Evaluation of the Performance of Warm Mix Asphalt in Washington State

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Warm mix asphalt (WMA) is a relatively new and emerging technology for the asphalt industry. It offers potential construction and environmental advantages over traditional hot mix asphalt (HMA). However, WMA must perform at least as well as HMA before it can be used to replace HMA. This study evaluates the performance of HMA and WMA mixes obtained from various field sites in the state of Washington. Different WMA technologies are examined in four separate projects; these technologies include Sasobit® and three water foaming technologies, Gencor® Green Machine Ultrafoam GX®, Aquablack™ and water injection. Performance tests are conducted on the cores and extracted binders to evaluate the resistance of HMA and WMA samples to fatigue and thermal cracking, rutting and moisture susceptibility. Additionally, the early-age field performance of WMA and HMA control pavements is compared.

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ABSTRACT

Warm mix asphalt (WMA) is a relatively new and emerging technology for the asphalt industry. It offers potential construction and environmental advantages over traditional hot mix asphalt (HMA). However, WMA must perform at least as well as HMA before it can be used to replace HMA. This study evaluates the performance of HMA and WMA mixes obtained from various field sites in the state of Washington. Different WMA technologies are examined in four separate projects; these technologies include Sasobit® and three water foaming technologies, Gencor® Green Machine Ultrafoam GX®, Aquablack™ and water injection. Performance tests are conducted on the cores and extracted binders to evaluate the resistance of HMA and WMA samples to fatigue and thermal cracking, rutting and moisture susceptibility. Additionally, the early-age field performance of WMA and HMA control pavements is compared.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The pavement industry stresses the importance of incorporating sustainable practices into pavement design for many reasons (Austerman et al. 2009). One technology that helps to address these issues by lowering fuel costs and reducing greenhouse gas emissions is warm mix asphalt (WMA).

WMA originated in Europe and has been used only recently in the United States (Wasiuddin et al. 2007). WMA can be produced using several different technologies that can lower the temperatures at which asphalt mixes are mixed and compacted. This objective is accomplished by either lowering the viscosity of the asphalt binder or improving the workability of the asphalt mix at temperatures lower than those used to produce traditional hot mix asphalt (HMA). Traditional HMA mixes must be heated to temperatures around 300°F or higher, whereas WMA mixes can be heated to around 250°F or even lower (Hurley and Prowell 2005).

WMA has several advantages over HMA. Due to the relatively low temperatures required to heat the asphalt for mixing, the use of WMA can lead to lower plant emissions and reduced fuel costs (Neitzke and Wasill 2009). The relatively low mixing temperatures for WMA help to reduce fumes. Furthermore, higher percentages of recycled asphalt pavement (RAP) can be incorporated into WMA mixes than into HMA mixes due to reduced aging to the virgin asphalt binder, which adds to WMA's environmental advantages (Button et al. 2007). WMA also can be paved in cold seasons if necessary because it remains more workable at lower temperatures than HMA. WMA mixes also can be transported longer distances than HMA, likewise due to the fact

that the mix can stay workable for longer periods. This increased workability of WMA can also lead to better density in the field (Hurley and Prowell 2006).

Three categories of WMA technologies are used in practice: organic additives, chemical additives and foaming. Each of these processes helps improve the workability of the mix at low temperatures in different ways. Organic additives use long chain hydrocarbons that have lower viscosity values at elevated temperatures compared to traditional asphalt. Chemical additives generally improve coating, mixture workability, and compaction by the use of emulsification agent. Lastly, water can be added to asphalt binder to create WMA in a unique process called *foaming*. When water comes in contact with the hot asphalt, small bubbles form in the binder, which causes a decrease in viscosity (Hodo et al. 2009).

The use of WMA, however, must not compromise the structural performance of the pavement. WMA technologies affect the properties of mixes (1) directly through the effects on the binder (e.g. reduced aging), aggregate and/or reclaimed asphalt pavement (RAP) (e.g., less drying) or affinity of the binder with the aggregate, and (2) indirectly through the effect on the density of the mix during compaction or under traffic loads. As previously stated, WMA is a relatively new technology in the United States, and long-term field performance assessments of WMA pavements have yet to be completed. One approach to predicting the field performance of pavements is to characterize the laboratory properties of WMA and HMA that have been proven to correlate with field performance.

1.2 RESEARCH OBJECTIVES

The primary objective of this study is to evaluate the performance of WMA via laboratory performance tests and the early-stage performance of pavements in the field.

Performance tests were conducted in the laboratory on HMA and WMA field cores and asphalt binders extracted from field cores. Field distress data were obtained for each of the pavements. The results of the laboratory tests and field distress data were compared between HMA and WMA samples to assess the performance of the WMA mixes.

1.3 ORGANIZATION OF REPORT

This study describes the performance evaluation of WMA in Washington State. Chapter 1 introduces the background of WMA. Chapter 2 includes an in-depth literature review of WMA, with an emphasis on performance. Chapter 3 presents background information about the study itself as well as the preparation of samples for testing and test procedures. Chapter 4 presents and discusses the test results for each project as well as field performance. Finally, Chapter 5 summarizes the test results in terms of stiffness, fatigue cracking, rutting, moisture susceptibility, and thermal cracking, as well as the early-stage field performance, and presents final conclusions. Chapter 6 provides a list of references.

CHAPTER 2: LITERATURE REVIEW

2.1 WMA TECHNOLOGIES

A number of different processes are available that can produce WMA. Each of these processes involves combining an additive, such as water, a chemical or organic compound, with the binder or mix. These technologies are discussed in the following sections.

2.1.1 Organic Additives

Sasobit® is a wax additive made via Fischer-Tropsch synthesis (D'Angelo et al. 2008) by the Sasol Wax Corporation. The wax has hydrocarbon chains of around 100 carbon atoms (Hurley and Prowell 2005). These long hydrocarbon chains greatly increase the melting point of the wax, which allows Sasobit® to be fully soluble in asphalt above 239°F (Kanitpong et al. 2007). Once Sasobit® fully melts into the asphalt, it forms a homogeneous 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). Sasobit® can be added directly to the asphalt binder or asphalt mix (D'Angelo et al. 2008). Sasol, the developer of Sasobit®, suggests adding 0.8% to 3% Sasobit® by the weight of the binder. Sasobit® can be added easily 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 a form of naturally occurring lake asphalt (Martin et al. 2011) and was used in the first asphalt pavements in the United States over a hundred years ago (West et al. 2010). It is mined from lake

deposits 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 moisture. TLA is highly resistant to cracking and permanent deformation, is easily blended with traditional asphalt binders, maintains a high stability level in asphalt mixtures and provides good adhesion with aggregate particles when used as an asphalt binder. For these reasons, Lake Asphalt of Trinidad and Tobago, Ltd. developed a mixture of TLA and rheological modifiers to produce TLA-X as a WMA additive technology. The product comes in pellet form and can be added directly 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 agglomeration during transport or storage, they are coated with a small amount of clay, which should be taken into account in the 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). The basis for this technology is that the addition of sulfur to asphalt binder can replace some of the binder that is required to fully coat the aggregate particles (Prowell et al. 2009). Sulfur that precipitates from the asphalt binder crystallizes, which provides stiffness and, thus, resistance to permanent deformation (Prowell et al. 2009). Shell Thiopave® is produced in the form of small pellets (Tran et al. 2010), and no plant modifications are necessary (West et al. 2010). Typically, it is added directly into the mixing drum. A recommended temperature of 284 ± 9°F should be maintained to ensure that the pellets melt quickly and the sulfur is mixed in thoroughly (Prowell et al. 2009).

2.1.2 Chemical Additives

MeadWestvaco's Evotherm® is a chemical WMA additive. Evotherm® ET (emulsion technology) 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 improves the coating of aggregates by the asphalt. When mixed with hot aggregate particles, the water evaporates out of the mix as steam (D'Angelo et al. 2008), and only the asphalt and aggregate are left (Hurley and Prowell 2006).

Evotherm® dispersed asphalt technology (DAT) was introduced in 2007 as the second generation of Evotherm®. Instead of being introduced as an emulsion, Evotherm® DAT is the same chemical package as the original Evotherm® ET, but is diluted with a small amount of water (D'Angelo et al. 2008). Evotherm® DAT is injected into the asphalt line directly, just before being added to the mixing drum or directly into the pug mill for batch plants (Prowell et al. 2009). According to MeadWestvaco, the third generation of this chemical additive, Evotherm™® 3G, is a water-free version of Evotherm® DAT. It is currently marketed under the name REVIX™ by a partnership of developers, Mathy Technology and Engineering Services and Paragon Technical Services.

Rediset™ WMX is another chemical WMA additive developed by the Akzo Nobel Surfactants Company. It is produced in solid additive form and contains surfactants and rheological modifiers (Martin et al. 2011). In addition, Rediset™ WMX can act as an anti-stripping agent to improve resistance to moisture damage, and the surfactants within it help increase the adhesion of the binder to the aggregate, even when the aggregate particles are wet (Prowell et al. 2009). This product may eliminate the need for separate anti-stripping agents in the mix. The additive is produced in the form of a small pastille, or bead (Santucci 2010).

Typically, the pastilles are blown into the binder tank or directly into the mixing drum. The addition rates vary, depending on the performance grade (PG) of the binder (Prowell et al. 2009).

CECA, a division of the Arkema Group, has developed a chemical WMA additive called Cecabase RT® (Santucci 2010), which 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% by weight of asphalt binder. Cecabase RT® can be introduced directly into the asphalt line in the plant (Prowell et al. 2009). Cecabase RT® acts at the aggregate/binder interface to improve the workability of the mix without changing the rheological properties of the binder (Gonzalez-Leon et al. 2009).

2.1.3 Water Foaming Processes

The water foaming technologies consist of two primary methods: water-containing and water-based processes. In the water-containing process, moisture is contained in the media solid, is released, and then bubbles (i.e., foams) when it contacts the hot binder. The water-based process utilizes water only to generate bubbles when contacting the hot binder.

Water-containing Technologies

Aspha-min®, developed by Eurovia Services GmbH, is a well-known WMA additive. Aspha-min® is a synthetic sodium aluminum silicate, also referred to as zeolite (Hurley and Prowell 2005). Aspha-min® contains approximately 21% water by mass (Akisetty et al. 2010). When mixed with the binder, the water is released as the temperature increases (D'Angelo et al. 2008) to approximately 185°F to 360°F, which causes the asphalt to foam, thereby reducing the viscosity and improving the workability of the mix (Button et al. 2007, Hurley and Prowell

2005). The water is released over time and can make the mix workable for up to six to seven hours or until the mix cools below 212°F (D'Angelo 2008). The recommended addition rate for Aspha-min® is 0.3% by the weight of mix (Kristjansdottir et al. 2007).

Advera® WMA, manufactured by the PQ Corporation, is a new generation of Aspha-min® (Prowell et al. 2009). It contains 20% water within its structure (Martin et al. 2011). The water is released slowly 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® is added at a rate of 0.25% by weight of the total asphalt mix. It should only be added in the plant through a modified fiber line close to the point where the 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 mixed first with aggregate until the aggregate is fully coated. Cold water is then added to the hardened binder at a rate of 2% to 5% by mass of hard binder (D'Angelo et al. 2008) to cause a foaming action, and the foamed binder is then added to the soft binder mixture (Button et al. 2007). The soft and hard binder blend produces the required final binder grade (Middleton and Forfylow 2009). The process creates a mix that has acceptable workability at low production temperatures (Wasiudden et al. 2007).

Low energy asphalt (LEA) is a foaming process that employs a different method than the other foaming technologies. To produce LEA, hot asphalt is first mixed with heated coarse

aggregate only. Once all the coarse aggregate particles are coated, a fine aggregate or RAP mixture is mixed with water and added to the asphalt coarse aggregate mix (Carter et al. 2010). The moisture in the fine aggregates or RAP causes the asphalt binder to foam (Button et al. 2007). During this process a coating/adhesive additive typically is added to the binder. Plant modifications are necessary for this process and include a pump to add the coating and adhesive additive and an additional feed bin to introduce the wet fine aggregates (Middleton and Forfylow 2009).

Water-based Technologies

The Double Barrel® Green System is a foaming machine 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 inside it that foam the asphalt and mix the foamed asphalt with the aggregate (D'Angelo et al. 2008). Approximately 1.1 pounds of water per metric ton of mix used is applied through the nozzles, which causes the binder to expand (Middleton and Forfylow 2009). Plant modifications that are necessary for this process include the installation of a foaming manifold over the asphalt injection system and feed lines to the manifold for the water and binder (Middleton and Forfylow 2009).

Terex® WMA system is another type of free water system. It is a patented technology that produces a foamed asphalt binder in an expansion chamber just outside of the rotating mixing drum, which ensures a consistent asphalt and water mix at various production rates (Martin et al. 2011, Santucci 2010). The foamed binder is then mixed with the aggregate particles in the

mixing drum (Prowell et al. 2009). The system is designed to fit on any counterflow mixing drum (Prowell et al. 2009).

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

Stansteel® produces a free water system, Accu-Shear™, which uses more than just water injection to foam the asphalt. The system uses a special shearing process to mix the water and asphalt (Martin et al. 2011). The process is driven by a colloidal pump and increases the foaming action of the asphalt more than traditional water injection methods, according to Stansteel® (Prowell et al. 2009). Stansteel® states that the patented design eliminates laminar flow and the separation of liquids. Other chemical modifiers also can be mixed using this machine.

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 to foam the 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 long 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 TEST PROCEDURES

Aggregate gradations that typically are used for HMA have 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 for WMA from those of HMA (Button et al. 2007). However, Tao and Mallick (2009) found that high contents of RAP can be incorporated into WMA due to the reduced aging of virgin asphalt, whereas high percentages of RAP are difficult to incorporate into HMA because of the severely aged binder present in RAP. Nonetheless, incorporating more than 20% RAP in a mix needs further binder testing to determine the PG of the blended binder (McDaniel et al. 2001). Also, other factors, such as variability of RAP and the degree of blending between virgin binder and RAP binder also affect the performance of mix (Copeland 2011). This is especially a concern at lowered mixing temperatures.

The National Cooperative Highway Research Program (NCHRP) Report 691, *Mix Design Practices for Warm Mix Asphalt*, recommends mix design methods for WMA (Bonaquist 2011). These recommendations for WMA mix design practices are 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. For example, the study 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 should still be evaluated for compactability, coating, rutting and moisture sensitivity, as these performance properties of WMA may vary from those of HMA. Compactability 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 is found that WMA mixes, in general, are more susceptible to moisture damage than HMA mixes, and an anti-stripping additive should be considered in the mix design.

Also, WMA processes with very low production temperatures may produce WMA mixes that are less resistant to rutting than HMA mixes. In short, a WMA mix produced with the same aggregate and binder as HMA will have similar properties with respect to volumetrics. However, the short term stiffness value from laboratory-compacted samples of the WMA mix is lower than that of the HMA mix.

The NCHRP 691 report also discusses problems inherent to performance testing of WMA in the laboratory. The lower production temperatures for WMA lead to problems in terms of achieving equal or comparable aging times. The NCHRP study suggests that WMA should be aged in a two-step process to achieve the same aging conditions that traditional HMA would reach. Generally, this process would consist of a first stage of aging at the production temperature for two hours, followed by a second aging sequence at the representative high in-service pavement temperature for varying periods of time. The time and temperature for the second aging sequence would need to be determined so that the HMA specimens that are conditioned using the two-step process would have similar stiffness values to those of HMA specimens that are aged for four hours at 275°F. The second aging sequence would be performed for moisture susceptibility and rutting test specimens only.

Results from the NCHRP 691 study indicate that reheating WMA samples changes their stiffness values. HMA samples are sometimes reheated for performance testing. To determine if reheating has the same effect on WMA as HMA, samples were tested for stiffness by determining their dynamic modulus values 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 for both WMA and HMA. The samples that were compacted and tested after a storage period without reheating showed slightly increased stiffness values as well.

It was determined that reheating WMA samples is acceptable, because the effect of reheating is similar to that for HMA. The NCHRP 691 project suggests that reheating times and temperatures should be minimized to reduce the effect of additional aging on the samples.

Further work with ongoing NCHRP WMA studies are attempting to confirm the results from NCHRP 691 or suggest changes.

2.3 IMPROVEMENTS TO VISCOSITY AND WORKABILITY OF MIX VIA WMA PROCESSES

Many studies show that WMA processes reduce the viscosity and/or improve the workability of an asphalt mix. Each WMA process leads to slightly different values for these reductions or improvements. These values also vary in terms of the amount of WMA additive that is used.

Austerman et al. (2009) found that dosage of 1.5% or 3.0% Sasobit® decrease viscosity and improve workability when compared to a control binder. The viscosity values were measured using a rotational viscometer in accordance with AASHTO T316, *Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer*. The workability of the mixes was determined using an asphalt workability device (AWD) developed by the University of Massachusetts – Dartmouth. The device records torque measurements from a paddle submerged in the mix 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 improve the workability so that compaction is satisfactory at temperatures that are lower than those required for traditional HMA mixes.

A study performed by Bennert et al. (2010) found that when 0%, 0.5%, 1.0% and 1.5% Sasobit® by binder mass were added to a PG 76-22 binder, the viscosity values were 1,330, 1,335, 1,290 and 1,262 cP, respectively. These values were obtained from dynamic shear rheometer (DSR) tests.

2.4 RUTTING RESISTANCE PROPERTIES OF WMA

Rutting resistance may be a concern for certain WMA technologies. The lower mixing and compaction temperatures for WMA cause the binder in WMA to age less than the binder in HMA, which indicates that WMA binder may be less stiff than HMA binder and, in turn, may cause rutting problems after paving.

Hurley and Prowell (2005, 2006) performed tests on various WMA additives and explored their rutting potential. An asphalt pavement analyzer (APA) was used to determine the rut depths of different specimens. Limestone and granite aggregates were used. Different binder grades also were included to determine if the binder grade has any significant impact on rutting. Specimens were compacted at different temperatures. It was found that the WMA additive Aspha-min® has 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 when compared to the control HMA specimens. These findings indicate that Sasobit® could actually decrease rut depths in WMA pavements. Evotherm® ET was found to have similar effects on rutting to Sasobit®. The addition of Evotherm® ET also decreased 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 depth for each WMA technology did not vary significantly when compared to the control HMA.

D'Angelo et al. (2008) conducted studies on the field performance of WMA for rutting in France, Germany and Norway. All the data were collected by the agencies within each of the respective countries. Several WMA technologies, including Aspha-min®, Sasobit® and other additives that are commonly used in Europe, were studied. In every section of WMA monitored, the rutting performance of WMA was considered to be equal to or better than that of traditional HMA pavement within three years.

In a related study by Wielinski et al. (2009), the Astec Double Barrel Green® foaming technology was evaluated to determine its effects on the performance of WMA. An APA was used in this study to determine the rut depths of different WMA specimens. The WMA specimens were found to be slightly more susceptible to rutting than the HMA control specimens. On average, the WMA specimens had a rut depth of 0.09 inch more than the HMA control specimens. However, the WMA rut depths were still acceptable values for the APA test. Middleton and Forfylow (2009) reported similar results with WMA produced via the Double Barrel Green® process. They determined that WMA with 15% RAP had slightly larger rut depths than the control HMA. The values for the rut depth for WMA were still less than the threshold of 0.31 inch, based on the results of the APA tests.

In a study performed by Copeland et al. (2010), the rutting performance of control HMA and WMA mixes was evaluated based on the flow number. Each mix contained 45% RAP, and the WMA was produced by foaming the asphalt binder by adding 2% water based on the weight of the binder. Four specimens were tested for each mix at 140°F. The test results indicate that the HMA specimens, on average, have significantly higher flow numbers than the WMA specimens. The authors concluded that WMA, even with the addition of 45% RAP, is more susceptible to rutting than HMA with RAP. The authors hypothesized that the WMA mix may not have

experienced complete blending with the RAP and suggest establishing an upper limit on RAP content in WMA mixes.

In a recent study performed by Williams et al. (2011), the flow numbers of three field mixes were determined in the laboratory. The WMA technologies used for the three field mixes are Evotherm®™ 3G/REVIX™, Sasobit® and the Double Barrel® Green foaming process. Each sample that was fabricated using a field mix consisted of laboratory-compacted dry, field-compacted dry, laboratory-compacted moisture-conditioned and field-compacted moisture-conditioned samples tested for flow numbers for both the WMA mixes and a HMA control mix. The moisture conditioning method follows the AASHTO T283 protocol. The results indicate that the HMA samples have higher flow numbers than the WMA mixes, except that the dry field-compacted samples for Sasobit® have a slightly higher flow number than the HMA mix. However, the Double Barrel® Green foaming samples showed higher flow numbers than the control HMA samples, except for the field-compacted dry samples. The moisture conditioning process was found to increase the flow number sometimes, which the authors attribute to the samples soaking in a warm water bath, which could possibly have resulted in additional aging or binder absorption.

Based on these results, it appears that the rutting performance of WMA is inconsistent when compared to that of HMA. Most of the rutting studies are based on laboratory-compacted specimens at the same air void levels, which may have different characteristics from the field-compacted mixes.

2.5 FATIGUE PROPERTIES OF WMA

Kanitpong et al. (2007) determined that asphalt binder modified with Sasobit® has a longer fatigue life than a control binder. The results were determined through the use of a DSR. It was determined also that the fatigue life (N_p) of a binder with Sasobit® is longer than that of the control binder without Sasobit®.

D'Angelo et al. (2008) found that both Sasobit® and Aspha-min® WMA pavements exhibit equivalent fatigue cracking to that in traditional HMA pavements, based on field pavement performance evaluations in France, Germany and Norway. Again, it should be noted that these WMA projects were in service less than three years. Therefore, the field performance is short-term, not long-term performance.

In a study by Diefenderfer and Hearon (2008), the fatigue performance of WMA produced with Sasobit® is compared to a control HMA. Two different mixes were tested in this study, Mix A and Mix B. Mix A is a 3/8" nominal maximum aggregate size (NMAS) mix with siltstone and granite aggregate, and Mix B is a 1/2" NMAS mix with limestone and gravel aggregate. Each mix used the same amount of Sasobit® additive. The fatigue resistance of the mixes was evaluated in accordance with AASHTO T321, also known as the third point flexural fatigue test. The targeted air voids for the two mixes were chosen as the average of the field trials with a 0.5% tolerance. The fatigue specimens were tested at strains of 300, 400 and 600 microstrain, and only some samples were tested at 800 microstrain. Using the failure criterion of 50% reduction in beam modulus, for Mix A, the plant-produced WMA samples exhibited a shorter fatigue life than HMA at a low strain level, but showed comparable fatigue life to that of the HMA at a high strain level. For Mix B, the plant-produced WMA samples showed a fatigue life comparable to that of the HMA samples. Another important observation is that as the

production temperature of the WMA increased, the fatigue life of the laboratory-produced samples lengthened. Overall, the WMA samples exhibited more fatigue damage at low strain levels, but as the strain levels increased, the WMA and HMA samples showed similar performance.

A study by Kvasnak et al. (2010) found similar results for the fatigue performance of WMA produced with the Gencor® Ultrafoam GX®. The HMA mixes had the same aggregate and mix design as the WMA mixes. To evaluate the fatigue performance of each mix, flexural beam fatigue tests were performed in accordance with AASHTO T321. Specimens were prepared from a plant-produced mix that was reheated in the laboratory. For this study, the beam specimens were aged according to AASHTO R30 for five days at 185°F. For each mix, three beams were tested at 200 and 400 microstrain. The failure criterion was defined as a 50% reduction in the initial beam modulus value. The test results indicate that the WMA specimens have a shorter fatigue life than HMA at 200 microstrain. However, at 400 microstrain, the WMA specimens have the same fatigue life as the HMA specimens.

In a study by Timm et al. (2011), bending beam fatigue testing was conducted on HMA control and WMA samples produced with Shell Thiopave® in accordance with AASHTO 321-07. A 50% reduction in beam stiffness was used as the fatigue failure criterion. The beam fatigue samples were tested at 200, 400 and 600 microstrain. Ten mix designs with varying air voids and percentages of Thiopave® were tested with two replicates per strain level. The findings indicate that increasing the percentage of Thiopave®, based on the mass of the binder, leads to a shorter fatigue life, especially at high strain levels. However, one mix in particular, the 30% Thiopave® mix with 2% air voids, exhibited the longest fatigue life. For this reason, this mix design was chosen for the bottom lift of the full-scale pavements. The 30% Thiopave® 2% air void base

mixture was evaluated further based on plant-produced HMA control and Thiopave® WMA mixes. Two replicates were tested at 200, 400 and 800 microstrain for each mix. The results indicate that the plant-produced Thiopave® mixes have a longer fatigue life than the HMA control mix at all strain levels. When compared to HMA control mixes, the percentages of increase in cycles to fatigue failure for the WMA mixes were 76.7%, 65.6% and 28.4% for the 200, 400 and 800 microstrain levels, respectively.

Based on the results of these studies, it is found that WMA mixes may exhibit equal or better resistance to fatigue cracking than traditional HMA at high strain levels. However, at low strain levels, WMA mixes suffered shorter fatigue life than the HMA mixes. There are discrepancies of findings between laboratory-produced and plant-produced mixes.

2.6 THERMAL CRACKING PROPERTIES OF WMA

Apeagyei and Buttlar (2007) found, via disk-shaped compact tension [DC(T)] tests, that WMA cores with Evotherm® additive and PG 64-22 binder compacted at 248°F in the field show more resistance to thermal cracking than the control HMA cores compacted at 302°F in the field.

Hurley and Prowell (2005, 2006) report that the reduced mixing and compaction temperatures of WMA mixes containing Evotherm®ET, Sasobit® and Aspha-min® lead to a decrease in the initial aging of the binder and a more ductile binder and thus, lead to less thermal cracking than the HMA.

D'Angelo et al. (2008) confirmed these findings as well. They discovered that all types of WMA are either equal to or better than the control HMA pavements in terms of resistance to thermal cracking, based on short-term field thermal cracking performance.

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

Kvasnak et al. (2010) evaluated the thermal cracking performance of four different WMA technologies using the indirect tensile (IDT) creep compliance test according to AASHTO T322. The WMA technologies observed were Sasobit®, Advera®, Astec® Double Barrel® Green and Evotherm® DAT. Three samples were tested and the results averaged for each mix. The Sasobit® and Advera® mixes had lower values of creep compliance than the HMA control mix at -4°F, 14°F and 32°F. The authors concluded that the Sasobit® and Advera® mixes would be more susceptible to thermal cracking because they are less compliant than the HMA control mix. The Astec® Double Barrel® Green and Evotherm® DAT mixes were found to have higher values of creep compliance than the control HMA mix at 14°F and 32°F, but slightly lower values at -4°F. The differences between the creep compliance values at -4°F are believed to be small and insignificant. Kvasnak et al. concluded that the Astec® Double Barrel® Green and Evotherm® DAT mixes positively affect the dissipation of thermal stress, and that low production temperatures may have improved their resistance to thermal cracking.

Cooper III et al. (2011) evaluated the thermal cracking resistance of WMA binder produced with Thiopave®. The HMA binder evaluated was a PG 70-22 styrene-butadiene-styrene (SBS) elastomeric polymer-modified binder, and the WMA binder was PG 64-22 modified with Thiopave®. The Thiopave® was added at 40% by total weight of the binder. The thermal stress

restraining specimen test (TSRST) was performed in accordance with AASHTO TP 10. The test involves placing an asphalt binder beam between two aluminum plates and then cooling the binder until it fractures. The results of the test show that the HMA binder has a 7.74°F lower fracture temperature than the Thiopave® WMA binder. The authors attribute the difference in fracture temperatures to the stiffening effect of the sulfur in Thiopave®. When statistical analysis was performed, the difference in fracture temperatures was found not to be significant, however.

Jones et al. (2011) evaluated the thermal cracking resistance of WMA mixes produced using the Aquablack™ system. For the thermal cracking analysis, a method known as *critical temperature analysis* was used. The critical temperature is defined as the temperature at which the estimated thermal stress in the specimen exceeds the IDT strength of the mixture tested at that temperature to assess low temperature cracking performance. Four plant-produced samples (without reheating) were tested for each of the HMA and WMA samples. The first sample was used for creep compliance testing to obtain the necessary parameters for the prediction of thermal stress. The remaining three samples were tested for IDT strength. The results show that HMA has a critical temperature of -13°F, whereas WMA has a critical temperature of -14°F. It was determined that the HMA and WMA mixes should have comparable thermal cracking resistance.

In summary, the findings with regard to resistance to thermal cracking of WMA vary and are technology-dependent.

2.7 MOISTURE SUSCEPTIBILITY IN WMA

Moisture susceptibility is probably the biggest performance concern for WMA, especially for the water-based or water containing WMA technologies. It has been thought that, because

WMA is not heated to the same high temperatures as HMA, the aggregate may not be completely dried before mixing (Kvasnak et al. 2009). If the aggregate is not dry prior to mixing, the inherent moisture could prevent the binder from bonding with the surface of the aggregate, which could lead to stripping.

Hurley and Prowell (2005, 2006) evaluated WMA moisture susceptibility using three different additives: Sasobit®, Aspha-min® and Evotherm®. Anti-stripping agents were also added to the mixtures to determine if resistance to moisture susceptibility would improve. Granite and limestone aggregates were used in the samples. The tensile strength ratio (TSR) and the Hamburg wheel tracking tests were conducted to evaluate moisture susceptibility, in accordance with AASHTO T283 and AASHTO T324, respectively. The parameters obtained from these two tests/specifications are the TSR and stripping inflection point, respectively. The results of the tests varied, depending on the WMA additive used. The recommended minimum TSR value is 0.80 (Cominsky et al. 1994), and the stripping inflection points greater than 10,000 passes are considered acceptable (Hurley and Prowell 2006). In general, all the WMA samples with granite aggregate showed less resistance to moisture than the control HMA sample with granite, except for the Evotherm® sample, which actually had no stripping inflection point and a TSR value fairly close to that of the control sample. When hydrated lime was added to the Aspha-min® samples, the resistance to moisture improved. This finding holds true also for Sasobit® samples when the anti-stripping agent, Magnabond as recommended by Sasol, was incorporated into the mix.

Xiao et al. (2009) performed a laboratory study regarding moisture susceptibility in WMA using Aspha-min® and Sasobit® as the WMA additives. Various samples were made from different aggregate stockpiles with various moisture contents. The tests were performed in

accordance with the South Carolina Department of Transportation standard procedures for determining moisture susceptibility. The TSR and toughness values were calculated to determine the samples' susceptibility to moisture. The test results indicate that, in almost all cases, when moist aggregate is used, more moisture damage is observed in the sample, even in the control specimen. This moisture susceptibility may be offset, however, by the addition of hydrated lime. This study's results also indicate that moisture susceptibility is affected significantly by the source of aggregate that is used. Three sources of aggregates were used in the study: two granite aggregate sources and one schist aggregate. Based on statistical analysis, the IDT strength values varied significantly amongst all the aggregate sources. It was determined that the chemical and physical properties of the aggregate play a large role in the stripping resistance of the mix.

Kvasnak et al. (2009) also performed a study on the moisture susceptibility of Evotherm® WMA. Three parameters were used to determine moisture susceptibility: the TSR (AASHTO T283) and the absorbed energy ratio from the IDT tests, and the stripping inflection point derived from the Hamburg wheel tracking test (AASHTO T324). The study used two different sources of samples: laboratory-mixed samples and plant-produced samples. The laboratory-mixed WMA samples failed the TSR, absorbed energy ratio and stripping inflection point criteria. These findings are reported to be due to the improper mixing of the Evotherm® in a bucket mixer. The plant-produced samples of WMA, however, passed all the 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 TSR values than the control HMA samples.

In a recent study performed by Williams et al. (2011), the TSR values of three field mixes, based on AASHTO T283, were determined in the laboratory. The WMA technologies

used for the three field mixes are Evotherm®™ 3G/REVIX™, Sasobit® and the Double Barrel® Green foaming process. The samples tested consisted of lab-compacted and field-compacted samples. No anti-stripping agents were used in any of the mixes. The results of the study indicate that overall, the average value of the TSR for the HMA samples was higher than that for the WMA samples, except for the Double Barrel® Green mix for which the WMA field-compacted samples had a higher value of TSR than the HMA samples.

In a study performed by Kvasnak et al. (2010), WMA produced using the Gencor® Ultrafoam GX® was evaluated for moisture susceptibility using TSR tests following AASHTO T283. The dry and wet IDT strength values of the WMA samples tended to be lower than those of the HMA samples. The TSR value for the WMA samples was 0.76, whereas the HMA samples had a TSR value of 0.94. The WMA samples were slightly below the recommended TSR minimum value of 0.80. It is also noted that a small amount of stripping was evident in the broken WMA samples. The HMA samples exhibited no visible stripping damage.

Based on these studies, it can be generalized that moisture susceptibility is a valid concern with the use of WMA. Anti-stripping agents can, in some cases, improve the resistance to 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 to the number of variables in each of the studies. Field performance evaluations and more tests of the moisture susceptibility of WMA are needed.

2.8 FIELD PERFORMANCE VERSUS LABORATORY PERFORMANCE

To date, the field performance of WMA indicates a disconnect between laboratory study results and field performance (Prowell et al. 2009). The WMA projects are in the early stages of

their design life and have not shown signs of performance problems to date (Prowell et al. 2009). WMA plant-produced samples have been compacted in the laboratory to simulate the actual aging that occurs in the field, but most of these mixes require reheating, which changes the properties of the binder, as previously discussed. Further studies are needed to find better correlations between laboratory performance tests and the actual field performance of WMA.

2.9 SUMMARY OF LITERATURE REVIEW

WMA is an emerging technology that allows mixes to be workable enough to be paved and compacted at temperatures lower than those for traditional HMA. WMA provides benefits that include lower fuel consumption, lower gas emissions, longer haul distances, an extended paving season, and the potential to incorporate higher percentages of RAP into the mix than is the case with traditional HMA mixes. The mix designs for WMA are generally the same as for HMA. However, a number of different additives and processes can be used to produce WMA; these can be categorized as organic additives, chemical additives or foaming technologies. All WMA additives and processes cause the mix to become more workable at lower temperatures than are required for traditional HMA mixes. The rutting performance of WMA mixes in the laboratory is reported to be inconsistent when compared to a control HMA mix. The fatigue cracking resistance of WMA may be slightly lower than HMA at low loading levels, based on laboratory mix testing. The findings regarding resistance to thermal cracking of WMA are mixed and are WMA technology-dependent. The findings regarding resistance to moisture of WMA are mixed and are WMA technology-dependent; it has been suggested that anti-stripping additives should be used in WMA for this reason. Further studies are needed to determine the long-term performance of WMA in the field.

CHAPTER 3: MATERIALS AND EXPERIMENTS

As stated previously, additional studies regarding the field performance of WMA are needed. Since 2008, the Washington State Department of Transportation (WSDOT) has built a handful of WMA pavements with a HMA control section. The long-term performance of these WMA pavements is not yet available. One approach that can be taken to assess the long-term performance of these WMA pavements is to characterize field cores extracted from these pavements based on laboratory performance tests which have been proven to generate parameters that correlate with long-term field performance. When compared to laboratory-compacted samples (either laboratory-produced or plant-produced), the use of field cores eliminates variables, such as different compaction methods that are employed between the field and the laboratory and reheating that is critical to WMA. This study evaluates HMA and WMA field cores taken from projects in Washington State using a series of performance tests. Binder performance tests also were performed on binder extracted and recovered from the cores.

3.1 FIELD CORES

Field cores were obtained by WSDOT from several different highways across Washington at the end of 2010 and in early 2011. A total of sixteen cores, which include eight HMA and eight WMA cores, for each of four projects (Contracts 7474, 7419, 7755, and 7645) were obtained, thus making a total of 64 cores. The WMA and HMA cores for each contract

were taken from the wheel path of the lane. Each of these four projects includes both WMA and HMA control sections.

3.1.1 Aquablack™ (Contract 7474)

The Aquablack™ (Contract 7474) project site is located in the eastbound travel lanes of US Highway 12, about three miles west of Walla Walla, WA. The HMA and WMA sections were constructed in April 2010. The HMA cores were taken between mileposts 334.0 and 335.0, and the WMA cores were taken between mileposts 332.0 and 333.0. The HMA is in the driving lane and the WMA is in the passing lane. The design traffic level was 3.8 million equivalent single axle loads (ESALs). The production temperatures of the WMA and HMA mixes were 275°F and 325°F, respectively. The project was a newly constructed widening project, but the pavement tested was the surface layer with a paving depth of 3 inches. The grade of the asphalt binder used was PG 64-28. About 20% RAP was used in the WMA and HMA mixes.

3.1.2 Sasobit® (Contract 7419)

The Sasobit® (Contract 7419) project site is located in the eastbound travel lane of Interstate 90, about three miles west of George, WA. The HMA and WMA sections were constructed in June 2008. The HMA cores were taken between mileposts 142.0 and 143.0, and the WMA cores were taken between mileposts 145.0 and 146.0. The design traffic level was 11 million equivalent single axle loads (ESALs). The production temperatures of the WMA and HMA mixes were 276°F and 330°F, respectively. The project was a grind and inlay with a thickness of 3 inches. The grade of the asphalt binder used was PG 76-28. About 15-20% RAP was used in the mixes.

3.1.3 Gencor® (Contract 7755)

The Gencor® (Contract 7755) project site is located in the eastbound and westbound travel lanes of US Highway 12, between Yakima and Naches, WA and constructed in August 2009. The WMA technology used was the Gencor® Green Machine Ultrafoam GX® technology. The HMA cores were taken between mileposts 194.0 and 195.0 in the westbound travel lane, and the WMA cores were taken between mileposts 194.0 and 195.0 in the eastbound travel lane. The design traffic level is 6 million equivalent single axle loads (ESALs). The production temperatures for the WMA and HMA mixes are 260°F and 295°F, respectively. The project was a grind and inlay with a paving and grinding depth of 1.8 inches. The grade of the asphalt binder used was PG 64-28 and about 20% RAP was used in the mixes.

3.1.4 Water Injection (Contract 7465)

The water injection (Contract 7465) project site is located in the eastbound travel lane of Washington State Highway 28, about four miles east of Quincy, WA and was constructed in June 2009. The HMA cores were taken between mileposts 33.0 and 33.2, and the WMA cores were taken between mileposts 31.0 and 31.2. The project design traffic was 3 million ESALs. The production temperatures for the WMA and HMA mixes were 250°F and 300°F, respectively. The project was a grind and inlay with a thickness of 1.8 inches. The grade of the asphalt binder used was PG 64-28. About 15-20% RAP was used in the mixes.

Table 3-1 presents the summary of four WMA projects with HMA control sections included in this study.

Table 3-1. Summary of WMA Projects Included in Study

Technologies (Contract #)	Highway, Location	Design ESALs, Millions	Production Temperature, °F		PG Grade	RAP, %
			WMA	HMA		
Aquablack™ (7474)	US 12, Walla Walla, WA	3.8	275	325	64-28	20%
Sasobit® (7419)	I-90, George, WA	11	276	330	76-28	15-20%
Gencor® (7755)	US 12, Yakima/Naches, WA	6	260	295	64-28	20%
Water Injection (7465)	Highway 28, Quincy, WA	3	250	300	64-28	15-20%

3.2 EXPERIMENTS ON FIELD CORES

3.2.1 Preparation of Field Cores

The top lift from each core was cut to a height of 1.5 inches by cutting both the top and bottom ends. Smooth surfaces were needed to mount the linear variable differential transformers (LVDTs) to measure deformation for determining the dynamic modulus. Samples that were tested for thermal cracking were cored from a diameter of 6 inches to a diameter of 4 inches to reduce the load level needed to break the specimens due to limitations of the equipment. Samples that were tested for dynamic modulus, rutting, and fatigue remained at the original diameter of 6 inches.

There are ten HMA and ten WMA cores for each project. From each set of ten cores, three samples were selected for dynamic modulus then fatigue testing, and three other cores were selected for low temperature testing for thermal cracking. Two cores were used for the high

temperature indirect tensile strength tests for rutting and another two for Hamburg Wheel-Tracking Device (HWDT) for rutting and moisture susceptibility. Because dynamic modulus tests are nondestructive, the fatigue tests were conducted after the dynamic modulus tests on the same cores. Three cores were selected for each group of tests (i.e., fatigue and thermal), so that the average air voids of the three cores was as close as possible to the average of the total population of the eight HMA or WMA cores for each project. The air void levels of the three cores selected for testing include low, medium and high levels within the range of the eight cores. Table 3-2 presents the air void percentages for the dynamic modulus/fatigue, thermal cracking and rutting tests.

Table 3-2. Air Voids of Field Cores

Contract	Mixes	Average Air Void (%)			
		Overall	Dynamic Modulus/ Fatigue	Thermal cracking	Rutting
7474	HMA	3.63	3.79	4.17	2.60
	Aquablack™	2.53	2.42	2.67	2.49
7419	HMA	4.56	4.54	4.70	4.37
	Sasobit®	4.71	4.59	4.69	4.93
7755	HMA	4.62	4.82	4.75	4.15
	Gencor®	4.21	4.43	4.30	3.55
7645	HMA	4.62	4.82	4.75	4.15
	Water Injection	2.85	3.05	2.68	2.73

The same mix design was used for both HMA and WMA for each project and the NMAS of mixes for all the projects was ½". Table 3-3 presents the aggregate gradations and volumetric properties of the mix designs and production mix.

Table 3-3. Mix Designs and Production for HMA and WMA

HMA/WMA Aggregate Gradation								
	Percentage Passing (%)							
Sieve Size	Aquablack™		Sasobit®		Gencor®		Water Injection	
	Design	Production	Design	Production	Design	Production	Design	Production
¾"	100	100	100	100	100	100	100	100
½"	94	94	95	94	95	95	95	95
3/8"	81	82	84	83	86	86	84	85
No. 4	52	51	55	54	59	59	55	55
No. 8	34	32	34	34	38	38	34	35
No. 16	23	23	22	22	26	26	22	22
No. 30	16	18	15	15	17	19	15	16
No. 50	12	15	11	11	11	12	11	12
No. 100	8	9	8	9	7	9	8	9
No. 200	5.6	5.8	6.3	6.3	5.9	6.5	6.3	6.8
HMA/WMA Mix Design Volumetrics								
PG Grade	64-28		76-28		64-28		64-28	
Binder, %	5.2	5.2	5.5	5.1	5.8	5.1	5.4	5.3
Effective Binder Content	4.7	4.6	4.7	4.9	5.0	4.9	4.6	4.1
Voids filled with asphalt (VFA)	74	74	73	67.2	75	67.2	73	73
Voids in mineral aggregate (VMA)	15.4	15	15.4	14.8	15.9	14.8	15.2	15
Anti-strip Additive	Superbond		None		None		Polarbond	
Anti-strip, %	0.25		None		None		0.5	
TSR	94		99		99		102	

3.2.2 Laboratory Experiments of Cores

3.2.2.1 Mixture Test Machine and Setup

A servo-hydraulic Geotechnical Consulting Testing System (GCTS) with an environmental chamber was used to test the samples. Four linear variable differential transformers (LVDTs) are mounted on the sample, two on the front and two on the back, to measure the deformations during the tests for determining the dynamic modulus values. The gauge length, or distance between the two mounts, is 2 inches. The mounts are placed so that two measurements of horizontal deformation and two measurements of vertical deformation can be taken. Once the LVDTs are attached, the specimen is placed in a loading apparatus. The loading apparatus consists of a plate on the top and bottom guided by four steel columns that keep the applied load strictly in the vertical plane. Each plate is equipped with loading strips of the proper curvature to load the specimens. The top plate of the apparatus is held up by four springs to prevent the weight of the plate from constantly sitting on top of the specimen. Figure 3-1 shows a picture of the IDT test setup.

Figure 3-1. Indirect Tensile Test Setup

3.2.2.2 Dynamic Modulus Test

The dynamic modulus, $|E^*|$, is an indicator to the stiffness of a material. The dynamic modulus test applies cyclic loading to determine the dynamic modulus value. For this study, the loads applied to the specimens were small enough to produce approximately 100 microstrain to avoid damage. The tests were run at six temperatures, -4, 14, 32, 50, 68 and 86ºF and five loading frequencies, 0.1, 1, 5, 10 and 20 Hz at each temperature. The order of the test temperatures is from lowest to highest, whereas the loading frequencies are from highest to lowest for each temperature.

Because the distribution of strain within the gauge length is not uniform, the deformation readings of the two vertical and two horizontal LVDTs are converted to strain in the center of the specimen along the vertical diameter at which the maximum tensile stress/strain or fracture occurs (Wen and Kim 2002). This conversion was accomplished in this study by multiplying a series of constant values that are dependent on the gauge length and specimen diameter by the average deformations in both the vertical and horizontal directions. First, Poisson's ratio was calculated based on Equation 3-1 and then was used to determine the center strain, based on Equation 3-2.

$$\nu = -\frac{\alpha_1 U(t) + V(t)}{\alpha_2 U(t) + \alpha_3 V(t)} \tag{3-1}$$

where ν = Poisson's ratio

α_1, α_2, and α_3 = constants related to geometry and gauge lengths: 3.80, 1.18, and 3.21, respectively, in this study

U(t) = average horizontal deformation, in.

V(t) = average vertical deformation, in.

t = time, sec.

$$\varepsilon_{x=0} = U(t)\frac{\gamma_1 + \gamma_2 \nu}{\gamma_3 + \gamma_4 \nu} \tag{3-2}$$

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

γ_1, γ_2, γ_3, and γ_4 = constants related to geometry and gauge length: 9.04, 27.32, 0.39, and 1.24, respectively, in this study

The tensile stress along the vertical diameter in an IDT test was determined based on Equation 3-3:

$$\sigma_{x=0} = \frac{2P}{\pi t D} \tag{3-3}$$

where $\sigma_{x=o}$ = tensile stress at center of specimen, psi

P = applied load, lbs.

t = height of specimen, in.

D = diameter of specimen, in.

The dynamic modulus values were calculated by dividing the amplitude of the stress cycles by the peak amplitude of the strain cycles. The amplitudes from the last ten cycles of each loading frequency were averaged to determine the dynamic modulus value for each combination of temperature and loading frequency, based on Equation 3-4.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{3-4}$$

where $|E^*|$ = dynamic modulus, psi

σ_0 = average of last ten load amplitudes, psi

ε_0 = average of last ten center strain amplitudes

Based on the time-temperature superposition (t-TS) principle, the mastercurves for the dynamic modulus can be constructed and represented by a sigmoidal model, as shown in Equation 3-5. The sigmoidal model uses so-called *shift factors* that essentially shift the data

points at different temperatures into a single curve at a given reference temperature. Figure 3-2 presents an example of a mastercurve.

$$Log|E^*| = a + \frac{b}{1+e^{c-d(Log(F)+Log(a_T))}} \quad (3\text{-}5)$$

where a, b, c, d = regressed model constants

F = frequency, Hz

a_T = shift factor for each temperature

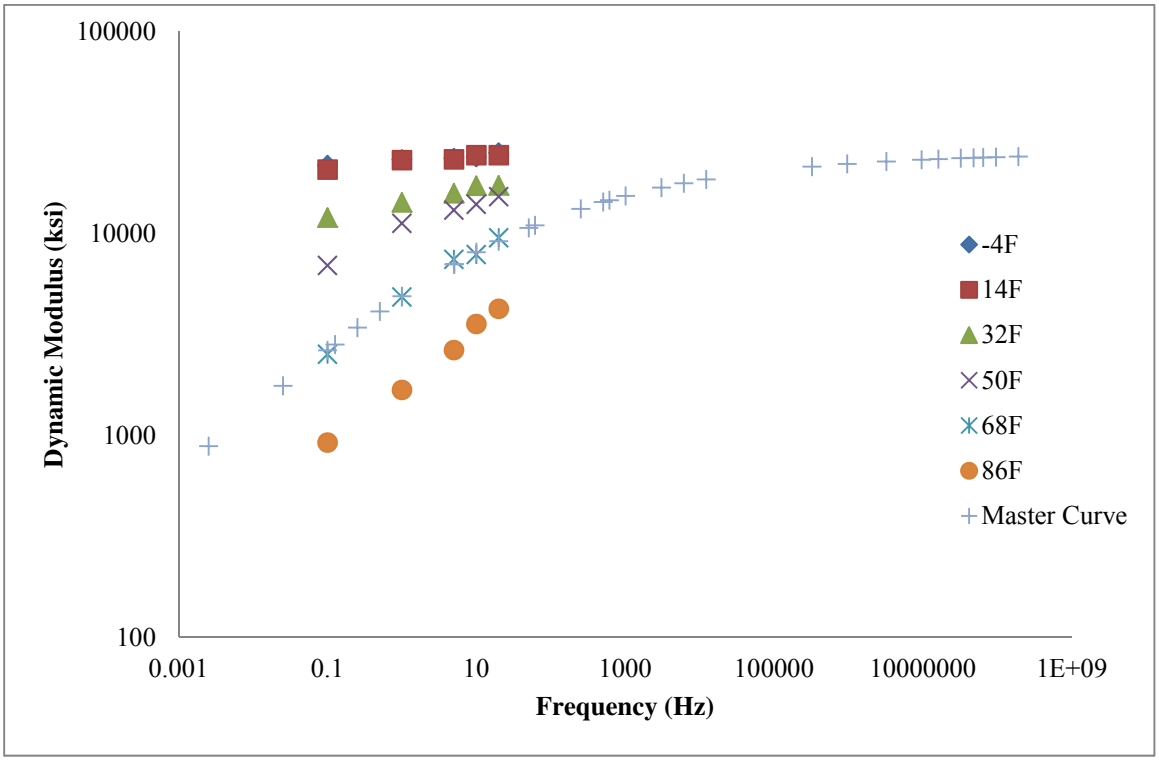

Figure 3-2. Example of Mastercurve

3.2.2.3 IDT Fracture Work for Fatigue

Fracture work at intermediate test temperatures has been found to correlate well with field fatigue performance (Wen 2011). The IDT strength test was performed on samples that had been tested to determine the dynamic modulus values. These fatigue tests were performed at 68°F with a deformation rate of 2 inches per minute by the GCTS ram. The deformation was continued until the load on the sample achieved a value close to zero.

Fracture work is defined as the entire area under the load versus the vertical displacement curve, as illustrated in Figure 3-3. The vertical displacement of the loading ram of the GCTS was used to calculate the fracture work, and LVDT readings were not needed. It is noted that *fatigue* in this study refers to bottom-up fatigue cracking. Currently, no commonly accepted performance test exists for top-down fatigue cracking, which is a primary concern in the State of Washington.

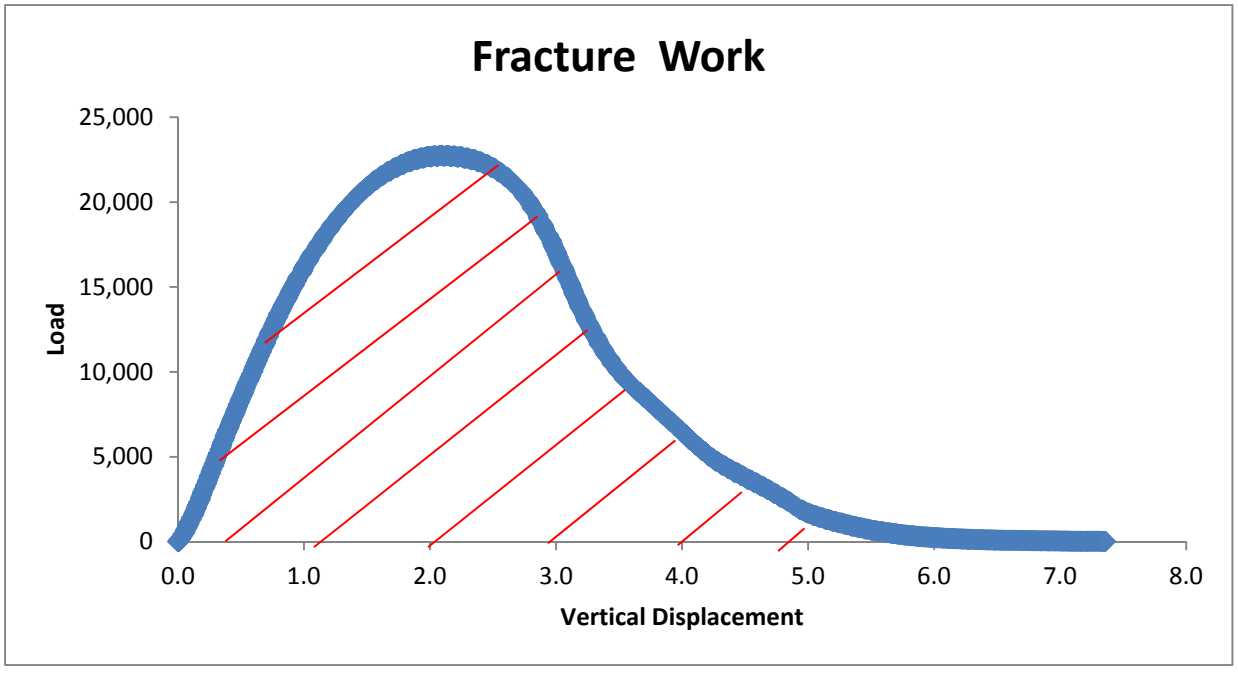

Figure 3-3. Determination of Fracture Work

3.2.2.4 IDT Fracture Work for Low Temperature Thermal Cracking

IDT fracture work at low test temperatures is found to correlate well with the field thermal cracking performance of pavements (Zborowski 2007). The tests were performed at 14°F with a deformation rate of 0.1 inch per minute. The deformation was continued until the load on the sample achieved a value of zero and the specimens completely split.

3.2.2.5 High Temperature Indirect Tensile Strength Test for Rutting

Researchers have reported that the IDT strength at high temperatures correlates well with the rutting resistance of asphalt concrete (Christenson and Bonaquist 2002, Anderson et al. 2003, Srinivasan 2004, Wen and Bhusal 2011). The high temperature IDT strength tests were performed at 122°F, the same temperature at which the Hamburg Wheel-Track Device (HWTD) tests were conducted by WSDOT to determine the rutting and moisture susceptibility of mixes. The samples selected for the tests were the remaining two of the eight cores from each contract, after the fatigue and thermal tests were completed. Therefore, the average air void percentages of the cores for high temperature IDT strength tests may not be close to the average of the average air void percentages of the eight HMA or WMA cores. The samples were loaded using a constant deformation rate of 2 inches per minute until the samples split. The peak load of each sample was then recorded. A high peak load value indicates a strong resistance to rutting.

3.2.2.5 Hamburg Wheel-Track Test for Rutting and Moisture Susceptibility

The HWTD is used to measure rutting and moisture damage of asphalt paving mixtures by repetitively rolling a steel wheel across the surface of a sample specimen while immersed in water at an elevated temperature. Figure 3-4 shows the HWTD device used in this study. Field

cores of 6-inches in diameter were tested at 122°F for 20,000 repetitions. The rut depth was measured during the tests. The moisture susceptibility, if any, is evaluated based on the number of passes corresponding to the stripping inflection point, as illustrated in Figure 3-5.

Figure 3-4. Hamburg Wheel-Tracking Device

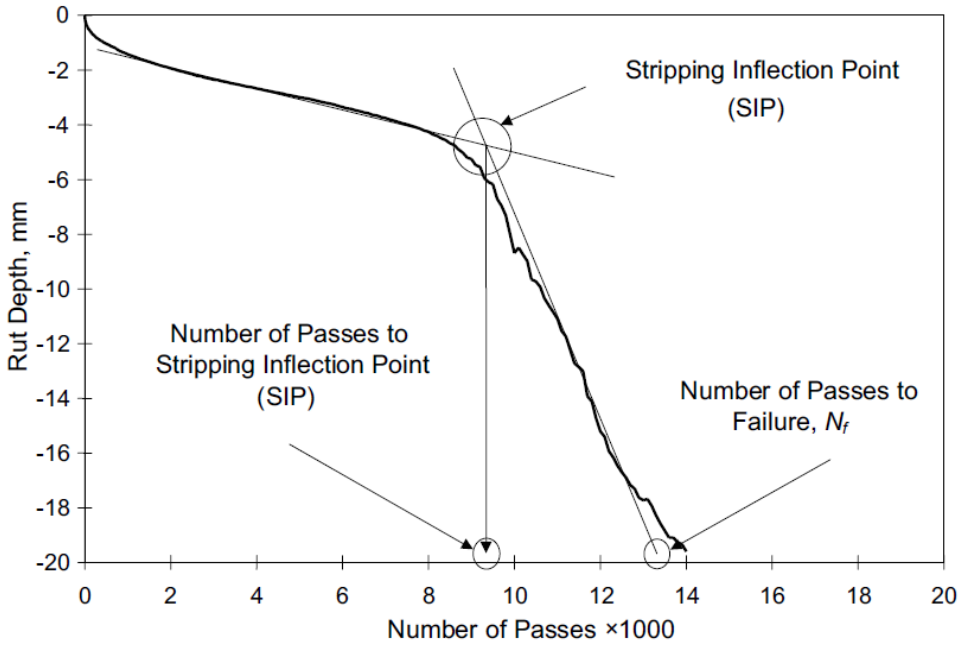

Figure 3-5. Evaluation of Rutting and Stripping from HWDT (after AASHTO T324)

3.3 EXPERIMENTS ON BINDER

3.3.1 Binder Extraction and Recovery

3.3.1.1 Binder Extraction Method

After the tests on field cores were completed, asphalt binders were extracted and recovered for laboratory testing. The binder extraction method used in this study follows AASHTO T164, *Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA), Method A*. A reagent grade trichloroethylene was used as the solvent. A Houghton centrifuge extractor capable of 3,600 RPM, as shown in Figure 3-6, was used to perform the extractions.

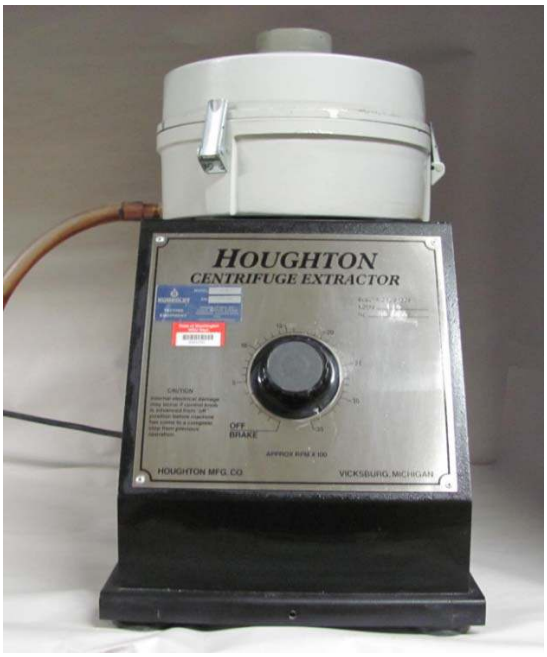

Figure 3-6. Centrifuge Used for Asphalt Extraction

After the tests on field cores were completed, approximately 1 pound of the loose mix was placed in the bowl of the extractor. Approximately 17 ounces of reagent grade trichloroethylene was placed in the bowl containing the loose mix to dissolve the binder for 15 minutes. After the 15-minute period, the extractor was turned on and the speed was slowly

increased so that no more than 3.5 oz/min of solution was extracted at a time. This process was accomplished by slowly increasing the speed of the extractor until it reached 3,600 RPM and no more solution was being extracted. Once this initial step was completed, three more washes with 8.5 oz. of trichloroethylene were used to extract the remaining binder.

3.3.1.2 Binder Recovery

The binder recovery method follows AASHTO T170, *Recovery of Asphalt from Solution by Abson Method*, to extract the asphalt from the trichloroethylene/asphalt solution. Figure 3-7 shows the recovery apparatus.

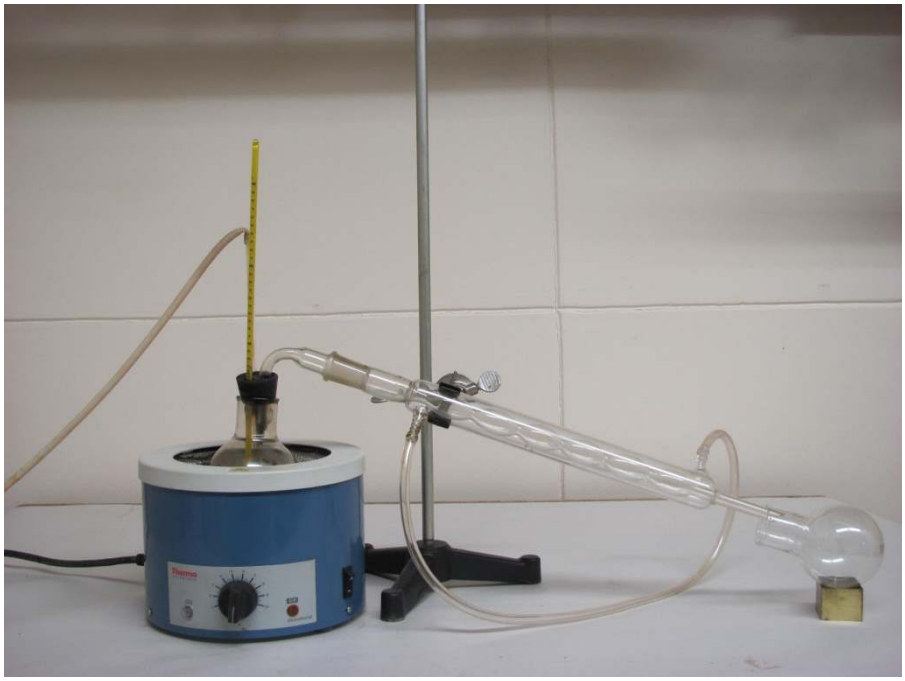

Figure 3-8. Apparatus Used for Recovery of Asphalt

The recovery method was performed by heating the solution of trichloroethylene and asphalt. Once the solution reaches its boiling point, the trichloroethylene begins to evaporate out of the solution. Carbon dioxide gas was introduced at a flow rate of 6.1 $in.^3$/min to prevent the

solution from foaming. The solution was distilled in this manner until about 5 ounces of solution remained. Once this point was reached, the temperature was decreased so that the remaining asphalt would reach a temperature of 320° ± 9°F. After the asphalt reached this temperature, the gas flow rate was increased to approximately 55 in^3/min, and the temperature was held at 320° ± 9°F for 15 minutes to ensure that no trichloroethylene was left in the asphalt.

3.3.2 Binder Tests

3.3.2.1 Performance Grading of Asphalt Binders

The performance grading of the recovered asphalt binders was determined in accordance with AASHTO PP6, *Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder*. The recovered binders were considered to have been short-term aged in the field, which is equivalent to the aging produced by the rolling thin-film oven (RTFO) in the laboratory. Therefore, no RTFO aging was applied to the recovered binders.

3.3.2.2 Frequency Sweep Test

The frequency sweep test applies a series of small oscillations at linearly increasing frequencies to determine the complex shear modulus (G*) of the binder at each of the frequencies. The frequency sweep tests were performed on recovered binders at temperatures of 41, 50, 59, 68, 77, 86 and 95°F, respectively, and at 15 frequencies linearly increasing between 0.1 and 60 Hz at each temperature. The complex shear modulus value was determined for each combination of these temperatures and frequencies. A TA Instruments DSR was used for the frequency sweep tests.

3.3.2.3 Monotonic Test

In a monotonic test, the binder is subjected to a constant shear strain rate, and the resultant stress is measured. The fracture energy of the asphalt is defined as the area underneath the shear stress vs. shear strain curve up to the peak stress, as shown in Figure 3-9. The fracture energy at intermediate temperatures is reported to correlate with the field fatigue cracking of asphalt pavement whereas the fatigue parameter in the Superpave Binder Specifications failed to do so (Wen et al. 2008). The strain at the peak stress at low temperatures is found to correlate with field thermal cracking whereas the creep stiffness and m-value, as well as the critical temperature from the ABCD test method did not (Wen 2011).

Monotonic tests were performed at 41°F and 68°F to characterize the resistance of the binder to thermal and fatigue cracking, respectively. A shear rate of 0.015 was used for the tests performed at 41°F to characterize the thermal cracking, and a shear rate of 0.15 was used at 68°F to characterize fatigue cracking. An exception is that the binders for the Sasobit® and water injection projects were tested for thermal cracking at 50°F with a shear rate of 0.015 and 0.06, respectively, based on trial and error, because the induced stress at 41°F exceeded the DSR capacity. Increasing the test temperature can reduce the induced stress in a monotonic test.

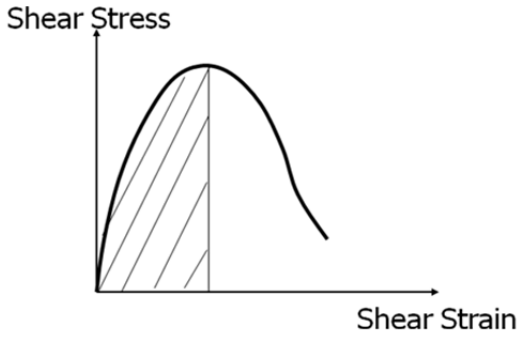

Figure 3-9. Fracture Energy from Monotonic Test

3.3.2.4 Multiple Stress Creep Recovery (MSCR) Test

The multiple stress creep recovery (MSCR) test applies a series of 10 oscillations at a stress level of 100 Pa for 1 second and a rest period of 9 seconds, which is immediately followed by the same loading pattern at a stress level of 3,200 Pa. During the 9-second rest period the viscoelastic binder recovers some of the strain induced by the stress. The non-recoverable compliance (J_{nr}) is calculated as the non-recovered strain divided by the cyclic stress. Previous research has shown that non-recoverable compliance correlates with field rutting performance, when compared to the rutting parameter in the Superpave Binder specifications (D'Angelo 2009). A high value of non-recoverable compliance indicates a low resistance to rutting.

The MSCR tests were performed on recovered binder at the base high temperature PG of the binder. MSCR tests on both HMA and WMA binders were performed at the base temperature of 147°F (64°C) prior to grade bumping. AASHTO TP70, *Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using the Dynamic Shear Rheometer (DSR)*, was followed.

CHAPTER 4: TEST RESULTS AND DISCUSSION

This chapter presents and discusses the results of the tests on mixes and binders to determine the effect of WMA technologies on the performance of the mixes. The WMA technologies affect the performance of mixes (1) directly via the WMA technology's effect on the binder (e.g. reduced aging, less blending between the RAP binder and the virgin binder due to the lower production temperatures), aggregates/RAP (e.g., less drying) or affinity of the binder and the aggregate, and (2) indirectly via the WMA technology's effect on the volumetrics (e.g. density) of the mix. The test results on field cores reflect the difference in performance between the HMA and WMA mixes. It is noted that the test results on the recovered binder, however, focus only on the effects of the WMA technologies on the binder itself in the laboratory, which may not be representative of behavior of binder in the field, due to insufficient blending between the RAP and virgin binders.

4.1 MIX TEST RESULTS

4.1.1 Dynamic Modulus

Figures 4-1 through 4-4 show the dynamic modulus master curves for the HMA and WMA samples. Table 4-1 provides the statistical analysis results, based on the analysis of variation (ANOVA) and a significance level of 0.05. The dynamic modulus values of the Aquablack™ mixes are significantly lower than those of the HMA samples, indicating that the Aquablack™ samples are not as stiff as the HMA control samples. No statistically significant difference in dynamic modulus values was found between the Sasobit®, Gencor® and water injection mixes and their corresponding HMA control mixes. It should be noted that the

Aquablack™ mix has only been in place for one year prior to testing, whereas the other WMA mixes were produced two or three years prior to the time of testing and may be a factor in these results.

Table 4-1. ANOVA Results of Dynamic Modulus of Mixes

Projects	Significance level (p-value)
Aquablack™	***0.00***
Sasobit®	0.58
Gencor®	0.96
Water Injection	0.35

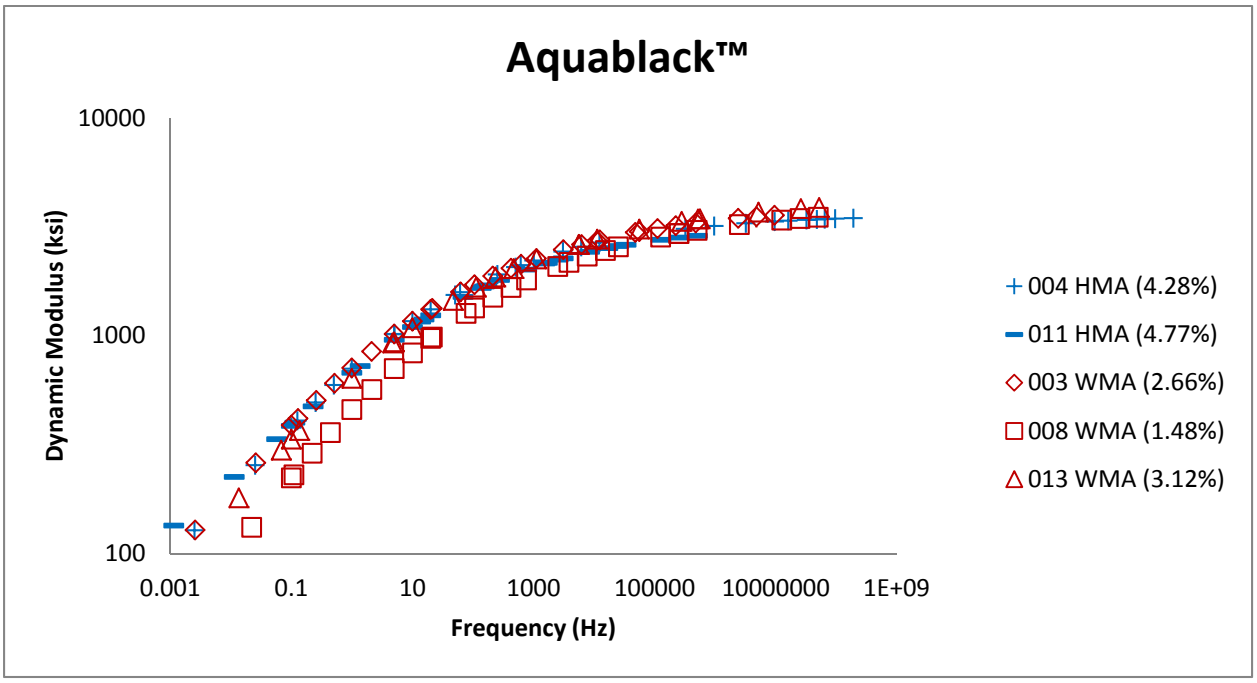

Figure 4-1. Dynamic Modulus Mastercurves of HMA and Aquablack™ Mixes

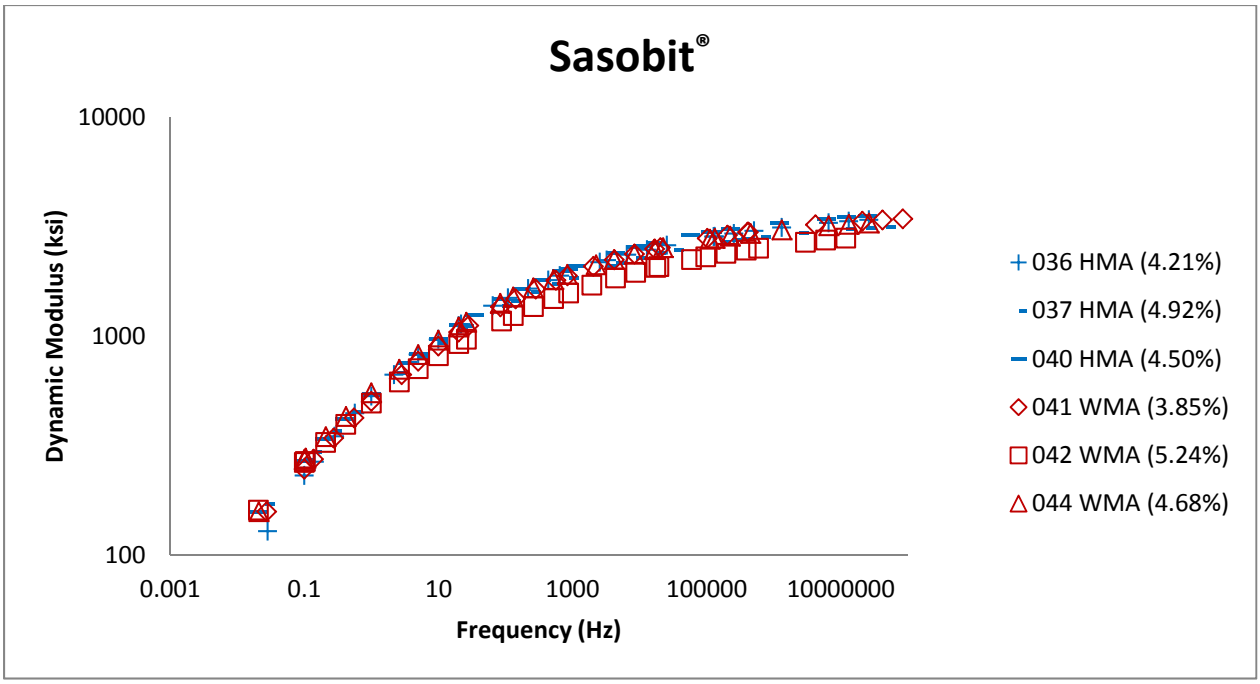

Figure 4-2. Dynamic Modulus Mastercurves of HMA and Sasobit® Mixes

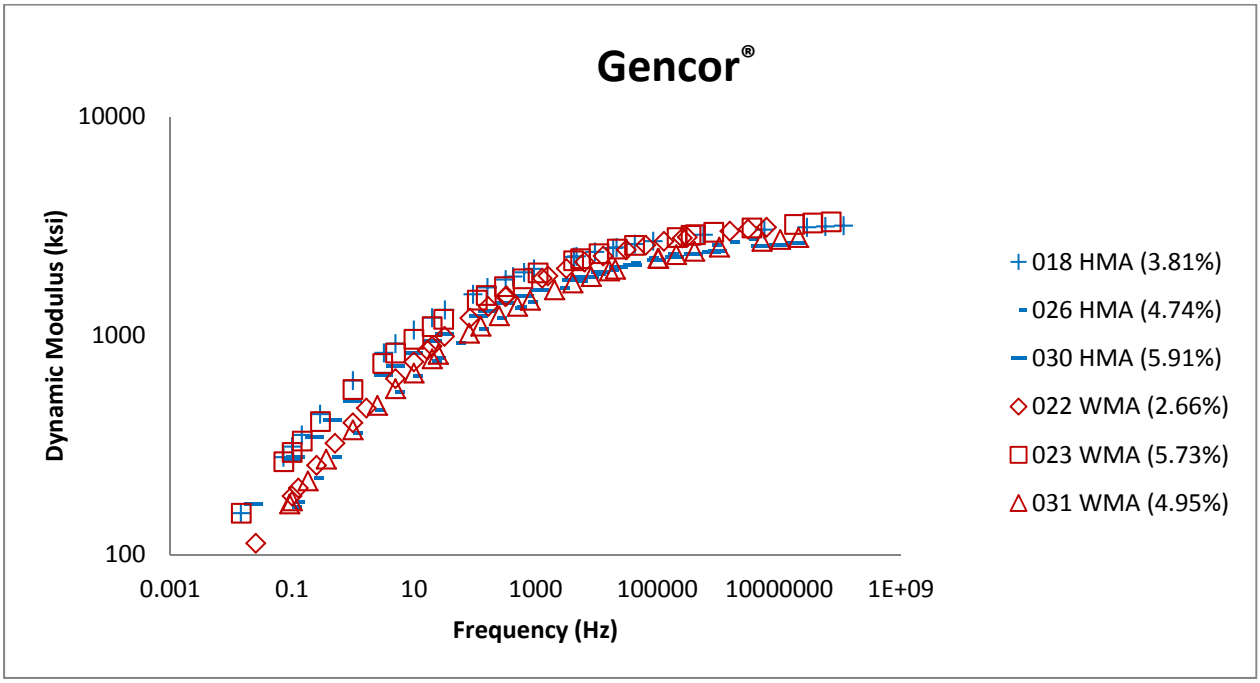

Figure 4-3. Dynamic Modulus Mastercurves of HMA and Gencor® Mixes

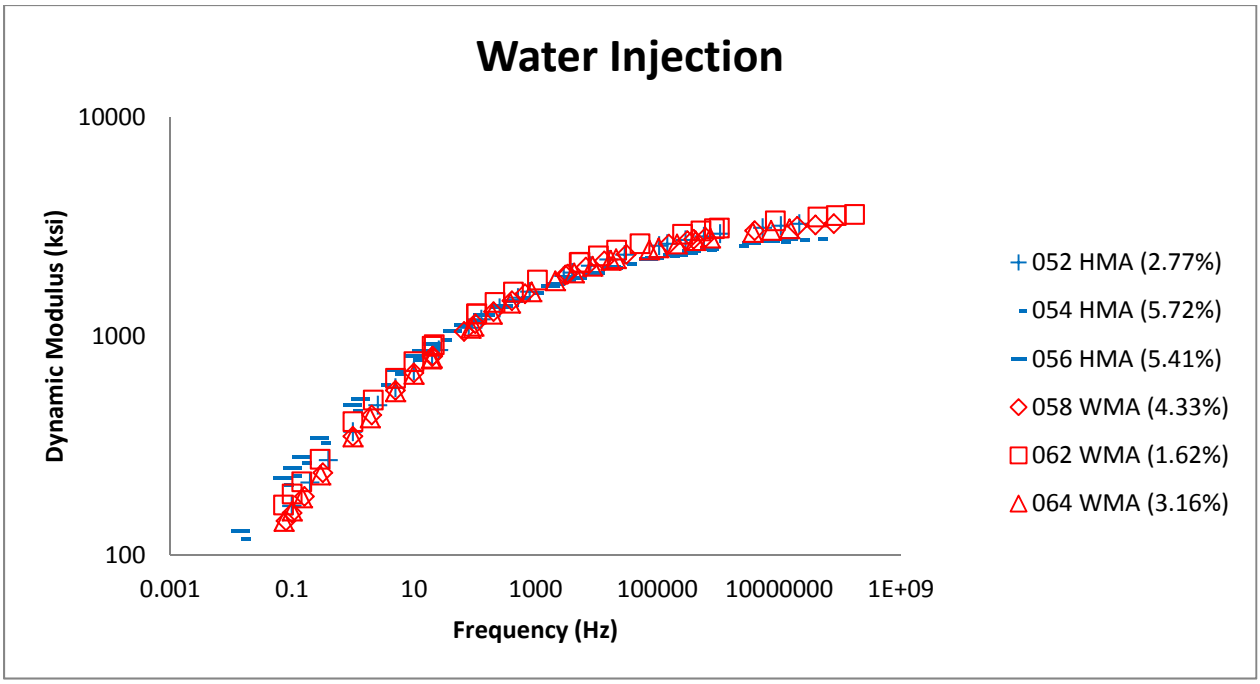

Figure 4-4. Dynamic Modulus Mastercurves of HMA and Water Injection Mixes

4.1.2 IDT Fatigue Cracking

Figures 4-5 through 4-8 show the IDT fatigue cracking test results. Because only three replicates were tested for HMA and WMA, statistical tests for significance, such as the t-test and resampling, are not applicable for the small number of data points and might be misleading. Instead, the 'effect size' method is adopted in this study. The effect size is determined by the difference in the means of two groups divided by the standard deviation (Cohn 1992), as shown in Equation (4-1). After consulting with a statistician, an effect size of 1.6 was used in this study to determine the effect of WMA technologies on the properties of the materials.

$$d = \frac{|\overline{x_t} - \overline{x_c}|}{\sqrt{\frac{(n_t - 1){s_t}^2 + (n_c - 1){s_c}^2}{n_t + n_c}}} \quad (4\text{-}1)$$

where d = effect size
$\overline{x_t}$ = mean of treatment group
$\overline{x_c}$ = mean of control group
n_t = number of samples in treatment group
n_c = number of samples in control group
s_t = standard deviation of treatment group
s_c = standard deviation of control group

Table 4-2 provides the mean values for the fracture work and effect sizes. The effect size of 3.35 indicates that the Sasobit® mix has statistically lower fracture work than the HMA control mix and, thus, is less resistant to fatigue cracking than the HMA control mix. The effect sizes for the other WMA mixes are less than 1.6, indicating no difference in fracture work or resistance to fatigue cracking between the Aquablack™, Gencor®, and water injection WMA mixes and their corresponding HMA control mixes.

Table 4-2. Fatigue Test Results

Project	Mean Fracture Work (lb-in)		Effect Size
	HMA	WMA	
Aquablack™	650	698	1.13
Sasobit®	665	592	***3.35***
Gencor®	611	602	0.12
Water Injection	633	609	0.62

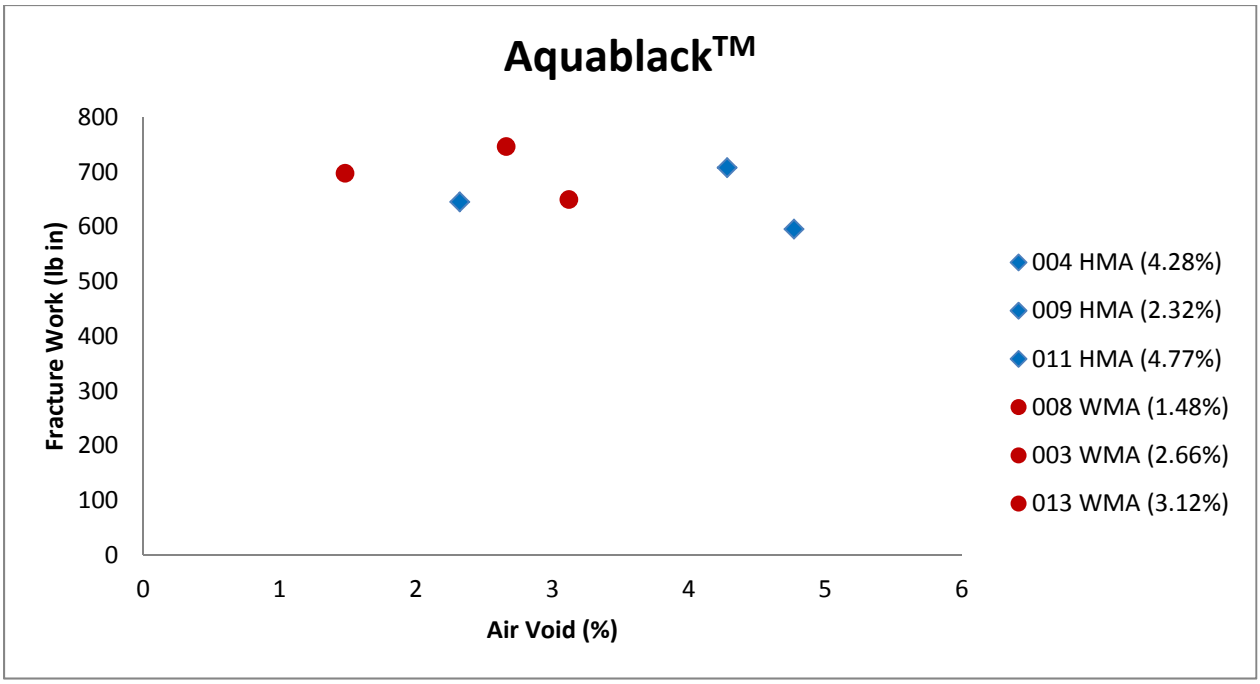

Figure 4-5. Fracture Work of HMA and Aquablack™ Mixes

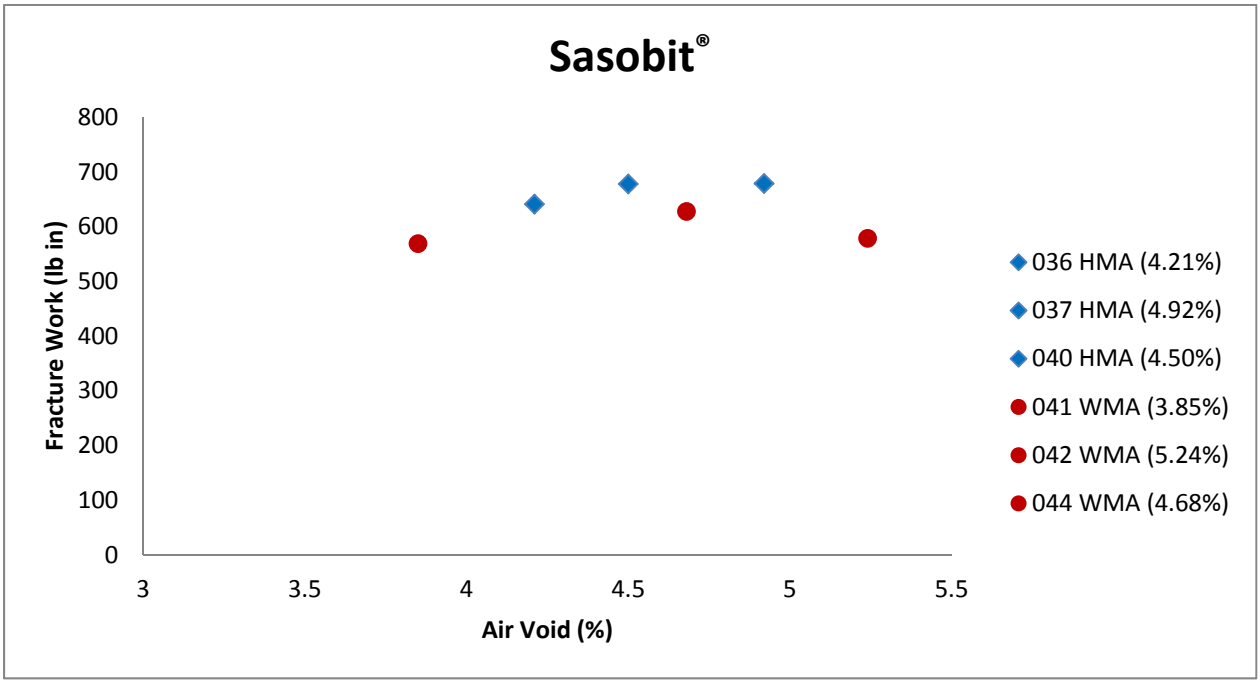

Figure 4-6. Fracture Work of HMA and Sasobit® Mixes

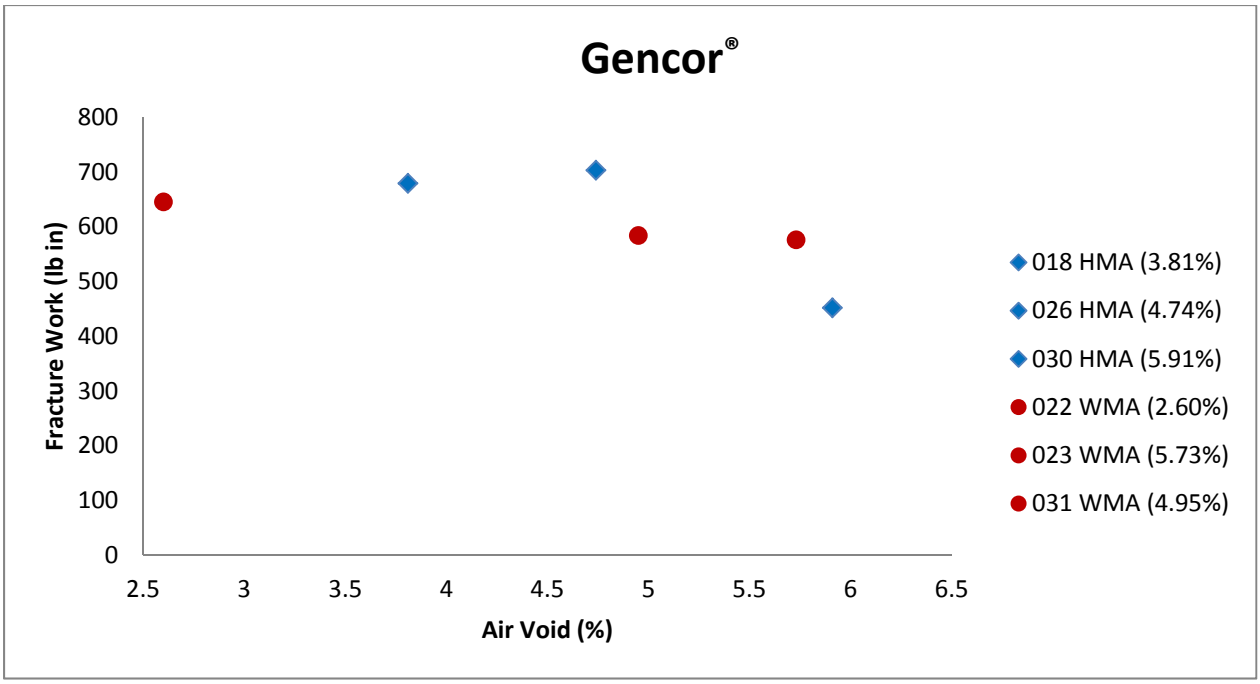

Figure 4-7. Fracture Work of HMA and Gencor® Mixes

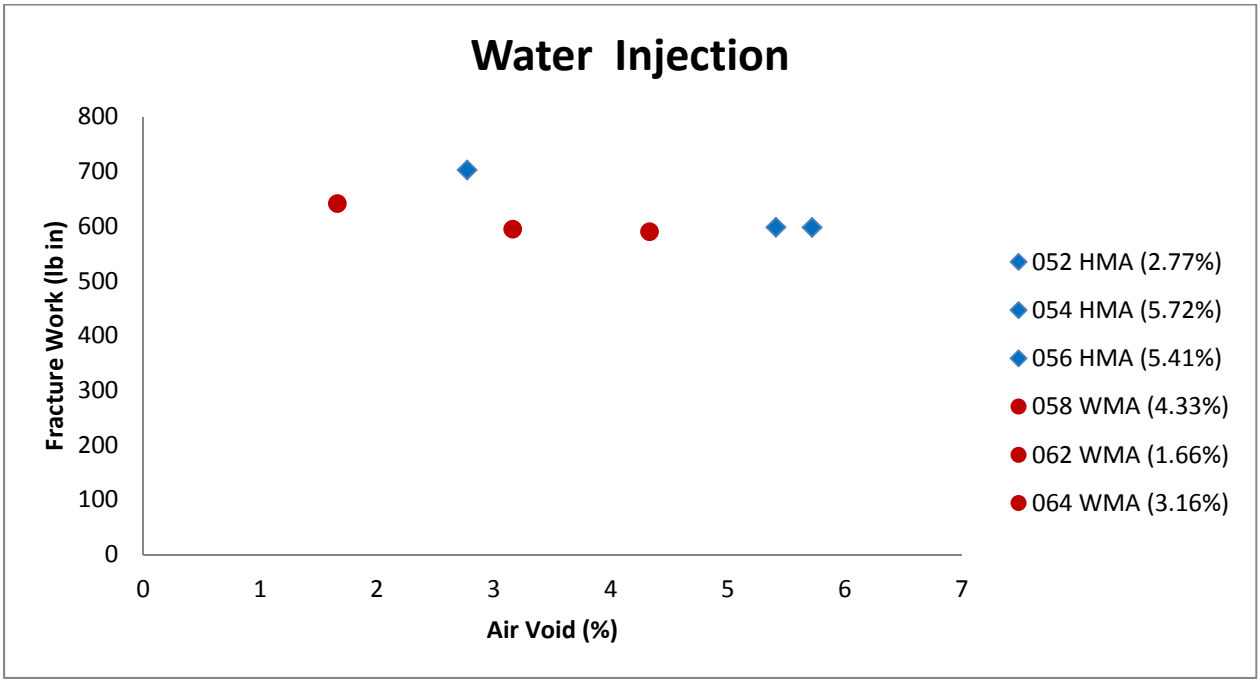

Figure 4-8. Fracture Work of HMA and Water Injection Mixes

4.1.3 IDT Thermal Cracking

Figures 4-9 through 4-12 show the IDT thermal cracking test results. Table 4-3 provides the mean values of fracture work and effect sizes. The effect size results indicate that the Gencor® and water injection WMA mixes have higher fracture work than their corresponding HMA control mixes, indicating more resistance to thermal cracking by the Gencor® and water injection WMA mixes than their corresponding HMA mixes. Statistical analysis showed no significant difference between the Aquablack™ and Sasobit® mixes and their corresponding HMA control mixes. However, the fracture work values of Aquablack™ and Sasobit® mixes were lower than their corresponding HMA control mixes.

Table 4-3. Thermal Cracking Test Results

Project	Mean Fracture Work (lb-in)		Effect Size
	HMA	WMA	
Aquablack™	275	246	1.55
Sasobit®	241	222	0.94
Gencor®	228	281	***1.62***
Water Injection	247	378	***1.82***

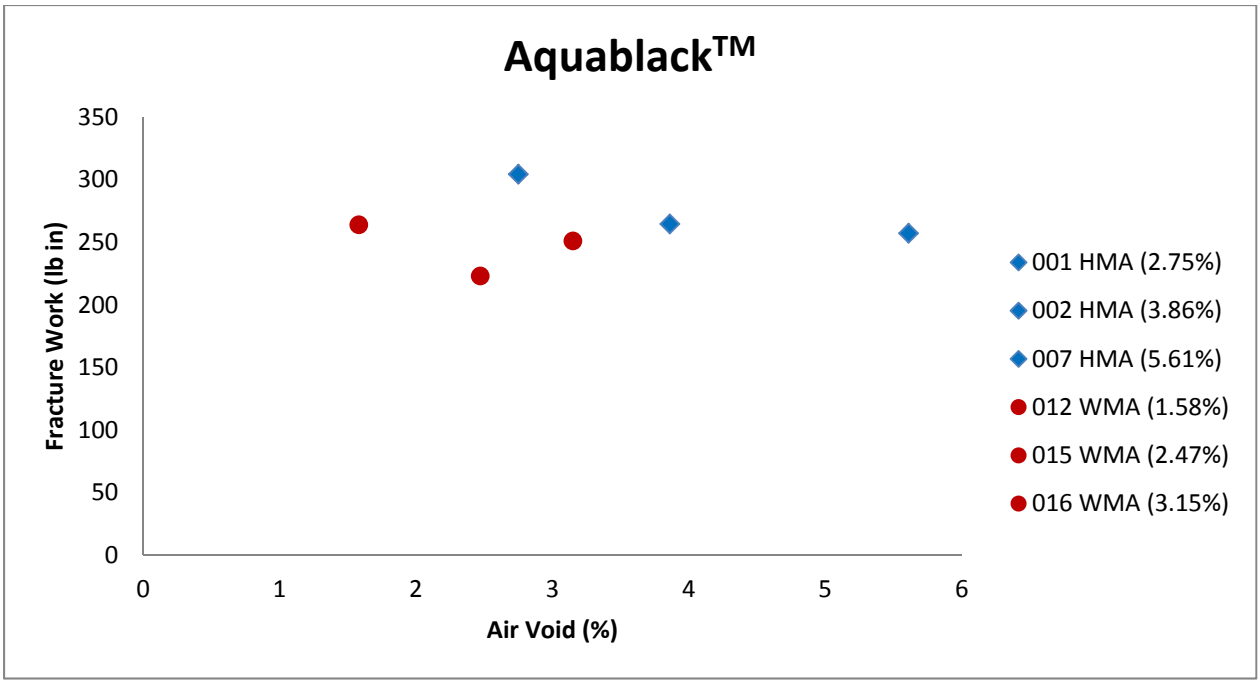

Figure 4-9. Fracture Work of HMA and Aquablack™ Mixes

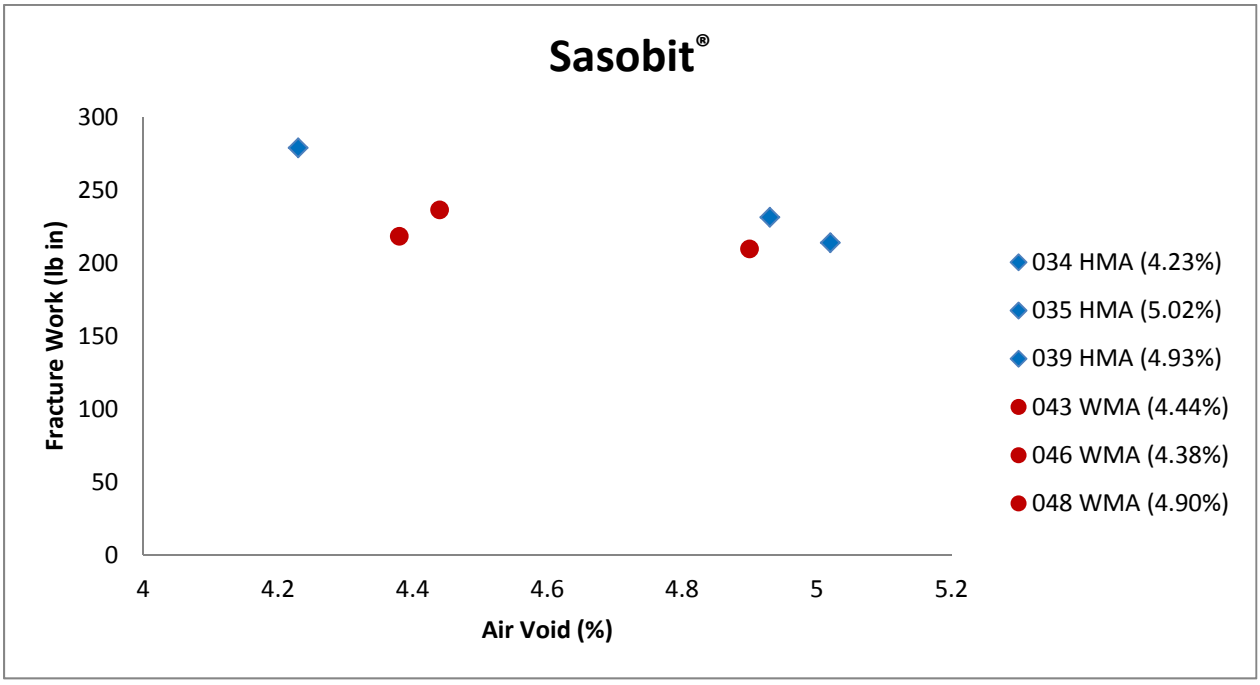

Figure 4-10. Fracture Work of HMA and Sasobit® Mixes

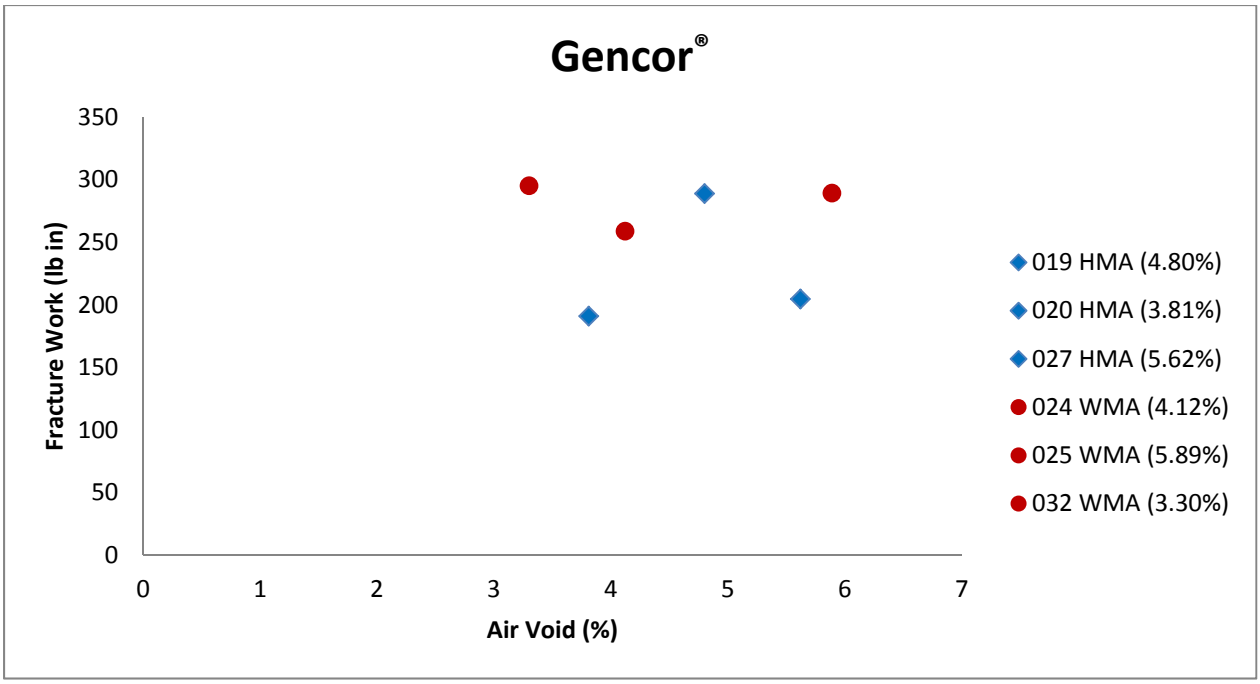

Figure 4-11. Fracture Work of HMA and Gencor® Mixes

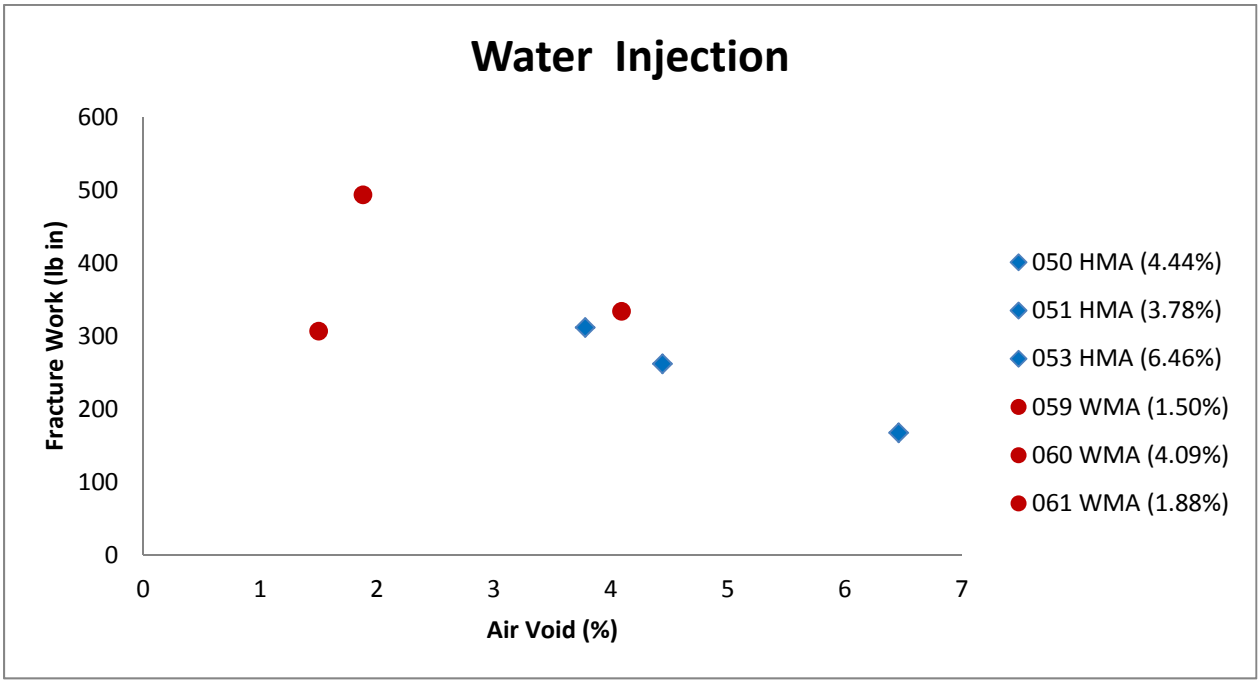

Figure 4-12. Fracture Work of HMA and Water Injection Mixes

4.1.4 High Temperature IDT Strength

Figures 4-13 through 4-16 show the high temperature IDT strength test results. Table 4-4 provides the mean values of the high temperature IDT strength values and effect sizes. The effect size results indicate that Aquablack™ WMA mix has a higher high temperature IDT strength or rutting resistance than the HMA control mix whereas Gencor® WMA mix had lower high temperature IDT strength than the HMA control mix. However, no difference is evident for the high temperature IDT strength or rutting resistance between the Sasobit® mix and the HMA control mix. Because only one sample was tested for the water injection mix, no conclusions can be drawn to compare the rutting resistance of the water injection mix to the HMA control mix.

Table 4-4. High Temperature IDT Strength Test Results

Project	IDT Strength (psi)		Effect Size
	HMA	WMA	
Aquablack™	23.1	29.7	***8.58***
Sasobit®	47.8	46.4	0.15
Gencor®	35.5	24.4	***4.12***
Water Injection	28.0	22.5	*N/A*

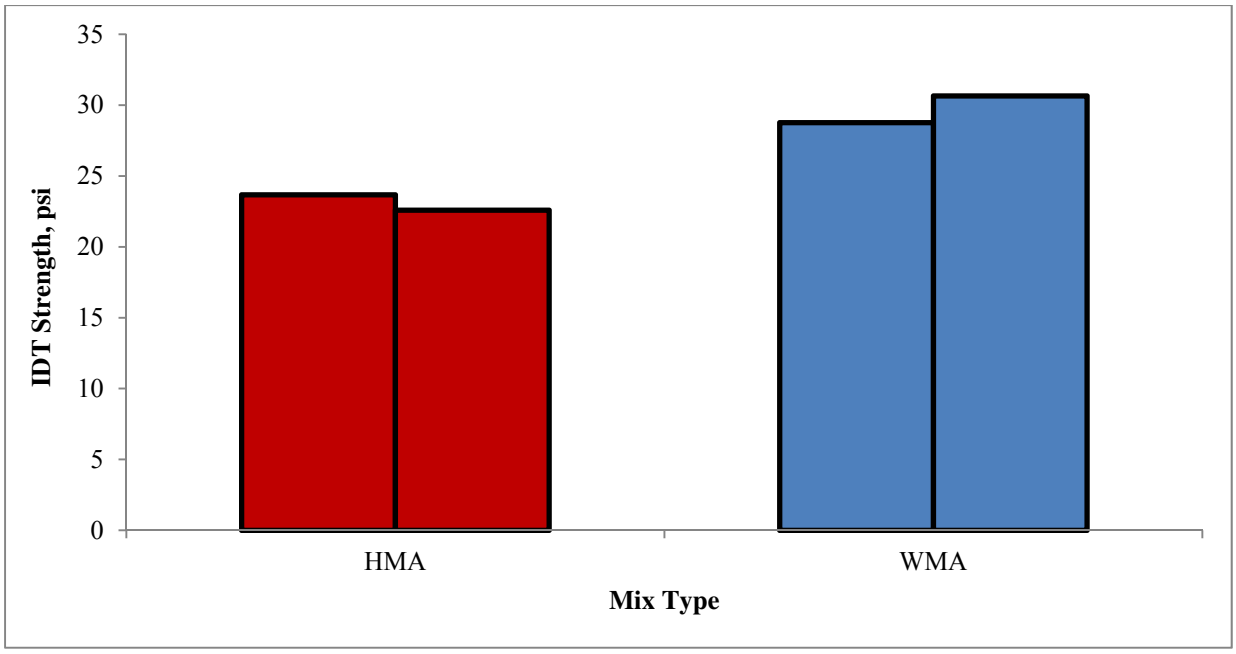

Figure 4-13. High Temperature IDT Peak Loads of HMA and Aquablack™ Mixes

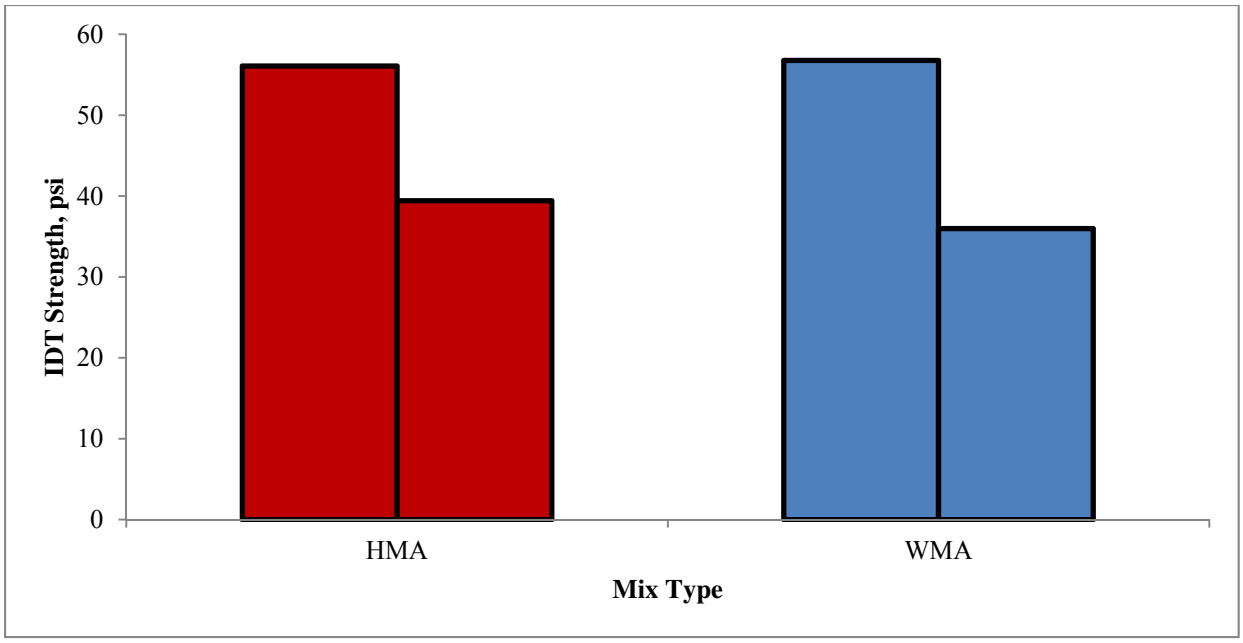

Figure 4-14. High Temperature IDT Peak Loads of HMA and Sasobit® Mixes

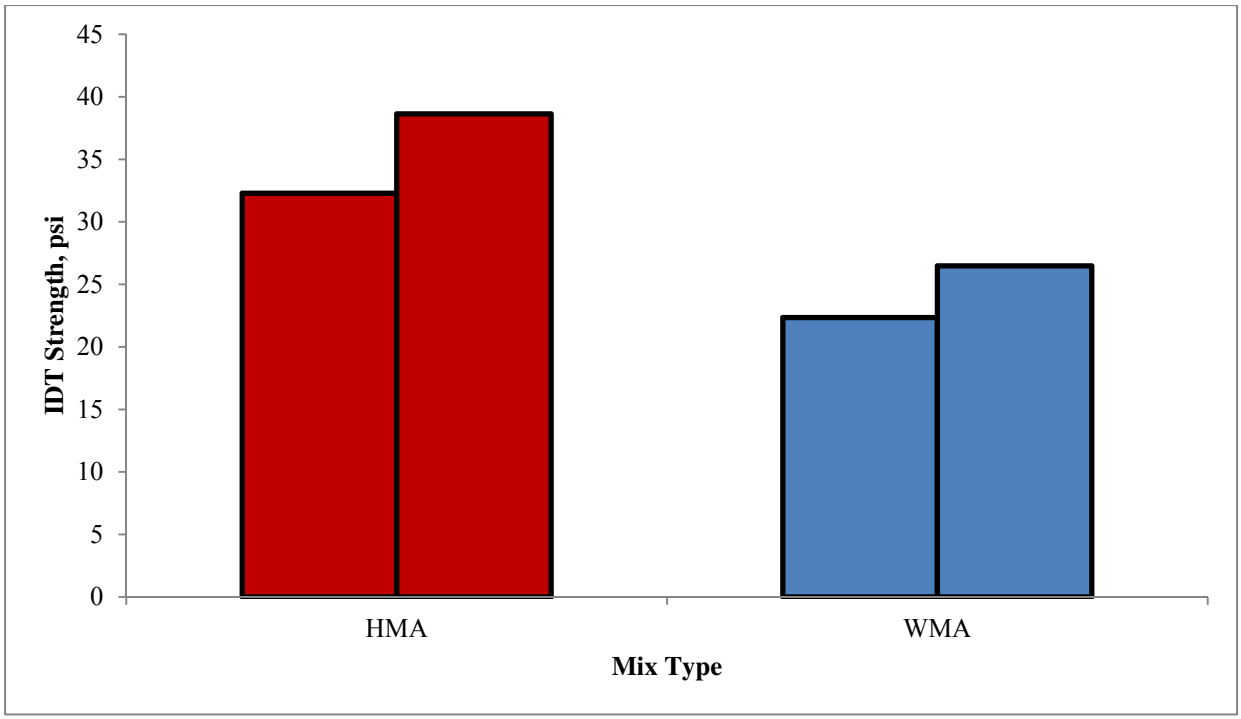

Figure 4-15. High Temperature IDT Peak Loads of HMA and Gencor® Mixes

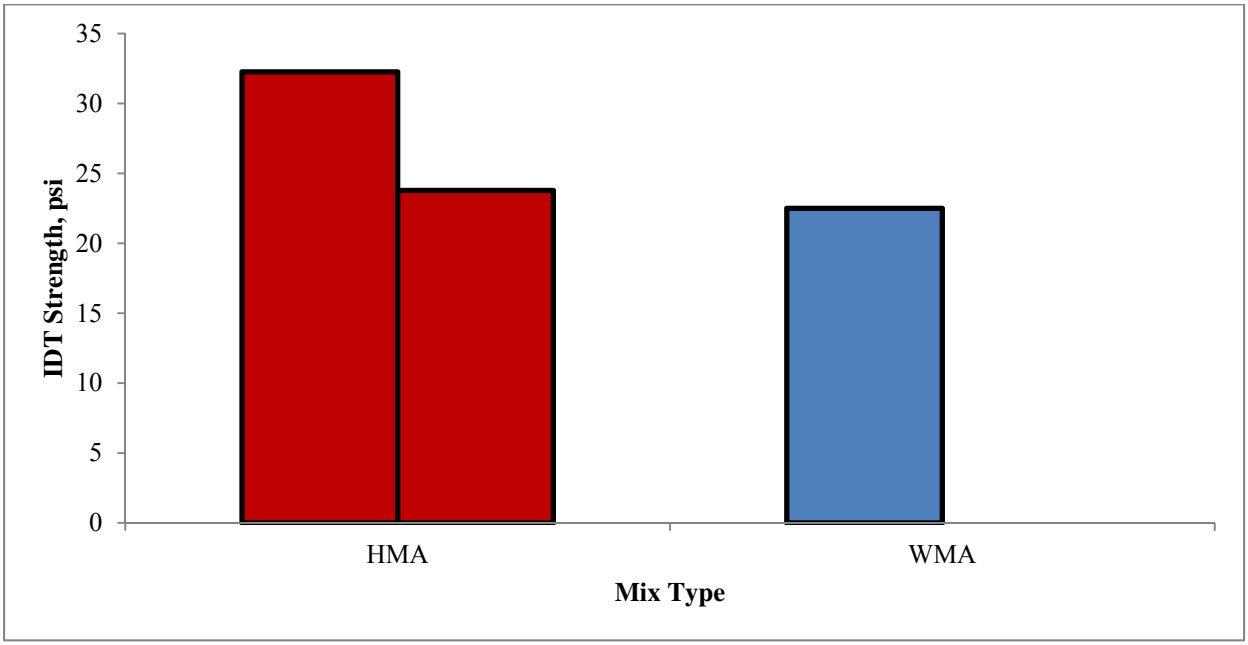

Figure 4-16. High Temperature IDT Peak Loads of HMA and Water Injection Mixes

4.1.5 HWTD Results for Rutting and Susceptibility

Figure 4-17 shows the results of HWTD tests on HMA and WMA for all four projects. Table 4-5 shows the t-test results on rut depth from HWTD tests. There is no statistically significant difference between the Sasobit® and Aquablack™ sections with their corresponding HMA mixes. The water injection and Gencor® mixes had statistically significantly larger rut depths than their corresponding HMA control mixes. However, the rut depth of both the water injection and Gencor® mixes are well within the acceptable level of rut depth, which is typically 12.5 mm after 20,000 passes. It can be seen that there is no pronounced stripping inflection point for all the mixes, indicating that all the mixes are not susceptible to moisture damage.

Table 4-5. High Temperature IDT Strength Test Results

Project	HWTD Rut Depth (mm)		p-value
	HMA	WMA	
Aquablack™	3.64	3.21	0.23
Sasobit®	1.80	1.85	0.58
Gencor®	3.16	4.17	***0.00***
Water Injection	2.66	3.92	***0.00***

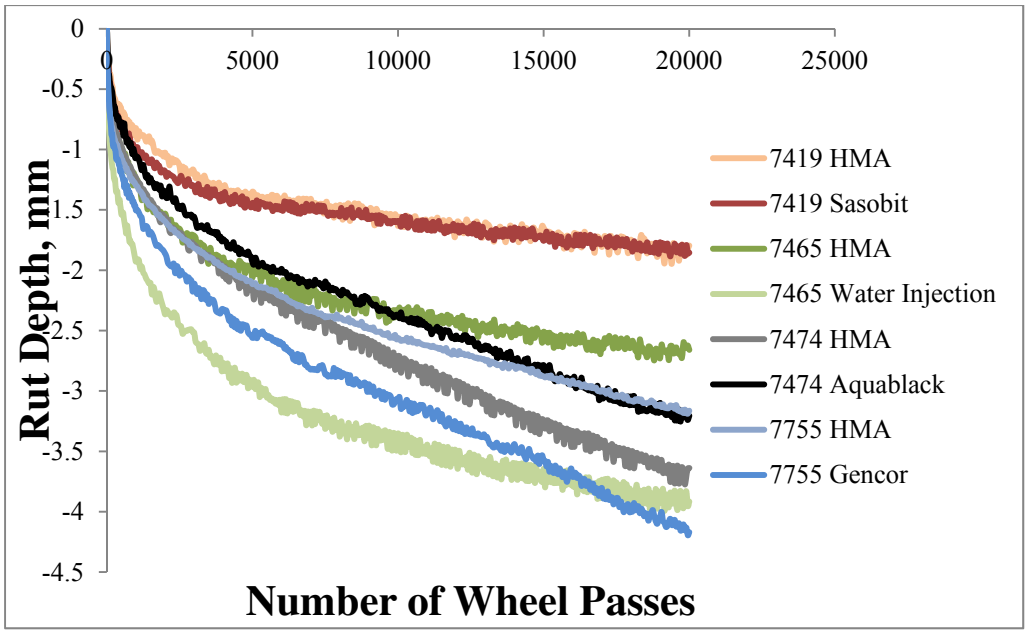

Figure 4-17. HWTD Test Results on HMA and WMA

4.1.6 Summary of Findings for Mix Test Results

The mix test results are summarized in Table 4-6. In the table, the "=" indicates no differences between the HMA and WMA mixes; "-" indicates that the performance of the WMA is adversely affected; and "+" indicates positive effects. However, for the dynamic modulus values, the signs indicates only the stiffness values and do not imply any effect on performance. Based on the test results, it seems that the rutting performance of the Gencor® and Water Injection mixes were adversely affected as well as the Sasobit® for fatigue cracking. But, even though the rutting performance for the WMA was not as good as the HMA, the WMA did not even approach the failure limits for rutting in the Hamburg.

In the other cases, the WMA mixes exhibit an equivalent or better performance than the HMA mixes. Because there are more differences in the mixes than just WMA additives (e.g.

inclusion and blending of RAP and air voids), these results do not necessarily suggest that the WMA technology should not be used.

Table 4-6. Summary of Mix Test Results

Projects	Dynamic Modulus	Fatigue cracking	Thermal cracking	Rutting	Moisture Susceptibility
Aquablack™	-	=	=	=	=
Sasobit®	=	-	=	=	=
Gencor®	=	=	+	-	=
Water Injection	=	=	+	-	=

Note: the rutting and moisture susceptibility results presented in this table are from the HWTD.

4.2 BINDER TEST RESULTS

4.2.1 Performance Grades of Binders

Tables 4-7 to 4-10 present the true grade test results of the extracted binders. Table 4-11 shows the PGs of the original and recovered binders. Note that even though the performance grading changed from the original binder, it is the same for both the HMA and WMA of the recovered binder, regardless of technology. For the three foaming technologies and their control HMAs, the PGs changed from the original PG 64-28 to PG 70-22. Both the high and low grades were bumped up one grade. For the organic additive, Sasobit®, and its control HMA, the PG of the binder changed from the original PG 76-28 to PG 76-22. Only the low temperature was bumped up one grade. Also, note that the recovered binder consists of completely blended RAP binder and virgin binder, whereas in a mix, the blending between the RAP binder and virgin binder could be only partial.

Table 4-7. True Grade Test Results of Contract 7419

Contract 7419 HMA						
	RTFO		PAV		BBR	
Temperature	76 ˚C	82 ˚C	25˚ C	28 ˚C	(- 18) ˚C	(-12)˚C
Pass/Fail	Pass	Fail	Pass	Pass	Fail	Pass
G*/sinδ kPa	3.27	1.88	-	-	-	-
G*sinδ kPa	-	-	3300	2290	-	-
m-value	-	-	-	-	0.276	0.32
Creep Stiffness MPa	-	-	-	-	277.04	141.46
True Grade	PG 76-22					
Contract 7419 WMA						
	RTFO		PAV		BBR	
Temp	76 ˚C	82˚C	25 ˚C	28 ˚C	(-18)˚C	(-12) ˚C
Pass/Fail	Pass	Fail	Pass	Pass	Fail	Pass
G*/sinδ kPa	3.39	1.91	-	-	-	-
G*sinδ kPa	-	-	4240	2980	-	-
m-value	-	-	-	-	0.263	0.303
Creep Stiffness MPa	-	-	-	-	287.55	155.3
True Grade	PG 76-22					

Table 4-8. True Grade Test Results of Contract 7645

Contract 7645 HMA							
	RTFO			PAV		BBR	
Temperature	64 ˚C	70 ˚C	76 ˚C	22 ˚C	25 ˚C	(-18) ˚C	(-12) ˚C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Fail	Pass
G*/sinδ kPa	8.44	4.09	2.08	-	-		-
G*sinδ kPa	-	-	-	5380	3910		-
m-value	-	-	-	-	-	0.268	0.328
Creep Stiffness MPa	-	-	-	-	-	265.65	130.47
True Grade	PG 70-22						
Contract 7645 WMA							
	RTFO			PAV		BBR	
Temperature	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 kPa	4.69	2.34	1.17	-	-		-
G*sinδ kPa	-	-	-	5970	4250		-
m-value	-	-	-	-	-	0.293	0.326
Creep Stiffness MPa	-	-	-	-	-	219.039	121.979
True Grade	PG 70-22						

Table 4-9. True Grade Test Results of Contract 7474

Contract 7474 HMA						
	RTFO			PAV		BBR
Temperature	64 ˚C	70 ˚C	76 ˚C	22 ˚C	25 ˚C	(-12)˚C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Pass
G*/sinδ kPa	6.73	3.14	1.52	-	-	-
G*sinδ kPa	-	-	-	6.53	4.81	-
m-value	-	-	-	-	-	0.313
Creep Stiffness MPa	-	-	-	-	-	173.535
True Grade	PG 70-22					
Contract 7474 WMA						
	RTFO			PAV		BBR
Temperature	64 ˚C	70 ˚C	76 ˚C	22 ˚C	25 ˚C	(-12) ˚C
Pass/Fail	Pass	Pass	Fail	Fail	Pass	Pass
G*/sinδ kPa	5.43	2.64	1.23	-	-	-
G*sinδ kPa	-	-	-	5470	4160	-
m-value	-	-	-	-	-	0.332
Creep Stiffness MPa	-	-	-	-	-	176.72
True Grade	PG 70-22					

Table 4-10. True Grade Test Results of Contract 7755

Contract 7755 HMA							
	Recovered			PAV		BBR	
Temperature	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 kPa	7.73	3.52	1.65	-	-	-	-
G*sinδ kPa	-	-	-	6.75	4.88	-	-
m-value	-	-	-	-	-	0.28	0.309
Creep Stiffness MPa	-	-	-	-	-	236.07	140.993
True Grade	PG 70-22						
Contract 7755 WMA							
	Recovered			PAV		BBR	
Temperature	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 kPa	5.22	2.47	1.17	-	-	-	-
G*sinδ kPa	-	-	-	6856	4890	-	-
m-value	-	-	-	-	-	0.257	0.303
Creep Stiffness MPa	-	-	-	-	-	221.85	146.06
True Grade	PG 70-22						

Table 4-11. Performance Grades of Binders

Projects	PG Grades		
	Original	Recovered	
		HMA	WMA
Aquablack™	64-28	70-22	70-22
Sasobit®	76-28	76-22	76-22
Gencor®	64-28	70-22	70-22
Water Injection	64-28	70-22	70-22

4.2.2 Complex Shear Modulus

Figures 4-18 through 4-21 present the results of the complex modulus frequency sweep tests. Table 4-12 provides the ANOVA statistical analysis results. The analysis was performed at 95% confidence interval with a p-value of 0.05. It can be seen that all four WMA binder samples have significantly lower complex shear modulus values than their corresponding HMA binder samples, which may be due to the lower production temperatures and reduced aging for the WMA mixes.

Table 4-12. ANOVA Analysis of Complex Shear Modulus

Projects	p-value
Aquablack™	***0.004***
Sasobit®	***0.000***
Gencor®	***0.047***
Water Injection	***0.025***

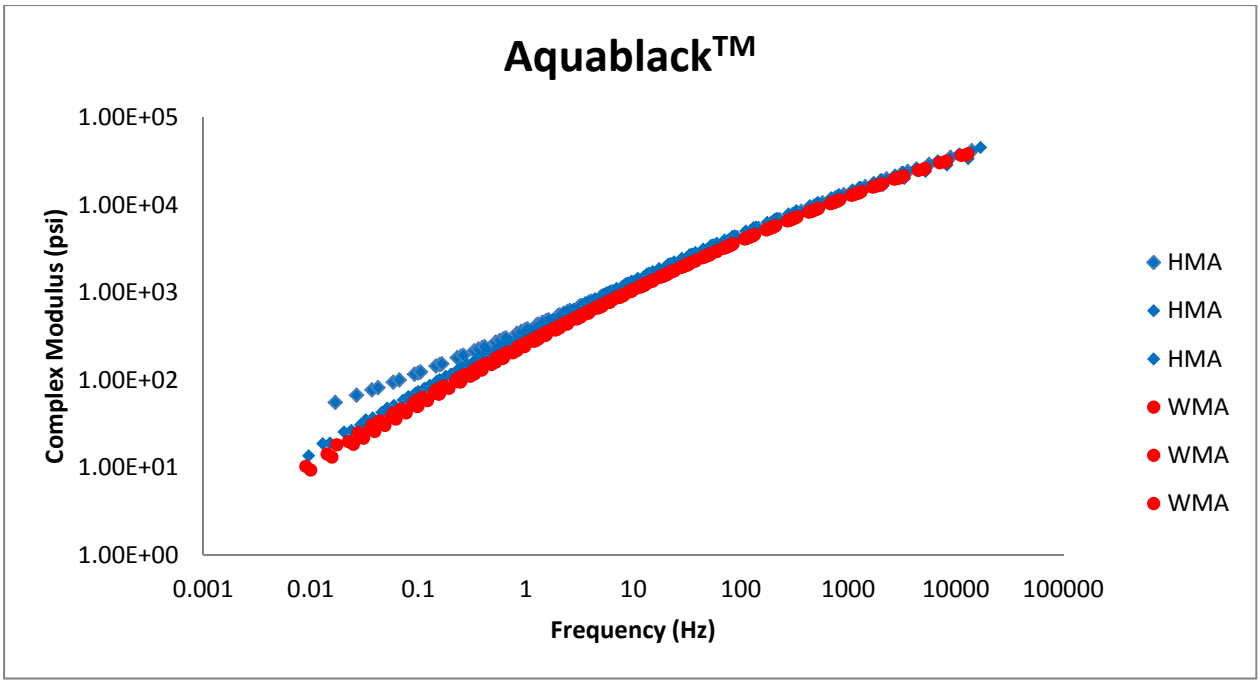

Figure 4-18. Complex Shear Modulus Mastercurves of Binders in HMA and Aquablack™ Mixes

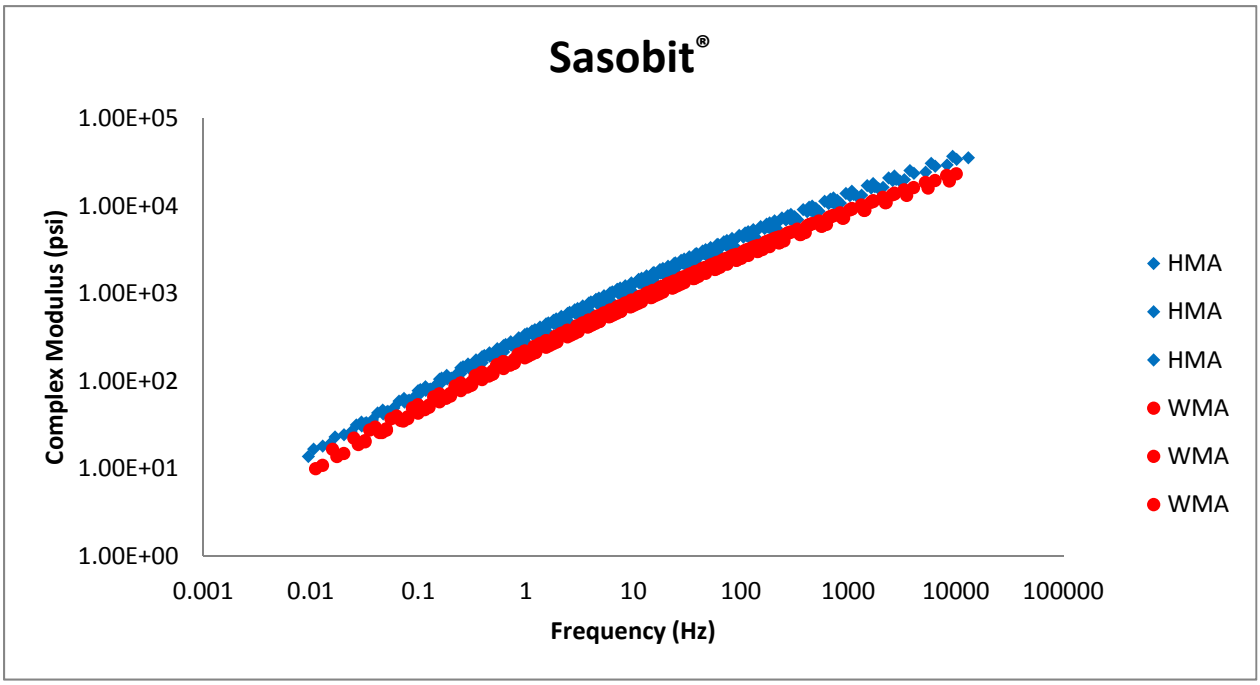

Figure 4-19. Complex Modulus Mastercurves of Binders in HMA and Sasobit® Mixes

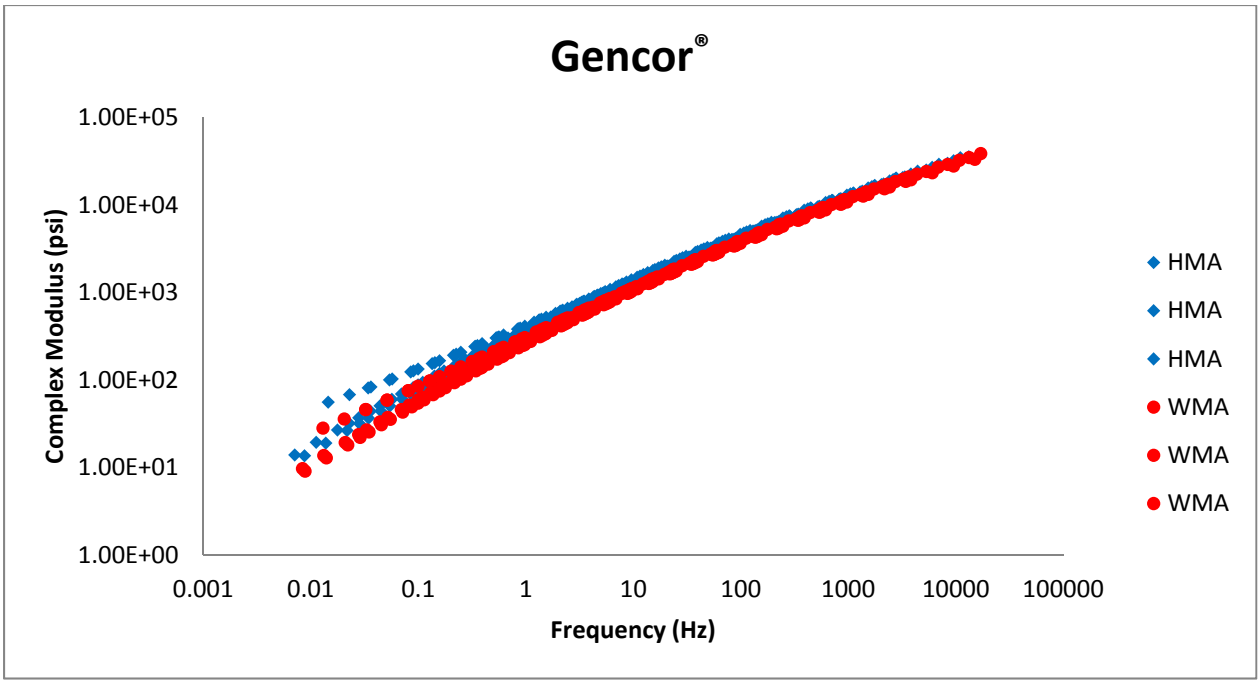

Figure 4-20. Complex Modulus Mastercurves of Binders in HMA and Gencor® Mixes

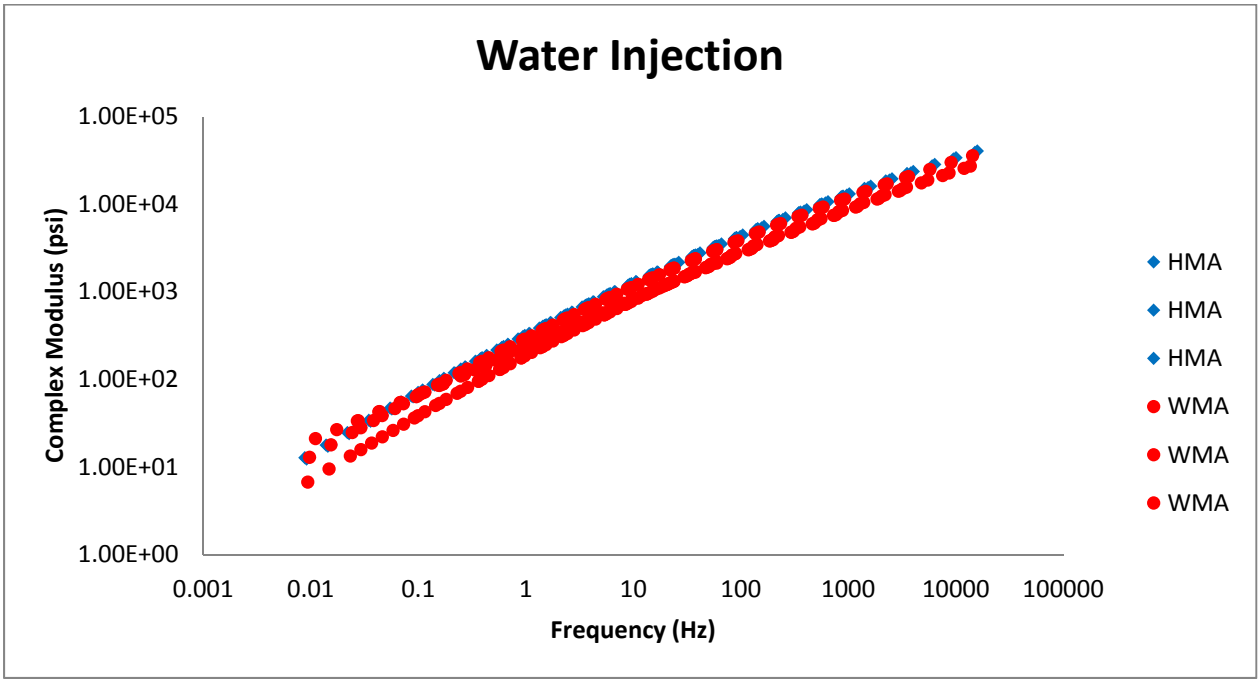

Figure 4-21. Complex Modulus Mastercurves of Binders in HMA and Water Injection Mixes

4.2.3 Multiple Stress Creep Recovery Test

Figures 4-22 through 4-25 show the results of the MSCR binder tests in terms of non-recoverable compliance (J_{nr}). Table 4-13 presents the means of the non-recoverable compliance and effect size results. The effect size results indicate no difference in the non-recoverable compliance and, thus, in the rutting resistance between the Sasobit® and HMA binders. However, the Aquablack™, Gencor®, and water injection binders show higher non-recoverable compliance than their corresponding HMA binders, indicating lower resistance to rutting by these WMA binders. For the Aquablack™, Gencor®, and water injection binders, the susceptibility of the binders to rutting may be due to the lowered production temperature and reduced aging. However, for the Sasobit® binder, the addition of the Sasobit® additive might stiffen the binder and offset the effect from reduced aging.

Table 4-13. Non-recoverable Compliance

Project	Mean J_{nr} (1/psi)		Effect Size
	HMA	WMA	
Aquablack™	1.23	1.71	***5.35***
Sasobit®	0.28	0.27	0.62
Gencor®	1.01	2.10	***22.96***
Water Injection	0.84	1.76	***27.39***

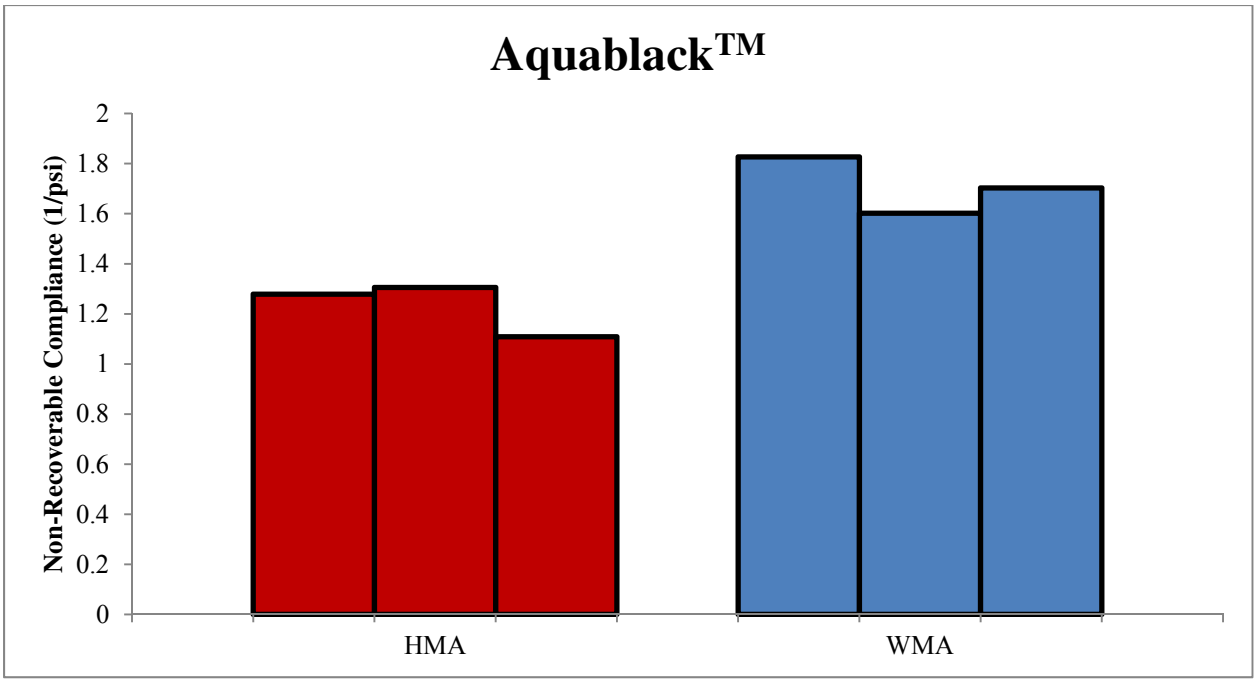

Figure 4-22 Non-Recoverable Compliance of Aquablack™ and HMA Binders

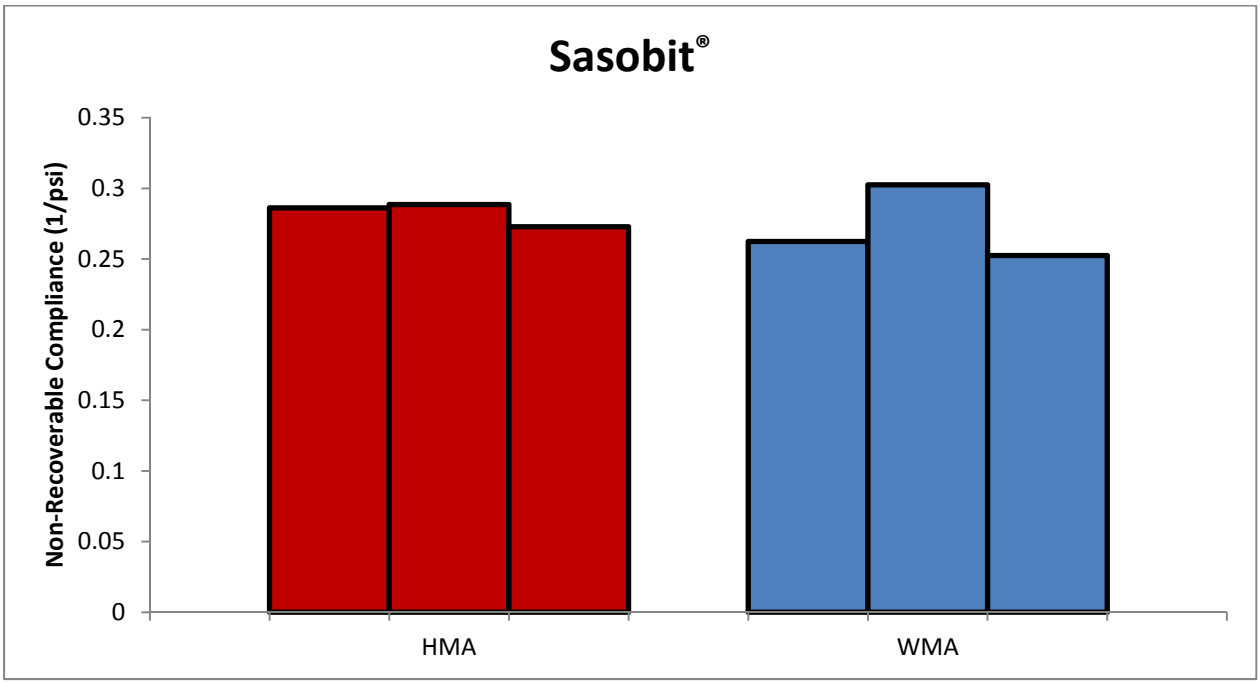

Figure 4-23. Non-Recoverable Compliance of HMA and Sasobit® Binders

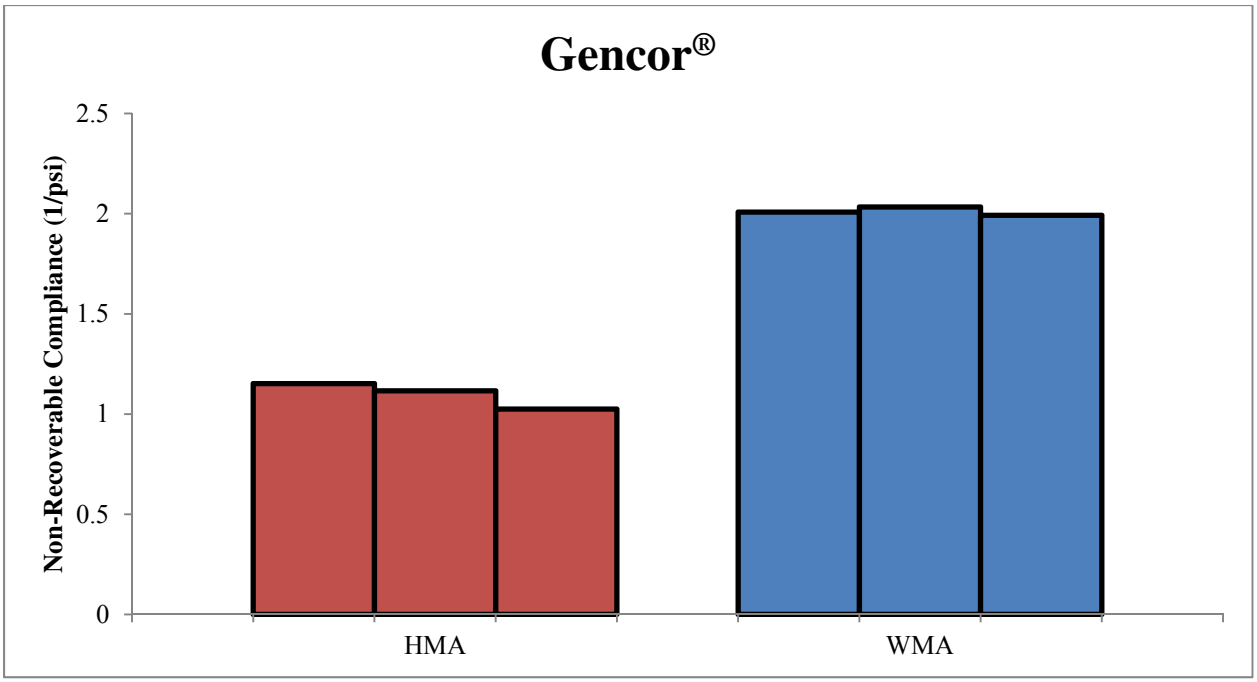

Figure 4-24. Non-Recoverable Compliance of HMA and Gencor® Binders

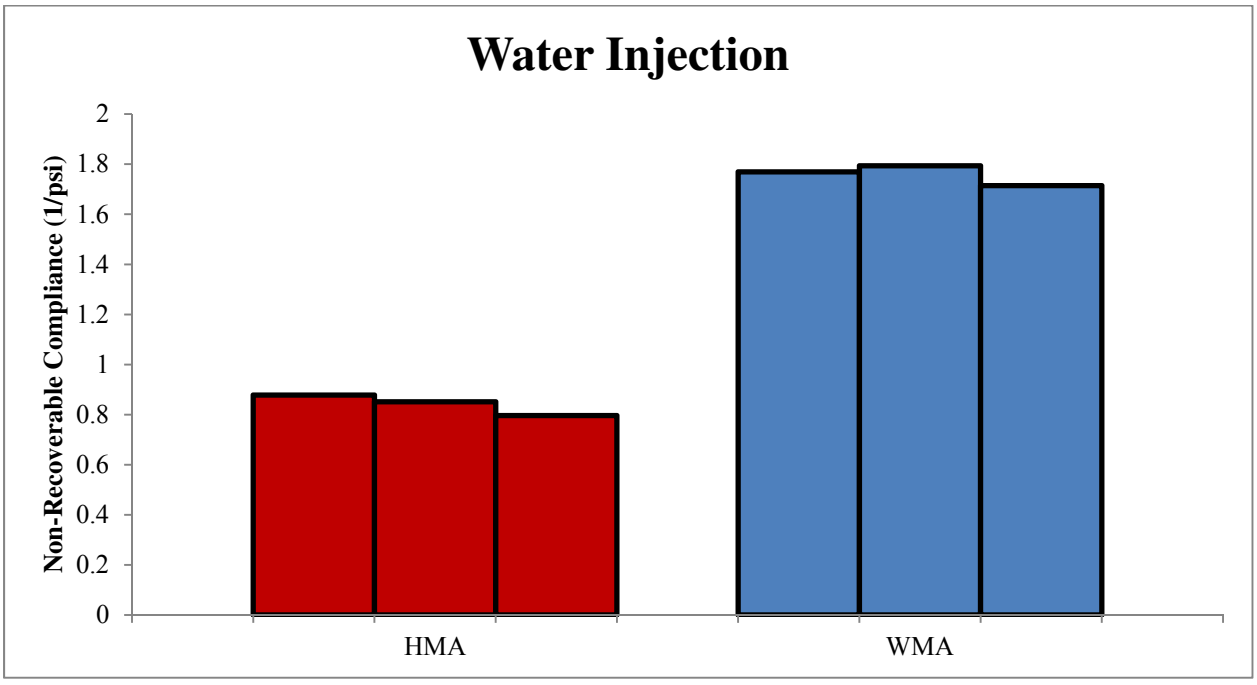

Figure 4-25. Non-Recoverable Compliance of HMA and Water Injection Binders

4.2.4 Fatigue

Figures 4-26 through 4-29 present the results of the fracture energy of the binders tested at 68ºF. Table 4-14 shows the results of the fracture energy of the binders for fatigue characterization and their effect sizes. The effect size results presented in Table 4-14 indicate that all the WMA binders show less fracture energy and, thus, lower resistance to fatigue cracking than their corresponding HMA binders. A comparison of the test results between the Aquablack™ and HMA binders is illustrated in Figure 4-30. The Aquablack™ binder's strength (maximum stress) is reduced. However, the ductility (or the failure shear strain at the maximum shear stress) of the Aquablack™ binder is comparable to that of the HMA binder, which may explain the reason that HMA binders have a higher fracture energy value than the WMA binders. Also note the absolute difference between the fracture energy results between the different mixes.

Table 4-14. Fracture Energy of Binders

Project	Fracture Energy (psi)		Effect Size
	HMA	WMA	
Aquablack™	114	86	***7.73***
Sasobit®	410	277	***2.45***
Gencor®	90	74	***3.33***
Water Injection	617	339	***4.85***

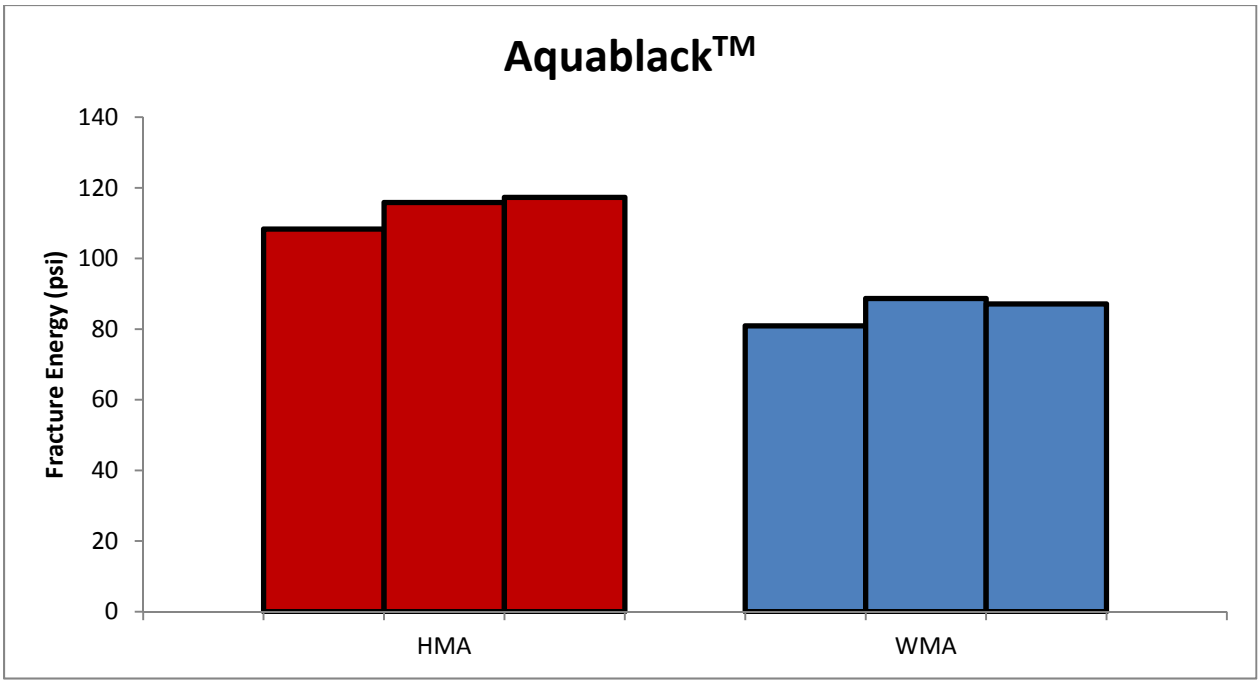

Figure 4-26. Fracture Energy of HMA and Aquablack™ Binders

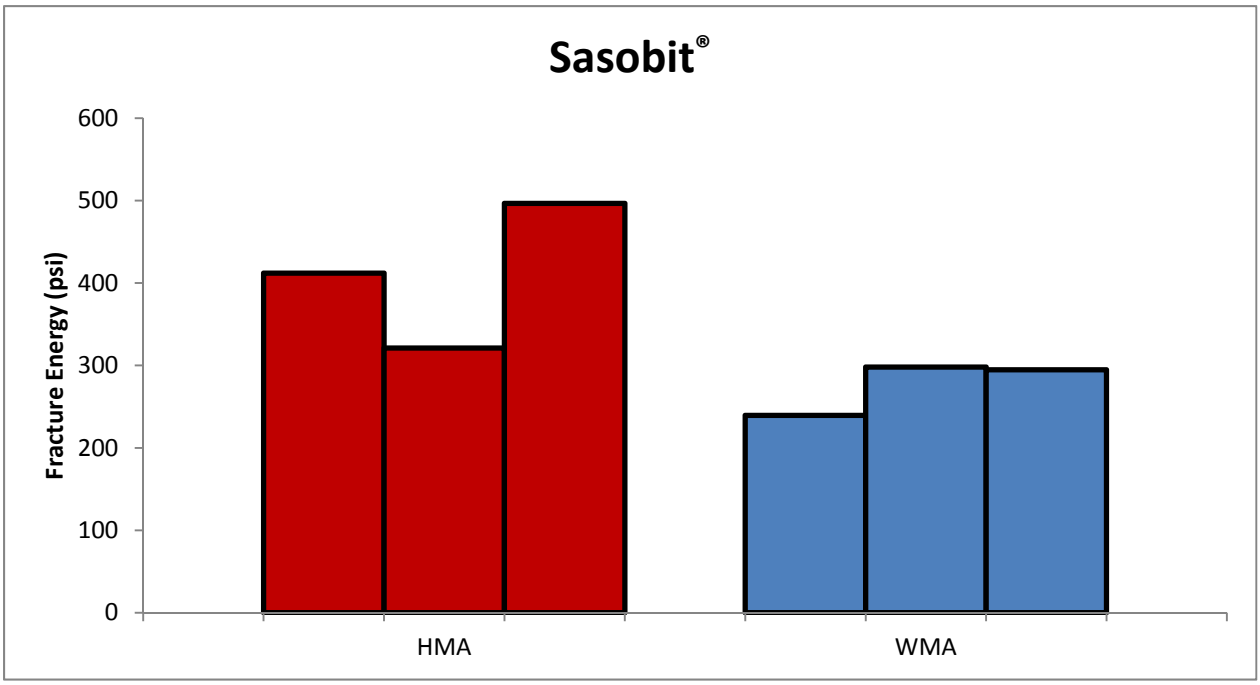

Figure 4-27. Fracture Energy of HMA and Sasobit® Binders

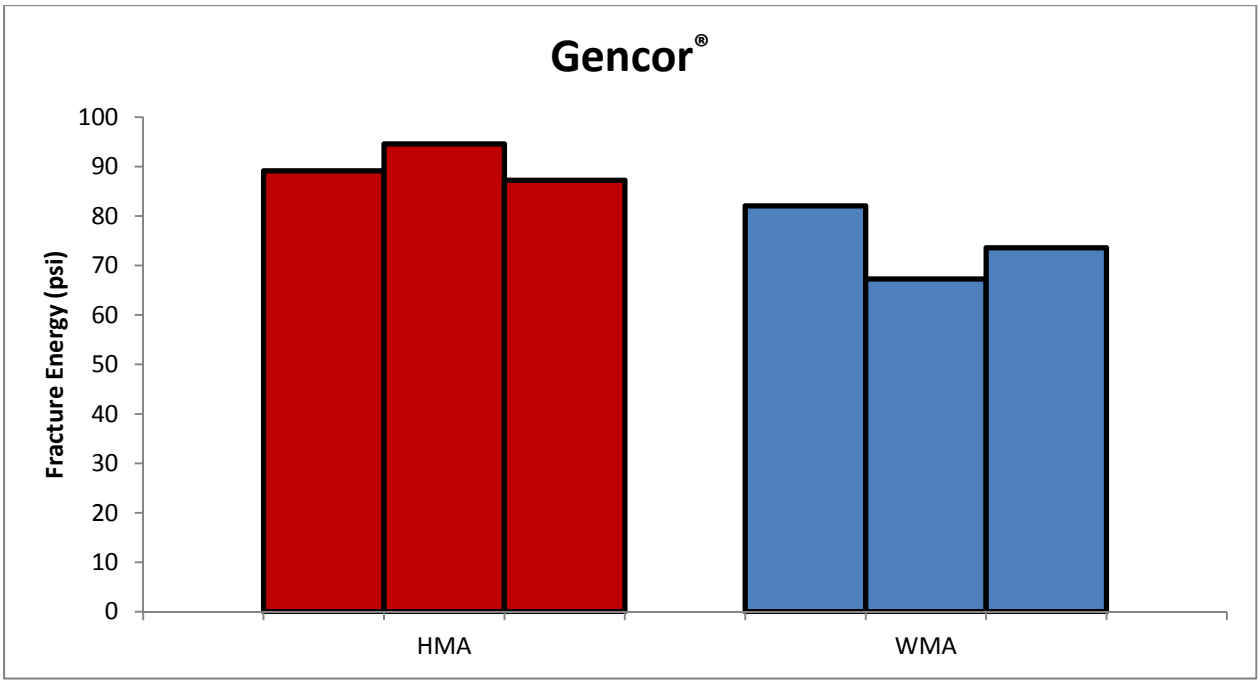

Figure 4-28. Fracture Energy of HMA and Gencor® Binders

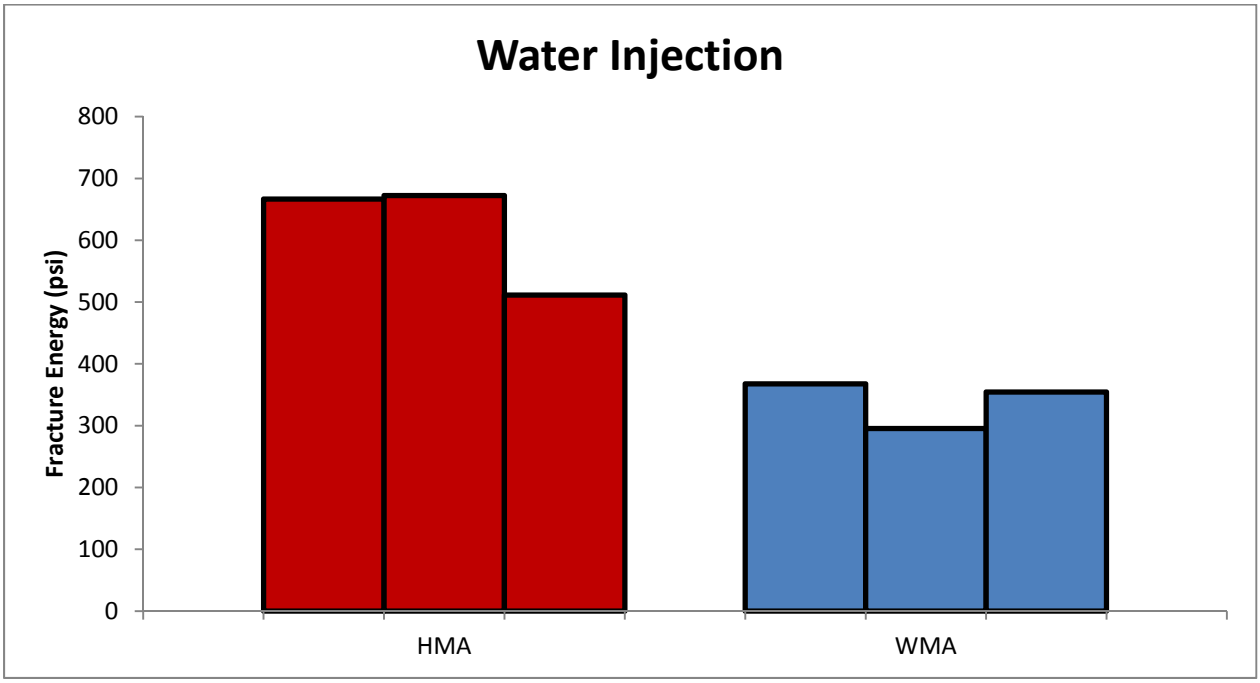

Figure 4-29. Fracture Energy of HMA and Water Injection Binders

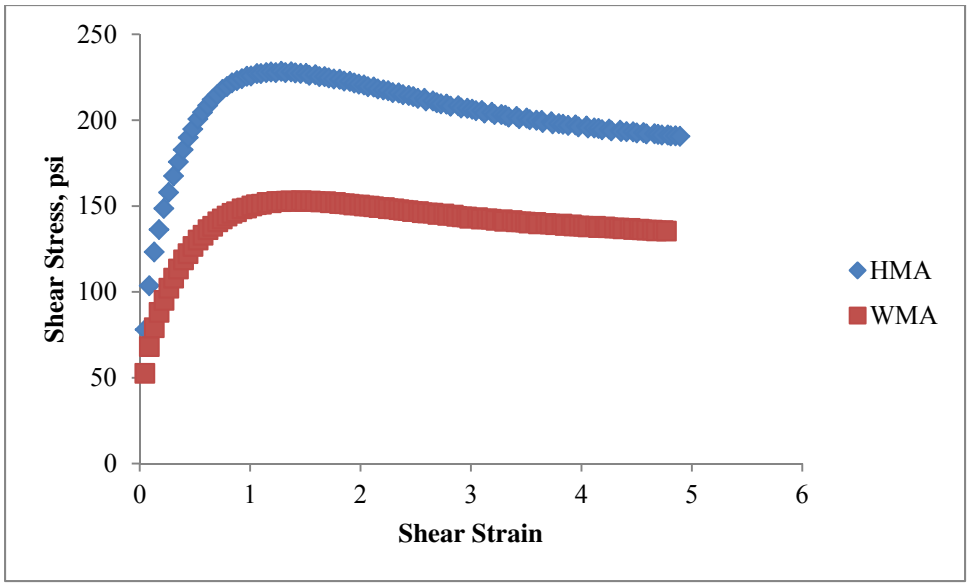

Figure 4-30. Test Results of HMA and Aquablack™ Binders

4.2.5 Thermal Cracking

The HMA and WMA binders were tested at low temperatures to characterize thermal cracking. Both the Aquablack™ and Gencor® binders were tested at 41ºF. The Sasobit® and water injection binders were tested at 50ºF, because the required stress at 41ºF exceeds the test machine's capacity. Figures 4-31 through 4-34 present the comparisons of failure strain between the HMA and WMA binders. Table 4-15 shows the average failure strain and the effect sizes. The effect sizes indicate that the Sasobit® binder exhibits significantly higher failure strain and, thus, more resistance to thermal cracking than the HMA binder. No difference in failure strain is evident between the Aquablack™, Gencor®, and water injection binders and their corresponding HMA binders. It seems that the water-based WMA technologies in this study do not affect the failure strain of the binders and resistance to thermal cracking, as compared to the effects caused by organic additives, such as Sasobit®. Among all contract sections, contract 7645 (Water Injection) showed much higher failure strain for both HMA and WMA than other contracts did.

Table 4-15. Failure Strain of Binders

Project	Failure Strain		Effect Size
	HMA	WMA	
Aquablack™	1.73	1.99	1.51
Sasobit®	3.63	4.54	***5.05***
Gencor®	1.74	1.58	1.57
Water Injection	10.06	9.63	0.59

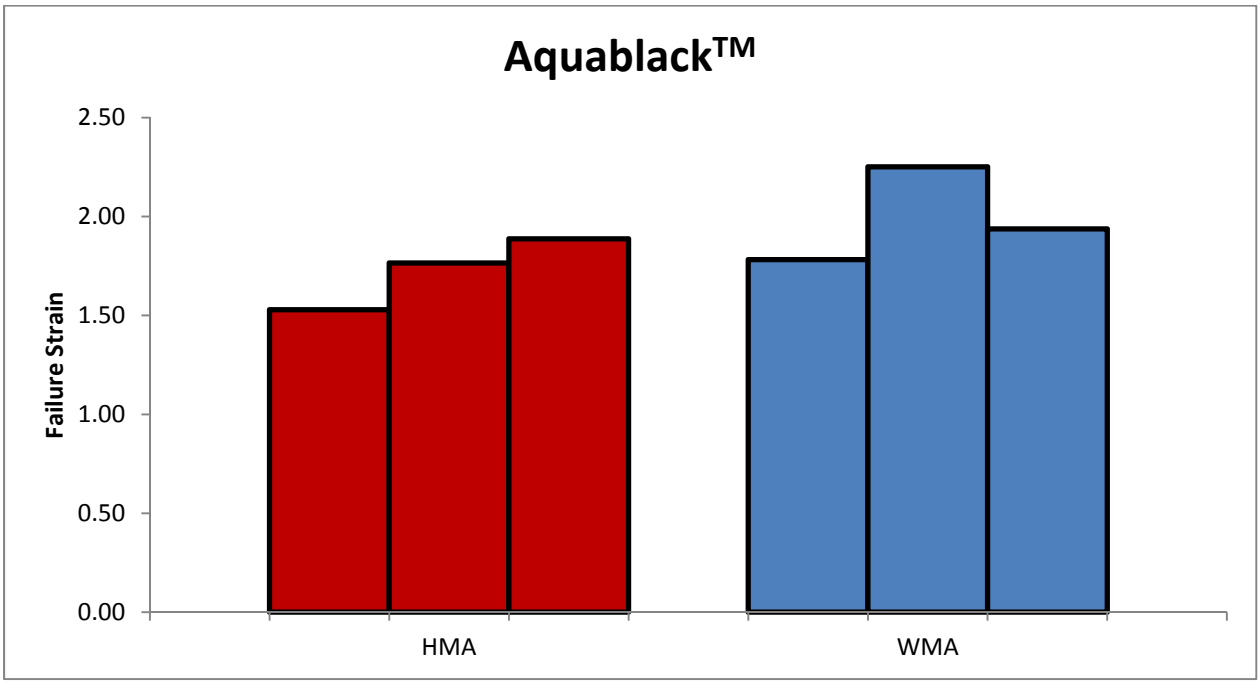

Figure 4-31. Failure Strain of HMA and Aquablack™ Binders

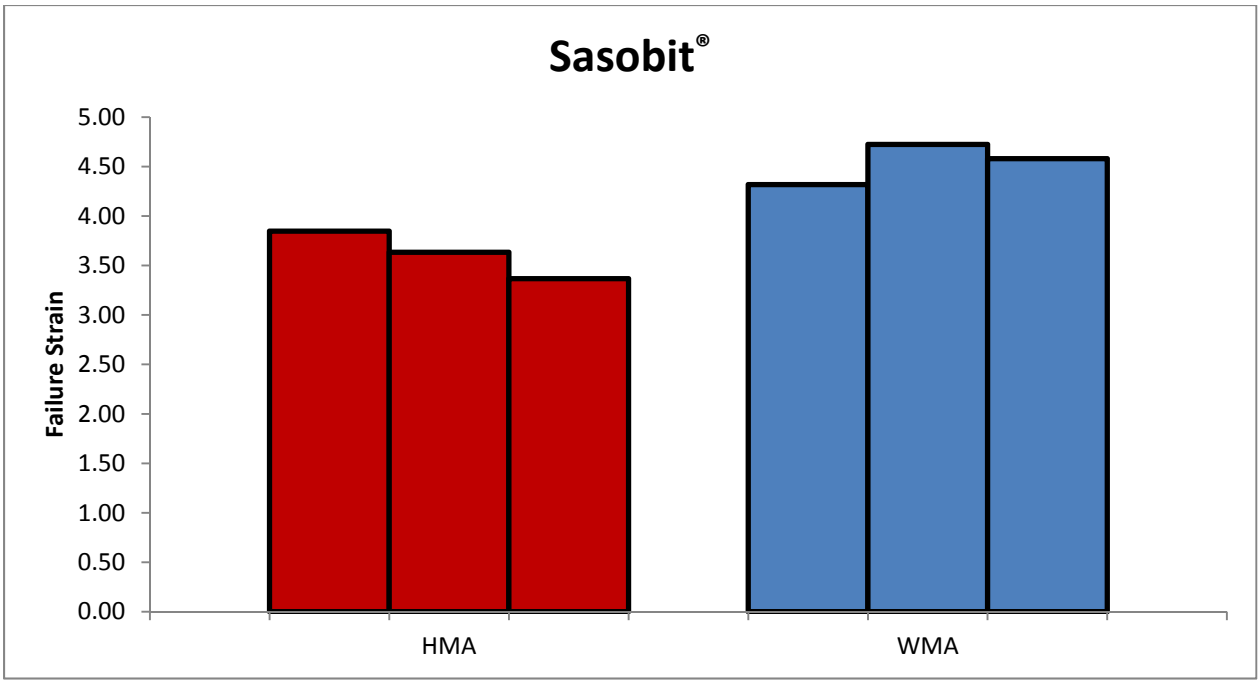

Figure 4-32. Failure Strain of HMA and Sasobit® Binders

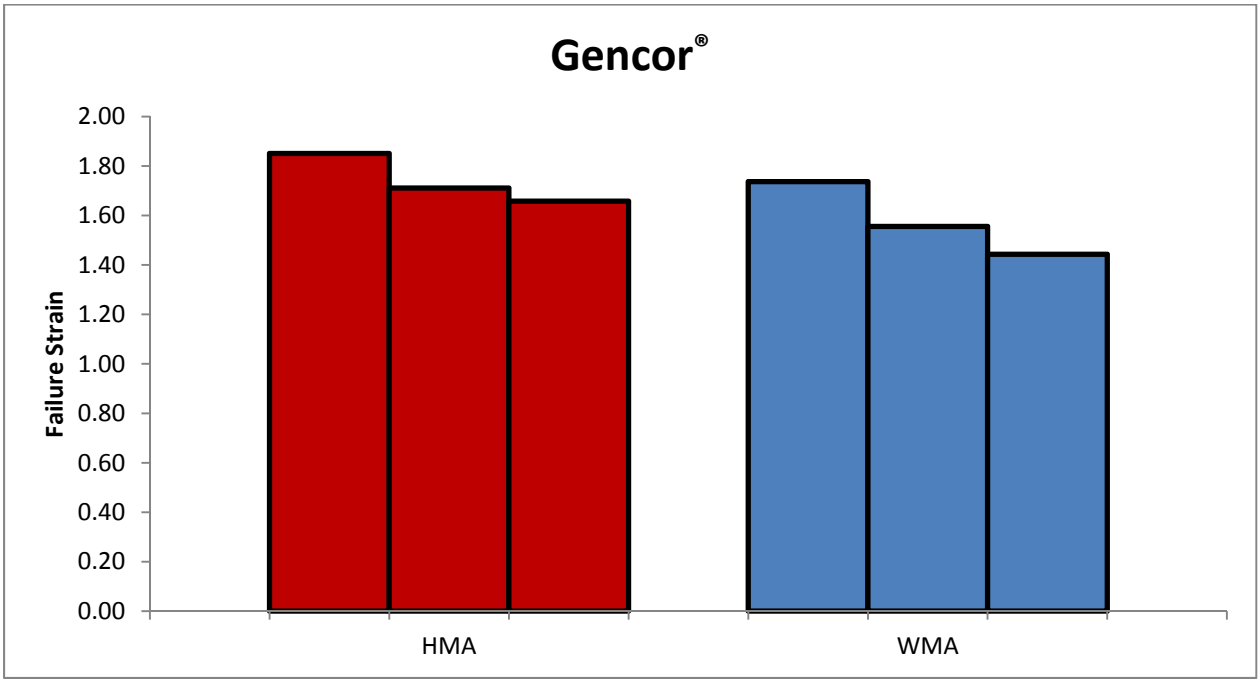

Figure 4-33. Failure Strain of HMA and Gencor® Binders

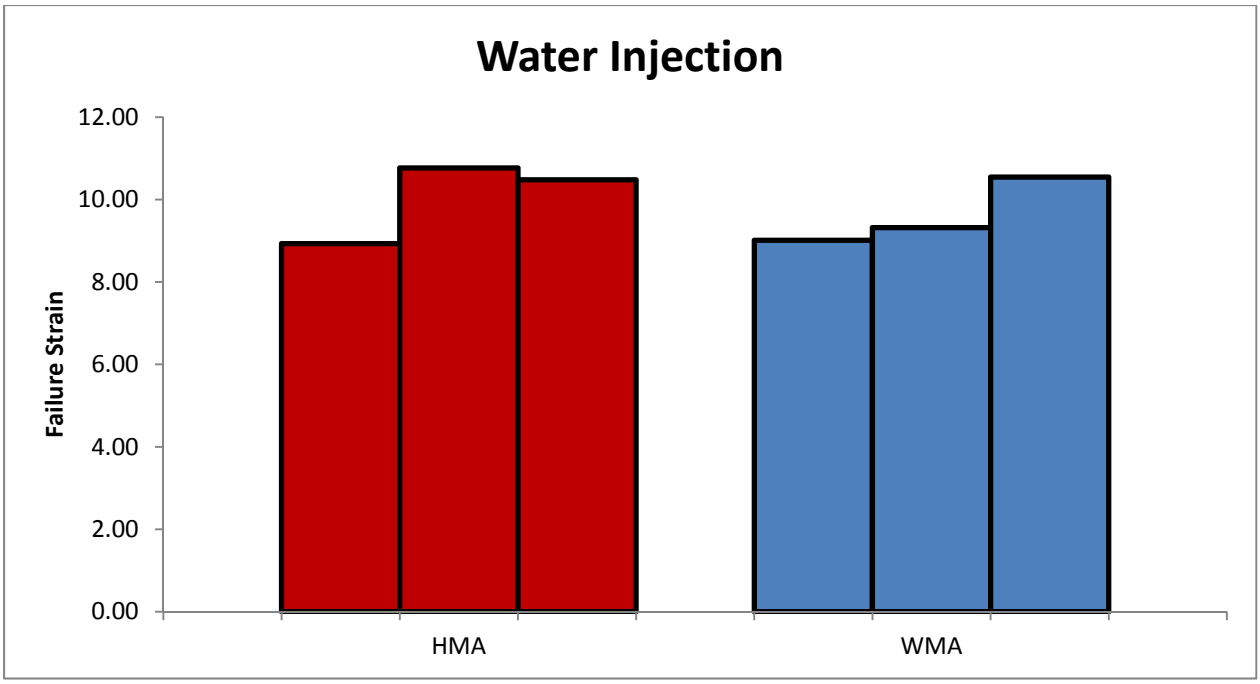

Figure 4-34. Failure Strain of HMA and Water Injection Binders

4.2.6 Summary of Binder Test Results

Table 4-16 shows the summary of the binder test results. The WMA binders exhibit consistently lower complex shear modulus values and less resistance to fatigue and rutting than the HMA binders (except for rutting with the Sasobit® binder). For thermal cracking, no difference is evident between the water-based foaming WMA binders and their corresponding HMA binders. The Sasobit® binder shows better resistance to thermal cracking than the HMA binder.

Table 4-16. Summary of Binder Test Results

Projects	Complex Shear Modulus	Fatigue	Thermal cracking	Rutting
Aquablack™	-	-	=	-
Sasobit®	-	-	+	=
Gencor®	-	-	=	-
Water Injection	-	-	=	-

The binder test results are not consistent with the mix test results. The tests on the mixes evaluated the effects of WMA technologies on the properties of field cores in terms of their materials (i.e. binder, aggregate) and volumetrics (i.e. air voids). The tests on extracted and recovered binders evaluated the effects of WMA on the binder only. In addition, the extraction and recovery process completely blends the virgin binder and the RAP binder, which may not occur in the mixes. Therefore, the findings based on the test results for the binders may be different than those for the mixes. However, between different WMA technologies, the test results on the binder are more consistent than those on mixes.

4.3 AIR VOID STATISTICAL ANALYSIS

Statistical analysis was performed on the air void content of the field cores to determine if the air voids in the HMA sections differ statistically from those in the WMA sections. A two-tailed t-test assuming equal variances with a p-value of 0.05 was used in the analysis. Air void measurements were taken immediately after paving and also at the time of this study after the pavements had been subjected to traffic one year or longer. Standard deviations of the air voids

were also determined. It is noted that the air voids that were present immediately after paving were measured using the nuclear density gauge in the field, and the air voids at the time of the study were measured using the field cores after slicing the top and bottom ends of field cores. The difference in measurement methods, specifically the slicing method for the field cores, may have led to some discrepancies. Therefore, the statistical analysis focuses on the comparison between the HMA and WMA air voids measured at the same time, instead of the change in air voids over time. Table 4-17 presents a summary of the statistical analysis of the air void parameter.

Table 4-17. Summary of Statistical Analysis of Air Voids

Density Measurement	Statistical Analysis	Aquablack™		Sasobit®		Gencor®		Water Injection	
		HMA	WMA	HMA	WMA	HMA	WMA	HMA	WMA
After Paving	Mean AV (%)	6.0	5.3	6.4	6.33	6.69	7.23	7.76	7.08
	Standard Dev.	0.97	1.13	0.63	0.69	0.85	0.92	1.24	1.07
	P-value	***0.04***		0.806		0.065		0.204	
At Time of Study	Mean AV (%)	3.63	2.53	4.56	4.71	4.62	4.21	4.66	2.85
	Standard Dev.	1.22	0.66	0.29	0.44	0.96	1.19	1.10	1.15
	P-value	***0.041***		0.442		0.460		***0.008***	

No statistical significant difference in air voids is evident between the HMA and WMA air void measurements immediately after paving, except for Aquablack™ for which the HMA

had higher air voids than the WMA did. The results of the statistical analysis of the air voids measured at the time when cores were taken indicate that the Aquablack™ and water injection mixes have statistically lower air void values than the control HMA mixes. The standard deviation values indicate that there is no consistent trend in terms of the variability in air void content between the HMA and WMA.

4.4 FIELD PERFORMANCE COMPARISON

The field performance data for the four study projects were obtained from the Washington State Pavement Management System (WSPMS). Because all but one of the projects are grind and inlay of existing asphalt pavements, both the pre-inlay and post-inlay conditions were obtained. Only the field performance data of the one-mile HMA or WMA sections where cores were taken were analyzed.

4.4.1 Aquablack™ Project

The field performance data for the Aquablack™ project are not yet available in the WSPMS as of the time of this study. Results from the field distress survey entitled, *Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies*, conducted by the NCHRP 9-47A project team were used instead. The HMA and WMA sections were constructed in April 2010. The field distress survey was conducted approximately 13 months after construction. It should be noted that the WMA section was located in the passing lane, which experienced less traffic than the HMA in the travel lane. The HMA section had an average rut depth of about 0.04 inches, and the WMA section had no measurable rut depth. No other distresses were observed in either the HMA or WMA sections at the time of the distress survey.

The HMA sections had an average surface texture depth of 0.04 inches with a standard deviation of 0.01 inch, and the WMA sections had an average surface texture depth of 0.03 inch with a standard deviation of 0.002 inch. In summary, the HMA control in the field experienced more rutting than the WMA section, likely due to the higher traffic volume in the travel lane.

4.4.2 Sasobit® Project

The HMA and WMA sections for the Sasobit® project were constructed in June 2008. The WSPMS indicated that the inlays were surveyed on July 12th, 2010. Table 4-18 presents the types and extent of pre-construction and post-construction field distresses. The standard deviation (σ) was also determined. The pre-grind-inlay pavement exhibited alligator cracking, longitudinal cracking, rutting, and transverse cracking. The HMA inlay exhibited transverse cracking, whereas the WMA inlay had none. Eleven transverse cracks, each of which was about 6 feet in length (a total of 66 feet), were observed in the one-mile HMA inlay section. The transverse cracks in the HMA inlay section were identified as reflective, as shown in Figure 4-35 where the existing transverse cracks are evident in the existing shoulder, which was not replaced. However, the transverse cracks in the existing pavement had not reflected through the WMA inlay section, as shown in Figure 4-36. It appears that the WMA mix may be more resistant to reflective cracking than the HMA mix. However, it is noted that the WMA section of existing pavement had fewer transverse cracks than the HMA section before construction. In terms of rutting and roughness, the field data indicate that WMA performs as well as HMA. Therefore, a long-term performance evaluation is needed to compare the performance in terms of resistance to reflective cracking.

Table 4-18. Sasobit® Project Field Distresses

Survey Year	Distress	HMA	WMA
Pre-overlay (2007)	Rutting (in.)	0.19 (σ = 0.03)	0.22 (σ = 0.01)
	Low Alligator Cracking (ft.)	6273	8890
	Medium Alligator Cracking (ft.)	N/A	21
	Low Longitudinal Cracking (ft.)	1459	328
	Low Transverse Cracks (count)	59 cracks	16 cracks
	IRI (in./mile)	67.39 (σ = 5.13)	57.06 (σ = 2.37)
Overlay (2010)	Rutting (in.)	0.13 (σ = 0.01)	0.13 (σ = 0.01)
	Low Transverse Cracks, Count (ft.)	11 cracks (66')	None
	IRI (in./mile)	51.24 (σ = 5.24)	49.40 (σ = 5.19)

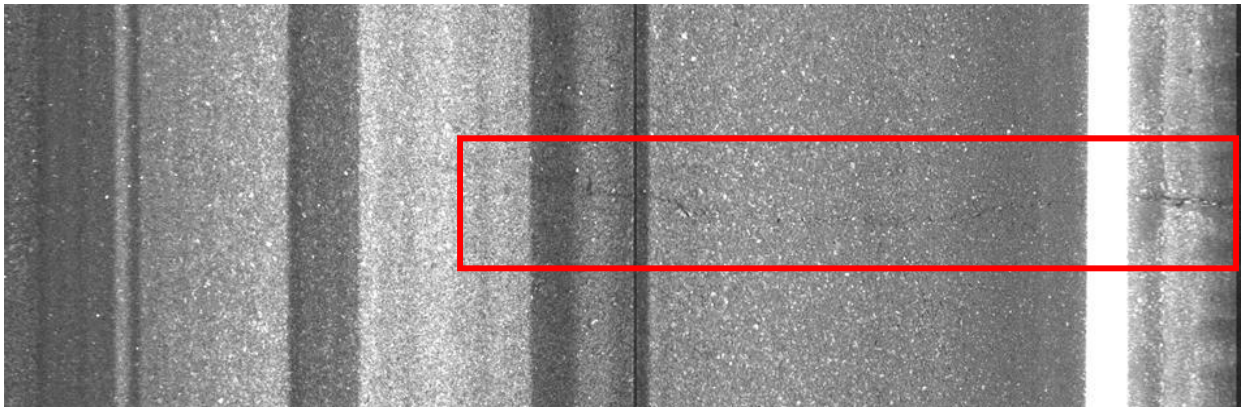

Figure 4-35. Reflective Transverse Crack in HMA Section

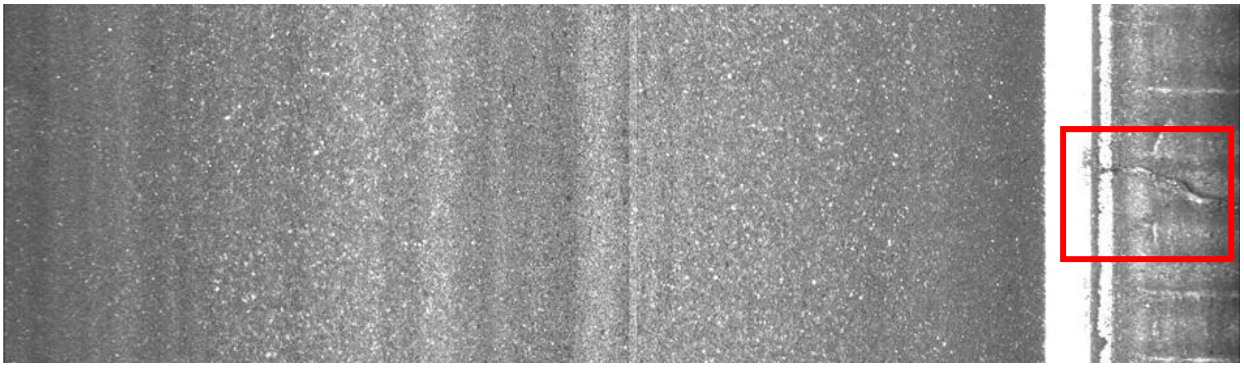

Figure 4-36. Existing Transverse Crack in the Shoulder of Sasobit® Section

4.4.3 Gencor® Project

The grind and inlays for the Gencor® project were constructed in August 2009. The WSPMS indicated that the inlays were surveyed on September 28th, 2010. Table 4-19 shows the pre-inlay and post-inlay field distresses. The existing asphalt pavement exhibited rutting, alligator cracking, longitudinal cracking and transverse cracking. The WSPMS data indicates 70 feet of longitudinal cracking in the HMA section. More transverse cracks were observed in the HMA inlay than in the WMA inlay, though the total number of transverse cracks in the existing pavements for both the HMA and WMA sections were close to each other. The field data indicate that the WMA section is performing as well as the HMA segments with respect to early-stage rutting and roughness.

Table 4-19. Gencor® Project Field Distresses

Survey Year	Distress	HMA	WMA
2009 (Pre-overlay)	Rutting (in.)	0.37 (σ = 0.05)	0.29 (σ = 0.05)
	Low Alligator Cracking (ft.)	62	3975
	Medium Alligator Cracking (ft.)	510	483
	High Alligator Cracking (ft.)	203	N/A
	Low Longitudinal Cracking (ft.)	622	1030
	Medium Longitudinal Cracking (ft.)	5519	12
	High Longitudinal Cracking (ft.)	586	N/A
	Low Transverse Cracks (Count)	54	98
	Medium Transverse Cracks (Count)	31	N/A
	High Transverse Cracks (Count)	2	N/A
	Low Faulting (Count)	N/A	1
	IRI (in./mile)	81.06 (σ = 12.68)	68.89 (σ = 8.06)
2010 (Overlay)	Rutting (in.)	0.08 (σ = 0.01)	0.08 (σ = 0.003)
	Low Transverse Cracks, Count (ft.)	15 (152’)	4 (30’)
	Low Longitudinal Cracking (ft.)	70’	N/A
	IRI (in./mile)	48.98 (σ = 3.44)	46.62 (σ = 2.72)

4.4.4 Water Injection Project

The HMA and WMA grind and inlay for the water injection project were constructed in June 2009. The WSPMS indicated that the inlays were surveyed on September 14th, 2010. Table 4-20 provides the pre-inlay and post-inlay pavement distresses. The existing pavement exhibited low alligator cracking, longitudinal cracking, transverse cracking, and rutting. Both the HMA and WMA inlays exhibited transverse cracks that are believed to be reflective cracking, as shown in Figure 4-37. Prior to the inlay, the existing HMA section had the same number of cracks as the existing WMA section. The WSPMS shows the HMA inlay has 8 transverse cracks compared to 6 transverse cracks in the WMA inlay. However, the total length (96 ft.) of the transverse cracks in the HMA inlay was more than the length (34 ft.) of the cracks in the WMA inlay. Therefore, WMA might be more beneficial in resisting reflective cracking than HMA. In addition, the HMA and WMA inlays had comparable rutting. However, the WMA inlay had a higher international roughness index (IRI) value than the HMA inlay.

Table 4-20. Water Injection Project Distress Data

Survey Year	Distress	HMA	WMA
2008 (Pre-overlay)	Rutting (in.)	0.18 (σ = 0.02)	0.13 (σ = 0.02)
	Low Alligator Cracking (ft.)	250	367
	Medium Alligator Cracking (ft.)	78	10
	Low Longitudinal Cracking (ft.)	52	55
	Low Transverse Cracks (Count)	8	N/A
	Medium Transverse Cracks (Count)	20	27
	IRI (in/mile)	63.55 (σ = 0.83)	52.75 (σ = 3.31)
2010 (Overlay)	Rutting (in.)	0.10 (σ = 0.02)	0.09 (σ = 0.01)
	Low Transverse Cracks, Count (ft.)	8 (96')	6 (34')
	IRI (in/mile)	52.10 (σ = 6.63)	60.82 (σ = 4.42)

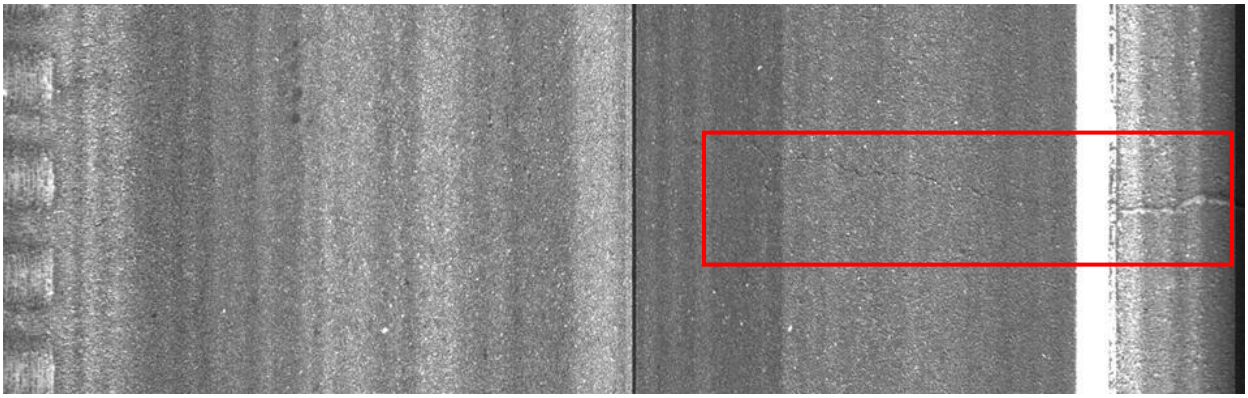

Figure 4-37. Reflective Thermal Crack in HMA

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This study characterizes the properties of field cores from WMA and HMA control pavements built by the WSDOT. Binders were extracted and recovered. The early-age field performance indicators for the WMA and HMA control pavements also were obtained and reviewed. The following observations can be made from this study.

5.1 FIELD COMPACTION

- No difference is evident in the air void content (density) and standard deviation between the Sasobit®, Gencor®, and water injection mixes and their HMA control counterparts immediately after paving, but the Aquablack™ section had a higher density than the HMA control. This finding indicates that WMA technologies achieve an equivalent amount of compaction even at lower production temperatures than the HMA control mixes.
- After pavements are opened to traffic, the Aquablack™ and water injection mixes exhibit statistically lower air void contents than the HMA control mixes, indicating that these water injection mixes may be prone to more consolidation than the HMA control mixes. However, the early-stage field reviews have not shown rutting in these sections.

5.2 LABORATORY PERFORMANCE OF MIXES

- The Sasobit®, Gencor®, and water injection mixes are comparable to their HMA control mix counterparts in terms of stiffness. The Aquablack™ mix has a lower stiffness value than the HMA control mix, likely due to the relatively short period (about one year) from

the time of production, compared to two or more years of service life for the other WMA mixes. To make broad conclusions, further measurement is required to determine the stiffness of Aquablack™ mix at a time period similar to other WMA mixes.

- For fatigue, the water-based foaming WMA shows resistance to fatigue that is comparable to that of the corresponding HMA control mixes. The Sasobit® mix shows less resistance to fatigue than the HMA control mix.
- For thermal cracking, the results are mixed. The Gencor® and water injection mixes show more resistance to thermal cracking than their corresponding HMA mixes. However, the Sasobit® and Aquablack™ mixes are comparable to their HMA control mixes in terms of resistance to thermal cracking.
- For rutting, the results are mixed. The Sasobit® and Aquablack™ mixes show comparable resistance to rutting than the HMA control mixes. The Gencor® and water injection mixes showed less resistance to rutting than the HMA control mix.
- For moisture susceptibility, there is no stripping inflection point observed in the HWTD tests for any of the mixes, indicating that all the WMA and HMA control mixes would perform similarly in terms of resistance to moisture damage.

Overall, the only adverse effect on the mixes caused by the use of WMA technology is the rutting performance (IDT) in the laboratory of the Gencor® and water injection mixes, and fatigue by the Sasobit®, though in the field none of the WMA sections have shown significant rutting or fatigue. Otherwise, equivalent or better performance is found for all of the other WMA mixes.

5.3 LABORATORY PERFORMANCE OF BINDERS

- The WMA binders exhibit consistently lower complex shear modulus values and less resistance to fatigue and rutting than the HMA binders.
- For thermal cracking, no difference is evident between the water-based foaming WMA binders and their corresponding HMA binders. The Sasobit® binder shows better resistance to thermal cracking than the HMA binder.

The reason for the discrepancy in the findings for the mixes and binders is that the tests evaluated the effects of WMA technologies on the properties of the field cores in terms of both materials and volumetrics. The tests on extracted and recovered binders evaluated the effects WMA on the binder only, which assumes that the RAP and virgin binders are blended completely. The test results for the mixes are, therefore, more representative of the performance of pavements than the results for the binders alone.

5.4 FIELD PERFORMANCE

- The WMA pavements are comparable to their corresponding HMA control pavements in terms of rutting and roughness.
- The WMA pavements show less reflective transverse cracking than their corresponding HMA control pavements.

To date, the overall short-term performance of WMA pavements is comparable to that of HMA pavements, except that WMA mixes seem to be more resistant to the early stages of reflective cracking than HMA mixes in the field.

5.5 RECOMMENDATIONS

Further study is needed to understand the discrepancies between the mix and binder test results and to understand more precisely the ways that WMA technologies affect the performance of mixes. In addition, it seems that different foaming WMA technologies perform differently. Further study is needed to understand the foaming mechanisms and other factors (i.e. moisture in aggregates) that affect the performance of mixes and pavements. Reflective cracking of transverse and longitudinal cracking is one of the primary distresses found in overlays. Effective measures are needed to prevent cracking in an asphalt pavement, to treat existing cracking prior to the overlay, and/or develop a crack-resistant mix. The long-term performance assessment of WMA pavements is needed for comparison with the performance of HMA pavements and WSDOT should continue to monitor the pavements. This will assist in validating the effectiveness of laboratory performance tests as well.

CHAPTER 6: REFERENCES

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