Short-Term Performance of Modified Stone Matrix Asphalt (SMA) Produced with Warm Mix Additives

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A report of the findings of
Early-Age Deformation/ Rutting of Modified Stone Matrix Asphalt (SMA) Produced with Warm Mix Additives Project

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16. Abstract

The short-term performance of the stone matrix asphalt (SMA) prepared with various warm-mix techniques (Evotherm™ 3G, Sasobit®, and foamed asphalt) was conducted using extensive laboratory tests and on-site stiffness measurement. The laboratory tests included the complex modulus, flow number, loaded wheel track, indirect tension (IDT) creep and strength, and semi-circular beam (SCB) fracture. In the laboratory tests, plant-produced mixes were compacted in the laboratory with and without reheating, and performance tests were conducted at various curing time periods after compaction. In addition, light weight deflectometer (LWD) tests were conducted to monitor the in-situ pavement stiffness development of the warm SMA field sections.

This study concludes that SMA containing different warm mix asphalt (WMA) additives show comparable performance with the control SMA. Both laboratory and field test results do not indicate any evidence that a longer curing time is needed before allowing traffic on warm SMA pavements. The mixtures containing WMA additives show similar variations in mixture properties due to curing time compared to the control SMA. The reheating process causes asphalt mixtures to have greater modulus, tensile strength, and rutting resistance, but smaller creep compliance and fracture resistance. The aging effect due to reheating is more significant on the control mixture than the three warm SMA mixtures due to a higher reheating temperature. An approach to determine the time for opening paved road to traffic is proposed for the tested materials.

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A successful testing plan required a collective effort from students, faculty and staff of the University of Illinois, Illinois Tollway employees, consultants, and asphalt producers. The contractor's QC managers and plant operators provided essential knowledge of the plants and mixes. Consultants provided additional help for mixture sampling, sample compaction, transportation, and project coordination.

This publication is based on the results of Short-Term Performance of Modified Stone Matrix Asphalt (SMA) Produced with Warm Mix Additives. This project was conducted in cooperation with the Illinois Center for Transportation and the Illinois Tollway.

EXECUTIVE SUMMARY

This study evaluated the short-term performance of stone matrix asphalt (SMA) prepared with various warm-mix techniques (Evotherm™ 3G, Sasobit®, and foamed asphalt) using extensive laboratory tests and on-site stiffness measurement. The laboratory tests included the complex modulus, flow number, loaded wheel track, indirect tension (IDT) creep and strength, and semi-circular beam (SCB) fracture. In the laboratory tests, plant-produced mixes were compacted in the laboratory with and without reheating, and performance tests were conducted at various curing time periods after compaction. In addition, light weight deflectometer (LWD) tests were conducted to monitor the in-situ pavement stiffness development of the warm SMA field sections.

This study concludes that SMA containing different warm mix asphalt (WMA) additives show comparable performance with the control SMA. Both laboratory and field test results do not indicate any evidence that a longer curing time is needed before allowing traffic on warm SMA pavements. The mixtures containing WMA additives show similar variations in mixture properties due to curing time compared to the control SMA. The reheating process causes asphalt mixtures to have greater modulus, tensile strength, and rutting resistance, but smaller creep compliance and fracture resistance. The aging effect due to reheating is more significant on the control mixture than the three warm SMA mixtures due to a higher reheating temperature. An approach to determine the time for opening paved road to traffic is proposed for the tested materials.

Table of Contents

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND ON WARM-MIX TECHNIQUES

Hot mix asphalt (HMA) has historically been the most popular paving material for roadways; its use dates back 130 years. HMA construction requires a high temperature to ensure workability of the asphalt mixture during mixing and compaction, and to achieve the desired in-place density. However, producing HMA at high temperatures can result in high energy consumption, significant greenhouse gas (GHG) emissions, hazardous fume, and unpleasant odors. In addition, the high temperature requirement results in shorter paving seasons, and relatively longer cooling periods before roadways can be opened to traffic; especially for high volume roadways built with heat-sensitive polymer modified mixes. Recently, increased environmental awareness and rising energy costs have led to the development of alternate paving materials that require lower operating temperatures; but possess similar in-service performance to the HMA.

Warm-mix asphalt (WMA), which originated in Europe in the mid '90s, appears to address the previously mentioned issues associated with HMA. WMA is mixed and compacted at temperatures lower than the required temperatures for conventional HMA. Typically, the mixing and compaction temperatures of WMA range from 100 to 140°C (212 to 280°F) in comparison to 150 to 180°C (300 to 350°F) for HMA (Angelo 2008). It has been proven that WMA techniques can provide a number of benefits due to the lowered production and placement temperatures. Although benefits can vary depending on the specific warm mix additive being used, the potential benefits of WMA techniques are summarized as follows (Chowdhury and Button 2008):

- Improved compaction of asphalt mix, especially stiff mixes;
- Increased use of reclaimed asphalt pavement (RAP);
- Extension of paving seasons;
- Night paving and longer haul distances;
- Reduction of asphalt oxidation for prolonged pavement life;
- Less fuel consumption and energy costs;
- Reduction of heat, odor, blue smoke at the plant and paving site, thus improved working conditions for the plant/paving crews;
- Reduction of GHG emissions such as NOx, SOx, and CO_2; and
- Easier to obtain permits for plant sites in urban areas.

In spite of the aforementioned advantages of WMA, some concerns have been raised regarding the durability of these mixtures due to the reduced mixing and compaction temperatures used in production. Several studies (Prowell et al. 2007, Wasiuddin et al. 2007, Mallick et al. 2008, Lee et al. 2008, Wielinski et al. 2009, Xiao et al. 2010, and Hurley and Prowell 2005a, 2005b, and 2006) have been conducted to determine the applicability of WMA techniques to paving operations and environmental conditions compared to the traditional HMA. One of the main concerns is the increased susceptibility of WMA to permanent deformation. For example, it is possible that the asphalt binder in WMA may not sufficiently harden at relatively low production

temperatures and, hence, may develop higher post-construction densification or distortion under early-age traffic. Another concern is that WMA may have an increased propensity to moisture-induced damage. In WMA, aggregates are heated to relatively low temperatures and therefore may not thoroughly dry before they are mixed with the asphalt binder; thereby reducing the amount of binder absorbed into the aggregates.

Due to different mechanisms of WMA preparation techniques, physical and chemical properties of the mixture can be altered, which can result in different short-term and long-term mechanical behaviors. Several researchers have evaluated the performance of WMA with regards to various pavement distresses. Prowell et al. (2007) reported that laboratory tests conducted in the asphalt pavement analyzer indicated similar performance for the emulsion-based WMA (Evotherm™ ET) and HMA surface mixes with the PG 67-22 base asphalt binder. However, laboratory tests indicated an increased moisture damage potential for WMA. Wasiuddin et al. (2007) compared the performance of WMA with Sasobit® and Aspha-Min® additives and found that Sasobit® decreased the WMA rutting potential more significantly than the Aspha-Min® additive. The addition of Sasobit® could increase the high temperature grading of the asphalt binder.

Mallick et al. (2008) investigated the feasibility of using a WMA additive, Sasobit®, with 75% reclaimed asphalt pavement (RAP) for producing a base course at a lower temperature and found that the performance of WMA with RAP was dependent on the stiffness of the combined (rejuvenated) binder in the mixture. Lee et al. (2008) investigated the performance properties of WMA binders (Aspha-Min® and Sasobit®) containing aged binder. They found that WMA additives might not have positive effects on the resistance to fatigue and thermal cracking when recycled binder was used in WMA. Wielinski et al. (2009) demonstrated that foam-based WMA with RAP could be produced and placed at relatively lower temperatures while yielding mix properties and field compaction similar to conventional HMA. Xiao et al. (2010) evaluated the rut depth, weight loss, and gyration number of dry and conditioned specimens containing warm mix additives (Aspha-Min®, Sasobit®, and Evotherm™ 3G). The results indicated that the aggregate source affected the mix rutting potential most significantly, regardless of the additive and moisture content.

A series of studies have been conducted at the National Center for Asphalt Technology (NCAT) to evaluate the laboratory performance of asphalt mixtures with different warm mix additives, Evotherm™ 3G, Sasobit®, and Aspha-min® (Hurley and Prowell 2005a, 2005b, and 2006). Their major findings from several reports are summarized herein:

- Adding WMA additives improved the compactability of the mixtures in both Superpave Gyratory Compactor (SGC) and vibratory compactors.
- Application of either warm mix process did not affect the resilient modulus or increase the rutting potential of asphalt mixtures compared to control mixtures having the same PG binder.

- Lower mixing and compaction temperatures for WMA may increase the potential for moisture damage. An anti-stripping agent may be added to yield an acceptable tensile strength ratio.
- Based on the compaction and rutting results, a minimum field mixing temperature of 135°C (275°F) and a minimum field compaction temperature of 121°C (250°F) is recommended.
- More research is needed to further evaluate in-situ WMA performance, selection of the optimum asphalt content, and appropriate binder grades for WMA.

Although a significant number of studies have been conducted to evaluate the performance of mixtures produced with WMA techniques, a number of concerns and challenges still remain regarding the implementation of WMA. The WMA technology is still relatively new, and many questions about the long-term performance and life cycle costs remain. To date, both the U.S. and Europe have reported positive performance results, which are comparable to or better than HMA for overlays. However, additional studies are needed to monitor the long-term performance of constructed WMA test sections. Because the oldest test sections of WMA around the world are just over ten years old, it is too early to truly predict long-term performance in the field.

It is noteworthy that the major economic benefits of WMA rely on the energy savings resulting from the reduction of mixing and compaction temperatures. However, the economic benefits of WMA depend on several factors and thus vary among different products and processes. These factors include the magnitude of the temperature reduction, the type and cost of the fuel/energy used, potential risks associated with WMA technologies and resulting paving materials, initial investments for modifying plants and updating equipment, and additional fixed costs for purchasing WMA additives/agents (Kristjánsdóttir et al. 2007).

1.2 PROBLEM STATEMENT

One case where WMA could provide significant economic benefits to the industry and state agencies is if it were applied to heat sensitive mixes, such as polymer or ground tire rubber (GTR) modified mixes designed for high traffic volume or heavy load roadways. Production and compaction of these modified mixes at relatively high temperatures restricts their placement in the northern states on cold bases or during cold weather. Using WMA additives with these mixes could significantly extend the construction season. However, before these modified mixes are used, the mechanical performance of WMA needs to be examined.

The early-age performance of WMA is a concern due to its curing process. After a relatively short period of time following construction, a time-dependent hardening, called curing, can occur in WMA as the asphalt binder regains its original apparent viscosity and/or a certain amount of entrapped moisture is evaporated from the WMA. Insufficient curing time can cause significant deterioration of WMA at an early stage, which can consequently affect its long-term performance. The curing time of WMA can be affected by additives, asphalt binder, aggregate, temperature, and other design parameters.

Therefore, it is crucial to investigate the early age performance of various WMA; especially within the first 24 hours of placement to determine the appropriate time to open the pavement to traffic. Furthermore, curing conditions of a specific WMA should be considered in the mix design and evaluation.

The effect of curing time on the moisture content and the stability of cold asphalt mixtures prepared using foaming techniques has been reported by earlier researchers (Ruckel et al. 1983; Brennen et al. 1983). Their work showed a strong correlation between moisture content and mixture strength. A considerable gain in strength was observed for specimens subjected to short-term (within one day) and intermediate-term (one to seven days) curing periods. The effect of WMA curing, prepared with various additives, has also been reported. For example, the rutting potential of WMA with Aspha-Min® and a two-hour curing period was higher than HMA (Hurley and Prowell, 2005a) and the tensile strength of WMA with Sasobit® within five days of curing was lower than or equivalent to HMA (Hurley and Prowell 2005b). Hence, to minimize premature deformation, WMA pavements should not be opened to heavy traffic until the WMA gains adequate stiffness.

The performance of WMA has been evaluated mostly through laboratory prepared specimens. However, the drawback of using laboratory prepared specimens is that they may not represent the plant-produced mix and may have some practical challenges; especially when a foaming procedure is needed. If the loose mix samples are obtained from the plants, reheating is needed for laboratory compaction, which results in an inordinate binder aging and uncontrolled curing. For example, the rut depth of reheated WMA samples is three times less than that of immediately compacted samples (Wielinski et al. 2009). In another field and laboratory study conducted by the Virginia Department of Transportation (Diefenderfer, 2007), volumetric properties and performance parameters were tested for the immediately prepared WMA samples, after mixing in the plant and in the laboratory after being reheated. The study clearly shows increase in strength and rutting resistance with increasing curing time and reheating. Hence, testing of WMA specimens should be conducted as soon as possible without reheating rightafter they are prepared in a plant or sampled from the field.

Gandhi et al. (2010) evaluated the aging characteristics of WMA using laboratory prepared specimens. Results of this study indicated that the warm asphalt additives reduced the moisture susceptibility of the unaged mixes. The mixes containing Sasobit® exhibited less rutting and the Aspha-Min® additive lowered the resilient modulus values of the unaged mixes. On the other hand, the additives did not have any significant effect on the moisture susceptibility or the rutting resistance of the aged mixes, but significantly increased the resilient modulus values of the mixes as they were aged. This suggested that the binder aging mechanism might change when warm mix additives were added into the mixture. Therefore, the effect of WMA additives on the mechanical properties of mixes with aged binders should be investigated.

1.3 RESEARCH OBJECTIVE AND SCOPE

The main objective of this study is to investigate the short-term performance of SMA mixtures produced with various WMA additives and recycled materials and to evaluate the effects of curing time and reheating process on the mixtures' mechanical properties. To achieve this objective, the following research tasks were conducted:

1) Evaluation of the mechanical properties of WMA with respect to HMA in terms of laboratory performance tests. Extensive laboratory tests were conducted on the control SMA and the SMA produced with three different WMA additives (Sasobit®, Evotherm™ 3G, and foamed asphalt). These tests included the complex modulus, flow number, loaded wheel track (LWT), indirect tensile (IDT) creep compliance and strength, and semi-circular bending (SCB) fracture.

2) Investigation of the effect of curing time on mechanical properties of WMA. On-site sampling and laboratory compaction were conducted at each producer's plant without reheating. The compacted samples were transported to the laboratory in order to conduct performance tests at various curing periods (3 hrs, 6 hrs, 12 hrs, 1 day, 3 days, and 7 days) after compaction. Given that fracture properties are not time-critical, the fracture tests were conducted at 12 hrs, 1 day, 3 days, 7 days, 3 weeks, 6 weeks, and 12 weeks after compaction.

3) Investigation of the effect of the reheating process (artificial aging) on the mechanical properties of WMA. Loose mixes collected from the field were reheated and compacted in the laboratory. The same set of performance tests were conducted for the reheated specimens following the same curing time as the mixtures that were in-situ compacted right after sampling.

4) Evaluation of the in-situ stiffness of WMA field sections using a light weight deflectometer (LWD) test. The LWD test was conducted at different time periods after compaction to monitor the surface modulus change as the pavement cooled and continued to cure.

1.4 ORGANIZATION OF THE REPORT

This report is divided into five chapters. The first chapter provides a background, problem statement, research objective, and scope. The second chapter describes the selection of testing materials, experimental design, and the preparation of testing specimens. The third chapter describes the conducted laboratory performance tests. The fourth chapter presents data analyses and discusses the test results for the asphalt mixtures without and with reheating. The fifth chapter presents the in-situ measured pavement stiffness during the initial curing time. The final chapter presents the study conclusions and future research recommendations.

CHAPTER 2 TESTING MATERIAL AND SPECIMEN PREPARATION

2.1 WARM MIX ADDITIVES

Numerous WMA techniques have been developed with the goal of either reducing the effective viscosity of the binder or allowing better workability to enable full coating and compactability at lower temperatures than a typical HMA allows. These techniques are typically classified into three categories: organic or wax additives, chemical additives, and foaming techniques. In this study, the three warm-mix techniques (Sasobit, Evotherm 3G, and foaming, respectively) are used to produce WMA. The three WMA materials were produced at the following asphalt plants in the Chicago area, respectively: K-Five Construction, Geneva Construction, and Rock Road Companies.

2.1.1 Organic Additives

Organic or wax additives are used to lower the viscosity of the asphalt binder at temperatures above 90°C (194°F). The additive must have a melting point that is higher than the expected in-service temperatures or the temperature when significant permanent deformation may occur. The fine crystalline nature of organic additives tends to increase the stiffness of the binder and the asphalt's resistance against deformation. Typical organic additives for WMA include Sasobit®, Asphaltan-B®, and Licomont BS 100® (Chowdhury and Button 2008).

For this study, Sasobit® was pre-blended by the asphalt binder material supplier and shipped to the K-Five plant for use in the mixture production. Sasobit® is a product of Sasol Wax (Figure 2.1). It is a fine white powder or granulate crystalline, long-chain aliphatic polyethylene hydrocarbon produced from Fischer-Troph synthesis, a process where coal or natural gas is partially oxidized to carbon monoxide which is subsequently reacted with hydrogen. Sasobit® has a congealing temperature of about 102°C (216°F) and is completely soluble in asphalt binder at temperatures higher than 120°C (216°F). This produces a long-chain apliphatic hydrocarbon wax with a melting point between 85°C (185°F) and 115°C (239°F). At temperatures below its melting point, Sasobit forms a crystalline network structure in the binder and increases the viscosity and stiffness of the binder. Sasol recommends that Sasobit® should be added at a rate of 0.8-3 percent by mass of the binder (Damm et al. 2002; Hurley and Prowell 2005b).

2.1.2 Chemical Additives

Chemical additives differ from organic additives as they typically do not lower the asphalt binder viscosity. They work at the microscopic interface of the aggregate and asphalt binder. Chemical additives include a combination of emulsions, surfactants, polymers and other additives that improve coating, workability, and compaction. Chemical additives regulate and reduce the frictional forces at the aggregate and binder interface over a range of temperatures, typically between 85-140°C (185-284°F). The chemical additive is typically used in the form of an emulsion or added to the asphalt binder and then mixed with the hot aggregates. Therefore, only minor modifications are

required to asphalt plants to produce chemically modified WMA. Typical chemical additives for WMA include Evotherm™, Rediset™ WMX, and Revix™ (Chowdhury and Button 2008).

Figure 2.1 Sasobit® Flakes (Left) and Prills (Right) (after Hurley and Prowell 2005b)

Evotherm™ 3G, developed by MeadWestvaco, was used in the WMA production at the Geneva asphalt plant and utilized in this study (http://www.meadwestvaco.com/, accessed December 04, 2011). Evotherm™ 3G is a water-free chemical package containing surfactant and anti-stripping agent, which is utilized to improve aggregate coating, workability, and compaction. Generally, Evotherm™ 3G can lower mix temperatures 33-45°C (60-85°F). In the plant, Evotherm™ 3G is stored in a tank and connected to the asphalt storage tank using pipes (Figure 2.2).

Figure 2.2 Injection of Evotherm™ 3G in the asphalt plant

2.1.3 Foaming Techniques

Foaming techniques use small amounts of water injected into the hot asphalt binder. The water turns to steam and expands significantly at atmospheric pressure. As the water turns to steam, the volume of the binder increases and reduces its viscosity for a short period until the material has cooled. The foam then collapses and the asphalt binder behaves normally. It is important that enough water is added to cause the foaming action and ensure workability. To avoid stripping, some producers recommend the use of anti-stripping agents to protect against possible moisture damage. The foaming process can be performed by using a foaming nozzle, adding a hydrate, or using moist aggregates. Typical foam techniques include Aspha-min®, Low-Energy Asphalt®, Double Barrel Green, Synthetic Zeolite, and WAM-Foam (Chowdhury and Button 2008).

The Rock Road plant performs the foaming process by using the Accu-Shear™ device, manufactured by Stansteel Inc (Figure 2.3) (http://www.stansteel.com, accessed December 04, 2011). The Accu-Shear™ is a multi-purpose device that can blend multiple liquids (70% water plus 30% anti-stripping agent (AD-here®) in this study) with liquid asphalt to create a variety of products instantaneously. Accu-Shear™ operates under a mechanical shearing process of forcing the liquid asphalt and water to mix together. Through mechanical blending instead of simply injecting, the producer avoids the inherent nature of laminar fluid flow and the foaming action is improved. Therefore, this provides a more uniform coating of asphalt on the aggregates and increases the workability of the asphalt concrete mixture.

Figure 2.3 Accu-Shear™ technology used for producing foamed asphalt

2.2. SMA DESIGN

A 12.5-mm stone matrix asphalt (SMA) has been often used by Chicago area contractors on large-scale expressway overlay projects. More than a million ton of SMA

has been produced for the Illinois Department of Transportation (IDOT) and Illinois Tollway projects in 2010, and similar quantities are expected to be produced in 2011. IDOT primarily specifies standard polymer modified SMA that requires fiber and allows up to 10% fractionated reclaimed asphalt pavement (FRAP) in coarse aggregate. The Illinois Tollway allows the option of using either ground tire rubber (GTR) liquid or styrene-butadiene-styrene (SBS) polymer modified asphalt in the mixture design. Up to 20% high class fine-graded FRAP is allowed in the Tollway mixes to replace the need for virgin fine aggregate. The Illinois Tollway also allows the option of using recycled roof shingles (RAS) as a substitute for fibers in the SBS polymer modified mix designs. No more than 30% of the virgin asphalt in a mix design may be replaced with recycled or residual asphalt binder.

The control SMA is a binder-lift mix, contains coarse crushed gravel aggregates and fine FRAP, produced by Geneva Construction. The FRAP is obtained from the I-290 resurfacing project. The control SMA has a nominal maximum aggregate size (NMAS) of 12.5 mm and 6.2% PG 64-22 asphalt binder with 12% GTR by weight of the asphalt binder. Anti-stripping agent is not used in the control SMA. The volumetric properties of the control SMA are shown in Table 2.1, which meets the standard IDOT requirements for SMA mix design, as modified by the Illinois Tollway special provisions.

Table 2.1 Volumetric Properties of Control SMA

N_{des}	Asphalt content (AC)	Bulk specific gravity (G_{mb})	Maximum specific gravity (G_{mm})	Air void content (AV)	Voids in mineral aggregate (VMA)	Voids filled with asphalt (VFA)	Tensile strength ratio (TSR)
80	6.2%	2.440	2.529	3.5%	15.7	77.7	0.94

The warm SMA is produced by adding warm mix additives into the SMA. The Geneva Control SMA and warm SMA, used in this study, are the same with the exception of the WMA additive. Table 2.2 presents the composition of various control and warm SMA. It is noted that the control SMA and warm SMA containing Evotherm™ 3G have 8% RAP. However, the mixture containing Sasobit® has 5% RAP and 5% RAS, while the mixture containing foamed asphalt has 13% RAP. Aggregate gradations of the four SMA mixtures are shown in Figure 2.4.

2.3 EXPERIMENTAL DESIGN

Understanding that the true mixture performance properties of the WMA may be affected by handling procedures, a considerable amount of effort was spent to plan the testing scenarios before mobilizing into the field. Determining the most appropriate method for compacting samples and testing without altering the natural curing process after mixing the WMA additive or foam was the critical component of this study. Another key issue with the study concerned the logistics. The asphalt plant locations are in Aurora and Naperville, Illinois, and near Beloit, Wisconsin. The University of Illinois's Advanced Transportation Research and Engineering Laboratory (ATREL) is located in

Rantoul, Illinois which is between 145-200 miles from the plant locations. Therefore, conducting a study regarding short-term curing was a challenge considering both travel and technical logistics.

Table 2.2 Composition of Asphalt Mixtures with Various Warm Mix Additives

Mix	N_{des}	NMAS (mm)	Binder	Fine FRAP	RAS	Compaction temp. (°C)	Warm mix additive
Control SMA	80	12.5	PG 64-22 12% GTR	8%	NA	152	NA
Evotherm™ 3G SMA			PG 64-22 12% GTR		NA	127	0.5% of binder
Sasobit® SMA			PG 70-22 SBS modified	5%	5%	127-138	1.5% of binder
Foamed SMA			PG 64-22 12% GTR	13%	NA	127	1.0% of binder

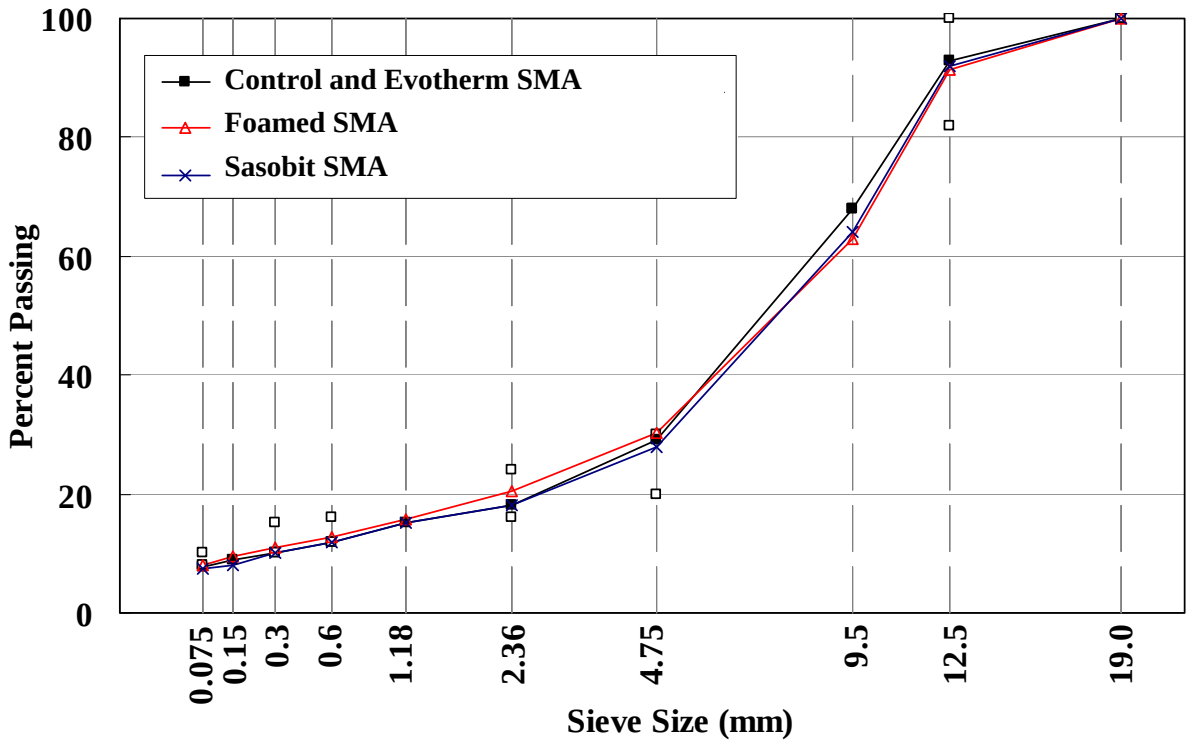


Figure 2.4 Aggregate gradation chart for control and warm SMAs

The research team determined that the only way to accurately represent the curing that occurs in the field was to compact the samples in the field. Field compaction eliminated the concerns from reheating WMA samples in the lab. Considering that a fair amount of samples were needed to be compacted, it became unreasonable to compact the samples using on-site QC equipment. It was determined that the samples would have to be compacted simultaneously to ensure that additional curing did not occur in the loose mixture. The simultaneous compaction also eliminated the need to reheat samples which could cause additional curing. Therefore, the mixture was sampled after it cured appropriately in the silo. Then the samples were transported to the on-site laboratory, blended, split to the appropriate sizes, and compacted in six individual gyratory compactors to the required raw sample heights and void contents.

Considering that a relatively small quantity of WMA was produced each day, the work was conducted very quickly to ensure that enough samples were taken before the silos were empty. Therefore, the process was streamlined through extensive planning and rehearsals until the entire sampling, compaction and preparation procedure for samples to be shipped back to ATREL could be completed in 20 to 30 min for each curing period. One complete rehearsal was performed on the HMA at the Aurora facility prior to actually working with the project mixtures. Each facility was visited prior to mobilization to ensure that it contained adequate space and power to handle additional six gyratory compactors.

2.4. SPECIMEN PREPARATION

2.4.1 Sampling of Plant Mix

For each SMA, each truck sampling yielded the following samples:

- Three complex modulus / flow number samples (one testing specimen produced from each mix sample);
- Two loaded wheel track samples (two testing specimens produced from each mix sample);
- One indirect tensile creep compliance (IDT) / strength sample (two testing specimens produced from each mix sample); and
- Four Maximum Specific Gravity (G_{mm}) samples.

The gyratory samples were compacted using truck samples that represented one of the six curing periods (3 hrs, 6 hrs, 12 hrs, 1 day, 3 days, and 7 days). Sampling was conducted six times to obtain all of the samples for the various curing times, and one additional sampling was performed to obtain all fracture test samples. After the sampled loose mixtures were transported to the QC laboratory, the loose samples were blended and split on a steel counter as quickly as possible. A small bucket of samples were stored separately to monitor temperature changes during splitting and compaction. Paper buckets were used to measure and transport samples as fast as possible to the gyratory compactors. For each gyratory sample, new paper buckets were used to maintain a constant weight loss as asphalt mixture residue adhered onto the bucket. Figure 2.5 shows the sampling and splitting process.

(a)

(b)

(c)

(d)

Figure 2.5 Mix sampling and splitting process: (a) Mix sampling from truck; (b) Mix transportation to lab; (c) Mix splitting in lab; (d) Mix temperature monitoring

2.4.2 Laboratory Compaction

Compaction was conducted at the asphalt plant immediately after sampling. A total of six portable gyratory compactors were used. Pine AFGB Superpave™ portable compactors were used to allow for easy transportation to each facility. Prior to compaction at each site, height calibrations were performed on each compactor. Specimens with three different heights, 160, 150, and 130 mm (6.3, 5.9, and 5.1 in) were compacted to create various performance samples needed for the study. The 160-mm (6.3-in) specimens were tapped and leveled so that the lid of the compactor could shut before compaction. This was necessary due to the height limitations of the portable compactors, which was also the reason why 160 mm (6.3 in) compacted samples were used rather than 170 mm (6.7 in). Compaction was initiated once the sample temperatures decreased to the observed compaction temperatures in the field. After compaction and a brief cooling period, the gyratory samples were ejected and immediately packed using PVC molds and industrial hose clamps to avoid undesirable deformations at high temperatures. Figure 2.6 shows the compaction process.

The air void content of each sample was a critical concern to the study. To ensure that each sample was compacted to the proper air void level, a trial run was performed for each mixture the day before sampling for performance tests were obtained. The same sampling and compaction plan was followed for this process; however, various mixture weights were compacted to three different sample heights, 130 mm, 150 mm and 160 mm (5.1, 5.9, and 6.3 in), in order to determine the amount of mixture needed to achieve the target air void level. Once this was finished, and the samples were cooled, volumetric testing was performed. Finally, the required weights were determined for the next day's production of the samples for performance tests.

(a) (b)

(c) (d) (e)

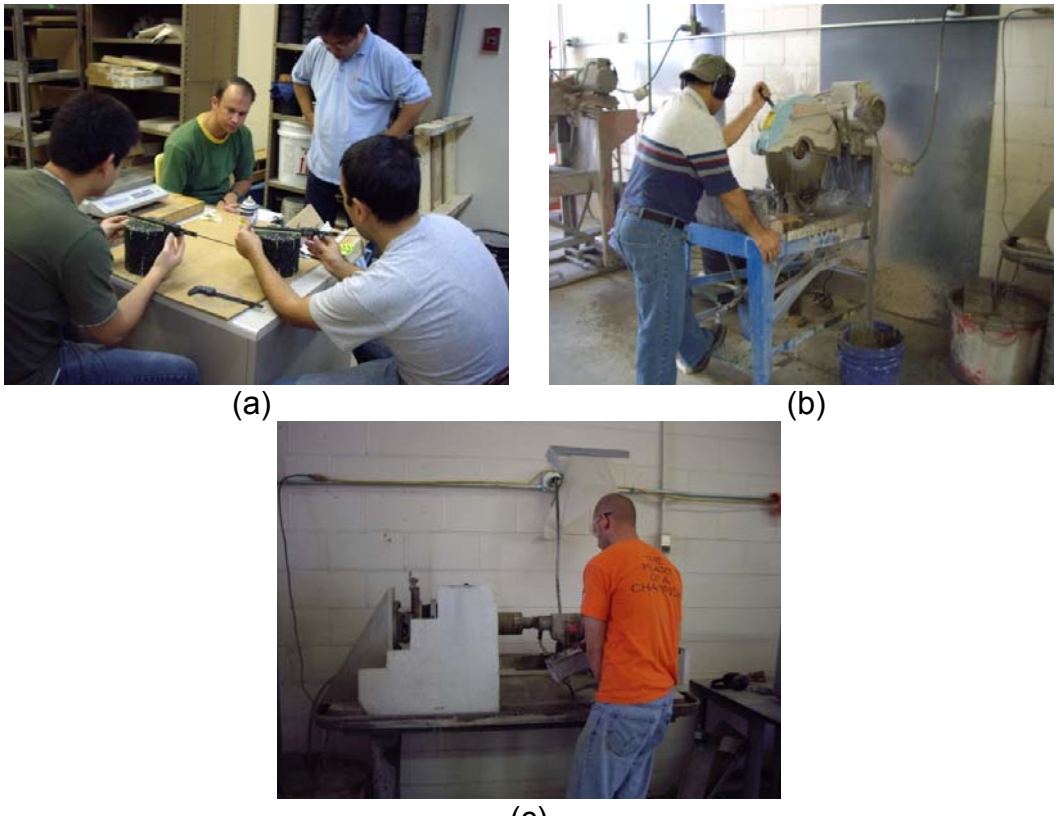
Figure 2.6 Mix compaction process: (a) Gyratory compactors in the QA lab; (b) Placing the gyratory mold into the compactor; (c) Setting up the specimen height; (d) Placing loose mix into the gyratory mold; (e) Protecting gyratory specimen using a PVC pipe

The specimens that needed to be tested 3 hrs after compaction were transported to ATREL at the University of Illinois using a chartered airplane (Figure 2.7), while the remaining samples were transported by trucks. Small coolers with ice were used for the samples that needed to be tested 3 hrs and 6 hrs after compaction to ensure that the samples were cooled enough to cut and test at the specified time. The samples were cut and/or cored at ATREL to different sizes in accordance with the performance test requirements (Figure 2.8). The sample dimensions were also measured, and air void

contents were determined prior to testing. The time and sample temperatures were recorded at each step of the process.

(a) (b)

Figure 2.7 Transporting of specimens for testing at 3 hrs after compaction: (a) Protecting and cooling the gyratory specimens in a cooler; (b) Transporting the cooler to the airplane



(a) (b)

(c)

Figure 2.8 Specimen fabrications for performance testing: (a) Specimen dimension measurement; (b) Specimen cutting; (c) Specimen coring

During the field compaction process, 30 bags of loose mixture were collected for each mix and transported to ATREL. The bagged mixtures were utilized to investigate the effect of sample reheating on mixture properties. They were initially preheated for 3 hrs and then blended and split into smaller samples. To minimize the effect of multiple reheating, the samples were immediately placed in an oven at the field compaction temperatures. As soon as the mixture reached the field compaction temperature, the samples were weighed and compacted using the portable gyratory compactors following the same procedures used at the production facilities. The target weights used for the reheated samples were similar to the field-compacted samples.

2.4.3. Air Voids of Prepared Specimens

The air void contents of the compacted gyratory specimens are measured. Tables 2.3 and 2.4 summarize the variation of air void contents in the specimens prepared for various laboratory tests, respectively, for the specimens compacted with and without reheating. The data show that generally the air void contents are within the range of 6.0±0.5%. Generally, the control mix specimens have relatively higher air void contents, while the mix specimens prepared with foamed asphalt have relatively lower air void contents.

Table 2.3 Air Void Contents for Specimens Compacted without Reheating

Mix	Dynamic modulus and flow number test		Loaded wheel track test		IDT creep and strength test		Semi-circular beam fracture test	
	Average	COV	Average	COV	Average	COV	Average	COV
Control mix	6.1	2%	6.6	2%	6.5	4%	6.5	5%
Mix with Evotherm™ 3G	6.1	2%	6.0	2%	5.8	2%	5.9	2%
Mix with foamed asphalt	6.0	1%	5.6	3%	5.4	4%	5.5	2%
Mix with Sasobit®	6.0	2%	6.0	1%	6.0	2%	6.0	3%

Table 2.4 Air Void Contents for Specimens Compacted after Reheating

Mix	Dynamic modulus and flow number test		Loaded wheel track test		IDT creep and strength test		Semi-circular beam fracture test	
	Average	COV	Average	COV	Average	COV	Average	COV
Control mix	5.9	2%	6.5	3%	6.5	4%	6.4	3%
Mix with Evotherm™ 3G	6.1	3%	6.2	2%	5.9	3%	5.9	2%
Mix with foamed asphalt	5.8	6%	5.2	4%	5.4	3%	5.5	6%
Mix with Sasobit®	6.6	3%	6.2	3%	5.9	1%	5.9	4%

CHAPTER 3 LABORATORY PERFORMANCE TESTS

Mechanical testing is a critical component in the design of asphalt mixtures and the evaluation of pavement performance. The main objective of this study is to conduct a comprehensive laboratory evaluation of asphalt mixtures produced with various WMA additives and recycled materials. To achieve this objective, an experimental matrix was developed to determine the mechanical properties of the evaluated mixtures. Laboratory performance testing included the evaluation of modulus, tensile strength, creep, rutting resistance, and fracture resistance using several tests including: dynamic modulus, IDT creep compliance and strength, loaded wheel track, flow number, and semi-circular beam fracture. Table 3.1 presents the experimental matrix that was conducted in this study. Due to the project logistics and timeframe constraints, specific testing parameters were established and maintained throughout the study to ensure consistency in the testing program.

Table 3.1 Performance Test Matrix for Asphalt Mixtures

Test	Complex modulus	Flow number	Wheel track	IDT creep	IDT strength	SCB
Material property	|E*|, phase angle	Fn	Rut depth	Creep compliance	Strength	Work of fracture
Temp. (^{o}C)	25	58	30	25	25	-12
Dimension	100 mm (D) 150 mm (H)		65 mm (H)	150 mm (D) 50 mm (H)		75 mm (R) 50 mm (H)
Condition	25, 10, 5, 1, 0.5, 0.1 Hz	Up to10k cycles or 5% strain	Up to 20k cycles (dry)	100 sec	Max. 10 kN	CMOD control at 0.7 mm/min

3.1 COMPLEX (DYNAMIC) MODULUS TEST

The complex modulus test provides structural characterization of asphalt mixtures and is used as a major input for the proposed Mechanistic Empirical Pavement Design Guide (MEPDG). The complex modulus test is performed by measuring the recoverable vertical strain when sinusoidal vertical loads are applied to the specimen at different frequencies (Figure 3.1). AASHTO TP-62, *Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*, was followed for the complex modulus test. For each mix and curing period, three replicates were prepared for testing. In this study, complex modulus tests are conducted at room temperature (25°C) with frequencies of 25, 10, 5, 1, 0.5 and 0.1 Hz. The complex modulus tests are conducted using a controlled stress mode, which produces strains smaller than 100 microstrain. This ensures that the response of the asphalt mixture was within the linear viscoelastic range. The measured complex modulus and phase angle is defined by Equations 3.1 to 3.3, respectively.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (3.1)$$

$$\sigma = \sigma_0 \sin(\omega t) \quad (3.2)$$

$$\varepsilon = \varepsilon_0 \sin(\omega t - \phi) \quad (3.3)$$

where, σ_0 is applied steady state stress amplitude;

ε_0 is measured strain amplitude;

ω is angular frequency ($2\pi f$, where f = frequency); and

ϕ is phase angle in radians ($\omega \Delta t$, where Δt = time lag between stress and strain).

Figure 3.1 Complex (dynamic) modulus test setup

3.2 FLOW NUMBER TEST

The National Cooperative Highway Research Program (NCHRP) report 465 recommends that the flow number test can be used to evaluate the permanent deformation potential of asphalt mixtures by applying repeated haversine loads and recording the cumulative deformation as a function of loading cycles (Witczak et al., 2002). The repeated load is applied for 0.1 sec with a rest period of 0.9 sec in one cycle. The cumulative permanent deformation curve is generally defined by three stages: primary, secondary, and tertiary. The permanent deformation rates decrease in the primary stage and increase again in the tertiary stage. In the tertiary stage, the permanent deformation increases rapidly. The flow number is defined as number of loading cycles at the beginning of the tertiary stage.

In this study, the flow number test was conducted using a uniaxial compression load without confinement at 58°C (136°F). A loading stress level of 200 kPa (29 psi) was selected to attain tertiary flow in a reasonable number of cycles. The test was conducted up to 10,000 cycles or until 5% of cumulative permanent stain was achieved. The Francken model was used to fit the measured permanent strain as a function of the number of loading cycles (Dongré et al. 2009). The Francken model is a combination of power law function and exponential function, as shown in Equation 3.4. The first derivative of the Francken model is calculated as the rate of permanent strain. Then the

second derivative of the Francken model is calculated to obtain the slope of the rate of permanent strain (Equation 3.5). The flow number is calculated at the point where the slope of the rate of permanent strain changes sign (from negative to positive).

$$\varepsilon_p = AN^B + C(e^{DN} - 1) \tag{3.4}$$

$$\frac{\partial^2 \varepsilon_p}{\partial N^2} = A \cdot B \cdot (B-1) \cdot N^{(B-2)} + C \cdot D^2 \cdot e^{D \cdot N} \tag{3.5}$$

where, ε_p is accumulated permanent strain;

N is number of loading cycles; and

A, B, C, and D are fitting parameters.

Figure 3.2 Flow number test setup

3.3 LOADED WHEEL TRACK TEST

A Hamburg-type loaded wheel tester, manufactured by PMW, Inc., was used to assess the rutting performance of mixtures. The test was conducted in accordance with a TxDOT procedure (Tex-242-F) with the exception of being conducted in a dry condition at 30°C (86°F). The dry condition was selected to better represent the short term performance immediately after construction. The test was performed by rolling a 738N (158lb) steel wheel on the specimen surface at 50 passes a minute for 20,000 total passes to compare the rutting performance between different mixtures. Figure 3.3 shows a typical test setup with samples in the air conditioned chamber. The rut depth at a specified number of wheel passes or the number of passes until failure was reported.

Figure 3.3 Loaded wheel test setup with air condition chamber

3.4 INDIRECT TENSILE CREEP AND STRENGTH TESTS

The IDT creep and strength test was performed in accordance with AASHTO T-322-07, *Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device*, on a universal testing machine manufactured by Instron, Inc. In the creep test, a constant static load was diametrically applied at room temperature (25°C/77°F) to the specimen for 100 sec. Horizontal and vertical extensometers mounted on the front and back sides of the specimen measured and recorded the deformations under the static load (Figure 3.4). The creep compliance was then computed using Equation 3.6. In the strength test, the specimen was loaded until failure at a rate of 12.7 mm/min (0.5 in/min) (Figure 3.5). The IDT strength was calculated using Equation 3.7. It was noted that the applied load could not exceed 10 kN (2248 lbf) due to the limit of the load cell used in the test. The same sample was used for both creep and strength tests at room temperature (25°C/77°F).

$$D(t) = \frac{\varepsilon_x(t) \cdot d \cdot b}{P} \cdot C \tag{3.6}$$

where, *D(t)* is creep compliance;

$\varepsilon_x(t)$ is measured horizontal strain with time;

t is testing time;

d is diameter of specimen;

b is thickness of specimen;

P is applied load; and

C is calculated calibration factor.

$$S_t = \frac{2P}{\pi \cdot d \cdot b} \tag{3.7}$$

where, S_t is tensile strength;

P is maximum applied load;
d is diameter of specimen; and
b is thickness of specimen.

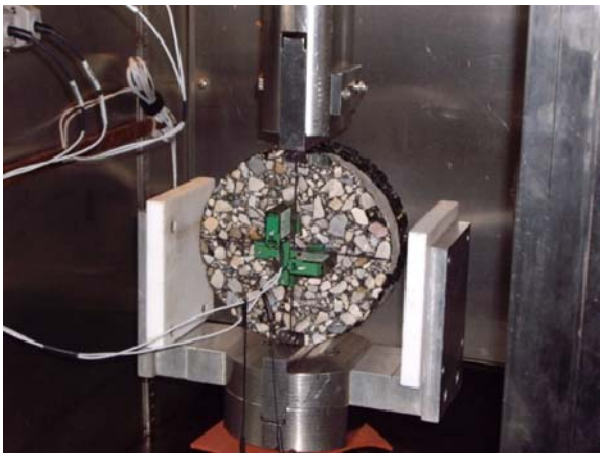


Figure 3.4 Indirect tensile creep compliance test setup

Figure 3.5 Indirect tensile strength test setup

3.5 SEMI-CIRCULAR BENDING FRACTURE TEST

Fracture characterization of the asphalt mixtures was conducted using the SCB fracture test (Figure 3.8). For this test, specimens were sliced into 50-mm (2-in) thick cylinders and cut in half along the diameter. A 15-mm (0.6-in) notch was cut into each half of the specimen. The test was performed at a temperature of -12°C (10°F), which is 10°C warmer than the low-temperature binder grade. The test was conducted in a constant crack mouth opening displacement (CMOD) rate mode and the load, displacement, and CMOD were recorded. The work of fracture was calculated from the SCB test by taking the area under the load- CMOD curve, as shown in Equation 3.8.

$$W_f = \int P du \quad (3.8)$$

where, W_f is work of fracture;

P is applied load; and

u is crack mouth opening displacement (CMOD).

Figure 3.6 Semi-circular beam fracture test setup

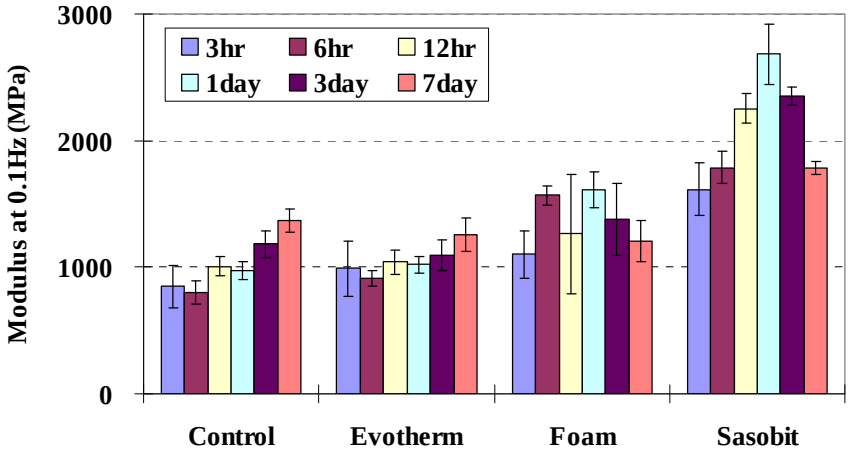
CHAPTER 4 TEST RESULTS ANALYSIS AND DISCUSSION

4.1 PERFORMANCE OF WARM MIX ASPHALT

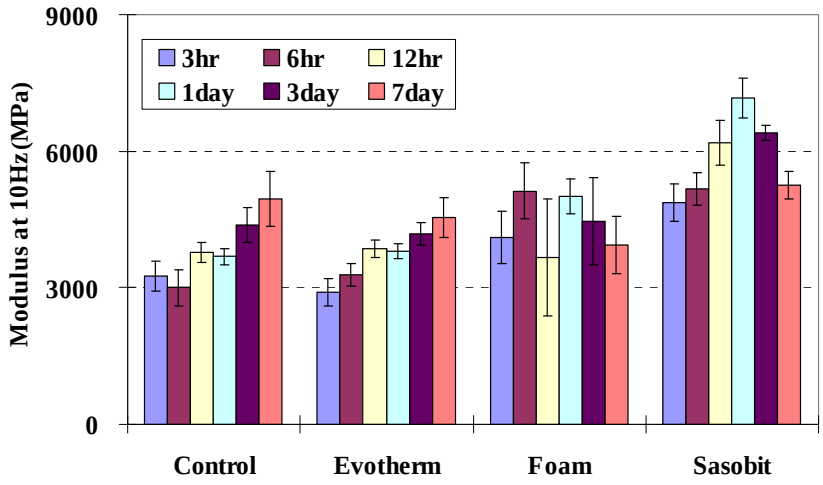
The mechanical properties of asphalt mixtures are affected by numerous factors including aggregate type and gradation, bitumen grade, compaction temperature, curing and aging, anti-stripping treatments, and volumetric parameters. In this study, laboratory test results were used to compare the performance of SMA containing various WMA additives and recycled material that were compacted at lower temperatures than the control SMA. The variation of mixture properties with curing time was analyzed. The curing time describes the possible oxidative hardening and strength gain processes after compaction. In addition, a study was conducted to determine the effect of the reheating process on the mechanical properties of warm SMA.

4.1.1 Complex (Dynamic) Modulus

Figures 4.1(a) and (b) compare the measured complex modulus at 25°C (77°F) for the control SMA and the mixtures containing various WMA additives, respectively, at 0.1 Hz and 10 Hz. The columns indicate the average value from the replicates, while the error bars indicate the spread of data within one standard deviation. The results show that the complex modulus trends with curing time are not the same across the four mixtures. The complex modulus has an increasing trend as the curing time increases for the control mixture and the mixture containing Evotherm™ 3G. However, for the mixtures containing foamed asphalt and Sasobit®, the complex modulus increases initially and then decreases as the curing time increases. Interestingly, for the mixtures containing foamed asphalt and Sasobit®, the complex modulus after a 7-day curing time is close to the modulus after a 3-hr curing time.



(a)

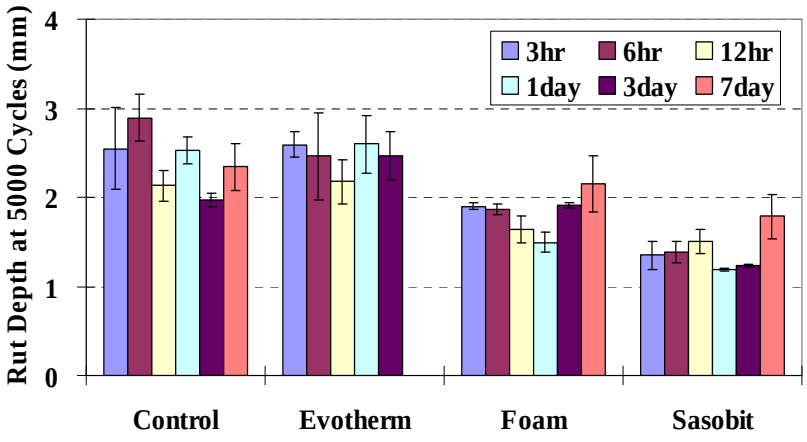


(b)

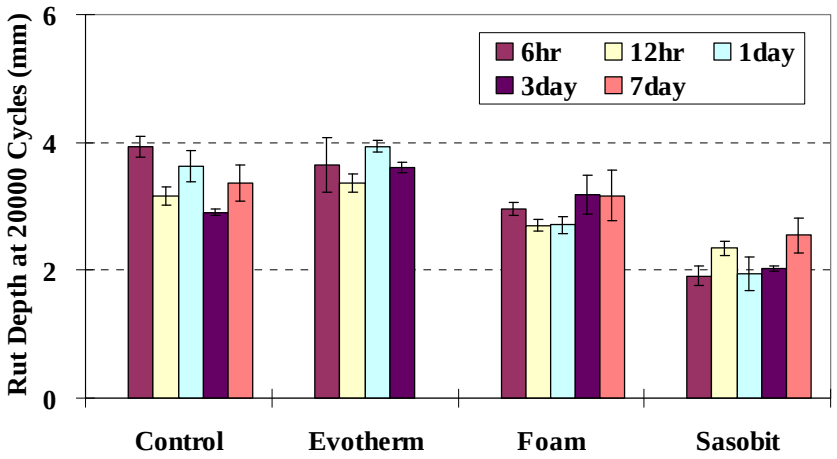
Figure 4.1 Complex moduli for various SMA at (a) 0.1 Hz and (b) 10 Hz

4.1.2 Rutting Potential

Figures 4.2 (a) and (b) compare the measured rut depths (dry condition) at 30°C (86°F) for the control SMA and the mixtures containing various WMA additives, respectively, at 5,000 and 20,000 cycles. Generally, no clear trend is observed between the mixtures' rutting potential and curing time.



(a)



(b)

Figure 4.2 Rut depths for various SMA after (a) 5,000 and (b) 20,000 cycles

The rutting potential of the SMA was also evaluated through the flow number test. Due to the time restriction, flow number tests were conducted only for the mixtures having more than 12 hrs curing time. Figure 4.3 shows the flow number test results at 58°C (136°F) for the control SMA and the mixtures containing various WMA additives. The results show that as the curing time increases, the flow number remains relatively constant for the control SMA and the mixture containing Evotherm™ 3G; while the flow number decreases significantly for the mixtures containing foamed asphalt and Sasobit®, for which the flow number is initially relatively high. However, these trends need further investigation due to the high variation between three test replicates. Test outcome at 3 day and 7 day for control SMA and SMA with Evotherm™ 3G, respectively, were not usable.

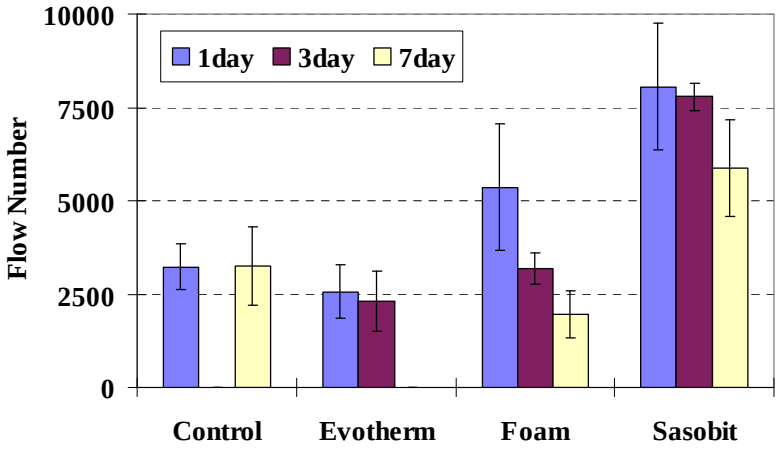


Figure 4.3 Flow number for various SMA

4.1.3 Tensile Strength and Creep Compliance

Figure 4.4 shows the measured IDT tensile strength at 25°C (77°F) for the control SMA and the mixtures containing various WMA additives. The actual tensile strength of the mixtures containing Sasobit® can be greater than the measured values because the maximum load limit (10 kN/2248 lbf) is reached in the test. It is found that the tensile strength increases with curing time for the control SMA and the mixture containing Evotherm™ 3G. However, for the mixtures containing foamed asphalt and Sasobit®, the tensile strengths increase initially and then decrease as the curing time increases. The trend of strength changing with curing time is consistent with the trend observed from the complex modulus data.

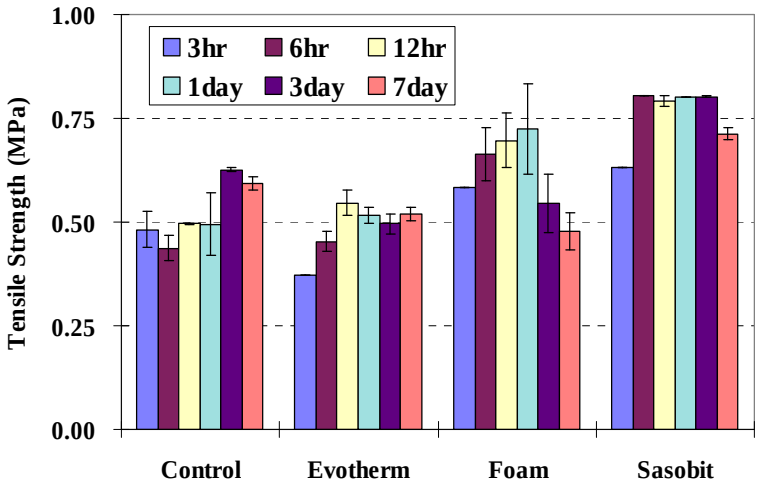
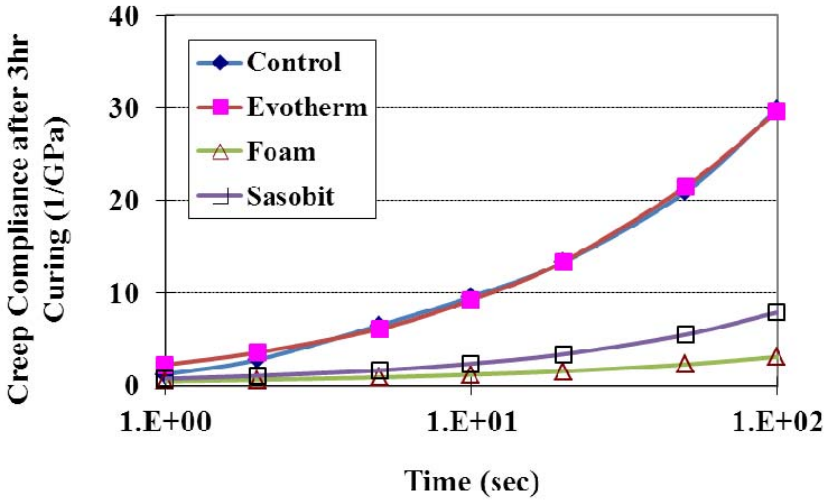
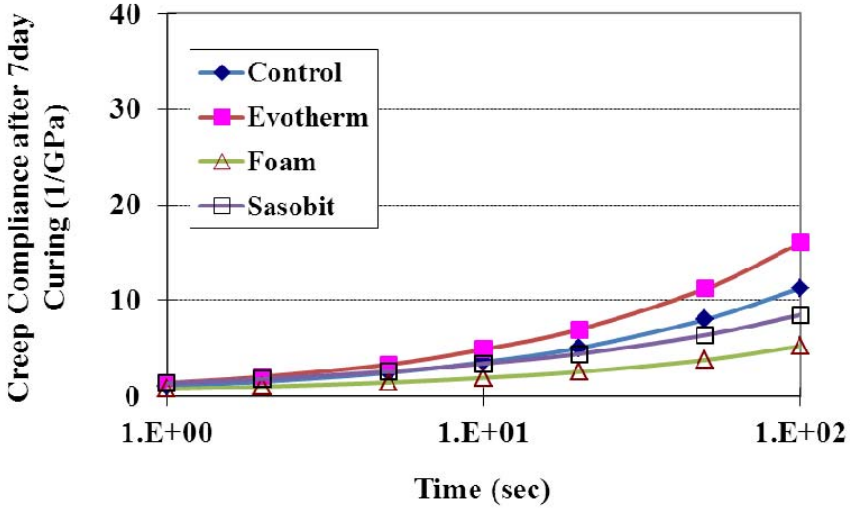


Figure 4.4 Tensile strength for various SMA

Figures 4.5 (a) and (b) show the measured creep compliance data at 25°C (77°F) for the control SMA and the mixtures containing various WMA additives, respectively after a 3hr and 7-day curing time. Creep deformation indicates the tendency of material to deform under static loading over a certain period of loading time. As expected, the creep compliance increases as the loading time increases. The four SMA mixtures have similar creep compliance values at very short loading periods. As the loading time increases, the mixtures containing foamed asphalt and Sasobit® have less creep compliance values than the control SMA and the SMA containing Evotherm™ 3G, especially for the specimens tested after a 3-hr curing time.



(a)



(b)

Figure 4.5 Creep compliance data for various SMA after (a) 3-hr and (b) 7-day curing

4.1.4 Fracture Properties

Figure 4.6 shows the measured fracture at -12°C (10°F) for the control SMA and the mixtures containing various WMA additives. Generally, the mixture resistance to fracture slightly decreases as the curing time increases. Among the four mixtures, the SMA containing Sasobit® shows the lowest work of fracture suggesting a stiffer mixture.

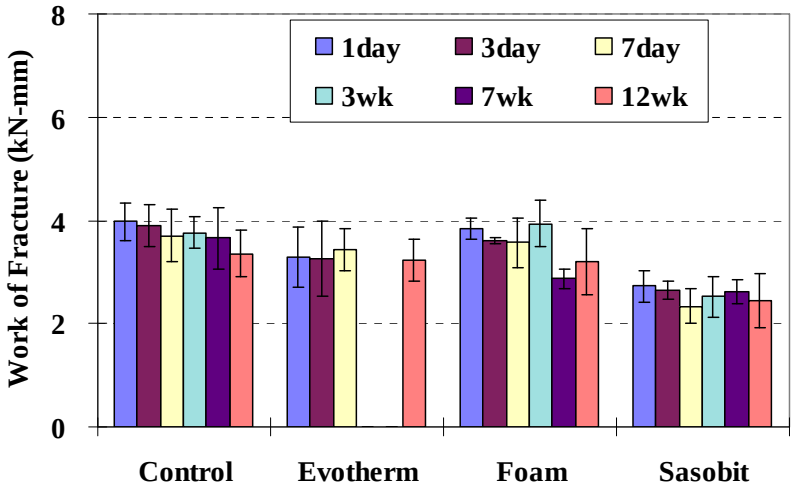


Figure 4.6 Work of fracture for various SMA

4.1.5 Variation of Mixture Properties due to Curing Time

Table 4.1 summarizes the variation of mixture properties due to curing time for various SMA. Among various mixture properties, creep compliance has the most variance. It has been previously hypothesized that WMA may continue to increase in strength over time and thus need prolonged curing time before being opened to traffic. However, the results show that the mixtures containing WMA additives have similar variations in their mechanical properties due to curing time compared to the control mixture, with the exception of the flow number test results.

The test results were statistically analyzed using the Statistical Analysis System (SAS) program. Two-way analysis of variance (ANOVA) was performed to analyze test results with each mixture property as the response variable. The factors considered in the analysis are curing time and mixture type. A Fisher LSD (Least Significant Difference) test was performed with ANOVA for multiple comparisons within each factor at a significant level of 0.05. The statistical significance of the changes in the mixture properties as a function of curing time or mixture type was analyzed. The test results were ranked using letters, and the letter was changed when the mean was statistically different from others. The letter A was assigned to the best performer followed by the other letters in alphabetic order. A double letter, such as A/B, indicated that the difference in the means was not statistically significant and that the results could fall in either group.

Table 4.2 shows the effect of curing time on each mixture property when the data are group together for all mixture types. The complex modulus at 10 Hz and the rut depth measured in the load wheel test at 20,000 cycles are used in the analysis. The results indicate that curing time is responsible for significant difference in the complex modulus and tensile strength but only for a small or almost negligible difference in the fracture and rutting resistance. As curing time increases, the complex modulus increases but the fracture resistance slightly decreases; while the tensile strength

initially increases and then slightly decreases. The results indicate that when comparing the performance between different SMA's, the mixtures should be tested after a consistent amount of storage time since compaction. Otherwise, the mixture performance may be falsely ranked because the mixture properties may change with curing time.

Table 4.1 Variation of Mixture Properties due to Curing Time

Property	Data	SMA			
		Control	Evotherm™ 3G	Foam	Sasobit®
Modulus at 10 Hz (MPa)	Average	3838	3761	4380	5838
	COV	19%	16%	13%	15%
Rut depth at 20,000 cycles (mm)	Average	3.4	3.6	2.9	2.2
	COV	12%	7%	8%	13%
Flow number	Average	3242	2431	3503	7235
	COV	1%	8%	49%	17%
IDT tensile strength (MPa)	Average	0.52	0.48	0.61	0.76
	COV	14%	13%	16%	9%
Creep compliance at 100 sec (1/GPa)	Average	23.13	17.40	6.92	3.18
	COV	45%	42%	36%	33%
Work of fracture (kN-mm)	Average	3.7	3.3	3.5	2.6
	COV	6%	3%	12%	6%

4.2 Effect of Aging on Mixture Properties due to Reheating

Aging is an important contributor to the loss of pavement serviceability. It is important to know how different WMA additives affect the aging of binders and mixtures, and the long-term pavement performance. The binder aging can be classified as short-term and long-term. Short-term aging refers to the oxidation and volatilization that occurs during mixing, storage, transportation, and paving processes, whereas long-term aging simulates the aging that occurs over the service life of a pavement after compaction. The referenced standard available for aging of asphalt mixtures is AASHTO R30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt.* AASHTO R30 specifies that short-term mixture conditioning for mechanical performance testing

can be simulated by putting loose mixtures in an oven for four hrs at a temperature of 85°C (275°F), while for long-term aging, loose material is compacted into cylindrical specimens and placed in an oven at 135°C (185°F) for 120 hrs.

Table 4.2 Fisher LSD Test Results for the Effect of Curing Time

Mixture property	Curing time					
	3 hr	6 hr	12 hr	1d ay	3 day	7 day
Modulus	D	C/D	B/C	A	A	A/B
Rut resistance	/	A	A	A	A	A
Tensile strength	D	B/C	A	A	A/B	C
Property	Curing time					
	1day	3day	7day	21day	42day	84day
Fracture resistance	A	A/B	A/B	A/B	B	A/B

In this study, the loose mixtures collected from the asphalt plant were reheated in the laboratory to investigate the influence of reheating on mixture properties. The reheating process could artificially age the mixture because chemical reactions might take place in the reheating process regardless of the duration of heating. The reheated specimens were tested at the same curing time as the specimens that were not reheated. Table 4.3 summarizes the variation of mixture properties due to curing time for various SMA's after reheating. Similar to the finding for the mixtures without reheating, the reheated mixtures containing WMA additives showed similar variations to the reheated control mixture due to curing time, with the exception of the flow number test results.

An aging ratio is used to quantify the extent of the binder hardening effect on mixture properties due to reheating. The aging ratio is calculated as the ratio of the mixture properties tested using the reheated specimens with respect to the mixture properties tested using the specimens without reheating. The aging ratios are calculated using the mixture properties measured at various curing times after compaction. Figure 4.7 compares the average aging ratios due to sample reheating for various SMA's. The comparison outcome show that the reheating process results in the SMA to have greater complex modulus, tensile strength, and rutting resistance; but lower creep compliance and fracture resistance. This is expected because the viscosity of binder could increase significantly during the reheating process and the binder becomes stiffer and more brittle. Among various mixture properties, reheating causes the relatively greater changes in the modulus, flow number, and creep compliance, in comparison to other mixture properties.

The results show that the effect of reheating is more significant for the control SMA, compared to the mixtures containing WMA additives. This is due to the fact that the

reheating temperature for the control mixture (152°C/305°F) is higher than the reheating temperature for the mixtures containing WMA additives (127 or 138 °C/260 or 280°F). Among the mixtures containing various WMA additives, the mixture containing Sasobit® has relatively smaller changes in mixture properties due to reheating; but also it is generally the stiffest tested mixture.

Table 4.3 Variation of SMA Properties due to Curing Time (Reheated)

Property	Data	SMA			
		Control	Evotherm™ 3G	Foam	Sasobit®
Modulus at 10 Hz (MPa)	Average	6985	5649	5463	7293
	COV	13%	6%	11%	11%
Rut depth at 20,000 cycles (mm)	Average	2.1	2.4	1.4	1.6
	COV	20%	13%	11%	9%
Flow number	Average	6637	3002	5504	9167
	COV	2%	5%	24%	16%
IDT tensile strength (MPa)	Average	0.65	0.66	0.79	0.77
	COV	14%	17%	8%	7%
IDT creep compliance at 100 sec (1/GPa)	Average	3.62	5.32	2.11	1.58
	COV	40%	37%	15%	28%
Work of fracture (kN-mm)	Average	2.5	2.7	3.3	2.3
	COV	9%	9%	7%	12%

4.3 PERFORMANCE COMPARISON BETWEEN MIXTURES

The performance of SMA's with various WMA additives and recycled materials were compared using the ANOVA with Fisher LSD test based on laboratory performance test results. Table 4.4 shows the rank of mixture performance for each mixture property when the data are grouped together for all curing times. The results show that in comparison to the control SMA, the mixture containing Evotherm™ 3G has statistically similar complex modulus but smaller rutting and fracture resistance. This could be due to the effect of the less aged binder and the residual moisture in the asphalt mixture containing Evotherm™ 3G; these two mixtures have the same mixture components except the Evotherm™ 3G additive.

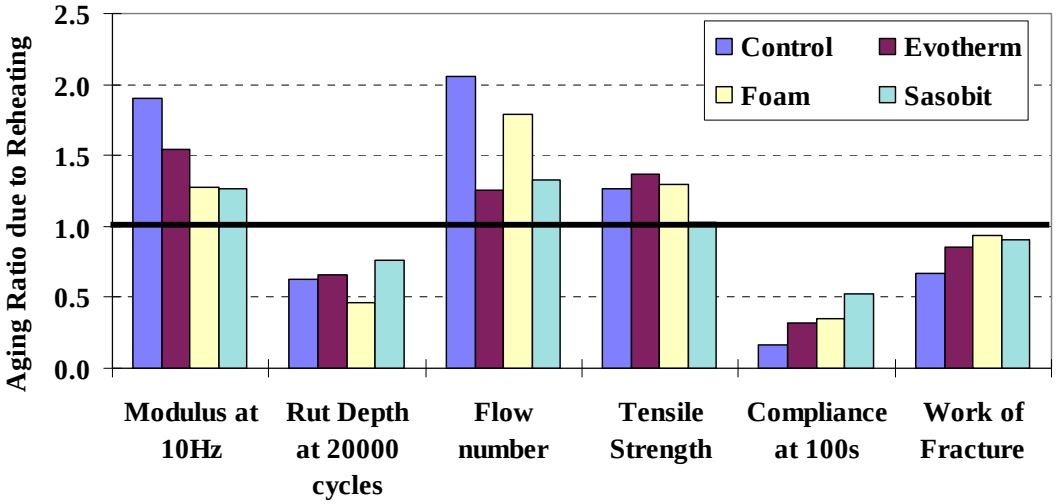


Figure 4.7 Aging ratios of mixture properties due to reheating

The SMA containing Sasobit® and foamed asphalt show superior performance in rutting resistance but worse performance in fracture resistance than the control SMA. This could be due to the combined effects of WMA additives, binder modification, and the RAP or RAS content. The control SMA has 8% RAP and a PG 64-22 binder modified with 12% GTR. However, the SMA containing foamed asphalt has 13% RAP; while the SMA containing Sasobit® has an SBS-modified PG 70-22 binder and 5% RAP and 5% RAS. The GTR is usually used to improve the high temperature properties of the virgin binder. Previous research has shown that the addition of 12% crumb rubber by weight of the virgin binder can increase the PG grade of the binder by at least one grade (e.g., from PG 64-22 to PG 70-22) (Putman et al. 2005). As discovered in previous research on RAP, higher RAP contents can increase the mixture stiffness; but decrease its fracture resistance (Al-Qadi et al. 2009). Previous research has also shown that the use of roof shingles results in the increase of complex modulus and rutting resistance. However, the mix may have a lower fatigue resistance and low temperature cracking resistance. This could be due to the use of higher viscosity asphalt in the shingles along with the reinforcing effect of the fiber (Sengoz and Topal 2003).

Table 4.5 shows the rank of SMA performance for each mixture property for the reheated specimens. It shows that the mixture properties were affected by the mixture type at statistical significance, which is similar to the comparison between the mixtures without reheating. However, the performance rank between various mixtures changes due to reheating. For example, the control SMA and the SMA containing Sasobit® have statistically similar modulus after reheating. The reheated mixture containing foamed asphalt shows superior performance in the tensile strength, rutting resistance, and fracture resistance. This indicates that the effect of WMA additives on mixture properties is affected by the aging of binder.

Table 4.4 Fisher LSD Test Results for the Effect of SMA Type

Mixture property	SMA			
	Control	Evotherm™ 3G	Foam	Sasobit®
Modulus	C	C	B	A
Rut resistance	C	D	B	A
Tensile strength	C	D	B	A
Fracture resistance	A	B	A/B	C

Table 4.5 Fisher LSD Test Results for the Effect of SMA Type (Reheated)

Mixture property	SMA			
	Control	Evotherm™ 3G	Foam	Sasobit®
Modulus	A	B	B	A
Rut resistance	C	D	A	B
Tensile strength	B	B	A	A
Fracture resistance	C	B	A	C

CHAPTER 5 FIELD EVALUATION USING LIGHT WEIGHT DEFLECTOMETER

Concurrent to the laboratory performance tests, light weight deflectometer (LWD) tests were also conducted in the field to monitor the early-age surface modulus of the pavement sections constructed with the SMA containing various WMA technologies.

5.1 PRINCIPLE OF LIGHT WEIGHT DEFLECTOMETER

A light weight deflectometer is field testing equipment that determines the stiffness of pavement material (Figure 5.1). Compared to the falling weight deflectometer (FWD), LWD is portable, easy to operate, less expensive, and small enough to be used anywhere.

The basic principle of the LWD is to measure surface deflections induced by the dropping weight using geophones. Figure 5.2 shows the typical data measured by the LWD. The calculation of the pavement surface deflection modulus is based on the Boussinesq solution as shown in the following equation:

$$E_0 = \frac{f(1-\mu^2)\sigma_0 a}{d_0} \tag{5.1}$$

where, E_0 is the surface deflection modulus (MPa);
f is the factor for stress distribution (2 is a standard value for a flexible plate);
μ is the Poisson's ratio (normally 0.35 for asphalt mixture);
σ_0 is the stress under the plate (kPa);
a is the radius of plate (mm); and
d_0 is the center deflection (micron).

Figure 5.1 Light weight deflectometer

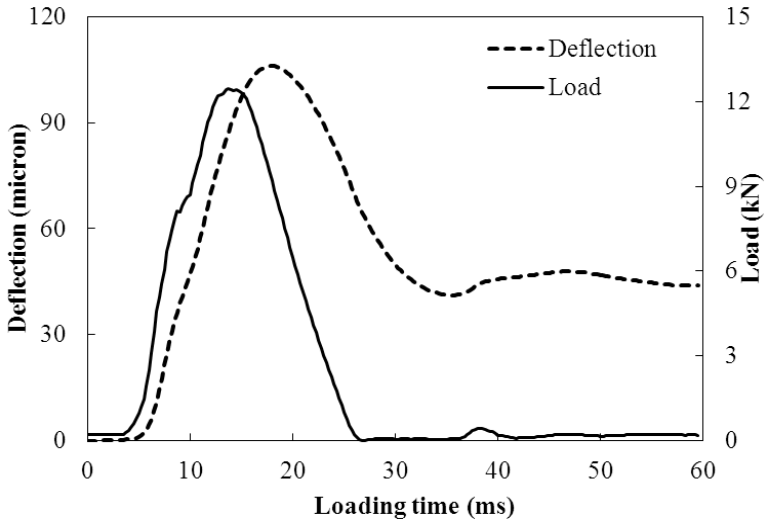


Figure 5.2 Typical load and deflection response of LWD testing

5.2 FIELD SECTION DESCRIPTION AND LWD TESTING PLAN

Three construction sites were selected in this study to evaluate the field performance of the SMA prepared using different WMA technologies. Figure 5.3 illustrates the construction sites on I-355 and I-90. The construction date of each site and the compaction ending time for each SMA are presented in Table 5.1.

Table 5.1 Construction Date and Compaction Ending Time for Each Mix

Construction site	I-355 (Site 1)		I-355 (Site 2)		I-90 (Site 3)
Mixture	Control	Evotherm™ 3G	Control	Sasobit®	Foamed
Construction date	08/31/2010		09/15/2010		11/14/2010
Compaction ending time	6:00pm	9:30pm	6:00pm	3:00pm	4:00pm

For each paved mixture, a leveled area was selected for the LWD test to eliminate the effect of the surface slope on the testing results. Three test locations were selected at each construction site, including one at the left wheel path, one at the central lane, and one at the right wheel path, as illustrated in Figure 5.4. The LWD testing started right after the final compaction pass. To monitor the surface modulus change with time after construction, the test was repeated every 30 min for 3 hrs, and then every 3 hrs until 24 hrs. Before each test, the pavement surface temperature was measured using a temperature gun.

(a)

(b)

(c)

Figure 5.3 (a) Evotherm™ 3G SMA construction site at I-355 driving lane; (b) Sasobit® SMA construction site at I-355 driving lane; and (c) foamed SMA construction site at I-90 ramp

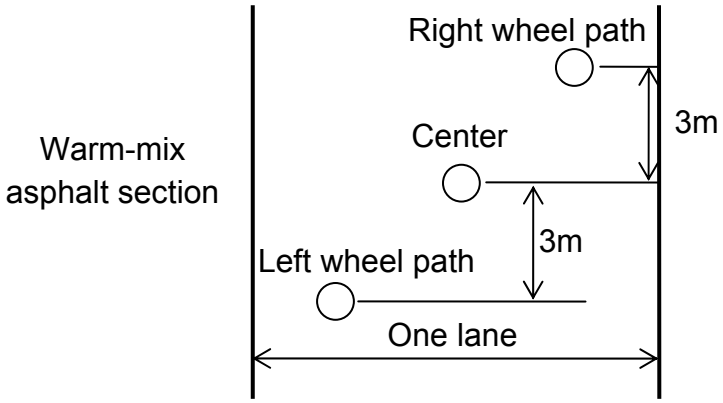


Figure 5.4 LWD test locations

5.3 LWD TESTING RESULTS

5.3.1 Pavement Surface Temperature after Compaction

Because an asphalt mixture is a viscoelastic material, its modulus is sensitively dependent on the temperature. Therefore, it is important to record the temperature for each test. The temperature of the asphalt mixture decreases after compaction, and its cooling rate is dependent on various factors, such as compaction temperature, pavement layer thickness, existing surface, and environmental condition (e.g., ambient temperature and wind speed).

Figures 5.5 to 5.7 show the measured surface temperatures up to 3 hrs after compaction for each construction site. These figures indicate that the pavement surface temperatures of the Evotherm™ 3G SMA, Sasobit® SMA, and foamed SMA, at the end of compaction, were approximately 49, 66, and 49°C (120, 150, and 120°F), respectively. After compaction, the surface temperatures of the Evotherm™ 3G SMA and Sasobit® SMA were 11°C (20°F) lower than the control SMA. The cooling rate of the foamed SMA is much higher than the Evotherm™ 3G SMA and Sasobit® SMA, because it was constructed on a cold day with an ambient temperature of approximately 4°C (39°F).

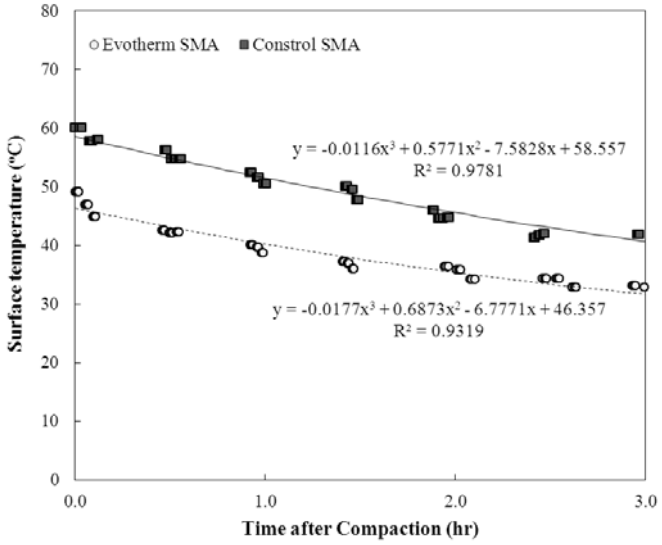


Figure 5.5 Pavement surface temperature of Evotherm™ 3G SMA construction site

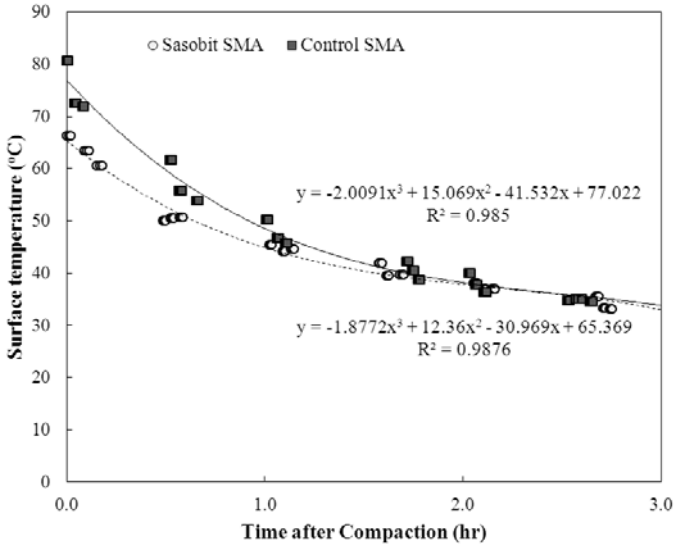


Figure 5.6 Pavement surface temperature of Sasobit® SMA construction site

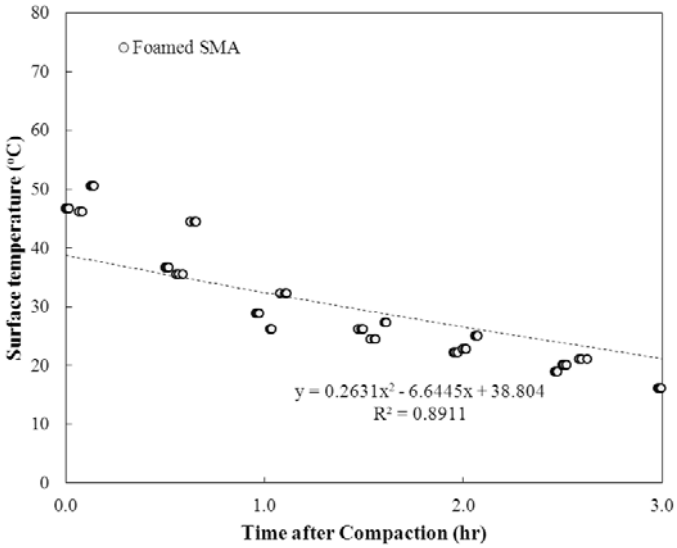


Figure 5.7 Pavement surface temperature of foamed SMA construction site

5.3.2 Relationship between Surface Modulus and Surface Temperature

After the asphalt mixture is placed and compacted in the field, the modulus will change with time, which can be captured in the LWD data. The change of the surface modulus with time after construction is essentially due to the change in mixture temperature.

Figures 5.8 to 5.10 show the relationship between the surface modulus and the temperature for all paved mixtures. It can be observed that with the decrease of pavement surface temperature, the surface moduli of all mixtures increased. At the same temperature, the control SMA provides a relatively higher surface modulus than

the Evotherm™ 3G SMA and the Sasobit® SMA. Control SMA was not placed at the construction site for evaluating the foamed SMA.

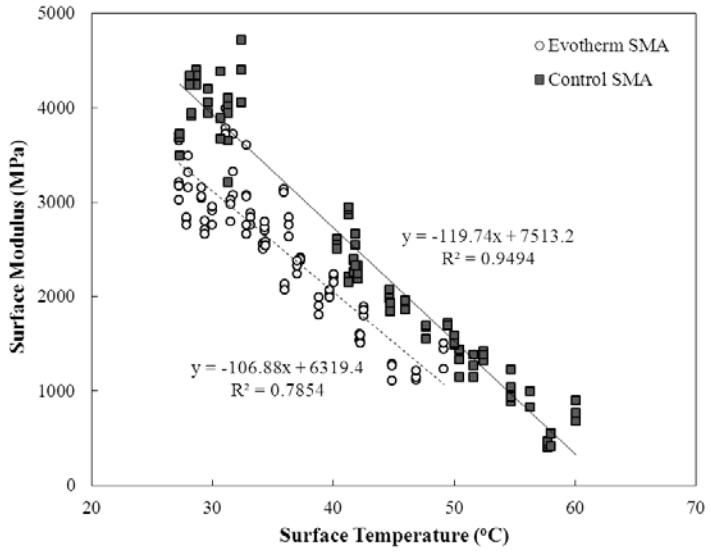


Figure 5.8 Surface modulus vs surface temperature (Evotherm™ 3G SMA)

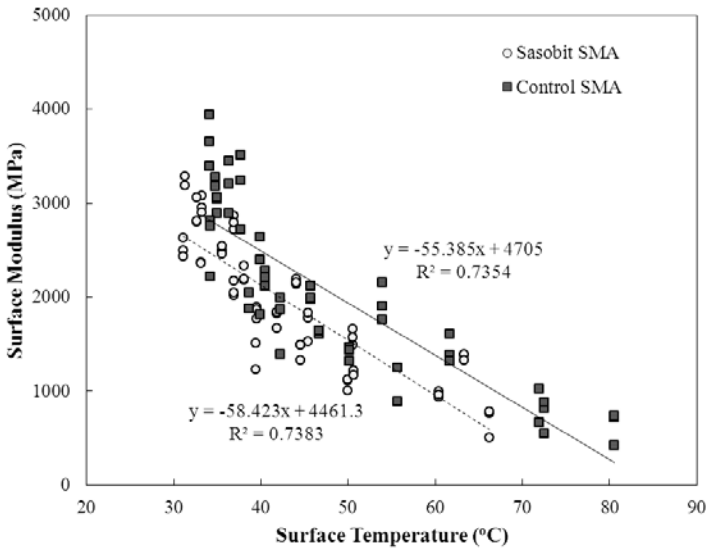


Figure 5.9 Surface modulus vs surface temperature (Sasobit® SMA)

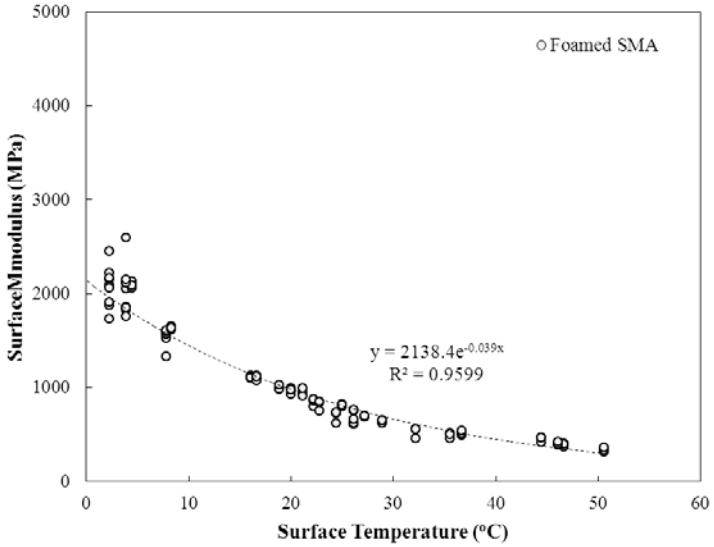


Figure 5.10 Surface modulus vs surface temperature (foamed SMA)

5.4 TRAFFIC OPENING TIME FOR WARM SMA

One of the concerns for WMA construction is the traffic opening time. The LWD testing allows determining the traffic opening time for WMA based on the surface modulus measurement. The criteria require that the warm SMA and control SMA should have the same modulus at the traffic opening time.

Based on Figure 5.8, the relationships between the surface modulus, *E*, and surface temperature, *T*, for the control SMA and Evotherm™ 3G SMA can be described using Equations 5.2 and 5.3, respectively. From Equation 5.2, the surface modulus of the control SMA at a certain traffic opening temperature can be determined. This surface modulus can then be input into Equation 5.3 to determine the traffic opening temperature for Evotherm™ 3G SMA. Note that because the control SMA and Evotherm™ 3G SMA were constructed at the same thickness above the same existing pavement structure, the same LWD surface modulus will lead to the same modulus of the two mixtures.

$$E_{control} = -119.74 T_{control} + 7513.2 \quad (5.2)$$

$$E_{Evotherm} = -106.88 T_{Evotherm} + 6319.4 \quad (5.3)$$

According to Figure 5.2, the relationship between the surface temperature, *T*, and the time after construction, *t*, for the control SMA and Evotherm™ 3G SMA can be described using the Equations 5.4 and 5.5, respectively. Then, the traffic opening times for the control SMA and Evotherm™ 3G SMA can be calculated using Equations 5.4 and 5.5, respectively. These traffic opening times offer the Evotherm™ 3G SMA and control SMA the same modulus at traffic opening time.

$$T_{control} = -0.0116t_{control}^{3} + 0.5771t_{control}^{2} - 7.5828t_{control} + 58.557 \quad (5.4)$$

$$T_{Evotherm} = -0.0177t_{Evotherm}^{3} + 0.6873t_{Evotherm}^{2} - 6.7771t_{Evotherm} + 46.357 \quad (5.5)$$

Table 5.2 presents the calculated traffic opening times for the Evotherm™ 3G SMA and control SMA, assuming the traffic opening temperatures for the control SMA are 60, 49, and 38°C (140,120, and 100°F). In Table 5.2, column 2 is calculated from column 1 using Equation 5.2; column 3 is calculated from column 2 using Equation 5.3; and columns 4 and 5 are calculated from column 3 using Equations 5.4 and 5.5, respectively. The data shows that when the traffic opening temperatures for the control SMA are 60, 49, 38°C (140, 120, and 100°F), the traffic opening times for the Evotherm™ 3G SMA are 0, 0.4, and 3.1 hours after construction, respectively.

Table 5.2 Traffic Opening Time for Evotherm SMA

Traffic Opening Temperature for Control (°C)	Surface Modulus (MPa)	Temperature for Evotherm (°C)	Traffic Opening Time (hr)	
			Control	Evotherm 3G
60	328.8	56.1	0	0
49	1645.9	43.6	1.4	0.4
38	2963.1	31.2	3.7	3.1

The same procedure can be followed to determine the traffic opening time for the Sasobit® SMA. According to Figures 5.9 and 5.3, the following relations exist:

$$E_{control} = -55.385T_{control} + 4705.0 \quad (5.6)$$

$$E_{Sasobit} = -58.423T_{Sasobit} + 4461.3 \quad (5.7)$$

$$T_{control} = -2.0091t_{control}^{3} + 15.069t_{control}^{2} - 41.532t_{control} + 77.022 \quad (5.8)$$

$$T_{Sasobit} = -1.8772t_{Sasobit}^{3} + 12.360t_{Sasobit}^{2} - 30.969t_{Sasobit} + 65.369 \quad (5.9)$$

Using the aforementioned equations 5.5 through 5.9, the traffic opening times for the Sasobit® SMA can be calculated when the traffic opening temperatures for the control SMA are 60, 49, and 38°C (140, 120, and 100°F), as presented in Table 5.3. The data shows that when the traffic opening temperatures for control SMA are 60, 49, and 38°C (140, 120, and 100°F), the traffic opening times for the Sasobit® SMA are 0.5, 1.3, and 3.1 hrs after construction, respectively.

Table 5.3 Traffic Opening Time for Sasobit® SMA

Traffic Opening Temperature for Control (^{o}C)	Surface Modulus (MPa)	Temperature for Sasobit (^{o}C)	Traffic Opening Time (hr)	
			Control	Sasobit
60	1381.9	52.7	0.5	0.5
49	1991.1	42.3	1.0	1.3
38	2600.4	31.9	2.1	3.1

It should be noted that the traffic opening times for the warm SMA presented above only apply to the particular cases in this study. To determine the traffic opening times of the mixtures paved under other environmental conditions, the temperature and cooling time relations can be obtained using some existing cooling model programs, such as the MultiCool software developed by the University of Minnesota. The same procedure used in this study can then be followed to determine the traffic opening time for a certain mixture paved under a specific environmental condition.

CHAPTER 6 SUMMARY AND CONCLUSIONS

This study evaluated the short-term performance of SMA WMA additives (Evotherm™ 3G, Sasobit®, and foamed asphalt) and other sustainable technologies (GTR modified binder, RAP, and RAS) using extensive laboratory tests. The laboratory tests included complex modulus, flow number, loaded wheel track, IDT creep and strength, and SCB fracture. In the laboratory tests, plant-produced mixes were compacted in the laboratory with and without reheating, and performance tests were conducted at various curing periods after compaction. In addition, a LWD test was conducted to evaluate the in-situ pavement stiffness of the in-situ warm SMA sections.

Generally, this study validates that WMA technologies are fully compatible with the modified binder (SBS or GTR) and recycled material used in SMA. Asphalt mixtures containing different WMA additives and recycled materials show comparable performance with the control SMA. The following specific findings were drawn from this study:

1) Adding Evotherm™ to the control SMA results in statistically similar complex modulus but smaller rutting and fracture resistance. Compared to the control SMA, the mixtures containing Sasobit® and foamed asphalt show superior performance in rutting resistance but worse performance in fracture resistance. This could be due to the combined effects of RAP and/or RAS content, WMA additives, and binder modification.
2) Both laboratory and field test results indicate no evidence that a longer curing time is needed before allowing traffic on warm SMA pavements. The mixtures containing WMA additives show similar variations in mixture properties due to the curing time in comparison to the control mixture. The effect of curing time on mixture properties is dependent on the mixture type and performance characteristics. However, a strong general trend is not found between mixture properties and curing time.
3) The reheating process causes control and warm SMA to have greater complex modulus, tensile strength, and rutting resistance, but smaller creep compliance and fracture resistance. Among the mixtures containing various WMA additives, the mixture containing Sasobit® shows relatively the smallest changes in mixture properties due to reheating. In addition, reheating effect on different mixtures varies.
4) An approach to determine the time for opening paved road to traffic is proposed for the tested materials.

A limited number of asphalt mixtures containing WMA additives were investigated in this study. These mixtures were compacted at specific temperatures and tested at various time periods after compaction. To further develop the findings and conclusions, the performance of asphalt mixtures with a broad range of binder types, aggregate sources, compaction temperatures, and various percentages of WMA additives needs to be evaluated in future investigations. In addition, further study on the moisture susceptibility of asphalt mixtures containing WMA additives and long-term performance monitoring of field sections is needed.

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APPENDIX A: QUALITY CONTROL (QC) AND QUALITY ASSURANCE (QA) RESULTS

Table A.1 QC Results of Evotherm SMA Produced at Geneva Plant

ASSIGNMENT INFORMATION									
Inspector #		Date	08/31/2010	Sequence #	018		Contract / Section No.	Job No.	Quantity
Bit Mix Plant	738-03	Mix Code	18435R	Quantity			RR-08-5572		1882.8
Resp. Loc.	90 - ILTollway	Lab	PP	Dist Mix #	90BIT1004				
Type Insp	PRO	Lab Name							
Mix Name	BITUMINOUS STONE MATRIX ASPHALT, N80, RECYCLED				Plant Type	Drum			

Sub Lot	01	Type	Belt	Washed	1	Lot	018-01			Sub Lot	01		Sub Lot	
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%		% PASS	AJMF		% PASS	AJMF
MIX %	8.0	0.0	0.0	0.0	0.0	0.0	2.5	6.2	1.5	100.0	100.0	1.5		
AGG %	8.0					88.3	3.5		1	100.0	100.0	1		
AC% in RAP	8.0								3/4	100.0	100.0	3/4		
Remarks 1									1/2	94.0	93.0	1/2		
Sub Lot		Type		Washed		Lot			3/8	65.0	68.0	3/8		
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%	#4	30.0	29.0	#4		
MIX %									#8	20.0	19.0	#8		
AGG %									#16	14.0	15.0	#16		
AC% in RAP									#30	11.0	12.0	#30		
Remarks 2									#50	9.0	10.0	#50		
	Producer	Material							#100	8.0	9.0	#100		
Asphalt	1757-05	10131 GTR	% AC						#200	6.8	7.7	#200		
Additive			6.2						AC			AC		

		Sub Lot	01			Sub Lot		Sub Lot	01	Sub Lot		
		Type	I			Type		Type	I	Type		
		Wash	yes			Wash		AC%	6.2	AC%		
	Corr.	% PASS	AJMF		Corr.	% PASS	AJMF	Target AC	6.2	Target AC	6.2	
1.5	0.0	100.0	100.0	1.5	0.0		100.0					
1	0.0	100.0	100.0	1	0.0		100.0	Remark 1				
3/4	0.0	100.0	100.0	3/4	0.0		100.0	Remark 2				
1/2	0.0	91.0	93.0	1/2	0.0		93.0					
3/8	0.0	68.0	68.0	3/8	0.0		68.0	Sub Lot	01			
#4	0.0	31.0	29.0	#4	0.0		29.0	Gyratory Results				
#8	0.0	18.0	19.0	#8	0.0		19.0	Nd	Gmb	Gmm	Voids	FVMA
#16	0.0	13.0	15.0	#16	0.0		15.0	80	2.426	2.531	4.2	16.1
#30	0.0	11.0	12.0	#30	0.0		12.0					
#50	0.0	10.0	10.0	#50	0.0		10.0	Sub Lot				
#100	0.0	9.0	9.0	#100	0.0		9.0	Gyratory Results				
#200	0.5	7.2	7.7	#200	0.5		7.7	Nd	Gmb	Gmm	Voids	FVMA
AC	0.0	6.2	6.2	AC								
Remarks 1												
Remarks 2								Tested By:		QC Manager		

Table A.2 QA Results of Evotherm SMA Produced at Geneva Plant

ASSIGNMENT INFORMATION									
Inspector #	910000000	Date	08/31/2010	Sequence #	018		Contract / Section No.	Job No.	Quantity
Bit Mix Plant	738-03	Mix Code	18435R	Quantity			RR-08-5572		0.0
Resp. Loc.	90 - ILTollway	Lab	IL	Dist Mix #	90BIT1004				
Type Insp	IND	Lab Name							
Mix Name	BITUMINOUS STONE MATRIX ASPHALT BINDER REC,N80				Plant Type	Drum			

Sub Lot	01	Type		Washed		Lot				Sub Lot	01		Sub Lot	
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%		% PASS	AJMF		% PASS	AJMF
MIX %									1.5			1.5		
AGG %									1			1		
AC% in RAP									3/4			3/4		
Remarks 1									1/2			1/2		
Sub Lot		Type		Washed		Lot			3/8			3/8		
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%	#4			#4		
MIX %									#8			#8		
AGG %									#16			#16		
AC% in RAP									#30			#30		
Remarks 2									#50			#50		
	Producer	Material							#100			#100		
Asphalt	1757-05	10135	% AC						#200			#200		
Additive			6.0						AC			AC		

		Sub Lot	01			Sub Lot		Sub Lot	01	Sub Lot		
		Type	I			Type		Type	I	Type		
		Wash	no			Wash		AC%	6.0	AC%		
	Corr.	% PASS	AJMF		Corr.	% PASS	AJMF	Target AC	6.0	Target AC	6.0	
1.5	0.0	100.0	100.0	1.5	0.0		100.0					
1	0.0	100.0	100.0	1	0.0		100.0	Remark 1				
3/4	0.0	100.0	100.0	3/4	0.0		100.0	Remark 2				
1/2	0.0	93.0	93.0	1/2	0.0		93.0					
3/8	0.0	67.0	68.0	3/8	0.0		68.0	Sub Lot	01			
#4	0.0	32.0	29.0	#4	0.0		29.0	Gyratory Results				
#8	0.0	20.0	19.0	#8	0.0		19.0	Nd	Gmb	Gmm	Voids	FVMA
#16	0.0	15.0	15.0	#16	0.0		15.0	80	2.419	2.509	3.6	16.3
#30	0.0	12.0	12.0	#30	0.0		12.0					
#50	0.0	10.0	10.0	#50	0.0		10.0	Sub Lot				
#100	0.0	9.0	9.0	#100	0.0		9.0	Gyratory Results				
#200	0.0	7.5	7.7	#200	0.0		7.7	Nd	Gmb	Gmm	Voids	FVMA
AC	0.0	6.0	6.0	AC								
Remarks 1		WARM MIX										
Remarks 2								Tested By:		QC Manager		

Table A.3 QC Results of Sasobit SMA Produced at K-Five Plant

ASSIGNMENT INFORMATION									
Inspector #	900000000	Date	09/16/2010	Sequence #	009		Contract / Section No.	Job No.	Quantity
Bit Mix Plant	4-07	Mix Code	18435R	Quantity			RR-08-5475		949.4
Resp. Loc.	90 - ILTollway	Lab	PP	Dist Mix #	90BIT1014				
Type Insp	PRO	Lab Name							
Mix Name	POLY HMA SMS REC BCS N80 12.5				Plant Type	Drum			

Sub Lot	01	Type	Belt	Washed	1	Lot	009-01			Sub Lot	01		Sub Lot	
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%		% PASS	AJMF		% PASS	AJMF
MIX %	10.0	47.5	26.4	0.0	7.5	0.0	3.0	5.9	1.5	100.0	100.0	1.5		
AGG %	9.1					87.7	4.0		1	100.0	100.0	1		
AC% in RAP	9.1								3/4	100.0	100.0	3/4		
Remarks 1	IGNITION OVEN GRADIATION PASS.								1/2	88.0	92.0	1/2		
Sub Lot		Type		Washed		Lot			3/8	58.0	64.0	3/8		
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%	#4	24.0	28.0	#4		
MIX %									#8	16.0	18.0	#8		
AGG %									#16	12.0	15.0	#16		
AC% in RAP									#30	10.0	12.0	#30		
Remarks 2									#50	9.0	10.0	#50		
	Producer	Material							#100	8.0	8.0	#100		
Asphalt	1757-05	10129	% AC						#200	6.8	7.5	#200		
Additive			5.9						AC			AC		

		Sub Lot	01			Sub Lot		Sub Lot	01	Sub Lot		
		Type	I			Type		Type	I	Type		
		Wash	yes			Wash		AC%	6.1	AC%		
	Corr.	% PASS	AJMF		Corr.	% PASS	AJMF	Target AC	5.9	Target AC	5.9	
1.5	0.0	100.0	100.0	1.5	0.0		100.0					
1	0.0	100.0	100.0	1	0.0		100.0	Remark 1	GRRATED AT275F WARM MIX.			
3/4	0.0	100.0	100.0	3/4	0.0		100.0	Remark 2				
1/2	0.0	88.0	92.0	1/2	0.0		92.0					
3/8	0.0	63.0	64.0	3/8	0.0		64.0	Sub Lot	01			
#4	0.0	28.0	28.0	#4	0.0		28.0	Gyratory Results				
#8	0.0	17.0	18.0	#8	0.0		18.0	Nd	Gmb	Gmm	Voids	FVMA
#16	0.0	14.0	15.0	#16	0.0		15.0	80	2.419	2.510	3.6	15.8
#30	0.0	12.0	12.0	#30	0.0		12.0					
#50	0.0	11.0	10.0	#50	0.0		10.0	Sub Lot				
#100	0.0	10.0	8.0	#100	0.0		8.0	Gyratory Results				
#200	0.2	8.9	7.5	#200	0.2		7.5	Nd	Gmb	Gmm	Voids	FVMA
AC	0.2	6.1	5.9	AC								
Remarks 1												
Remarks 2								Tested By:		QC Manager		

Table A.4 QA Results of Sasobit SMA Produced at K-Five Plant

ASSIGNMENT INFORMATION									
Inspector #	910000000	Date	09/16/2010	Sequence #	009		Contract / Section No.	Job No.	Quantity
Bit Mix Plant	4-07	Mix Code	18435R	Quantity			RR-08-5475		0.0
Resp. Loc.	90 - ILTollway	Lab	IL	Dist Mix #	90BIT1014				
Type Insp	IND	Lab Name							
Mix Name	BITUMINOUS STONE MATRIX ASPHALT BINDER REC,N80				Plant Type	Drum			

Sub Lot	01	Type		Washed		Lot				Sub Lot	01		Sub Lot	
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%		% PASS	AJMF		% PASS	AJMF
MIX %									1.5			1.5		
AGG %									1			1		
AC% in RAP									3/4			3/4		
Remarks 1									1/2			1/2		
Sub Lot		Type		Washed		Lot			3/8			3/8		
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%	#4			#4		
MIX %									#8			#8		
AGG %									#16			#16		
AC% in RAP									#30			#30		
Remarks 2									#50			#50		
	Producer	Material							#100			#100		
Asphalt	1757-05	10130	% AC						#200			#200		
Additive			5.9						AC			AC		

		Sub Lot	01			Sub Lot		Sub Lot	01	Sub Lot		
		Type	I			Type		Type	I	Type		
		Wash	no			Wash		AC%	6.3	AC%		
	Corr.	% PASS	AJMF		Corr.	% PASS	AJMF	Target AC	5.9	Target AC	5.9	
1.5	0.0	100.0	100.0	1.5	0.0		100.0					
1	0.0	100.0	100.0	1	0.0		100.0	Remark 1				
3/4	0.0	100.0	100.0	3/4	0.0		100.0	Remark 2				
1/2	0.0	93.0	92.0	1/2	0.0		92.0					
3/8	0.0	65.0	64.0	3/8	0.0		64.0	Sub Lot	01			
#4	0.0	28.0	28.0	#4	0.0		28.0	Gyratory Results				
#8	0.0	18.0	18.0	#8	0.0		18.0	Nd	Gmb	Gmm	Voids	FVMA
#16	0.0	15.0	15.0	#16	0.0		15.0	80	2.420	2.512	3.7	15.9
#30	0.0	12.0	12.0	#30	0.0		12.0					
#50	0.0	11.0	10.0	#50	0.0		10.0	Sub Lot				
#100	0.0	10.0	8.0	#100	0.0		8.0	Gyratory Results				
#200	0.0	8.2	7.5	#200	0.0		7.5	Nd	Gmb	Gmm	Voids	FVMA
AC	0.0	6.3	5.9	AC								
Remarks 1		WARM MIX										
Remarks 2								Tested By:		QC Manager		

Table A.5 QA Results of Foamed SMA Produced at RockRoad Plant

ASSIGNMENT INFORMATION								
Inspector #	90000000	Date	11/05/2010	Sequence #	003		Contract / Section No.	Job No.	Quantity
Bit Mix Plant	4066-07	Mix Code	19436	Quantity			RR-10-5612		685.8
Resp. Loc.	90 - ILTollway	Lab	PQ	Dist Mix #	90WMA1016				
Type Insp	PRO	Lab Name							
Mix Name	BITUMINOUSSTONE MATRIX ASPHALT, N80				Plant Type	Drum			

Sub Lot	003	Type	CF	Washed	1	Lot	003-01			Sub Lot	003		Sub Lot	
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%		% PASS	AJMF		% PASS	AJMF
MIX %	14.1	0.0	0.0	5.5	27.3	42.4	0.0	6.0	1.5	100.0	100.0	1.5		
AGG %	14.1	0.0	0.0	5.5	27.3	45.4	4.9		1	100.0	100.0	1		
AC% in RAP	14.1								3/4	100.0	100.0	3/4		
Remarks 1									1/2	95.0	91.0	1/2		
Sub Lot		Type		Washed		Lot			3/8	62.0	63.0	3/8		
	RAP	BIN5	BIN4	BIN3	BIN2	BIN1	MF	NEW AC%	#4	31.0	30.0	#4		
MIX %									#8	20.0	21.0	#8		
AGG %									#16	15.0	16.0	#16		
AC% in RAP									#30	13.0	13.0	#30		
Remarks 2									#50	11.0	11.0	#50		
	Producer	Material							#100	9.0	9.0	#100		
Asphalt	1757-05	10131	% AC						#200	7.5	8.0	#200		
Additive			6.0						AC			AC		

		Sub Lot	003			Sub Lot		Sub Lot	003	Sub Lot		
		Type	I			Type		Type	I	Type		
		Wash	yes			Wash		AC%	5.8	AC%		
	Corr.	% PASS	AJMF		Corr.	% PASS	AJMF	Target AC	6.0	Target AC	6.0	
1.5	0.0	100.0	100.0	1.5	0.0		100.0					
1	0.0	100.0	100.0	1	0.0		100.0	Remark 1				
3/4	0.0	100.0	100.0	3/4	0.0		100.0	Remark 2				
1/2	0.0	91.0	91.0	1/2	0.0		91.0					
3/8	0.0	60.0	63.0	3/8	0.0		63.0	Sub Lot	003			
#4	0.0	31.0	30.0	#4	0.0		30.0	Gyratory Results				
#8	0.0	20.0	21.0	#8	0.0		21.0	Nd	Gmb	Gmm	Voids	FVMA
#16	0.0	16.0	16.0	#16	0.0		16.0	80	2.426	2.487	2.5	14.6
#30	0.0	14.0	13.0	#30	0.0		13.0					
#50	0.0	11.0	11.0	#50	0.0		11.0	Sub Lot				
#100	0.0	9.0	9.0	#100	0.0		9.0	Gyratory Results				
#200	0.0	6.9	8.0	#200	0.0		8.0	Nd	Gmb	Gmm	Voids	FVMA
AC	0.0	5.8	6.0	AC								
Remarks 1												
Remarks 2								Tested By:		QC Manager		