonably assumed for each traffic level. In addition, the dynamic modulus values of the HMA and WMA mixtures acquired from lab testing were used as input characteristics of the asphalt layer. Finally, the asphalt pavement structure designed comprised three structural layers: the asphalt cement layer, crushed stone base layer and subgrade with only the thickness of the asphalt layer varying with the increase in traffic volume. The MEPDG software runs generate an output that estimates the primary distresses resulting from the accumulation of damage in the structure of the pavement over a specific period of time. Typical distresses estimated by MEPDG are permanent deformation, alligator (fatigue) cracking and the International Roughness Index (IRI) which is an indicator of pavement smoothness and overall quality.

The MEPDG output predicting the performance of different mixtures through the estimation of pavement distresses generally agreed with observations deduced from the laboratory test results. The estimated rutting and terminal IRI values agreed with the trends exhibited by the results of flow number and dynamic modulus tests, respectively. ANOVA statistical analysis of MEPDG output data showed that RAP content is a significant factor that affects alligator cracking while the incorporation of WMA additives impact on the rutting of the AC layer is statistically significant for the limestone mixtures only. In addition, for rutting in the full layers of the pavement was affected by both RAP content and WMA additives for the limestone mixtures however only the addition of WMA was significant for the quartzite mixtures. Moreover, multiple comparison techniques showed that for limestone mixtures, the control mix was significantly different from all three mixtures incorporating WMA additives in terms of its rutting and IRI predicted performance. On the other hand, for the quartzite mixtures, Evotherm mixtures were the only WMA technology to be deemed statistically different from the control mixtures.

6.2.3. WMA Binder Testing

The viscosity of the binders incorporating WMA additives: Sasobit which is a Fisher-Tropsch wax and the chemical additive, Evotherm J1 was lower than that of the control binder at 135°C. The complex modulus G* values of Evotherm binder was similar to that of the control binder with the Sasobit binder recording the highest G* values among the unmodified binders. On the other hand, upon modifying the binders with SBS polymers, the complex moduli of all binders increased with the Sasobit modified binder again recording highest G* values which caused the shifting of the high temperature grade to 76°C. This indicates the possible presence of a combining effect between the SBS polymers and the wax WMA additive that could have recrystallized in the binder causing a notable increase in the stiffness of the binder. Thus, polymer modified Sasobit binders could be suitable for usage in hot climatic regions where high resistance to rutting is a vital requirement. Such observations were reinforced by the test results of the creep and frequency sweeps that confirm Sasobit unmodified binder superior stiffness compared to other unmodified binders at high temperature ranges. Moreover, the midrange temperature performance of the WMA unmodified binders indicates that there are no concerns arising regarding their resistance to fatigue cracking.

As for modified binders, the binder incorporating Sasobit exhibited lower phase angles which are indicative of the formation of higher degree of polymer networks in the binder. In contrast, the higher phase angles of the Evotherm unmodified binders indicate lower resistance to rutting. Moreover, all the binders investigated illustrated shear-thinning behavior at 60°C with the unmodified Evotherm binder looking more susceptible to rutting than other binders. In addition, master curves were constructed using the complex modulus test data acquired from the frequency sweeps carried on the unmodified and polymer modified WMA binders. The master curves of the unmodified binders show that the complex modulus of the control binder was not significantly different from the moduli of the WMA binders.

The incorporation of Sasobit pellets to the unmodified binder reduced the aging rate of the binder in the PAV as the waxy WMA additive behaved as an antioxidant. On the other hand, the addition of Evotherm had the opposite effect on the aging rate of the unmodified binder. The addition of SBS polymer significantly altered the aging behavior of WMA binders. For example, the introduction of the SBS polymers seemed to inhibit the antioxidant effect of Sasobit on the aging rate of the binder in the PAV oven causing an increase in the rate of aging. The polymer introduction to the Evotherm binder weakened the effect of the WMA additive on the aging rate of the binder in the PAV oven as indicated by the values of the complex shear modulus.

6.3. Recommendations

Based on the results of this research, it is recommended to explore the following:

- The properties of WMA mixtures incorporating higher percentage of RAP should be investigated in terms of its dynamic modulus characterization and its permanent deformation
- Mixtures using the same constituents and proportions of the laboratory mixtures manufactured in this study should be tried in small field projects, with field samples

cored out at regular intervals to assess the performance of the pavements throughout the life cycle of the pavement.

- The properties of the binders utilized in this work should be studied in correlation to the properties of the asphalt mixtures with the objective to explore the presence of any relationship or correlation present between the binder phase properties and the asphalt mix matrix.
- Due to the high variability in the results of the flow number test, it is recommended to evaluate the permanent deformation properties of WMA mixtures using other experimental procedures using equipment like the asphalt pavement analyzer (APA) or the Hamburg Wheel Tracking (HWT) machine.
- Conducting a study that investigates the volumetric and performance characteristics of polymer modified WMA mixtures is recommended. A comprehensive value engineering study in using WMA additives with and without polymer modification is suggested.
- To study the binder properties at significantly lower and higher temperatures using suitable rheological equipment such as differential scanning calorimetry (DSC) to capture the rheological behavior of the binders at a wider temperature range.
- Conducting chromatographic tests to separate the asphalt constituents to acquire better understanding of the chemical interactions between the WMA additives, SBS and the binder constituents.
- Performing an environmental impact study of incorporating WMA additives and RAP including the calculation of carbon footprints of different mixture designs and

construction approaches is recommended for future work to accurately quantify the impact of WMA usage on reducing carbon emissions.

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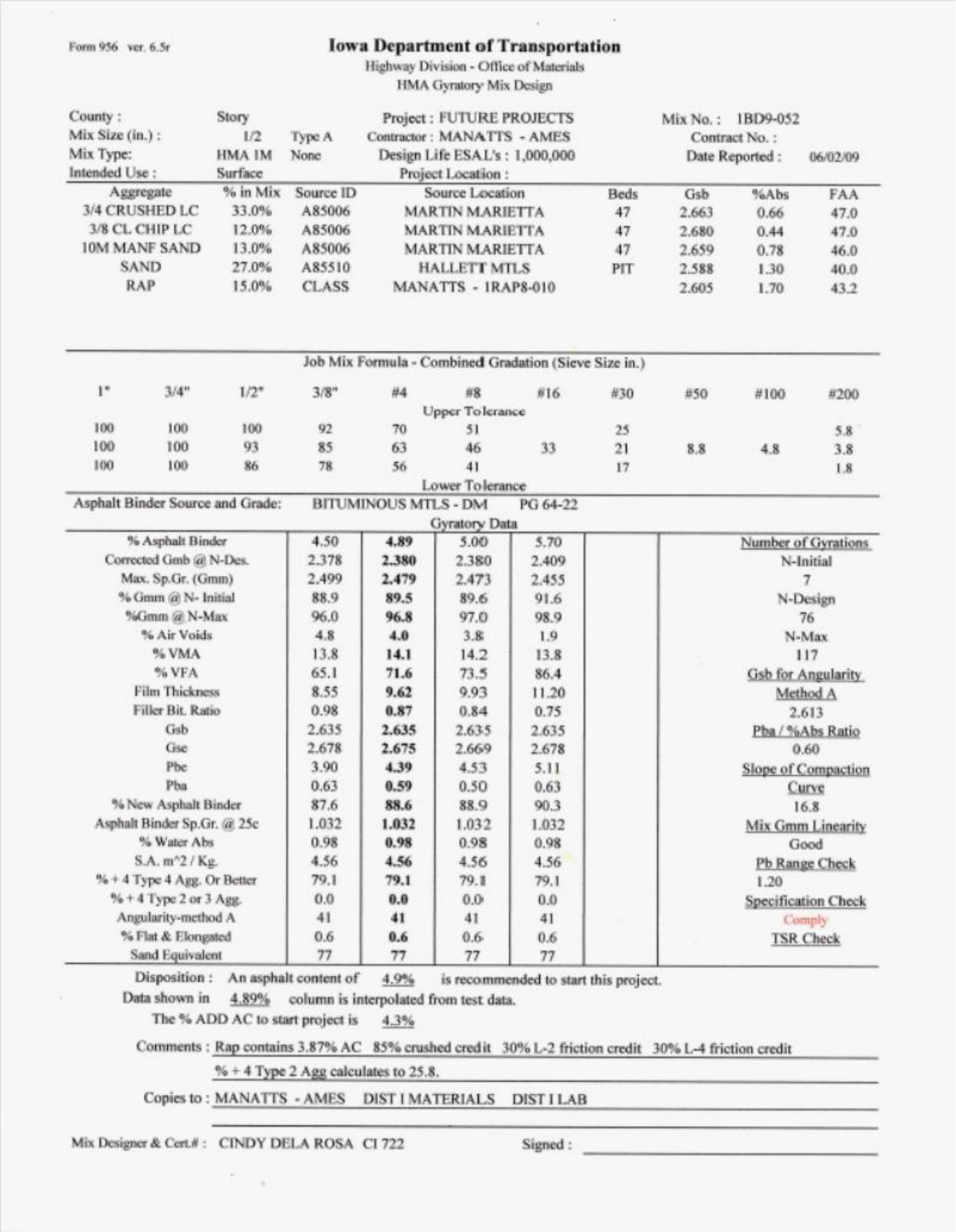
APPENDIX A SAMPLE JOB MIX FORMULAS OF WMA MIXTURES



Form 956 ver. 6.5r

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

County :	Story		Project : FUTURE PROJECTS	Mix No. : 1BD9-052
Mix Size (in.) :	1/2	Type A	Contractor : MANATTS - AMES	Contract No. :
Mix Type:	HMA 1M	None	Design Life ESAL's : 1,000,000	Date Reported : 06/02/09
Intended Use :	Surface		Project Location :	

Aggregate	% in Mix	Source ID	Source Location	Beds	Gsb	%Abs	FAA
3/4 CRUSHED LC	33.0%	A85006	MARTIN MARIETTA	47	2.663	0.66	47.0
3/8 CL CHIP LC	12.0%	A85006	MARTIN MARIETTA	47	2.680	0.44	47.0
10M MANF SAND	13.0%	A85006	MARTIN MARIETTA	47	2.659	0.78	46.0
SAND	27.0%	A85510	HALLETT MTLS	PIT	2.588	1.30	40.0
RAP	15.0%	CLASS	MANATTS - 1RAP8-010		2.605	1.70	43.2

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	92	70	51		25			5.8
100	100	93	85	63	46	33	21	8.8	4.8	3.8
100	100	86	78	56	41		17			1.8
					Lower Tolerance					

Asphalt Binder Source and Grade: BITUMINOUS MTLS - DM PG 64-22

Gyratory Data

% Asphalt Binder	4.50	**4.89**	5.00	5.70		
Corrected Gmb @ N-Des.	2.378	**2.380**	2.380	2.409		
Max. Sp.Gr. (Gmm)	2.499	**2.479**	2.473	2.455		
% Gmm @ N- Initial	88.9	**89.5**	89.6	91.6		
%Gmm @ N-Max	96.0	**96.8**	97.0	98.9		
% Air Voids	4.8	**4.0**	3.8	1.9		
% VMA	13.8	**14.1**	14.2	13.8		
% VFA	65.1	**71.6**	73.5	86.4		
Film Thickness	8.55	**9.62**	9.93	11.20		
Filler Bit. Ratio	0.98	**0.87**	0.84	0.75		
Gsb	2.635	**2.635**	2.635	2.635		
Gse	2.678	**2.675**	2.669	2.678		
Pbe	3.90	**4.39**	4.53	5.11		
Pba	0.63	**0.59**	0.50	0.63		
% New Asphalt Binder	87.6	**88.6**	88.9	90.3		
Asphalt Binder Sp.Gr. @ 25c	1.032	**1.032**	1.032	1.032		
% Water Abs	0.98	**0.98**	0.98	0.98		
S.A. m^2 / Kg.	4.56	**4.56**	4.56	4.56		
% + 4 Type 4 Agg. Or Better	79.1	**79.1**	79.1	79.1		
% + 4 Type 2 or 3 Agg.	0.0	**0.0**	0.0	0.0		
Angularity-method A	41	**41**	41	41		
% Flat & Elongated	0.6	**0.6**	0.6	0.6		
Sand Equivalent	77	**77**	77	77		

Number of Gyrations
N-Initial
7
N-Design
76
N-Max
117
Gsb for Angularity
Method A
2.613
Pba / %Abs Ratio
0.60
Slope of Compaction
Curve
16.8
Mix Gmm Linearity
Good
Pb Range Check
1.20
Specification Check
Comply
TSR Check

Disposition : An asphalt content of 4.9% is recommended to start this project.
Data shown in 4.89% column is interpolated from test data.
The % ADD AC to start project is 4.3%

Comments : Rap contains 3.87% AC 85% crushed credit 30% L-2 friction credit 30% L-4 friction credit
% + 4 Type 2 Agg calculates to 25.8.

Copies to : MANATTS - AMES DIST I MATERIALS DIST I LAB

Mix Designer & Cert.# : CINDY DELA ROSA CI 722 Signed :

APPENDIX B DYNAMIC MODULUS TEST RESULTS

The results of the dynamic modulus test and phase angle for the mixtures are presented in Tables B-1 and B-2, respectively.

Table B-1 Dynamic modulus for non-moisture conditioned mixes (Pa)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM1-NMC	Mean	4	1.57E+07	1.49E+07	1.41E+07	1.31E+07	1.25E+07	1.07E+07	9.82E+06	9.18E+06	7.54E+06
LM1-NMC	SD	4	1.13E+06	1.01E+06	9.36E+05	8.73E+05	1.22E+06	9.31E+05	7.82E+05	8.84E+05	7.14E+05
LM1-NMC	CoV	4	7.17	6.79	6.66	6.69	9.74	8.73	7.96	9.63	9.48
LM1-NMC	Mean	21	6.86E+06	6.21E+06	5.77E+06	4.98E+06	4.15E+06	3.09E+06	2.61E+06	2.54E+06	1.71E+06
LM1-NMC	SD	21	4.18E+05	3.49E+05	2.80E+05	2.73E+05	2.98E+05	3.14E+05	3.48E+05	2.78E+05	1.62E+05
LM1-NMC	CoV	21	6.09	5.62	4.85	5.49	7.17	10.17	13.30	10.97	9.44
LM1-NMC	Mean	37	2.80E+06	2.36E+06	2.12E+06	1.69E+06	1.24E+06	9.27E+05	7.73E+05	6.65E+05	4.46E+05
LM1-NMC	SD	37	4.06E+05	3.53E+05	3.14E+05	2.47E+05	2.04E+05	1.22E+05	1.22E+05	1.09E+05	5.22E+04
LM1-NMC	CoV	37	14.50	14.98	14.83	14.59	16.37	13.20	15.81	16.33	11.70
LM4-NMC	Mean	4	1.45E+07	1.41E+07	1.33E+07	1.21E+07	1.08E+07	9.09E+06	8.61E+06	8.08E+06	6.09E+06
LM4-NMC	SD	4	7.97E+05	2.02E+06	1.96E+06	1.83E+06	2.25E+06	1.72E+06	1.31E+06	1.37E+06	1.62E+06
LM4-NMC	CoV	4	5.49	14.28	14.77	15.12	20.81	18.94	15.23	16.95	26.56
LM4-NMC	Mean	21	6.06E+06	5.30E+06	4.79E+06	4.00E+06	3.16E+06	2.24E+06	1.87E+06	1.55E+06	9.88E+05
LM4-NMC	SD	21	2.71E+05	1.71E+05	1.41E+05	1.42E+05	1.79E+05	1.64E+05	1.55E+05	1.56E+05	1.23E+05
LM4-NMC	CoV	21	4.47	3.23	2.95	3.54	5.67	7.34	8.29	10.05	12.44
LM4-NMC	Mean	37	1.85E+06	1.52E+06	1.32E+06	1.05E+06	7.50E+05	5.42E+05	4.36E+05	3.85E+05	2.60E+05
LM4-NMC	SD	37	3.85E+05	3.25E+05	2.73E+05	1.87E+05	1.14E+05	1.09E+05	7.79E+04	6.72E+04	3.59E+04
LM4-NMC	CoV	37	20.85	21.37	20.76	17.91	15.26	20.14	17.87	17.43	13.82

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM7-NMC	Mean	4	1.26E+07	1.15E+07	1.09E+07	1.00E+07	9.19E+06	7.47E+06	6.72E+06	6.57E+06	4.90E+06
LM7-NMC	SD	4	1.15E+06	9.06E+05	9.25E+05	8.11E+05	7.49E+05	5.42E+05	7.26E+05	3.92E+05	2.90E+05
LM7-NMC	CoV	4	9.12	7.87	8.51	8.10	8.15	7.25	10.81	5.96	5.92
LM7-NMC	Mean	21	4.75E+06	4.21E+06	3.78E+06	3.08E+06	2.38E+06	1.65E+06	1.33E+06	1.08E+06	6.63E+05
LM7-NMC	SD	21	4.06E+05	3.03E+05	2.56E+05	1.91E+05	1.29E+05	8.84E+04	5.79E+04	4.02E+04	1.07E+04
LM7-NMC	CoV	21	8.55	7.21	6.78	6.20	5.43	5.36	4.33	3.73	1.61
LM7-NMC	Mean	37	1.48E+06	1.24E+06	1.07E+06	8.58E+05	6.26E+05	4.96E+05	3.97E+05	3.66E+05	2.31E+05
LM7-NMC	SD	37	1.47E+04	2.39E+04	3.73E+04	2.82E+04	1.49E+04	2.43E+04	1.59E+04	2.66E+04	2.72E+03
LM7-NMC	CoV	37	0.99	1.93	3.47	3.28	2.39	4.89	4.00	7.27	1.18
LM10-NMC	Mean	4	1.41E+07	1.29E+07	1.20E+07	1.10E+07	1.01E+07	8.58E+06	7.80E+06	7.27E+06	5.36E+06
LM10-NMC	SD	4	1.25E+06	1.03E+06	1.03E+06	8.89E+05	8.06E+05	7.97E+05	8.74E+05	6.73E+05	4.93E+05
LM10-NMC	CoV	4	8.81	8.00	8.56	8.09	7.96	9.30	11.21	9.26	9.19
LM10-NMC	Mean	21	5.98E+06	5.23E+06	4.70E+06	3.92E+06	3.15E+06	2.22E+06	1.84E+06	1.52E+06	9.79E+05
LM10-NMC	SD	21	3.30E+05	3.01E+05	2.55E+05	2.38E+05	2.31E+05	1.55E+05	1.17E+05	1.05E+05	7.99E+04
LM10-NMC	CoV	21	5.52	5.76	5.43	6.07	7.35	6.99	6.35	6.91	8.16
LM10-NMC	Mean	37	1.80E+06	1.48E+06	1.29E+06	1.03E+06	7.23E+05	5.44E+05	4.39E+05	3.83E+05	3.02E+05
LM10-NMC	SD	37	9.63E+04	5.17E+04	5.45E+04	5.71E+04	4.36E+04	6.46E+04	6.52E+04	6.10E+04	5.65E+04
LM10-NMC	CoV	37	5.35	3.49	4.21	5.55	6.02	11.88	14.84	15.90	18.71

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM3-NMC	Mean	4	1.81E+07	1.70E+07	1.61E+07	1.54E+07	1.45E+07	1.31E+07	1.20E+07	1.16E+07	1.00E+07
LM3-NMC	SD	4	1.74E+06	1.62E+06	1.42E+06	1.40E+06	1.25E+06	1.64E+06	1.24E+06	1.01E+06	1.13E+06
LM3-NMC	CoV	4	9.64	9.51	8.78	9.05	8.57	12.56	10.33	8.71	11.29
LM3-NMC	Mean	21	9.50E+06	8.70E+06	8.12E+06	7.19E+06	6.32E+06	5.02E+06	4.35E+06	3.96E+06	2.98E+06
LM3-NMC	SD	21	5.22E+05	4.64E+05	4.41E+05	3.62E+05	4.10E+05	2.98E+05	2.47E+05	2.05E+05	1.52E+05
LM3-NMC	CoV	21	5.49	5.33	5.43	5.03	6.50	5.94	5.69	5.19	5.09
LM3-NMC	Mean	37	3.78E+06	3.35E+06	3.00E+06	2.49E+06	1.91E+06	1.42E+06	1.23E+06	1.06E+06	7.64E+05
LM3-NMC	SD	37	2.26E+05	1.72E+05	1.55E+05	1.12E+05	9.15E+04	7.70E+04	9.69E+04	8.22E+04	8.15E+04
LM3-NMC	CoV	37	5.96	5.14	5.15	4.52	4.79	5.43	7.89	7.79	10.67
LM6-NMC	Mean	4	1.88E+07	1.80E+07	1.72E+07	1.60E+07	1.51E+07	1.32E+07	1.22E+07	1.10E+07	9.42E+06
LM6-NMC	SD	4	1.61E+06	1.31E+06	1.37E+06	1.23E+06	1.50E+06	8.92E+05	8.65E+05	1.33E+06	6.49E+05
LM6-NMC	CoV	4	8.57	7.27	7.98	7.65	9.92	6.75	7.08	12.05	6.90
LM6-NMC	Mean	21	7.74E+06	6.92E+06	6.39E+06	5.52E+06	4.64E+06	3.49E+06	2.99E+06	2.62E+06	1.83E+06
LM6-NMC	SD	21	3.58E+05	2.97E+05	2.90E+05	2.76E+05	2.10E+05	1.89E+05	1.22E+05	1.08E+05	8.89E+04
LM6-NMC	CoV	21	4.63	4.29	4.54	5.01	4.53	5.42	4.08	4.12	4.85
LM6-NMC	Mean	37	2.91E+06	2.40E+06	2.10E+06	1.66E+06	1.18E+06	7.78E+05	6.93E+05	5.67E+05	4.40E+05
LM6-NMC	SD	37	2.57E+05	2.05E+05	1.81E+05	1.56E+05	1.14E+05	8.72E+04	1.38E+05	1.02E+05	1.15E+05
LM6-NMC	CoV	37	8.82	8.56	8.62	9.41	9.62	11.20	19.92	18.00	26.25

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM9-NMC	Mean	4	1.59E+07	1.50E+07	1.43E+07	1.33E+07	1.24E+07	1.05E+07	9.97E+06	9.15E+06	7.31E+06
LM9-NMC	SD	4	1.64E+06	1.32E+06	1.15E+06	9.73E+05	8.91E+05	8.05E+05	9.73E+05	8.44E+05	4.52E+05
LM9-NMC	CoV	4	10.31	8.82	7.98	7.32	7.20	7.65	9.76	9.23	6.19
LM9-NMC	Mean	21	6.79E+06	6.08E+06	5.54E+06	4.70E+06	3.85E+06	2.80E+06	2.38E+06	2.08E+06	1.40E+06
LM9-NMC	SD	21	5.04E+04	5.03E+04	2.26E+04	3.95E+04	4.55E+04	3.79E+04	5.06E+04	6.09E+04	2.35E+04
LM9-NMC	CoV	21	0.74	0.83	0.41	0.84	1.18	1.35	2.13	2.93	1.68
LM9-NMC	Mean	37	2.26E+06	1.87E+06	1.63E+06	1.29E+06	9.02E+05	6.28E+05	4.80E+05	4.03E+05	3.15E+05
LM9-NMC	SD	37	1.10E+05	8.73E+04	6.72E+04	5.32E+04	5.50E+04	7.11E+04	5.47E+04	4.56E+04	6.19E+04
LM9-NMC	CoV	37	4.87	4.67	4.12	4.11	6.10	11.32	11.40	11.33	19.65
LM12-NMC	Mean	4	1.56E+07	1.44E+07	1.37E+07	1.26E+07	1.19E+07	9.91E+06	9.26E+06	8.53E+06	6.64E+06
LM12-NMC	SD	4	2.00E+06	1.92E+06	1.62E+06	1.41E+06	1.54E+06	1.19E+06	1.22E+06	1.19E+06	8.45E+05
LM12-NMC	CoV	4	12.80	13.29	11.84	11.16	13.02	12.04	13.22	13.94	12.72
LM12-NMC	Mean	21	6.83E+06	6.08E+06	5.54E+06	4.70E+06	3.83E+06	2.81E+06	2.40E+06	2.06E+06	1.35E+06
LM12-NMC	SD	21	9.08E+05	7.87E+05	7.61E+05	6.79E+05	5.90E+05	4.20E+05	4.01E+05	3.32E+05	2.04E+05
LM12-NMC	CoV	21	13.30	12.94	13.74	14.43	15.39	14.94	16.70	16.08	15.12
LM12-NMC	Mean	37	2.20E+06	1.81E+06	1.59E+06	1.25E+06	8.61E+05	5.69E+05	4.37E+05	3.66E+05	2.65E+05
LM12-NMC	SD	37	2.07E+05	1.47E+05	1.25E+05	8.79E+04	4.16E+04	2.28E+04	1.78E+04	1.40E+04	1.45E+04
LM12-NMC	CoV	37	9.45	8.09	7.91	7.04	4.83	4.01	4.08	3.83	5.48

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM13-NMC	Mean	4	1.57E+07	1.54E+07	1.48E+07	1.35E+07	1.24E+07	1.04E+07	9.41E+06	9.08E+06	7.33E+06
LM13-NMC	SD	4	1.60E+06	1.46E+06	1.50E+06	1.13E+06	1.56E+06	1.35E+06	1.09E+06	1.24E+06	9.05E+05
LM13-NMC	CoV	4	10.16	9.50	10.16	8.33	12.53	13.04	11.56	13.62	12.36
LM13-NMC	Mean	21	7.87E+06	7.06E+06	6.50E+06	5.58E+06	4.58E+06	3.44E+06	2.95E+06	2.57E+06	1.75E+06
LM13-NMC	SD	21	5.19E+05	4.07E+05	3.56E+05	2.94E+05	2.98E+05	2.34E+05	1.79E+05	1.49E+05	7.96E+04
LM13-NMC	CoV	21	6.59	5.76	5.48	5.28	6.50	6.81	6.08	5.80	4.55
LM13-NMC	Mean	37	2.93E+06	2.43E+06	2.11E+06	1.69E+06	1.14E+06	7.95E+05	6.10E+05	5.21E+05	3.82E+05
LM13-NMC	SD	37	2.71E+05	2.23E+05	1.81E+05	1.26E+05	1.01E+05	1.16E+05	7.41E+04	6.16E+04	6.42E+04
LM13-NMC	CoV	37	9.22	9.17	8.55	7.50	8.87	14.58	12.13	11.82	16.82
LM15-NMC	Mean	4	1.52E+07	1.41E+07	1.31E+07	1.25E+07	1.17E+07	9.79E+06	8.93E+06	8.48E+06	6.69E+06
LM15-NMC	SD	4	2.57E+06	2.30E+06	1.00E+06	1.65E+06	1.75E+06	1.47E+06	1.11E+06	9.99E+05	6.36E+05
LM15-NMC	CoV	4	16.92	16.31	7.63	13.13	14.93	14.98	12.42	11.78	9.51
LM15-NMC	Mean	21	6.31E+06	5.66E+06	5.13E+06	4.30E+06	3.40E+06	2.43E+06	2.07E+06	1.69E+06	1.09E+06
LM15-NMC	SD	21	2.06E+05	2.41E+05	2.01E+05	2.14E+05	9.89E+04	1.36E+05	1.20E+05	1.20E+05	6.08E+04
LM15-NMC	CoV	21	3.26	4.26	3.93	4.97	2.91	5.60	5.78	7.10	5.60
LM15-NMC	Mean	37	1.86E+06	1.52E+06	1.32E+06	1.07E+06	7.21E+05	5.41E+05	4.48E+05	3.70E+05	2.63E+05
LM15-NMC	SD	37	1.51E+05	1.20E+05	8.28E+04	7.68E+04	5.49E+04	6.20E+04	6.61E+04	1.29E+04	2.46E+04
LM15-NMC	CoV	37	8.11	7.87	6.26	7.18	7.62	11.48	14.74	3.49	9.33

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM17-NMC	Mean	4	1.38E+07	1.25E+07	1.19E+07	1.07E+07	9.62E+06	7.78E+06	6.98E+06	6.57E+06	5.06E+06
LM17-NMC	SD	4	1.25E+06	8.87E+05	9.44E+05	8.45E+05	1.00E+06	9.65E+05	8.20E+05	7.32E+05	6.31E+05
LM17-NMC	CoV	4	9.02	7.11	7.95	7.90	10.43	12.40	11.75	11.15	12.48
LM17-NMC	Mean	21	5.37E+06	4.77E+06	4.29E+06	3.50E+06	2.71E+06	1.94E+06	1.59E+06	1.33E+06	8.42E+05
LM17-NMC	SD	21	2.43E+05	2.57E+05	2.04E+05	1.73E+05	1.79E+05	1.20E+05	1.50E+05	1.34E+05	8.34E+04
LM17-NMC	CoV	21	4.52	5.39	4.74	4.94	6.59	6.20	9.47	10.12	9.90
LM17-NMC	Mean	37	1.68E+06	1.37E+06	1.20E+06	9.79E+05	6.52E+05	4.60E+05	3.51E+05	3.37E+05	2.34E+05
LM17-NMC	SD	37	1.86E+05	1.47E+05	1.16E+05	1.01E+05	9.05E+04	6.42E+04	2.41E+04	2.63E+04	2.03E+04
LM17-NMC	CoV	37	11.04	10.73	9.72	10.35	13.88	13.95	6.88	7.79	8.67
LM20-NMC	Mean	4	1.49E+07	1.38E+07	1.30E+07	1.19E+07	1.09E+07	9.05E+06	8.44E+06	7.70E+06	5.11E+06
LM20-NMC	SD	4	1.76E+06	1.39E+06	1.24E+06	1.06E+06	1.23E+06	9.52E+05	8.98E+05	9.03E+05	9.54E+05
LM20-NMC	CoV	4	11.86	10.05	9.56	8.87	11.24	10.51	10.64	11.73	18.68
LM20-NMC	Mean	21	6.02E+06	5.29E+06	4.80E+06	4.01E+06	3.16E+06	2.32E+06	1.92E+06	1.64E+06	1.07E+06
LM20-NMC	SD	21	5.64E+05	4.59E+05	3.67E+05	2.70E+05	1.70E+05	1.67E+05	1.29E+05	1.23E+05	1.24E+05
LM20-NMC	CoV	21	9.36	8.68	7.64	6.72	5.38	7.18	6.75	7.49	11.61
LM20-NMC	Mean	37	2.05E+06	1.70E+06	1.47E+06	1.20E+06	7.98E+05	5.76E+05	4.79E+05	4.09E+05	3.07E+05
LM20-NMC	SD	37	1.72E+05	1.57E+05	1.46E+05	1.12E+05	9.34E+04	7.62E+04	9.60E+04	8.00E+04	3.22E+04
LM20-NMC	CoV	37	8.42	9.24	9.89	9.31	11.70	13.24	20.03	19.58	10.48

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM14-NMC	Mean	4	1.24E+07	1.41E+07	1.39E+07	1.31E+07	1.25E+07	1.08E+07	9.96E+06	9.42E+06	7.80E+06
LM14-NMC	SD	4	4.23E+05	1.16E+06	1.04E+06	3.71E+05	3.59E+05	1.94E+05	2.50E+05	2.26E+05	6.20E+05
LM14-NMC	CoV	4	3.42	8.24	7.47	2.82	2.86	1.80	2.51	2.40	7.96
LM14-NMC	Mean	21	7.88E+06	7.15E+06	6.62E+06	5.77E+06	4.96E+06	3.79E+06	3.37E+06	3.02E+06	2.18E+06
LM14-NMC	SD	21	6.66E+05	4.78E+05	4.06E+05	3.45E+05	3.28E+05	2.66E+05	2.24E+05	2.10E+05	1.70E+05
LM14-NMC	CoV	21	8.45	6.68	6.14	5.98	6.61	7.01	6.63	6.97	7.78
LM14-NMC	Mean	37	2.99E+06	2.57E+06	2.30E+06	1.89E+06	1.35E+06	9.62E+05	7.96E+05	6.61E+05	4.90E+05
LM14-NMC	SD	37	1.61E+05	1.17E+05	1.30E+05	1.11E+05	6.90E+04	4.06E+04	3.42E+04	9.38E+03	5.92E+03
LM14-NMC	CoV	37	5.40	4.55	5.64	5.90	5.13	4.22	4.29	1.42	1.21
LM16-NMC	Mean	4	1.55E+07	1.45E+07	1.37E+07	1.29E+07	1.23E+07	1.03E+07	9.56E+06	8.98E+06	7.24E+06
LM16-NMC	SD	4	8.32E+05	6.75E+05	4.56E+05	4.06E+05	6.68E+05	2.59E+05	1.38E+05	2.46E+05	2.75E+05
LM16-NMC	CoV	4	5.36	4.66	3.32	3.14	5.45	2.52	1.44	2.74	3.80
LM16-NMC	Mean	21	6.64E+06	5.94E+06	5.45E+06	4.67E+06	3.78E+06	2.83E+06	2.43E+06	2.12E+06	1.42E+06
LM16-NMC	SD	21	4.07E+05	2.98E+05	2.47E+05	1.92E+05	1.78E+05	7.82E+04	5.66E+04	3.51E+04	3.23E+04
LM16-NMC	CoV	21	6.13	5.01	4.53	4.11	4.72	2.76	2.33	1.66	2.27
LM16-NMC	Mean	37	2.43E+06	2.03E+06	1.77E+06	1.42E+06	9.47E+05	7.27E+05	5.93E+05	4.86E+05	3.25E+05
LM16-NMC	SD	37	2.58E+05	2.04E+05	1.88E+05	1.40E+05	1.03E+05	9.23E+04	8.42E+04	3.54E+04	3.34E+04
LM16-NMC	CoV	37	10.62	10.04	10.58	9.87	10.83	12.69	14.20	7.29	10.30

Table B-1 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM19-NMC	Mean	4	1.65E+07	1.53E+07	1.46E+07	1.33E+07	1.18E+07	1.01E+07	9.04E+06	8.43E+06	6.76E+06
LM19-NMC	SD	4	1.28E+06	8.69E+05	7.21E+05	7.00E+05	8.10E+05	5.43E+05	4.28E+05	4.11E+05	4.62E+05
LM19-NMC	CoV	4	7.78	5.69	4.95	5.25	6.85	5.39	4.74	4.87	6.83
LM19-NMC	Mean	21	6.00E+06	5.36E+06	4.94E+06	4.16E+06	3.36E+06	2.51E+06	2.16E+06	1.88E+06	1.27E+06
LM19-NMC	SD	21	8.43E+05	7.70E+05	7.15E+05	6.15E+05	5.41E+05	3.95E+05	3.52E+05	3.34E+05	2.30E+05
LM19-NMC	CoV	21	14.04	14.38	14.47	14.79	16.10	15.69	16.30	17.75	18.10
LM19-NMC	Mean	37	2.04E+06	1.71E+06	1.49E+06	1.20E+06	8.09E+05	5.98E+05	4.73E+05	3.97E+05	2.81E+05
LM19-NMC	SD	37	2.01E+05	1.39E+05	1.31E+05	9.50E+04	3.83E+04	5.93E+04	6.44E+04	5.21E+04	4.98E+04
LM19-NMC	CoV	37	9.81	8.15	8.80	7.92	4.74	9.91	13.63	13.11	17.72
LM21-NMC	Mean	4	1.72E+07	1.61E+07	1.52E+07	1.42E+07	1.30E+07	1.12E+07	1.02E+07	9.82E+06	8.07E+06
LM21-NMC	SD	4	1.11E+06	7.96E+05	7.64E+05	5.06E+05	6.29E+05	6.70E+05	7.18E+05	6.91E+05	6.38E+05
LM21-NMC	CoV	4	6.41	4.95	5.02	3.56	4.82	5.99	7.05	7.04	7.91
LM21-NMC	Mean	21	6.50E+06	5.79E+06	5.30E+06	4.55E+06	3.73E+06	2.82E+06	2.45E+06	2.17E+06	1.44E+06
LM21-NMC	SD	21	5.92E+05	4.64E+05	3.92E+05	3.19E+05	3.03E+05	2.07E+05	1.64E+05	1.30E+05	8.80E+04
LM21-NMC	CoV	21	9.11	8.02	7.39	7.02	8.10	7.32	6.71	6.00	6.10
LM21-NMC	Mean	37	2.49E+06	2.09E+06	1.87E+06	1.51E+06	1.07E+06	8.15E+05	6.49E+05	5.50E+05	3.79E+05
LM21-NMC	SD	37	3.05E+05	2.72E+05	2.50E+05	1.81E+05	1.37E+05	9.71E+04	1.04E+05	7.38E+04	7.62E+04
LM21-NMC	CoV	37	12.27	13.01	13.37	11.99	12.83	11.91	16.04	13.41	20.12

Table B-2 Phase angle for non-moisture conditioned mixes (degrees)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM1-NMC	Mean	4	5.90	8.05	8.98	10.38	10.89	12.09	12.79	13.89	17.86
LM1-NMC	SD	4	0.62	0.59	0.42	0.53	0.55	1.65	1.09	5.15	3.99
LM1-NMC	CoV	4	10.43	7.32	4.72	5.09	5.08	13.65	8.54	37.04	22.33
LM1-NMC	Mean	21	15.27	17.32	18.21	20.76	24.18	24.84	27.78	31.18	34.92
LM1-NMC	SD	21	0.82	0.54	0.74	0.63	1.60	3.10	0.93	2.47	5.50
LM1-NMC	CoV	21	5.36	3.14	4.06	3.05	6.63	12.46	3.35	7.93	15.74
LM1-NMC	Mean	37	23.57	24.62	25.28	26.94	30.81	31.80	35.97	37.38	39.15
LM1-NMC	SD	37	0.65	0.71	0.51	0.55	1.19	1.47	2.34	1.12	0.53
LM1-NMC	CoV	37	2.75	2.88	2.03	2.04	3.87	4.62	6.51	2.99	1.34
LM4-NMC	Mean	4	6.11	9.47	10.55	11.92	13.43	16.23	17.17	18.90	27.72
LM4-NMC	SD	4	2.56	0.79	0.35	0.31	0.33	0.31	0.47	1.14	3.12
LM4-NMC	CoV	4	41.91	8.37	3.31	2.61	2.49	1.92	2.75	6.05	11.27
LM4-NMC	Mean	21	19.21	20.90	22.68	25.53	29.91	31.75	36.40	37.58	37.20
LM4-NMC	SD	21	0.93	0.95	0.96	0.98	0.68	1.10	3.40	1.78	2.13
LM4-NMC	CoV	21	4.84	4.54	4.23	3.85	2.26	3.47	9.33	4.75	5.72
LM4-NMC	Mean	37	28.90	28.79	28.77	28.38	32.23	28.29	33.96	37.59	39.35
LM4-NMC	SD	37	0.52	0.30	0.34	0.89	1.11	3.57	2.15	2.50	2.16
LM4-NMC	CoV	37	1.80	1.04	1.17	3.13	3.45	12.63	6.34	6.64	5.50

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM7-NMC	Mean	4	8.27	9.95	11.04	13.09	14.66	15.08	15.54	23.96	28.90
LM7-NMC	SD	4	0.48	0.54	0.31	0.27	0.25	1.42	1.17	2.59	3.97
LM7-NMC	CoV	4	5.81	5.42	2.84	2.03	1.70	9.41	7.54	10.79	13.75
LM7-NMC	Mean	21	21.82	23.48	25.12	28.09	30.67	32.72	34.54	38.43	36.92
LM7-NMC	SD	21	0.75	0.20	0.10	0.11	1.75	2.92	3.63	1.06	3.76
LM7-NMC	CoV	21	3.43	0.85	0.42	0.39	5.70	8.94	10.51	2.76	10.18
LM7-NMC	Mean	37	28.88	28.87	29.01	27.68	31.30	29.60	32.85	36.43	36.44
LM7-NMC	SD	37	0.91	0.44	0.57	0.66	1.45	2.51	1.37	1.91	1.03
LM7-NMC	CoV	37	3.15	1.53	1.97	2.40	4.64	8.48	4.17	5.24	2.82
LM10-NMC	Mean	4	8.17	9.83	10.74	12.47	13.49	16.01	16.70	19.07	26.87
LM10-NMC	SD	4	0.51	0.43	0.42	0.51	0.44	0.65	0.64	3.95	3.35
LM10-NMC	CoV	4	6.28	4.42	3.95	4.08	3.26	4.06	3.83	20.68	12.47
LM10-NMC	Mean	21	19.21	21.01	22.77	25.58	29.41	32.09	34.52	37.23	37.25
LM10-NMC	SD	21	0.56	0.57	0.69	0.67	1.48	1.27	0.78	1.48	1.24
LM10-NMC	CoV	21	2.94	2.71	3.02	2.64	5.04	3.97	2.26	3.99	3.33
LM10-NMC	Mean	37	27.73	28.60	28.72	28.95	32.41	32.13	34.83	36.51	37.65
LM10-NMC	SD	37	0.96	0.96	0.87	0.68	1.05	2.57	1.66	2.00	2.62
LM10-NMC	CoV	37	3.48	3.36	3.03	2.36	3.25	8.01	4.77	5.48	6.97

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM3-NMC	Mean	4	4.20	6.22	7.00	8.33	9.07	10.54	11.13	11.85	15.37
LM3-NMC	SD	4	1.34	0.47	0.49	0.15	0.64	1.34	1.38	1.25	3.86
LM3-NMC	CoV	4	31.88	7.59	6.99	1.75	7.02	12.70	12.44	10.51	25.11
LM3-NMC	Mean	21	12.81	14.47	15.69	17.92	19.70	22.47	24.20	26.04	29.94
LM3-NMC	SD	21	0.41	0.56	0.69	0.78	0.94	0.83	1.02	1.34	1.23
LM3-NMC	CoV	21	3.22	3.84	4.42	4.33	4.79	3.67	4.22	5.15	4.10
LM3-NMC	Mean	37	21.06	22.48	23.42	25.27	28.46	30.34	33.82	36.42	37.29
LM3-NMC	SD	37	0.49	0.47	0.32	0.29	1.07	1.71	2.77	0.82	1.10
LM3-NMC	CoV	37	2.33	2.11	1.35	1.15	3.76	5.62	8.19	2.25	2.95
LM6-NMC	Mean	4	5.33	7.39	8.13	9.43	10.05	12.25	12.61	13.65	18.11
LM6-NMC	SD	4	0.96	0.31	0.22	0.42	0.29	0.92	0.58	1.39	2.86
LM6-NMC	CoV	4	18.01	4.24	2.67	4.42	2.91	7.52	4.61	10.20	15.81
LM6-NMC	Mean	21	16.34	18.07	19.47	22.06	24.23	27.59	30.04	33.24	36.49
LM6-NMC	SD	21	0.90	1.06	0.97	1.01	1.20	0.79	1.18	1.73	1.10
LM6-NMC	CoV	21	5.51	5.88	5.00	4.56	4.97	2.88	3.94	5.19	3.01
LM6-NMC	Mean	37	25.83	27.51	28.11	29.39	33.36	35.03	36.02	37.69	37.11
LM6-NMC	SD	37	0.72	1.06	0.54	0.60	1.50	1.38	1.76	2.52	4.05
LM6-NMC	CoV	37	2.77	3.84	1.92	2.03	4.49	3.93	4.89	6.68	10.91

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM9-NMC	Mean	4	6.68	8.03	9.22	10.83	11.63	12.29	13.11	18.33	21.36
LM9-NMC	SD	4	0.92	0.29	0.09	0.29	0.46	0.72	0.63	1.99	1.14
LM9-NMC	CoV	4	13.76	3.60	0.93	2.68	3.99	5.87	4.80	10.85	5.34
LM9-NMC	Mean	21	17.91	19.64	21.10	23.64	25.58	29.83	32.09	35.17	38.02
LM9-NMC	SD	21	0.43	0.30	0.31	0.28	0.51	0.70	0.54	1.17	0.91
LM9-NMC	CoV	21	2.40	1.52	1.48	1.20	1.98	2.35	1.69	3.32	2.40
LM9-NMC	Mean	37	26.29	27.52	28.21	28.92	31.75	33.83	34.71	36.06	34.47
LM9-NMC	SD	37	1.09	0.26	0.79	0.33	1.56	1.73	1.46	4.21	5.37
LM9-NMC	CoV	37	4.16	0.96	2.81	1.15	4.91	5.11	4.20	11.67	15.59
LM12-NMC	Mean	4	7.28	8.75	9.95	11.63	12.39	14.31	16.15	17.64	24.22
LM12-NMC	SD	4	0.18	0.38	0.33	0.74	0.67	0.34	0.95	1.05	1.04
LM12-NMC	CoV	4	2.54	4.35	3.33	6.32	5.45	2.40	5.90	5.93	4.31
LM12-NMC	Mean	21	17.87	19.71	21.16	23.95	26.33	30.71	32.71	38.76	39.60
LM12-NMC	SD	21	1.42	0.93	1.18	1.06	1.76	0.63	0.89	2.18	1.41
LM12-NMC	CoV	21	7.97	4.73	5.56	4.43	6.70	2.04	2.72	5.62	3.56
LM12-NMC	Mean	37	27.42	27.87	28.45	29.28	32.40	34.12	35.25	34.48	31.28
LM12-NMC	SD	37	0.47	0.29	0.14	0.23	0.51	1.75	0.57	1.04	1.37
LM12-NMC	CoV	37	1.72	1.05	0.51	0.78	1.57	5.13	1.61	3.02	4.39

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM13-NMC	Mean	4	6.62	8.50	9.92	11.56	13.22	13.68	15.14	17.46	22.22
LM13-NMC	SD	4	1.38	0.67	0.25	0.25	0.68	1.16	0.91	1.21	4.56
LM13-NMC	CoV	4	20.84	7.91	2.48	2.20	5.11	8.47	6.01	6.93	20.51
LM13-NMC	Mean	21	16.53	18.43	19.60	22.37	25.99	27.48	32.84	33.77	35.88
LM13-NMC	SD	21	0.72	0.55	0.39	0.45	1.28	1.09	3.10	2.00	0.49
LM13-NMC	CoV	21	4.36	2.96	1.98	2.00	4.92	3.98	9.44	5.93	1.38
LM13-NMC	Mean	37	25.23	26.67	27.16	27.96	33.15	35.05	35.19	37.03	34.73
LM13-NMC	SD	37	0.46	0.27	0.38	0.79	3.06	1.25	1.09	2.67	3.68
LM13-NMC	CoV	37	1.83	1.03	1.38	2.82	9.22	3.57	3.10	7.21	10.58
LM15-NMC	Mean	4	7.14	8.29	9.11	11.42	12.89	14.37	15.86	17.52	23.28
LM15-NMC	SD	4	1.41	0.99	1.42	0.59	0.63	1.06	1.35	1.41	1.95
LM15-NMC	CoV	4	19.83	11.90	15.60	5.12	4.89	7.39	8.49	8.03	8.39
LM15-NMC	Mean	21	18.34	21.21	22.27	25.15	29.43	31.90	34.20	38.66	38.45
LM15-NMC	SD	21	0.52	0.72	0.84	0.83	1.37	0.56	0.62	1.15	1.51
LM15-NMC	CoV	21	2.81	3.40	3.79	3.31	4.65	1.75	1.83	2.98	3.92
LM15-NMC	Mean	37	27.96	27.83	27.70	27.57	33.56	32.27	35.41	37.58	39.11
LM15-NMC	SD	37	0.86	0.51	0.39	0.38	3.05	1.77	2.56	2.36	4.56
LM15-NMC	CoV	37	3.09	1.82	1.41	1.37	9.09	5.49	7.23	6.28	11.67

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM17-NMC	Mean	4	8.58	9.99	11.63	13.75	15.31	16.39	18.54	20.95	29.16
LM17-NMC	SD	4	0.84	1.76	1.16	1.23	1.68	0.91	1.26	1.54	3.60
LM17-NMC	CoV	4	9.84	17.62	9.95	8.98	11.00	5.53	6.82	7.34	12.36
LM17-NMC	Mean	21	20.34	22.47	23.97	26.64	30.17	33.05	36.22	38.31	39.71
LM17-NMC	SD	21	1.32	0.89	0.69	0.88	2.01	2.04	0.86	0.40	1.50
LM17-NMC	CoV	21	6.47	3.95	2.87	3.31	6.67	6.16	2.38	1.04	3.79
LM17-NMC	Mean	37	28.55	28.09	27.31	27.18	31.24	31.00	34.73	38.02	37.26
LM17-NMC	SD	37	0.99	0.39	0.31	0.30	1.07	1.19	0.70	2.81	3.17
LM17-NMC	CoV	37	3.47	1.39	1.13	1.11	3.42	3.84	2.03	7.40	8.52
LM20-NMC	Mean	4	7.79	9.55	10.54	12.47	14.00	15.14	16.62	19.28	26.34
LM20-NMC	SD	4	2.12	0.66	0.21	0.33	0.63	1.08	0.29	1.00	4.85
LM20-NMC	CoV	4	27.18	6.92	1.97	2.68	4.47	7.14	1.72	5.20	18.43
LM20-NMC	Mean	21	19.61	21.11	22.55	25.30	29.09	32.13	35.50	39.38	39.12
LM20-NMC	SD	21	0.63	0.44	0.66	0.53	1.87	0.79	2.63	1.09	1.90
LM20-NMC	CoV	21	3.22	2.10	2.93	2.09	6.44	2.45	7.42	2.77	4.86
LM20-NMC	Mean	37	28.30	27.72	28.15	28.32	33.56	32.53	36.82	40.83	40.82
LM20-NMC	SD	37	1.06	0.56	0.86	0.96	2.72	2.27	3.22	2.86	2.21
LM20-NMC	CoV	37	3.75	2.01	3.04	3.41	8.11	6.99	8.75	7.00	5.42

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM14-NMC	Mean	4	10.00	7.00	8.63	9.70	10.62	11.47	12.09	15.05	17.28
LM14-NMC	SD	4	17.51	2.16	1.29	0.73	1.24	0.94	1.31	2.72	3.55
LM14-NMC	CoV	4	175.19	30.85	14.88	7.55	11.67	8.23	10.88	18.07	20.54
LM14-NMC	Mean	21	13.73	16.14	17.37	19.75	22.19	24.78	26.65	30.26	32.11
LM14-NMC	SD	21	0.60	0.20	0.14	0.16	0.62	1.06	1.54	1.47	1.48
LM14-NMC	CoV	21	4.36	1.26	0.83	0.83	2.80	4.29	5.77	4.86	4.62
LM14-NMC	Mean	37	23.26	24.10	24.76	26.11	30.33	32.13	34.57	36.31	37.11
LM14-NMC	SD	37	1.90	1.15	0.97	0.78	1.97	2.12	1.36	3.07	4.38
LM14-NMC	CoV	37	8.17	4.77	3.90	3.00	6.51	6.59	3.94	8.46	11.80
LM16-NMC	Mean	4	4.95	8.80	9.69	11.24	11.88	13.48	15.19	16.07	20.51
LM16-NMC	SD	4	2.61	1.05	0.42	0.70	0.78	0.57	1.76	2.08	2.16
LM16-NMC	CoV	4	52.68	11.91	4.38	6.27	6.56	4.26	11.61	12.97	10.52
LM16-NMC	Mean	21	16.82	18.84	20.34	22.96	25.49	28.86	31.29	35.28	37.19
LM16-NMC	SD	21	0.59	0.57	0.43	0.41	1.10	1.12	0.99	1.36	0.41
LM16-NMC	CoV	21	3.51	3.04	2.09	1.80	4.32	3.87	3.17	3.85	1.09
LM16-NMC	Mean	37	26.08	27.81	28.48	28.96	35.15	34.94	39.03	41.72	41.54
LM16-NMC	SD	37	1.16	0.10	0.50	1.08	3.04	2.34	1.96	1.90	0.33
LM16-NMC	CoV	37	4.46	0.37	1.75	3.73	8.64	6.69	5.03	4.54	0.79

Table B-2 (Continued)

Mix	Sample	Temperature	25Hz	15Hz	10Hz	5Hz	3Hz	1Hz	0.5Hz	0.3Hz	0.1Hz
LM19-NMC	Mean	4	6.88	8.60	9.86	11.51	12.65	13.28	14.32	19.70	22.53
LM19-NMC	SD	4	0.37	0.23	0.40	0.62	0.59	0.91	1.58	1.91	0.87
LM19-NMC	CoV	4	5.45	2.70	4.10	5.36	4.70	6.83	11.03	9.71	3.86
LM19-NMC	Mean	21	19.01	20.75	21.82	24.64	27.30	30.46	33.49	36.59	39.12
LM19-NMC	SD	21	1.88	1.46	1.53	1.43	2.12	1.53	1.54	0.66	1.30
LM19-NMC	CoV	21	9.89	7.02	7.00	5.79	7.78	5.03	4.61	1.80	3.31
LM19-NMC	Mean	37	26.90	27.79	27.67	28.21	33.52	33.68	36.72	41.78	41.23
LM19-NMC	SD	37	0.96	0.54	0.60	0.33	3.32	1.25	2.43	1.00	1.41
LM19-NMC	CoV	37	3.59	1.94	2.17	1.16	9.91	3.70	6.61	2.40	3.43
LM21-NMC	Mean	4	5.82	8.18	9.49	10.97	12.11	11.78	13.45	16.48	19.18
LM21-NMC	SD	4	0.89	0.74	0.47	0.71	1.18	1.46	1.60	1.54	0.63
LM21-NMC	CoV	4	15.24	9.06	4.91	6.50	9.76	12.37	11.88	9.36	3.29
LM21-NMC	Mean	21	17.15	19.23	20.47	22.97	26.35	27.95	32.42	35.30	37.43
LM21-NMC	SD	21	2.08	0.88	0.81	0.89	0.86	0.27	2.78	1.16	1.92
LM21-NMC	CoV	21	12.14	4.58	3.96	3.88	3.26	0.97	8.58	3.29	5.12
LM21-NMC	Mean	37	26.14	26.78	26.99	27.84	32.78	31.99	36.51	40.98	40.43
LM21-NMC	SD	37	0.93	0.90	0.89	0.66	0.66	1.50	1.59	2.39	1.31
LM21-NMC	CoV	37	3.56	3.35	3.29	2.37	2.02	4.70	4.35	5.82	3.23

APPENDIX C DYNAMIC MODULUS MASTER CURVES

In this section, master curves of the dynamic modulus test results are charted for each of the sixteen mixtures investigated in this work in Figures C1 to C16. All the data was shifted to a shift temperature of 21°C using a sigmoidal function.

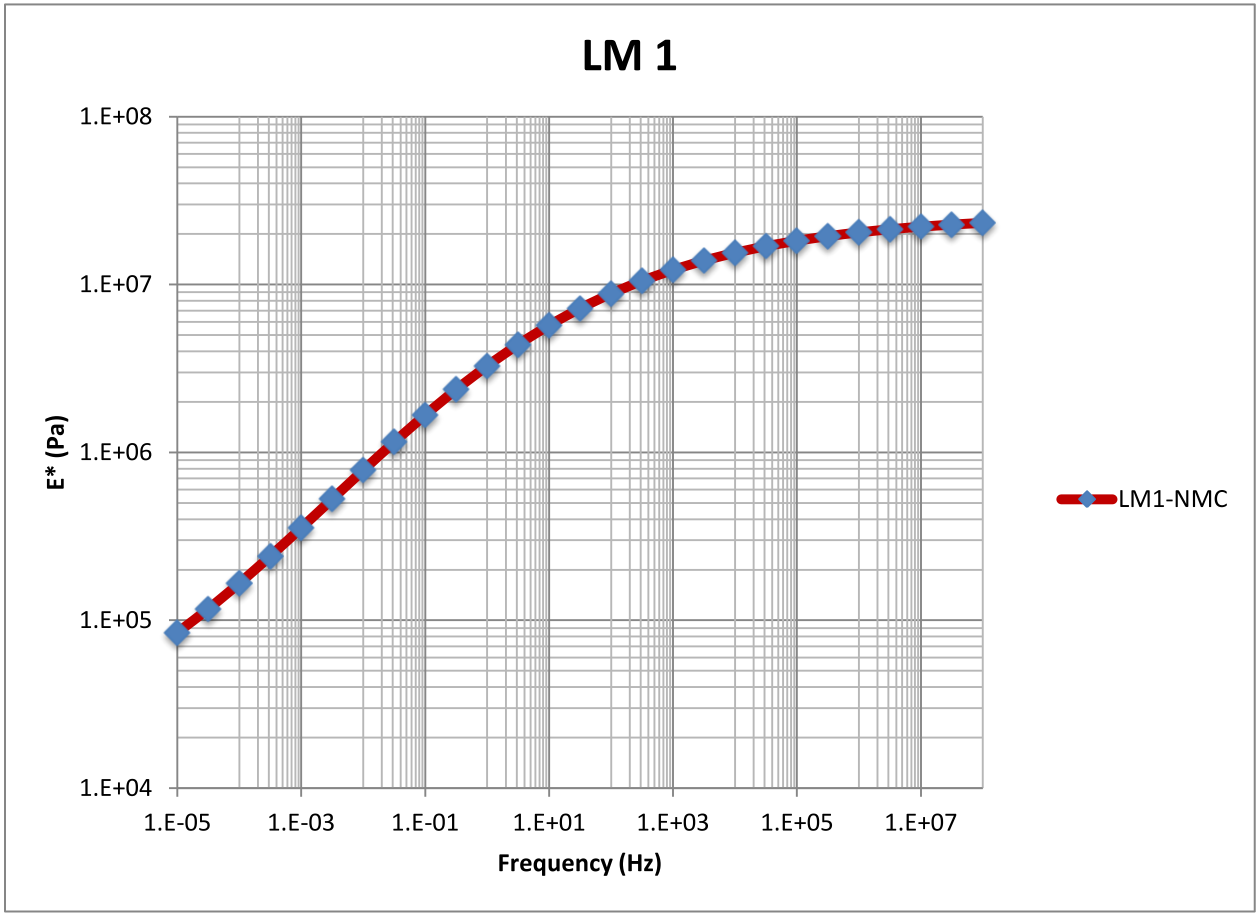


Figure C1 Master curve for control limestone mix with 0% RAP

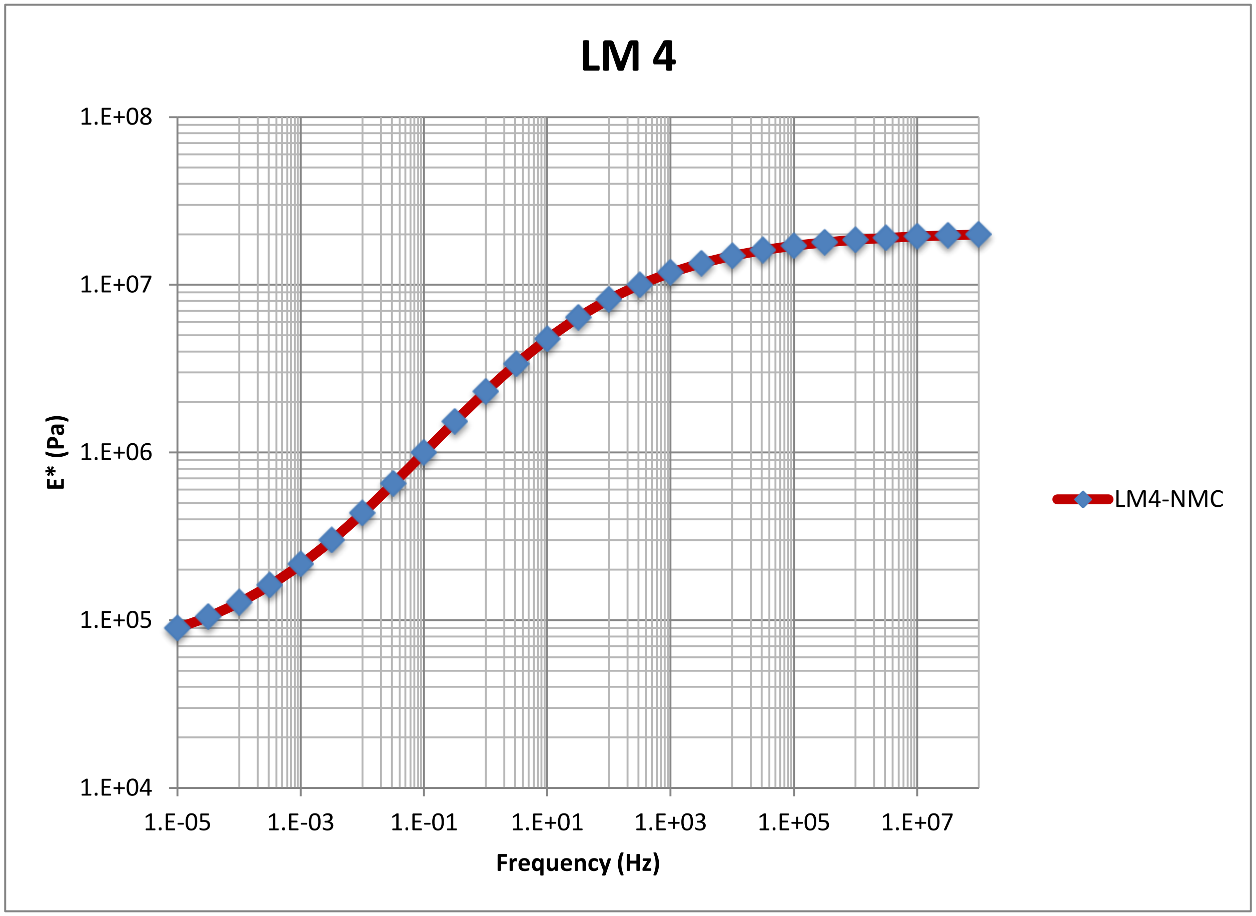


Figure C2 Master curve for Advera limestone mix with 0% RAP

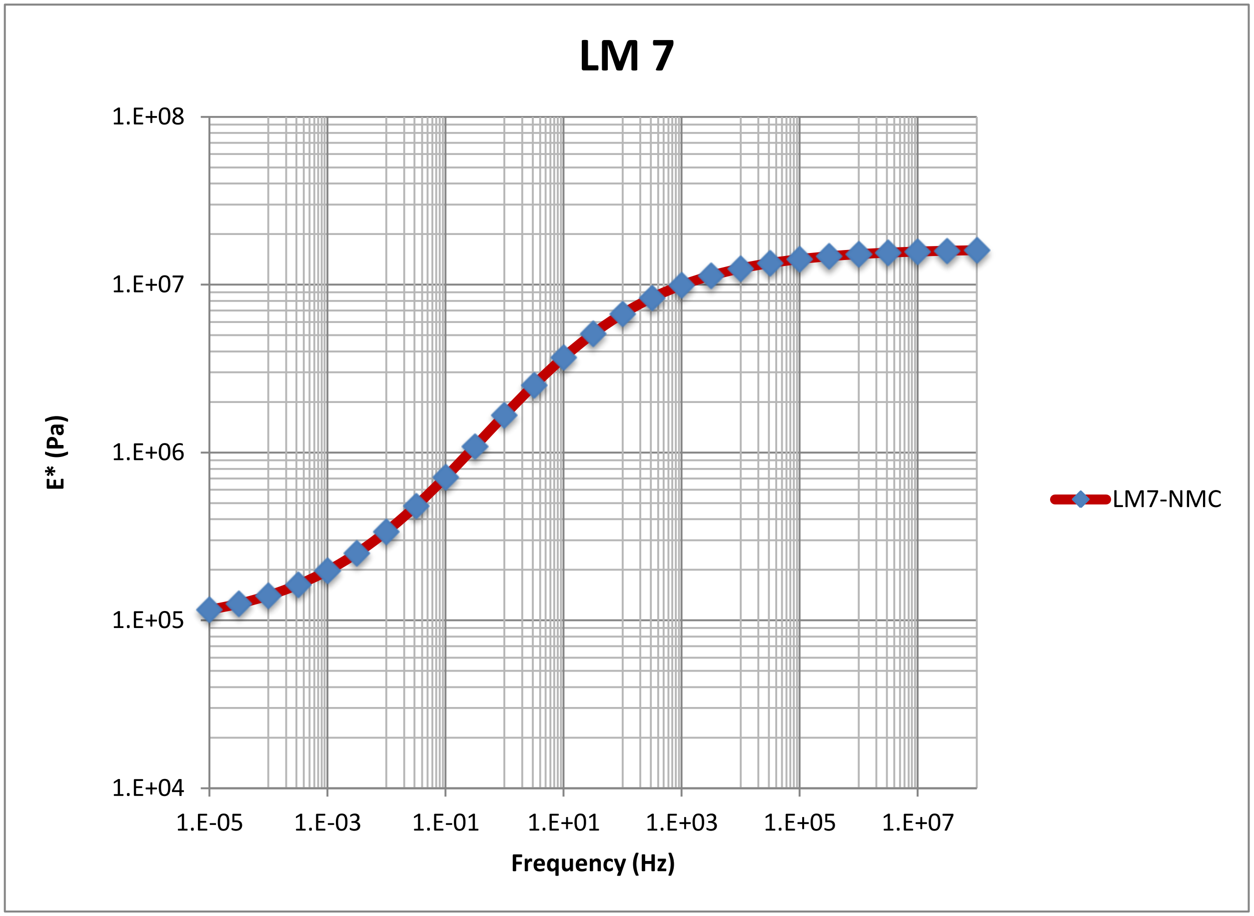


Figure C3 Master curve for Evotherm limestone mix with 0% RAP

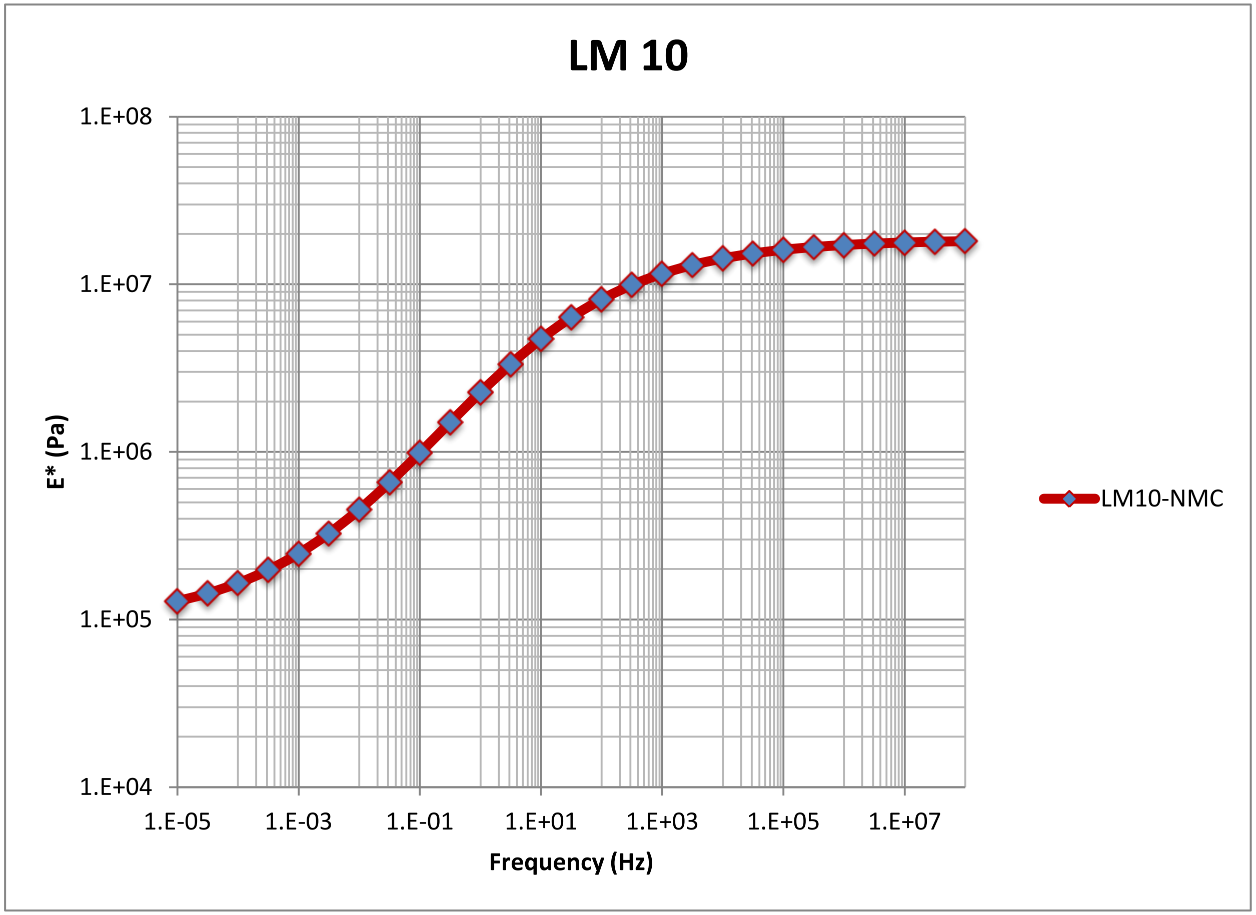


Figure C4 Master curve for Sasobit limestone mix with 0% RAP

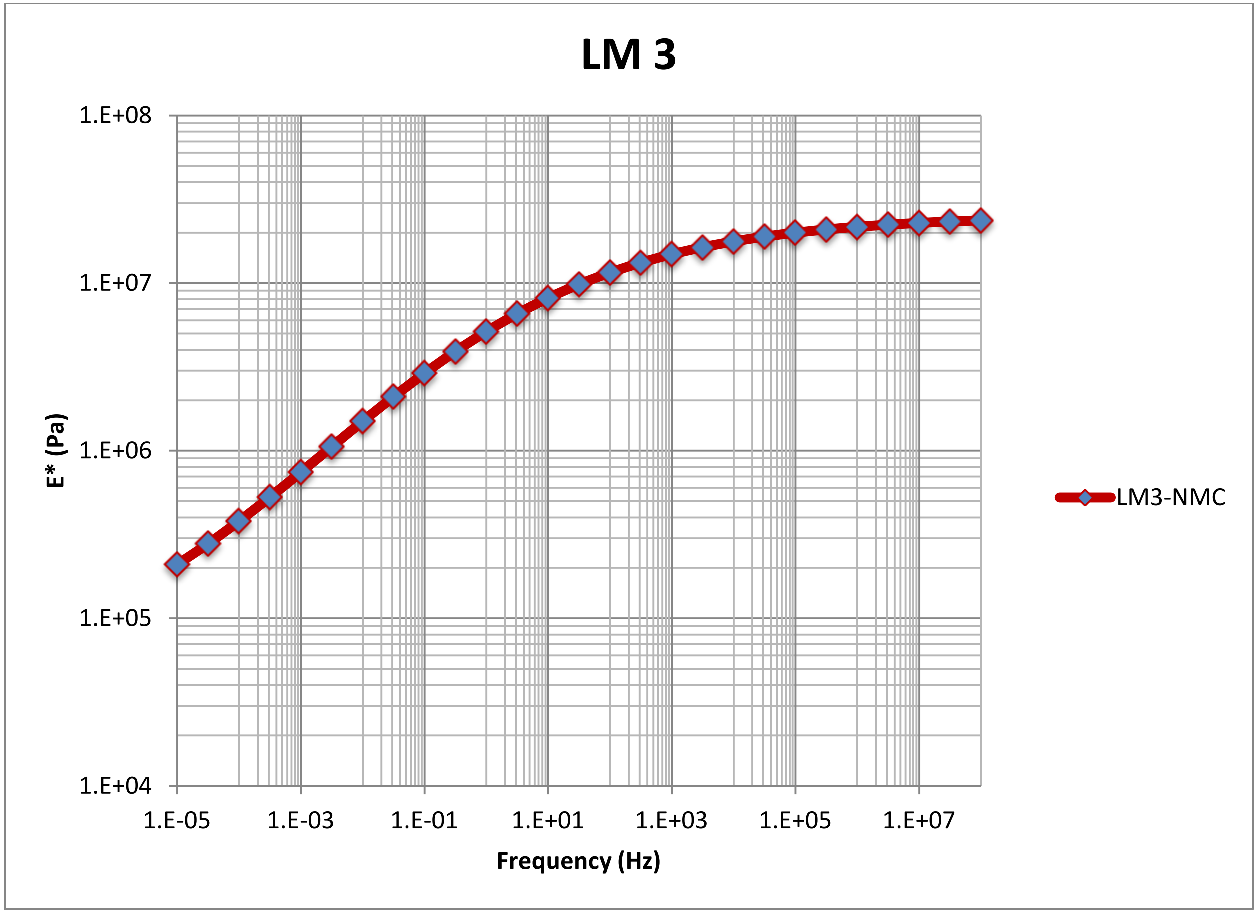


Figure C5 Master curve for control limestone mix with 30 % RAP

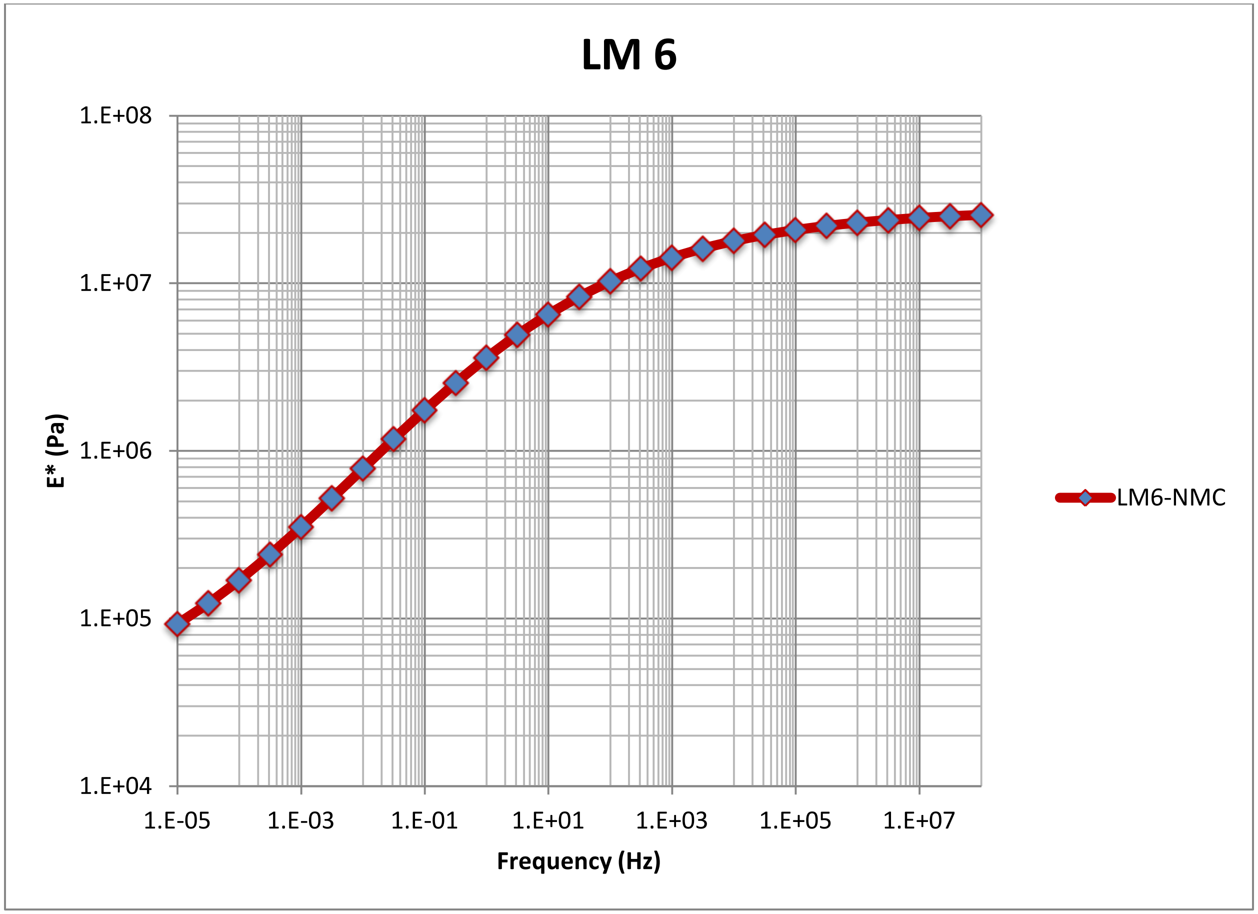


Figure C6 Master curve for Advera limestone mix with 30 % RAP

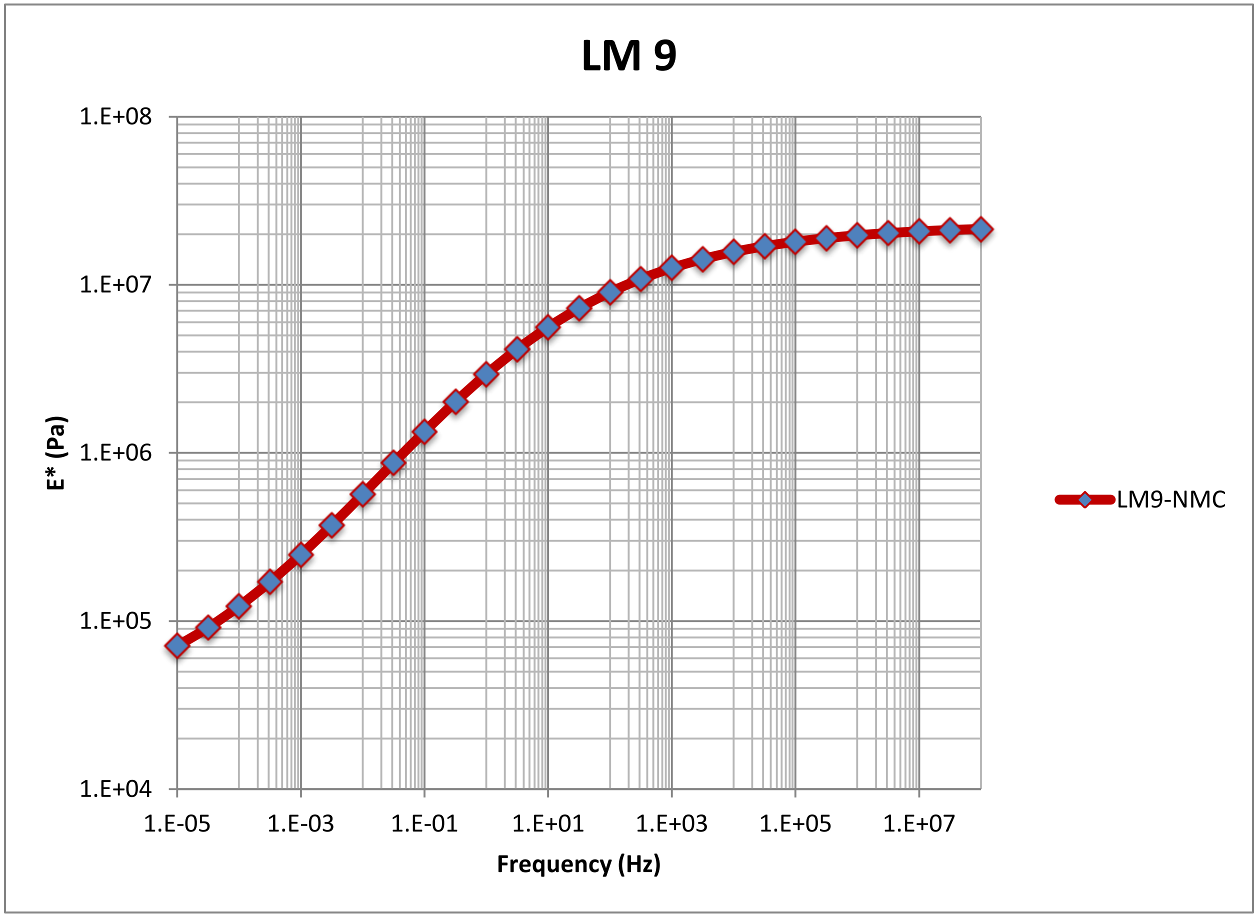


Figure C7 Master curve for Evotherm limestone mix with 30% RAP

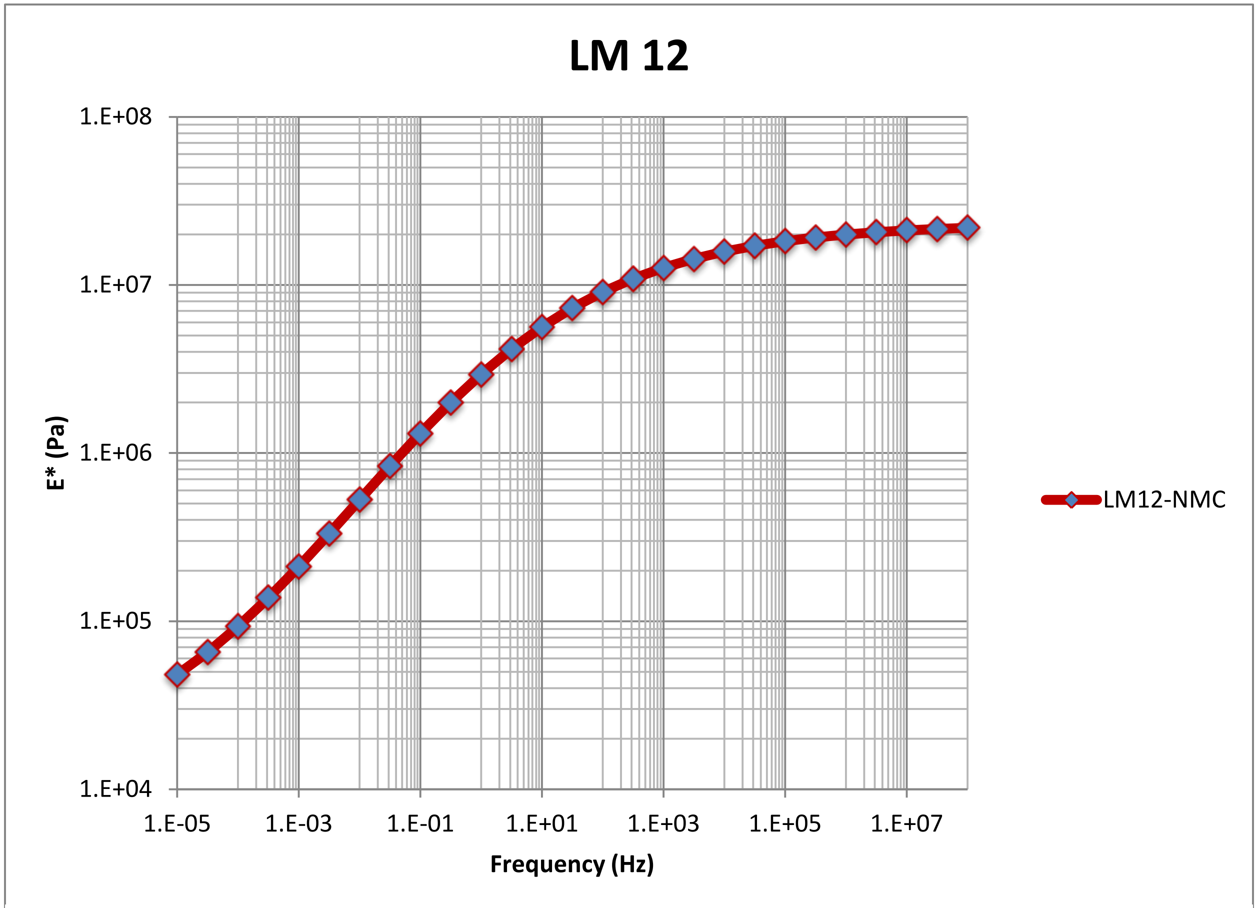


Figure C8 Master curve for Sasobit limestone mix with 30% RAP

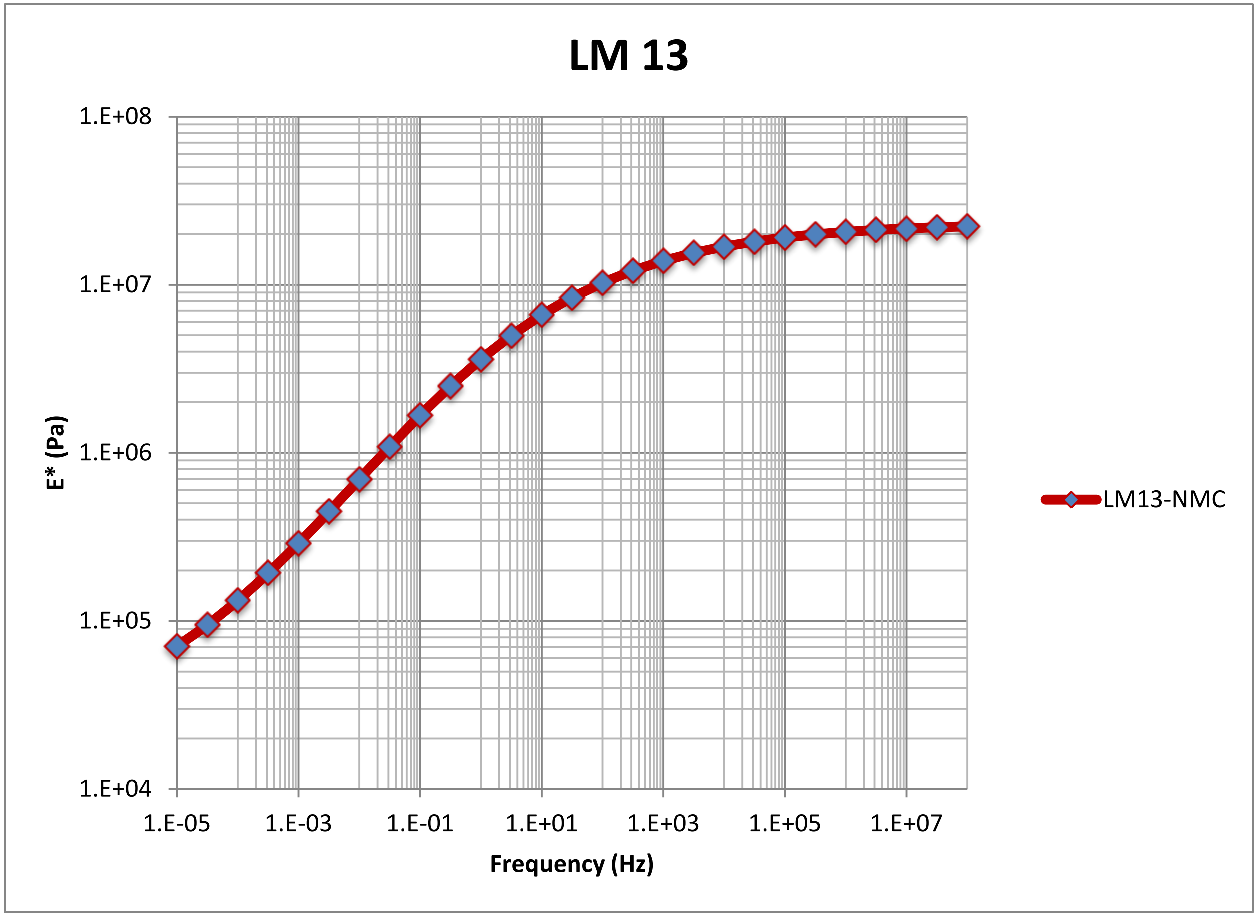


Figure C9 Master curve for control quartzite mix with 0% RAP

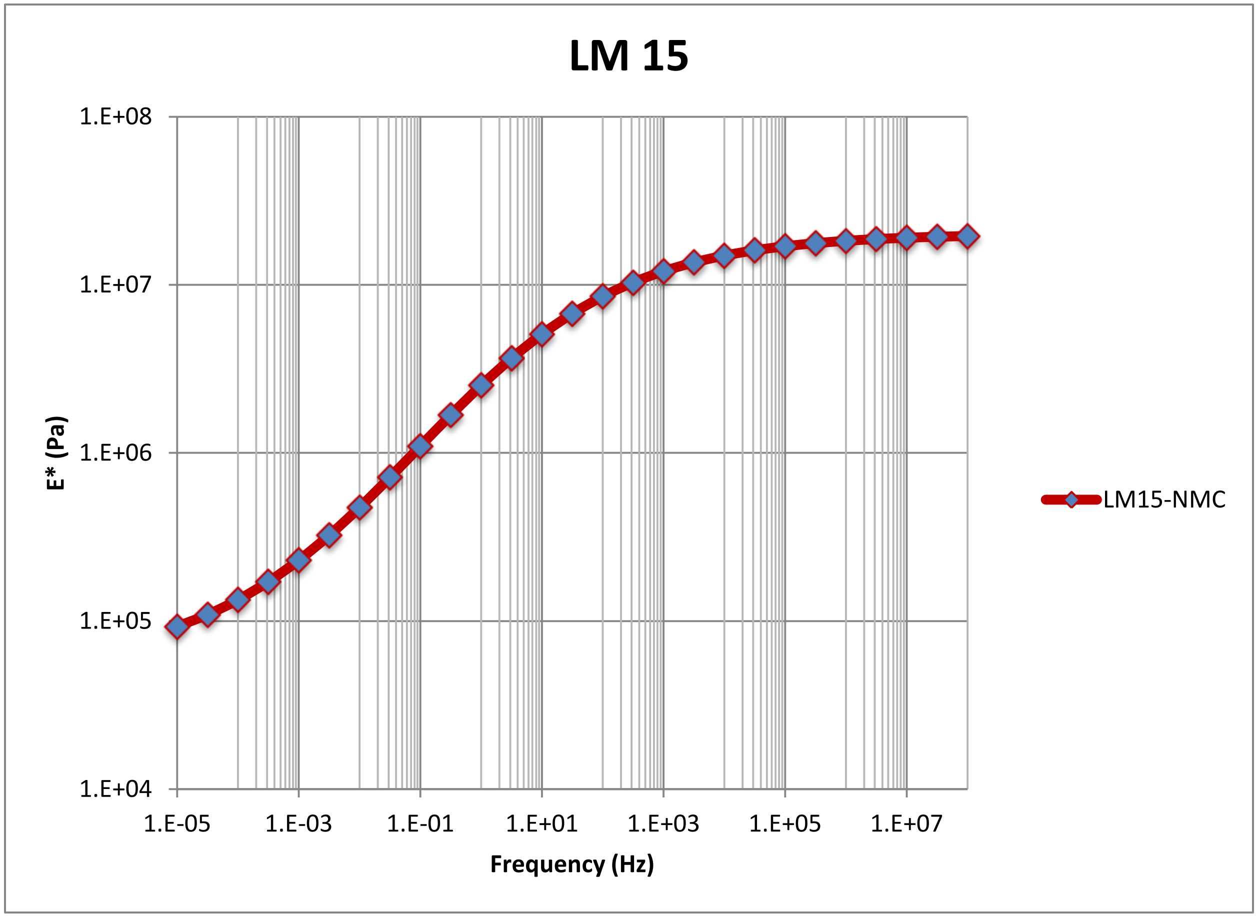


Figure C10 Master curve for Advera quartzite mix with 0% RAP

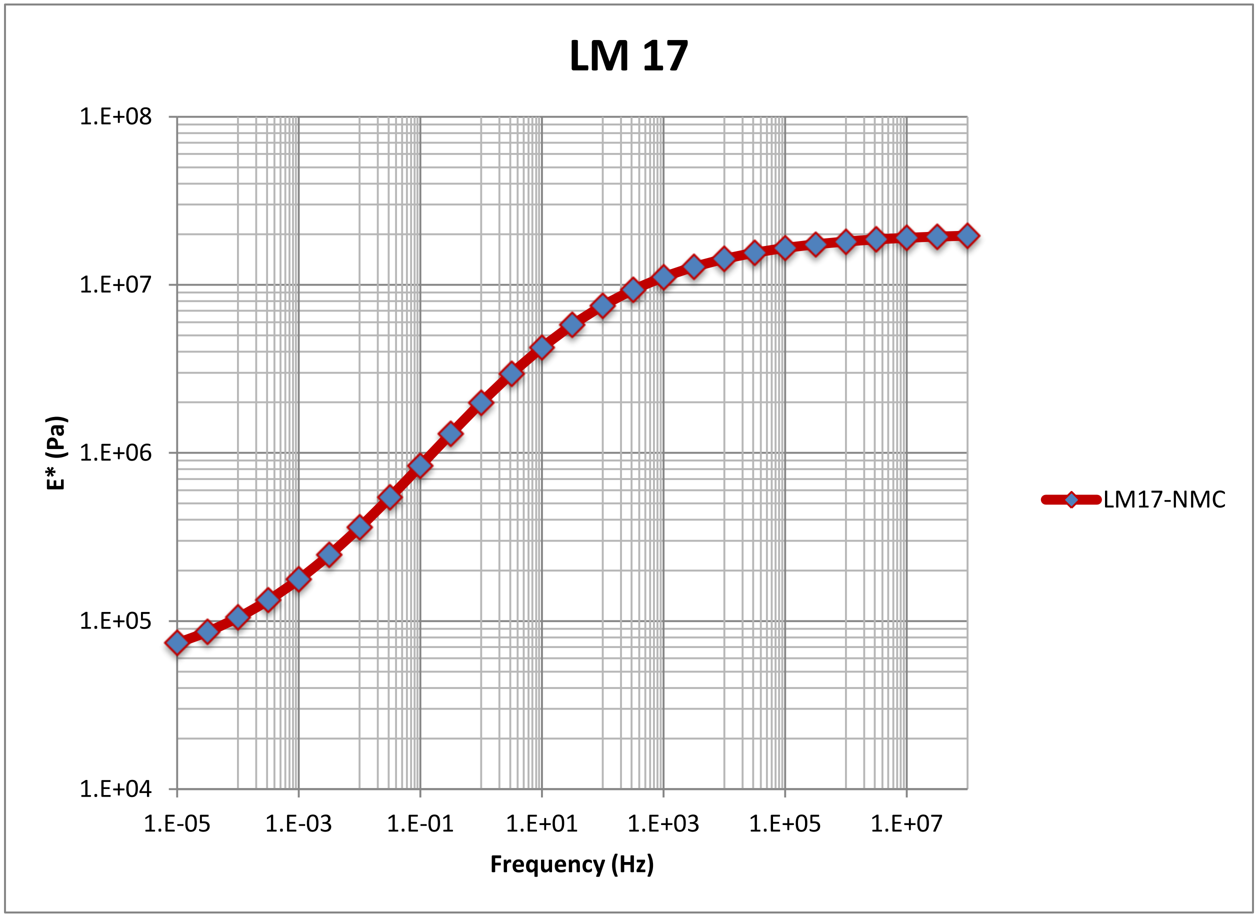


Figure C11 Master curve for Evotherm quartzite mix with 0% RAP

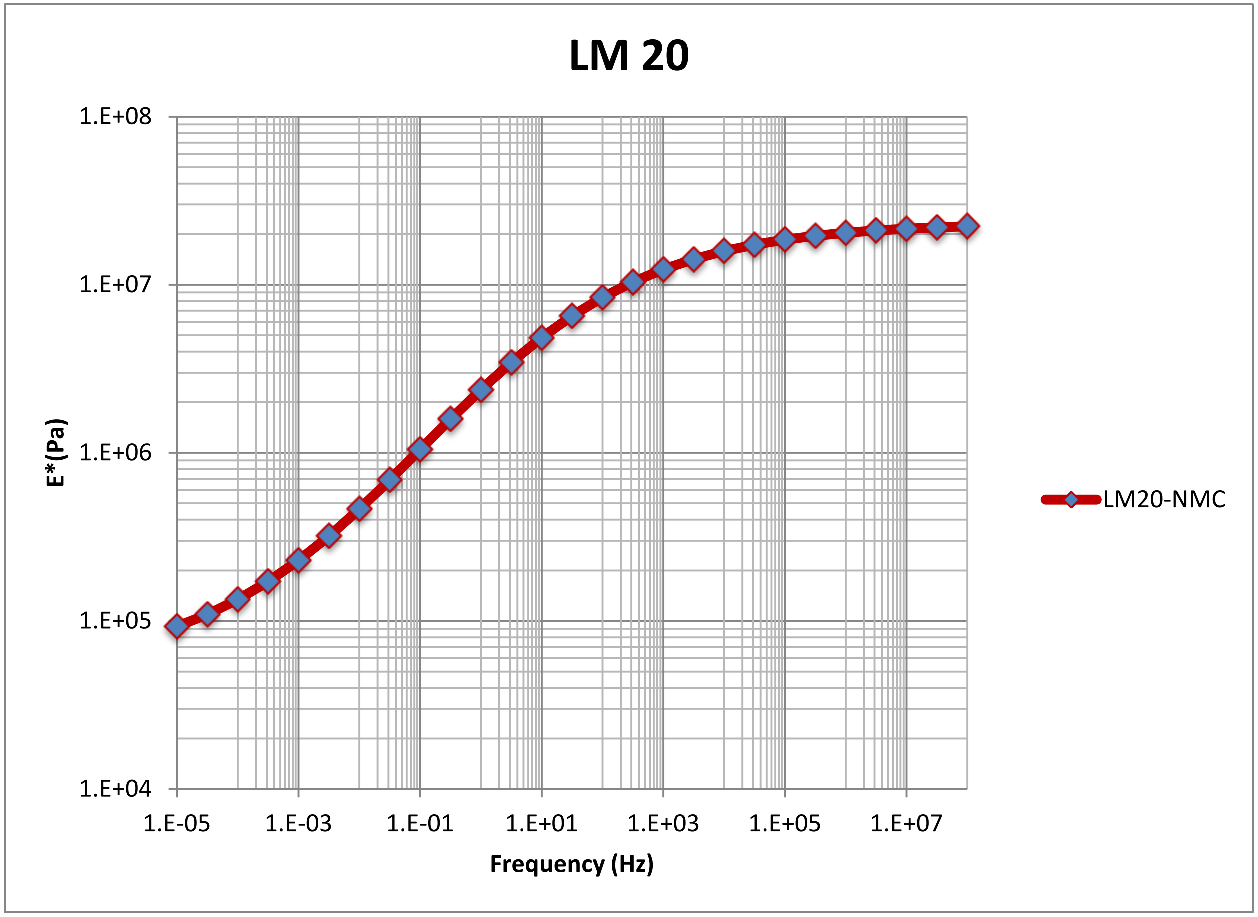


Figure C 12Master curve for Sasobit quartzite mix with 0% RAP

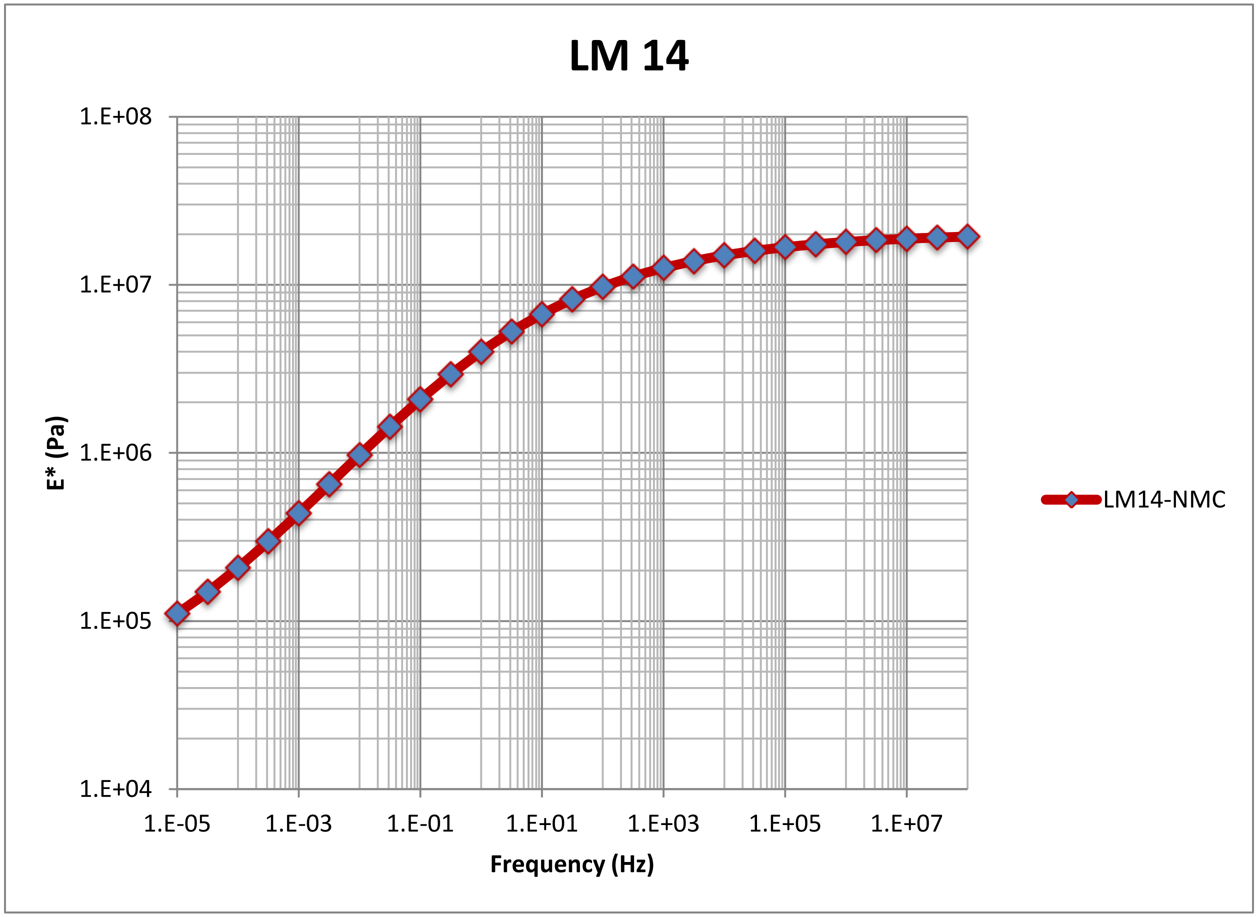


Figure C 13 Master curve for control quartzite mix with 30 % RAP

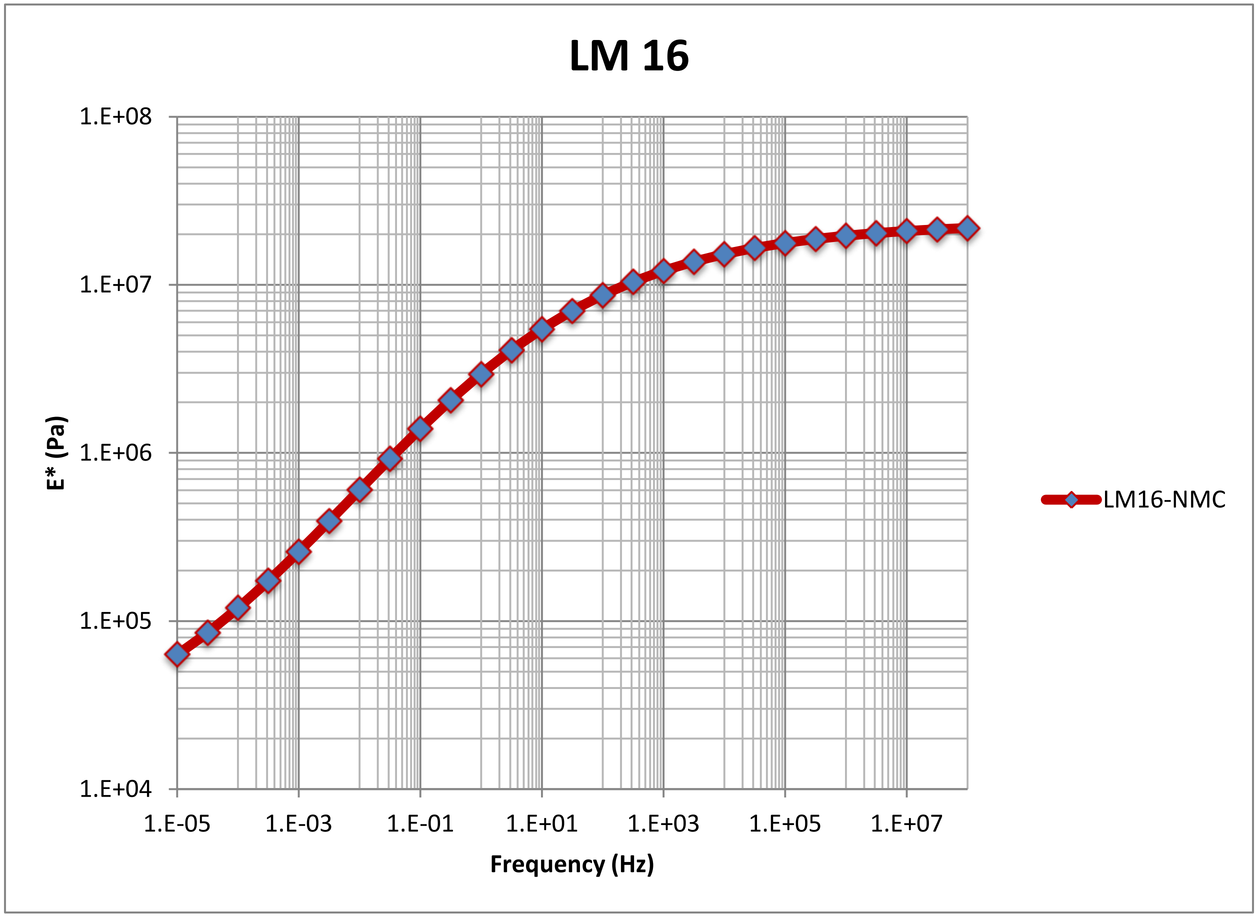


Figure C 14Master curve for Advera quartzite mix with 30% RAP

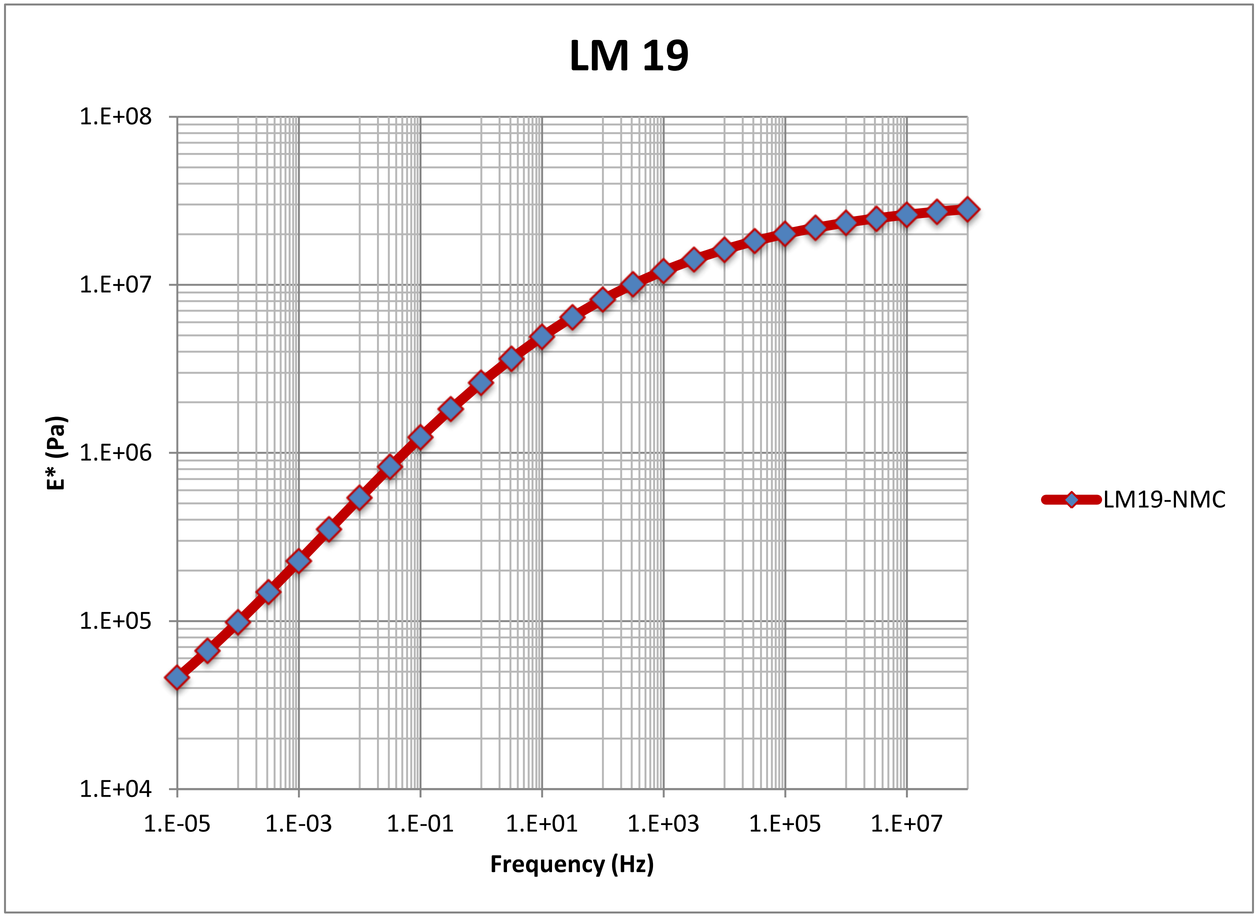


Figure C 15Master curve for Evotherm quartzite mix with 30% RAP

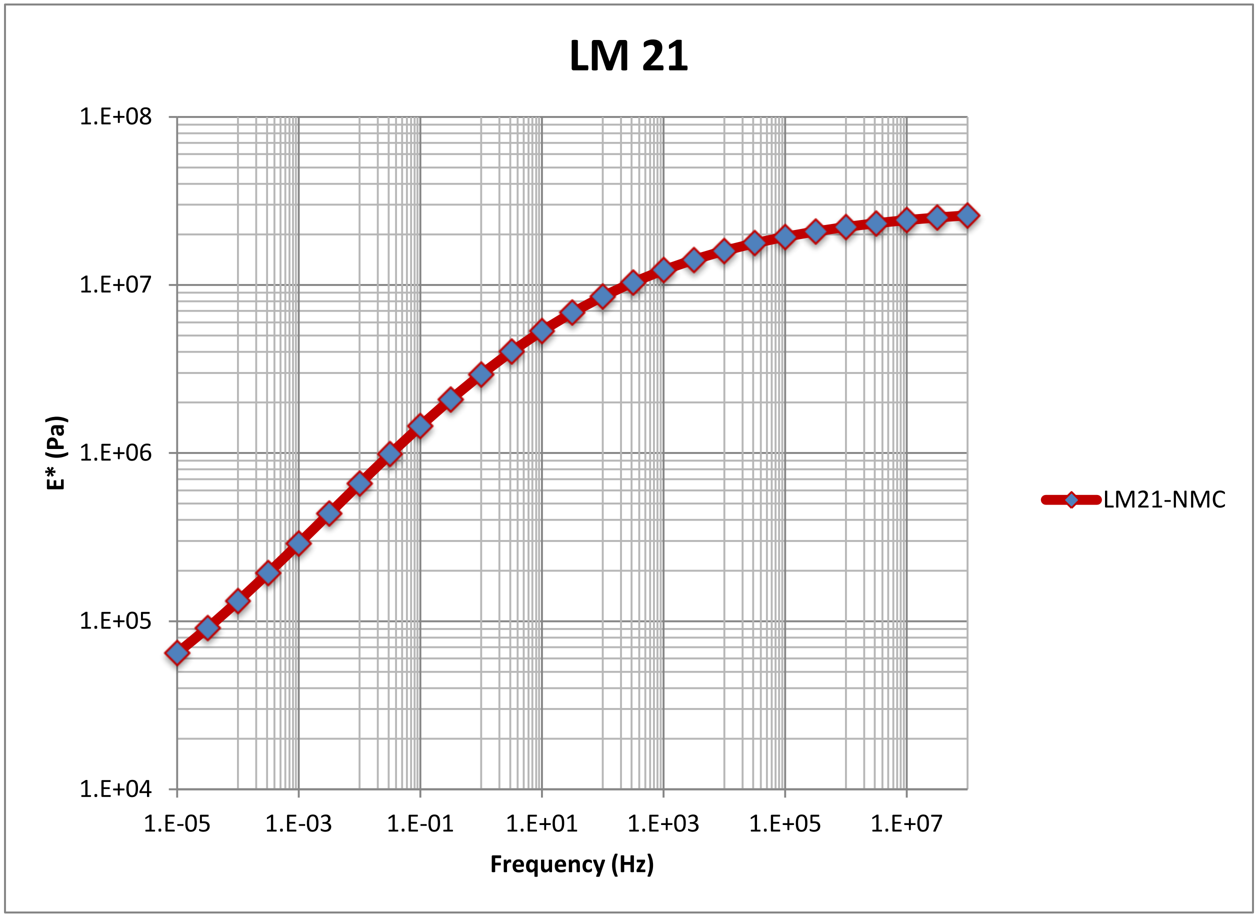


Figure C 16 Master curve for Sasobit quartzite mix with 30 % RAP

APPENDIX D FREQUENCY SWEEPS OF WMA BINDERS

The results of the frequency sweeps conducted on control, Evotherm and Sasobit binders, both unmodified and polymer modified are presented in Tables D-1 to D-6. Tables D-1 and D-2 lists the frequency sweeps data of the control binders, the unmodified and modified binders, respectively. Likewise, tables D-3 and D-4 presents the sweep data for the binders incorporating Evotherm. Moreover, tables D-5 and D-6 tabulates the data of binders incorporating Sasobit.

Table D-1 Frequency sweeps data output for PAV-aged control unmodified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	1.52E+03	8.05E+06	7.01E+06	8.71E-01	41.1	1.07E+07
0.158	13	-8.01E-01	2.40E+03	1.02E+07	8.48E+06	8.30E-01	39.7	1.33E+07
0.251	13	-6.00E-01	3.81E+03	1.26E+07	1.00E+07	7.95E-01	38.5	1.61E+07
0.398	13.1	-4.00E-01	6.04E+03	1.55E+07	1.18E+07	7.62E-01	37.3	1.95E+07
0.631	13.1	-2.00E-01	9.58E+03	1.90E+07	1.39E+07	7.31E-01	36.2	2.35E+07
1	13	0.00E+00	1.52E+04	2.32E+07	1.62E+07	7.01E-01	35.1	2.83E+07
1.585	13	2.00E-01	2.41E+04	2.80E+07	1.89E+07	6.74E-01	34.0	3.38E+07
2.512	13	4.00E-01	3.81E+04	3.35E+07	2.17E+07	6.48E-01	33.0	4.00E+07
3.981	13	6.00E-01	6.04E+04	4.01E+07	2.50E+07	6.23E-01	31.9	4.72E+07
6.31	13	8.00E-01	9.58E+04	4.75E+07	2.85E+07	5.99E-01	31.0	5.54E+07
10	13	1.00E+00	1.52E+05	5.60E+07	3.22E+07	5.75E-01	29.9	6.46E+07
15.849	13	1.20E+00	2.41E+05	6.57E+07	3.64E+07	5.54E-01	29.0	7.51E+07
25.121	13	1.40E+00	3.81E+05	7.68E+07	4.07E+07	5.31E-01	28.0	8.69E+07
39.809	13	1.60E+00	6.04E+05	8.94E+07	4.53E+07	5.07E-01	26.9	1.00E+08
50	13	1.70E+00	7.59E+05	9.57E+07	4.75E+07	4.96E-01	26.4	1.07E+08

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	1.57E+02	2.01E+06	2.30E+06	1.14E+00	48.9	3.05E+06
0.158	21	-8.01E-01	2.49E+02	2.61E+06	2.86E+06	1.09E+00	47.6	3.88E+06
0.251	21	-6.00E-01	3.95E+02	3.42E+06	3.57E+06	1.05E+00	46.3	4.95E+06
0.398	21	-4.00E-01	6.26E+02	4.42E+06	4.42E+06	1.00E+00	45.0	6.26E+06
0.631	21	-2.00E-01	9.93E+02	5.66E+06	5.43E+06	9.59E-01	43.8	7.84E+06
1	21	0.00E+00	1.57E+03	7.18E+06	6.61E+06	9.19E-01	42.6	9.76E+06
1.585	21	2.00E-01	2.49E+03	9.06E+06	8.00E+06	8.83E-01	41.5	1.21E+07
2.512	21	4.00E-01	3.95E+03	1.13E+07	9.62E+06	8.48E-01	40.3	1.49E+07
3.981	21	6.00E-01	6.26E+03	1.41E+07	1.15E+07	8.14E-01	39.2	1.82E+07
6.31	21	8.00E-01	9.93E+03	1.75E+07	1.37E+07	7.82E-01	38.1	2.22E+07
10	21	1.00E+00	1.57E+04	2.14E+07	1.61E+07	7.53E-01	37.0	2.68E+07
15.849	21	1.20E+00	2.49E+04	2.62E+07	1.89E+07	7.22E-01	35.9	3.23E+07
25.121	21	1.40E+00	3.95E+04	3.18E+07	2.20E+07	6.94E-01	34.8	3.87E+07
39.809	21	1.60E+00	6.26E+04	3.85E+07	2.56E+07	6.65E-01	33.6	4.62E+07
50	21	1.70E+00	7.87E+04	4.21E+07	2.74E+07	6.51E-01	33.1	5.02E+07

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	1.53E+01	4.01E+05	6.24E+05	1.56E+00	56.1	7.42E+05
0.158	29	-8.01E-01	2.42E+01	5.51E+05	8.18E+05	1.48E+00	54.9	9.86E+05
0.251	29	-6.00E-01	3.84E+01	7.49E+05	1.06E+06	1.42E+00	53.7	1.30E+06
0.398	29	-4.00E-01	6.08E+01	1.01E+06	1.37E+06	1.36E+00	52.5	1.71E+06
0.631	29	-2.00E-01	9.65E+01	1.36E+06	1.76E+06	1.30E+00	51.3	2.23E+06
1	29	0.00E+00	1.53E+02	1.81E+06	2.25E+06	1.24E+00	50.1	2.88E+06
1.585	29	2.00E-01	2.42E+02	2.39E+06	2.84E+06	1.19E+00	48.9	3.71E+06
2.512	29	4.00E-01	3.84E+02	3.13E+06	3.57E+06	1.14E+00	47.7	4.75E+06
3.981	29	6.00E-01	6.09E+02	4.08E+06	4.46E+06	1.09E+00	46.5	6.04E+06
6.31	29	8.00E-01	9.65E+02	5.27E+06	5.53E+06	1.05E+00	45.4	7.64E+06
10	29	1.00E+00	1.53E+03	6.78E+06	6.80E+06	1.00E+00	44.3	9.60E+06
15.849	29	1.20E+00	2.42E+03	8.65E+06	8.32E+06	9.62E-01	43.0	1.20E+07
25.121	29	1.40E+00	3.84E+03	1.10E+07	1.01E+07	9.22E-01	41.8	1.49E+07
39.809	29	1.60E+00	6.09E+03	1.38E+07	1.22E+07	8.85E-01	40.7	1.85E+07
50	29	1.70E+00	7.64E+03	1.55E+07	1.34E+07	8.67E-01	40.1	2.05E+07

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	1.60E+00	8.76E+04	1.66E+05	1.90E+00	62.2	1.88E+05
0.158	37	-8.01E-01	2.53E+00	1.25E+05	2.26E+05	1.81E+00	61.0	2.59E+05
0.251	37	-6.00E-01	4.02E+00	1.76E+05	3.04E+05	1.72E+00	59.9	3.51E+05
0.398	37	-4.00E-01	6.37E+00	2.46E+05	4.07E+05	1.65E+00	58.9	4.75E+05
0.631	37	-2.00E-01	1.01E+01	3.42E+05	5.43E+05	1.59E+00	57.8	6.42E+05
1	37	0.00E+00	1.60E+01	4.71E+05	7.18E+05	1.52E+00	56.8	8.59E+05
1.585	37	2.00E-01	2.54E+01	6.46E+05	9.46E+05	1.46E+00	55.7	1.15E+06
2.512	37	4.00E-01	4.02E+01	8.81E+05	1.24E+06	1.41E+00	54.6	1.52E+06
3.981	37	6.00E-01	6.37E+01	1.19E+06	1.61E+06	1.35E+00	53.5	2.00E+06
6.31	37	8.00E-01	1.01E+02	1.61E+06	2.08E+06	1.30E+00	52.4	2.63E+06
10	37	1.00E+00	1.60E+02	2.15E+06	2.67E+06	1.24E+00	51.2	3.42E+06
15.849	37	1.20E+00	2.54E+02	2.85E+06	3.40E+06	1.19E+00	50.1	4.44E+06
25.121	37	1.40E+00	4.02E+02	3.76E+06	4.30E+06	1.14E+00	48.9	5.71E+06
39.809	37	1.60E+00	6.37E+02	4.95E+06	5.43E+06	1.10E+00	47.7	7.35E+06
50	37	1.70E+00	8.00E+02	5.65E+06	6.09E+06	1.08E+00	47.2	8.31E+06

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	9067.5	2.43E+04	2.68E+00	69.56	
0.158	46	-8.01E-01	1.58E-01	13420	3.37E+04	2.51E+00	68.27	3.63E+04
0.251	46	-6.00E-01	2.51E-01	19590	4.64E+04	2.37E+00	67.10	5.04E+04
0.398	46	-4.00E-01	3.98E-01	28385	6.39E+04	2.25E+00	66.03	6.99E+04
0.631	46	-2.00E-01	6.31E-01	40360	8.69E+04	2.15E+00	65.09	9.58E+04
1	46	0.00E+00	1.00E+00	56630	1.17E+05	2.07E+00	64.26	1.30E+05
1.585	46	2.00E-01	1.59E+00	78950	1.58E+05	2.01E+00	63.49	1.77E+05
2.512	46	4.00E-01	2.51E+00	109700	2.13E+05	1.95E+00	62.79	2.40E+05
3.981	45.9	6.00E-01	3.98E+00	151850	2.87E+05	1.89E+00	62.12	3.25E+05
6.31	45.9	8.00E-01	6.31E+00	208600	3.84E+05	1.84E+00	61.47	4.37E+05
10	45.9	1.00E+00	1.00E+01	2.96E+05	5.22E+05	1.76E+00	60.45	6.00E+05
15.849	45.9	1.20E+00	1.58E+01	4.30E+05	7.18E+05	1.67E+00	59.10	8.37E+05
25.121	45.9	1.40E+00	2.51E+01	6.11E+05	9.69E+05	1.59E+00	57.77	1.15E+06

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	1.01E-02	6.80E+02	3.33E+03	4.90E+00	7.85E+01	3.40E+03
0.158	58	-8.01E-01	1.59E-02	1.15E+03	4.95E+03	4.30E+00	7.69E+01	5.08E+03
0.251	58	-6.00E-01	2.53E-02	1.88E+03	7.21E+03	3.84E+00	7.54E+01	7.45E+03
0.398	58	-4.00E-01	4.01E-02	3.00E+03	1.04E+04	3.48E+00	7.40E+01	1.08E+04
0.631	58	-2.00E-01	6.36E-02	4.72E+03	1.50E+04	3.18E+00	7.26E+01	1.57E+04
1	58	0.00E+00	1.01E-01	7.26E+03	2.15E+04	2.95E+00	7.13E+01	2.26E+04
1.585	58	2.00E-01	1.60E-01	1.10E+04	3.04E+04	2.77E+00	7.01E+01	3.23E+04
2.512	58	4.00E-01	2.53E-01	1.64E+04	4.28E+04	2.62E+00	6.91E+01	4.58E+04
3.981	58	6.00E-01	4.01E-01	2.40E+04	5.97E+04	2.49E+00	6.81E+01	6.43E+04
6.31	58	8.00E-01	6.36E-01	34825	8.30E+04	2.38E+00	6.72E+01	9.00E+04
10	58	1.00E+00	1.01E+00	49935	1.15E+05	2.29E+00	6.64E+01	1.25E+05
15.849	58	1.20E+00	1.60E+00	71095	1.57E+05	2.21E+00	6.57E+01	1.73E+05
25.121	58	1.40E+00	2.53E+00	99835	2.14E+05	2.14E+00	6.50E+01	2.36E+05

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	1.08E-03	4.47E+01	5.04E+02	1.13E+01	8.49E+01	5.06E+02
0.158	70.1	-8.01E-01	1.70E-03	8.18E+01	7.60E+02	9.30E+00	8.39E+01	7.65E+02
0.251	69.9	-6.00E-01	2.70E-03	1.53E+02	1.18E+03	7.70E+00	8.26E+01	1.19E+03
0.398	69.9	-4.00E-01	4.28E-03	2.71E+02	1.78E+03	6.56E+00	8.13E+01	1.80E+03
0.631	70	-2.00E-01	6.79E-03	4.71E+02	2.67E+03	5.68E+00	8.00E+01	2.72E+03
1	70	0.00E+00	1.08E-02	8.04E+02	4.01E+03	4.98E+00	7.87E+01	4.09E+03
1.585	70	2.00E-01	1.71E-02	1.34E+03	5.93E+03	4.44E+00	7.73E+01	6.08E+03
2.512	70	4.00E-01	2.70E-02	2.17E+03	8.71E+03	4.01E+00	7.60E+01	8.97E+03
3.981	70	6.00E-01	4.28E-02	3.45E+03	1.26E+04	3.67E+00	7.47E+01	1.31E+04
6.31	70	8.00E-01	6.79E-02	5.40E+03	1.83E+04	3.39E+00	7.35E+01	1.91E+04
10	70	1.00E+00	1.08E-01	8.34E+03	2.63E+04	3.16E+00	7.24E+01	2.76E+04
15.849	70.1	1.20E+00	1.71E-01	1.27E+04	3.77E+04	2.97E+00	7.14E+01	3.98E+04
25.121	70.1	1.40E+00	2.70E-01	1.91E+04	5.34E+04	2.80E+00	7.04E+01	5.67E+04

Table D-1 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	4.01E-04	10.485	2.09E+02	1.99E+01	8.71E+01	2.09E+02
0.158	76	-8.01E-01	6.33E-04	21.135	3.22E+02	1.52E+01	8.62E+01	3.23E+02
0.251	75.9	-6.00E-01	1.01E-03	42.035	5.02E+02	1.20E+01	8.52E+01	5.04E+02
0.398	76.1	-4.00E-01	1.60E-03	78.74	7.69E+02	9.76E+00	8.42E+01	7.73E+02
0.631	76	-2.00E-01	2.53E-03	144.2	1.17E+03	8.14E+00	8.30E+01	1.18E+03
1	76	0.00E+00	4.01E-03	261.25	1.80E+03	6.90E+00	8.18E+01	1.82E+03
1.585	76	2.00E-01	6.35E-03	454.05	2.71E+03	5.97E+00	8.05E+01	2.75E+03
2.512	76.1	4.00E-01	1.01E-02	767.25	4.03E+03	5.25E+00	7.92E+01	4.10E+03
3.981	76.1	6.00E-01	1.60E-02	1286.5	6.01E+03	4.67E+00	7.79E+01	6.14E+03
6.31	76.1	8.00E-01	2.53E-02	2094.5	8.83E+03	4.22E+00	7.67E+01	9.07E+03
10	76.1	1.00E+00	4.01E-02	3377.5	1.30E+04	3.84E+00	7.54E+01	1.34E+04
15.849	76.1	1.20E+00	6.35E-02	5324	1.88E+04	3.54E+00	7.42E+01	1.96E+04
25.121	76	1.40E+00	1.01E-01	8288	2.72E+04	3.28E+00	7.30E+01	2.84E+04

Table D-2 Frequency sweeps data output for PAV-aged control SBS-modified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	6.93E+02	7.61E+06	6.07E+06	7.98E-01	38.6	9.73E+06
0.158	13	-8.01E-01	1.09E+03	9.47E+06	7.23E+06	7.64E-01	37.4	1.19E+07
0.251	13	-6.00E-01	1.74E+03	1.16E+07	8.50E+06	7.34E-01	36.3	1.44E+07
0.398	13.1	-4.00E-01	2.76E+03	1.41E+07	9.94E+06	7.06E-01	35.2	1.72E+07
0.631	13.1	-2.00E-01	4.37E+03	1.70E+07	1.16E+07	6.80E-01	34.2	2.06E+07
1	13	0.00E+00	6.93E+03	2.04E+07	1.34E+07	6.55E-01	33.2	2.44E+07
1.585	13	2.00E-01	1.10E+04	2.43E+07	1.54E+07	6.32E-01	32.3	2.88E+07
2.512	13	4.00E-01	1.74E+04	2.89E+07	1.76E+07	6.09E-01	31.4	3.38E+07
3.981	13	6.00E-01	2.76E+04	3.41E+07	2.00E+07	5.87E-01	30.4	3.96E+07
6.31	13	8.00E-01	4.37E+04	4.01E+07	2.27E+07	5.66E-01	29.5	4.61E+07
10	13	1.00E+00	6.93E+04	4.70E+07	2.57E+07	5.46E-01	28.6	5.36E+07
15.849	13	1.20E+00	1.10E+05	5.47E+07	2.87E+07	5.25E-01	27.7	6.18E+07
25.121	13	1.40E+00	1.74E+05	6.35E+07	3.20E+07	5.03E-01	26.7	7.11E+07
39.809	13	1.60E+00	2.76E+05	7.33E+07	3.55E+07	4.84E-01	25.8	8.14E+07
50	13	1.70E+00	3.46E+05	7.84E+07	3.71E+07	4.74E-01	25.4	8.68E+07

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	6.94E+01	2.14E+06	2.17E+06	1.01E+00	45.4	3.05E+06
0.158	21	-8.01E-01	1.10E+02	2.73E+06	2.67E+06	9.79E-01	44.4	3.82E+06
0.251	21	-6.00E-01	1.74E+02	3.49E+06	3.29E+06	9.43E-01	43.3	4.79E+06
0.398	21	-4.00E-01	2.76E+02	4.43E+06	4.02E+06	9.08E-01	42.2	5.98E+06
0.631	21	-2.00E-01	4.38E+02	5.57E+06	4.87E+06	8.74E-01	41.2	7.40E+06
1	21	0.00E+00	6.94E+02	6.97E+06	5.87E+06	8.42E-01	40.1	9.11E+06
1.585	21	2.00E-01	1.10E+03	8.65E+06	7.02E+06	8.11E-01	39.1	1.11E+07
2.512	21	4.00E-01	1.74E+03	1.07E+07	8.35E+06	7.82E-01	38.0	1.35E+07
3.981	21	6.00E-01	2.76E+03	1.31E+07	9.87E+06	7.54E-01	37.0	1.64E+07
6.31	21	8.00E-01	4.38E+03	1.60E+07	1.16E+07	7.27E-01	36.0	1.97E+07
10	21	1.00E+00	6.94E+03	1.94E+07	1.36E+07	7.02E-01	35.1	2.37E+07
15.849	21	1.20E+00	1.10E+04	2.34E+07	1.58E+07	6.75E-01	34.0	2.82E+07
25.121	21	1.40E+00	1.74E+04	2.81E+07	1.83E+07	6.52E-01	33.1	3.35E+07
39.809	21	1.60E+00	2.76E+04	3.36E+07	2.11E+07	6.27E-01	32.1	3.97E+07
50	21	1.70E+00	3.47E+04	3.66E+07	2.25E+07	6.15E-01	31.6	4.30E+07

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	9.00E+00	5.44E+05	6.86E+05	1.26E+00	51.6	8.75E+05
0.158	29	-8.01E-01	1.42E+01	7.24E+05	8.83E+05	1.22E+00	50.6	1.14E+06
0.251	29	-6.00E-01	2.26E+01	9.55E+05	1.13E+06	1.18E+00	49.8	1.48E+06
0.398	29	-4.00E-01	3.58E+01	1.25E+06	1.43E+06	1.14E+00	48.8	1.90E+06
0.631	29	-2.00E-01	5.68E+01	1.64E+06	1.81E+06	1.10E+00	47.8	2.44E+06
1	29	0.00E+00	9.00E+01	2.13E+06	2.27E+06	1.07E+00	46.8	3.11E+06
1.585	29	2.00E-01	1.43E+02	2.75E+06	2.82E+06	1.03E+00	45.8	3.94E+06
2.512	29	4.00E-01	2.26E+02	3.53E+06	3.50E+06	9.91E-01	44.7	4.97E+06
3.981	29	6.00E-01	3.58E+02	4.51E+06	4.30E+06	9.54E-01	43.7	6.23E+06
6.31	29	8.00E-01	5.68E+02	5.71E+06	5.27E+06	9.22E-01	42.7	7.77E+06
10	29	1.00E+00	9.00E+02	7.20E+06	6.41E+06	8.90E-01	41.7	9.64E+06
15.849	29	1.20E+00	1.43E+03	9.03E+06	7.74E+06	8.57E-01	40.6	1.19E+07
25.121	29	1.40E+00	2.26E+03	1.13E+07	9.30E+06	8.25E-01	39.5	1.46E+07
39.809	29	1.60E+00	3.58E+03	1.40E+07	1.11E+07	7.96E-01	38.5	1.79E+07
50	29	1.70E+00	4.50E+03	1.56E+07	1.22E+07	7.81E-01	38.0	1.97E+07

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	1.30E+00	1.37E+05	2.03E+05	1.48E+00	56.0	2.45E+05
0.158	37	-8.01E-01	2.05E+00	1.86E+05	2.68E+05	1.45E+00	55.3	3.26E+05
0.251	37	-6.00E-01	3.26E+00	2.50E+05	3.53E+05	1.42E+00	54.8	4.33E+05
0.398	37	-4.00E-01	5.17E+00	3.34E+05	4.62E+05	1.38E+00	54.1	5.70E+05
0.631	37	-2.00E-01	8.20E+00	4.49E+05	6.04E+05	1.34E+00	53.3	7.53E+05
1	37	0.00E+00	1.30E+01	6.04E+05	7.87E+05	1.30E+00	52.5	9.92E+05
1.585	37	2.00E-01	2.06E+01	8.05E+05	1.02E+06	1.26E+00	51.6	1.30E+06
2.512	37	4.00E-01	3.27E+01	1.07E+06	1.31E+06	1.22E+00	50.8	1.69E+06
3.981	37	6.00E-01	5.18E+01	1.40E+06	1.67E+06	1.19E+00	49.9	2.18E+06
6.31	37	8.00E-01	8.20E+01	1.84E+06	2.11E+06	1.15E+00	48.9	2.81E+06
10	37	1.00E+00	1.30E+02	2.42E+06	2.67E+06	1.11E+00	47.9	3.60E+06
15.849	37	1.20E+00	2.06E+02	3.13E+06	3.35E+06	1.07E+00	47.0	4.59E+06
25.121	37	1.40E+00	3.27E+02	4.06E+06	4.19E+06	1.03E+00	46.0	5.83E+06
39.809	37	1.60E+00	5.18E+02	5.22E+06	5.21E+06	9.99E-01	45.0	7.38E+06
50	37	1.70E+00	6.50E+02	5.90E+06	5.79E+06	9.82E-01	44.5	8.27E+06

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	2.38E+04	4.31E+04	1.81E+00	61.0	4.92E+04
0.158	46	-8.01E-01	1.58E-01	3.25E+04	5.71E+04	1.76E+00	60.4	6.57E+04
0.251	46	-6.00E-01	2.51E-01	4.43E+04	7.61E+04	1.72E+00	59.8	8.81E+04
0.398	46	-4.00E-01	3.98E-01	5.95E+04	1.00E+05	1.69E+00	59.4	1.17E+05
0.631	46	-2.00E-01	6.31E-01	7.87E+04	1.31E+05	1.67E+00	59.1	1.53E+05
1	46	0.00E+00	1.00E+00	1.04E+05	1.72E+05	1.65E+00	58.8	2.01E+05
1.585	46	2.00E-01	1.59E+00	1.46E+05	2.37E+05	1.63E+00	58.5	2.78E+05
2.512	46	4.00E-01	2.51E+00	1.92E+05	3.10E+05	1.61E+00	58.2	3.65E+05
3.981	45.9	6.00E-01	3.98E+00	2.51E+05	4.02E+05	1.60E+00	58.0	4.74E+05
6.31	45.9	8.00E-01	6.31E+00	3.46E+05	5.36E+05	1.55E+00	57.2	6.38E+05
10	45.8	1.00E+00	1.00E+01	4.85E+05	7.23E+05	1.49E+00	56.1	8.70E+05
15.849	45.9	1.20E+00	1.58E+01	6.76E+05	9.64E+05	1.43E+00	55.0	1.18E+06
25.121	45.9	1.40E+00	2.51E+01	9.24E+05	1.26E+06	1.37E+00	53.8	1.56E+06

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	1.01E-02	3.03E+03	7.98E+03	2.63E+00	69.2	8.54E+03
0.158	58	-8.01E-01	1.59E-02	4.62E+03	1.12E+04	2.41E+00	67.5	1.21E+04
0.251	58	-6.00E-01	2.53E-02	6.87E+03	1.54E+04	2.25E+00	66.0	1.69E+04
0.398	58	-4.00E-01	4.01E-02	1.00E+04	2.12E+04	2.12E+00	64.7	2.34E+04
0.631	58	-2.00E-01	6.36E-02	1.43E+04	2.89E+04	2.02E+00	63.6	3.22E+04
1	58	0.00E+00	1.01E-01	2.01E+04	3.91E+04	1.94E+00	62.8	4.40E+04
1.585	58	2.00E-01	1.60E-01	2.79E+04	5.27E+04	1.89E+00	62.1	5.96E+04
2.512	58	4.00E-01	2.53E-01	3.83E+04	7.10E+04	1.85E+00	61.7	8.07E+04
3.981	58	6.00E-01	4.01E-01	5.22E+04	9.53E+04	1.83E+00	61.3	1.09E+05
6.31	58	8.00E-01	6.36E-01	7.08E+04	1.28E+05	1.80E+00	61.0	1.46E+05
10	58	1.00E+00	1.01E+00	9.55E+04	1.71E+05	1.78E+00	60.7	1.95E+05
15.849	58	1.20E+00	1.60E+00	1.29E+05	2.27E+05	1.77E+00	60.5	2.61E+05
25.121	58	1.40E+00	2.53E+00	1.71E+05	2.99E+05	1.75E+00	60.2	3.45E+05

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	1.08E-03	2.83E+02	1.45E+03	5.11E+00	78.9	1.47E+03
0.158	70.1	-8.01E-01	1.70E-03	4.90E+02	2.15E+03	4.40E+00	77.2	2.21E+03
0.251	69.9	-6.00E-01	2.70E-03	8.15E+02	3.14E+03	3.85E+00	75.5	3.24E+03
0.398	69.9	-4.00E-01	4.28E-03	1.33E+03	4.55E+03	3.42E+00	73.7	4.74E+03
0.631	70	-2.00E-01	6.79E-03	2.14E+03	6.54E+03	3.06E+00	71.9	6.88E+03
1	70	0.00E+00	1.08E-02	3.34E+03	9.29E+03	2.78E+00	70.2	9.87E+03
1.585	70	2.00E-01	1.71E-02	5.12E+03	1.31E+04	2.56E+00	68.6	1.41E+04
2.512	70	4.00E-01	2.70E-02	7.63E+03	1.82E+04	2.39E+00	67.3	1.97E+04
3.981	70	6.00E-01	4.28E-02	1.12E+04	2.52E+04	2.26E+00	66.1	2.75E+04
6.31	70	8.00E-01	6.79E-02	1.61E+04	3.47E+04	2.16E+00	65.1	3.82E+04
10	70	1.00E+00	1.08E-01	2.28E+04	4.76E+04	2.09E+00	64.4	5.28E+04
15.849	70.1	1.20E+00	1.71E-01	3.20E+04	6.51E+04	2.03E+00	63.8	7.26E+04
25.121	70.1	1.40E+00	2.70E-01	4.46E+04	8.87E+04	1.99E+00	63.3	9.93E+04

Table D-2 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	4.01E-04	7.37E+01	6.14E+02	8.33E+00	83.2	6.18E+02
0.158	76	-8.01E-01	6.33E-04	1.35E+02	9.31E+02	6.90E+00	81.8	9.40E+02
0.251	75.9	-6.00E-01	1.01E-03	2.43E+02	1.40E+03	5.77E+00	80.2	1.42E+03
0.398	76.1	-4.00E-01	1.60E-03	4.28E+02	2.10E+03	4.90E+00	78.5	2.14E+03
0.631	76	-2.00E-01	2.53E-03	7.28E+02	3.09E+03	4.24E+00	76.7	3.17E+03
1	76	0.00E+00	4.01E-03	1.22E+03	4.52E+03	3.71E+00	74.9	4.68E+03
1.585	76	2.00E-01	6.35E-03	1.97E+03	6.50E+03	3.30E+00	73.1	6.79E+03
2.512	76.1	4.00E-01	1.01E-02	3.13E+03	9.30E+03	2.97E+00	71.4	9.81E+03
3.981	76.1	6.00E-01	1.60E-02	4.87E+03	1.32E+04	2.71E+00	69.8	1.41E+04
6.31	76.1	8.00E-01	2.53E-02	7.34E+03	1.85E+04	2.51E+00	68.3	1.99E+04
10	76.1	1.00E+00	4.01E-02	1.09E+04	2.57E+04	2.36E+00	67.1	2.79E+04
15.849	76.1	1.20E+00	6.35E-02	1.58E+04	3.55E+04	2.25E+00	66.0	3.89E+04
25.121	76	1.40E+00	1.01E-01	2.26E+04	4.89E+04	2.16E+00	65.2	5.39E+04

Table D-3 Frequency sweeps data output for PAV-aged Evotherm (F-P) unmodified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	800	7.04E+06	6.28E+06	8.92E-01	41.7	9.44E+06
0.158	13	-8.01E-01	1264	9.02E+06	7.64E+06	8.47E-01	40.3	1.18E+07
0.251	13	-6.00E-01	2008	1.12E+07	9.08E+06	8.10E-01	39.0	1.44E+07
0.398	13.1	-4.00E-01	3184	1.38E+07	1.07E+07	7.76E-01	37.8	1.75E+07
0.631	13.1	-2.00E-01	5048	1.70E+07	1.26E+07	7.43E-01	36.6	2.12E+07
1	13	0.00E+00	8000	2.07E+07	1.48E+07	7.13E-01	35.5	2.55E+07
1.585	13	2.00E-01	12680	2.51E+07	1.72E+07	6.85E-01	34.4	3.04E+07
2.512	13	4.00E-01	20096	3.02E+07	1.99E+07	6.58E-01	33.4	3.61E+07
3.981	13	6.00E-01	31848	3.61E+07	2.28E+07	6.32E-01	32.3	4.27E+07
6.31	13	8.00E-01	50480	4.28E+07	2.61E+07	6.08E-01	31.3	5.01E+07
10	13	1.00E+00	80000	5.07E+07	2.97E+07	5.86E-01	30.4	5.88E+07
15.849	13	1.20E+00	126792	5.97E+07	3.34E+07	5.60E-01	29.3	6.84E+07
25.121	13	1.40E+00	200968	6.98E+07	3.75E+07	5.38E-01	28.3	7.93E+07
39.809	13	1.60E+00	318472	8.12E+07	4.18E+07	5.15E-01	27.2	9.13E+07
50	13	1.70E+00	400000	8.71E+07	4.38E+07	5.03E-01	26.7	9.75E+07

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	8.00E+01	1.72E+06	2.02E+06	1.17E+00	49.5	2.65E+06
0.158	21	-8.01E-01	1.26E+02	2.26E+06	2.53E+06	1.12E+00	48.2	3.39E+06
0.251	21	-6.00E-01	2.01E+02	2.96E+06	3.16E+06	1.07E+00	46.9	4.33E+06
0.398	21	-4.00E-01	3.18E+02	3.83E+06	3.92E+06	1.02E+00	45.7	5.49E+06
0.631	21	-2.00E-01	5.05E+02	4.93E+06	4.83E+06	9.80E-01	44.4	6.90E+06
1	21	0.00E+00	8.00E+02	6.28E+06	5.90E+06	9.39E-01	43.2	8.62E+06
1.585	21	2.00E-01	1.27E+03	7.96E+06	7.17E+06	9.00E-01	42.0	1.07E+07
2.512	21	4.00E-01	2.01E+03	1.00E+07	8.65E+06	8.65E-01	40.8	1.32E+07
3.981	21	6.00E-01	3.18E+03	1.25E+07	1.04E+07	8.30E-01	39.7	1.62E+07
6.31	21	8.00E-01	5.05E+03	1.55E+07	1.24E+07	7.97E-01	38.6	1.98E+07
10	21	1.00E+00	8.00E+03	1.91E+07	1.47E+07	7.69E-01	37.5	2.41E+07
15.849	21	1.20E+00	1.27E+04	2.35E+07	1.72E+07	7.33E-01	36.2	2.91E+07
25.121	21	1.40E+00	2.01E+04	2.85E+07	2.01E+07	7.06E-01	35.2	3.48E+07
39.809	21	1.60E+00	3.18E+04	3.45E+07	2.34E+07	6.77E-01	34.1	4.17E+07
50	21	1.70E+00	4.00E+04	3.79E+07	2.51E+07	6.63E-01	33.5	4.55E+07

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	8.50E+00	3.59E+05	5.46E+05	1.52E+00	56.6	6.53E+05
0.158	29	-8.01E-01	1.34E+01	4.96E+05	7.20E+05	1.45E+00	55.5	8.74E+05
0.251	29	-6.00E-01	2.13E+01	6.76E+05	9.40E+05	1.39E+00	54.3	1.16E+06
0.398	29	-4.00E-01	3.38E+01	9.13E+05	1.22E+06	1.33E+00	53.1	1.52E+06
0.631	29	-2.00E-01	5.36E+01	1.23E+06	1.57E+06	1.28E+00	51.9	1.99E+06
1	29	0.00E+00	8.50E+01	1.64E+06	2.01E+06	1.22E+00	50.8	2.59E+06
1.585	29	2.00E-01	1.35E+02	2.17E+06	2.55E+06	1.17E+00	49.6	3.35E+06
2.512	29	4.00E-01	2.14E+02	2.85E+06	3.21E+06	1.13E+00	48.5	4.30E+06
3.981	29	6.00E-01	3.38E+02	3.72E+06	4.03E+06	1.08E+00	47.3	5.48E+06
6.31	29	8.00E-01	5.36E+02	4.83E+06	5.01E+06	1.04E+00	46.1	6.96E+06
10	29	1.00E+00	8.50E+02	6.22E+06	6.19E+06	9.95E-01	44.9	8.78E+06
15.849	29	1.20E+00	1.35E+03	7.96E+06	7.62E+06	9.58E-01	43.8	1.10E+07
25.121	29	1.40E+00	2.14E+03	1.01E+07	9.29E+06	9.16E-01	42.5	1.38E+07
39.809	29	1.60E+00	3.38E+03	1.28E+07	1.13E+07	8.79E-01	41.3	1.71E+07
50	29	1.70E+00	4.25E+03	1.44E+07	1.24E+07	8.62E-01	40.8	1.90E+07

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	1.20E+00	6.95E+04	1.37E+05	1.97E+00	63.1	1.54E+05
0.158	37	-8.01E-01	1.90E+00	9.92E+04	1.87E+05	1.88E+00	62.0	2.11E+05
0.251	37	-6.00E-01	3.01E+00	1.41E+05	2.54E+05	1.79E+00	60.9	2.90E+05
0.398	37	-4.00E-01	4.78E+00	1.97E+05	3.40E+05	1.72E+00	59.9	3.93E+05
0.631	37	-2.00E-01	7.57E+00	2.75E+05	4.55E+05	1.65E+00	58.9	5.32E+05
1	37	0.00E+00	1.20E+01	3.81E+05	6.06E+05	1.59E+00	57.8	7.16E+05
1.585	37	2.00E-01	1.90E+01	5.26E+05	8.02E+05	1.53E+00	56.8	9.59E+05
2.512	37	4.00E-01	3.01E+01	7.21E+05	1.06E+06	1.46E+00	55.7	1.28E+06
3.981	37	6.00E-01	4.78E+01	9.83E+05	1.38E+06	1.41E+00	54.6	1.70E+06
6.31	37	8.00E-01	7.57E+01	1.33E+06	1.80E+06	1.35E+00	53.4	2.23E+06
10	37	1.00E+00	1.20E+02	1.80E+06	2.31E+06	1.29E+00	52.2	2.93E+06
15.849	37	1.20E+00	1.90E+02	2.40E+06	2.97E+06	1.24E+00	51.1	3.82E+06
25.121	37	1.40E+00	3.01E+02	3.20E+06	3.79E+06	1.18E+00	49.8	4.96E+06
39.809	37	1.60E+00	4.78E+02	4.24E+06	4.81E+06	1.13E+00	48.6	6.41E+06
50	37	1.70E+00	6.00E+02	4.88E+06	5.41E+06	1.11E+00	48.0	7.28E+06

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	8.14E+03	2.37E+04	2.91E+00	71.0	
0.158	46	-8.01E-01	1.58E-01	1.23E+04	3.33E+04	2.70E+00	69.7	3.55E+04
0.251	46	-6.00E-01	2.51E-01	1.84E+04	4.66E+04	2.53E+00	68.4	5.01E+04
0.398	46	-4.00E-01	3.98E-01	2.70E+04	6.47E+04	2.39E+00	67.3	7.01E+04
0.631	46	-2.00E-01	6.31E-01	3.87E+04	8.85E+04	2.29E+00	66.4	9.66E+04
1	46	0.00E+00	1.00E+00	5.49E+04	1.21E+05	2.20E+00	65.5	1.32E+05
1.585	46	2.00E-01	1.59E+00	7.70E+04	1.63E+05	2.12E+00	64.7	1.80E+05
2.512	46	4.00E-01	2.51E+00	1.08E+05	2.22E+05	2.05E+00	64.0	2.47E+05
3.981	45.8	6.00E-01	3.98E+00	1.52E+05	3.03E+05	1.99E+00	63.3	3.39E+05
6.31	45.7	8.00E-01	6.31E+00	2.10E+05	4.06E+05	1.93E+00	62.6	4.58E+05
10	45.7	1.00E+00	1.00E+01	3.04E+05	5.59E+05	1.84E+00	61.5	6.36E+05
15.849	45.6	1.20E+00	1.58E+01	4.45E+05	7.75E+05	1.74E+00	60.1	8.93E+05
25.121	45.6	1.40E+00	2.51E+01	6.38E+05	1.05E+06	1.65E+00	58.8	1.23E+06

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	1.01E-02	5.90E+02	3.23E+03	5.48E+00	79.7	3.29E+03
0.158	58	-8.01E-01	1.59E-02	1.03E+03	4.89E+03	4.74E+00	78.1	5.00E+03
0.251	58	-6.00E-01	2.53E-02	1.72E+03	7.23E+03	4.20E+00	76.6	7.43E+03
0.398	58	-4.00E-01	4.01E-02	2.81E+03	1.06E+04	3.77E+00	75.1	1.10E+04
0.631	58	-2.00E-01	6.36E-02	4.43E+03	1.52E+04	3.44E+00	73.8	1.59E+04
1	58	0.00E+00	1.01E-01	6.89E+03	2.19E+04	3.17E+00	72.5	2.29E+04
1.585	58	2.00E-01	1.60E-01	1.06E+04	3.13E+04	2.96E+00	71.3	3.30E+04
2.512	58	4.00E-01	2.53E-01	1.60E+04	4.45E+04	2.78E+00	70.2	4.72E+04
3.981	58	6.00E-01	4.01E-01	2.37E+04	6.26E+04	2.64E+00	69.2	6.69E+04
6.31	58	8.00E-01	6.36E-01	3.47E+04	8.73E+04	2.51E+00	68.3	9.40E+04
10	58	1.00E+00	1.01E+00	5.02E+04	1.21E+05	2.41E+00	67.5	1.31E+05
15.849	58	1.20E+00	1.60E+00	7.17E+04	1.67E+05	2.33E+00	66.7	1.82E+05
25.121	58	1.40E+00	2.53E+00	1.01E+05	2.27E+05	2.25E+00	66.0	2.48E+05

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	1.30E-03	3.74E+01	4.94E+02	1.32E+01	85.7	4.96E+02
0.158	70.1	-8.01E-01	2.05E-03	6.92E+01	7.45E+02	1.08E+01	84.7	7.48E+02
0.251	69.9	-6.00E-01	3.26E-03	1.34E+02	1.17E+03	8.74E+00	83.5	1.18E+03
0.398	69.9	-4.00E-01	5.17E-03	2.40E+02	1.77E+03	7.38E+00	82.3	1.79E+03
0.631	70	-2.00E-01	8.20E-03	4.22E+02	2.68E+03	6.34E+00	81.0	2.71E+03
1	70	0.00E+00	1.30E-02	7.24E+02	4.00E+03	5.52E+00	79.7	4.07E+03
1.585	70	2.00E-01	2.06E-02	1.22E+03	5.94E+03	4.89E+00	78.4	6.06E+03
2.512	70	4.00E-01	3.27E-02	2.01E+03	8.80E+03	4.38E+00	77.1	9.03E+03
3.981	70	6.00E-01	5.18E-02	3.25E+03	1.29E+04	3.97E+00	75.9	1.33E+04
6.31	70	8.00E-01	8.20E-02	5.17E+03	1.88E+04	3.65E+00	74.7	1.95E+04
10	70	1.00E+00	1.30E-01	8.05E+03	2.73E+04	3.38E+00	73.5	2.84E+04
15.849	70.1	1.20E+00	2.06E-01	1.24E+04	3.92E+04	3.16E+00	72.5	4.11E+04
25.121	70.1	1.40E+00	3.27E-01	1.88E+04	5.58E+04	2.98E+00	71.4	5.89E+04

Table D-3 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	4.90E-04	8.40E+00	2.03E+02	2.42E+01	87.6	2.03E+02
0.158	76	-8.01E-01	7.74E-04	1.75E+01	3.16E+02	1.81E+01	86.8	3.16E+02
0.251	75.9	-6.00E-01	1.23E-03	3.54E+01	4.93E+02	1.39E+01	85.9	4.95E+02
0.398	76.1	-4.00E-01	1.95E-03	6.74E+01	7.56E+02	1.12E+01	84.9	7.59E+02
0.631	76	-2.00E-01	3.09E-03	1.28E+02	1.18E+03	9.17E+00	83.8	1.18E+03
1	76	0.00E+00	4.90E-03	2.32E+02	1.79E+03	7.72E+00	82.6	1.81E+03
1.585	76	2.00E-01	7.77E-03	4.10E+02	2.71E+03	6.63E+00	81.4	2.74E+03
2.512	76.1	4.00E-01	1.23E-02	7.06E+02	4.08E+03	5.77E+00	80.2	4.14E+03
3.981	76.1	6.00E-01	1.95E-02	1.19E+03	6.08E+03	5.11E+00	78.9	6.20E+03
6.31	76.1	8.00E-01	3.09E-02	1.96E+03	8.99E+03	4.58E+00	77.7	9.20E+03
10	76.1	1.00E+00	4.90E-02	3.19E+03	1.32E+04	4.15E+00	76.5	1.36E+04
15.849	76.1	1.20E+00	7.77E-02	5.12E+03	1.94E+04	3.80E+00	75.2	2.01E+04
25.121	76	1.40E+00	1.23E-01	8.03E+03	2.81E+04	3.50E+00	74.1	2.93E+04

Table D-4 Frequency sweeps data output for PAV-aged Evotherm (F-P) SBS modified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	8.00E+02	7.47E+06	6.34E+06	8.49E-01	40.3	9.80E+06
0.158	13	-8.01E-01	1.26E+03	9.44E+06	7.65E+06	8.10E-01	39.0	1.22E+07
0.251	13	-6.00E-01	2.01E+03	1.17E+07	9.06E+06	7.78E-01	37.9	1.48E+07
0.398	13.1	-4.00E-01	3.18E+03	1.43E+07	1.07E+07	7.47E-01	36.8	1.78E+07
0.631	13.1	-2.00E-01	5.05E+03	1.74E+07	1.25E+07	7.18E-01	35.7	2.14E+07
1	13	0.00E+00	8.00E+03	2.11E+07	1.46E+07	6.90E-01	34.6	2.56E+07
1.585	13	2.00E-01	1.27E+04	2.54E+07	1.69E+07	6.63E-01	33.6	3.05E+07
2.512	13	4.00E-01	2.01E+04	3.04E+07	1.94E+07	6.38E-01	32.5	3.61E+07
3.981	13	6.00E-01	3.18E+04	3.62E+07	2.22E+07	6.14E-01	31.6	4.25E+07
6.31	13	8.00E-01	5.05E+04	4.29E+07	2.53E+07	5.90E-01	30.6	4.99E+07
10	13	1.00E+00	8.00E+04	5.04E+07	2.87E+07	5.69E-01	29.6	5.80E+07
15.849	13	1.20E+00	1.27E+05	5.91E+07	3.23E+07	5.46E-01	28.6	6.73E+07
25.121	13	1.40E+00	2.01E+05	6.89E+07	3.60E+07	5.23E-01	27.6	7.77E+07
39.809	13	1.60E+00	3.18E+05	8.00E+07	4.01E+07	5.01E-01	26.6	8.95E+07
50	13	1.70E+00	4.00E+05	8.59E+07	4.21E+07	4.90E-01	26.1	9.56E+07

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	8.00E+01	2.02E+06	2.18E+06	1.08E+00	47.2	2.97E+06
0.158	21	-8.01E-01	1.26E+02	2.62E+06	2.72E+06	1.04E+00	46.1	3.77E+06
0.251	21	-6.00E-01	2.01E+02	3.38E+06	3.37E+06	9.96E-01	44.9	4.77E+06
0.398	21	-4.00E-01	3.18E+02	4.32E+06	4.14E+06	9.58E-01	43.8	5.98E+06
0.631	21	-2.00E-01	5.05E+02	5.50E+06	5.06E+06	9.21E-01	42.6	7.47E+06
1	21	0.00E+00	8.00E+02	6.94E+06	6.15E+06	8.85E-01	41.5	9.27E+06
1.585	21	2.00E-01	1.27E+03	8.70E+06	7.42E+06	8.53E-01	40.5	1.14E+07
2.512	21	4.00E-01	2.01E+03	1.08E+07	8.90E+06	8.21E-01	39.4	1.40E+07
3.981	21	6.00E-01	3.18E+03	1.34E+07	1.06E+07	7.92E-01	38.4	1.71E+07
6.31	21	8.00E-01	5.05E+03	1.65E+07	1.26E+07	7.62E-01	37.3	2.07E+07
10	21	1.00E+00	8.00E+03	2.01E+07	1.48E+07	7.33E-01	36.3	2.50E+07
15.849	21	1.20E+00	1.27E+04	2.45E+07	1.73E+07	7.06E-01	35.2	3.00E+07
25.121	21	1.40E+00	2.01E+04	2.97E+07	2.01E+07	6.78E-01	34.1	3.59E+07
39.809	21	1.60E+00	3.18E+04	3.57E+07	2.33E+07	6.52E-01	33.1	4.26E+07
50	21	1.70E+00	4.00E+04	3.91E+07	2.49E+07	6.38E-01	32.5	4.63E+07

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	1.00E+01	4.88E+05	6.55E+05	1.34E+00	53.3	8.16E+05
0.158	29	-8.01E-01	1.58E+01	6.56E+05	8.52E+05	1.30E+00	52.4	1.07E+06
0.251	29	-6.00E-01	2.51E+01	8.74E+05	1.10E+06	1.26E+00	51.5	1.40E+06
0.398	29	-4.00E-01	3.98E+01	1.16E+06	1.41E+06	1.21E+00	50.5	1.83E+06
0.631	29	-2.00E-01	6.31E+01	1.53E+06	1.79E+06	1.17E+00	49.5	2.36E+06
1	29	0.00E+00	1.00E+02	2.01E+06	2.27E+06	1.13E+00	48.5	3.03E+06
1.585	29	2.00E-01	1.59E+02	2.61E+06	2.85E+06	1.09E+00	47.5	3.87E+06
2.512	29	4.00E-01	2.51E+02	3.39E+06	3.56E+06	1.05E+00	46.4	4.91E+06
3.981	29	6.00E-01	3.98E+02	4.37E+06	4.42E+06	1.01E+00	45.3	6.21E+06
6.31	29	8.00E-01	6.31E+02	5.59E+06	5.45E+06	9.74E-01	44.2	7.80E+06
10	29	1.00E+00	1.00E+03	7.13E+06	6.66E+06	9.34E-01	43.0	9.76E+06
15.849	29	1.20E+00	1.58E+03	9.01E+06	8.15E+06	9.04E-01	42.1	1.21E+07
25.121	29	1.40E+00	2.51E+03	1.14E+07	9.86E+06	8.67E-01	40.9	1.51E+07
39.809	29	1.60E+00	3.98E+03	1.43E+07	1.19E+07	8.34E-01	39.8	1.86E+07
50	29	1.70E+00	5.00E+03	1.59E+07	1.30E+07	8.17E-01	39.2	2.05E+07

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	1.50E+00	1.15E+05	1.83E+05	1.59E+00	57.8	2.16E+05
0.158	37	-8.01E-01	2.37E+00	1.57E+05	2.44E+05	1.55E+00	57.2	2.90E+05
0.251	37	-6.00E-01	3.77E+00	2.14E+05	3.24E+05	1.52E+00	56.6	3.88E+05
0.398	37	-4.00E-01	5.97E+00	2.90E+05	4.28E+05	1.48E+00	55.9	5.17E+05
0.631	37	-2.00E-01	9.47E+00	3.91E+05	5.63E+05	1.44E+00	55.2	6.85E+05
1	37	0.00E+00	1.50E+01	5.28E+05	7.39E+05	1.40E+00	54.5	9.08E+05
1.585	37	2.00E-01	2.38E+01	7.09E+05	9.63E+05	1.36E+00	53.6	1.20E+06
2.512	37	4.00E-01	3.77E+01	9.51E+05	1.25E+06	1.32E+00	52.8	1.57E+06
3.981	37	6.00E-01	5.97E+01	1.27E+06	1.62E+06	1.27E+00	51.8	2.06E+06
6.31	37	8.00E-01	9.47E+01	1.69E+06	2.07E+06	1.23E+00	50.8	2.67E+06
10	37	1.00E+00	1.50E+02	2.24E+06	2.64E+06	1.18E+00	49.7	3.46E+06
15.849	37	1.20E+00	2.38E+02	2.94E+06	3.36E+06	1.14E+00	48.8	4.46E+06
25.121	37	1.40E+00	3.77E+02	3.86E+06	4.23E+06	1.10E+00	47.7	5.72E+06
39.809	37	1.60E+00	5.97E+02	5.03E+06	5.31E+06	1.06E+00	46.6	7.31E+06
50	37	1.70E+00	7.50E+02	5.72E+06	5.94E+06	1.04E+00	46.1	8.25E+06

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	1.69E+04	3.30E+04	1.95E+00	62.8	3.70E+04
0.158	46	-8.01E-01	1.58E-01	2.39E+04	4.49E+04	1.88E+00	62.0	5.08E+04
0.251	46	-6.00E-01	2.51E-01	3.26E+04	5.97E+04	1.83E+00	61.4	6.80E+04
0.398	46	-4.00E-01	3.98E-01	4.49E+04	8.06E+04	1.80E+00	60.9	9.23E+04
0.631	46	-2.00E-01	6.31E-01	6.06E+04	1.07E+05	1.77E+00	60.5	1.23E+05
1	46	0.00E+00	1.00E+00	8.11E+04	1.42E+05	1.75E+00	60.2	1.63E+05
1.585	46	2.00E-01	1.59E+00	1.09E+05	1.87E+05	1.73E+00	59.9	2.17E+05
2.512	46	4.00E-01	2.51E+00	1.48E+05	2.52E+05	1.71E+00	59.6	2.92E+05
3.981	45.8	6.00E-01	3.98E+00	1.99E+05	3.35E+05	1.69E+00	59.4	3.90E+05
6.31	45.8	8.00E-01	6.31E+00	2.69E+05	4.46E+05	1.66E+00	58.9	5.21E+05
10	45.8	1.00E+00	1.00E+01	3.83E+05	6.09E+05	1.59E+00	57.9	7.19E+05
15.849	45.8	1.20E+00	1.58E+01	5.41E+05	8.24E+05	1.52E+00	56.7	9.86E+05
25.121	45.9	1.40E+00	2.51E+01	7.52E+05	1.09E+06	1.46E+00	55.5	1.33E+06

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	9.00E-03	1.95E+03	5.71E+03	2.93E+00	71.1	6.04E+03
0.158	58	-8.01E-01	1.42E-02	3.04E+03	8.10E+03	2.67E+00	69.5	8.65E+03
0.251	58	-6.00E-01	2.26E-02	4.62E+03	1.14E+04	2.47E+00	67.9	1.23E+04
0.398	58	-4.00E-01	3.58E-02	6.77E+03	1.57E+04	2.32E+00	66.7	1.71E+04
0.631	58	-2.00E-01	5.68E-02	9.91E+03	2.18E+04	2.20E+00	65.5	2.39E+04
1	58	0.00E+00	9.00E-02	1.41E+04	2.98E+04	2.11E+00	64.6	3.29E+04
1.585	58	2.00E-01	1.43E-01	2.00E+04	4.09E+04	2.04E+00	63.9	4.55E+04
2.512	58	4.00E-01	2.26E-01	2.80E+04	5.57E+04	1.99E+00	63.3	6.23E+04
3.981	58	6.00E-01	3.58E-01	3.86E+04	7.54E+04	1.95E+00	62.9	8.47E+04
6.31	58	8.00E-01	5.68E-01	5.32E+04	1.02E+05	1.92E+00	62.6	1.15E+05
10	58	1.00E+00	9.00E-01	7.25E+04	1.38E+05	1.90E+00	62.3	1.56E+05
15.849	58	1.20E+00	1.43E+00	9.91E+04	1.86E+05	1.88E+00	62.0	2.11E+05
25.121	58	1.40E+00	2.26E+00	1.34E+05	2.49E+05	1.86E+00	61.7	2.83E+05

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	1.00E-03	1.61E+02	9.79E+02	6.10E+00	80.7	9.92E+02
0.158	70.1	-8.01E-01	1.58E-03	2.85E+02	1.47E+03	5.17E+00	79.1	1.50E+03
0.251	69.9	-6.00E-01	2.51E-03	4.82E+02	2.16E+03	4.49E+00	77.4	2.22E+03
0.398	69.9	-4.00E-01	3.98E-03	8.13E+02	3.19E+03	3.93E+00	75.7	3.29E+03
0.631	70	-2.00E-01	6.31E-03	1.32E+03	4.62E+03	3.50E+00	74.0	4.81E+03
1	70	0.00E+00	1.00E-02	2.11E+03	6.66E+03	3.15E+00	72.4	6.98E+03
1.585	70	2.00E-01	1.59E-02	3.30E+03	9.47E+03	2.87E+00	70.8	1.00E+04
2.512	70	4.00E-01	2.51E-02	5.00E+03	1.33E+04	2.66E+00	69.4	1.42E+04
3.981	70	6.00E-01	3.98E-02	7.46E+03	1.86E+04	2.50E+00	68.2	2.01E+04
6.31	70	8.00E-01	6.31E-02	1.09E+04	2.60E+04	2.37E+00	67.1	2.82E+04
10	70	1.00E+00	1.00E-01	1.58E+04	3.60E+04	2.28E+00	66.3	3.94E+04
15.849	70.1	1.20E+00	1.58E-01	2.26E+04	5.00E+04	2.21E+00	65.6	5.49E+04
25.121	70.1	1.40E+00	2.51E-01	3.21E+04	6.91E+04	2.15E+00	65.1	7.62E+04

Table D-4 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	4.00E-04	3.86E+01	4.06E+02	1.05E+01	84.6	4.08E+02
0.158	76	-8.01E-01	6.32E-04	7.35E+01	6.26E+02	8.52E+00	83.3	6.31E+02
0.251	75.9	-6.00E-01	1.00E-03	1.36E+02	9.53E+02	7.00E+00	81.9	9.63E+02
0.398	76.1	-4.00E-01	1.59E-03	2.45E+02	1.43E+03	5.85E+00	80.3	1.45E+03
0.631	76	-2.00E-01	2.52E-03	4.29E+02	2.14E+03	4.98E+00	78.7	2.18E+03
1	76	0.00E+00	4.00E-03	7.32E+02	3.16E+03	4.31E+00	77.0	3.24E+03
1.585	76	2.00E-01	6.34E-03	1.22E+03	4.61E+03	3.79E+00	75.2	4.77E+03
2.512	76.1	4.00E-01	1.00E-02	1.97E+03	6.66E+03	3.39E+00	73.6	6.95E+03
3.981	76.1	6.00E-01	1.59E-02	3.10E+03	9.51E+03	3.07E+00	72.0	1.00E+04
6.31	76.1	8.00E-01	2.52E-02	4.78E+03	1.35E+04	2.82E+00	70.5	1.43E+04
10	76.1	1.00E+00	4.00E-02	7.24E+03	1.90E+04	2.63E+00	69.2	2.04E+04
15.849	76.1	1.20E+00	6.34E-02	1.08E+04	2.67E+04	2.48E+00	68.0	2.88E+04
25.121	76	1.40E+00	1.00E-01	1.57E+04	3.71E+04	2.36E+00	67.1	4.03E+04

Table D-5 Frequency sweeps data output for PAV-aged Sasobit (F-T) unmodified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	1.20E+03	7.87E+06	6.84E+06	0.87	41.0	1.04E+07
0.158	13	-8.01E-01	1.90E+03	9.99E+06	8.28E+06	0.83	39.7	1.30E+07
0.251	13	-6.00E-01	3.01E+03	1.23E+07	9.76E+06	0.80	38.5	1.57E+07
0.398	13.1	-4.00E-01	4.78E+03	1.51E+07	1.15E+07	0.76	37.3	1.90E+07
0.631	13.1	-2.00E-01	7.57E+03	1.85E+07	1.36E+07	0.73	36.2	2.29E+07
1	13	0.00E+00	1.20E+04	2.25E+07	1.58E+07	0.70	35.1	2.75E+07
1.585	13	2.00E-01	1.90E+04	2.72E+07	1.84E+07	0.67	34.0	3.29E+07
2.512	13	4.00E-01	3.01E+04	3.27E+07	2.12E+07	0.65	33.0	3.89E+07
3.981	13	6.00E-01	4.78E+04	3.90E+07	2.43E+07	0.62	31.9	4.60E+07
6.31	13	8.00E-01	7.57E+04	4.63E+07	2.77E+07	0.60	30.9	5.40E+07
10	13	1.00E+00	1.20E+05	5.46E+07	3.15E+07	0.58	30.0	6.30E+07
15.849	13	1.20E+00	1.90E+05	6.40E+07	3.53E+07	0.55	28.9	7.31E+07
25.121	13	1.40E+00	3.01E+05	7.46E+07	3.97E+07	0.53	28.0	8.45E+07
39.809	13	1.60E+00	4.78E+05	8.68E+07	4.42E+07	0.51	27.0	9.75E+07
50	13	1.70E+00	6.00E+05	9.30E+07	4.63E+07	0.50	26.5	1.04E+08

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	1.20E+02	1.95E+06	2.23E+06	1.14	48.7	2.96E+06
0.158	21	-8.01E-01	1.90E+02	2.58E+06	2.81E+06	1.09	47.4	3.82E+06
0.251	21	-6.00E-01	3.01E+02	3.35E+06	3.50E+06	1.04	46.2	4.84E+06
0.398	21	-4.00E-01	4.78E+02	4.33E+06	4.32E+06	1.00	45.0	6.11E+06
0.631	21	-2.00E-01	7.57E+02	5.54E+06	5.30E+06	0.96	43.8	7.66E+06
1	21	0.00E+00	1.20E+03	7.04E+06	6.47E+06	0.92	42.6	9.56E+06
1.585	21	2.00E-01	1.90E+03	8.89E+06	7.83E+06	0.88	41.4	1.18E+07
2.512	21	4.00E-01	3.01E+03	1.11E+07	9.43E+06	0.85	40.3	1.46E+07
3.981	21	6.00E-01	4.78E+03	1.39E+07	1.13E+07	0.81	39.1	1.79E+07
6.31	21	8.00E-01	7.57E+03	1.71E+07	1.34E+07	0.78	38.0	2.17E+07
10	21	1.00E+00	1.20E+04	2.10E+07	1.58E+07	0.75	37.0	2.63E+07
15.849	21	1.20E+00	1.90E+04	2.57E+07	1.85E+07	0.72	35.9	3.17E+07
25.121	21	1.40E+00	3.01E+04	3.12E+07	2.16E+07	0.69	34.7	3.79E+07
39.809	21	1.60E+00	4.78E+04	3.76E+07	2.50E+07	0.67	33.6	4.52E+07
50	21	1.70E+00	6.00E+04	4.12E+07	2.69E+07	0.65	33.1	4.92E+07

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	1.53E+01	4.27E+05	6.24E+05	1.46	55.6	7.56E+05
0.158	29	-8.01E-01	2.42E+01	5.85E+05	8.20E+05	1.40	54.5	1.01E+06
0.251	29	-6.00E-01	3.84E+01	7.92E+05	1.07E+06	1.35	53.4	1.33E+06
0.398	29	-4.00E-01	6.08E+01	1.06E+06	1.38E+06	1.29	52.3	1.74E+06
0.631	29	-2.00E-01	9.65E+01	1.42E+06	1.77E+06	1.24	51.2	2.27E+06
1	29	0.00E+00	1.53E+02	1.89E+06	2.26E+06	1.19	50.1	2.94E+06
1.585	29	2.00E-01	2.42E+02	2.49E+06	2.85E+06	1.15	48.9	3.79E+06
2.512	29	4.00E-01	3.84E+02	3.26E+06	3.59E+06	1.10	47.7	4.85E+06
3.981	29	6.00E-01	6.09E+02	4.24E+06	4.49E+06	1.06	46.6	6.18E+06
6.31	29	8.00E-01	9.65E+02	5.48E+06	5.57E+06	1.02	45.5	7.82E+06
10	29	1.00E+00	1.53E+03	7.05E+06	6.87E+06	0.97	44.3	9.85E+06
15.849	29	1.20E+00	2.42E+03	8.99E+06	8.40E+06	0.94	43.1	1.23E+07
25.121	29	1.40E+00	3.84E+03	1.14E+07	1.02E+07	0.90	41.9	1.53E+07
39.809	29	1.60E+00	6.09E+03	1.43E+07	1.24E+07	0.86	40.8	1.89E+07
50	29	1.70E+00	7.64E+03	1.60E+07	1.35E+07	0.85	40.2	2.10E+07

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	1.80E+00	8.95E+04	1.66E+05	1.85	61.6	1.88E+05
0.158	37	-8.01E-01	2.84E+00	1.27E+05	2.25E+05	1.77	60.6	2.59E+05
0.251	37	-6.00E-01	4.52E+00	1.77E+05	3.01E+05	1.70	59.6	3.49E+05
0.398	37	-4.00E-01	7.16E+00	2.46E+05	4.02E+05	1.64	58.6	4.71E+05
0.631	37	-2.00E-01	1.14E+01	3.41E+05	5.37E+05	1.58	57.6	6.36E+05
1	37	0.00E+00	1.80E+01	4.68E+05	7.10E+05	1.52	56.6	8.51E+05
1.585	37	2.00E-01	2.85E+01	6.40E+05	9.35E+05	1.46	55.6	1.13E+06
2.512	37	4.00E-01	4.52E+01	8.70E+05	1.22E+06	1.41	54.6	1.50E+06
3.981	37	6.00E-01	7.17E+01	1.18E+06	1.60E+06	1.35	53.5	1.98E+06
6.31	37	8.00E-01	1.14E+02	1.59E+06	2.07E+06	1.30	52.5	2.61E+06
10	37	1.00E+00	1.80E+02	2.12E+06	2.65E+06	1.25	51.4	3.39E+06
15.849	37	1.20E+00	2.85E+02	2.82E+06	3.38E+06	1.20	50.2	4.40E+06
25.121	37	1.40E+00	4.52E+02	3.73E+06	4.29E+06	1.15	49.0	5.68E+06
39.809	37	1.60E+00	7.17E+02	4.90E+06	5.41E+06	1.10	47.8	7.30E+06
50	37	1.70E+00	9.00E+02	5.60E+06	6.06E+06	1.08	47.3	8.25E+06

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tanδ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	8.42E+03	2.43E+04	2.89	70.9	2.58E+04
0.158	46	-8.01E-01	1.58E-01	1.27E+04	3.41E+04	2.69	69.6	3.64E+04
0.251	46	-6.00E-01	2.51E-01	1.89E+04	4.77E+04	2.53	68.4	5.13E+04
0.398	46	-4.00E-01	3.98E-01	2.74E+04	6.57E+04	2.40	67.4	7.12E+04
0.631	46	-2.00E-01	6.31E-01	3.92E+04	9.00E+04	2.29	66.4	9.81E+04
1	46	0.00E+00	1.00E+00	5.53E+04	1.22E+05	2.21	65.6	1.34E+05
1.585	46	2.00E-01	1.59E+00	7.70E+04	1.64E+05	2.14	64.9	1.82E+05
2.512	46	4.00E-01	2.51E+00	1.07E+05	2.22E+05	2.07	64.2	2.47E+05
3.981	45.8	6.00E-01	3.98E+00	1.50E+05	3.02E+05	2.01	63.6	3.37E+05
6.31	45.9	8.00E-01	6.31E+00	2.08E+05	4.07E+05	1.96	63.0	4.57E+05
10	45.9	1.00E+00	1.00E+01	3.00E+05	5.60E+05	1.87	61.9	6.35E+05
15.849	46	1.20E+00	1.58E+01	4.40E+05	7.77E+05	1.77	60.5	8.93E+05
25.121	46	1.40E+00	2.51E+01	6.32E+05	1.06E+06	1.67	59.1	1.23E+06

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	9.00E-03	5.75E+02	3.15E+03	5.47	79.6	3.20E+03
0.158	58	-8.01E-01	1.42E-02	9.86E+02	4.70E+03	4.76	78.1	4.80E+03
0.251	58	-6.00E-01	2.26E-02	1.64E+03	6.92E+03	4.22	76.7	7.11E+03
0.398	58	-4.00E-01	3.58E-02	2.65E+03	1.01E+04	3.80	75.3	1.04E+04
0.631	58	-2.00E-01	5.68E-02	4.22E+03	1.46E+04	3.46	73.9	1.52E+04
1	58	0.00E+00	9.00E-02	6.54E+03	2.09E+04	3.20	72.6	2.19E+04
1.585	58	2.00E-01	1.43E-01	1.00E+04	2.99E+04	2.98	71.5	3.15E+04
2.512	58	4.00E-01	2.26E-01	1.52E+04	4.26E+04	2.80	70.4	4.52E+04
3.981	58	6.00E-01	3.58E-01	2.24E+04	5.97E+04	2.66	69.4	6.38E+04
6.31	58	8.00E-01	5.68E-01	3.28E+04	8.34E+04	2.54	68.5	8.96E+04
10	58	1.00E+00	9.00E-01	4.72E+04	1.15E+05	2.44	67.7	1.25E+05
15.849	58	1.20E+00	1.43E+00	6.77E+04	1.59E+05	2.35	67.0	1.73E+05
25.121	58	1.40E+00	2.26E+00	9.58E+04	2.18E+05	2.28	66.3	2.38E+05

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	1.01E-03	3.21E+01	4.38E+02	13.62	85.8	4.39E+02
0.158	70.1	-8.01E-01	1.60E-03	6.20E+01	6.79E+02	10.95	84.8	6.81E+02
0.251	69.9	-6.00E-01	2.54E-03	1.15E+02	1.04E+03	9.04	83.7	1.05E+03
0.398	69.9	-4.00E-01	4.02E-03	2.10E+02	1.60E+03	7.60	82.5	1.61E+03
0.631	70	-2.00E-01	6.37E-03	3.71E+02	2.42E+03	6.52	81.3	2.44E+03
1	70	0.00E+00	1.01E-02	6.39E+02	3.63E+03	5.67	80.0	3.68E+03
1.585	70	2.00E-01	1.60E-02	1.08E+03	5.40E+03	5.01	78.7	5.50E+03
2.512	70	4.00E-01	2.54E-02	1.78E+03	7.98E+03	4.49	77.4	8.17E+03
3.981	70	6.00E-01	4.02E-02	2.87E+03	1.17E+04	4.07	76.2	1.20E+04
6.31	70	8.00E-01	6.37E-02	4.56E+03	1.70E+04	3.74	75.0	1.76E+04
10	70	1.00E+00	1.01E-01	7.12E+03	2.46E+04	3.46	73.9	2.57E+04
15.849	70.1	1.20E+00	1.60E-01	1.10E+04	3.54E+04	3.23	72.8	3.71E+04
25.121	70.1	1.40E+00	2.54E-01	1.66E+04	5.06E+04	3.04	71.8	5.33E+04

Table D-5 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	4.01E-04	7.48E+00	1.82E+02	24.30	87.6	1.82E+02
0.158	76	-8.01E-01	6.33E-04	1.53E+01	2.82E+02	18.45	86.9	2.83E+02
0.251	75.9	-6.00E-01	1.01E-03	3.07E+01	4.40E+02	14.36	86.0	4.41E+02
0.398	76.1	-4.00E-01	1.60E-03	5.91E+01	6.81E+02	11.53	85.0	6.84E+02
0.631	76	-2.00E-01	2.53E-03	1.10E+02	1.05E+03	9.49	84.0	1.05E+03
1	76	0.00E+00	4.01E-03	1.99E+02	1.59E+03	7.99	82.9	1.61E+03
1.585	76	2.00E-01	6.35E-03	3.56E+02	2.43E+03	6.83	81.7	2.46E+03
2.512	76.1	4.00E-01	1.01E-02	6.17E+02	3.67E+03	5.94	80.4	3.72E+03
3.981	76.1	6.00E-01	1.60E-02	1.04E+03	5.48E+03	5.25	79.2	5.57E+03
6.31	76.1	8.00E-01	2.53E-02	1.73E+03	8.12E+03	4.69	78.0	8.30E+03
10	76.1	1.00E+00	4.01E-02	2.81E+03	1.19E+04	4.25	76.8	1.23E+04
15.849	76.1	1.20E+00	6.35E-02	4.49E+03	1.74E+04	3.88	75.6	1.80E+04
25.121	76	1.40E+00	1.01E-01	7.05E+03	2.53E+04	3.58	74.4	2.62E+04

Table D-6 Frequency sweeps data output for PAV-aged Sasobit (F-T) SBS modified binder

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	13	-1.00E+00	1.10E+03	8.91E+06	6.86E+06	7.70E-01	37.6	1.12E+07
0.158	13	-8.01E-01	1.74E+03	1.11E+07	8.18E+06	7.37E-01	36.4	1.38E+07
0.251	13	-6.00E-01	2.76E+03	1.34E+07	9.54E+06	7.10E-01	35.4	1.65E+07
0.398	13.1	-4.00E-01	4.38E+03	1.63E+07	1.11E+07	6.84E-01	34.3	1.97E+07
0.631	13.1	-2.00E-01	6.94E+03	1.96E+07	1.29E+07	6.59E-01	33.4	2.34E+07
1	13	0.00E+00	1.10E+04	2.34E+07	1.48E+07	6.35E-01	32.4	2.77E+07
1.585	13	2.00E-01	1.74E+04	2.78E+07	1.70E+07	6.13E-01	31.5	3.26E+07
2.512	13	4.00E-01	2.76E+04	3.29E+07	1.95E+07	5.92E-01	30.6	3.82E+07
3.981	13	6.00E-01	4.38E+04	3.87E+07	2.21E+07	5.71E-01	29.7	4.46E+07
6.31	13	8.00E-01	6.94E+04	4.53E+07	2.50E+07	5.53E-01	28.9	5.17E+07
10	13	1.00E+00	1.10E+05	5.28E+07	2.82E+07	5.35E-01	28.1	5.99E+07
15.849	13	1.20E+00	1.74E+05	6.15E+07	3.15E+07	5.12E-01	27.1	6.90E+07
25.121	13	1.40E+00	2.76E+05	7.09E+07	3.52E+07	4.96E-01	26.4	7.92E+07
39.809	13	1.60E+00	4.38E+05	8.17E+07	3.89E+07	4.77E-01	25.5	9.05E+07
50	13	1.70E+00	5.50E+05	8.72E+07	4.06E+07	4.66E-01	25.0	9.62E+07

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	21	-1.00E+00	1.10E+02	2.61E+06	2.54E+06	9.72E-01	44.2	3.64E+06
0.158	21	-8.01E-01	1.74E+02	3.34E+06	3.14E+06	9.38E-01	43.2	4.58E+06
0.251	21	-6.00E-01	2.76E+02	4.23E+06	3.83E+06	9.06E-01	42.2	5.71E+06
0.398	21	-4.00E-01	4.38E+02	5.32E+06	4.65E+06	8.75E-01	41.2	7.07E+06
0.631	21	-2.00E-01	6.94E+02	6.64E+06	5.61E+06	8.46E-01	40.2	8.69E+06
1	21	0.00E+00	1.10E+03	8.24E+06	6.73E+06	8.17E-01	39.2	1.06E+07
1.585	21	2.00E-01	1.74E+03	1.02E+07	8.02E+06	7.90E-01	38.3	1.29E+07
2.512	21	4.00E-01	2.76E+03	1.25E+07	9.50E+06	7.62E-01	37.3	1.57E+07
3.981	21	6.00E-01	4.38E+03	1.52E+07	1.12E+07	7.35E-01	36.3	1.89E+07
6.31	21	8.00E-01	6.94E+03	1.86E+07	1.32E+07	7.08E-01	35.3	2.28E+07
10	21	1.00E+00	1.10E+04	2.24E+07	1.54E+07	6.86E-01	34.4	2.72E+07
15.849	21	1.20E+00	1.74E+04	2.70E+07	1.78E+07	6.59E-01	33.4	3.23E+07
25.121	21	1.40E+00	2.76E+04	3.23E+07	2.05E+07	6.36E-01	32.4	3.82E+07
39.809	21	1.60E+00	4.38E+04	3.84E+07	2.36E+07	6.13E-01	31.5	4.51E+07
50	21	1.70E+00	5.50E+04	4.18E+07	2.52E+07	6.03E-01	31.1	4.88E+07

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	29	-1.00E+00	1.53E+01	7.24E+05	8.69E+05	1.20E+00	50.2	1.13E+06
0.158	29	-8.01E-01	2.42E+01	9.56E+05	1.11E+06	1.17E+00	49.4	1.47E+06
0.251	29	-6.00E-01	3.84E+01	1.25E+06	1.42E+06	1.13E+00	48.6	1.89E+06
0.398	29	-4.00E-01	6.08E+01	1.63E+06	1.79E+06	1.10E+00	47.7	2.42E+06
0.631	29	-2.00E-01	9.65E+01	2.11E+06	2.25E+06	1.07E+00	46.8	3.08E+06
1	29	0.00E+00	1.53E+02	2.72E+06	2.81E+06	1.03E+00	45.9	3.91E+06
1.585	29	2.00E-01	2.42E+02	3.50E+06	3.48E+06	9.96E-01	44.9	4.93E+06
2.512	29	4.00E-01	3.84E+02	4.46E+06	4.30E+06	9.62E-01	43.9	6.20E+06
3.981	29	6.00E-01	6.09E+02	5.68E+06	5.27E+06	9.28E-01	42.8	7.75E+06
6.31	29	8.00E-01	9.65E+02	7.18E+06	6.44E+06	8.97E-01	41.9	9.64E+06
10	29	1.00E+00	1.53E+03	9.00E+06	7.77E+06	8.64E-01	40.8	1.19E+07
15.849	29	1.20E+00	2.42E+03	1.12E+07	9.36E+06	8.33E-01	39.8	1.46E+07
25.121	29	1.40E+00	3.84E+03	1.39E+07	1.12E+07	8.03E-01	38.7	1.79E+07
39.809	29	1.60E+00	6.09E+03	1.72E+07	1.34E+07	7.74E-01	37.7	2.18E+07
50	29	1.70E+00	7.64E+03	1.91E+07	1.45E+07	7.59E-01	37.2	2.40E+07

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	37	-1.00E+00	2.00E+00	1.95E+05	2.78E+05	1.42E+00	54.9	3.40E+05
0.158	37	-8.01E-01	3.16E+00	2.65E+05	3.67E+05	1.38E+00	54.2	4.53E+05
0.251	37	-6.00E-01	5.02E+00	3.56E+05	4.81E+05	1.35E+00	53.5	5.98E+05
0.398	37	-4.00E-01	7.96E+00	4.74E+05	6.25E+05	1.32E+00	52.9	7.85E+05
0.631	37	-2.00E-01	1.26E+01	6.28E+05	8.08E+05	1.29E+00	52.2	1.02E+06
1	37	0.00E+00	2.00E+01	8.33E+05	1.04E+06	1.25E+00	51.4	1.34E+06
1.585	37	2.00E-01	3.17E+01	1.10E+06	1.34E+06	1.22E+00	50.6	1.73E+06
2.512	37	4.00E-01	5.02E+01	1.45E+06	1.71E+06	1.18E+00	49.7	2.25E+06
3.981	37	6.00E-01	7.96E+01	1.90E+06	2.17E+06	1.14E+00	48.9	2.89E+06
6.31	37	8.00E-01	1.26E+02	2.48E+06	2.75E+06	1.11E+00	47.9	3.70E+06
10	37	1.00E+00	2.00E+02	3.22E+06	3.45E+06	1.07E+00	47.0	4.72E+06
15.849	37	1.20E+00	3.17E+02	4.15E+06	4.30E+06	1.04E+00	46.0	5.98E+06
25.121	37	1.40E+00	5.02E+02	5.35E+06	5.34E+06	9.98E-01	44.9	7.56E+06
39.809	37	1.60E+00	7.96E+02	6.86E+06	6.60E+06	9.63E-01	43.9	9.52E+06
50	37	1.70E+00	1.00E+03	7.74E+06	7.34E+06	9.48E-01	43.5	1.07E+07

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	45.9	-1.00E+00	1.00E-01	2.69E+04	4.81E+04	1.79E+00	60.8	5.51E+04
0.158	46	-8.01E-01	1.58E-01	3.67E+04	6.36E+04	1.73E+00	60.0	7.34E+04
0.251	46	-6.00E-01	2.51E-01	4.96E+04	8.37E+04	1.69E+00	59.4	9.73E+04
0.398	46	-4.00E-01	3.98E-01	6.61E+04	1.10E+05	1.66E+00	58.9	1.28E+05
0.631	46	-2.00E-01	6.31E-01	8.75E+04	1.43E+05	1.63E+00	58.5	1.68E+05
1	46	0.00E+00	1.00E+00	1.15E+05	1.85E+05	1.61E+00	58.2	2.18E+05
1.585	46	2.00E-01	1.59E+00	1.58E+05	2.52E+05	1.59E+00	57.9	2.98E+05
2.512	46	4.00E-01	2.51E+00	2.06E+05	3.26E+05	1.58E+00	57.7	3.86E+05
3.981	45.8	6.00E-01	3.98E+00	2.71E+05	4.22E+05	1.56E+00	57.3	5.01E+05
6.31	45.9	8.00E-01	6.31E+00	3.75E+05	5.65E+05	1.51E+00	56.4	6.78E+05
10	45.9	1.00E+00	1.00E+01	5.21E+05	7.56E+05	1.45E+00	55.4	9.18E+05
15.849	46	1.20E+00	1.58E+01	7.21E+05	1.00E+06	1.39E+00	54.3	1.24E+06
25.121	45.9	1.40E+00	2.51E+01	9.82E+05	1.31E+06	1.34E+00	53.2	1.64E+06

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	58	-1.00E+00	9.00E-03	3.30E+03	8.55E+03	2.59E+00	68.9	9.17E+03
0.158	58	-8.01E-01	1.42E-02	5.03E+03	1.20E+04	2.38E+00	67.2	1.30E+04
0.251	58	-6.00E-01	2.26E-02	7.46E+03	1.66E+04	2.22E+00	65.8	1.82E+04
0.398	58	-4.00E-01	3.58E-02	1.08E+04	2.26E+04	2.10E+00	64.5	2.50E+04
0.631	58	-2.00E-01	5.68E-02	1.54E+04	3.07E+04	2.00E+00	63.4	3.43E+04
1	58	0.00E+00	9.00E-02	2.16E+04	4.15E+04	1.92E+00	62.5	4.68E+04
1.585	58	2.00E-01	1.43E-01	3.00E+04	5.60E+04	1.87E+00	61.8	6.35E+04
2.512	58	4.00E-01	2.26E-01	4.10E+04	7.48E+04	1.83E+00	61.3	8.53E+04
3.981	58	6.00E-01	3.58E-01	5.56E+04	9.99E+04	1.79E+00	60.9	1.14E+05
6.31	58	8.00E-01	5.68E-01	7.50E+04	1.33E+05	1.77E+00	60.6	1.53E+05
10	58	1.00E+00	9.00E-01	1.01E+05	1.76E+05	1.75E+00	60.3	2.03E+05
15.849	58	1.20E+00	1.43E+00	1.35E+05	2.33E+05	1.73E+00	60.0	2.69E+05
25.121	58	1.40E+00	2.26E+00	1.79E+05	3.07E+05	1.71E+00	59.7	3.55E+05

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	69.9	-1.00E+00	9.00E-04	2.20E+02	1.16E+03	5.26E+00	79.2	1.18E+03
0.158	70.1	-8.01E-01	1.42E-03	3.98E+02	1.81E+03	4.55E+00	77.6	1.85E+03
0.251	69.9	-6.00E-01	2.26E-03	6.80E+02	2.72E+03	3.99E+00	75.9	2.80E+03
0.398	69.9	-4.00E-01	3.58E-03	1.12E+03	3.97E+03	3.54E+00	74.2	4.13E+03
0.631	70	-2.00E-01	5.68E-03	1.81E+03	5.73E+03	3.17E+00	72.5	6.01E+03
1	70	0.00E+00	9.00E-03	2.82E+03	8.12E+03	2.88E+00	70.9	8.59E+03
1.585	70	2.00E-01	1.43E-02	4.32E+03	1.14E+04	2.64E+00	69.3	1.22E+04
2.512	70	4.00E-01	2.26E-02	6.47E+03	1.59E+04	2.46E+00	67.9	1.72E+04
3.981	70	6.00E-01	3.58E-02	9.48E+03	2.20E+04	2.32E+00	66.7	2.39E+04
6.31	70	8.00E-01	5.68E-02	1.37E+04	3.02E+04	2.21E+00	65.6	3.32E+04
10	70	1.00E+00	9.00E-02	1.95E+04	4.14E+04	2.13E+00	64.8	4.58E+04
15.849	70.1	1.20E+00	1.43E-01	2.73E+04	5.65E+04	2.07E+00	64.2	6.28E+04
25.121	70.1	1.40E+00	2.26E-01	3.79E+04	7.68E+04	2.03E+00	63.7	8.56E+04

Table D-6 (Continued)

Frequency	temperature	Log(Freq)	Freq*aT	G'	G"	Tan δ	δ	G*
Hz	°C			Pa	Pa		deg	Pa
0.1	76	-1.00E+00	3.50E-04	6.18E+01	5.39E+02	8.72E+00	83.5	5.43E+02
0.158	76	-8.01E-01	5.53E-04	1.15E+02	8.29E+02	7.24E+00	82.1	8.37E+02
0.251	75.9	-6.00E-01	8.79E-04	2.04E+02	1.24E+03	6.09E+00	80.7	1.26E+03
0.398	76.1	-4.00E-01	1.39E-03	3.60E+02	1.86E+03	5.17E+00	79.1	1.90E+03
0.631	76	-2.00E-01	2.21E-03	6.16E+02	2.75E+03	4.46E+00	77.4	2.82E+03
1	76	0.00E+00	3.50E-03	1.05E+03	4.06E+03	3.88E+00	75.5	4.20E+03
1.585	76	2.00E-01	5.55E-03	1.69E+03	5.82E+03	3.45E+00	73.8	6.06E+03
2.512	76.1	4.00E-01	8.79E-03	2.67E+03	8.28E+03	3.10E+00	72.1	8.70E+03
3.981	76.1	6.00E-01	1.39E-02	4.15E+03	1.17E+04	2.82E+00	70.5	1.24E+04
6.31	76.1	8.00E-01	2.21E-02	6.31E+03	1.64E+04	2.60E+00	68.9	1.76E+04
10	76.1	1.00E+00	3.50E-02	9.36E+03	2.28E+04	2.43E+00	67.6	2.46E+04
15.849	76.1	1.20E+00	5.55E-02	1.37E+04	3.15E+04	2.30E+00	66.5	3.44E+04
25.121	76	1.40E+00	8.79E-02	1.96E+04	4.33E+04	2.20E+00	65.6	4.76E+04