LABORATORY EVALUATION OF PERFORMANCE OF WARM MIX ASPHALT IN WASHINGTON STATE

By

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A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

DECEMBER 2011

To the Faculty of Washington State University:

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ACKNOWLEDGMENT

First, I would like to thank my advisor, Dr. Haifang Wen for all of his support. I would never have been where I am today without your knowledge and guidance. I would like to thank you so much for supporting me financially throughout this whole process. I simply could not be where I am now without you.

I would also like to thank Dr. Shihui Shen for her knowledge and encouragement. I learned a lot from you through the classes we had together. Thank you for sharing your knowledge with me.

Additionally, I would like to thank Dr. Balasingam Muhunthan. Numerical Modeling of Geomaterials was not an easy class and I couldn't have made it through without your guidance and support. Thank you for always being there to help me in any way you could.

A special thanks to the Washington State Department of Transportation for their support with this project.

Thank you everyone.

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Abstract

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Washington State University
December 2011

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Warm mix asphalt (WMA) is a new and emerging technology. It has constructability, environmental and economic advantages over traditional hot mix asphalt (HMA). However, the performance of WMA must be proven to be at least equivalent to HMA before it can be used as a replacement. This study evaluated the performance of HMA and WMA cores extracted from various field sites in the state of Washington. There were four separate projects observed each with a different WMA technology. The WMA technologies included Sasobit®, an organic wax additive and three water foaming technologies, which included the Gencor® Green Machine, Ultrafoam GX®, Aquablack® and water injection. A variety of performance tests were performed on the cores and also the extracted binders. The performance tests evaluated the fatigue and thermal cracking resistance as well as the rutting potential of the WMA and HMA control for each project. The stiffness of the mixes and binders were also tested. Additionally, distresses in these pavements were retrieved from the Washington State Pavement Management System (WSPMS). The results of the laboratory tests and field performance were compared between WMA and HMA control. The stiffness of the HMA and WMA overall were found to be comparable with only slight differences for Sasobit® and the Ultrafoam GX® WMA binders. For

fatigue cracking resistance the water foaming technologies were found to be comparable to HMA while Sasobit® was found to have slightly worse fatigue cracking resistance. The thermal cracking resistance of the HMA and WMA were found to be comparable for all technologies except Aquablack® which may have a slightly lower thermal cracking resistance. The water foaming technologies exhibited lower rutting resistance from binder tests compared to HMA while Sasobit® showed comparable resistance. In the field the HMA and WMA appear to be performing equally well from distress observations. Overall, WMA appears to be an acceptable replacement for HMA.

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Dedication

This thesis is dedicated to my parents, grandparents, brother and my family and friends who supported me in so many ways. None of this would have been possible without all of you.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The pavement industry has been stressing the importance of incorporating sustainable practices into its designs for many reasons, including more strict environmental regulations and rising cost of materials (Austerman et al. 2009). One technology that addresses these issues through lowering fuel costs and reducing greenhouse gas emissions is Warm Mix Asphalt (WMA).

WMA is a relatively new technology in the United States but was originated in Europe (Wasiuddin, et al. 2007). WMA is produced by a series of technologies that lower the temperatures at which asphalt can be mixed and compacted. This is accomplished by either lowering the viscosity of the asphalt binder or improving the workability of the asphalt mix at temperatures lower than HMA. Traditional HMA mixes require to be heated up to temperatures of around 300° F (149°C) or higher while WMA asphalt mixes are often heated to around 250° F (121°C) or even lower (Hurley and Prowell 2005).

WMA has many advantages over HMA. Due to reduced heating temperatures required of the asphalt, lower plant emissions and reduced fuel costs can be observed (Neitzke and Wasill 2009). Lower mixing temperatures for WMA also reduce harmful emissions that radiate directly from the asphalt during compaction, which can lead to improved work zone health. Higher percentages of Recycled Asphalt Pavement (RAP) can be incorporated into mixes of WMA due to its improved workability, which further increases environmental advantages (Button et al. 2007). Also WMA makes it possible to pave in colder seasons because the asphalt mix can remain workable at lower temperatures. WMA mixes can also be transported longer distances

due to the mix staying workable for longer periods. Increased workability of the asphalt can lead to decreased energy required for compaction as well, which in turn can lead to better density results (Hurley and Prowell 2006).

There are three categories of WMA technologies that are used in practice, including organic additives, chemical additives and foaming the asphalt by adding water. Each of these processes helps improve the workability of the mix at lower temperatures in different ways. Organic additives use long chain hydrocarbons that have lower viscosity at elevated temperatures compared to asphalt. Chemical additives generally improve the workability of an asphalt mix by reducing the friction between the asphalt binder and aggregates. Water can be added to asphalt binder to create WMA in a unique process called foaming. When water is added to asphalt, a series of small bubbles are formed in the binder, causing decreased viscosity (Hodo et al. 2009). There are a number of ways to produce WMA but the difficulty comes in choosing the best.

The advantages of using WMA are not as important as the structural performance of the pavement. Since WMA is heated to lower temperatures than HMA there can be differences in aging of the mixes. When a binder is aged it becomes stiffer. This means that WMA pavements could be softer than traditional HMA pavements. Some WMA technologies can also change properties of the asphalt binder. Since WMA can significantly change the properties of an asphalt mix the resulting change in performance must be fully understood. There is currently a need for studies to be performed on how WMA will perform in the field. As previously stated, WMA is a relatively new technology for the United States. There is lacking long-term field performance of WMA pavement. The performance of WMA needs to be compared to traditional HMA using laboratory and field studies to determine if it can be used as a replacement.

1.2 RESEARCH OBJECTIVES

The primary objective of this study was to evaluate the performance of WMA through laboratory performance tests and field distresses.

A series of performance tests were performed in the laboratory on HMA and WMA cores and asphalt binder from pavements in Washington State. Field distresses were obtained for each of the pavements. The results of the laboratory tests and field distresses were compared between HMA and WMA to determine the performance.

1.3 ORGANIZATION OF THESIS

This study describes the performance evaluation of WMA from pavements in Washington State. Chapter 1 describes an introduction of WMA with benefits and further research possibilities. Chapter 2 includes an in depth literature review of WMA with an emphasis on performance. Background information about the study is described in Chapter 3 with project locations and WMA technologies used. Chapter 4 describes the preparation of samples for testing as well as mix and binder test procedures. The results of testing for each contract as well as field performance are shown and discussed in chapter 5. Finally, chapter 6 summarizes the test results in terms of stiffness, fatigue cracking, rutting susceptibility, thermal cracking and field performance. Final conclusions are drawn in this chapter as well. Chapter 7 is a list of references.

CHAPTER 2: LITERATURE REVIEW

2.1 WMA TECHNOLOGIES

There are a number of different processes that can create WMA. All processes involve combining some type of additive to the binder or mix, whether it is water, or a chemical or organic compound. There are several processes and additives that have begun to stand out as most practical based on various studies.

2.1.1 Organic Additives

Sasobit® is a wax made through Fischer-Tropsch synthesis (D'Angelo et al. 2008) by the Sasol Wax Corporation that allows the wax to have hydrocarbon chains of around 100 carbon atoms (Hurley and Prowell 2005). These long hydrocarbon chains greatly increase the melting point of the wax. This allows Sasobit® to be fully soluble in asphalt above 115 °C (Kanitpong et al. 2007). Once Sasobit® is fully melted into the asphalt it forms a homogenous solution that reduces the viscosity of the asphalt at temperatures higher than the melting point of Sasobit®. Sasobit® is also able to increase the resistance to permanent deformation of the asphalt when it is cooled below its melting point by forming a lattice structure in the asphalt (Kanitpong et al. 2007, Akisetty et al. 2010). This means that the wax in the asphalt forms into small microscopic stick like particles (D'Angelo et al. 2008). Sasobit® can be added directly to the asphalt binder or asphalt mix (D'Angelo et al. 2008). Sasol, the makers of Sasobit®, suggest adding 0.8 to 3% Sasobit® by weight of the binder. Sasobit® can be easily added to the binder without significant plant modifications (Prowell et al. 2009).

TLA-X Warm Mix is another organic WMA additive. Trinidad Lake Asphalt (TLA) is naturally occurring lake asphalt (Martin et al. 2011). It was used in the first asphalt pavements in the U.S. over a hundred years ago (West et al. 2010). It is mined from a lake deposit in solid form and is composed of mineral matter, soluble bitumen, water and other minor components (Prowell et al. 2009). After TLA is mined, it is processed to remove the moisture. TLA has a high resistance to cracking and permanent deformation, is easily blended with traditional asphalt binders, maintains a high stability level in asphalt mixtures and provides good adhesion to aggregates when used as an asphalt binder (Prowell et al. 2009). For these reasons, Lake Asphalt of Trinidad and Tobago Limited developed a mixture of TLA and rheological modifiers to produce TLA-X as a WMA additive technology. The product is produced in pelletized form and can be directly added to the binder or blown into the asphalt mix close to where the asphalt binder is added (Prowell et al. 2009). To prevent the pellets from sticking together during transport or storage they are coated with a small amount of clay that should be accounted for in mix design (West et al. 2010).

Shell Thiopave™ is a WMA additive that includes sulfur and a patented organic compaction agent (Tran et al. 2010). This technology is based on the fact that the addition of sulfur to asphalt binder can replace some of the binder required to fully coat aggregates (Prowell et al. 2009). Sulfur that precipitates from the asphalt binder crystallizes which provides more stiffness and thus more resistance to permanent deformation as well (Prowell et al. 2009). Shell Thiopave® comes in the form of small pellets (Tran et al. 2010), so no plant modifications are necessary (West et al. 2010). It is usually added directly into the mixing drum after the asphalt binder. When mixing Thiopave™ into the asphalt mixing drum a recommended temperature of

284 ± 9° F (140 ± 5°C) should be maintained to ensure quick melting of the pellets and thorough mixing of the sulfur (Prowell et al. 2009).

2.1.2 Chemical Additives

Meadwestvaco's Evotherm® is a popular chemical WMA additive. Evotherm® Emulsion Technology (ET) is an asphalt emulsion agent (Middleton and Forfylow 2009). It is a combination of chemicals that allows water to be present in the binder which reduces friction between the binder and aggregate to improve workability of the mix. When mixed with hot aggregate, the water evaporates out of the mix as steam (D'Angelo et al. 2008) and only the asphalt and aggregates are left, making the WMA mix have the same color and coating properties as HMA (Hurley and Prowell 2006). Evotherm® ET can also be used with polymer modified binder (Button et al. 2007). Newer generations of Evotherm® have been developed that contain the same emulsion chemical package with other additives that can reduce friction between asphalt binder and aggregates for better coating ability (Prowell et al. 2009). Evotherm® Dispersed Asphalt Technology (DAT) was the second generation of Evotherm® introduced in 2007. Instead of being introduced as an emulsion, Evotherm® DAT is the same chemical package diluted with a small amount of water (D'Angelo et al. 2008) and is injected into the asphalt line directly, just before being incorporated into the mixing drum or directly into the pug mill for batch plants (Prowell et al. 2009). According to Meadwestvaco, the third generation, Evotherm™® 3G is a water free version of the Evotherm® DAT technology. It is currently marketed under the name REVIX™ by the partnership of developers, Mathy Technology and Engineering Services and Paragon Technical Services. It is also marketed as Evotherm™® 3G by Meadwestvaco Asphalt Innovations Inc. (Anderson et al. 2008).

Rediset™ WMX is another chemical WMA additive developed by Akzo Nobel Surfactants Company. It is produced in a solid additive form and contains surfactants and rheology modifiers (Martin et al. 2011). Rediset™ WMX can act as an anti-stripping agent to improve moisture susceptibility and the surfactants contained within it help promote better adhesion of binder to aggregates, even when the aggregates are wet (Prowell et al. 2009). This may eliminate the need for separate anti-stripping agents in the mix. The technology comes in the form of a small pastille, or bead (Santucci 2010). It is generally blown into the binder tank or directly into the mixing drum. The addition rates vary depending on the grade of binder used (Prowell et al. 2009).

CECA, a division of the Arkema Group, have developed a chemical WMA additive called Cecabase RT® (Santucci 2010). It is a patented liquid chemical additive that is made of 50% renewable raw materials. Recommended rates of addition range from 0.3 to 0.5 percent by weight of asphalt binder and Cecabase RT® can be introduced directly into the asphalt line in the plant (Prowell et al. 2009). It has been observed that Cecabase RT® acts at the aggregate/binder interphase to improve workability of the mix without changing the rheological properties of the binder (Gonzalez-Leon et al. 2009).

2.1.3 Water Foaming Processes

Aspha-min® developed by Eurovia Services GmbH, is also a well-known WMA additive. Aspha-min® is a synthetic sodium aluminum silicate which is also referred to as a zeolite (Hurley and Prowell 2005). Aspha-min® contains around 21 percent water by mass (Akisetty et al. 2010). When mixed with binder, water is released at increasing temperatures (D'Angelo et al. 2008), approximately 185-360° F which causes a foaming action (Button et al. 2007) in the asphalt that

reduces the viscosity and improves the workability of the mix (Hurley and Prowell 2005). The water is released over time and can make the mix workable for up to 6 to 7 hours or until the mix cools below 100°C (212° F) (D'Angelo 2008). The recommended addition rate for Aspha-min® is 0.3% by mix weight (Kristjansdottir et al. 2007).

Advera® WMA is a new generation of the synthetic zeolite Aspha-min®. It is manufactured by PQ Corporation (Prowell et al. 2009). It contains 20 percent water within its structure (Martin et al. 2011) and the moisture is slowly released over time within the binder as steam to produce a small scale foaming action that allows the binder to have improved workability (Santucci 2010). This steam is removed upon compaction of the asphalt or absorbed back into the Advera® zeolite after paving so that no excess moisture is present in the asphalt (Prowell et al. 2009). Advera® has a gradation that completely passes the no. 200 sieve, which makes it finer than Aspha-min® (D'Angelo 2008). It is suggested that Advera® be added at a rate of 0.25 percent by weight of the total asphalt mix. It should also only be added in the plant through a modified fiber line close to the point where asphalt binder is added (Prowell et al. 2009).

WAM-Foam is a technology developed by Shell International Petroleum Company Ltd. in London and Kolo-Veidekke in Oslo, Norway (Button et al. 2007). The process consists of a soft binder that is first mixed with the aggregate until it is fully coated. Cold water is then added to the harder binder at a rate of 2 to 5 percent by mass of hard binder (D'Angelo et al. 2008) to cause a foaming action and the foamed binder is added to the soft binder mixture (Button et al. 2007). The soft and hard binder blend is selected to produce the required final binder grade (Middleton and Forfylow 2009). The hard binder is typically around a 58/64-22 grade (D'Angelo et al. 2008). The process creates a mix that has acceptable workability at lower production

temperatures. The process may be difficult to perform effectively in the laboratory setting, however (Wasiudden et al. 2007).

Low Energy Asphalt (LEA) is a foaming process with a different method. To make LEA hot asphalt is first mixed with heated coarse aggregate only. Once all coarse aggregates are coated a fine aggregate or RAP (Carter et al. 2010) is mixed with added water and added to the asphalt coarse aggregate mix. The moisture in the fine aggregates or RAP causes the asphalt binder to foam (Button et al. 2007). In the process a coating and adhesion additive is generally added to the binder. Plant modifications are necessary for this process and include a pump to add the coating and adhesion additive as well as an additional feed bin to introduce the wet fine aggregate (Middleton and Forfylow 2009).

The Double Barrel® Green System is a foaming machine that was developed by Astec Industries (Carter et al. 2010). This type of technology is known as a "free water system" (Prowell et al. 2009) because it is a mechanical system that incorporates water into the asphalt binder. The process uses a specially designed Astec Double Barrel® drum that has a series of 10 nozzles (D'Angelo et al. 2008) inside it that foam the asphalt and mix it with the aggregate. Around 0.5 kg of water per metric ton of mix used is administered through the nozzles which causes the binder to expand (Middleton and Forfylow 2009). Modifications necessary to the plant for this process include installation of the foaming manifold over the asphalt injection system and feed lines for water and binder to the manifold (Middleton and Forfylow 2009).

Another type of free water system is the Terex® Warm Mix Asphalt System. It is a patented technology that produces a foamed asphalt binder in an expansion chamber (Martin et al. 2011) just outside of the rotating mixing drum which ensures a consistent asphalt and water mix at varying production rates (Santucci 2010). The foamed binder is then incorporated into the

mixing drum with the aggregate (Prowell et al. 2009). The system is designed to fit on any unitized counterflow mixing drum (Prowell et al. 2009). Lines for asphalt binder and water are the only items that are not included with the system.

The Gencor® Ultrafoam GX® is a free water system as well. The system is unique because it uses just the energy supplied by the pump for the asphalt to foam the asphalt, so no powered mixing device is needed (Martin et al. 2011). The asphalt binder and water can be incorporated at varying temperatures, pressures and flow rates to produce small evenly sized bubbles (Santucci 2010). The Ultrafoam GX® can be attached to a variety of drum plants (Kvasnak et al. 2010). The patented spring loaded valve on the Ulrtrafoam GX® allows for constant pressure and flow which leads to more consistent asphalt foaming (Prowell et al. 2009).

Stansteel® has produced a free water system that uses more than just water injection to foam the asphalt. The Accu-Shear™ system uses a special shearing process to mix water and asphalt together (Martin et al. 2011). The process is driven by a colloidal pump and will increase the foaming action of the asphalt over traditional water injection according to Stantseel (Prowell et al. 2009). Stansteel® states that the patented design eliminates laminar flow and separation of liquids. Other chemical modifiers could be mixed with this machine as well.

The Aquablack™ WMA system developed by Maxam Equipment, Inc. is another free water system. It utilizes a patent pending foaming gun with a center convergence nozzle design to foam asphalt binder (Prowell et al. 2009). The Aquablack™ system incorporates micro bubbles that can be retained in the asphalt binder throughout the mixing process (Santucci 2010). The process allows for the mix to be workable for longer periods of time (Prowell et al. 2009). According to Maxam Equipment Inc. Aquablack™ also has a heated enclosure for cold weather paving operations.

2.2 MIXTURE DESIGN AND LABORATORY TESTING PROCEDURES

One very important aspect of WMA is mixture design. It has been suggested that because certain WMA additives can change the properties of the mix when compared to traditional HMA, mix design should be adjusted accordingly (Button et al. 2007). However, further research is needed before modifications can be made from Superpave mix design methods for HMA (Newcomb 2006).

There have been suggestions made for binder grade selection in WMA. However, these suggestions vary depending on the method used to achieve the WMA. For example, it has been observed that the addition of certain WMA additives allow the percentage of air voids to be equal to an HMA mixture that has one binder grade lower than the WMA. It has been recommended that the WMA binder grade be bumped up one high temperature grade in light of these findings (Hurley and Prowell 2005). However, further research will be needed to verify these findings (Button et al. 2007).

Optimum asphalt content should be determined with respect to the HMA mixture without WMA technology. WMA technologies can facilitate compaction thus dropping required optimum asphalt content by up to half a percent. However this is not advised as it raises concerns for moisture susceptibility and durability of the pavement (Button et al. 2007).

Aggregate gradation typical in HMA has been found to be adequate for use in WMA (Hurley and Prowell 2005). Based on this finding there appears to be no reason to change the gradation specifications of WMA from that of HMA (Button et al. 2007). However, it has been found that higher contents of RAP can be incorporated into WMA (Tao and Mallick 2009). High percentages of RAP are difficult to incorporate into HMA because of stiffer aged binder present

in RAP. However WMA processes increase the workability of the mix which helps mitigate this effect.

The National Cooperative Highway Research Program (NCHRP) Report 691, "Mix Design Practices for Warm Mix Asphalt," developed and recommended mix design methods for WMA (Bonaquist 2011). The recommendations for mix design practices for WMA have been included in AASHTO R35, as an appendix, "Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)."

A number of conclusions were drawn from the NCHRP study. It was determined that for an HMA mixture with 1% binder absorption or less, the HMA mix design results can be applied to WMA. The WMA specimens produced should still be evaluated for compactibility, coating, rutting and moisture sensitivity as these performance properties of WMA could vary from the HMA mix. Compactibility was found to vary based on the WMA process used as well as the production temperature, especially for mixtures containing RAP. In terms of performance it was found that WMA mixes in general will be more susceptible to moisture damage than HMA and should consider using an anti-stripping additive. Also WMA processes with very low production temperatures may show reduced rutting resistance compared to HMA. In short, a WMA mix produced with the same aggregates and binder as HMA will have close to the same properties with respect to volumetrics, but the stiffness of the WMA will be lower than that of HMA and performance properties of WMA will be affected accordingly.

NCHRP 691 also discusses problems that are present in performance testing for WMA in the laboratory. WMA has lower production temperatures than HMA; therefore problems exist relative to achieving equal aging times. It has been suggested by the study that WMA be aged in a two-step process to achieve the same aging condition that traditional HMA would receive.

Generally this process would consist of a first stage of aging at production temperature for two hours followed by a second aging sequence at the representative high in-service pavement temperature for a varying period of time. The time and temperature for the second aging sequence would need to be determined so that the HMA conditioned using the two-step process would have similar stiffness to HMA aged for four hours at 275° F (135°C). The second aging sequence would be performed for moisture susceptibility and rutting test specimens only.

It was determined from NCHRP 691 that reheating of WMA samples changes their stiffness. HMA samples are sometimes reheated for performance tests. To determine if reheating had the same effect on WMA as HMA, samples were tested for stiffness by determining their dynamic modulus before being reheated, after being reheated and after a delayed period of time after compaction without being reheated. As expected, samples that had been reheated were stiffer in both WMA and HMA. The samples that were compacted and tested after a storage period without reheating showed slightly increased stiffness as well. It was determined that reheating of WMA samples is acceptable because the effect of reheating is similar to HMA. It was suggested that reheating times and temperatures be minimized to reduce the effect the additional aging on the sample.

2.3 IMPROVEMENTS TO VISCOSITY AND WORKABILITY OF MIX THROUGH WMA PROCESSES

There have been many studies performed that show that WMA processes reduce the viscosity and/or improve the workability of an asphalt mix. Each process has slightly different values in these reductions or improvements. These values also vary on the amount of WMA additive used as well.

In a study performed by Bennert et al. (2010) it was found that when 0%, 0.5%, 1.0% and 1.5% of Sasobit® by binder mass was added to a PG 76-22 binder, the viscosity values of the three mixes were 1.33, 1.335, 1.29 and 1.262 Pa-s, respectively. These values were obtained from a Dynamic Shear Rheometer (DSR) test. This indicates that the addition of Sasobit® is effective in reducing the viscosity of an asphalt binder when the amount is greater than 0.8% by binder mass as recommended by Sasol.

In a similar study, Austerman et al. (2009) found that with dosages of 1.5% and 3.0% Sasobit® decreased viscosity and improved workability when compared to the control binder. The viscosities were measured using a rotational viscometer in accordance with AASHTO T316. The workability of the mixes was measured using an Asphalt Workability Device (AWD) fabricated by the University of Massachusetts Dartmouth. The device recorded torque measurements from a paddle submerged in the mixes while operating at a speed of 15 rpm.

Middleton and Forfylow (2009) found that Sasobit®, Evotherm®, Aspha-min®, LEA, Double Barrel® Green and WAM-Foam® all had viscosities that were adequate enough to compact at temperatures that were lower than that of traditional HMA. This also proves that WMA additives help improve the viscosity and workability of asphalt at decreased temperatures.

2.4 RUTTING RESISTANCE PROPERTIES OF WMA

Rutting resistance is also a concern when it comes to WMA. WMA technologies decrease the viscosity of the asphalt at lower service temperatures. The lower mixing and compaction temperatures for WMA cause binder in WMA to age less than HMA, which means the binder will be less stiff which could lead to rutting after paving.

Hurley and Prowell (2005, 2006) studied and performed tests on various WMA additives and explored their rutting potential. An Asphalt Pavement Analyzer machine was used to determine rut depths in different specimens. Limestone and granite aggregate were tested in each of the mix samples. Different binder grades were also used in each of the tests to determine if the binder grade had any significant impact on rutting. Specimens that were compacted at different temperatures were tested as well. It was found that the WMA additive Aspha-min® had very little impact on rut depth when compared to the control HMA specimens. The addition of Sasobit® to asphalt mixes was found to decrease rut depths compared to the control HMA specimens. This indicates that Sasobit® could actually decrease rut depth in WMA pavements. Evotherm® was found to have similar effects on rutting as Sasobit®. It was found that the addition of Evotherm® would actually decrease the rut depth of the WMA pavement. Xiao et al. (2010) found similar results when Aspha-min®, Sasobit® and Evotherm® were used as WMA additives. The rutting depths for each WMA did not vary significantly when compared to the control HMA. Therefore, the rutting susceptibility of WMA with these additives would be approximately the same as HMA.

In a related study by Wielinski et al. (2009), the Astec Double Barrel Green® foaming process was explored to determine its effects on performance of WMA. An Asphalt Pavement Analyzer (APA) was used in this study as well to determine the rut depths of different specimens of WMA. It was found that the WMA samples that were compacted in the laboratory were slightly more susceptible to rutting than that of the HMA control specimens. On average the WMA samples had a rut depth of 2.3mm more than the HMA control samples. However the WMA rut depths were still acceptable values for the APA test. Middleton and Forfylow (2009) reported similar results with WMA produced through the Double Barrel Green® process. It was

determined that WMA with 15% RAP content had slightly larger rut depths than that of the control HMA specimen. The values for rut depth were still less than 8mm which is the value at which a pavement is susceptible to rutting according to the APA test.

D'Angelo et al. (2008) conducted a study on field performance for rutting of WMA in France, Germany and Norway. All data was collected by the responsible agencies within the respective countries. A variety of WMA technologies were studied throughout these countries including Aspha-min®, Sasobit® and other additives which are commonly used in Europe. In every section of WMA monitored, the rutting was considered to be equal to or better than traditional HMA pavement. It should be noted that the pavements had been monitored 3 years or less after they were paved which is fairly short term with respect to typical pavement lifetimes.

Based on these results it appears that WMA has a rutting susceptibility that is equal to or lower than traditional HMA. Most rutting studies were based on laboratory-fabricated specimens. For this reason field performance of rutting or laboratory tests on field samples need to be explored as well.

2.5 FATIGUE PROPERTIES OF WMA

Fatigue cracking is less of a concern in WMA. This is due to WMA technologies reducing the aging effect on the binder. A more ductile binder is generally more resistant to fatigue cracks. Kanitpong et al. (2007) determined that asphalt binder modified with Sasobit® had a greater fatigue life than its control binder. It is important to note that the study was performed in Thailand where PG grades for binder have not been specified and the binder was also un-aged; however since it was compared to a control specimen with the same properties the results should still be valid. The results were determined through the use of a Dynamic Shear

Rheometer (DSR). A graph of cycles to failure versus dissipated energy can be seen in Figure 2-1.

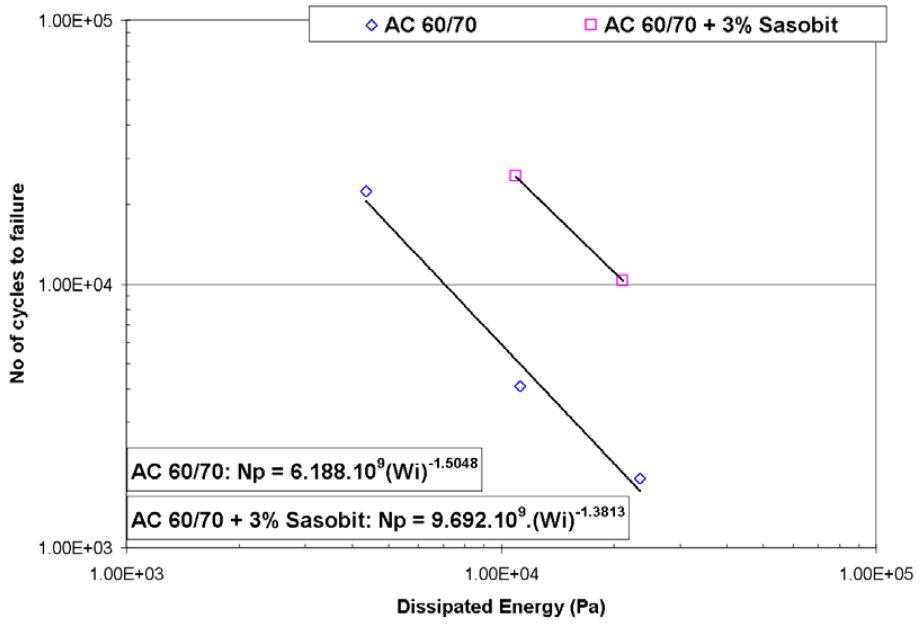

Figure 2-1. Number of Cycles vs. Dissipated Energy. (Kanitpong et al. 2007)

It can be seen that the fatigue life (N_p) of the binder with Sasobit® added is greater than that of the control specimen without Sasobit®.

Study by Hurley and Prowell (2005) also confirmed these results. In their study binder with Sasobit® was tested using a DSR to evaluate potential fatigue cracking susceptibility. In the case of the PAV aged binder, all samples of WMA binder showed G*Sinδ values of less than 5,000 kPa which is the maximum value for Superpave specifications for HMA. This indicates that the WMA binder tested in this study passed Superpave specifications on binder fatigue.

D'Angelo et al. (2008) found that Sasobit® as well as Aspha-min® WMA projects both had fatigue cracking that was equivalent to traditional HMA, based on the field pavement performance in France, Germany and Norway. Again it should be noted that these WMA

projects were in service less than 3 years. Therefore, the field performance is short-term, instead of long-term performance.

Based on the results of these studies it can be concluded that WMA will have resistance to fatigue cracking that is better or equal to traditional HMA, based on laboratory performance tests on laboratory-prepared samples. Long-term field performance or laboratory tests on field samples are needed.

2.6 THERMAL CRACKING PROPERTIES OF WMA

Thermal cracking is another performance issue that needs to be examined in WMA.

MeadWestvaco (2009), the developer of Evotherm®, evaluated the effects of Evotherm® WMA on thermal cracking, based on a field study in Crow Wing County in Minnesota. It was found that because WMA does not need to be heated as high as HMA, less aging to the binder occurs and the binder is more flexible in cold temperatures. This improved ductility lead to less thermal cracking compared to HMA pavements in Crow Wing County.

Apeagyei and Buttlar (2007) found that through disk-shaped compact tension tests [DC(T)] WMA cores compacted at 120°C in the field with Evotherm® additive and PG 64-22 binder showed 18-34% higher resistance to thermal cracking than the control HMA cores compacted at 150°C in the field.

Hurley and Prowell (2005, 2006) also reported that WMA mixes containing Evotherm®, Sasobit® and Aspha-min® all reduce mixing and compacting temperatures which leads to a decrease in the initial aging of the binder. Again, this decreased aging leads to a more ductile binder and less thermal cracking.

D'Angelo et al. (2008) confirmed these findings as well. Several different countries in Europe had performed laboratory tests to determine if WMA was resistant to thermal cracking. It was discovered that all types of WMA were either equal to or better than the control HMA specimens for thermal cracking resistance, based on the short-term field thermal cracking performance.

Despite these findings, there is still a need to evaluate the long-term performance of thermal cracking of WMA pavements.

2.7 MOISTURE SUSCEPTIBILITY IN WMA

Moisture susceptibility is probably the biggest performance concern with water based WMA technology. It has been thought that since WMA is not heated to as high of temperatures as HMA that aggregate may not become completely dry before mixing (Kvasnak et al. 2009). If the aggregate is not dry before mixing the water could prevent the binder from bonding with the surface of the aggregate which could lead to stripping.

Xiao et al. (2009) performed a laboratory study regarding moisture susceptibility in WMA. The study involved Aspha-min® and Sasobit® as WMA additives. Various samples were made from different aggregate stockpiles with varying contents of moisture and an anti-stripping agent of hydrated lime. The tests were performed according to South Carolina Department of Transportation standard procedures for determining moisture susceptibility. From these procedures, values of indirect tensile strength (ITS), tensile strength ratio (TSR) and toughness could be calculated to determine the susceptibility to moisture of the samples. The results of the tests indicated that in almost all cases when moist aggregate was used more moisture damage of the sample was observed, even in the control specimen. This moisture susceptibility could be

offset, however, with the addition of hydrated lime. From this study it also appeared that a factor that influenced moisture susceptibility significantly was the source of aggregate used. Three sources of aggregates were used in the study, two granite aggregates and one schist aggregate. Based on statistical analysis, it was found that ITS values varied significantly between all aggregate sources used. It was determined that aggregate chemical and physical properties play a large role in the stripping resistance of mixes.

Another study on moisture susceptibility of WMA was performed by Kvasnak et al. (2009). Three parameters were used to determine the moisture susceptibility including tensile strength ratio, absorbed energy ratio and stripping inflection point. The tests performed to determine these parameters were the indirect tension test (IDT) and Hamburg Wheel Tracking test. Evotherm® was the WMA additive that was used. The study consisted of two different sources of samples, laboratory-mixed samples and plant-produced samples. It was observed that the laboratorymixed WMA samples failed the TSR, absorbed energy ratio and stripping inflection point criteria. This was reported to be due to improper mixing of the Evotherm® mix in a bucket mixer. The plant-produced samples of WMA, however, passed all moisture susceptibility tests according to Alabama Department of Transportation standards except for one. Although almost all of the WMA samples passed the specifications for moisture susceptibility, it should be noted that the WMA samples had lower values of TSR than that of the control HMA samples. A summarization of the results of the tests can be seen in Table 2-1.

Table 2-1. Summary of Moisture Susceptibility Results. (Kvasnak et al. 2009)

Material	Sample	Tensile Strength Ratio	Absorbed Energy Ratio	Stripping Inflection Point
Lab HMA	1	Pass	Pass	N/A
Lab WMA	1	Fail	Fail	N/A
HMA Day 1	1	Pass	Pass	Pass
WMA Day 2	1	Pass	Pass	Pass
WMA Day 3	1	Fail	Pass	Pass
	3	Pass	Pass	Pass
HMA Day 4	1	Pass	Pass	Pass
	2	Pass	Pass	N/A

Hurley and Prowell (2005, 2006) evaluated WMA moisture susceptibility with three different additives including Sasobit®, Aspha-min® and Evotherm®. Anti-stripping agents were also added to the mixtures to determine if moisture susceptibility would improve. Granite and limestone aggregates were used in the samples as well. The tests used for moisture susceptibility were the Hamburg Wheel Tracking and ASTM D 4867, Effect of Moisture on Asphalt Concrete Paving Mixtures. The parameters obtained from these tests were the stripping inflection point and TSR, respectively. The results of the tests varied depending on the WMA additive used. A summary of the results can be seen in Table 2-2. It should be noted that the recommended minimum TSR value, according to Superpave, is 0.80 (Cominsky et al. 1994) and generally stripping inflection points greater than 10,000 are considered acceptable (Hurley and Prowell 2006). It can be observed that in general all the WMA samples with granite aggregate had less

resistance to moisture damage than the control HMA sample except for the Evotherm® sample which actually had no stripping inflection point and a TSR value fairly close to the control. When hydrated lime was added to the Aspha-min® sample, the resistance to moisture damage was improved. This was true also for Sasobit® when the anti-stripping agent known as Magnabond was recommended by Sasol to be incorporated into the mix.

Table 2-2. Hamburg Wheel Tracking Device Results. (Hurley and Prowell 2005, 2006)

Aggregate	Mix Type	Treatment	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	TSR
Granite	Control	None	6500*	1.841	1.16
Granite	Sasobit®	None	3975	2.961	0.71
Granite	Zeolite	None	3450	5.139	0.67
Granite	Evotherm	None	NA	1.708	0.96
Granite	Zeolite	1.5% Hydrated Lime 2 Stage Addition	8500*	1.912	0.87
Granite	Zeolite	1.5% Hydrated Lime All Added Dry	NA	0.687	0.75
Granite	Sasobit®	0.4% Magnabond	NA	0.164	0.94
Limestone	Control	None	2500	4.284	0.65
Limestone	Zeolite	None	1700	2.835	0.51
Limestone	Sasobit®	None	2900	3.976	0.91
Limestone	Evotherm	None	2550	3.178	0.62

Note: * individual sample did not have a stripping inflection point; reported value is average of 10,000 cycles and recorded stripping inflection point of second sample; NA = No stripping inflection point determined

Based on these studies it can be generalized that moisture susceptibility is a valid concern with WMA. Anti-stripping agents can in some cases improve the moisture susceptibility to acceptable values but this is not always the case with certain WMA processes. The results of testing to date have been somewhat inconsistent due largely in part to the number of variables in each of the studies. More tests of moisture susceptibility in WMA are needed to make any valid conclusions.

2.8 FIELD PERFORMANCE VS. LABORATORY PERFORMANCE

At this time there has been great difficulty finding a correlation between performance of WMA in a laboratory setting compared to the field. Field performance of WMA to date shows that there may be a disconnect between laboratory studies and field performance (Prowell et al. 2009). The problem with the WMA that has been observed in the field is that the projects are in the early stages of their design life. According to most field studies the average pavement age is around two or three years. An average service life of a pavement is expected to be about 20 years. Generally, the WMA pavements that have been observed in the field have had no signs of performance issues to date (Prowell et al. 2009). WMA plant produced samples have been compacted in the lab to simulate actual aging that occurs in the field, but most of these mixes needed reheating which thus changed aging properties of the binder as previously discussed. Further studies are needed to find better correlations between laboratory performance tests and actual field performance for WMA.

2.9 SUMMARY OF LITERATURE REVIEW

WMA is an emerging technology that allows asphalt pavement mix to be workable enough to be paved and compacted at temperatures much lower than standard HMA. It provides benefits that include lower fuel consumption, lower gas emissions, longer haul distances, extended paving season, less energy for compaction and the ability to incorporate higher percentages of RAP into the mix. Mixture design of WMA is generally the same as for HMA. There are a number of different additives and processes that can be used to achieve WMA, and can be categorized as organic additive, chemical additive or foaming technologies. All WMA additives and processes cause the asphalt to be less viscous at lower temperatures. The

performance of WMA is generally equal and sometimes better than that of HMA in terms of rutting, fatigue and thermal cracking based on laboratory studies. WMA produced through water-based or water-containing processes have a higher susceptibility to moisture than that of HMA. It has been suggested that anti-stripping additives be used in WMA for this reason. Further studies are needed to be able to determine how WMA will actually perform in the field and how its durability will compare to HMA.

CHAPTER 3: PROJECT BACKGROUND

This study was performed in accordance with the Washington State Department of Transportation. As stated previously, more studies for field performance of WMA are needed. This study evaluated HMA and WMA field cores taken from projects in Washington State using a series of performance tests. Binder performance tests were also performed on extracted binder from the cores. A better understanding of the field performance of WMA was the primary goal of this study.

3.1 ORIGIN OF ASPHALT CORES

Cores were obtained by the WSDOT from the field from several different highways across Washington. A total of sixteen cores for each contract were obtained which included eight HMA and eight WMA cores. There were a total of 64 cores for four contracts. The WMA and HMA cores from each contract were taken from the wheel path of the lane. All of these four contracts included WMA and HMA control sections.

3.1.1 Contract 7474

The cores from contract 7474 were taken from US highway 12 between milepost 332 and 335 in the eastbound travel lane. This section of the highway is located about 3 miles west of Walla Walla. The asphalt binder used for the highway was PG 64-28. Contract 7474 was constructed in April 2010 and the WMA section used the Aquablack™ free water system as the technology.

3.1.2 Contract 7419

The cores from contract 7419 were taken from Interstate 90 between milepost 142 and 146 in the eastbound travel lane. This section of the interstate is located about 3 miles west of George. The asphalt binder used for the highway was PG 76-28 which was also modified with a polymer. The contract was constructed in June 2008 and used Sasobit® as an additive for the WMA section.

3.1.3 Contract 7755

The cores from contract 7755 were taken from US highway 12 between milepost 194 and 195 in both the eastbound and westbound travel lanes. This section of highway is located between Yakima and Naches. The asphalt binder used for the highway was PG 64-28. The contract was constructed in August 2009 and used the Gencor® Green Machine Ultrafoam GX® for the WMA technology.

3.1.4 Contract 7645

The cores from contract 7645 were taken from Washington State highway 28 between milepost 31.0 and 33.2 in the eastbound travel lane. This section of highway is located about 4 miles east of the town of Quincy. The asphalt binder used for the highway was PG 64-28 which was also modified with a polymer. The contract was constructed in June 2009 and used water injection for a WMA technology.

CHAPTER 4: SAMPLE PREPARATIONS AND TEST PROCEDURES

4.1 PREPARATIONS FOR MIX TESTING

The cores received at the beginning of the project included the entire depth of the pavement to the base course. The cores contained different lifts of pavement that had been constructed over many years. Since the primary focus of this study was the most recent contract, the top lift of each asphalt core was cut with a saw. Each core was given an identification number for ease of referencing in figures and tables. The identification numbers of all cores can be seen in Tables 4-1 and 4-2.

Table 4-1. Core Identification and Air Void Percentages of Fatigue and Thermal Samples

Contract	Core ID	Core #	SR	MP	HMA/WMA	Air Void 6" Diameter (%)	Air Void 4" Diameter (%)
7419	038	1	I-90	142.0	HMA	4.44	-
	037	2		142.0		4.92	-
	036	3		142.5		4.21	-
	035	4		142.5		4.92	5.02
	034	5		143.0		4.30	4.23
	033	6		143.0		4.35	-
	039	7		143.0		4.87	4.93
	040	8		143.0		4.50	-
	041	1		145.0	WMA	3.85	-
	042	2		145.0		5.24	-
	043	3		145.5		4.36	4.44
	044	4		145.5		4.68	-
	045	5		146.0		4.94	-
	046	6		146.0		4.67	4.38
	047	7		146.0		4.92	-
	048	8		146.0		5.03	4.90
7474	011	1	US 12	334.0	HMA	4.77	-
	007	2		334.0		5.65	5.61
	004	3		334.5		4.28	-
	002	4		334.5		3.95	3.86
	001	5		335.0		2.90	2.75
	005	6		335.0		2.42	-
	009	7		335.0		2.32	-
	010	8		335.0		2.78	-
	016	1		332.0	WMA	2.82	2.47
	015	2		332.0		3.41	3.15
	012	3		332.5		1.78	1.58
	008	4		332.5		1.48	-
	006	5		332.9		2.20	-
	003	6		332.9		2.66	-
	014	7		332.9		2.78	-
	013	8		332.9		3.12	-

Table 4-2. Core Identification and Air Void Percentages of Fatigue and Thermal Samples

Contract	Core ID	Core #	SR	MP	HMA/WMA	Air Void 6" Diameter (%)	Air Void 4" Diameter (%)
7755	030	1	US 12	195.0	HMA	5.91	-
	027	2		195.0		5.62	5.68
	026	3		194.5		4.74	-
	021	4		194.5		3.14	-
	020	5		194.0		3.81	3.71
	018	6		194.0		3.81	-
	017	7		194.0		5.15	-
	019	8		194.0		4.80	4.58
	022	1		194.0	WMA	2.60	-
	024	2		194.0		4.12	3.99
	028	3		194.5		3.39	-
	031	4		194.5		4.95	-
	032	5		195.0		3.30	3.17
	029	6		195.0		3.71	-
	025	7		195.0		5.89	5.74
	023	8		195.0		5.73	-
7645	049	1	WA 28	33.0	HMA	4.25	-
	050	2		33.0		4.29	4.44
	051	3		33.1		3.69	3.78
	052	4		33.1		2.77	4.63
	053	5		33.2		5.93	6.46
	054	6		33.2		5.72	-
	055	7		33.2		5.26	-
	056	8		33.2		5.41	-
	057	1		31.0	WMA	2.73	1.50
	058	2		31.0		4.33	-
	059	3		31.1		1.69	1.50
	060	4		31.1		4.34	4.09
	061	5		31.2		2.02	1.88
	062	6		31.2		1.66	-
	063	7		31.2		N/A	-
	064	8		31.2		3.16	-

4.1.1 Cutting and Coring of Samples

In order to test the samples the top lift from each core was cut to a height of 38.1 mm. This cut was taken from the center of the top lift in all cases to maintain consistency. Samples that were tested for thermal cracking were cored from a diameter of 152.4 mm to a diameter of 101.6 mm due to limitations of the equipment used. Samples that were tested for dynamic modulus, creep and fatigue were left at the original cored diameter of 152.4 mm.

4.1.2 Air Void Determination of Samples

To determine the air void of each sample, AASHTO T 166, "Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens" was followed. All air void determinations were performed on cut specimens. The maximum theoretical density (G_{mm}) was measured by the WSDOT during construction for quality assurance. The air void values for fatigue and thermal samples are shown in Tables 4-1 and 4-2.

4.1.3 Preparation of Mix Samples

Each mix sample had a set of four linear variable differential transformers (LVDT), two on the front and two on the back, placed on its surfaces so that deformations could be measured in the sample. The "gauge length" or distance between each mount was 50.8 mm" and the mounts were placed in the center of the sample. The mounts were arranged so that two measurements of horizontal deformation and two measurements of vertical deformation could be determined. An example of the LVDT mount setup can be seen in Figure 4-1.

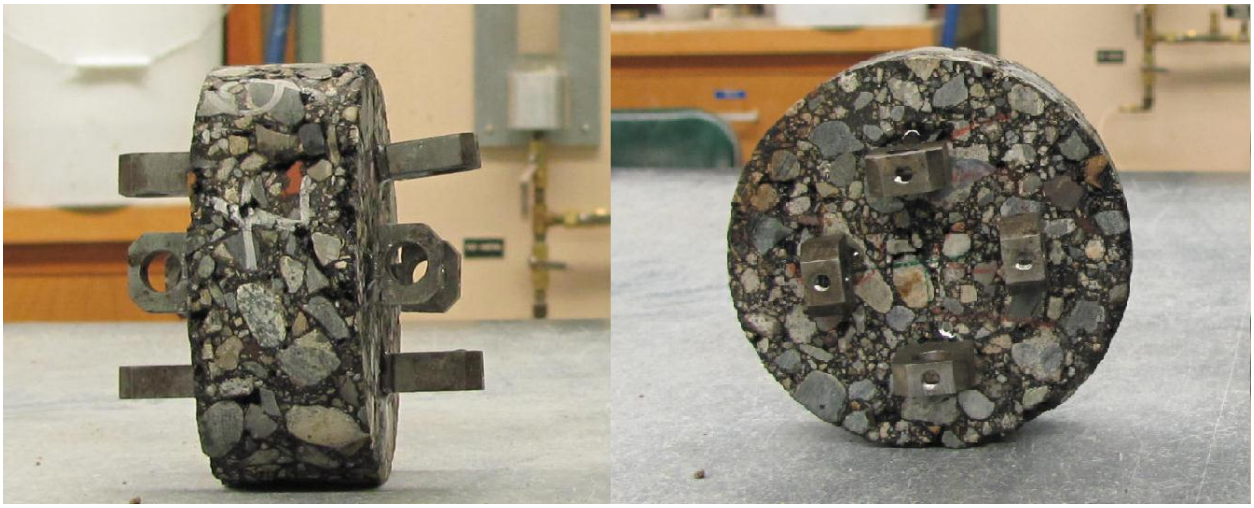

Figure 4-1. Front and Side View of Sample with LVDT Mounts

4.2 CORE SELECTION METHODS

There were eight HMA and eight WMA cores for each contract. From each set of these eight cores three samples were selected for dynamic modulus, creep compliance and fatigue testing while three other cores were selected for thermal testing.

Three cores were selected for testing (fatigue and thermal) so that the average of the three cores came as close as possible to the average of the total population of cores for HMA and WMA. The air void levels of the three cores selected for testing included high, medium and low levels within the range of eight cores.

4.3 MIXTURE PROCEDURES

4.3.1 Mixture Test Machine and Setup

The machine used for mix testing was an MTS hydraulic powered system with a Geotechnical Consulting Testing Systems (GCTS) environmental chamber, servo valve

controlled computer and software. A 44,000 N capacity load cell was used for all the tests. The actuator of the system had a maximum force output of 48,000 N. The system and software allow for a combination of loading or deformation rates to be used on a specimen. A picture of the test machine and computer setup can be seen in Figure 4-2.

Figure 4-2. GCTS Mix Test Machine Setup

To measure the deformations in the sample a series of four LVDT's were attached to the mounts placed on the specimen. The LVDT's were mounted directly in the center of the samples and consisted of two in the horizontal direction and two in the vertical direction. From these LVDT deformation measurements, strain in the center of the specimen was able to be calculated. A specimen mounted with LVDT's can be seen in Figure 4-3.

Once LVDT's were attached the specimen was placed in a loading apparatus. The loading apparatus consisted of a plate on top and bottom guided by four steel bars. The bars were used to keep the load applied strictly in the vertical plane. Each plate was equipped with fittings for the specimen to sit in with the proper diameter so the specimen would stay in place and the load would be applied evenly. The top plate of the apparatus was held up by four springs to prevent the weight of the plate from constantly sitting on top of the specimen. A picture of the apparatus can be seen in Figure 4-3 as well.

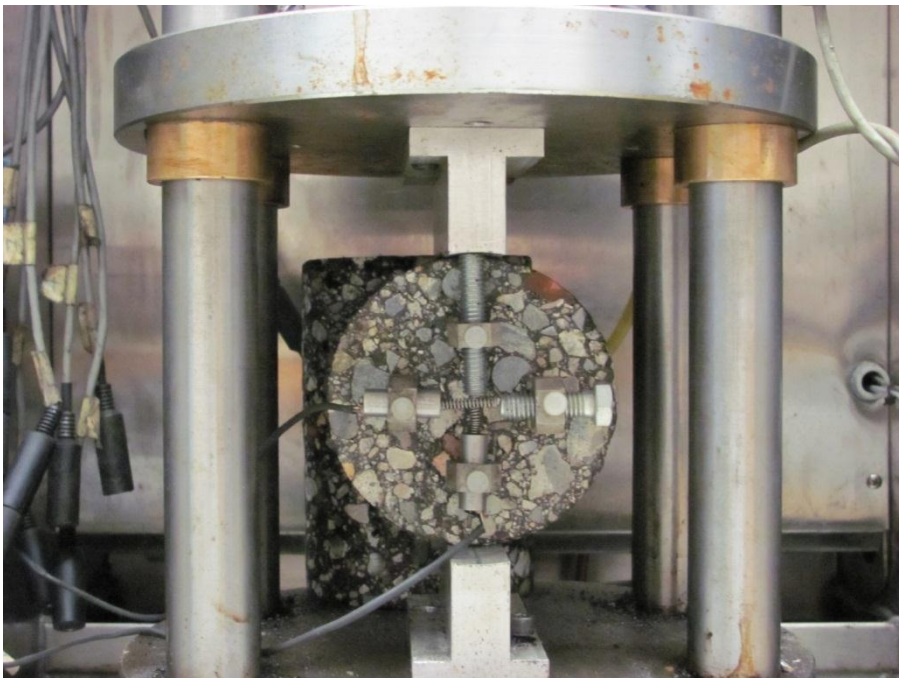

Figure 4-3. Specimen Mounted with LVDT's and Mix Test Apparatus

4.3.2 Calculations of Center Strain

In a previous study (Wen and Kim 2002), the deformation readings of two vertical and two horizontal LVDT's have been converted to strain in the center of the specimen. This is done by multiplying a series of constant values dependent on the gauge length and specimen diameter to the average deformations in both the vertical and horizontal directions. First, a Poisson ratio is calculated using the deformations and constants. The calculated Poisson ratio is then used in the equation for center strain along with horizontal deformation readings and constants. The Poisson ratio equation can be seen in Equation 4-1 and the center strain equation can be seen in Equation 4-2.

$$\nu = -\frac{\alpha_1 U(t) + V(t)}{\alpha_2 U(t) + \alpha_3 V(t)} \tag{4-1}$$

where ν = Poisson ratio

α_1, α_2, and α_3 = constants

U(t) = average horizontal deformation (m)

V(t) = average vertical deformation (m)

t = time (s)

$$\varepsilon_{x=0} = U(t)\frac{\gamma_1 + \gamma_2 \nu}{\gamma_3 + \gamma_4 \nu} \tag{4-2}$$

where $\varepsilon_{x=o}$ = strain at center of specimen

γ_1, γ_2, γ_3, and γ_4 = constants

4.3.3 Fracture Energy and Work Calculation for Fatigue and Thermal Samples

The fracture energy and fracture work required to split the specimens was calculated for both fatigue and thermal tests. These calculations came from previous research and have been shown to correlate well to actual field performance of pavement. The greater the fracture energy required to split the specimen, the greater the resistance to fatigue (Wen and Kim 2002) or thermal cracking (Zborowski 2007). Fracture work was also found to correlate with field fatigue performance, especially when the mixtures have different sources of asphalt binders (Wen 2011).

To calculate fracture energy, the load in the sample was converted to a stress based on the specimen thickness and diameter. Then the center strain in the sample was calculated using Equation 4-2. The peak stress was then calculated. Finally, the fracture energy was determined by taking the area under the stress vs. center strain curve up to the peak stress, as is illustrated in Figure 4-4.

To calculate the fracture work, a very similar approach was followed. Instead of calculating the area under the stress vs. strain curve to the peak stress, the entire area under the load vs. vertical displacement curve was calculated. This is illustrated in Figure 4-5.

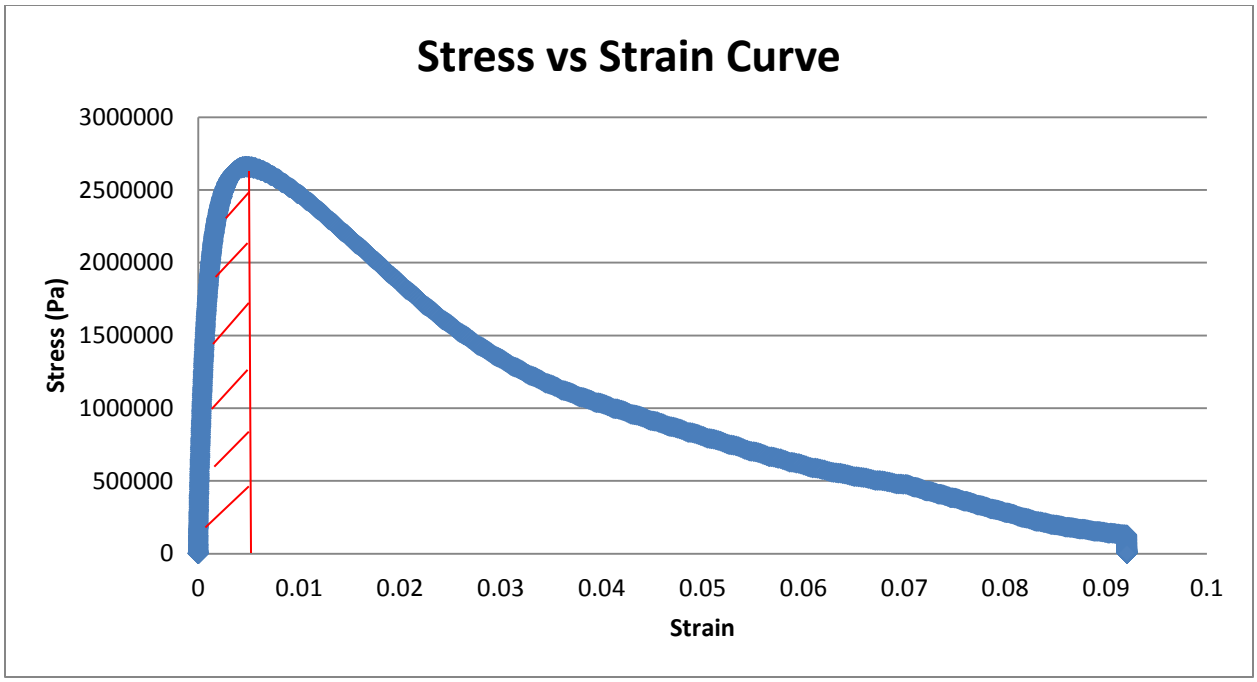

Figure 4-4. Fracture Energy Area Calculation

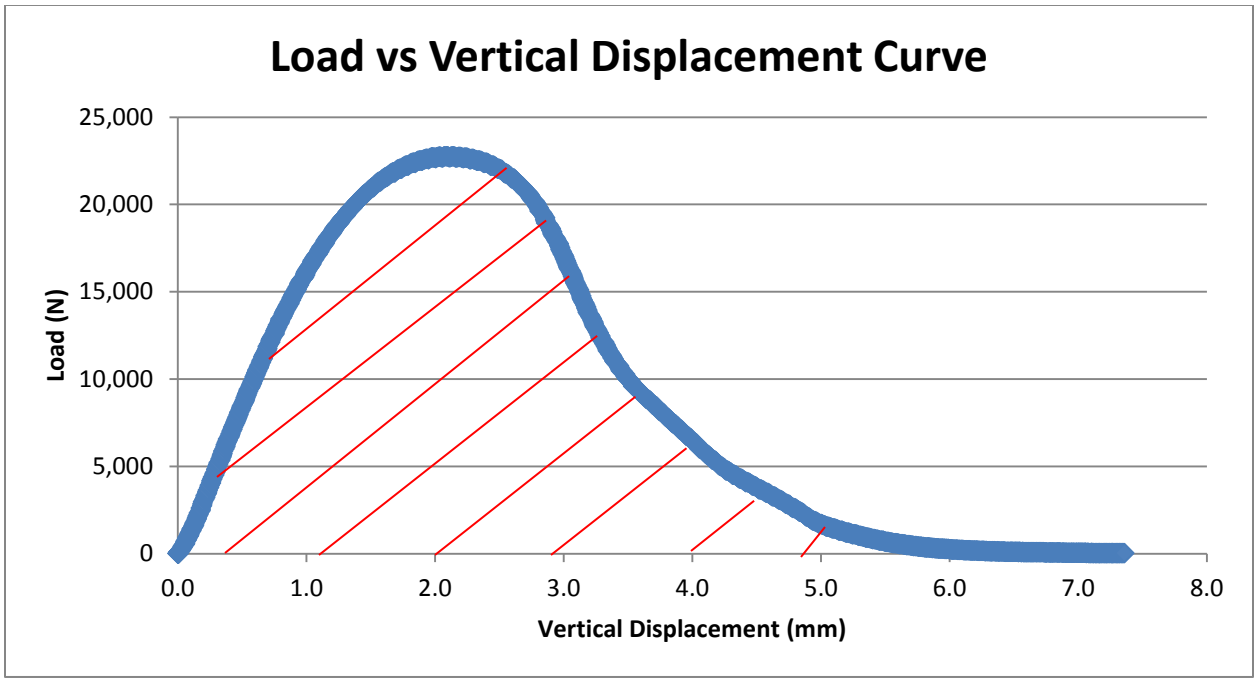

Figure 4-5. Fracture Work Area Calculation

4.3.4 Development of Master Curves for Stiffness Tests

Based on the time-temperature superposition principle and previous research by others (Brown et al. 2009), the master curves of dynamic modulus or creep compliance were created. The master curve depicts predictions of material properties at a wide range of frequencies (i.e. for dynamic modulus) or times (i.e. for creep compliance). All of the stiffness tests were performed at varying temperatures, -20, -10, 0, 10, 20 and 30ºC. The sigmoidal model uses "shift factors" to essentially shift data points at different temperatures to a single curve. A visual example of these shift factors can be seen in Figure 4-6. The sigmoidal model is defined as follows:

$$Log|G^*| = a + \frac{b}{1+e^{c-d(Log(FT)+Log(aT))}} \quad (4\text{-}3)$$

where a,b,c,d = Model constants

FT = Frequency (Hz) or Time (sec)

aT = Shift factor for each temperature

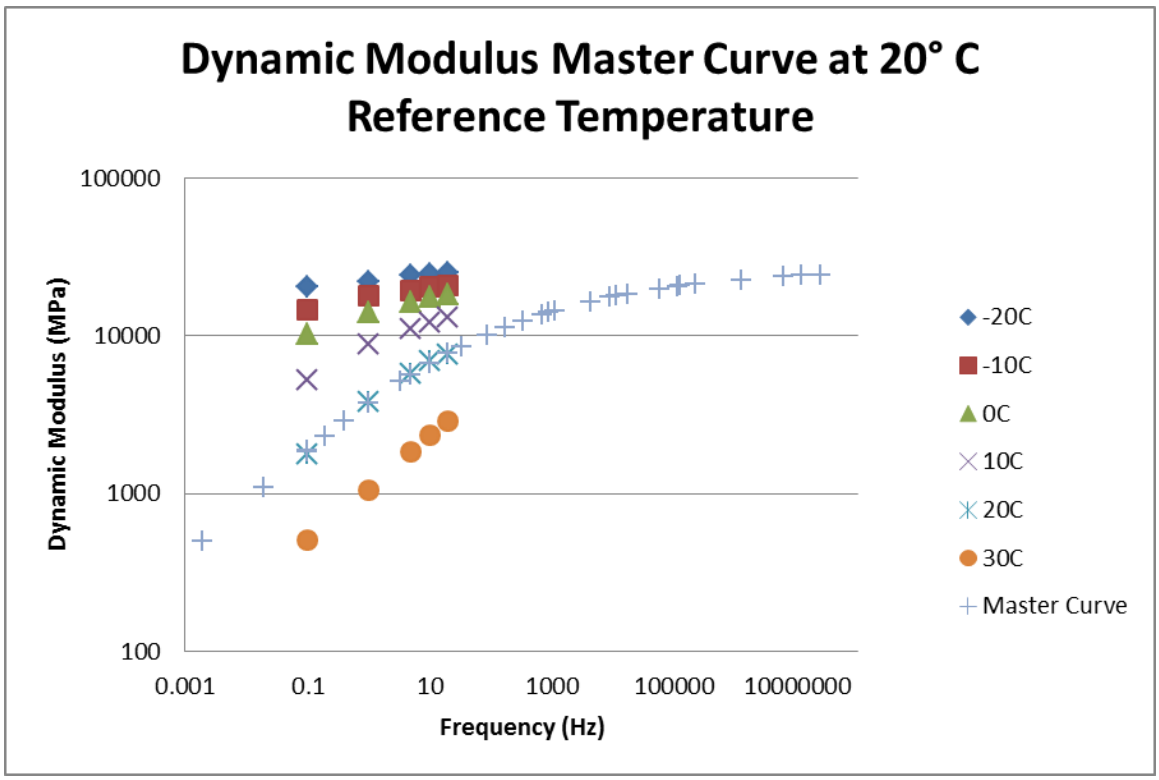

Figure 4-6. Example of Shift Factors Used for Master Curves

4.4 MIXTURE TESTS

4.4.1 Dynamic Modulus Test

The dynamic modulus test applies cyclic loading while the corresponding strains in the specimen are observed. The loads applied to the specimen induce low strain values so that the test does not cause permanent strain or damage. Using the amplitude of the loading cycle and corresponding amplitude of strain, a value for dynamic modulus can be determined. The dynamic modulus of a specimen is an indicator of its stiffness. Higher values of dynamic modulus indicate that the specimen is stiffer.

The dynamic modulus test was first performed on fatigue samples as it does not cause damage to the sample. AASHTO TP 62, "Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)" was followed as the test protocol. The test was run at six different temperatures which included -20, -10, 0, 10, 20 and 30℃ as well as five different loading frequencies at each temperature, including 0.1, 1, 5, 10 and 20 Hz. The loads applied to the specimen were small enough to produce approximately 100 microstrain in the specimen to avoid damage. The order of the test temperatures began at the lowest and increased to the highest, whereas the loading frequencies began from the highest and decreased to the lowest at each temperature. Values of loads and deformations were recorded to determine the dynamic modulus.

The dynamic modulus was calculated by dividing the peak amplitude of stress by the peak amplitude of strain. The amplitudes from the last 10 cycles of each loading frequency were averaged to determine the dynamic modulus for each temperature and loading frequency combination. Equation 4-4 illustrates the calculation.

$$E^* = \frac{\sigma_0}{\varepsilon_0} \tag{4-4}$$

where E^* = dynamic modulus

σ_0 = average of last ten load amplitudes

ε_0 = average of last ten center strain amplitudes

4.4.2 Creep Compliance Test

The creep compliance test applies a constant static load while the corresponding strains in the specimen are observed. The loads applied to the specimen are small enough that no

permanent strain or damage is induced. Similar to dynamic modulus, the creep compliance is also an indicator of specimen stiffness. However, unlike dynamic modulus a higher value of creep compliance implies that a sample is softer.

The creep compliance tests were performed on the same fatigue samples as dynamic modulus after the loading cycles of the dynamic modulus tests were complete. The test was also performed at each of the same temperatures as dynamic modulus (-20, -10, 0, 10, 20 and 30°C). Since the test was performed after each cycle of the dynamic modulus test, the order of the test temperatures also increased from lowest to highest.

Creep compliance is calculated by dividing the strain at each time interval by the static load applied. In this case, Equation 4-5 from previous research (Wen and Kim 2002) was used to determine the creep compliance.

$$D(t) = -\frac{d}{P}(\beta_1 U(t) + \beta_2 V(t)) \quad (4\text{-}5)$$

where D(t) = creep compliance

d = specimen thickness (m)

P = applied load (N)

β_1 and β_2 = constants

U(t) = average horizontal deformation (m)

V(t) = average vertical deformation (m)

t = time (s)

4.4.3 Fatigue Cracking Indirect Tensile Test

The indirect tensile (IDT) strength test for fatigue measures the resistance to fatigue cracking of a specimen. The test consists of using a constant deformation rate while measuring the corresponding load until the specimen fails. Generally, the greater the peak load achieved by the specimen, the greater the fatigue resistance.

The IDT strength test was performed on samples that had already been tested for dynamic modulus and creep compliance. The IDT strength test was performed last as it damages the sample to split. The test was performed at 20°C with a deformation rate of 50.8 mm/min. The deformation was continued until the load on the sample achieved a value close to zero. The fracture energy and fracture work required to split the sample were then calculated for this test.

4.4.4 Thermal Cracking Indirect Tensile Test

The IDT test at low temperatures measures the resistance to thermal cracking of a specimen. It is much like the IDT fatigue test except that it uses a smaller deformation rate and lower test temperature. Generally, the greater the peak load achieved by the specimen the greater the thermal resistance.

The IDT thermal test was performed on samples that were just selected for thermal cracking. No previous tests had been performed on the samples. Unlike other mix tests, these samples were four-inch diameter samples. The test was performed at -10°C with a deformation rate of 2.54 mm/min. The deformation was continued until the load on the sample achieved a value close to zero. Fracture energy and fracture work were also calculated for this test.

4.4.5 Verification of Maximum Theoretical Specific Gravity of Mix

The maximum theoretical specific gravity (G_{mm}) of each mix was verified by performing AASHTO T 209 titled "Theoretical Maximum Specific Gravity and Density of Hot Mix Paving Mixtures." To obtain samples for the test, specimens that had been destroyed from fatigue and thermal mix testing were heated and broken apart. All faces of aggregate that had been cut with the saw were removed from the sample so that only aggregates fully coated with asphalt were used for the test. Once enough sample was obtained, AASHTO T 209 was performed to determine the G_{mm} for each mix.

4.5 BINDER EXTRACTION METHOD

The binder extraction method used was AASHTO T 164, "Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA).", Method A. Reagent grade trichloroethylene was used as a solvent for this test. A Houghton centrifuge extractor capable of 3600 rev/min was used to perform the extractions. The centrifuge extractor can be seen in Figure 4-7.

Before the extraction process could be completed, broken mix samples were heated in the oven at a low temperature to make the asphalt soft. Once the asphalt was soft enough the samples were broken into tiny pieces. These tiny pieces of binder and aggregate were used for extraction.

Figure 4-7. Centrifuge Used for Asphalt Extraction

Once the mix samples were broken down, approximately 500 grams of the aggregate and binder pieces were placed in the bowl of the extractor. Approximately 500 ml of reagent grade trichloroethylene was placed in the bowl with the aggregate and binder. The trichloroethylene mixture was allowed to sit for 15 minutes to solve the binder. After the 15 minute waiting period the extractor was turned on and slowly increased in speed so that no more than 100 ml/min of solution was being extracted at a time. This was done by slowly increasing the speed of the extractor until it reached 3600 rev/min and no more solution was being extracted. Once this initial step was completed, three more washes with 250 mL of trichloroethylene were used to extract the remaining binder. Once the extraction was complete, approximately 1.25 L of asphalt/trichloroethylene solution was recovered.

4.6 BINDER RECOVERY METHOD

The binder recovery method followed AASHTO T 170, "Recovery of Asphalt from Solution by Abson Method." The recovery method was used to extract the asphalt from the trichloroethylene/asphalt solution in the extraction step. The distillation apparatus used can be seen in Figure 4-8.

Figure 4-8. Apparatus Used for Recovery of Asphalt

The recovery method was performed by heating the solution of trichloroethylene and asphalt. Once the solution reached its boiling point, the trichloroethylene began to evaporate out of the solution. Carbon dioxide gas was introduced at a flow rate of 100 ml/min to prevent the solution from foaming. The solution was distilled in this manner until about 150 ml of solution remained. Once this point was reached, the temperature was decreased so that the remaining asphalt would reach a temperature of 160° ± 5°C. Once the asphalt reached this temperature the

gas flow rate was increased to approximately 900 ml/min and the temperature was held at 160° ± 5°C for 15 minutes to ensure that no trichloroethylene was left in the asphalt. After 15 minutes the asphalt was recovered and ready for testing. Since the samples had been in the field for at least a year, the recovered binder was considered rolling thin film oven (RTFO) aged. There was no original binder used in testing.

4.7 BINDER TESTING EQUIPMENT

4.7.1 Dynamic Shear Rheometer (DSR)

A dynamic shear rheometer (DSR) was used for all binder tests, except for determination of creep stiffness and m-value of binder for low temperature grading purposes. A total of three trials were performed for each test used on the DSR to ensure accuracy of results. A picture of the DSR can be seen in Figure 4-9.

Figure 4-9. Dynamic Shear Rheometer

4.7.2 Bending Beam Rheometer (BBR)

The bending beam rheometer (BBR) was used for the low temperature performance grading of the binders. The load and corresponding strains are used to develop values of m-value and creep stiffness that must meet Superpave standards in order to pass at a given temperature. Figure 4-10 displays a picture of the BBR machine.

Figure 4-10. Bending Beam Rheometer

4.8 BINDER TESTS

4.8.1 Frequency Sweep

The frequency sweep test applies a series of small oscillations at linearly increasing frequencies to determine the complex modulus (G*) of the binder at each of these frequencies. The test is also often performed at several different temperatures as well. The stresses used are small enough so that the binder is not damaged during the test. G* is used as a measure of binder stiffness, similar to E* for mix specimens. A greater value of G* implies a stiffer binder.

The frequency sweep test was performed on RTFO binder. There were 15 frequencies linearly increasing between 0.1 and 60 Hz and temperatures of 5, 10, 15, 20, 25, 30 and 35°C that

were used. G* was determined at each of these frequency and temperature combinations so that binder stiffness could be compared between samples.

4.8.2 Monotonic

The monotonic test applies a constant shear rate to a binder sample and measures the corresponding stress in the sample. The test can be performed at a variety of different temperatures and shear rates. Generally, lower temperatures are used to help determine thermal cracking potential while intermediate temperatures are used to determine fatigue cracking resistance. Much like the IDT fatigue and thermal mix tests the fracture energy of the asphalt can be determined by taking the area underneath the stress vs. strain curve up to the peak stress. The fracture energy was used to determine fatigue cracking resistance. To determine thermal cracking resistance the strain at failure of the sample was recorded as it has been shown to have a good correlation with field thermal cracking performance (Wen 2011). Higher fracture energy or failure strain implies greater resistance to fatigue or thermal cracking, respectively.

The monotonic test was performed at temperatures of 5 and 20°C for thermal and fatigue cracking respectively. A shear rate of 0.01 was used for the tests performed at 5°C while a shear rate of 0.1 was used for 20°C. An exception is that contract 7419 and 7645 binders were tested for thermal cracking at 10°C with a shear rate of 0.01 and 0.04 respectively. This was because of added polymers which made the test too variable at 5°C. The fracture energy or failure strain for each sample was determined.

4.8.3 Multiple Stress Creep Recovery (MSCR)

The multiple stress creep recovery (MSCR) test applies a series of 10 oscillations producing a stress of 100 Pa with a loading period of 1 second and a rest period of 9 seconds which is immediately followed by the same loading pattern at a stress level of 3200 Pa. Figure 4-11 displays a typical accumulated strain vs. time plot of an MSCR test. During the 9 second rest period the viscoelastic binder recovers some of the strain induced by the stress. This is the percent recovery (ε_r) of the binder and it is averaged over the ten cycles performed. The non-recoverable compliance (J_{nr}) can also be calculated from the strain at the end of each cycle and the cycle stress. Through previous research (D'Angelo 2009), these parameters have been shown to help predict the rutting potential of a binder. Higher values of percent recovery and lower values of non-recoverable compliance indicate higher resistance to rutting.

The MSCR test was performed on recovered binder at the high temperature performance grade of the binder. Contract 7419 was an exception and MSCR testing was performed at both 64 and 76°C. AASHTO TP 70, "Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using the Dynamic Shear Rheometer (DSR)" was followed.

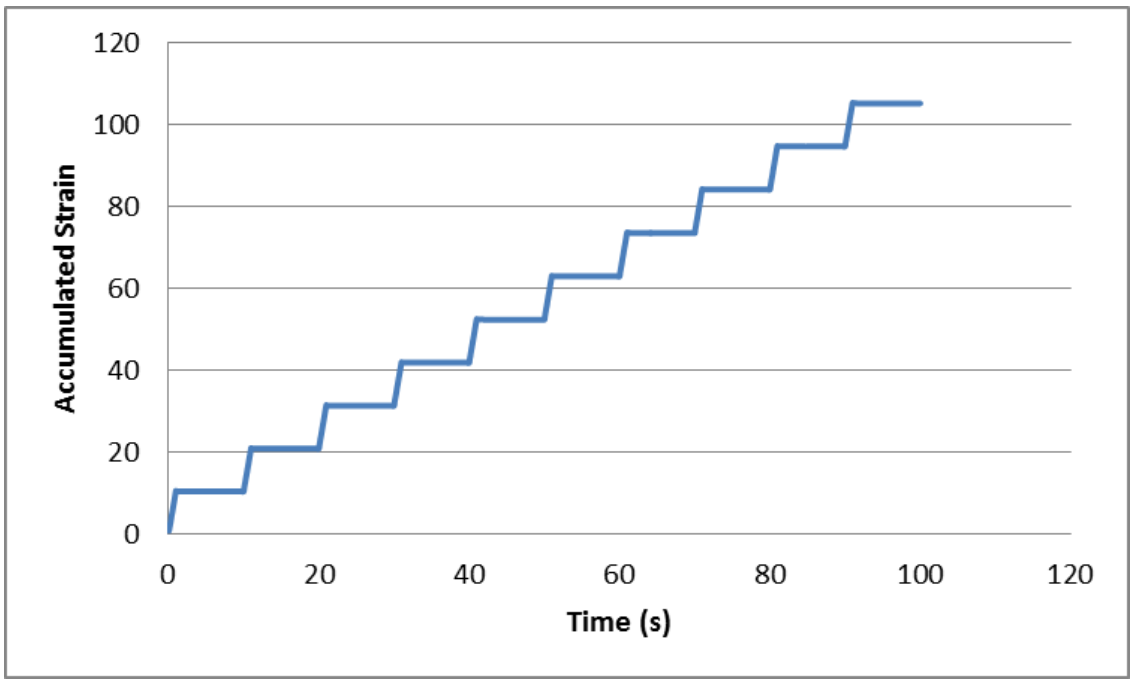

Figure 4-11. Typical Accumulated Strain vs. Time Plot of the MSCR Test

4.8.4 Performance Grading of Asphalt Binders

The performance grading of the recovered asphalt binders was performed in accordance with AASHTO PP 6, "Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder." The practice is also known as Superpave performance grading. All binders were first tested at their original high and low performance grade temperatures and then higher or lower temperatures to see if any performance grades had "bumped" or increased due to asphalt aging in the field. The performance grading of the binders was performed using the DSR and BBR. The DSR was used to find values of G* and phase angle (δ) to determine the high and low performance grade of the binders. The BBR was used only for low temperature performance grading of binders and calculated values of m-value and creep stiffness. No original binder was

used for the performance grade determination. The direct tension test was not needed for any of the binders tested.

CHAPTER 5: TESTING RESULTS AND DISCUSSION

This chapter displays and briefly discusses the results of tests performed. The data is organized by contract and discusses mix and binder test results as well as field performance. Summaries of the results of each contract are included.

5.1 CONTRACT 7474 TESTING RESULTS

5.1.1 Dynamic Modulus

The dynamic modulus master curves for control HMA and WMA are shown in Figure 5-1. For this contract it appeared that one HMA sample was much stiffer than any of the other samples. This increased stiffness was due to very small horizontal deformations in the sample. No other samples experienced these small deformations. Aside from the HMA outlier, it appears the HMA specimens were slightly stiffer at lower frequencies which would imply greater stiffness than WMA at low traffic speeds or high temperatures.

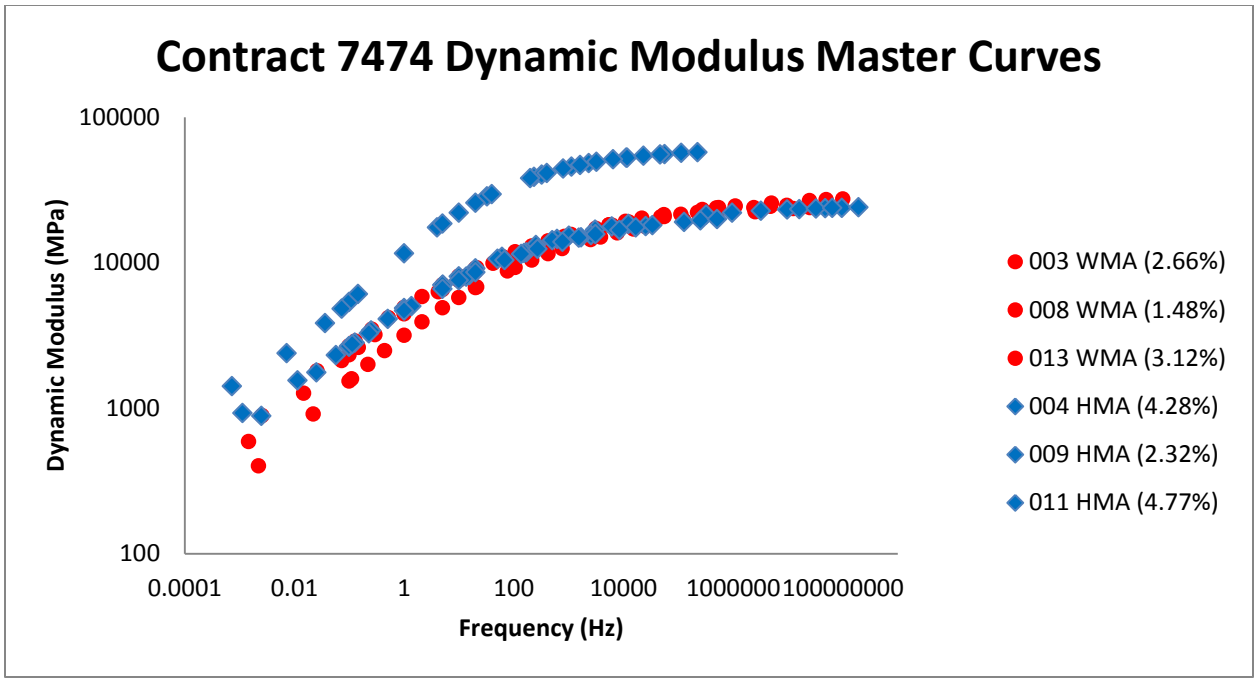

Figure 5-1. Contract 7474 Dynamic Modulus Master Curves

5.1.2 Creep Compliance

Figure 5-2 shows the creep compliance master curves for control HMA and WMA. From the master curves it appears that HMA was stiffer.

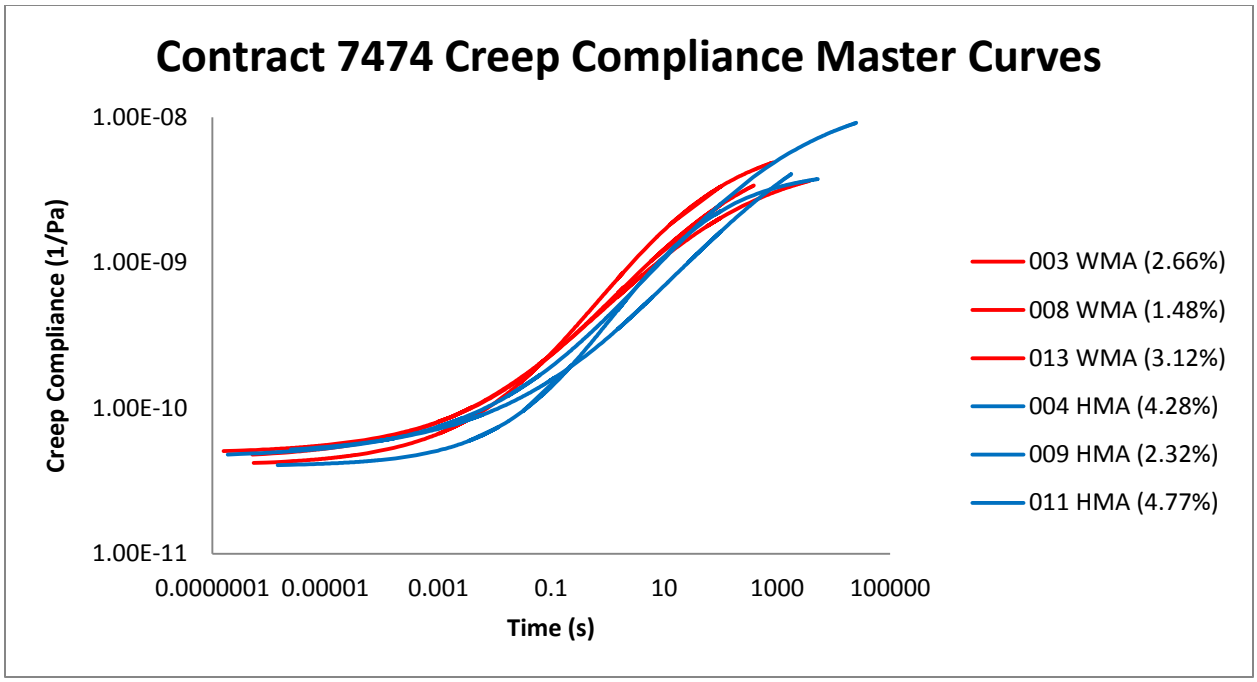

Figure 5-2. Contract 7474 Creep Compliance Master Curves

5.1.3 IDT Fatigue Cracking

Figures 5-3 and 5-4 show the IDT fatigue cracking test results for fracture energy and fracture work, respectively. From the results of fracture energy, it appears that there is no appreciable difference between HMA and WMA specimens. The average fracture energy of the HMA specimens was 9,470 Pa compared to 9,834 Pa for WMA. The same is also true for the fracture work of HMA and WMA specimens; there is no appreciable difference. The average fracture work for HMA was 73,394 N mm compared to 78,855 N mm for WMA. These findings imply that the bottom-up fatigue cracking resistance of HMA and WMA are comparable.

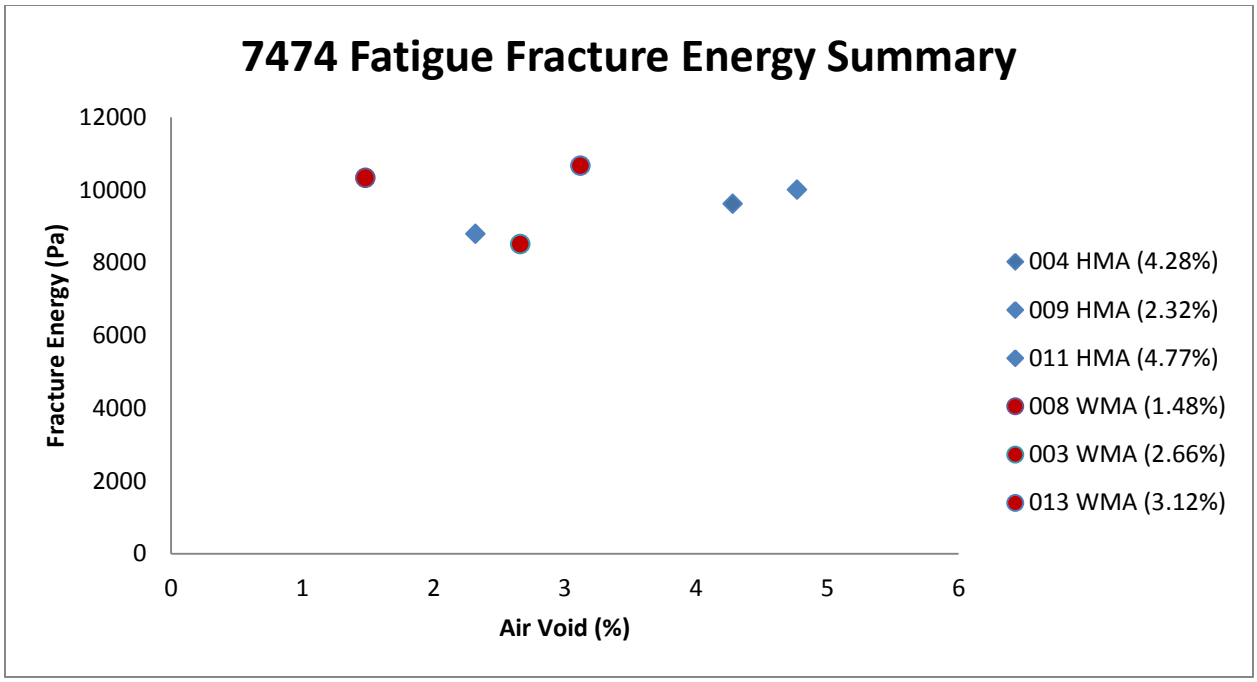

Figure 5-3. Contract 7474 Fatigue Fracture Energy

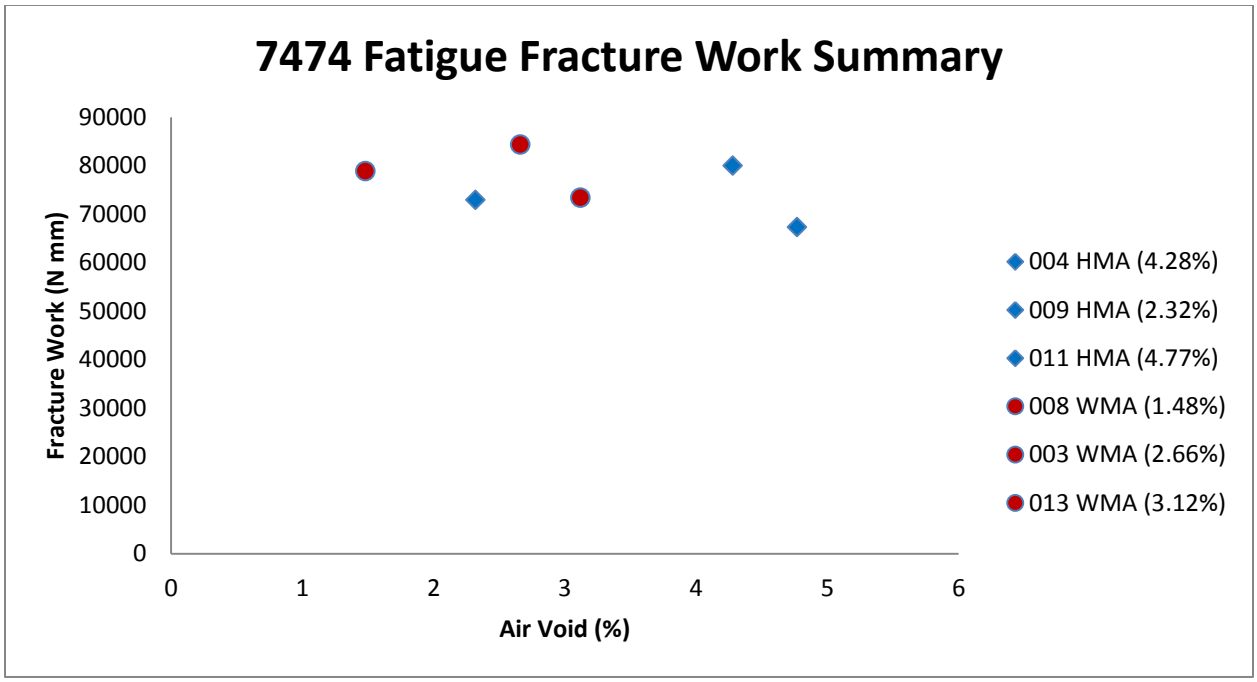

Figure 5-4. Contract 7474 Fatigue Fracture Work

5.1.4 IDT Thermal Cracking

Figures 5-5 and 5-6 show the IDT thermal cracking test results for fracture work and fracture energy, respectively. For both fracture energy and work, it is apparent that HMA had better performance than WMA. The average fracture energy for HMA was 11,777 Pa compared to 7,694 Pa for WMA. The average fracture work for HMA was 31,123 N mm compared to 27,803 N mm for WMA. The results imply that HMA may have higher thermal cracking resistance than WMA.

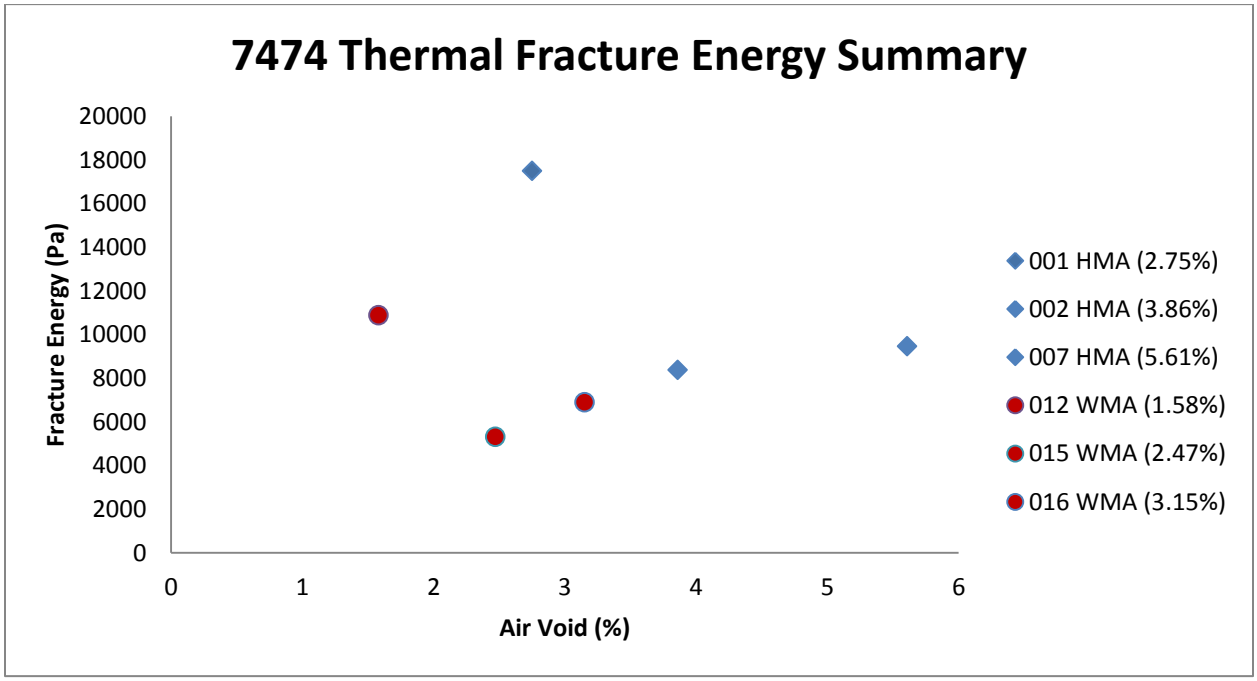

Figure 5-5. Contract 7474 Thermal Fracture Energy

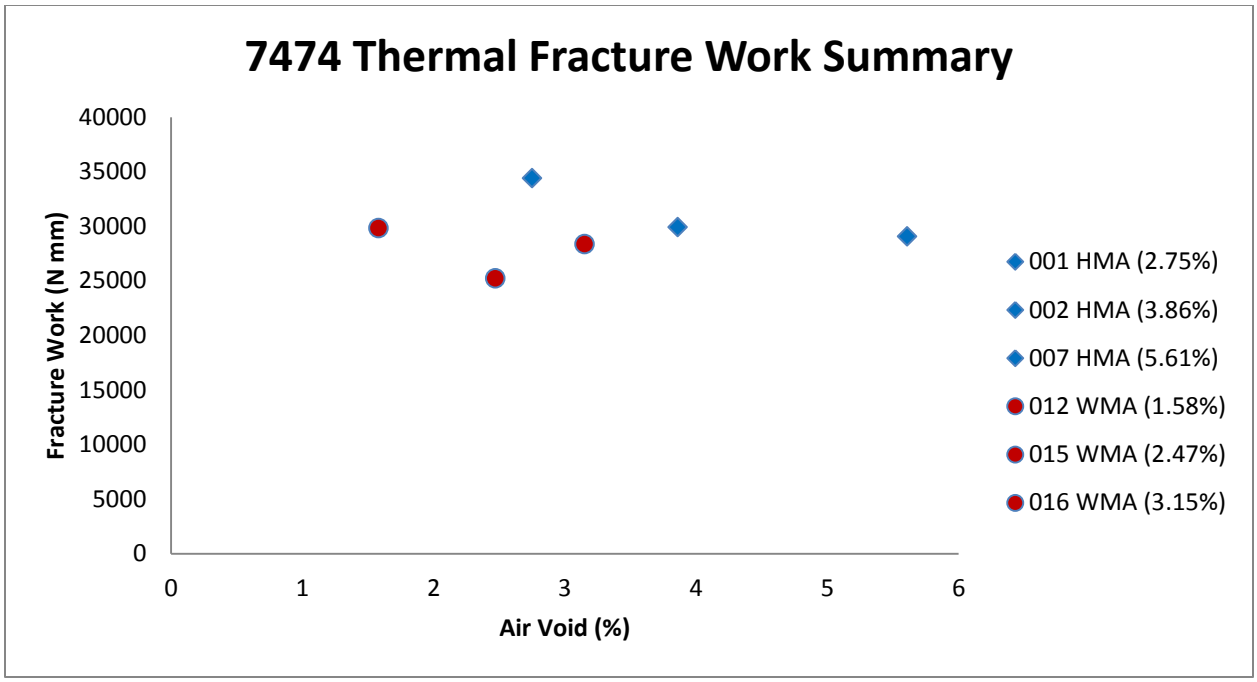

Figure 5-6. Contract 7474 Thermal Fracture Work

5.1.5 Theoretical Maximum Density Verification

Table 5-1. Theoretical Maximum Density Verification for Contract 7474

7474 HMA	
Weight of Pycnometer + Water	8110.3
Dry Weight of Sample	1590.0
Weight of Pycnometer + Sample + Water	9088.7
Gmm	2.599
Gmm from DOT	2.596
7474 WMA	
Weight of Pycnometer + Water	8109.3
Dry Weight of Sample	1827.1
Weight of Pycnometer + Sample + Water	9229.1
Gmm	2.583
Gmm from DOT	2.596

5.1.6 Complex Modulus Frequency Sweep

The results of the complex modulus frequency sweep are shown in Figure 5-7. The results show that the HMA binder was slightly stiffer at lower frequencies or higher temperatures than the WMA binder.

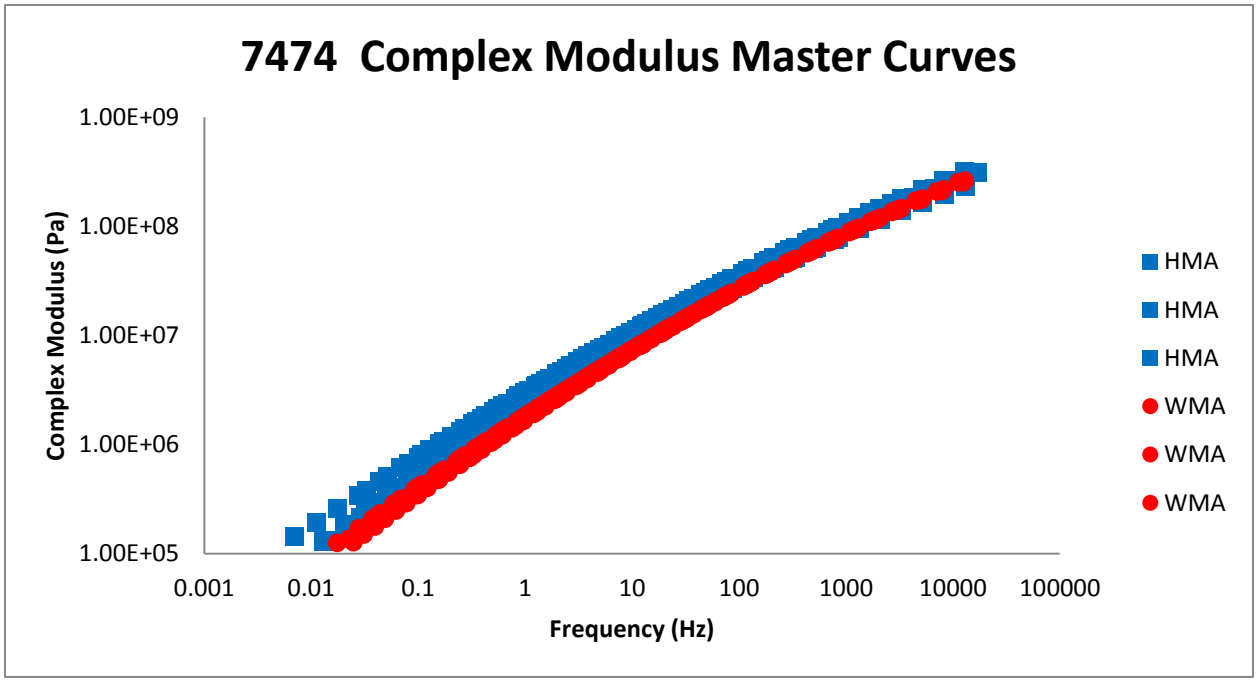

Figure 5-7. Contract 7474 Binder Complex Modulus Master Curves

5.1.7 Multiple Stress Creep Recovery

The results of the MSCR binder test with respect to percent recovery and non-recoverable compliance are shown in Figures 5-8 and 5-9, respectively. For the 3200 Pa stress level HMA had a higher value of percent recovery and a lower value of non-recoverable compliance compared to WMA. The average percent recovery for the HMA binder was 5.75% compared to

4.52% for WMA. The average non-recoverable compliance for HMA was 1.23 compared to 1.71 for WMA. The results suggest that the WMA binder would be more susceptible to rutting.

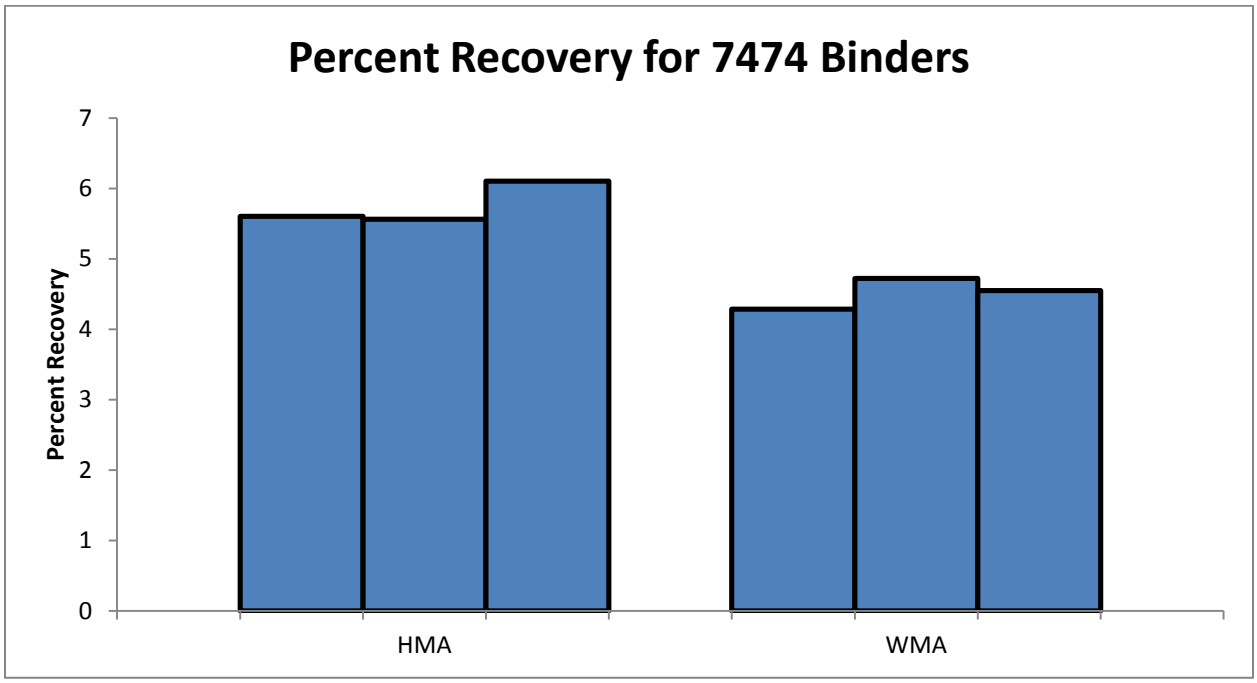

Figure 5-8. Contract 7474 Binder Percent Recovery

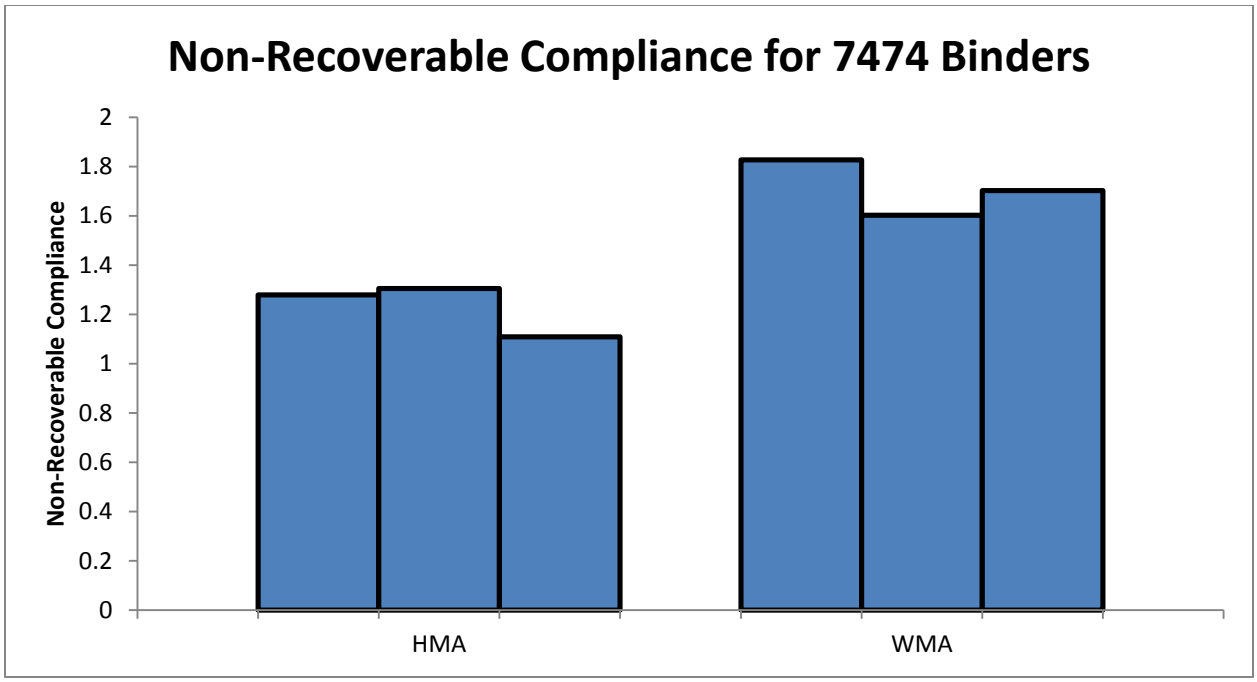

Figure 5-9. Contract 7474 Binder Non-Recoverable Compliance

5.1.8 Monotonic

The results of the binder monotonic tests for thermal cracking at 5°C and fatigue cracking at 20°C are shown in Figures 5-10 and 5-11, respectively. The HMA had a lower failure strain than WMA at 5°C but higher fracture energy than WMA at 20°C. The average failure strain of HMA at 5°C was 1.15 compared to 1.35 for WMA. The average fracture energy for HMA at 20°C was 1,697 kPa compared to 1,275 kPa for WMA. The results suggest the WMA binder may have more thermal cracking resistance than HMA, but less resistance with respect to fatigue cracking. The difference in binder tests results and mix test results might result from the fact that the binder test results are only representative of the material properties whereas the mix test

results include effects of materials as well as construction, such as adhesion of binder to aggregates and compaction.

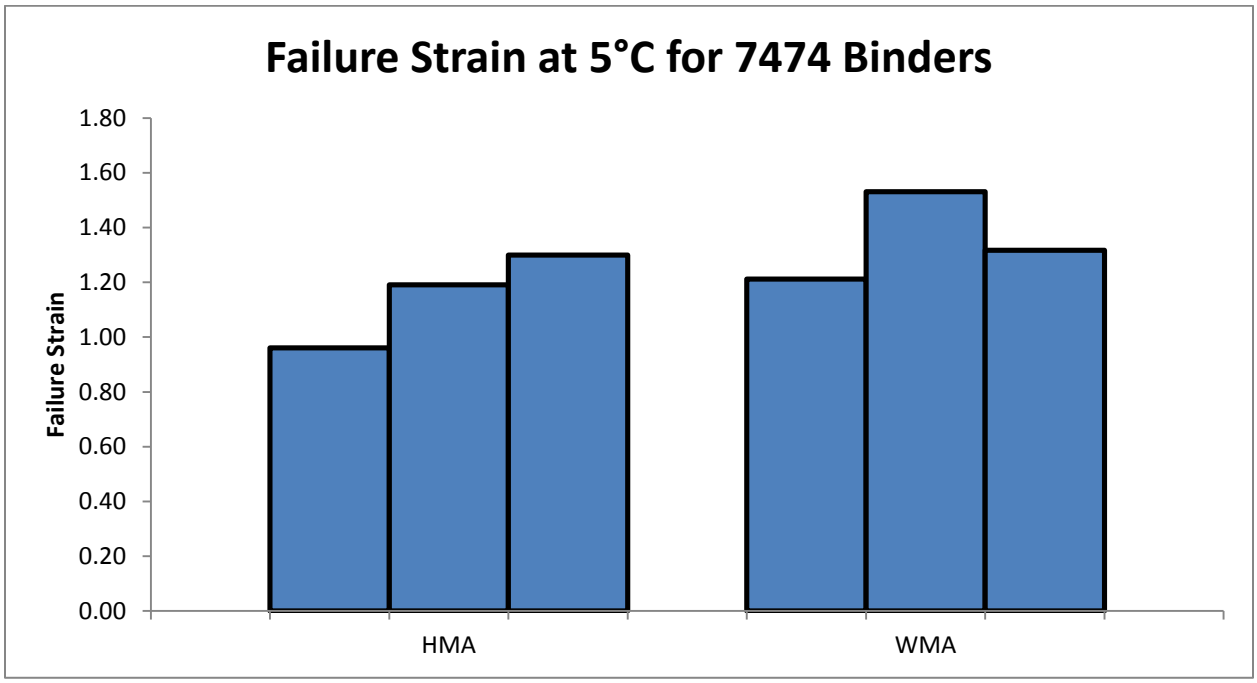

Figure 5-10. Contract 7474 Binder Monotonic Failure Strain at 5°C

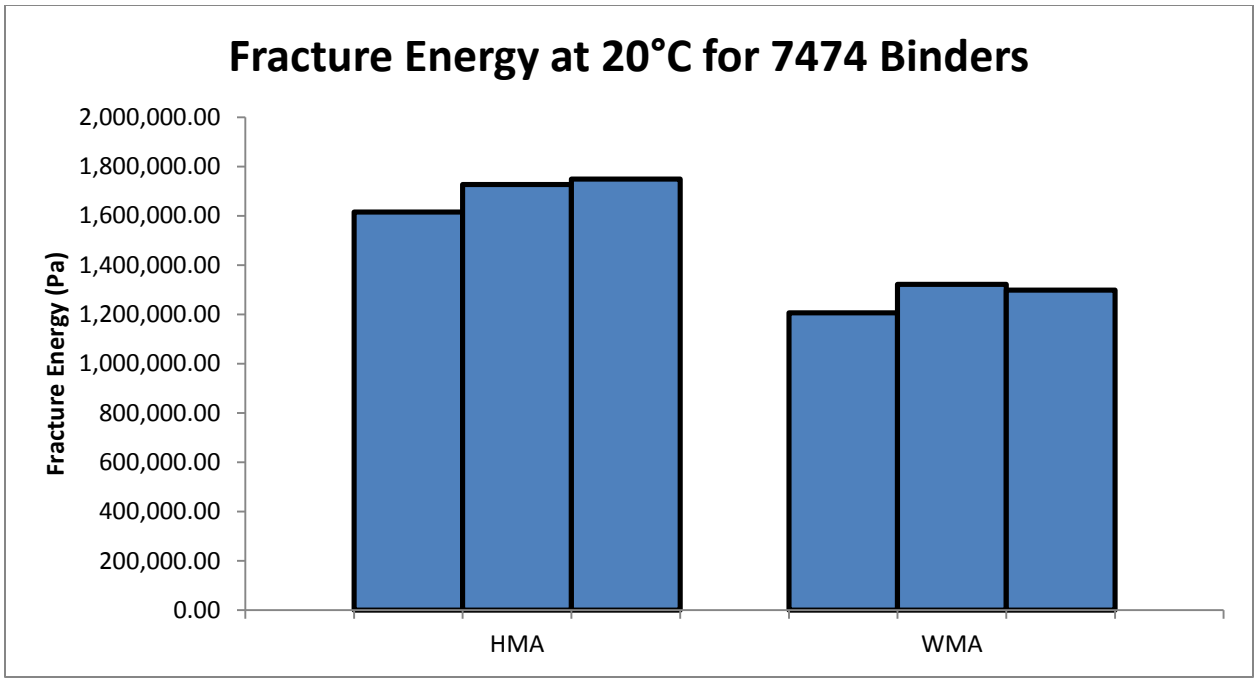

Figure 5-11. Contract 7474 Binder Monotonic Fracture Energy at 20°C

5.1.9 Performance Grading

The results of the performance grading tests for HMA and WMA can be seen in Tables 5-2 and 5-3 respectively. The HMA and WMA binders were graded as 64-28 at the time of construction but were both graded at 70-22 at the time of this study.

Table 5-2. Performance Grading Summary for 7474 HMA Binder

	Recovered			PAV		BBR
Temp	64 C	70 C	76 C	22 C	25 C	-12 C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Pass
G*/sinδ	6.73	3.14	1.52	-	-	-
G*•sinδ	-	-	-	6.53	4.81	-
m-value	-	-	-	-	-	0.313
Creep Stiffness	-	-	-	-	-	173.535

Table 5-3. Performance Grading Summary for 7474 WMA Binder

	Recovered			PAV		BBR
Temp	64 C	70 C	76 C	22 C	25 C	-12 c
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Pass
G*/sinδ	5.43	2.64	1.23	-	-	-
G*•sinδ	-	-	-	5.47	4.16	-
m-value	-	-	-	-	-	0.332
Creep Stiffness	-	-	-	-	-	176.720

5.1.10 Field Performance Comparison

The field performance for contract 7474 was obtained from a quarterly progress report for the NCHRP 9-47A project, "Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies." The field inspection was performed approximately 13 months after construction. It should be noted that the WMA section from this report was in the passing lane, which experienced less traffic than the travel lane. According to the report, neither the HMA nor WMA section showed any significant rutting. The HMA had an average rut depth of about 1 mm while the WMA had no measurable value of rut depth. No fatigue or thermal cracking was found in either the HMA or WMA sections. The HMA sections had average surface texture depths of 1.00 mm with a standard deviation of 0.13 mm while the WMA sections had average surface texture depths of 0.74 with a standard deviation of 0.05 mm. In summary, the HMA control in the field experienced more field distress with respect to rutting and raveling than WMA, but this is likely due to the increased traffic load from being in the travel lane.

5.1.11 Contract 7474 Summary

From the stiffness tests performed on both mix and binder specimens it appears that the HMA is slightly stiffer at higher temperatures than the WMA. From the results of the MSCR binder testing it is also apparent that the HMA is more rut resistant than the WMA as well. The fatigue cracking resistance of the WMA seems to be comparable to HMA in mix tests, but slightly worse in binder tests. However, as previously stated binder tests only account for material properties of binder and do not account for complex mix properties. HMA displayed better thermal cracking performance in mix testing, but worse thermal cracking performance in binder testing. Both binders "bumped" a high and low grade temperature most likely due to aging from construction and time in the field. The field performance of WMA appears to be adequate from the NCHRP report. However, it is difficult to make any conclusions based on field data because the pavement is only one year old and also because the WMA analyzed was in the passing lane where there was less traffic. Based on the binder test results, WMA created with the Aquablack™ foaming method may have more problems with rutting than HMA.

5.2 CONTRACT 7419 TESTING RESULTS

5.2.1 Dynamic Modulus

The results of the dynamic modulus mix testing are shown in Figure 5-12. From the figure there does not appear to be a significant difference in stiffness between the HMA and WMA samples.

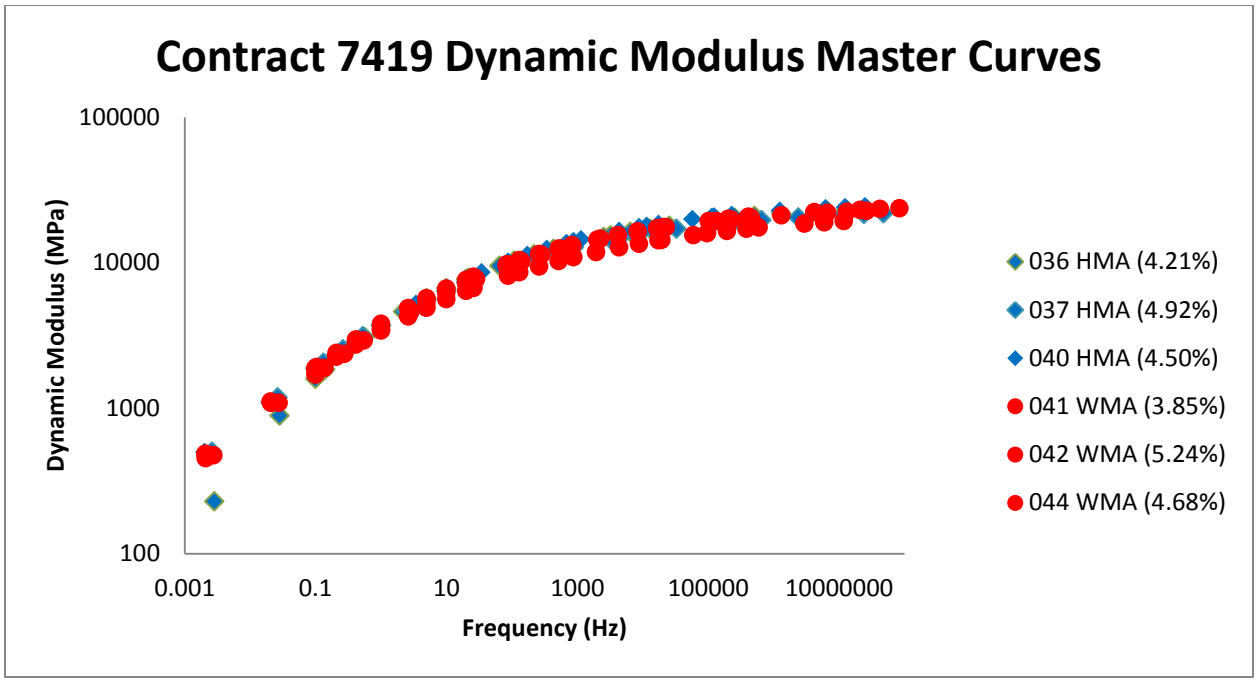

Figure 5-12. Contract 7419 Dynamic Modulus Master Curves

5.2.2 Creep Compliance

The plot of the master curves of creep compliance can be seen in Figure 5-13. The curves suggest that the WMA specimens were stiffer than the HMA specimens.

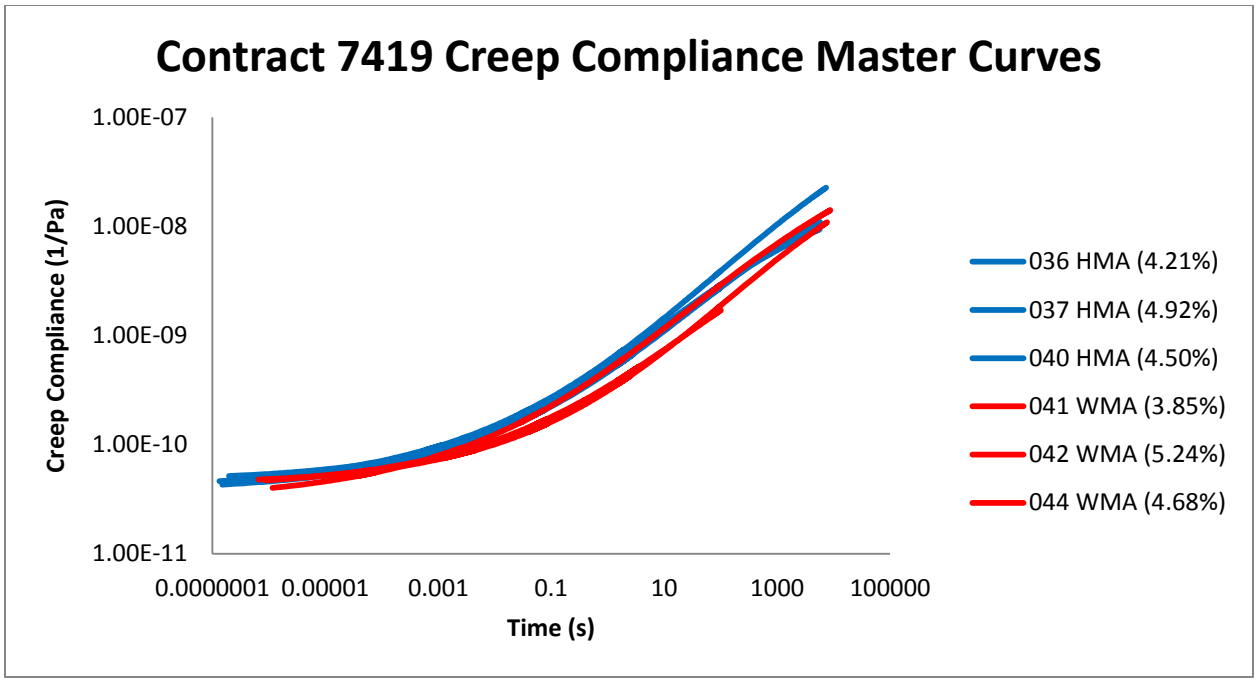

Figure 5-13. Contract 7419 Creep Compliance Master Curves

5.2.3 IDT Fatigue Cracking

The IDT fatigue cracking mix test results for fracture energy and fracture work are shown in Figures 5-14 and 5-15, respectively. From the plots it appears that HMA had higher values of both fracture energy and fracture work with respect to fatigue cracking. The average value of fracture energy for HMA was 12,338 Pa compared to 11,021 Pa for WMA. The average value for fracture work for HMA was 75,226 N mm compared to 66,860 N mm for WMA. The results suggest that HMA has higher bottom-up fatigue cracking resistance than WMA.

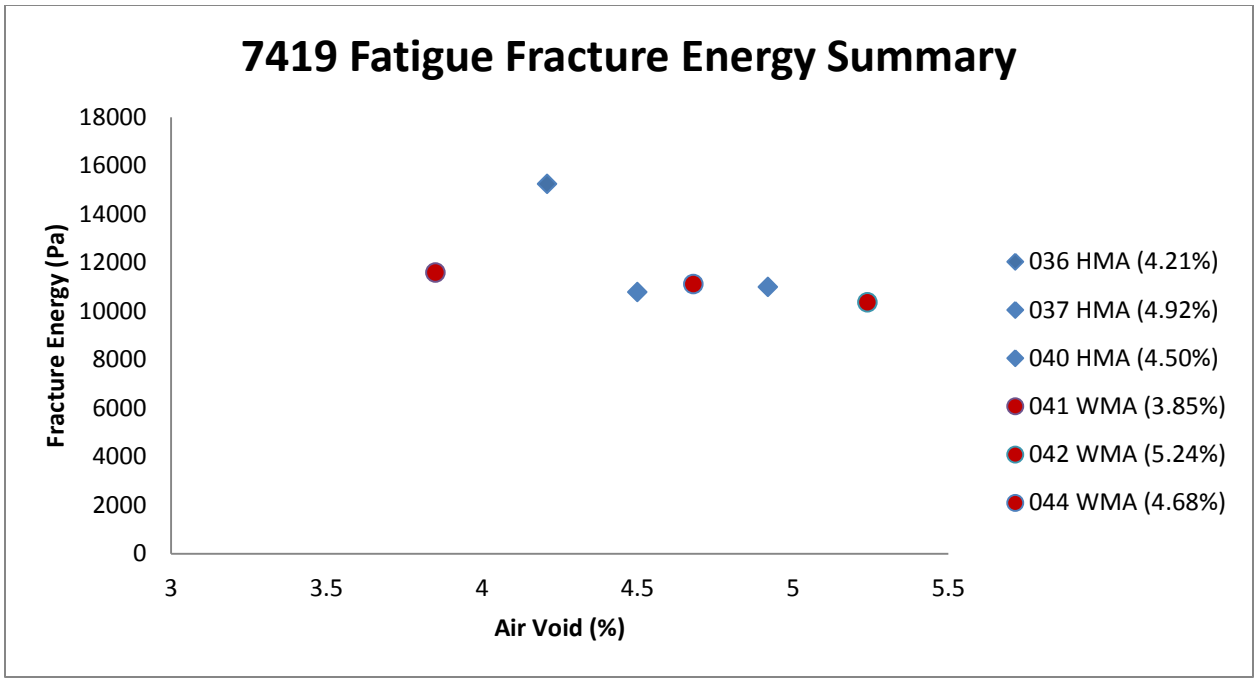

Figure 5-14. Contract 7419 Fatigue Fracture Energy

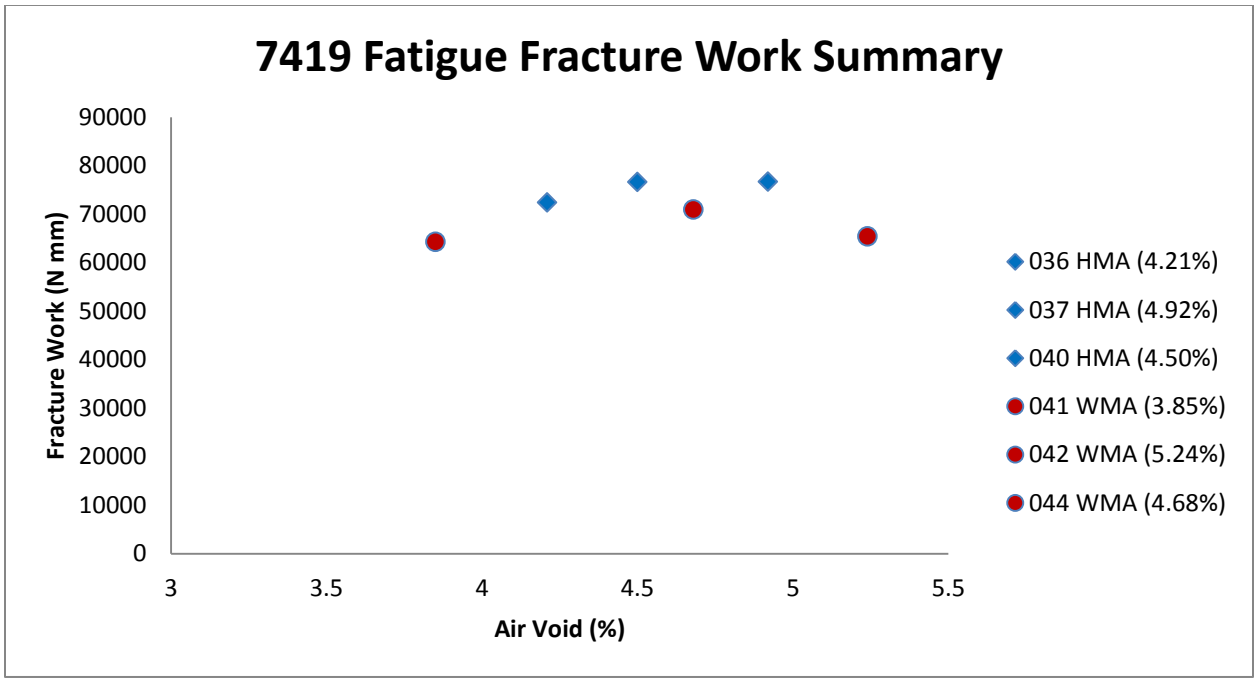

Figure 5-15. Contract 7419 Fatigue Fracture Work

5.2.4 IDT Thermal Cracking

The IDT thermal cracking mix results for fracture energy and fracture work are shown in Figures 5-16 and 5-17 respectively. In each of the figures, there does not appear to be a large difference between the fracture energy or fracture work for HMA and WMA samples. The average fracture energy for HMA was 9,206 Pa compared to 9,470 Pa for WMA. The average fracture work for HMA was 27,276 N mm compared to 25,033 N mm for WMA. It appears the thermal cracking resistance of HMA and WMA are comparable.

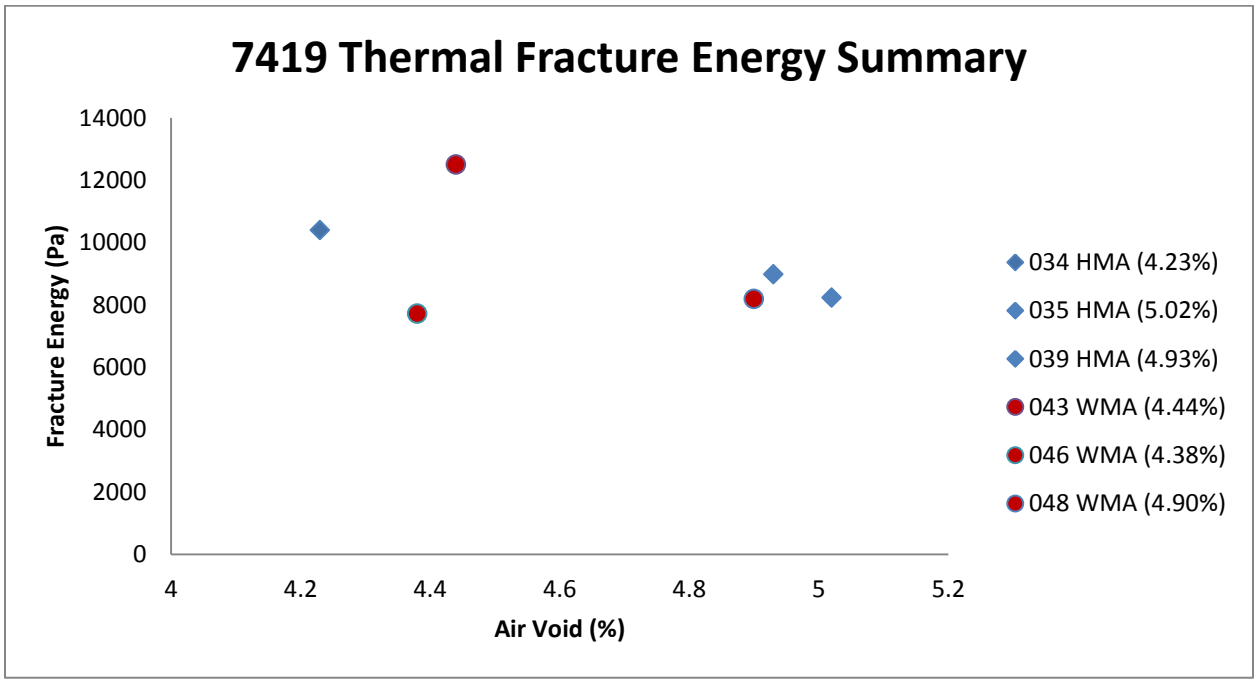

Figure 5-16. Contract 7419 Thermal Fracture Energy

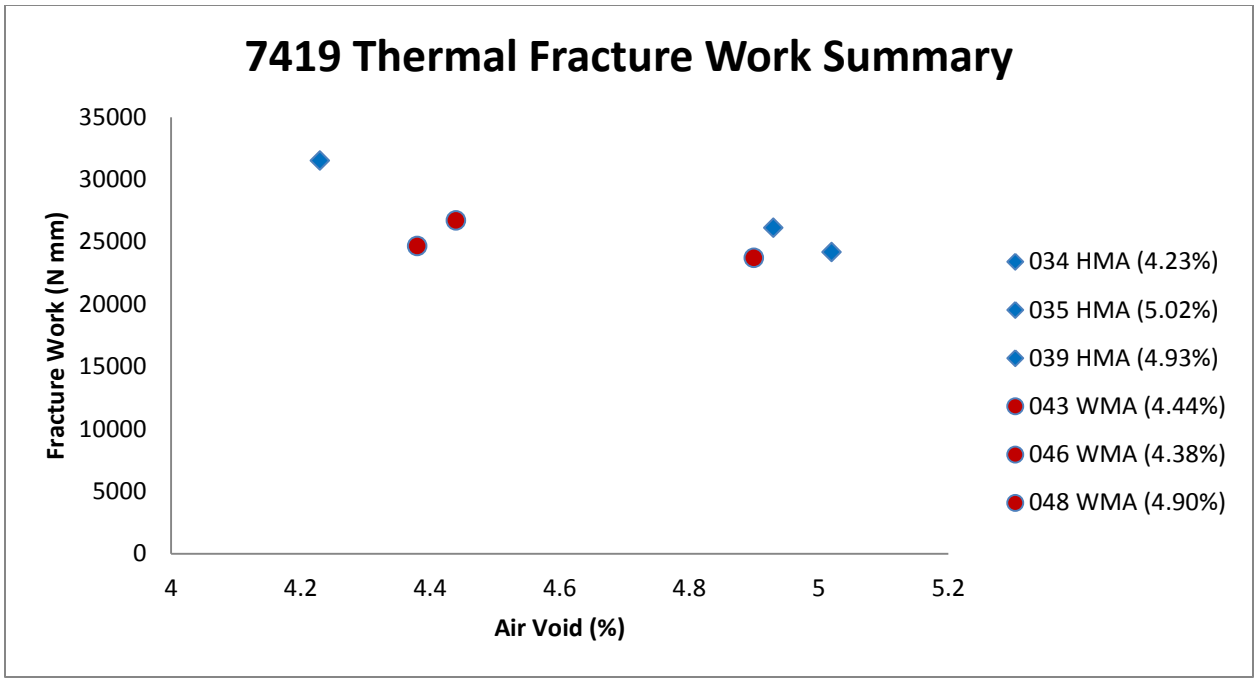

Figure 5-17. Contract 7419 Thermal Fracture Work

5.2.5 Theoretical Maximum Density Verification

Table 5-4. Theoretical Maximum Density Verification for Contract 7419

7419 HMA	
Weight of Pycnometer + Water	8109.4
Dry Weight of Sample	1729.4
Weight of Pycnometer + Sample + Water	9173.3
Gmm	2.598
Gmm from DOT	2.601
7419 WMA	
Weight of Pycnometer + Water	8109.3
Dry Weight of Sample	1772.5
Weight of Pycnometer + Sample + Water	9198.6
Gmm	2.594
Gmm from DOT	2.601

5.2.6 Complex Modulus Frequency Sweep

The complex modulus frequency sweep test results are shown in Figure 5-18. From the figure it appears that the WMA binder was slightly softer than the HMA binder.

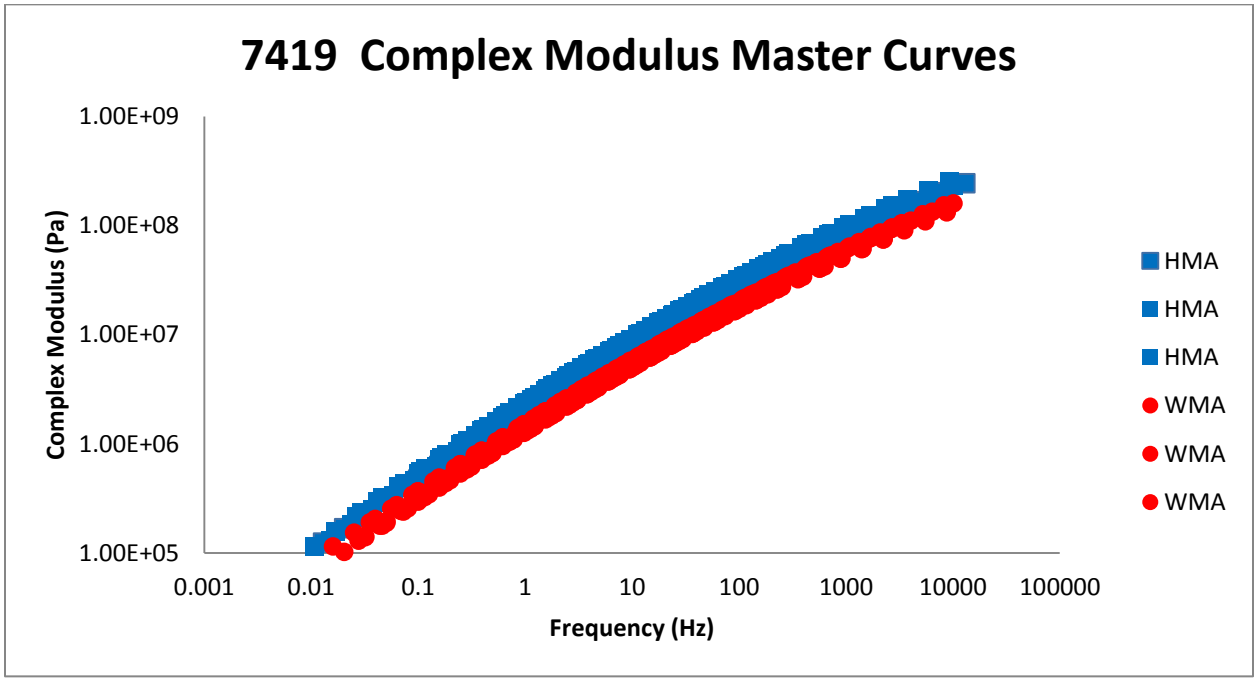

Figure 5-18. Contract 7419 Complex Modulus Master Curves

5.2.7 Multiple Stress Creep Recovery

The MSCR binder test results for 64°C for percent recovery and non-recoverable compliance are shown in Figures 5-19 and 5-20. The percent recovery and non-recoverable compliance values at 76°C are shown in figures 5-21 and 5-22. It appears that at both temperatures HMA and WMA had similar values of percent recovery at the 3200 Pa stress cycle. The average percent recovery at 64°C for HMA was 60.39% compared to 65.17% for WMA.

The average percent recovery at 76°C for HMA was 20.53% compared to 19.08% for WMA. The average non-recoverable compliance value at 64°C for HMA was 0.28 for HMA compared to 0.27 for WMA. The average non-recoverable compliance value at 76°C for HMA was 1.69 compared to 2.63 for WMA. Based on the values of non-recoverable compliance at 76°C, the WMA may be slightly more susceptible to rutting than HMA.

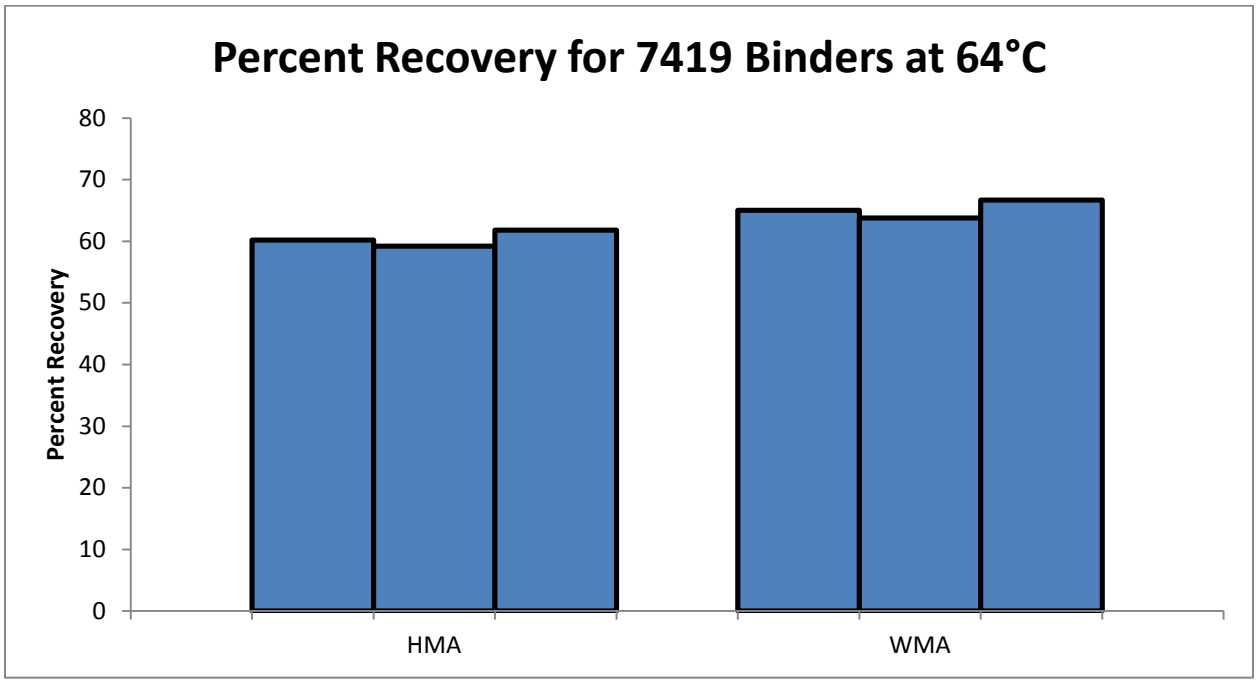

Figure 5-19. Contract 7419 Percent Recovery at 64°C

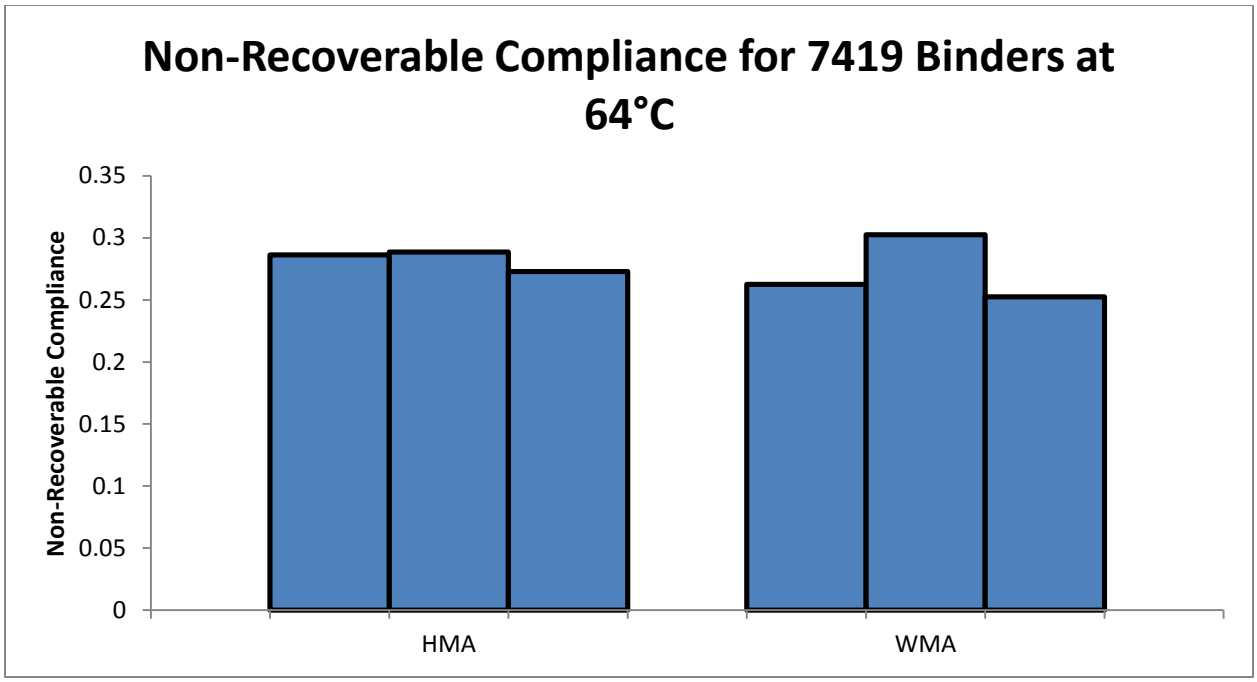

Figure 5-20. Contract 7419 Non-Recoverable Compliance at 64°C

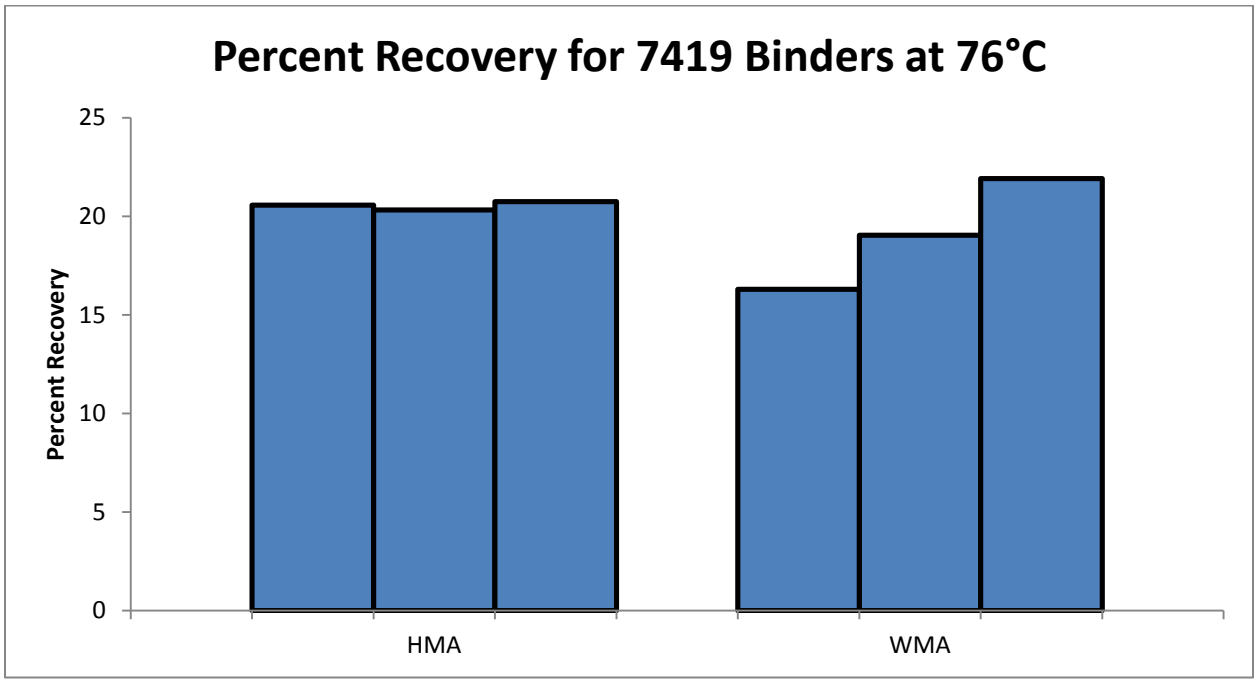

Figure 5-21. Contract 7419 Percent Recovery at 76°C

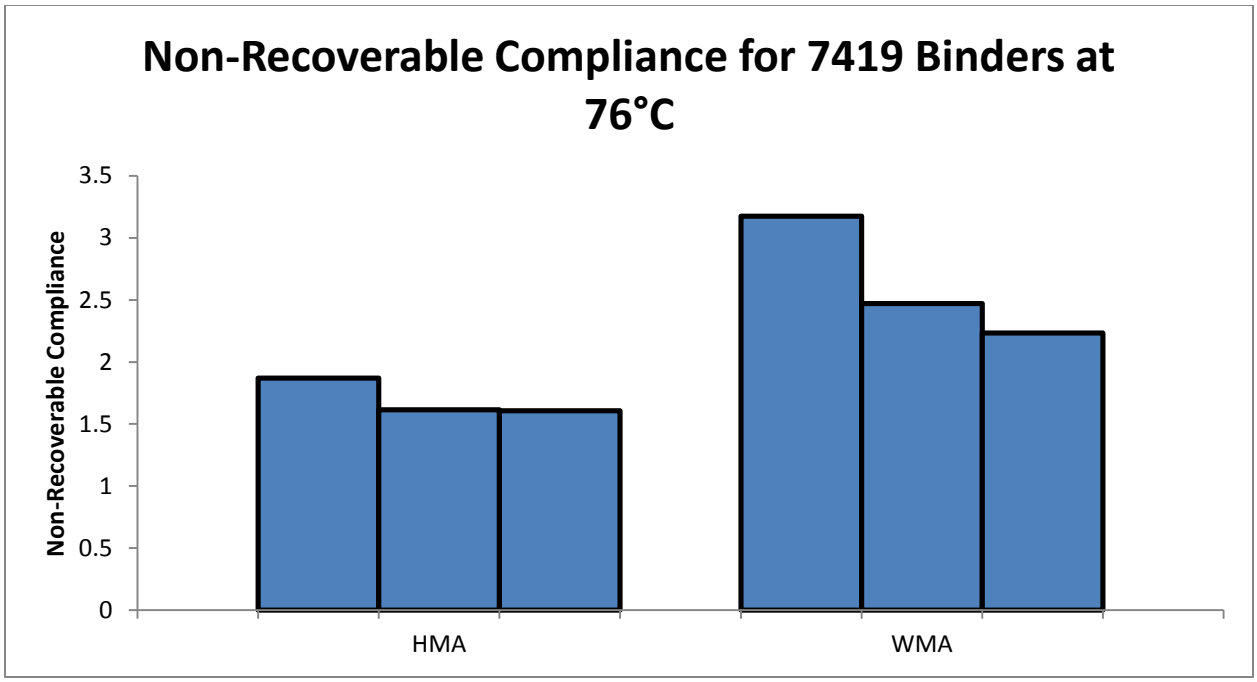

Figure 5-22. Contract 7419 Non-Recoverable Compliance at 76°C

5.2.8 Monotonic

The results of the monotonic binder tests at 10°C and 20°C are shown in Figures 5-23 and 5-24, respectively. At 10°C the WMA binder had a higher failure strain than HMA binder and at 20°C the HMA binder had higher fracture energy than WMA. At 10°C the average failure strain for HMA was 2.47 compared to 3.08 for WMA. At 20°C the average fracture energy for HMA binder was 6,524 kPa compared to 4,136 kPa for WMA binder. This data agrees with the IDT fatigue cracking mix tests and somewhat contradicts the thermal mix tests. It is noted that the performance tests on both mix and binder are designed for bottom-up cracking, instead of top-down longitudinal fatigue cracking in the wheel path.

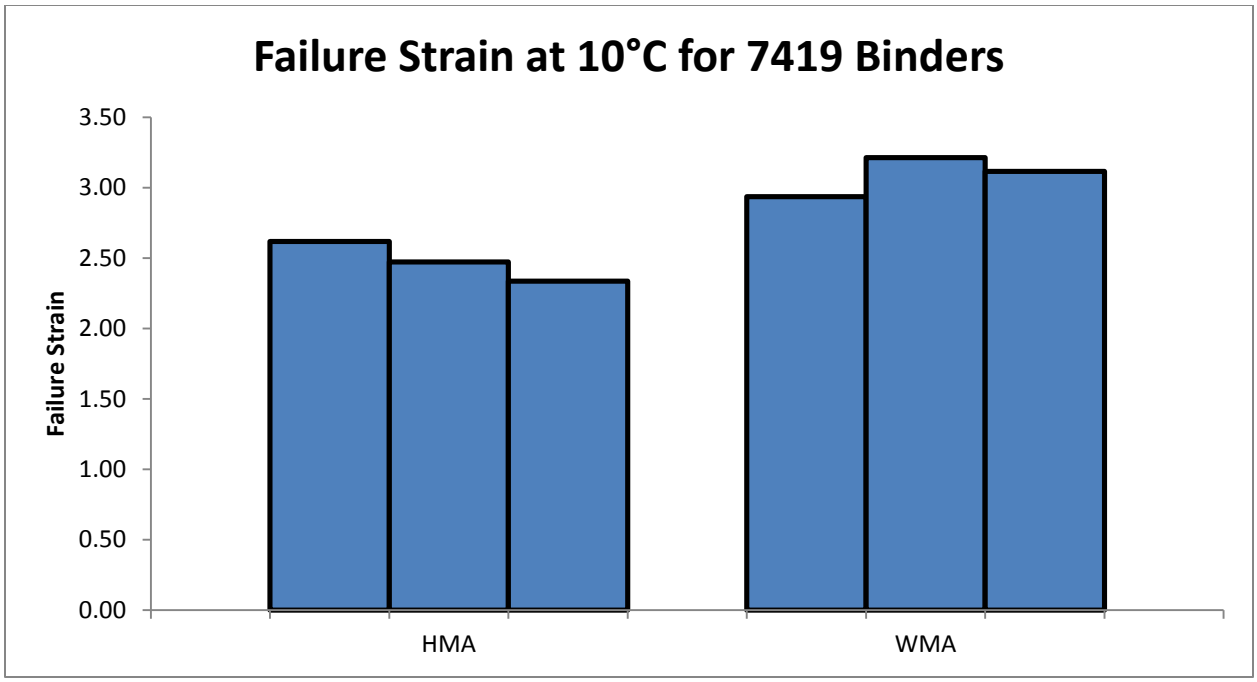

Figure 5-23. Contract 7419 Monotonic Failure Strain at 5°C

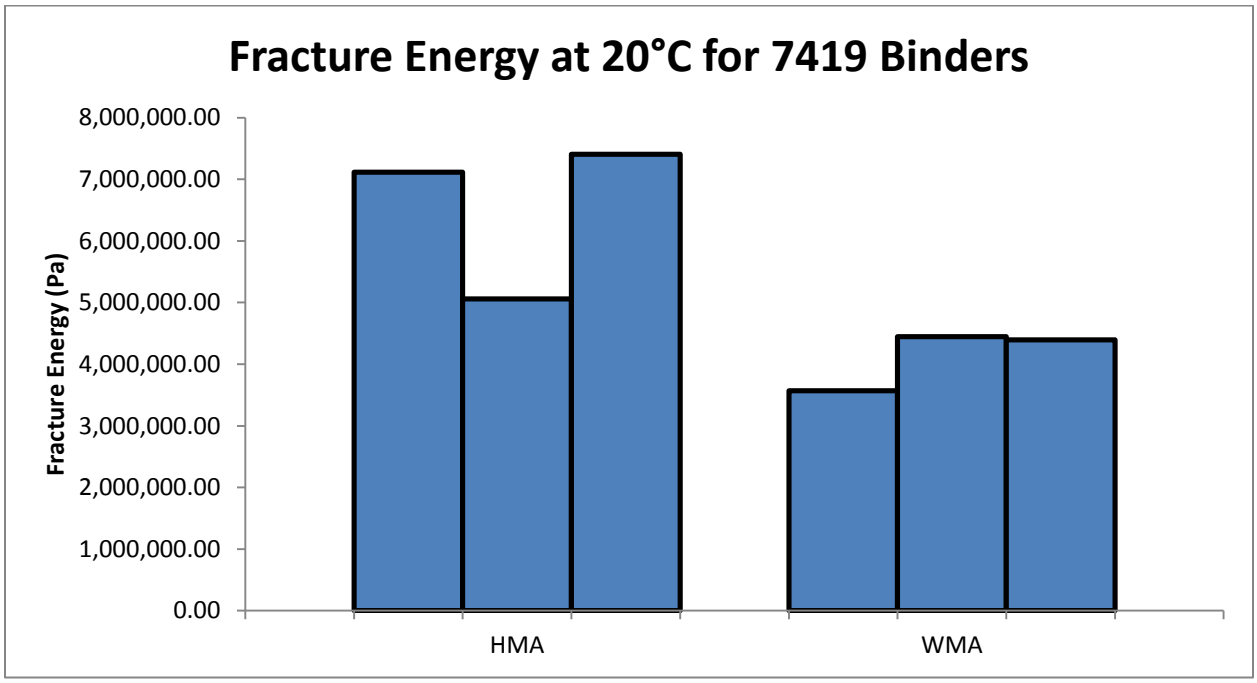

Figure 5-24. Contract 7419 Monotonic Fracture Energy at 20°C

5.2.9 Performance Grading

The results of the performance grading tests are shown in Tables 5-5 and 5-6 for HMA and WMA, respectively. Neither binder's high temperature grade was increased. However, the low temperature grade for each binder did bump one grade. Each binder was originally graded at 76-28 but at the time of this study each binder was graded at 76-22. From the values of complex modulus and phase angle from testing it appears the WMA binder was actually slightly stiffer than the HMA.

Table 5-5. Performance Grading Summary for 7419 HMA Binder

	Recovered		PAV		BBR	
Temp	76 C	82C	25 C	28 C	-18C	-12 C
Pass/Fail	Pass	Fail	Pass	Pass	Fail	Pass
G*/sinδ	3.27	1.88	-	-	-	-
G*•sinδ	-	-	3.30	2.29	-	-
m-value	-	-	-	-	0.27697	0.3209
Creep Stiffness	-	-	-	-	277.047	141.469

Table 5-6. Performance Grading Summary for 7419 WMA Binder

	Recovered		PAV		BBR	
Temp	76 C	82C	25 C	28 C	-18C	-12 C
Pass/Fail	Pass	Fail	Pass	Pass	Fail	Pass
G*/sinδ	3.39	1.91	-	-	-	-
G*•sinδ	-	-	4.24	2.98	-	-
m-value	-	-	-	-	0.263	0.303
Creep Stiffness	-	-	-	-	287.556	155.306

5.2.10 Field Performance Comparison

The data for the field performance for contract 7419 was obtained from Segment Viewer in the WSDOT WSPMS system. The average rutting for the HMA section was 0.13” with a standard deviation of 0.01”. The average rutting for the WMA section was 0.13” with a standard deviation of 0.01”. The HMA section displayed low severity longitudinal cracking and low severity transverse cracking. The longitudinal cracking occurred in two segments between milepost 142.0 and 142.1, and also between milepost 142.72 and 142.82. The transverse cracking also occurred in two segments between milepost 142.22 and 142.62 and between milepost 142.82 and 142.92. For WMA no cracking was observed. The HMA had an average International Roughness Index (IRI) value of 51.24 in/mi with a standard deviation of 5.24 in/mi. The average IRI for WMA was 49.39 in/mi with a standard deviation of 5.19 in/mi. The field data shows WMA performed equally as well as HMA with respect to rutting and roughness. The WMA performed better than HMA with respect to fatigue and thermal cracking.

5.2.11 Contract 7419 Summary

From the results of the mix stiffness tests, HMA and WMA appeared to have comparable stiffness. The complex modulus frequency sweep binder test seemed to contradict these findings slightly, suggesting that HMA binder was slightly more stiff than WMA binder. The results from the MSCR binder test showed similar values of percent recovery for each binder, but higher values of non-recoverable compliance for WMA, suggesting the WMA may be slightly more susceptible to rutting than HMA. From mix testing, HMA seemed to have a higher bottom-up fatigue cracking resistance than WMA. The monotonic binder test for fatigue cracking agreed with these results. Thermal cracking resistance of HMA and WMA was comparable with respect

to mix testing. The thermal cracking binder tests contradicted these results, suggesting that WMA had a higher thermal cracking resistance than HMA. Both the HMA and WMA binder bumped one low temperature grade, while the high temperature grade remained the same. WMA actually showed better performance in the field with respect to top-down fatigue and thermal cracking. It is noted that for thermal cracking, it seems the binder test results correlate with the field performance better than the mix test results. From the lab test results, WMA made with Sasobit® may have slightly higher susceptibility to rutting and fatigue cracking. For rutting tests, it seems that the percent recovery correlates better with the field rutting than the non-recoverable compliance.

5.3 CONTRACT 7755 TESTING RESULTS

5.3.1 Dynamic Modulus

The results of the dynamic modulus mix testing are shown in Figure 5-25. From the plot of the master curves, there does not appear to be any difference between the stiffness of the HMA and WMA samples.

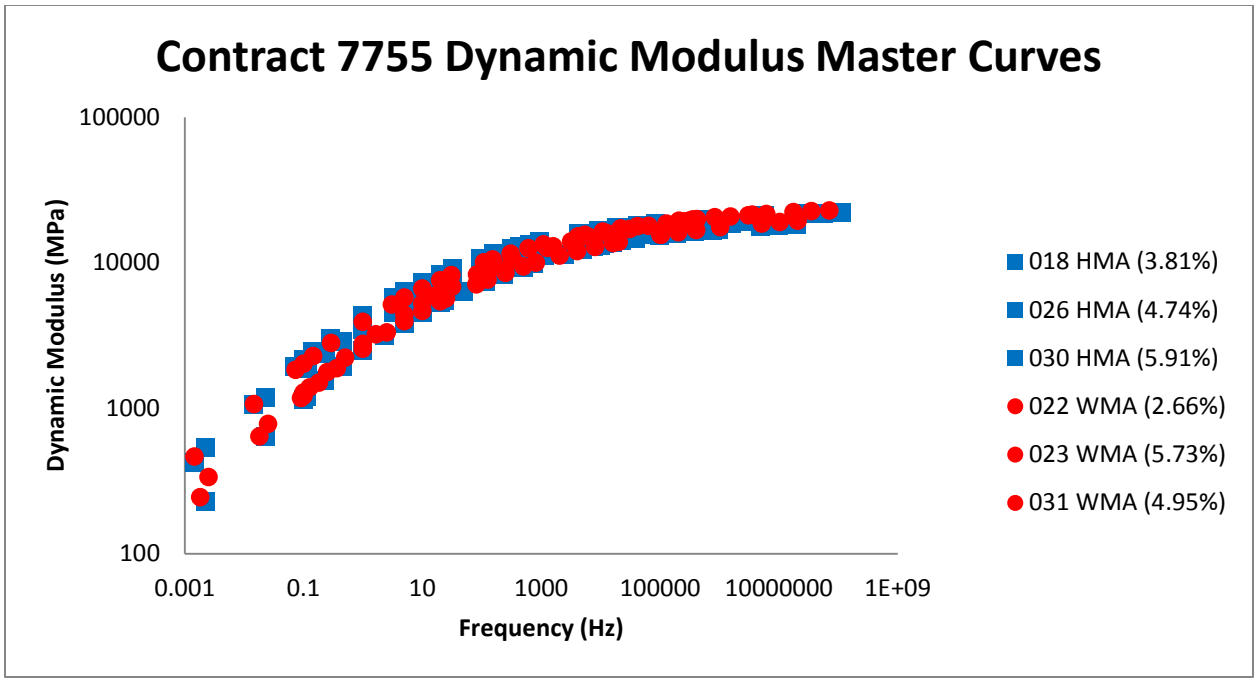

Figure 5-25. Contract 7755 Dynamic Modulus Master Curves

5.3.2 Creep Compliance

The master curves for creep compliance testing are shown in Figure 5-26. One WMA sample appeared to be stiffer than the other WMA and HMA control samples. This WMA sample data does not agree with the data from the dynamic modulus test. The rest of the samples had similar master curves, implying similar stiffness.

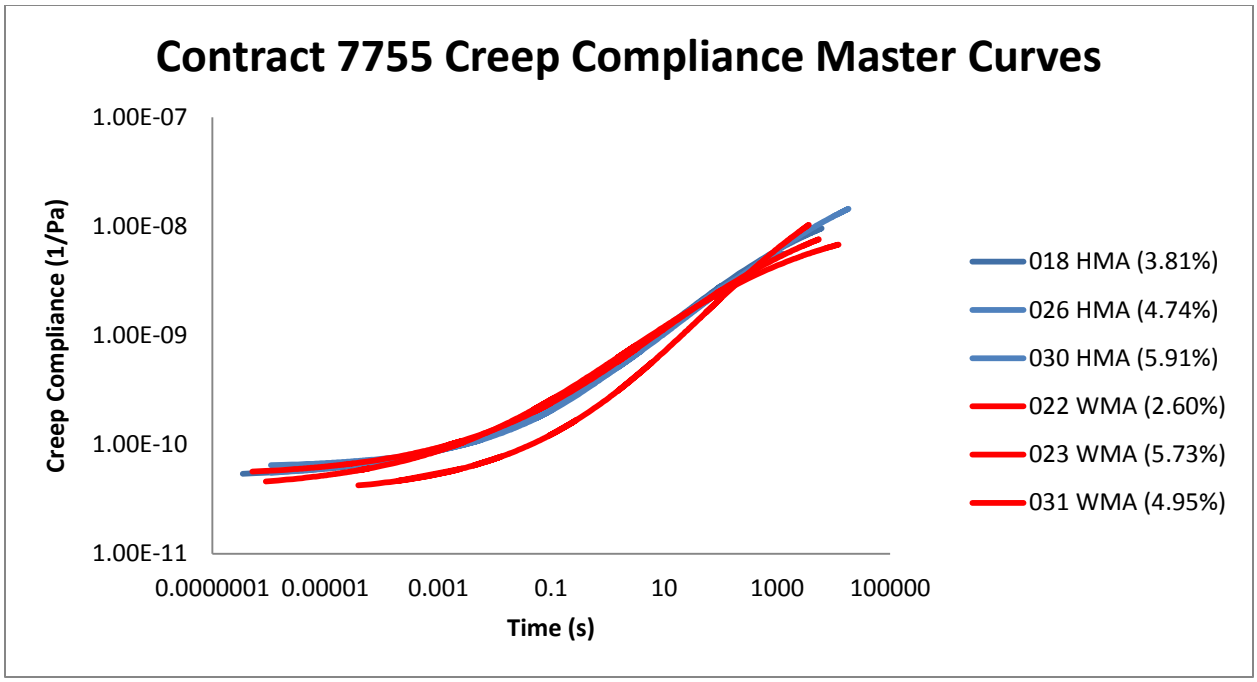

Figure 5-26. Contract 7755 Creep Compliance Master Curves

5.3.3 IDT Fatigue Cracking

The results of the IDT fatigue tests for fracture energy and fracture work are shown in Figures 5-27 and 5-28, respectively. HMA samples had slightly higher fracture energy than the WMA samples. The average fracture energy for HMA was 8,240 Pa compared to 7,232 Pa for WMA. There appeared to be no appreciable difference between the fracture work values for HMA and WMA. The average fracture work for HMA was 69,071 N mm compared to 67,997 N mm for WMA. According to the data, the HMA and WMA samples should have comparable bottom-up fatigue cracking resistance.

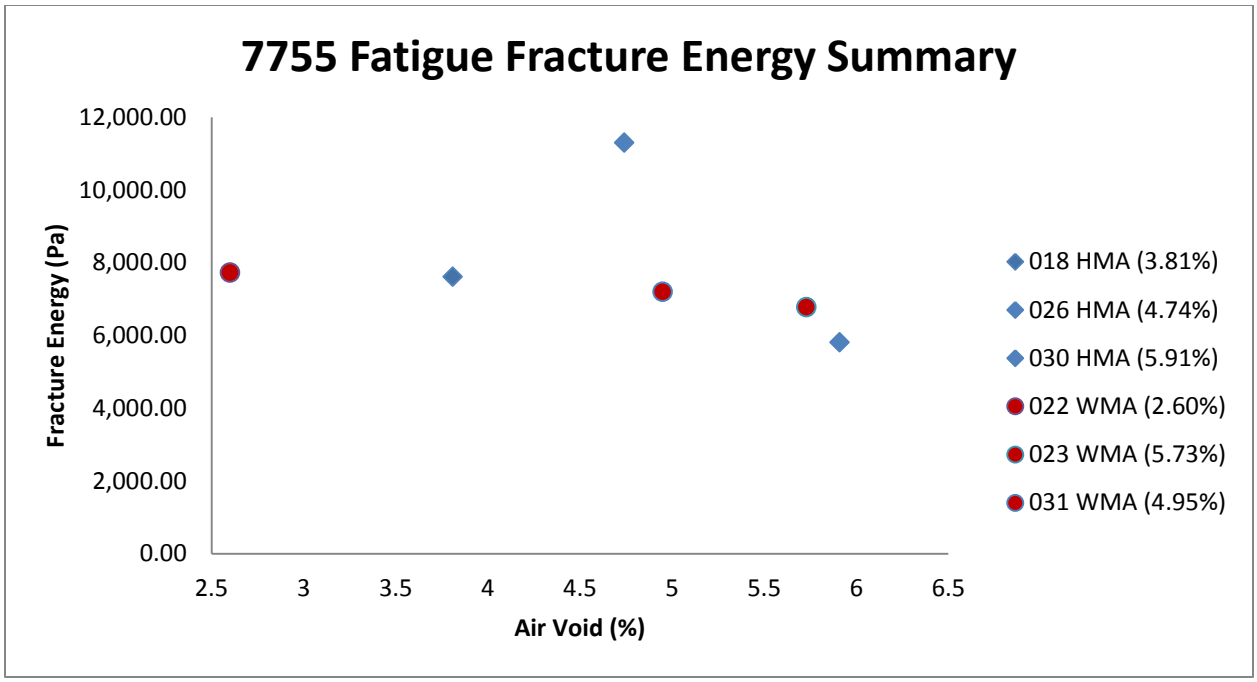

Figure 5-27. Contract 7755 Fatigue Fracture Energy

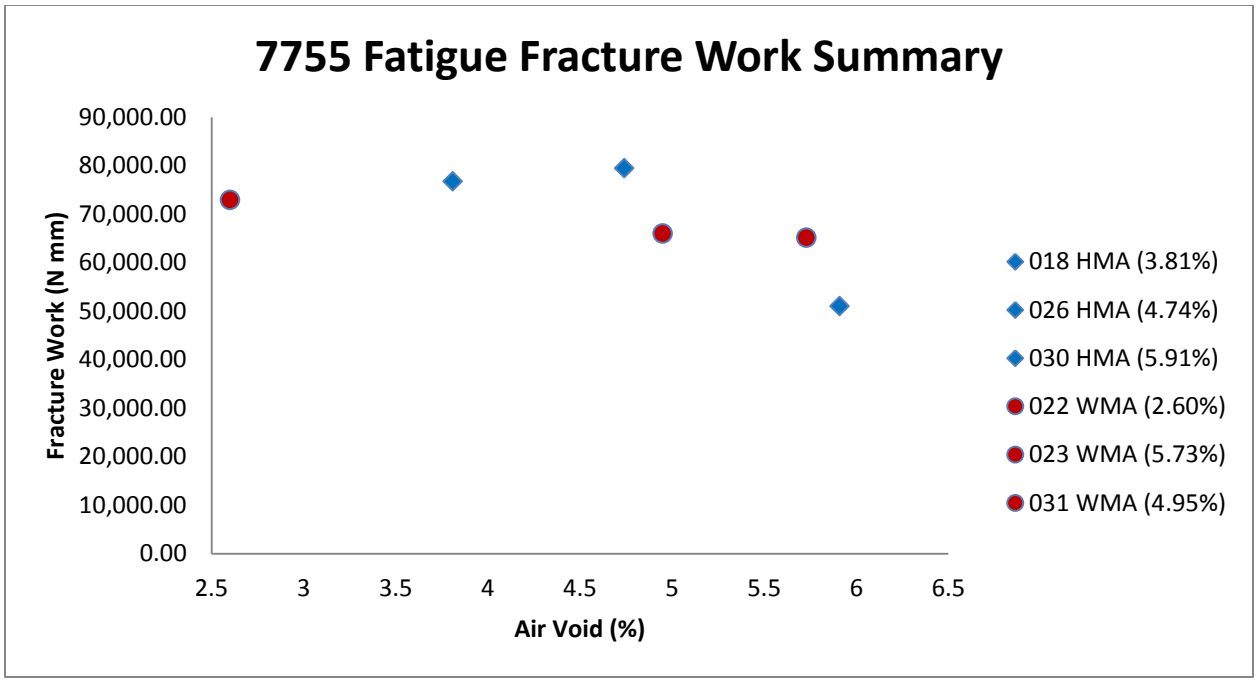

Figure 5-28. Contract 7755 Fatigue Fracture Work

5.3.4 IDT Thermal Cracking

The fracture energy and work values for thermal cracking are displayed in Figures 5-29 and 5-30 respectively. The HMA samples had higher values of fracture energy than WMA. The average fracture energy for HMA was 6,924 Pa compared to 4,221 Pa for WMA. However, the WMA samples had a slightly higher average value of fracture work compared to the HMA samples. The average value of fracture work for HMA was 25,789 N mm compared to 31,767 N mm for WMA. For this particular contract no brittle failures occurred. Instead of the samples failing rapidly, they slowly split apart.

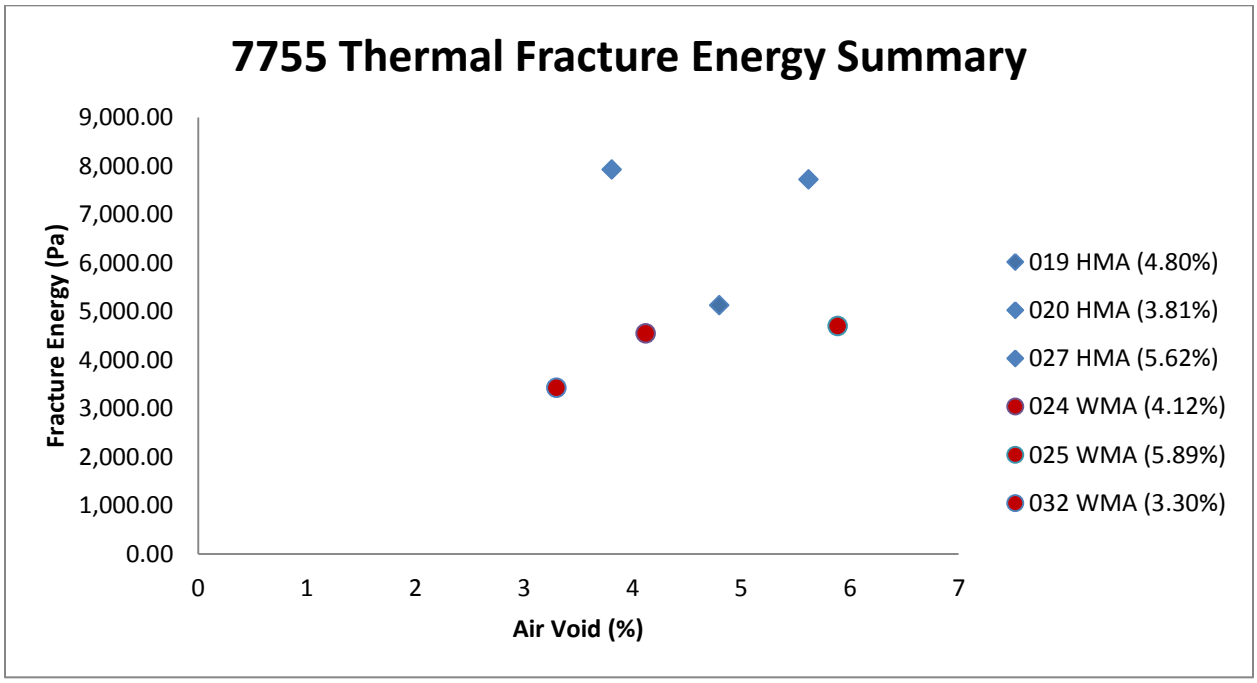

Figure 5-29. Contract 7755 Thermal Fracture Energy

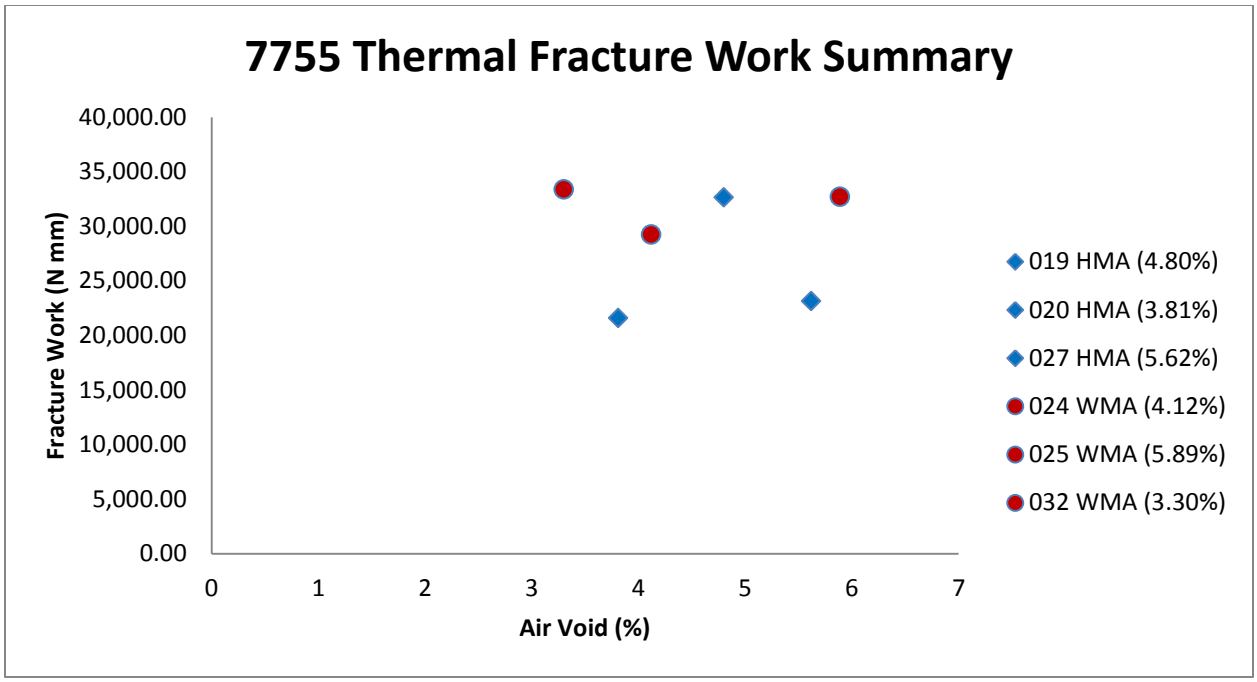

Figure 5-30. Contract 7755 Thermal Fracture Work

5.3.5 Theoretical Maximum Density Verification

Table 5-7. Theoretical Maximum Density Verification for Contract 7755

7755 HMA	
Weight of Pycnometer + Water	8109.6
Dry Weight of Sample	1635.9
Weight of Pycnometer + Sample + Water	9102.9
Gmm	2.545
Gmm from DOT	2.542
7755 WMA	
Weight of Pycnometer + Water	8109.3
Dry Weight of Sample	1702.4
Weight of Pycnometer + Sample + Water	9141.7
Gmm	2.540
Gmm from DOT	2.544

5.3.6 Complex Modulus Frequency Sweep

The complex modulus master curves are shown in Figure 5-31. From the figure it appears that the HMA binder was slightly stiffer at low frequencies or high temperatures. This result is slightly different than the mix result which showed no difference in stiffness between HMA and WMA.

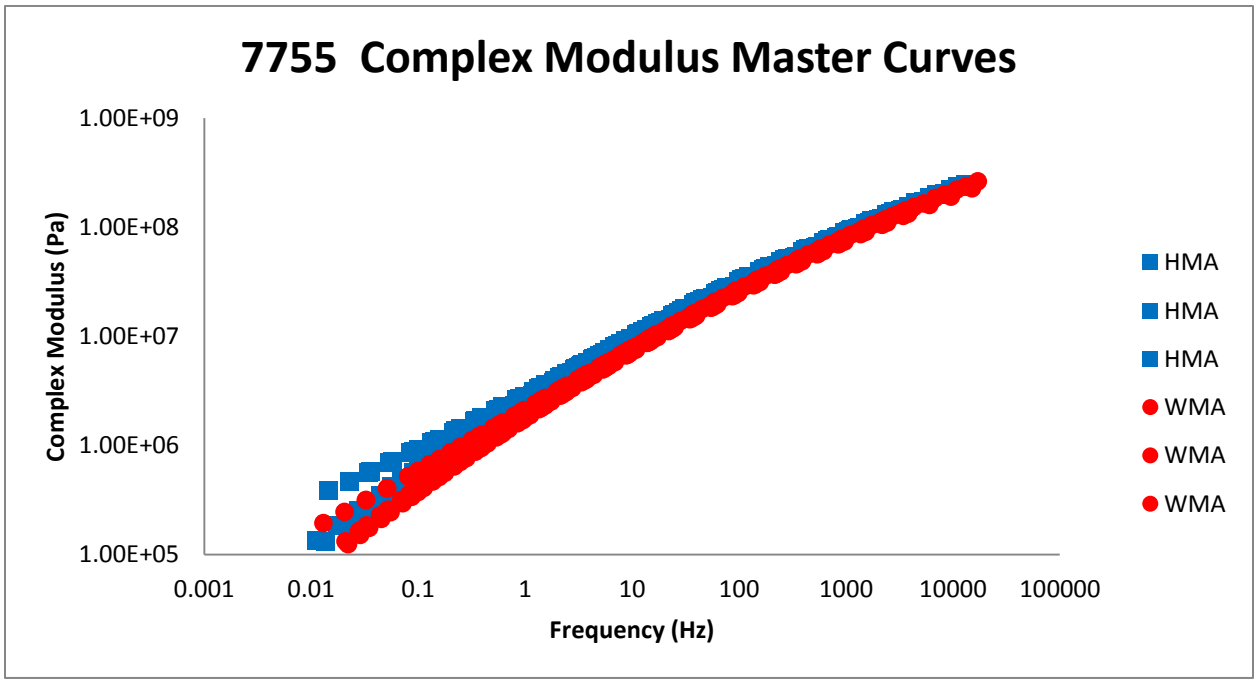

Figure 5-31. Contract 7755 Complex Modulus Master Curves

5.3.7 Multiple Stress Creep Recovery

The results of the multiple stress creep recovery tests with respect to percent recovery and non-recoverable compliance shown in Figures 5-32 and 5-33, respectively. The HMA binder had a higher average percent recovery and lower average value of non-recoverable compliance compared to WMA. The average percent recovery of the HMA was 6.63% compared to 2.89%

for WMA. The average non-recoverable compliance for HMA was 1.09 compared to 2.01 for WMA. This data suggests that the WMA binder would be more susceptible to rutting than HMA.

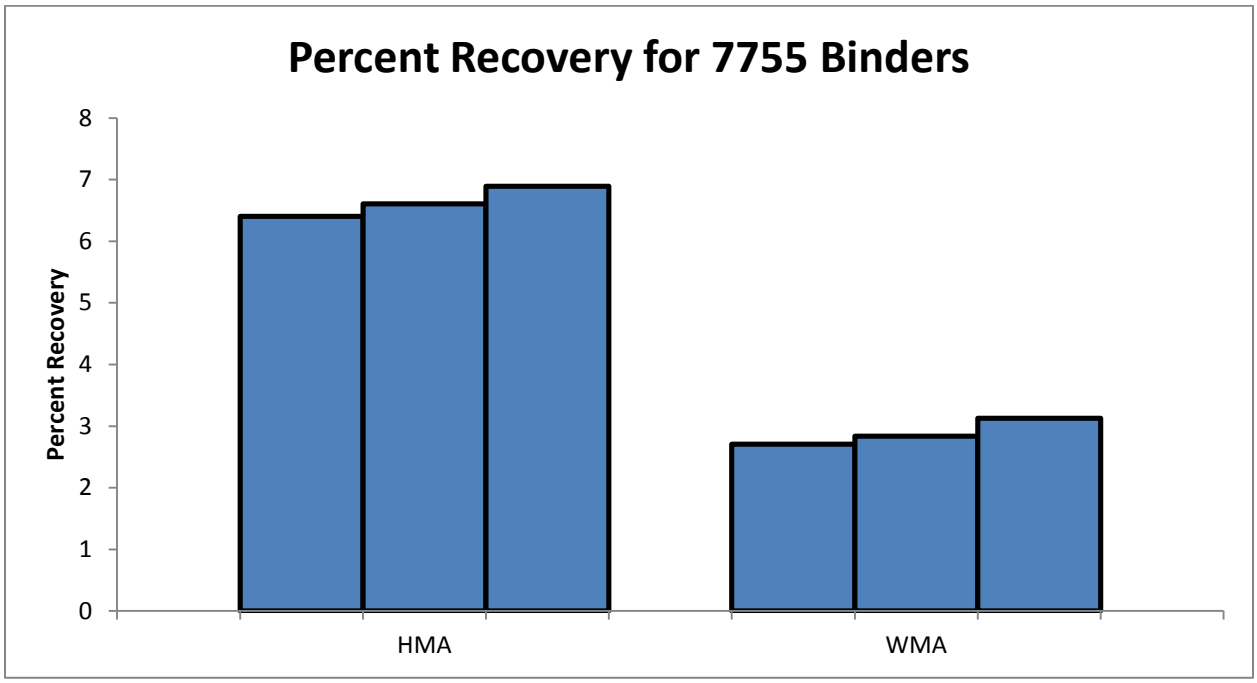

Figure 5-32. Contract 7755 Percent Recovery

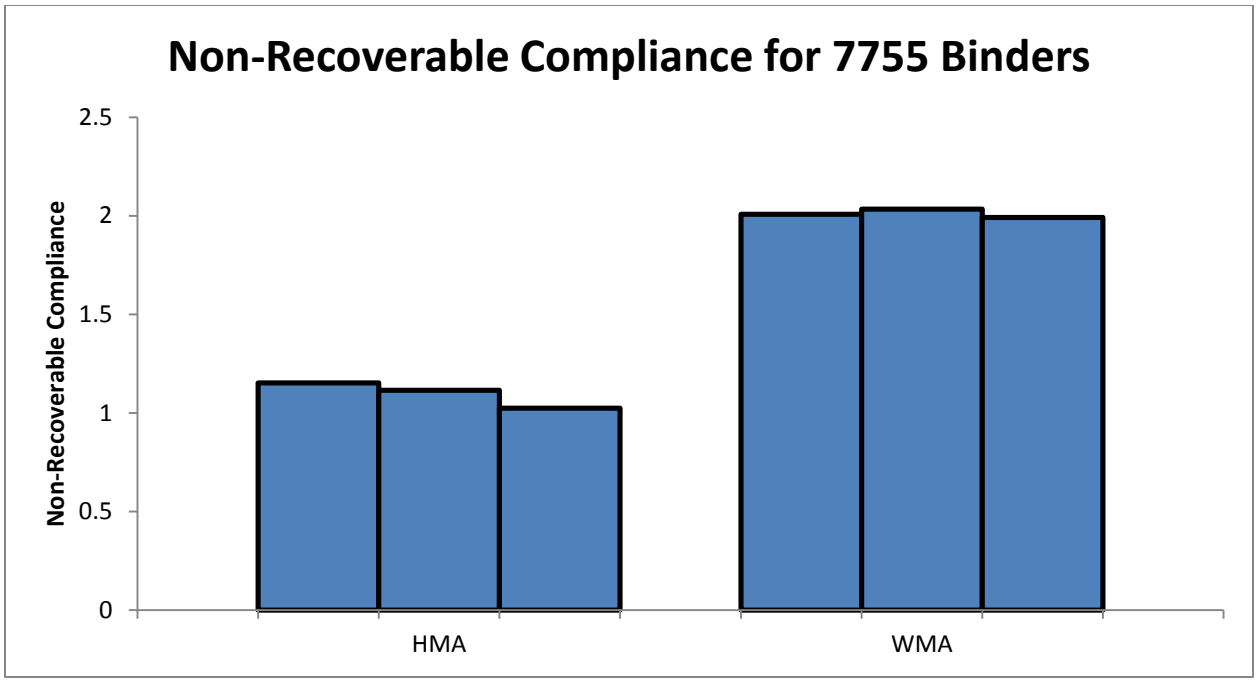

Figure 5-33. Contract 7755 Non-Recoverable Compliance

5.3.8 Monotonic

The average failure strain and fracture energy values for the monotonic binder test at 5°C and 20°C are shown in Figures 5-34 and 5-35, respectively. The failure strain at 5°C for HMA binder was comparable to WMA binder. HMA had an average failure strain of 1.18 while WMA had an average failure strain of 1.12. The fracture energy of HMA was higher at 20°C than WMA. The average fracture energy for HMA was 1, 346 kPa while WMA was 1,107 kPa. The data suggests that the HMA binder would have a greater resistance to bottom-up fatigue cracking than WMA which somewhat disagrees with the mix testing.

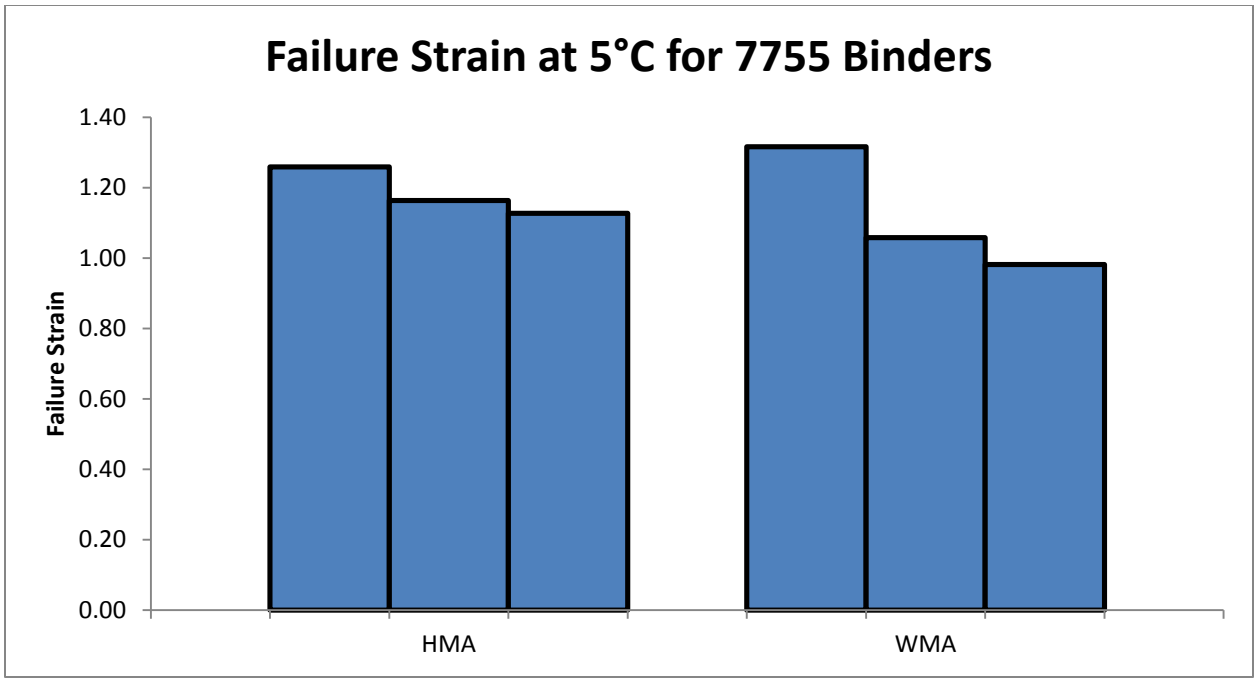

Figure 5-34. Contract 7755 Monotonic Failure Strain at 5°C

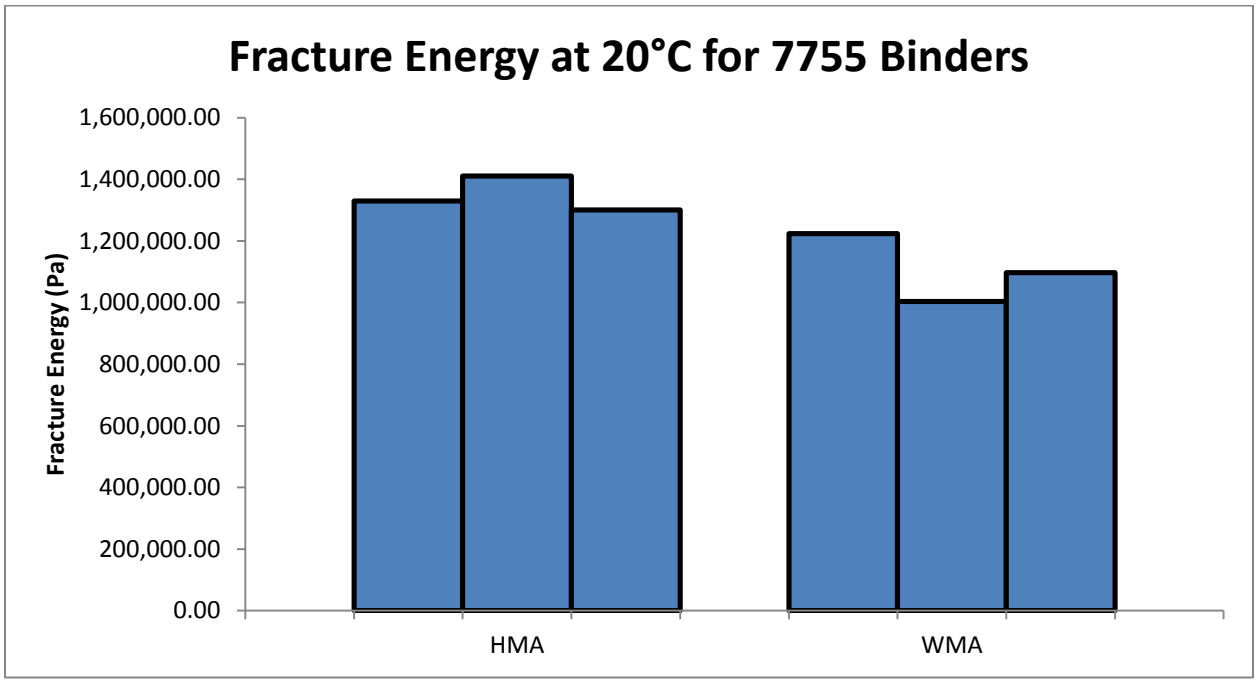

Figure 5-35. Contract 7755 Monotonic Fracture Energy at 20°C

5.3.9 Performance Grading

The performance grading results for HMA and WMA are displayed in Tables 5-8 and 5-9. The binders were originally graded PG 64-28 before construction but were found to be PG 70-22 at the time of this study. From the values of complex modulus and phase angle the HMA binder appeared to be stiffer at high temperatures than the WMA binder.

Table 5-8. Performance Grading Summary for 7755 HMA Binder

	Recovered			PAV		BBR	
Temp	64 C	70 C	76 C	18 C	22 C	-18 C	-12 C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Fail	Pass
G*/sinδ	7.73	3.52	1.65	-	-	-	-
G*•sinδ	-	-	-	6.75	4.88	-	-
m-value	-	-	-	-	-	0.280	0.309
Creep Stiffness	-	-	-	-	-	236.070	140.993

Table 5-9. Performance Grading Summary for 7755 WMA Binder

	Recovered			PAV		BBR	
Temp	64 C	70 C	76 C	18 C	22 C	-18 C	-12 C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Fail	Pass
G*/sinδ	5.22	2.47	1.17	-	-	-	-
G*•sinδ	-	-	-	6.80	4.89	-	-
m-value	-	-	-	-	-	0.257	0.303
Creep Stiffness	-	-	-	-	-	221.853	146.066

5.3.10 Field Performance Comparison

The data for the field performance for contract 7755 was obtained from Segment Viewer in the WSDOT WSPMS system. The average rutting for the HMA section was 0.08” with a standard deviation of 0.01”. The average rutting for the WMA section was 0.08” with a standard

deviation of less than 0.01". The HMA section displayed low severity longitudinal cracking and low severity transverse cracking. The longitudinal cracking occurred in two segments between milepost 194.06 and 194.16, and also between milepost 194.46 and 194.56. The transverse cracking also occurred in two segments between milepost 194.00 and 194.46 and between milepost 194.56 and 194.66. For WMA no cracking was observed. The average IRI value for HMA was 48.98 in/mi with a standard deviation of 5.24 in/mi. For WMA, the average IRI value was 46.62 in/mi with a standard deviation of 2.71 in/mi. The field data shows WMA performed equally as well as HMA with respect to rutting and roughness. However, WMA actually performed better than HMA with respect to top-down fatigue and thermal cracking.

5.3.11 Contract 7755 Summary

From the results of mix testing, HMA and WMA were comparable in stiffness. The binder test results agreed with the mix testing except for at low frequencies or high temperatures where WMA was observed to be slightly less stiff. Overall, HMA and WMA had comparable stiffness. The results of the MSCR test indicate that the WMA binder would be more susceptible to rutting than HMA. The mix test results indicated no appreciable difference between HMA and WMA for bottom-up fatigue cracking resistance. The monotonic binder test for bottom-up fatigue cracking showed that HMA had a slightly higher bottom-up fatigue resistance than WMA. For thermal cracking the mix testing was contradictory with respect to the calculations of fracture energy and work. For the monotonic binder thermal cracking tests HMA and WMA were comparable. Both HMA and WMA binders bumped from an at construction grade of 64-28 to 70-22 at the time of this study. The field performance of WMA was comparable to HMA. WMA performed better than HMA with respect to top-down fatigue and thermal cracking in the

field. Based on the lab binder results, WMA created using the Gencor® Green Machine Ultrafoam GX® may exhibit larger rut depths than traditional HMA.

5.4 CONTRACT 7645 TESTING RESULTS

5.4.1 Dynamic Modulus

The dynamic modulus master curves are displayed in Figure 5-36. From the plot of the curves it does not appear that there is any significant difference in the stiffness of the mixes.

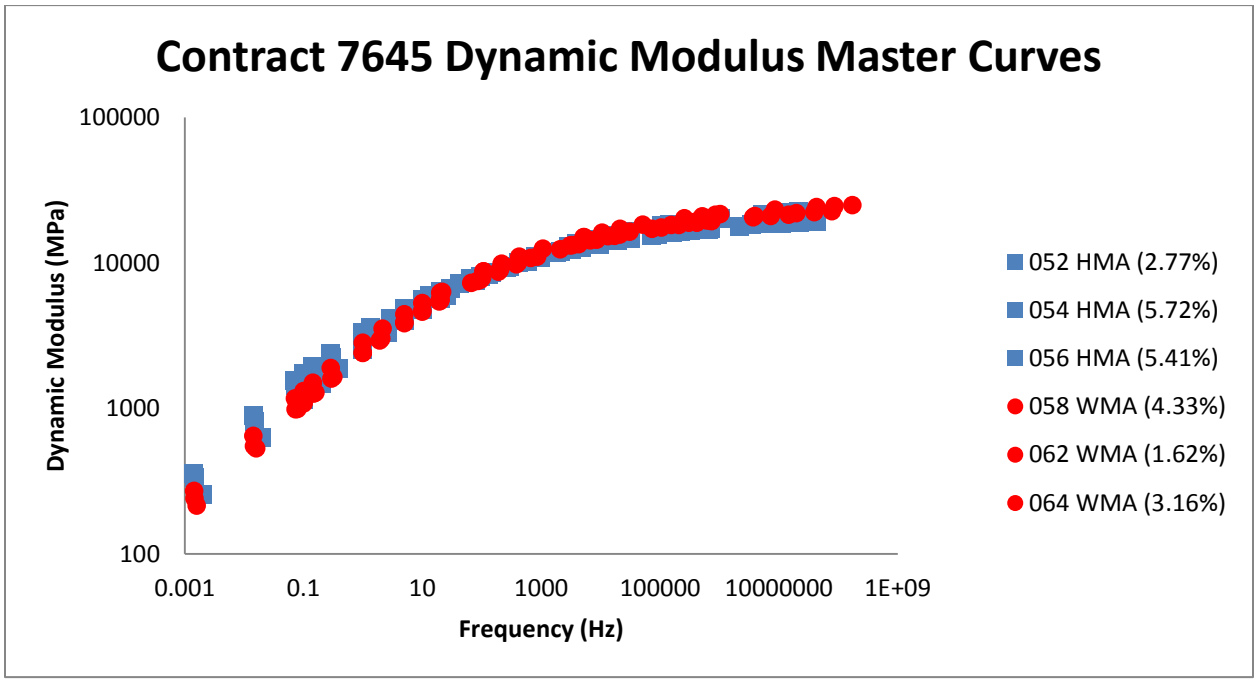

Figure 5-36. Contract 7645 Dynamic Modulus Master Curves

5.4.2 Creep Compliance Mix Test Results

The creep compliance master curves can be seen in Figure 5-37. Aside from one outlier WMA sample, the stiffness of the HMA and WMA samples was comparable.

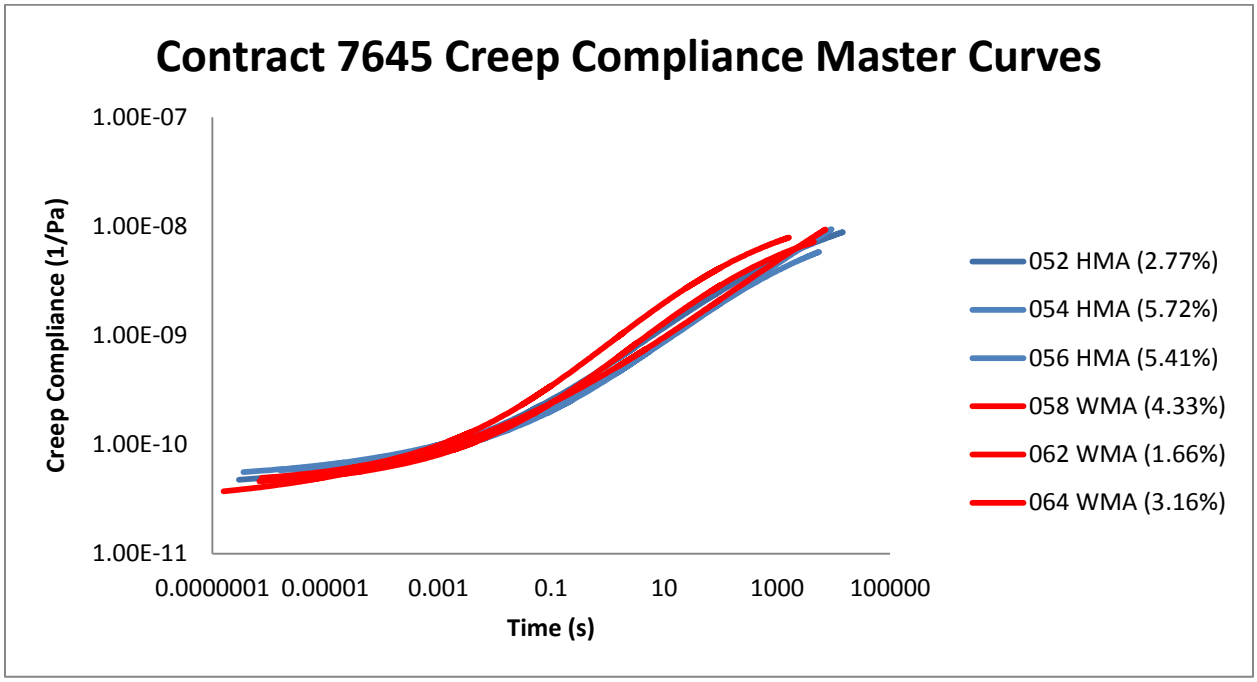

Figure 5-37. Contract 7645 Creep Compliance Master Curves

5.4.3 IDT Fatigue Cracking

The results of the IDT fatigue cracking tests are shown in Figures 5-38 and 5-39 for fracture energy and fracture work, respectively. The fracture energy values were comparable with an average value of HMA at 8,219 Pa and WMA at 8,421 Pa. With respect to fracture work the HMA samples had a slightly higher average value of 71,491 N mm compared to a value of 68,786 N mm for WMA. The bottom-up fatigue cracking resistance of HMA and WMA is comparable.

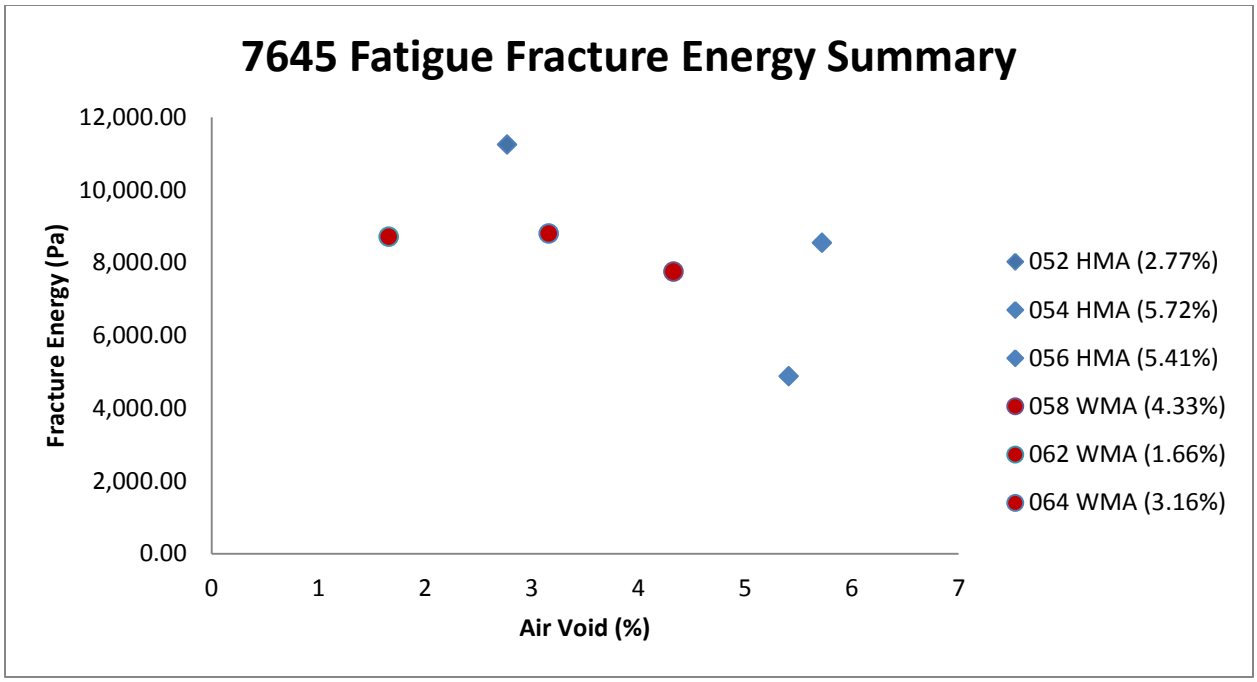

Figure 5-38. Contract 7645 Fatigue Fracture Energy

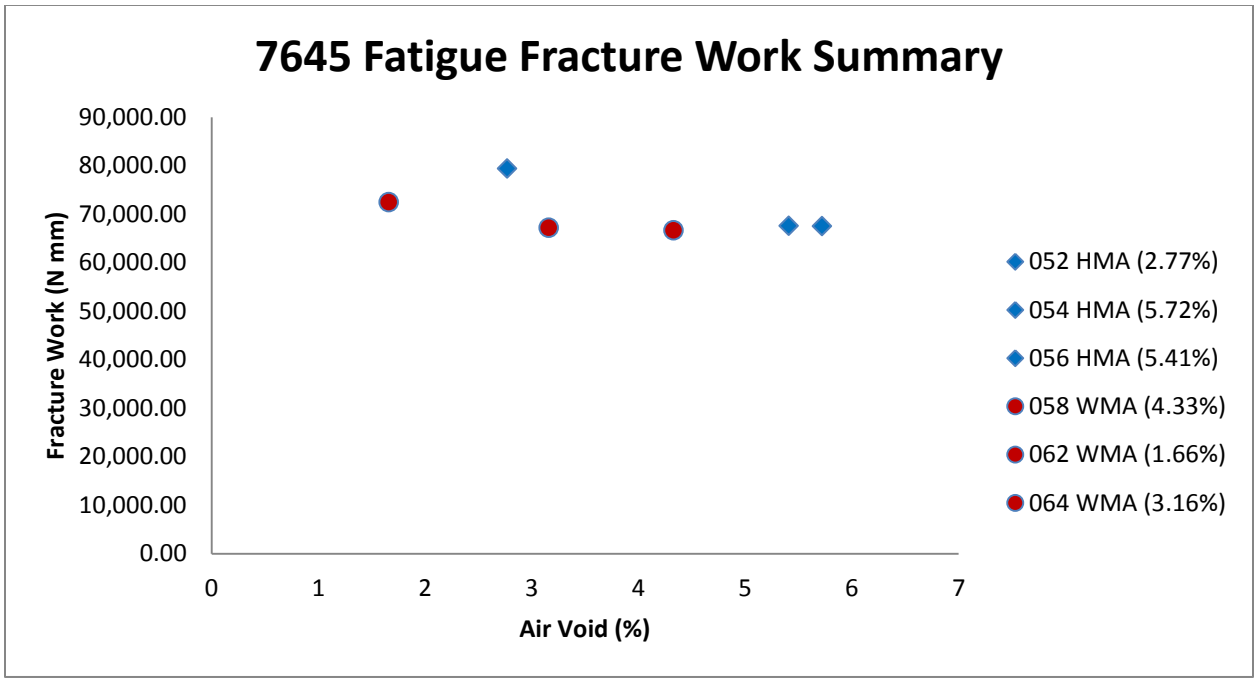

Figure 5-39. Contract 7645 Fatigue Fracture Work

5.4.4 IDT Thermal Cracking

The results of the IDT thermal cracking tests are shown in Figures 5-40 and 5-41 for fracture energy and fracture work, respectively. WMA had higher values of both fracture energy and fracture work than HMA. The average value of fracture energy for WMA was 9,699 Pa compared to 6,933 for HMA. The average values of fracture work for WMA and HMA were 42,722 and 27,908 N mm respectively. WMA appears to have a higher resistance to thermal cracking over HMA.

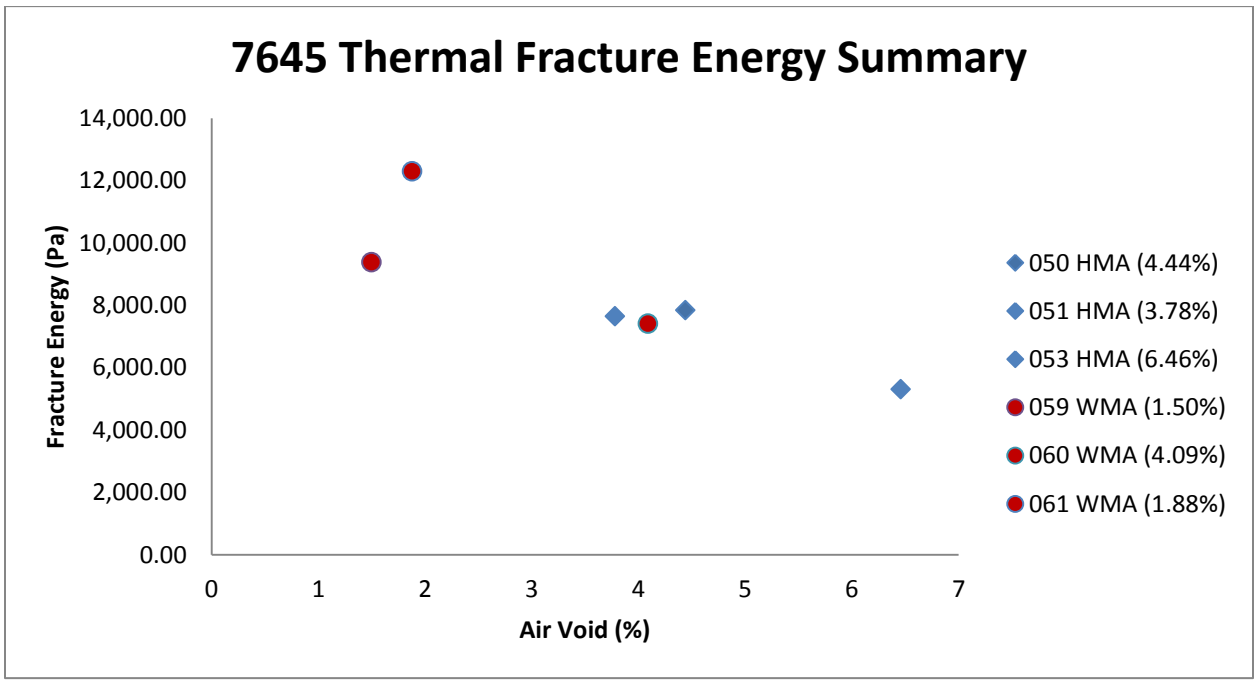

Figure 5-40. Contract 7645 Thermal Fracture Energy

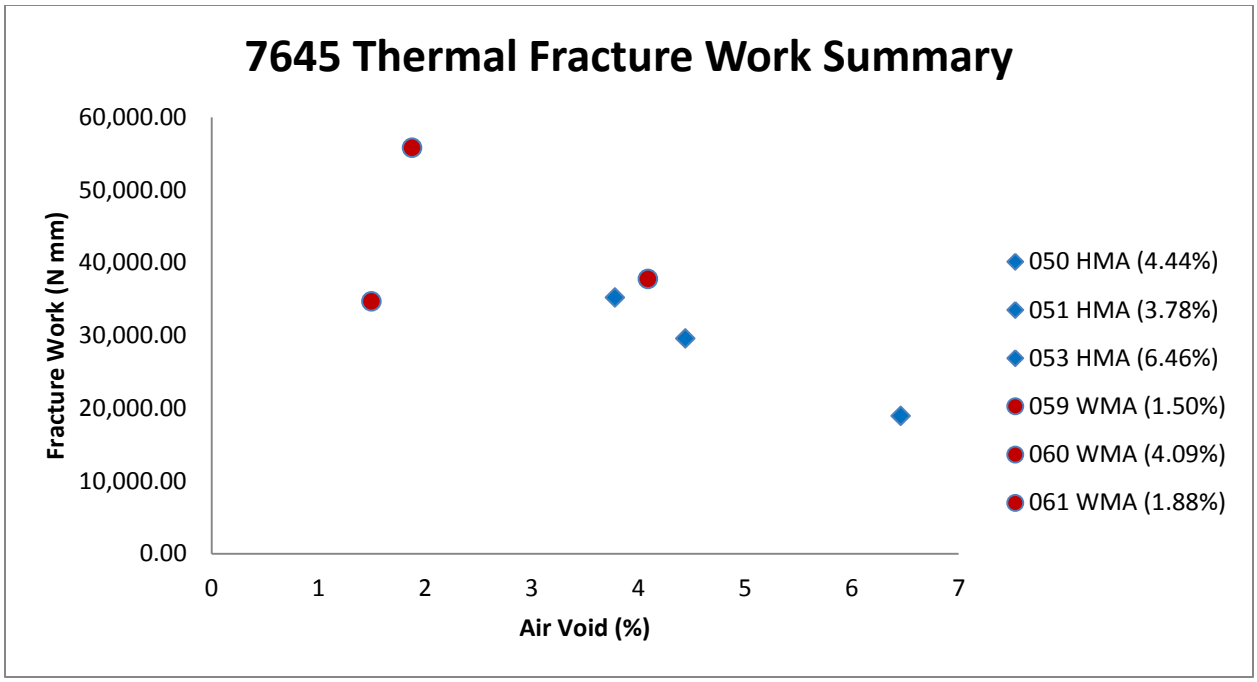

Figure 5-41. Contract 7645 Thermal Fracture Work

5.4.5 Theoretical Maximum Density Verification Results

Table 5-10. Theoretical Maximum Density Verification for Contract 7645

7645 HMA	
Weight of Pycnometer + Water	8109.3
Dry Weight of Sample	1747.3
Weight of Pycnometer + Sample + Water	9181.2
Gmm	2.587
Gmm from DOT	2.590
7645 WMA	
Weight of Pycnometer + Water	8109.3
Dry Weight of Sample	1741.2
Weight of Pycnometer + Sample + Water	9176.1
Gmm	2.582
Gmm from DOT	2.590

5.4.6 Complex Modulus Frequency Sweep

Figure 5-42 shows the complex modulus master curves for HMA and WMA binders. From the figure it does not appear that there is any significant difference in stiffness between the two binders. This data agrees with the mix stiffness data.

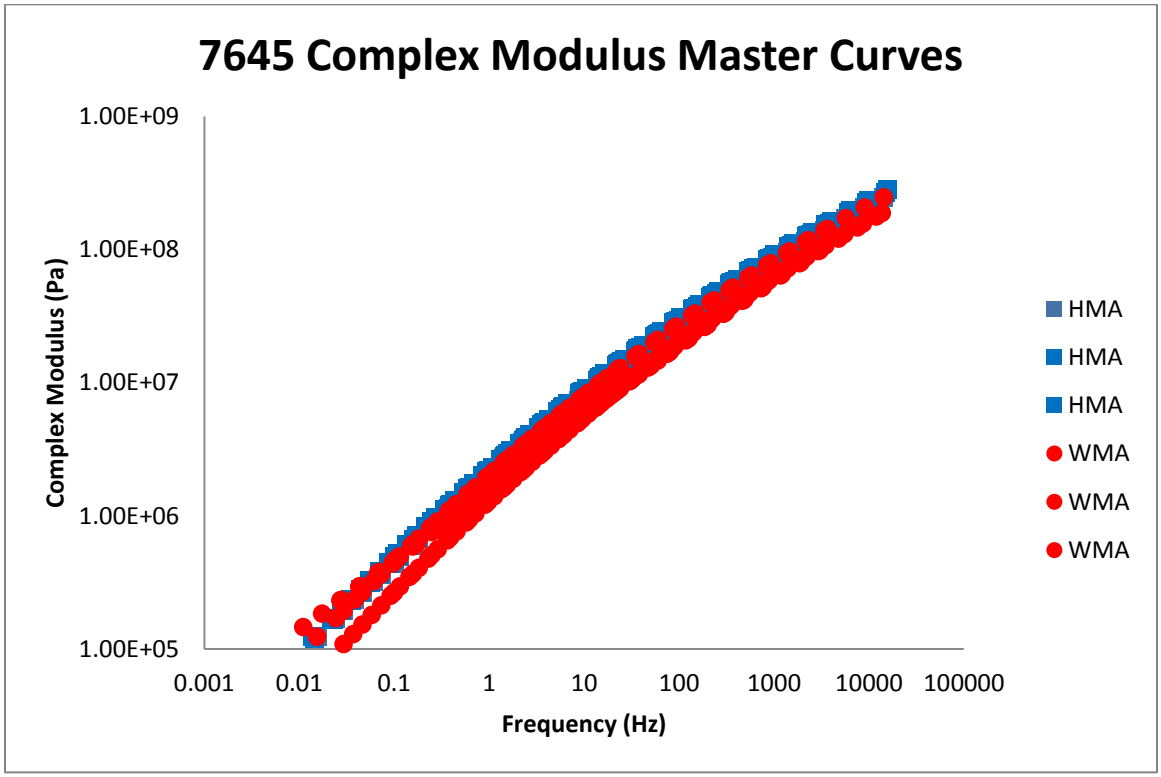

Figure 5-42. Contract 7645 Complex Modulus Master Curves

5.4.7 Multiple Stress Creep Recovery

The percent recovery and non-recoverable compliance results from the MSCR test are shown in Figures 5-43 and 5-44, respectively. HMA binder had a higher percent recovery and lower value of non-recoverable compliance compared to WMA. The average percent recovery at the 3200 Pa stress level for HMA was close to 20% while WMA was around 9.8%. The average

non-recoverable compliance value at the 3200 Pa stress level for HMA was about 0.84 while WMA was 1.76. The data suggests that the WMA binder is more susceptible to rutting than HMA binder.

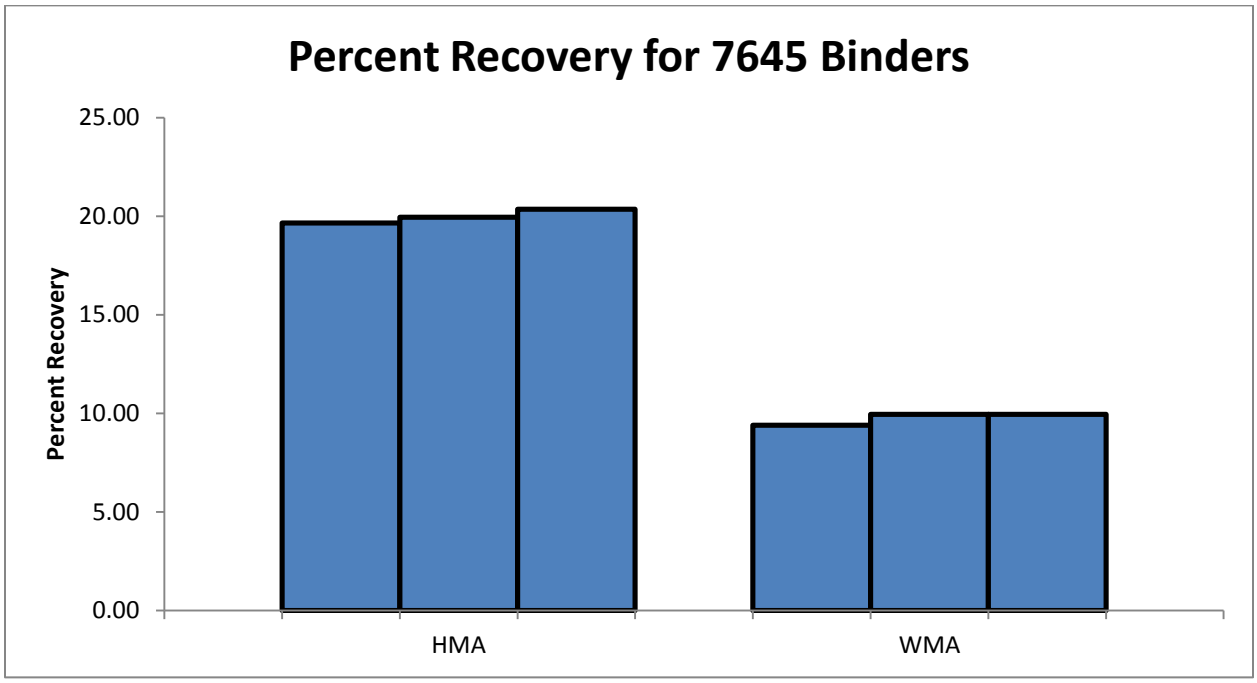

Figure 5-43. Contract 7645 Percent Recovery

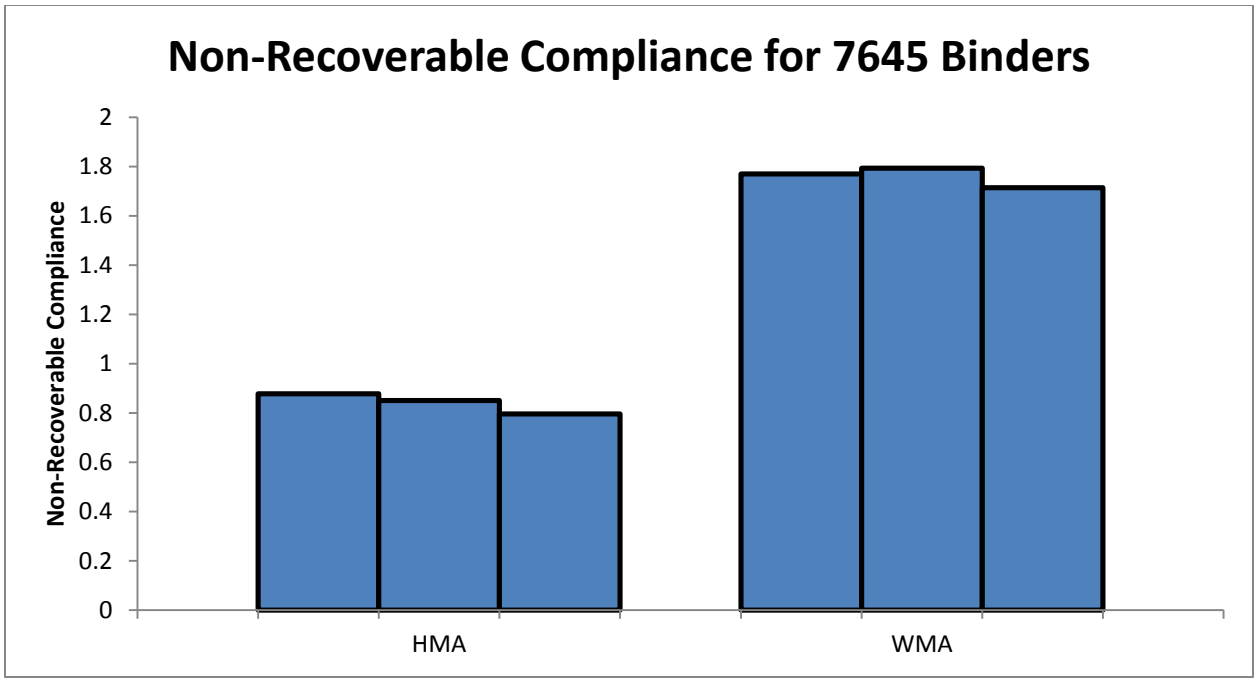

Figure 5-44. Contract 7645 Non-Recoverable Compliance

5.4.8 Monotonic

Figures 5-45 and 5-46 show the results from the monotonic binder test at 10 and 20°C, respectively. At low temperatures HMA binder had a close failure strain to that of WMA binder. The average failure strain for HMA at 10°C was 6.84 compared to 6.52 for WMA. At 20°C HMA binder had higher average fracture energy than WMA binder. The average fracture energy at 20°C for HMA was 9,197 kPa and 5,056 kPa for WMA. The data suggests that HMA would have higher bottom-up fatigue and thermal cracking resistance than WMA. The results do not agree with the fatigue or thermal cracking testing results on mixes.

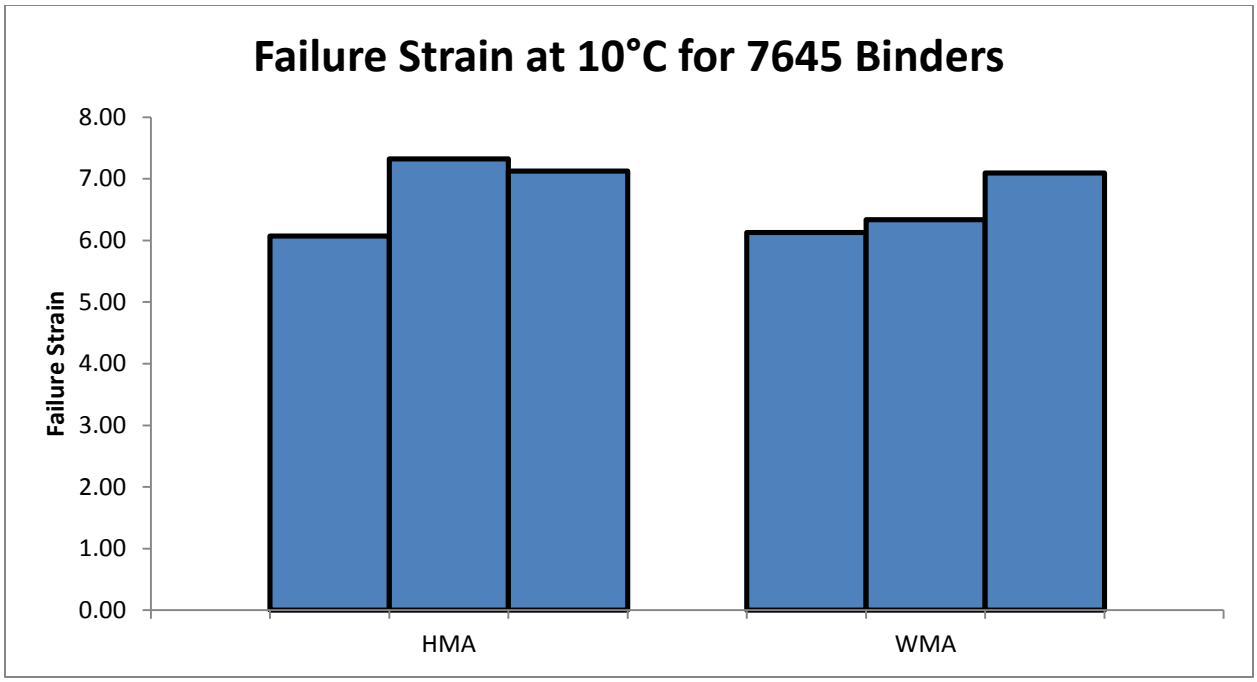

Figure 5-45. Contract 7645 Monotonic Failure Strain at 10°C

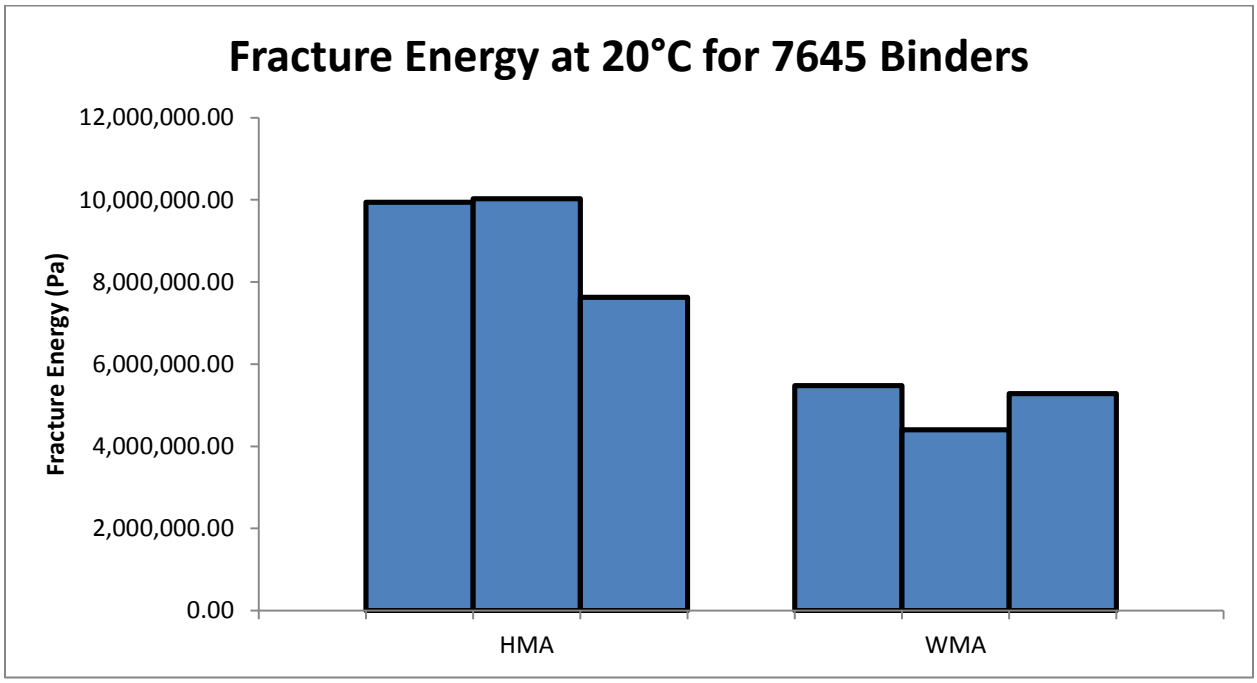

Figure 5-46. Contract 7645 Monotonic Fracture Energy at 20°C

5.4.9 Performance Grading

The results of the performance grading for both HMA and WMA binders are shown in Tables 5-11 and 5-12. Both HMA and WMA binders bumped one high and low temperature grade from 64-28 to 70-22. From the values of complex modulus and phase angle it appears as though the HMA binder was stiffer than the WMA.

Table 5-11. Performance Grading Summary for 7645 HMA Binder

	Recovered			PAV		BBR
Temp	64 C	70 C	76 C	22 C	25 C	-12 C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Pass
G*/sinδ	8.44	4.09	2.08	-	-	-
G*•sinδ	-	-	-	5.38	3.91	-
m-value	-	-	-	-	-	0.328
Creep Stiffness	-	-	-	-	-	130.477

Table 5-12. Performance Grading Summary for 7645 WMA Binder

	Recovered			PAV		BBR	
Temp	64 C	70 C	76 C	19 C	22 C	-18 C	-12 C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Fail	Pass
G*/sinδ	4.69	2.34	1.17	-	-	-	-
G*•sinδ	-	-	-	5.97	4.25	-	-
m-value	-	-	-	-	-	0.293	0.326
Creep Stiffness	-	-	-	-	-	219.039	121.979

5.4.10 Field Performance Comparison

The data for the field performance for contract 7645 was obtained from Segment Viewer in the WSDOT WSPMS system. The average rutting for the HMA section was 0.10” with a

standard deviation of 0.02”. The average rutting for the WMA section was 0.09” with a standard deviation of 0.01”. The HMA and WMA section did not exhibit any longitudinal cracking. The HMA section displayed low severity transverse cracking throughout the entire 0.2 mile segment. The WMA also experienced low severity transverse cracking throughout the 0.2 mile segment except for the last 0.03 miles. The average IRI value for HMA was 52.10 in/mi for HMA with a standard deviation of 6.63 in/mi. For WMA the average IRI value was 60.82 in/mi with a standard deviation of 4.42 in/mi. The field data shows WMA performed equally as well as HMA.

5.4.11 Contract 7645 Summary

From the results of the mix tests there did not appear to be any significant difference between the stiffness of HMA and WMA. The complex modulus binder testing seems to agree with the mix tests. It appears the stiffness of HMA and WMA are comparable. From MSCR binder testing it is apparent that the HMA will have a much higher rut resistance than WMA. From mix testing HMA and WMA showed similar bottom-up fatigue cracking resistance. The monotonic binder testing for fatigue cracking contradicted these results, showing that HMA had a higher resistance to bottom-up fatigue cracking than WMA. The mix test results indicate that WMA has a higher thermal cracking resistance than HMA. The monotonic binder thermal cracking test results conflict with these results. Both HMA and WMA binders were bumped one high and low temperature grade from the time of construction. The field performance of WMA was comparable to HMA. The lab binder test results suggest that WMA prepared by water injection will have larger rut depths but will be more resistant to thermal cracking than HMA.

CHAPTER 6: OVERALL SUMMARY OF WMA PERFORMANCE AND CONCLUSIONS

6.1 STIFFNESS TESTS

The results of the mix stiffness tests were fairly consistent. Aside from a few outliers the stiffness values from dynamic modulus and creep compliance testing were comparable between HMA and WMA. With the exception of contracts 7419 and 7755 the complex modulus binder stiffness tests agreed with the results of the mix stiffness tests. Contract 7419 WMA binder appeared to be softer than the HMA binder which did not agree with the mix stiffness results. Contract 7755 binder also appeared to be slightly softer than the HMA binder however only at high temperatures. Overall, even with these slight contradictions it appears that the stiffness of HMA and WMA mixes is comparable.

6.2 FATIGUE CRACKING TESTS

Aside from contract 7419, all WMA and HMA samples had comparable bottom-up fatigue cracking resistance from mix test results. For contract 7419, HMA showed slightly higher bottom-up fatigue cracking resistance from the IDT mix results. For binder fatigue cracking tests, HMA binder had higher average fracture energy values than WMA binder for all contracts. Contract 7419 HMA binder had the highest difference in fracture energy from WMA binder. All other differences between fracture energy for HMA and WMA binders were fairly small. The results suggest that WMA produced with water foaming processes will have comparable bottom-up fatigue cracking resistance to HMA. The lab test results indicate that WMA created with Sasobit® could have a lower bottom-up fatigue cracking resistance to HMA.

6.3 THERMAL CRACKING TESTS

The results of the thermal cracking tests were different for each contract. For contract 7474 HMA showed a slightly higher resistance to thermal cracking than WMA from mix tests. Contract 7419 HMA and WMA showed comparable thermal cracking resistance from mix testing. For contract 7755 the calculations of fracture energy and work for mix testing contradicted each other. Contract 7645 WMA showed a greater resistance to thermal cracking than HMA through mix testing. With the exception of contracts 7474 and 7419, for monotonic binder thermal cracking tests HMA binder had higher average failure strains than WMA binder, indicating higher thermal cracking resistance. The differences between failure strains for the binder tests were generally small. Based on the field results WMA is performing equally as well and in some cases better with respect to thermal cracking than HMA. Based on the laboratory results and field observations, water foaming WMA technologies and Sasobit® WMA specifically, should have comparable thermal cracking resistance to HMA.

6.4 MULTIPLE STRESS CREEP RECOVERY BINDER RUTTING TESTS

With the exception of contract 7419, All WMA binders tested with the MSCR test displayed lower values of percent recovery and higher values of non-recoverable compliance compared to the HMA control binders. Contract 7419 WMA displayed similar values of percent recovery compared to HMA binder. Even though WMA had a comparable percent recovery for contract 7419 it also had a slightly higher non-recoverable compliance. Contract 7474 WMA showed just slightly worse values of percent recovery and non-recoverable compliance compared to the control HMA binder. Contracts 7755 and 7645 displayed the worst rut resistance, with around half the value of percent recovery and double the value of non-recoverable compliance

compared to control HMA binder. Based on the lab results, it appears that WMA produced with water foaming processes will have lower rut resistance than HMA even though field performance to date does not show differences in rutting. WMA produced with the organic additive Sasobit® will likely have a slightly lower rut resistance compared to HMA.

6.5 FIELD PERFORMANCE

In all cases in this study the WMA projects performed equally as well or better than the HMA control in the field. The WMA in all contracts had similar rut depths to HMA. With respect to fatigue and thermal cracking, contract 7419 (Sasobit®) and 7755 (Gencor® Green Machine Ultrafoam GX®) WMA actually displayed no cracking while the HMA control sections had low severity transverse and longitudinal cracks. The IRI roughness values for HMA and WMA of all contracts were also comparable. All contracts were constructed within the past 3 years so no definite conclusions about the long-term field performance of WMA can be made. However, at this time it appears all the WMA technologies observed are performing equally as well as HMA in the field.

6.6 AIR VOID STATISTICAL ANALYSIS RESULTS

A statistical analysis was performed based on the field air voids from each contract. The goal was to determine if the air voids in the HMA sections were statistically different from WMA sections. A two sample two-tailed t-test assuming equal variances with an alpha value of 0.05 was used for the analysis. Air voids were compared between HMA and WMA measured after construction and also between air void measurements taken at the time of this study for each contract.

The results of the statistical analysis for air voids of HMA and WMA measured after construction indicated that no contract had HMA and WMA air void measurements that were statistically different. It is important to note that contract 7474 was excluded from this analysis due to lack of data. Contract 7755 had a fairly low p-value of 0.065, however.

The results of the statistical analysis for air voids of HMA and WMA measured at the time of this study indicated that contracts 7474 and 7645 had statistically different air void values between HMA and WMA specimens. The p-value for contract 7474 was found to be 0.041. The mean air void measurement for HMA was 3.63 compared to 2.53 for WMA. The p-value for contract 7645 was 0.008. The mean air void measurement for HMA was 4.66 compared to 2.85 for WMA.

The results of the analysis seem to suggest that some WMA technologies may compact in the field faster than HMA. The results seem to agree with literature review findings that WMA can reach equivalent densities of HMA with less energy.

6.7 CONCLUSIONS

Various water foaming WMA technologies including the Gencor® Green Machine Ultrafoam GX®, Aquablack™ and water injection were analyzed along with the organic additive technology, Sasobit®. Based on results from mix and binder testing, all these WMA technologies should have comparable mix stiffness to traditional HMA. Lab results suggest the fatigue cracking resistance of the WMA technologies should be comparable with HMA with the exception of Sasobit® which may have a slightly lower fatigue cracking resistance than HMA. With the exception of Aquablack™, the water foaming technologies should have higher resistance to thermal cracking than HMA. Sasobit® has comparable thermal cracking resistance

to HMA and Aquablack™ has slightly worse thermal cracking resistance than HMA. The water foaming WMA technologies have less rutting resistance than HMA, especially WMA produced by the Gencor® Green Machine Ultrafoam GX® and straight water injection. Sasobit® appears to be the most promising WMA technology with respect to rutting with a rut resistance only slightly less than HMA. All the WMA technologies observed are performing as well or better than HMA in the field to date. Sasobit® and the Gencor® Green Machine Ultrafoam GX® appear to have better thermal and longitudinal cracking resistance in the field. However, these field observations cannot be extrapolated to long-term performance as all the projects were constructed in the past three years. Due to their increased rutting susceptibility, WMA produced through water foaming may be an adequate substitution for HMA in mild cooler climates while a technology like Sasobit® may be more appropriate for use in warmer areas because of its similar rut resistance to HMA. Due to the strengths and weakness of each WMA technology, great care should be taken in considering whether WMA is appropriate or choosing the correct technology for a particular job.

CHAPTER 7: REFERENCES

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