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# Evaluation of Warm Mix Technologies for Use in Asphalt Rubber - Asphaltic Concrete Friction Courses (AR-ACFC)

Arizona Department of Transportation Research Center

ADOT

# Evaluation of Warm Mix Technologies for Use in Asphalt Rubber – Asphaltic Concrete Friction Courses (AR-ACFC)

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**July 2016**


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16. Abstract
The objective of this research project was to determine whether warm mix asphalt (WMA) technologies can be used by the Arizona Department of Transportation (ADOT) for the production of an asphalt rubber-asphaltic concrete friction course (AR-ACFC) without detrimental effects on performance of the pavement. The study consisted of a laboratory study and the monitoring of a field construction project. Three ADOT-approved warm mix additives (Evotherm, Sasobit, and Advera) were investigated. The study showed that when the additives were used at the manufacturer's suggested target dosage level there was no negative impact on the durability or the moisture susceptibility of the AR-ACFC as compared to the control (no additive) mix.

The field study confirmed that the use of WMA technologies during AR-ACFC construction is feasible with no adverse effects on paving operations.

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| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ADOT | Arizona Department of Transportation |
| AR-ACFC | asphaltic rubber-asphaltic concrete friction course |
| AR | asphalt rubber |
| ASTM | American Society for Testing Materials |
| ANOVA | analysis of variance |
| Caltrans | California Department of Transportation |
| $CO_2$ | carbon dioxide |
| DAT | dispersed asphalt technology |
| DOT | department of transportation |
| GTR | ground tire rubber |
| HMA | hot-mix asphalt |
| IRI | International Roughness Index |
| kPa | kilopascal |
| NAPA | National Asphalt Pavement Association |
| $NO_x$ | oxides of nitrogen |
| OGFC | open-graded friction course |
| PG | performance graded (as in performance-graded asphalts) |
| RAP | recycled asphalt pavement |
| RAS | recycled asphalt shingles |
| TSR | tensile strength ratio |
| WMA | warm mix asphalt |

**TRADEMARKS**

Evotherm – MeadWestvaco Corporation, 501 South Street, Law Dept., Richmond, Virginia. Registration date June 2, 2009.

Sasobit – (Registrant) Schumann Sasol GMBH & Co., KG Joint Stock Company, Fed Rep Germany, Worthdamm 13-27 D-20457, Hamburg, Fed Rep Germany. (Last listed owner) Sasol Wax GMBH LLC. Fed Rep Germany. Worthdamm 13-27. Hamburg. Fed Rep Germany D-20457. Registration date October 31, 2000.

Advera – PQ Corporation, PO Box 840, Valley Forge, Pennsylvania 19482. Registration date November 9, 1999.

Rediset – Akzo Nobel Chemicals, B.V. Private Limited Company, Netherlands, Stationstraat 77 NL-3811 MH Amersfoort, Netherlands. Registration date April 7, 2009.

SonneWarmix – (Registrant) Sonneborn Inc., 575 Corporate Drive, Suite 415, Mahwah, New Jersey 07430. (Last Listed Owner) Sonneborn, LLC, 600 Parsippany Road, Parsippany, New Jersey 07054. Registration date October 4, 2011.

# EXECUTIVE SUMMARY


The objective of this research project was to determine whether warm mix asphalt (WMA) technologies can be used for the production of an asphalt rubber-asphaltic concrete friction course (AR-ACFC) without detrimental effects on performance of the pavement, and to provide the Arizona Department of Transportation (ADOT) with suggestions on mix design procedures when WMA technologies are used. The usage of WMA technologies for the construction of an AR-ACFC surfacing course can result in an extended paving season, reduced emissions, and reduced energy usage during construction. The current ADOT policy is that WMA technologies may be used, provided that all the requirements of the specifications for asphalt concrete are met and the WMA technologies are preapproved.

The study consisted of two independent phases, a laboratory study and the monitoring of a field construction project. In each of these phases, the use of warm mix additives approved by ADOT (Evotherm, Sasobit, and Advera) was investigated.

The three major concerns with construction and performance of an AR-ACFC are the following: draindown of the binder during construction, resistance of the mixture to raveling, and raveling caused by moisture damage over the life of the pavement surface. The premise of the research was to demonstrate that ADOT could achieve the same pavement life characteristics with the use of WMA as with current practice. Therefore, a laboratory study sought to identify the effect of each of the warm mix additives on the performance (i.e., draindown, durability, and moisture susceptibility) of the AR-ACFC samples compared to the no-additive AR-ACFC samples. Three dosage rates were tested for each additive: the manufacturer's suggested rate (target rate), a higher rate (above target), and a lower rate (below target).

Binder testing on the asphalt rubber (AR) showed that the stiffness of the AR tended to increase as higher percentages of Sasobit were applied. However, increasing percentages of Evotherm had little to no effect on the stiffness of the AR. Resilience testing indicated that the Sasobit and Evotherm additives had little effect on the elasticity of the AR. Advera is a solid additive and thus, it is not possible to directly measure its effect on the asphalt binder.

Use of the additives did not affect the draindown of the WMA mixtures. None of the three WMA additive mixes at the target dosage had a negative impact on the durability or moisture susceptibility of the AR-ACFC. However, the aged Evotherm mix at a below-target dosage and the aged Sasobit mix at an above-target dosage showed inferior durability performance compared to the control AR-ACFC mix, and the aged Advera mix at all dosage levels indicated superior durability. For moisture susceptibility, the Sasobit mix at an above-target dosage was the only mix that showed inferior performance.

The field study confirmed that the use of WMA technologies during AR-ACFC construction is feasible with no adverse effects on paving operations. The field study also showed that neither direct injection of WMA additives into the binder supply lines nor addition of the products in pellet form at the plant is detrimental to the construction process. Future observations and testing of the test sections placed during the field study are recommended to determine long-term performance of the pavement.

# CHAPTER 1. REVIEW OF CURRENT PRACTICE

## SCOPE OF REVIEW

This review discusses the current usage and potential benefits of warm mix asphalt (WMA) technologies, the more prominent WMA technologies, and the use of those technologies in asphalt rubber (AR).

## WARM MIX USAGE AND BENEFITS

Warm mix asphalt is a general term for technologies that reduce temperatures needed to produce and compact asphaltic concrete mixtures for pavement construction. Conventional hot-mix asphalt (HMA) is produced at 280° F to 320° F. WMA is produced at 212° F to 280° F. A recent survey by the National Asphalt Pavement Association (NAPA) states that 30 WMA technologies are available in the United States (Hansen 2014), although not all are widely used. These technologies generally fall into four groups: chemical additives, organic additives, chemical foaming additives, and hot-mix plant water-injection foaming systems. NAPA found that hot-mix plant water-injection foaming systems are the most popular of the WMA technologies and are used in 87 percent of applications (Hansen 2014).

Arizona Department of Transportation (ADOT) policy permits the use of WMA technologies, provided that all requirements of the specifications for asphalt concrete are met and the WMA technology is preapproved by ADOT (ADOT 2012). The potential benefits of using WMA technologies to produce asphaltic concrete have been identified as:

- Reduced fuel usage
- Extended paving season
- Increased workability and compaction
- Reduced plant emissions
- Increased use of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS)
- Improved working conditions for paving crews

### Reduced Fuel Usage

The manufacture of asphaltic concrete requires high temperatures to dry and heat the aggregates and to reduce the asphalt binder viscosity so proper mixing can be achieved. The reduced temperatures allowed by WMA technologies can result in fuel savings of from 10 to 35 percent. The fuel savings to be realized on a particular project depends on a number of factors, including the grade of the asphalt binder, the required temperature of the mix, and the moisture content of the aggregate (Prowell 2012).

### Extended Paving Season

WMA can be compacted at lower ambient temperatures than HMA can. The result is an extended paving season: because the cooling rate depends on the difference between the ambient temperature and the asphalt mixture, a mixture placed at a cooler temperature cools more slowly (Prowell 2012) and can remain compactable for a longer period of time. This allows paving contractors to construct pavements earlier in the spring and later in the fall when ambient temperatures are cooler than ideal for HMA pavement construction.

**Better Workability and Compaction**

WMA pavements maintain workability at lower temperatures. The result is increased time available to compact the WMA pavements and complete necessary handwork, thereby providing a more consistent pavement density. At lower temperatures, the roller train can be closer to the paving machine, leaving fewer gaps in roller coverage across the mat and resulting in a more uniform density.

**Reduced Plant Emissions**

Emissions such as carbon dioxide ($CO_2$) and oxides of nitrogen ($NO_x$) are reduced when lower plant temperatures are used. The concentration of $CO_2$ is dependent on the production temperature and can be reduced 15 to 20 percent by using WMA (Perkins 2009).

**Increased Use of RAP and RAS**

When RAP or RAS is added to an asphaltic concrete mixture, the aged binder in the RAP or RAS can result in a binder with high stiffness, which increases the potential for early cracking. For this reason, many highway agencies limit the amount of RAP or RAS in an asphaltic concrete mixture to 20 percent. However, the lower temperatures used for producing WMA pavement cause less aging in the binder during production than conventional processing does. Therefore, higher percentages of RAP and RAS could be possible with WMA without increasing the stiffness of the binder.

**Improved Working Conditions**

The use of WMA creates improved working conditions. First, the lower temperatures reduce the fumes emitted during placement and compaction operations. Second, the ambient temperatures around the paving machine and residual heat emanating from freshly laid asphalt pavement are reduced.

**WMA TECHNOLOGIES**

Currently, there are four general groups of WMA technologies:

- Chemical additives. Chemical additives act as surfactants to regulate and reduce the frictional forces at the microscopic interface of the aggregates with asphalt binder at a range of temperatures, typically between 185$^{o}$ F and 285$^{o}$ F. It is therefore possible to mix the bitumen and aggregates, and compact the mix, at lower temperatures than with conventional HMA.
- Organic additives. Organic additives lower the viscosity of asphalt binder at any temperature, thus allowing lower compaction temperatures and making the compacted mix more workable. To minimize embrittlement of the asphalt at low temperatures, an organic additive must be selected carefully so that its melting point is higher than the expected in-service temperature of the pavement. Organic additives are usually waxes or fatty acid amides, are in granular form,

and can be added either to the mixture or to the binder. However, they are more effective when dispersed in the binder before the WMA is made.

- Chemical foaming additives. Chemical foaming additives involve the addition of zeolite to the mix at the same time the binder is added. The zeolite contains 20 percent water. At a mix temperature of about 275° F, the zeolite slowly releases the water to create foamed asphalt, making the mixture more workable. The amount of water added into the system from zeolite is very small.
- Hot-mix plant water-injection foaming systems. Hot-mix plant water-injection systems add a small amount of water to the hot asphalt binder at a rate of 1 to 3 percent of water by weight of total mixture. The water creates steam that is encapsulated in the binder, and foaming results in a large volume increase of the binder. This decreases the viscosity of the binder allowing it to coat the aggregates at lower temperatures.

At the time of this report, ADOT allowed the use of four WMA technologies: Evotherm, Sasobit, Advera, and water-injection technologies:

- Evotherm is a chemical additive. It can be delivered to the asphalt plant via two different systems. Evotherm DAT (dispersed asphalt technology) is a concentrated solution of water and chemical additives directly injected into the asphalt line at the asphalt plant. Evotherm 3G is a water-free chemical additive that is either blended into the asphalt binder at the terminal or directly injected into the asphalt line at the asphalt plant. The manufacturer states that the use of Evotherm will not change the performance grade (PG) of the asphalt binder. It is added at dosage rates from 0.4 to 0.7 percent by weight of total binder (Prowell 2012).
- Sasobit, an organic additive. It is a wax consisting of long hydrocarbon chains that increase the melting point of the wax, allowing Sasobit to be fully soluble in asphalt above 239° F. When Sasobit fully melts into the asphalt binder, it forms a homogeneous solution that reduces the viscosity of the asphalt at temperatures higher than Sasobit's melting point. When cooled below its melting point, Sasobit may also increase the asphalt's resistance to permanent deformation of the asphalt when it is cooled below its melting point by forming a lattice structure in the asphalt. Sasol, the developer of Sasobit, suggests adding 0.8 to 3 percent Sasobit by weight of total binder.
- Advera is a chemical foaming additive. It is a manufactured synthetic zeolite (sodium aluminum silicate) with 18 to 21 percent of its mass as water entrapped in its crystalline structure. This water is released at temperatures above 210° F. When the zeolite contacts the heated asphalt binder, the water is released, causing the binder to foam. This amount of water (0.05 percent of the mix), yields improved workability of the asphalt mix with minor binder volume increase. Advera releases water slowly over time as steam within the binder producing a small-scale foaming action that allows the binder to have improved workability. The gradation of Advera is 100 percent passing the No. 200 sieve. It is added at a rate of 0.25 percent by weight of the total asphaltic concrete mix.

- Hot-mix plant water-injection systems include a variety of methods to disperse water into the asphalt. In 2012, 11 commercially available processes were being marketed in the United States as water-injection technologies (Prowell 2012).

## USE OF WMA TECHNOLOGIES FOR ASPHALT RUBBER MIXTURES

The use of asphalt rubber in either dense-graded or open-graded friction course (OGFC) mixes provides significant benefit to the pavement through reduced reflection cracking, reduced pavement noise, and increased durability. The increased durability is of particular value because it reduces raveling of the OGFC mixture. However, the introduction of asphalt rubber into an asphalt concrete mixture increases the stiffness of the mixture, thereby reducing its workability. To counter this reduction in workability, the mixtures are placed at higher mixing and compaction temperatures. In Arizona, asphalt rubber production is limited by restrictions on allowable emissions. Its use is also affected by seasonal limitations, such as extreme desert heat. Thus, the use of WMA technologies for asphalt rubber pavement construction could provide significant benefits.

This study addresses field-blended asphalt rubber binders. Because the use of ground tire rubber (GTR) in asphalt pavements is limited in the United States, published information about WMA technologies in dense or open-graded asphalt rubber mixtures is also limited. Most information comes from work done in Florida and California, where approximately 65 percent of the GTR used in the United States is placed; both states use WMA technologies for asphalt rubber mixtures.

Recent studies on using WMA technologies for mixes containing asphalt rubber have been completed by the California Pavement Preservation Center (Hicks 2010), the Pavement Research Center (Santucci 2010), and the University of California at Berkeley (Jones 2013). These studies looked at additive technologies for WMA production but did not include the water-injection systems. The most commonly used products were Sasobit, Advera, and Evotherm (Hicks 2010), although the California Department of Transportation (Caltrans) had eight technologies on their approved list as of May 2014 (Caltrans 2014). The Hicks study concluded that the use of WMA technologies reduces the paving temperatures by 30 to 80° F, allowing placement of these mixes at night and in cooler climates.

Farshidi et al. (2013) evaluated hot rubber asphalt and warm mix asphalt with respect to emissions and found that the warm mix technology type, the plant mixing temperature, and the level of compaction had a significant effect on the nature of emissions from the paving operations. The study also indicated that warm mix technologies have the potential to reduce emissions during construction of asphaltic concrete pavement.

The researcher’s conversations (during February and March 2015) with contractors, industry representatives, and Caltrans employees indicate that the use of water-injection warm mix technology for AR-ACFC mixtures has had mixed success in California. There are reports of clumping of the AR-ACFC mixture with only a small reduction in temperature. Nonetheless, according to the Caltrans Flexible Pavement Materials Engineer (telephone interview, March 24, 2015), the official position of Caltrans is that all the WMA technologies on the Caltrans list of approved additives are acceptable (this includes three water-injection systems).

Although the Florida Department of Transportation (DOT) has not published research reports on their use of WMA technologies in asphaltic concrete mixtures, they do allow the use of 10 different WMA technologies. Approximately 3 percent of their total asphaltic concrete production uses a warm mix technology (67 percent water-injection foaming systems and 33 percent chemical additives) (Nash 2014). According to the Florida DOT bituminous engineer (telephone interview, March 13, 2015), Florida contractors had good success with all WMA technologies on the approved list for asphalt rubber mixes.

The probable reason for Florida's success compared to Caltrans' mixed success with the use of water-injection systems for asphalt rubber mixes is that while both systems use ground tire rubber (GTR) as an additive in their asphalt binders, the gradation and percentages of rubber used are different. The GTR used in California has a gradation of primarily No. 10 to No. 30-sized particles, but the GTR used in Florida has a minimum of 98 percent passing the No. 30 sieve. Further, the rubber gradation used in California has a higher percentage of GTR. In California, an asphalt rubber binder contains approximately 20 percent ground tire rubber whereas Florida uses both 5 percent and 12 percent ground tire rubber in their asphalt rubber blends. The asphalt rubber used by Caltrans is very similar to that used by ADOT.

# CHAPTER 2. LABORATORY STUDY

The three major concerns with construction and performance of an AR-ACFC are draindown of the binder during construction, raveling over the life of the pavement surface, and moisture damage over the life of the pavement surface. Amec Foster Wheeler evaluated the four warm mix technologies approved by ADOT—three additives (Evotherm, Sasobit, Advera) and the AQUA-Black water injection system—to determine:

- What effect these WMA technologies have on the asphalt rubber binders used in ADOT's AR-ACFC mixes.
- What impact these WMA technologies have on the performance of an AR-ACFC mixture.
- How ADOT's AR-ACFC design procedure needs to be modified to accommodate WMA technologies.

This chapter discusses the materials used during the laboratory study and presents WMA asphalt rubber and AR-ACFC mixture test results. This chapter also discusses the feasibility of using foaming technology to produce AR-ACFC warm mixes.

## MATERIALS

### Aggregates

Aggregates used to produce the laboratory AR-ACFC mixtures were sampled from approved individual aggregate stockpiles for ADOT's AR-ACFC placement project on State Loop 101 from 27th Avenue to 7th Avenue (Project 101-B-(207)T). The contractor used three stockpiles to manufacture the AR-ACFC. Table 1 shows the gradation of the final aggregate blend. The aggregates met the requirements of ADOT Specification 414, Asphaltic Concrete Friction Course (ADOT 2008). The aggregate was laboratory blended by Amec Foster Wheeler to achieve the required gradation shown in Table 1 below.

**Table 1. Aggregate Gradation**

| Sieve | % Passing |
|---|---|
| 3/8″ | 100 |
| 1/4″ | 74 |
| #4 | 33 |
| #8 | 7 |
| #200 | 0.7 |

### Asphalt Rubber Binder

Asphalt rubber manufactured by HollyFrontier was used to produce the AR-ACFC mixtures for laboratory testing. The base asphalt consisted of a PG 64-16. The design binder content used was 9.7 percent by weight of total blend. The binder used met the requirements of ADOT Specification Section 1009, CRA-1 (ADOT 2008). The asphalt rubber binder contained 18.6 percent Type B Ground Tire Rubber.

### Warm Mix Asphalt Additives

Three ADOT-approved WMA additives were evaluated. Each of the three additives (Evotherm, Sasobit, and Advera) was added at three different concentration rates to simulate a typical range that might occur during field production of a WMA mixture. The additive rates used to conduct the laboratory analysis were based on the target additive rate recommended by the manufacturers:

- Evotherm
    - Below target – 0.25 percent by weight of asphalt binder
    - At target – 0.40 percent by weight of asphalt binder
    - Above target – 0.70 percent by weight of asphalt binder
- Sasobit
    - Below target – 0.50 percent by weight of asphalt binder
    - At target – 1.5 percent by weight of asphalt binder
    - Above target – 3.0 percent by weight of asphalt binder
- Advera
    - Below target – 0.15 percent by weight of asphalt concrete mixture
    - At target – 0.25 percent by weight of asphalt concrete mixture
    - Above target – 0.35 percent by weight of asphalt concrete mixture

## TEST PROCEDURES

### Asphalt Rubber Binder Testing

The following testing was conducted on the base asphalt rubber binder and on the asphalt rubber binder modified by the addition of the Evotherm and Sasobit:

- Viscosity using a Rion Handheld Viscotester with a No. 1 rotor at 250, 275, 300, 325, and 350$^{o}$ F
- Viscosity at 350$^{o}$ F, centipoises (cP) at 60, 90, 240, 360, and 1440 minutes
- Penetration at 39.2$^{o}$ F (200 gm, 60 sec, 0.10 mm), at 60, 90, 240, 360, and 1440 minutes
- Ring and Ball Softening Point, $^{o}$C at 60, 90, 240, 360, and 1440 minutes
- Dynamic Shear, $G^*/\sin\delta$, kPa at 76, 82, and 88$^{o}$ C

The protocol for the dynamic shear testing was modified because of the granular sizing of the ground tire rubber in the asphalt rubber sample. A 2 mm gap setting was used with the 25 mm parallel plates.

**AR-ACFC Mix Testing**

The effects of WMA technologies on AR-ACFC mixes was evaluated with regard to draindown, durability (abrasion resistance), and moisture susceptibility using various test procedures, including tests specified by the American Society for Testing Materials (ASTM).

*Draindown*

Draindown testing was conducted at 275$^{o}$ F and 325$^{o}$ F using ASTM Test Procedure D6390-11, *Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures*. The basket used for the draindown testing is shown in Figure 1.

**Figure 1. Draindown Basket Used**

*Durability*

Durability of the mixtures was determined by conducting the Cantabro abrasion test (Cooley et al. 2009). Used to evaluate the resistance of an asphalt concrete friction course to abrasion loss, the test consists of compacting the mix, allowing the specimen to cool to room temperature, weighing the specimen to the nearest 0.1 gram, and placing the specimen in a Los Angeles abrasion machine without the steel spheres. The machine is operated for 300 revolutions at 30 to 33 rpm. After the 300 revolutions, the specimen is removed and weighed. The percent mass loss is determined based upon the original specimen mass. The criteria for the test results are based on the conditioning method: unaged, aged, or moisture conditioned. The criterion generally used is a maximum of 20 percent for an unaged specimen and 30 percent for an aged specimen (Cooley et al. 2009).

For this study, the test was conducted on unaged and aged AR-ACFC mixtures. For the aged AR-ACFC mixtures, the mixture was placed in a one-to two-inch deep pan and placed into a forced draft oven at compaction temperature. The loose mixture was aged for 48 hours ±1 hour at 275° F (mixture was stirred at 24 hours). The aging procedure was chosen to simulate the aging of the mixture after several years of service. Following aging, the mixture was compacted at 300° F by a gyratory compactor (50 gyrations). Figure 2 shows an unaged compacted specimen. Figure 3 shows an unaged compacted specimen after treatment in the Los Angeles abrasion machine, while Figure 4 shows an aged specimen after treatment in the Los Angeles abrasion machine.

**Figure 2. Unaged Cantabro Specimen as Manufactured Prior to Testing**

**Figure 3. Unaged Cantabro Specimen after Testing**

**Figure 4. Aged Cantabro Specimen after Testing**

*Moisture Susceptibility*

Moisture susceptibility of the mixtures was determined according to specifications by the American Association of State Highway and Transportation Officials (AASHTO), AASHTO T283, *Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage,* although the standard test procedure was modified. The standard test procedure requires the conditioned specimens to be vacuum saturated at 7 percent air voids. However, because of the open characteristics of the AR-ACFC (air voids of approximately 19 percent) this was not possible. To ensure that the AR-ACFC mixture did not disintegrate in the 140$^{o}$ F water bath during the 24 hours of soaking, the specimens were placed in a sleeve (see Figures 5 and 6). The sleeve was manufactured from a 4-inch concrete cylinder mold.

**Figure 5. Sleeve Used for Moisture Susceptibility Samples**

**Figure 6. Test Sample after Sample Is Placed in Sleeve**

**ASPHALT RUBBER TEST RESULTS**

The purpose of the AR testing conducted in this study was to evaluate the effect of the chemical modifiers on the properties of the asphalt rubber. ADOT requires asphalt rubber used on ADOT projects to meet the requirements for rotational viscosity, penetration, softening point, and resilience in accordance with ADOT Specification Section 1009-2 (ADOT 2008). Therefore, unmodified asphalt rubber and asphalt rubber that had been modified with Evotherm and Sasobit were tested to evaluate their conformance to the specifications. Complete test results of the modified asphalt rubber binders are presented in Appendix A. A summary of the data is included in Table 2.

Additionally, the AR was tested to determine its shear modulus at different temperatures. These data were used to determine the pass/fail temperature for each of the binders, original and modified. The pass/fail temperature is the temperature at which the asphalt binder has a test value of 1 kilopascal (kPa). It is an indicator of the stiffness of the asphalt binder; the higher the pass/fail temperature, the stiffer the asphalt binder.

The data in Table 2 indicate that the stiffness of the AR tended to increase as higher percentages of Sasobit were applied. However, increasing percentages of the Evotherm modifier had little to no effect on the stiffness of the AR (as evidenced by the ring and ball softening point, the penetration, and the pass/fail temperature). The resilience testing, which addresses the AR's elasticity, indicated that the Sasobit and Evotherm additives have little effect on elasticity.

**Table 2. Physical Properties of Unmodified and Modified Asphalt Rubber Binders**

| **Material** | **Percent Additive** | **Property** | | | |
|---|---|---|---|---|---|
| | | **Ring and Ball Softening Point (°C)** | **Penetration at 77° F (mm)** | **Resilience at 77° F %** | **Pass/Fail Temperature (°C)** |
| | | | | | |
| Unmodified asphalt rubber | 0.0% | 66 | 24 | 36 | 92.3 |
| | | | | | |
| Asphalt rubber modified with Sasobit | 0.50% | 67 | 24 | 32 | 92.3 |
| | 1.50% | 76 | 22 | 35 | 94.3 |
| | 3.00% | 90 | 21 | 33 | 96 |
| | | | | | |
| Asphalt rubber modified with Evotherm | 0.25% | 67 | 24 | 36 | 92.1 |
| | 0.40% | 66 | 24 | 35 | 94.5 |
| | 0.70% | 67 | 24 | 34 | 92.8 |

The data in Table 3 provide information on the effect of the additives on the viscosity of the asphalt rubber. The testing conducted for this study shows that the addition of WMA additives to asphalt rubber has little effect on the viscosity of the asphalt rubber.

Table 3. **Viscosity Test Results for Unmodified and Modified Asphalt Rubber Binders**

| Material | Percent Additive | Viscosity at (Pascal Seconds) | | | | |
|---|---|---|---|---|---|---|
| | | 350° F | 325° F | 300° F | 275° F | 250° F |
| Unmodified asphalt rubber | 0.0% | 2.0 | 2.9 | 4.1 | 6.0 | 9.0 |
| Asphalt rubber modified with Sasobit | 0.50% | 2.0 | 2.8 | 3.5 | 6.0 | 8.5 |
| | 1.50% | 2.0 | 2.5 | 3.5 | 5.5 | 8.0 |
| | 3.00% | 1.9 | 2.4 | 3.1 | 5.4 | 7.8 |
| Asphalt rubber modified with Evotherm | 0.25% | 2.3 | 3.2 | 4.3 | 6.1 | 9.0 |
| | 0.40% | 2.3 | 3.0 | 4.1 | 6.0 | 9.0 |
| | 0.70% | 2.3 | 3.1 | 4.0 | 6.0 | 9.0 |

**AR-ACFC TESTING**

AR-ACFC mixtures were prepared in the laboratory to evaluate the effects of WMA additives on the mixture properties. A summary of the testing is presented in Table 4. Complete test results of AR-ACFC mixture properties are included in Appendix B.

**Table 4. Lab Test Plan**

| Property | Test Procedure | Additive | Number of Replicates | | Additive: Evotherm | Additive: Sasobit | Additive: Advera | Total Number of Specimens Tested |
|---|---|---|---|---|---|---|---|---|
| | | | 275 | 325 | | | | |
| Draindown | Basket | No additive | 3 | 3 | X | X | X | 18 |
| | | Below Target | 3 | 3 | X | X | X | 18 |
| | | At Target | 3 | 3 | X | X | X | 18 |
| | | Above Target | 3 | 3 | X | X | X | 18 |
| | Cantabro on Unaged Samples | No additive | 9* | | X | X | X | 27 |
| | | Below Target | 9* | | X | X | X | 27 |
| | | At Target | 9* | | X | X | X | 27 |
| | | Above Target | 9* | | X | X | X | 27 |
| | Cantabro on Aged Samples | No additive | 9* | | X | X | X | 27 |
| | | Below Target | 9* | | X | X | X | 27 |
| | | At Target | 9* | | X | X | X | 27 |
| | | Above Target | 9* | | x | X | X | 27 |
| Moisture Susceptibility | T283 | No additive | 18* | | X | X | X | 54 |
| | | Below Target | 18* | | X | X | X | 54 |
| | | At Target | 18* | | X | X | X | 54 |
| | | Above Target | 18* | | X | X | X | 54 |

* These values were averaged to produce three test results.

## Test Results

Draindown test results are summarized in Table 5. The results show that the additives had no discernible effect on the draindown characteristics of the AR-ACFC mixtures. Cantabro and moisture susceptibility test results are summarized in Tables 6 and 7.

**Table 5. Summary of Draindown Test Data Percent Binder Loss**

| | Additive | | | | | |
|---|---|---|---|---|---|---|
| | Evotherm | | Sasobit | | Advera | |
| | 275° F | 325° F | 275° F | 325° F | 275° F | 325° F |
| No Additive | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Below Target | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 |
| At Target | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Above Target | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |

**Table 6. Summary of Cantabro Test Data Percent Loss of Mixture**

| | Additive | | | | | |
|---|---|---|---|---|---|---|
| | Evotherm | | Sasobit | | Advera | |
| | Unaged | Aged | Unaged | Aged | Unaged | Aged |
| No Additive | 0.6 | 38.6 | 0.6 | 38.6 | 0.6 | 38.6 |
| Below Target | 1.2 | 45.8 | 0.9 | 41.3 | 0.7 | 28.4 |
| At Target | 1.7 | 35.5 | 1.4 | 42.1 | 0.8 | 21.8 |
| Above Target | 0.6 | 39.7 | 0.5 | 47.0 | 0.6 | 27.0 |

**Table 7. Summary of Moisture Susceptibility Test Data Percent Retained Strength**

| | Additive | | |
|---|---|---|---|
| | Evotherm | Sasobit | Advera |
| No Additive | 43 | 43 | 43 |
| Below Target | 54 | 59 | 42 |
| At Target | 50 | 61 | 47 |
| Above Target | 62 | 66 | 47 |

# STATISTICAL ANALYSIS

## Introduction

The data obtained from the series of the laboratory tests were analyzed with the analysis of variance (ANOVA). ANOVA is an effective statistical technique to determine whether there are any statistically significant differences in means between groups or treatments. In this study, ANOVA was used to identify the effect of each warm mix additive on the performance (i.e., durability and moisture susceptibility) of the AR-ACFC samples compared to the no-additive AR-ACFC samples.

In ANOVA, it is common to set up two hypotheses (the null and alternative hypotheses). The two hypotheses are evaluated with sample means and variances to determine whether either hypothesis is accepted, automatically rejecting the counterpart hypothesis. A typical hypothesis setting is:

- Null hypothesis ($H_0$): The means of all groups are equal (i.e., there is no treatment effect or difference in means among groups)
- Alternative hypothesis ($H_1$): The null hypothesis is not true for at least one sample group mean (i.e., at least one group is different from other groups)

If $H_0$ is accepted, it implies that the sample means are equal for all groups and that the difference observed in sample group means is statistically insignificant. Therefore, it can be concluded that there is no treatment effect. On the other hand, if $H_1$ is accepted, it implies that the difference observed in sample group means is statistically significant and there is a high possibility that the difference is due to actual differences in population means. In this case, a further analysis—a comparison analysis among groups—is required to determine which group is different. The comparison analysis can use either a pairwise comparison or a comparison with a control group. In this study, the "comparison with a control" method was used (i.e., the WMA-treated sample groups were compared with the no-additive AR-ACFC sample group, which is considered the control group).

For this study, the hypothesis setting is that accepting $H_0$ indicates that there is no warm mix additive effect on the AR-ACFC mix performance; in contrast, accepting $H_1$ indicates that the mix performance of at least one group is different from the other groups. As mentioned, this case is further analyzed in order to reveal which WMA additive makes the difference in the AR-ACFC mix performance. The Dunnett's test procedure for multiple comparisons was employed for this "comparison with a control" analysis.

A level of significance for the ANOVA, which becomes a threshold for the determination of acceptance or rejection, was set to 0.05. If a p-value resulting from an ANOVA is less than the significance level (0.05), the conclusion would accept $H_1$ (i.e., that there is a treatment effect).

*Analysis Procedure*

The statistical analysis for the AR-ACFC performance test results was conducted with the following procedure:

1. Enter the raw test result data in a data sheet and calculate the basic statistics (e.g., mean and variance) of each treatment group based on performance test results. Note that:
    - There are two factors (WMA additive type and dosage level) to influence the performance response. Each factor has multiple levels: three different WMA types and four different dosage levels.

- The number of replicates for each treatment level varies by testing.

2. Conduct a series of ANOVA tests with the following setup:
   - Hypotheses
     - $H_0$: All sample group means are equal
     - $H_1$: At least one sample group mean is different
   - In this ANOVA, both the WMA additive type and the dosage are treated as a fixed variable because the levels of each factor were preselected.
   - Since two factors are involved, a two-way ANOVA was selected with a significance level of 0.05, or 5 percent.
   - If the hypothesis testing accepts $H_1$, then conduct Dunnett's test for a comparison purpose with a control group.
   - Using the no-additive AR-ACFC mix as a control mix group, compare each of the three WMA additive mix groups, at each dosage level, with the control mix.

3. Using boxplots, graphically compare the means of each group with the means of the other treatment groups.

**Results and Interpretation**

The following statistical analyses were conducted with a commercial statistical computer program, Minitab 17, for:

- Durability with Cantabro test results from lab-prepared *unaged* samples
- Durability with Cantabro test results from lab-prepared *aged* samples
- Moisture susceptibility with tensile strength ratio (TSR) from unaged lab-prepared samples

*Durability With Lab-Prepared Samples*

The Cantabro test result of lab-prepared *unaged* AR-ACFC samples containing each of the three WMA additives was compared with that of the no-additive control AR-ACFC sample group. An initial ANOVA test accepted $H_1$ for both additive type and dosage level, indicating that at least one sample group shows a difference in Cantabro results from the other groups (associated with additive type, dosage level, or both). Therefore, the Dunnett's test was used to determine what additive and/or dosage level makes the difference. Three groups showed a statistically significant difference between the means of the Cantabro result and the mean of the control group. Table 8 presents the means and standard deviation values for each sample group. The Evotherm mixes with the below-target and at-target dosage levels, and the Sasobit mix at the target dosage level, showed a statistically significant difference from the no-additive control mix.

The boxplot in Figure 7 depicts the difference in sample means of all groups. The far left box is the control group, and the other WMA-treated groups with different dosage levels can visually compared with the control group. The three orange boxes represent the significantly different groups.

In Figure 7, however, outliers were identified in the Evo-T1 and Sas-T2 groups (shown by an asterisk above each box). The outliers make the average of the two groups high. Usually, it would be appropriate to remove the outliers from a sample group and recalculate the statistics. In this analysis, however, the outliers were not removed because it is difficult to statistically conclude that the outliers are true outliers in this small group (only nine replicates per group in this analysis.) Also, the standard deviation is much larger for the Evo-T2 group than for the other groups.

**Table 8. Summary of Descriptive Statistics for Cantabro Test Results (Durability) on Unaged Samples**

| Cantabro Test on Unaged Samples | | | | | |
|---|---|---|---|---|---|
| **Additive Type** | **Dosage Level** | **No. of Replicates** | **Mean** | **Standard Deviation** | **Significant Difference from Control Mix** |
| No Additive (Control Mix) | | 9 | 0.58 | 0.42 | N/A |
| Evotherm | Below Target (T1) | 9 | 1.15 | 0.61 | Yes |
| | At Target (T2) | 9 | 1.66 | 0.86 | Yes |
| | Above Target (T3) | 9 | 0.63 | 0.29 | No |
| Sasobit | Below Target (T1) | 9 | 0.92 | 0.39 | No |
| | At Target (T2) | 9 | 1.45 | 0.32 | Yes |
| | Above Target (T3) | 9 | 0.52 | 0.16 | No |
| Advera | Below Target (T1) | 9 | 0.68 | 0.28 | No |
| | At Target (T2) | 9 | 0.85 | 0.27 | No |
| | Above Target (T3) | 9 | 0.61 | 0.18 | No |

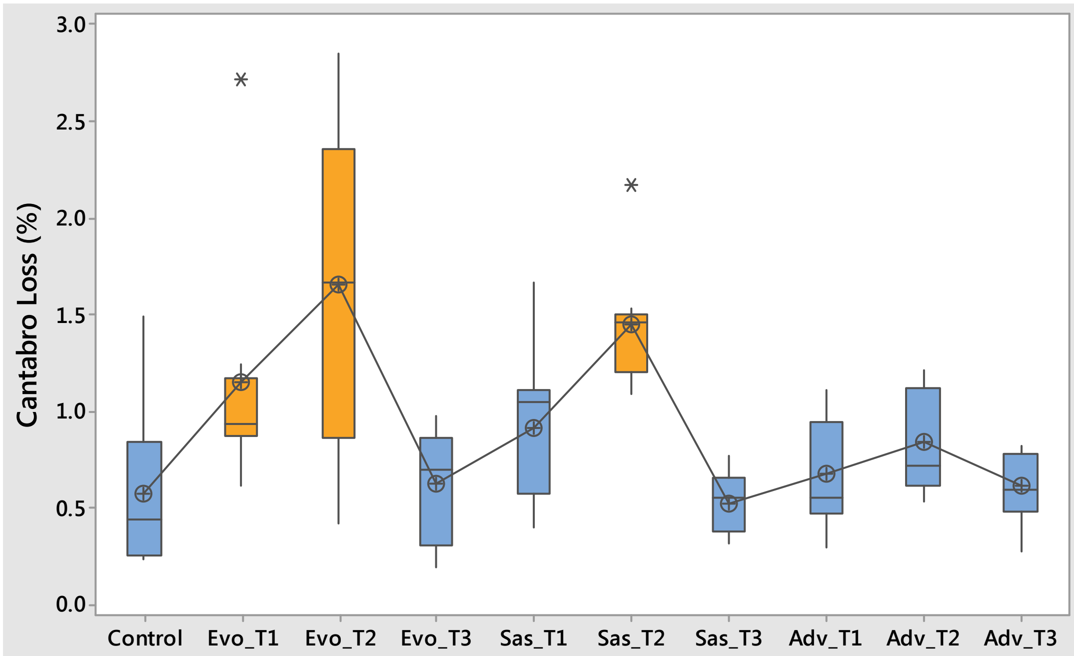


**Figure 7. Boxplot of Cantabro Results for Unaged AR-ACFC Samples**

A similar statistical analysis was conducted for the Cantabro results of the *aged* AR-ACFC mix sample groups. The ANOVA test accepted $H_1$, indicating that at least one sample group showed a difference in means of the unaged sample groups. Table 9 summarizes the statistics, showing that the Evotherm mix at a below-target dosage and the Sasobit mix at an above-target dosage have significantly larger Cantabro results. For the Advera mixes at all dosage levels, it should be recognized that, although the Dunnett's test revealed differences in the means of all the Advera mixes, the Cantabro results for these mixes were less than the result for the control mix; this proves the durability performance of the Advera mixes is even better than that of the control mix. At the target dosage level for all WMA additives, it was found that none of the three mix groups had a negative impact on the durability performance. The boxplot in Figure 8 depicts the difference in sample means of all groups.

**Table 9. Summary of Descriptive Statistics for Cantabro Test Results (Durability) on Aged Samples**

| Cantabro Test on Aged Samples | | | | | |
|---|---|---|---|---|---|
| **Additive Type** | **Dosage Level** | **No. of Replicates** | **Mean** | **Standard Deviation** | **Significant Difference from Control Mix** |
| No Additive (Control Mix) | | 9 | 38.60 | 7.64 | N/A |
| Evotherm | Below Target (T1) | 8 | 46.90 | 5.07 | Yes |
| | At Target (T2) | 9 | 35.96 | 5.84 | No |
| | Above Target (T3) | 9 | 39.77 | 9.24 | No |
| Sasobit | Below Target (T1) | 9 | 43.21 | 2.41 | No |
| | At Target (T2) | 9 | 39.56 | 3.88 | No |
| | Above Target (T3) | 9 | 46.99 | 2.17 | Yes |
| Advera | Below Target (T1) | 9 | 28.39 | 5.40 | Yes |
| | At Target (T2) | 9 | 21.81 | 1.88 | Yes |
| | Above Target (T3) | 9 | 26.98 | 7.84 | Yes |

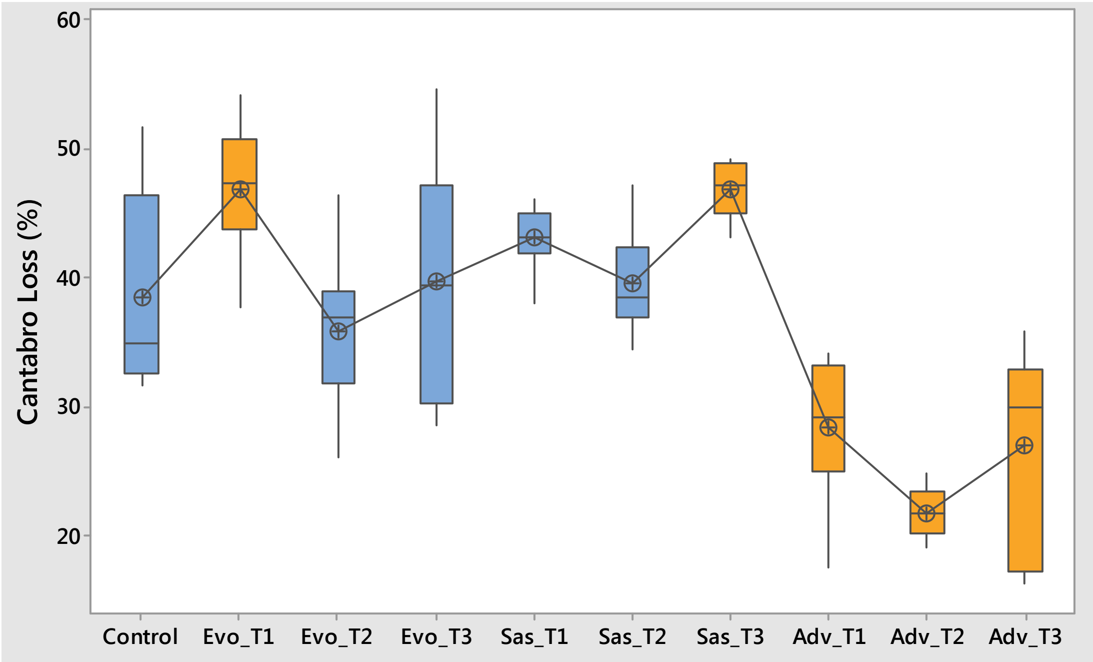


**Figure 8. Boxplot of Cantabro Results for Aged AR-ACFC Samples**

*Moisture Susceptibility With Lab-Prepared Samples*

A similar statistical analysis was also conducted to evaluate the AR-ACFC mix performance with respect to moisture susceptibility. The TSR values used in the ANOVA were calculated from three sets of unconditioned and conditioned samples. Hence, one TSR value is calculated with three replicates. Table 10 summarizes the descriptive statistics for the TSR results; although the table shows the number of replicates as three, nine samples were used to obtain the three TSR values.

The ANOVA test accepted the $H_1$ hypothesis, indicating that at least one group was different in means from other groups compared. The Dunnett's test was conducted, and the result is presented in Figure 9. The Sasobit mix at an above-target dosage level was found to be the only mix that showed a significant difference at the highest TSR value; this indicates that the mix is relatively more resistant to moisture damage than the other mixes.

**Table 10. Summary of Descriptive Statistics for Tensile Strength Ratio Results (Moisture Susceptibility)**

| Moisture Susceptibility Test (Tensile Strength Ratio) with Lab Samples | | | | | |
|---|---|---|---|---|---|
| **Additive Type** | **Dosage Level** | **No. of Replicates** | **Mean (psi)** | **Standard Deviation (psi)** | **Significant Difference from Control Mix** |
| No Additive (Control Mix) | | 3 | 48.67 | 4.93 | N/A |
| Evotherm | Below Target (T1) | 3 | 54.33 | 1.53 | No |
| | At Target (T2) | 3 | 49.67 | 3.06 | No |
| | Above Target (T3) | 3 | 58.00 | 14.93 | No |
| Sasobit | Below Target (T1) | 3 | 58.67 | 1.53 | No |
| | At Target (T2) | 3 | 61.67 | 2.52 | No |
| | Above Target (T3) | 3 | 66.33 | 1.53 | Yes |
| Advera | Below Target (T1) | 3 | 43.00 | 1.00 | No |
| | At Target (T2) | 3 | 46.33 | 1.53 | No |
| | Above Target (T3) | 3 | 46.33 | 5.86 | No |

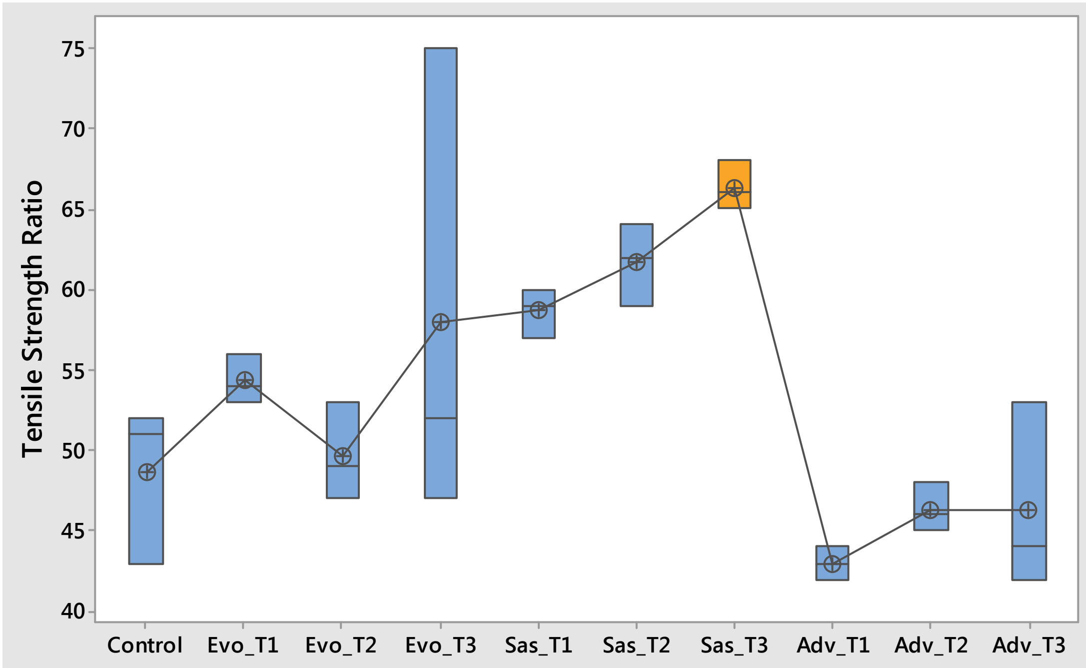


**Figure 9. Boxplot of Tensile Strength Ratio Results with Lab-Prepared Samples**

### Findings from the Statistical Analysis

Some specific findings drawn from this study include the following:

- The unaged Evotherm mix at below-target and at-target dosage levels and the unaged Sasobit mix at a target dosage level showed inferior performance in durability compared to the control AR-ACFC mix. However, for this finding, some statistical abnormalities such as outliers and a large variance were seen. Further research is recommended to confirm this finding.
- The aged Evotherm mix at a below-target dosage and the aged Sasobit mix at an above-target dosage showed inferior performance in durability compared to the regular AR-ACFC mix. The aged Advera mix at all dosage levels actually showed superior performance.
- The three WMA additive mixes at the target dosage level showed no negative impact on the durability performance compared to the control mix.
- In regard to moisture susceptibility, the Sasobit mix at an above-target dosage level was the only mix that showed superior performance.

## LABORATORY EVALUATION OF FOAMING CHARACTERISTICS OF ASPHALT RUBBER BINDER

NAPA found that hot-mix plant water-injection foaming systems are the most popular of the WMA technologies and are used in 87 percent of applications (Hansen 2014). Because foamed asphalt systems are so widely used to produce WMA mixtures, this research project includes a laboratory evaluation of foamed asphalt rubber. Testing was performed to determine the foaming characteristics of the asphalt rubber. AR-ACFC mixtures using foamed AR were not prepared or tested, as discussed later in this section.

A laboratory evaluation of the feasibility of foaming an AR was conducted using a Wirtgen Laboratory foaming machine at Amec Foster Wheeler's Albuquerque location. See Figure 10.

**Figure 10. Wirtgen Laboratory Foaming Machine Used in This Evaluation**

### Foamed Asphalt

Foamed asphalt is produced by introducing pressurized cold water and air to the heated asphalt through specially designed nozzles (Wirtgen Group 2012). Upon the mixing of cold water and hot asphalt, heat transfers from the hot asphalt to the cold water, causing the water to evaporate and in turn causing the asphalt to foam. The foaming characteristics of the asphalt binder are affected by the temperature of the asphalt and the stiffness of the asphalt binder: the asphalt binder will foam more easily at higher temperatures, and a soft asphalt binder is easier to foam than a stiff asphalt binder.

The foamed asphalt is characterized by two properties: expansion ratio and half-life. The expansion ratio is defined as the maximum volume of foamed asphalt divided by the original volume of the binder. The half-life is defined as the time, in seconds, for foamed asphalt to collapse from its maximum expansion volume to half of its maximum expansion volume. These properties provide an understanding of the potential for a particular asphalt binder to produce high-quality asphalt foam. The typical industry specifications call for an expansion ratio of 10 and a half-life of 8 seconds. The expansion ratio and half-life of an asphalt binder are dependent on the following:

- The water content used in foaming the asphalt (typically, 2 percent water)
    - The expansion ratio increases with an increase in foaming water content.
    - The half-life decreases with an increase in foaming water content.
- The temperature of the binder (i.e., the viscosity of the binder at the time of foaming)
    - The expansion ratio increases with an increase in the foaming temperature.
    - The half-life decreases with an increase in foaming temperature.
- The grade or stiffness of the asphalt binder. Softer asphalt binders have better foaming characteristics and are more stable.

To understand the foaming properties of a specific binder, a series of foaming tests are conducted at different water contents and temperatures using a laboratory foaming machine.

**Asphalt Binders Tested**

The foaming characteristics of three asphalt binders were evaluated as part of this study:

- Holly asphalt rubber (used for the Sasobit and Evotherm testing previously discussed)
- PG 76-22 asphalt binder
- PG 64-22 asphalt binder

PG 76-22 and PG 64-22 binders were to provide the research team with a basis for evaluating the results of testing on the AR.

**Test Results**

The objective of the testing was to determine whether or not each of the binders could produce a foamed asphalt in the laboratory that meets the typical industry specifications discussed above. The asphalt binders were foamed at differing water injection percentages, and the results were plotted.

Appendix C contains plots of the test data, with plots for each asphalt binder grouped in a separate section. There are three types of plots:

- The asphalt binder expansion ratio and half-life versus the percentage of the water used for foaming.
- The asphalt binder expansion ratio and half-life versus the temperature of the binder at the time when the water is added for foaming.
- Both expansion ratio and half-life versus percent water plotted on the same graph. A separate graph is provided for each temperature.

**Discussion**

The foaming characteristics for the PG 64-22 indicated that it will provide a stable foamed asphalt with approximately 2 percent water at a foaming temperature of 306° F. See Figure 11.

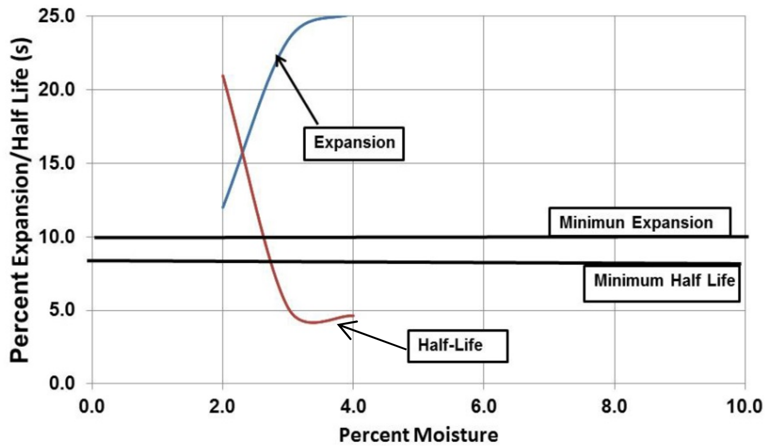


**Figure 11. PG 64-22 Expansion & Half-Life vs. Moisture (306° F)**

The testing performed on the PG76-22 asphalt binder showed that the design criteria were not met at either the 351° F or 369° F foaming temperatures. See Figures 12 and 13.

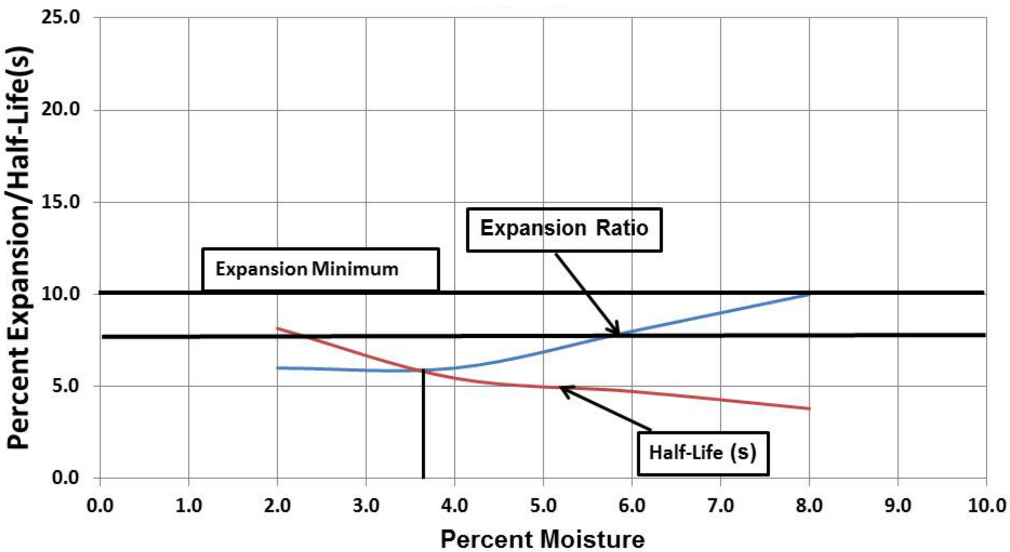


**Figure 12. PG 76-22 Expansion and Half-Life vs. Moisture (351° F)**

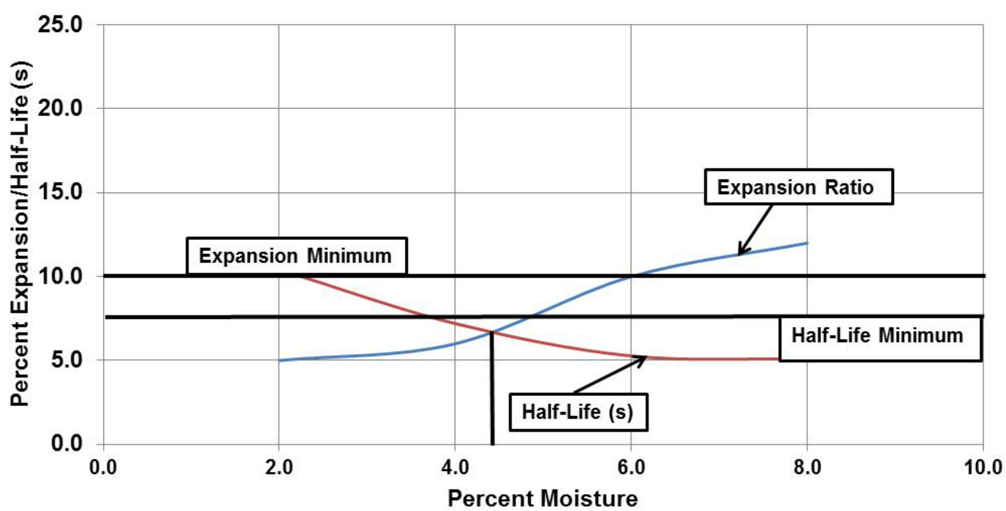


**Figure 13. PG 76-22 Expansion and Half-Life vs. Moisture (369° F)**

The foaming characteristics of the AR binder showed that no combination of water and temperature produces a foamed asphalt binder meeting the design criteria for half-life and expansion ratio. See Figures 14 and 15.

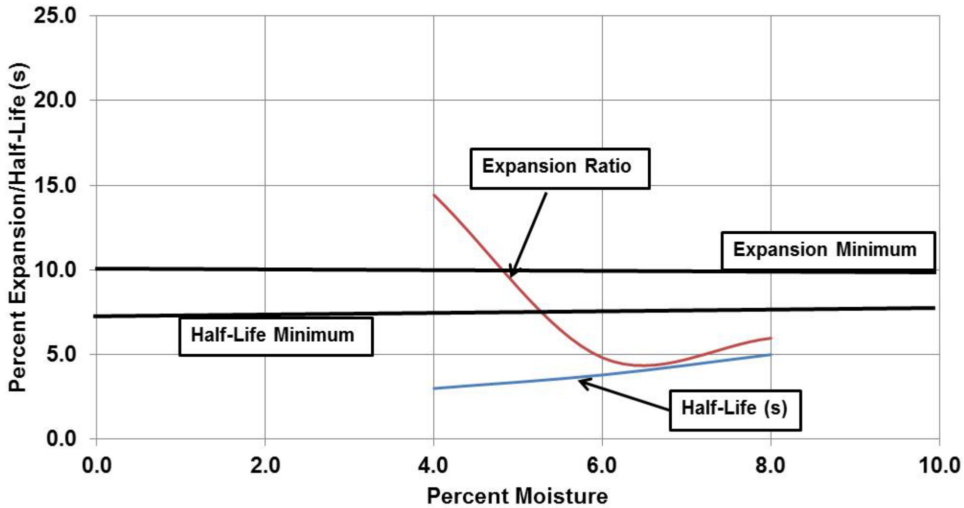


**Figure 14. Asphalt Rubber Expansion and Half-Life vs. Moisture (369° F)**

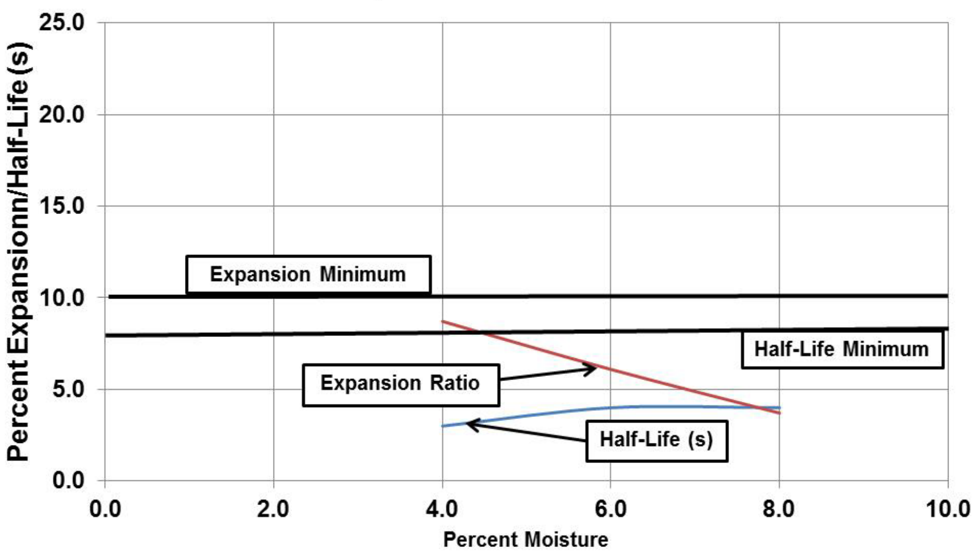


**Figure 15. Asphalt Rubber Expansion and Half-Life vs. Moisture (387° F)**

## Conclusions and Recommendations

The information in this report is based on a limited amount of laboratory testing. However, the concept that an increase in water content increases the expansion ratio and decreases the foamed asphalt half-life was validated. The data on the effect of temperature on foaming characteristics were mixed, and no definite conclusion could be drawn from the data developed in this study.

It was shown that the grade or stiffness of the asphalt binder has significant effects on the foaming characteristics of the asphalt binder.

The primary purpose of this laboratory study was to evaluate whether or not the foaming technology for manufacturing WMA mixtures could be used in an AR application. This limited study indicates the need for further evaluation of the use of water injection to produce WMA mixes for AR-ACFC.

# CHAPTER 3. FIELD STUDY

The objectives of the field study in this project were to determine whether WMA technologies could be used to construct AR-ACFC and to document the properties of the mixtures. The WMA sections were constructed on Interstate 17 (I-17) along with a control section of AR-ACFC containing no WMA. Sampling and testing was conducted using the data-collection guidelines developed by the WMA Technical Working Group (2006). This chapter discusses field observations about the placement of the mixture and describes both field test data and laboratory performance data.

## PROJECT DESCRIPTION

The project consisted of rehabilitating a section of I-17 south of Camp Verde, Arizona, between mile point 269.2 and mile point 279.6 (ADOT Project H813501C, I-17, MP 269.20 to MP 279.60). Fann Contracting of Prescott, Arizona, performed the paving. The project consisted of milling 4.5 inches of asphaltic concrete and replacing it with 0.5 inches of AR-ACFC over 4 inches of asphaltic concrete. The mix was produced in a CMI drum plant at the rate of 190 tons per hour. Three WMA technologies were used on the project: Sasobit, Advera, and Evotherm. Table 11 shows the locations and tonnages of the test sections within the project.

**Table 11. Locations of Test Sections**

| Additive | Date Section Placed | Direction | Lane | Start Station | Milepost | End Station | Milepost | Tonnage Placed (tons) |
|---|---|---|---|---|---|---|---|---|
| Sasobit | 16 Sep | South | Travel | 4106+75 | 279.6 | 3894+75 | 275.6 | 1006 |
| Advera | 18-Sep | South | Travel | 3894+75 | 274.8 | 3576+45 | 268.8 | 1571 |
| Control | 22 Sep | South | Passing | 4106+75 | 279.6 | 3808+98 | 273.9 | 1290 |
| Evotherm | 24 & 25-Sep | North | Travel | 3576+90 | 269.2 | 3913+25 | 275.5 | 1951 |

## MATERIALS

The gravel aggregate used in the AR-ACFC mixture was obtained from a source near the project site. The AR-ACFC binder was an asphalt rubber meeting the requirements of ADOT Specification 1009 (ADOT 2008). The base asphalt for the asphalt rubber was a PG 58-22 supplied by Western Refining. The asphalt rubber containing 20 percent ground tire rubber was blended on-site by Cactus Asphalt. Sasobit was added to the mixture at the drum plant in a pelletized form at a rate of 1.5 percent by weight of the asphalt rubber binder. Advera was added to the mixture at the drum plant at a rate of 0.25 percent by total weight of the AR-ACFC mixture. Evotherm was added to the asphalt rubber binder at the drum plant through an in-line portal at a rate of 0.40 percent by weight of asphalt rubber binder.

Tables 12 and 13 present binder test results for the control asphalt rubber and the Evotherm-modified asphalt rubber. Binders for the other additives could not be tested because the WMAs were added directly to the mixture during production.

**Table 12. Binder Test Results for Control**

| Test Performed | Reaction Time (Minutes) | | | | | |
|---|---|---|---|---|---|---|
| | **60** | **90** | **240** | **360** | **1440** | **Specification** |
| Rotational Viscosity, Haake – 350° F, Pascal Seconds | 2.5 | 2.8 | 2.7 | 2.4 | 2.2 | 1.5-4.0 |
| Penetration, ASTM D5 – 39.2° F, dmm, 200 g. | 35 | 35 | 39 | 40 | 41 | 15 minimum |
| Softening Point, ASTM D36 – °C, min. | 64 | 66 | 63 | 62 | 62 | 57 minimum |
| Resilience, ASTM D5329 – 77° F,% Rebound | 42 | 39 | 38 | 36 | 35 | 20 minimum |
| Pass/Fail Temperature, °C | 91.9 | 94.9 | 91.1 | 89.5 | 95.6 | NA |

**Table 13. Binder Test Results for Evotherm-Modified Asphalt Rubber**

| Test Performed | Reaction Time (Minutes) | | | | | |
|---|---|---|---|---|---|---|
| | **60** | **90** | **240** | **360** | **1440** | **Specification** |
| Rotational Viscosity, Haake – 350° F, Pascal Seconds | 2.3 | 2.5 | 2.4 | 2.3 | 2.0 | 1.5-4.0 |
| Penetration, ASTM D5 – 39.2° F, dmm, 200 g. | 33 | 31 | 31 | 32 | 32 | 15 minimum |
| Softening Point, ASTM D36 – ° C, min. | 65 | 66 | 67 | 66 | 66 | 57 minimum |
| Resilience, ASTM D5329 – 77° F, % Rebound | 42 | 46 | 46 | 47 | 46 | 20 minimum |
| Pass/Fail Temperature ° C | 92.4 | 89.9 | 95.9 | 91.5 | 93.2 | NA |

The project mix design indicated the aggregate met all of the quality requirements of ADOT Specification 414, Asphaltic Concrete Friction Course (Asphalt Rubber) (ADOT 2008). Table 14 shows the design aggregate gradation and the optimum asphalt content for the mixture.

**Table 14. Gradation of Aggregates and Binder Content Used in AR-ACFC Mixture**

| Sieve Size | Percent Passing |
|---|---|
| 3/8 inch | 100 |
| No. 4 | 36 |
| No. 8 | 9 |
| No. 200 | 2.5 |
| % Asphalt rubber by weight of total mixture | 9.3 |

## RESULTS AND DISCUSSION

### Construction

The following information was developed based on notes from Amec Foster Wheeler technicians, and on conversations with ADOT staff on March 19, 2015, and with a Fann Contracting employee on March 27, 2015. The performance criterion used during construction was the appearance of clumping or tearing of the AR-ACFC during the placement operations. For each test section, the production temperature was started at 300° to 320° F. Then the temperature was dropped in 10-degree increments until clumping of the mix or tearing of the surface occurred. The AR-ACFC was placed in a windrow, and a pickup machine was used to move the AR-ACFC from the windrow into the paver. Appendix D contains the mix temperatures and notes from Amec Foster Wheeler technicians during placement of the AR-ACFC.

The Sasobit test section was placed on September 16, 2014. The average air temperature was 75.6° F. The placement of the AR-ACFC was started at the normal mix temperature of 320° F, and the temperature was then reduced to 290° F in 10-degree increments. Temperature logs indicate that the average mat temperature was 271° F. At one point, the mat temperature dropped to 236° F. When that occurred, clumping developed in the mixture. At that time, the plant temperature was increased to 310° F. There were no other performance problems with the placement of the Sasobit mix.

The Advera test section was placed on September 18, 2014. The average air temperature was 80.6° F. The placement of the AR-ACFC was started at a mix temperature of 320° F, and the temperature was then reduced to 295° F in 10-degree increments with no observed clumping in the mixture. Temperature logs indicate the average mat temperature was 277° F. During placement of the Advera test section, the hot mix plant broke down for three hours. The contractor reduced the paving speed and was able to place the mix without needing to stop placement operations. Clumping developed in the mix when the mat temperature dropped to 257° F.

The Evotherm test section was placed on September 23 and 24, 2014. The average air temperatures on the 23rd and 24th were 83.9° F and 86.8° F, respectively. Initially the mixture was produced at 310° F with an average mat temperature of 292° F. The mix temperature was dropped to 290° F, resulting in an average mat temperature of 274° F. The last mix placed on the 23rd was produced at 280° F. The average mat temperature dropped to 263° F. No clumping in the mixture was observed.

**Performance Testing**

Samples of the mixture were obtained during the field study. Moisture susceptibility of the mixtures was evaluated using the modified AASHTO T283 test procedure, and durability of the mixtures were evaluated using the Cantabro test. These tests are described in Chapter 2, and the results are presented in Table 15. The purpose of the testing was to compare the properties of the mixtures with the additives against the control mixture (no additive).

**Table 15. Laboratory Results on Field Samples**

| Additive | Date Section Placed | Test Set Number | Moisture Susceptibility Test Results | | | Cantabro Loss (%) |
|---|---|---|---|---|---|---|
| | | | Dry Strength (psi) | Wet Strength (psi) | Tensile Splitting Ratio (%) | |
| Sasobit | 16 Sep | 1 | 33 | 16 | 56 | 0.42 |
| | | 2 | 40 | 22 | 55 | 0.26 |
| | | 3 | 39 | 23 | 59 | 0.31 |
| | | Average | 37 | 20 | 57 | 0.33 |
| Advera | 18 Sep | 1 | 40 | 20 | 50 | 1.04 |
| | | 2 | 45 | 21 | 46 | 0.40 |
| | | 3 | 43 | 22 | 50 | 0.68 |
| | | Average | 43 | 21 | 49 | 0.71 |
| Control | 22 Sep | 1 | 48 | 29 | 61 | 0.16 |
| | | 2 | 50 | 30 | 61 | 0.13 |
| | | 3 | 51 | 30 | 61 | 0.08 |
| | | Average | 50 | 30 | 61 | 0.12 |
| Evotherm | 24 & 25 Sep | 1 | 41 | 27 | 66 | 1.62 |
| | | 2 | 42 | 27 | 64 | 1.36 |
| | | 3 | 48 | 27 | 57 | 2.63 |
| | | Average | 44 | 27 | 62 | 1.87 |

*Statistical Analysis*

The tensile splitting ratio and Cantabro loss for the control mix and each additive were analyzed, using ANOVA and comparison testing similar to the analyses described in Chapter 2.

**Durability (Cantabro Loss) With Field Samples**

The ANOVA output for Cantabro tests with the field samples resulted in accepting $H_1$, indicating a difference in means among groups. Table 16 and Figure 16 present the statistical summary and boxplot, respectively. It was found that the Evotherm treated sample group was different from the control mix group. However, it should be mentioned that the test was conducted with only three replicates, and it is therefore quite difficult to draw a meaningful conclusion with such a small sample.

**Table 16. Summary of Descriptive Statistics for Cantabro Test Results (Durability) with Field Samples**

| Cantabro Test with Field Samples | | | | | |
|---|---|---|---|---|---|
| Additive Type | Dosage Level | No. of Replicates | Mean | Standard Deviation | Significant Difference from Control Mix |
| No Additive (Control Mix) | | 3 | 0.12 | 0.04 | N/A |
| Evotherm | At Target (0.40%) | 3 | 1.87 | 0.67 | Yes |
| Sasobit | At Target (1.5%) | 3 | 0.33 | 0.08 | No |
| Advera | At Target (0.25%) | 3 | 0.71 | 0.32 | No |

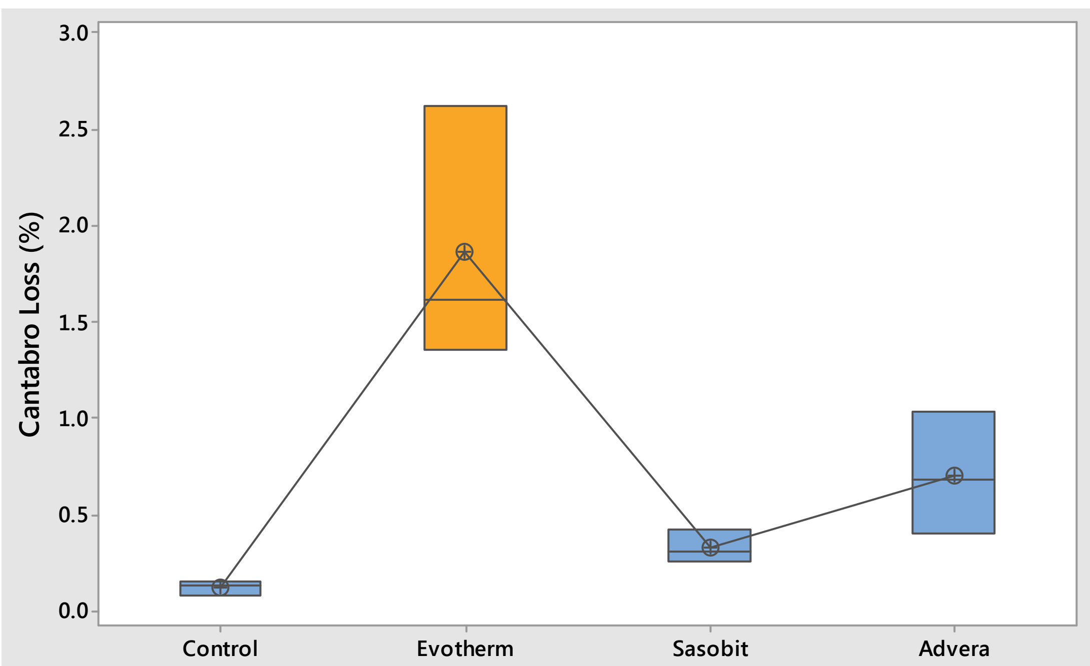


**Figure 16. Boxplot of Cantabro Results for Field AR-ACFC Samples**

**Moisture Susceptibility (TSR) With Field Samples**

Table 17 and Figure 17 present the statistical analysis result for the moisture susceptibility performance with field samples as measured by TSR. The TSR of the Advera mix was found to be significantly lower than that of the control group.

**Table 17. Summary of Descriptive Statistics for TSR Test Results with Field Samples**

| TSR Result with Field Samples | | | | | |
|---|---|---|---|---|---|
| **Additive Type** | **Dosage Level** | **No. of Replicates** | **Mean** | **Standard Deviation** | **Significant Difference from Control Mix** |
| No Additive (Control Mix) | | 3 | 61.00 | 0.00 | N/A |
| Evotherm | At Target | 3 | 62.33 | 4.73 | No |
| Sasobit | At Target | 3 | 56.67 | 2.08 | No |
| Advera | At Target | 3 | 48.67 | 2.31 | Yes |

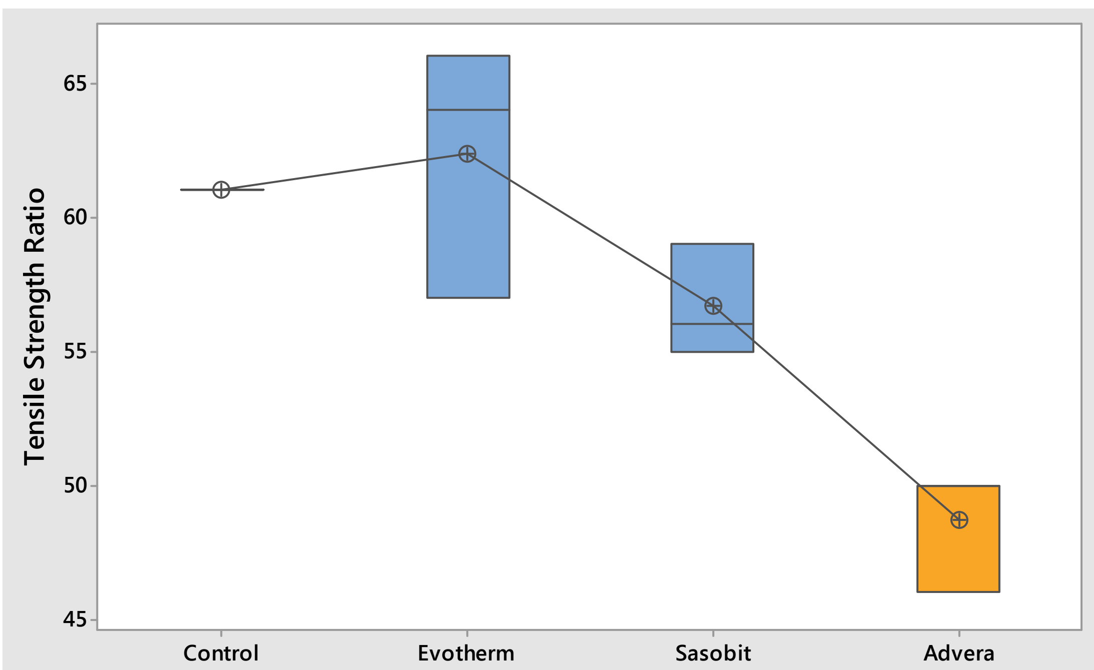


**Figure 17. Boxplot of Tensile Strength Ratio Results w/ Field Samples**

In summary, the field samples' performance testing showed that:

- The Evotherm mix had lower durability than the control mix
- The Evotherm and Sasobit mixes were no different from the control mix in moisture susceptibility performance.
- The Advera mix showed inferior moisture susceptibility performance.

As indicated, however, it is hard to draw a valid conclusion with only three replicates. Further research is recommended to fully evaluate the WMA additives mix performance in the field.

**Surface Smoothness (International Roughness Index)**

The smoothness of pavement surface constructed with the three WMA additives was explored; the evaluation was based on the International Roughness Index (IRI). Table 18 summarizes the descriptive statistics on the IRI measurement, and Figure 18 shows boxplots of the IRI values. The mean IRI of the control pavement section is approximately 40 inches per 0.1 mile with a standard deviation of 3.97. The pavement section treated with the Evotherm additive has a very similar IRI value with the control section and thus is not statistically different. The Advera section is significantly different from the control section, having an even smoother surface (a mean IRI of 37.47 with a standard deviation of 4.78). Unlike the other two WMA-treated pavement sections, however, the Sasobit section shows a significantly higher IRI compared to the control section (a mean IRI of 46.6 with a standard deviation of 8.33).

**Table 18. Summary of Descriptive Statistics for Surface Smoothness**

| Additive Type | No. of IRI Data | Mean | Standard Deviation | Significant Difference from Control Mix |
|---|---|---|---|---|
| No Additive (Control Mix) | 58 | 40.04 | 3.97 | N/A |
| Evotherm | 64 | 40.00 | 5.05 | No |
| Sasobit | 41 | 46.60 | 8.33 | Yes |
| Advera | 52 | 37.47 | 4.78 | Yes |

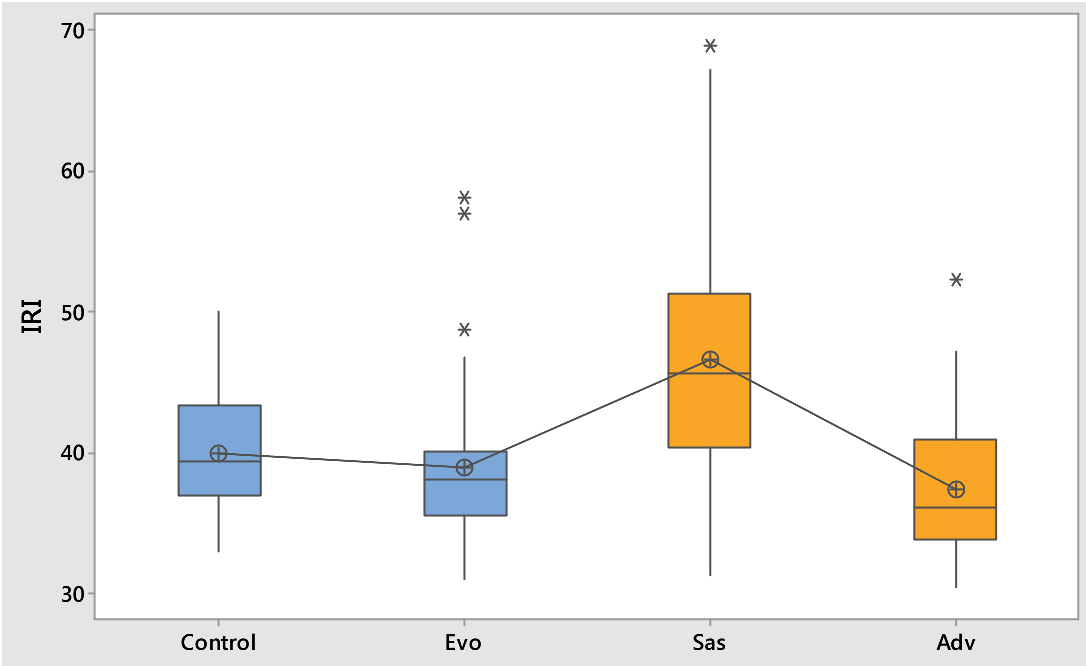


**Figure 18. Boxplot of International Roughness Index**

Further investigation was conducted to see the Sasobit IRI data in detail. Figure 19 shows the IRI values of all four pavement sections. The distribution plots on the right show that the distribution of the Sasobit section contains a wide range of data, implying that the IRI data of the Sasobit section have a high variance and that the data of the other three sections have relatively lower variances.

The IRI values of the Sasobit section show an unusual pattern. The first half of the data is unusually high, causing the mean IRI value of the section to be significantly higher than the mean IRI of the control section. The second half of the data is closer to the mean IRI of the control group. If the high IRI values of the Sasobit section had been caused by the Sasobit, the whole pavement section would have consistently had the higher IRI. It is suspected that the high IRI value of the first half section is caused by other construction-related reasons, not by the WMA additive.

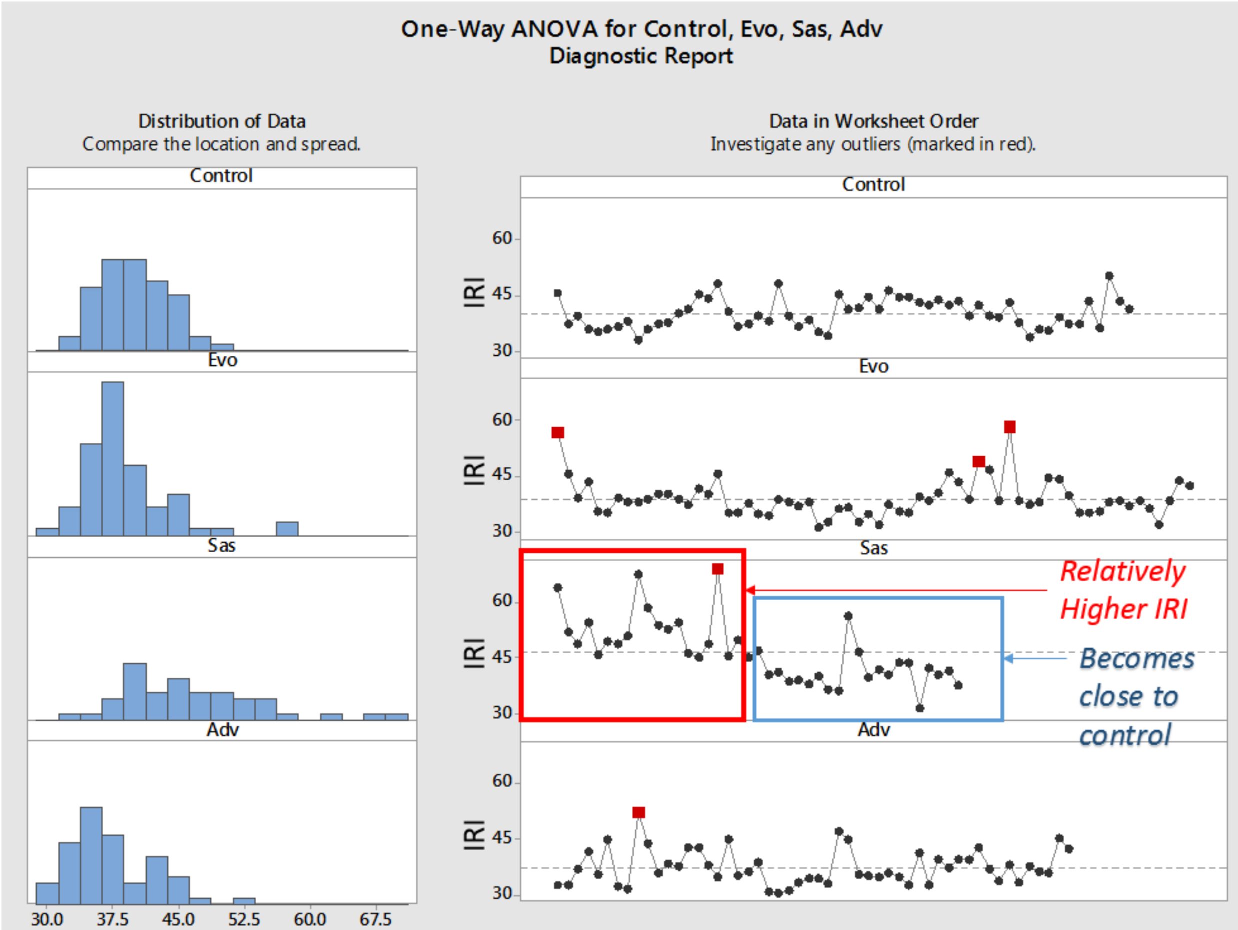


**Figure 19. IRI Data Distribution (Left) and Presentation in Order (Right)**

# CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The results of this study lead to the following conclusions:

- The use of Sasobit will increase the stiffness of the asphalt rubber binder.
- The use of Evotherm will have no effects on the properties of the asphalt rubber binder.
- When the three additives (Sasobit, Evotherm and Advera) included in this study are used at the manufacturer's suggested dosage rate, there will be no detrimental effects on the performance of an AR-ACFC.
- When the WMA AR-ACFC is placed at a mat temperature of $250^{o}$ F or higher, the AR-ACFC can be successfully placed and compacted.

In addition, the researchers make the following recommendations:

- That ADOT not allow the use of the water-injection WMA technology until further research and field studies have been completed.
- That ADOT not make any changes in its current (June 2015) procedures for the design of AR-ACFC mixes.

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## APPENDIX A: ASPHALT RUBBER LAB TEST DATA

## Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 08-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | |
|---|---|---|---|
| | | Project No.: | Product Testing |
| | | Sample ID: | As Received ARB with No Additives |
| | | AMEC Lab No.: | 1341172 |
| | | Date Received: | 05-31-2012 |
| | | Sample Date: | 05-31-2012 |
| | | Sample Type: | Submittal |
| Tests on Original Asphalt-Rubber | | | |
| Viscosity, 350°F, Pa.s | (1) | Report | 2.0 |
| Viscosity, 325°F, Pa.s | (1) | Report | 2.9 |
| Viscosity, 300°F, Pa.s | (1) | Report | 4.1 |
| Viscosity, 275°F, Pa.s | (1) | Report | 6.0 |
| Viscosity, 250°F, Pa.s | (1) | Report | 9.0 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | |
|---|---|
| Client: ADOT | AMEC Job No.: 19-2012-2149 |
| Project Name: Warm Mix Study | Date Reported: 07-18-2013 |
| | Material: Asphalt-Rubber Binder |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | | |
| | | Sample ID: | As Received ARB with No Additives | | | | | |
| | | AMEC Lab No.: | 1341172 | | | | | |
| | | Date Received: | 05-31-2012 | | | | | |
| | | Sample Date: | 05-31-2012 | | | | | |
| | | Sample Type: | Submittal | | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 | |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 1.9 | 2.1 | 2.1 | 2.1 | 2.0 | |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 23 | 24 | 25 | 26 | 25 | |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 66 | 66 | 65 | 65 | 66 | |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 36 | 37 | 35 | 37 | 36 | |
| Dynamic Shear, G*/sinδ, kPa (2mm GAP | AASHTO T315 | | | | | | | |
| 76°C | | 1.00 min. | 3.68 | 4.48 | 4.01 | 4.14 | 4.23 | |
| 82°C | | | 2.10 | 2.77 | 2.33 | 2.39 | 2.51 | |
| 88°C | | | 1.17 | 1.69 | 1.34 | 1.46 | 1.47 | |
| Pass / Fail Temperature, °C | | Report | 89.6 | 94.5 | 91.1 | 92.7 | 92.3 | |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 08-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | |
|---|---|
| Project No.: | Product Testing |
| Sample ID: | ARB with 0.25% EVOTHERM M1 (Low Target) |
| AMEC Lab No.: | 1341356 |
| Date Received: | 05-31-2012 |
| Sample Date: | 05-31-2012 |
| Sample Type: | Submittal |

| Tests on Original Asphalt-Rubber | | | |
|---|---|---|---|
| Viscosity, 350°F, Pa.s | (1) | Report | 2.3 |
| Viscosity, 325°F, Pa.s | (1) | Report | 3.2 |
| Viscosity, 300°F, Pa.s | (1) | Report | 4.3 |
| Viscosity, 275°F, Pa.s | (1) | Report | 6.1 |
| Viscosity, 250°F, Pa.s | (1) | Report | 9.0 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 07-19-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | |
| | | Sample ID: | ARB with 0.25% EVOTHERM M1 (Low Target) | | | | |
| | | AMEC Lab No.: | 1341356 | | | | |
| | | Date Received: | 05-31-2012 | | | | |
| | | Sample Date: | 05-31-2012 | | | | |
| | | Sample Type: | Submittal | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 2.1 | 2.4 | 2.4 | 2.4 | 2.2 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 24 | 22 | 22 | 22 | 23 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 67 | 67 | 67 | 67 | 67 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 37 | 37 | 38 | 36 | 36 |
| Dynamic Shear, G*/sinδ, kPa (2mm GA | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 4.04 | 3.58 | 3.99 | 3.81 | 3.94 |
| 82°C | | | 2.29 | 2.05 | 2.34 | 2.28 | 2.35 |
| 88°C | | | 1.41 | 1.26 | 1.39 | 1.37 | 1.41 |
| Pass / Fail Temperature, °C | | Report | 92.2 | 90.8 | 91.8 | 91.7 | 92.1 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

MISSING SHEET – VISCOSITIES 0.4% Evotherm

# Asphalt Classification Summary

amec

| | |
|---|---|
| Client: ADOT | AMEC Job No.: 19-2012-2149 |
| Project Name: Warm Mix Study | Date Reported: 07-19-2013 |
| | Material: Asphalt-Rubber Binder |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | | |
| | | Sample ID: | ARB with 0.4% EVOTHERM M1 (Target) | | | | | |
| | | AMEC Lab No.: | 1341357 | | | | | |
| | | Date Received: | 05-31-2012 | | | | | |
| | | Sample Date: | 05-31-2012 | | | | | |
| | | Sample Type: | Submittal | | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 | |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 2.1 | 2.3 | 2.2 | 2.3 | 1.9 | |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 24 | 22 | 23 | 24 | 24 | |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 64 | 65 | 65 | 66 | 66 | |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 36 | 36 | 36 | 36 | 35 | |
| Dynamic Shear, G*/sinδ, kPa (2mm GA | AASHTO T315 | | | | | | | |
| 76°C | | 1.00 min. | 3.57 | 3.99 | 4.00 | 4.41 | 4.43 | |
| 82°C | | | 2.16 | 2.32 | 2.44 | 2.64 | 2.66 | |
| 88°C | | | 1.33 | 1.40 | 1.51 | 1.71 | 1.66 | |
| Pass / Fail Temperature, °C | | Report | 91.5 | 92.1 | 93.1 | 95.4 | 94.5 | |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

## Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 08-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | |
|---|---|---|---|
| | | Project No.: | Product Testing |
| | | Sample ID: | ARB with 0.7% EVOTHERM M1 (High Target) |
| | | AMEC Lab No.: | 1341358 |
| | | Date Received: | 05-31-2012 |
| | | Sample Date: | 05-31-2012 |
| | | Sample Type: | Submittal |
| Tests on Original Asphalt-Rubber | | | |
| Viscosity, 350°F, Pa.s | (1) | Report | 2.3 |
| Viscosity, 325°F, Pa.s | (1) | Report | 3.1 |
| Viscosity, 300°F, Pa.s | (1) | Report | 4.0 |
| Viscosity, 275°F, Pa.s | (1) | Report | 6.0 |
| Viscosity, 250°F, Pa.s | (1) | Report | 9.0 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 07-24-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | |
|---|---|
| Project No.: | Product Testing |
| Sample ID: | ARB with 0.7% EVOTHERM M1 (High Target) |
| AMEC Lab No.: | 1341358 |
| Date Received: | 05-31-2012 |
| Sample Date: | 05-31-2012 |
| Sample Type: | Submittal |

| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
|---|---|---|---|---|---|---|---|
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 2.2 | 2.4 | 2.4 | 2.4 | 2.1 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 21 | 22 | 22 | 22 | 25 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 64 | 65 | 66 | 66 | 67 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 38 | 39 | 40 | 36 | 34 |
| | | | | | | | |
| Dynamic Shear, G*/sinδ, kPa (2mm GA | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 3.49 | 3.67 | 3.34 | 3.96 | 4.29 |
| 82°C | | | 2.05 | 2.22 | 1.99 | 2.35 | 2.46 |
| 88°C | | | 1.20 | 1.36 | 1.16 | 1.43 | 1.49 |
| Pass / Fail Temperature, °C | | Report | 90.0 | 91.8 | 89.7 | 92.4 | 92.8 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | |
|---|---|
| Client: ADOT | AMEC Job No.: 19-2012-2149 |
| Project Name: Warm Mix Study | Date Reported: 08-30-2013 |
| | Material: Asphalt-Rubber Binder |

| | |
|---|---|
| Project No.: | Product Testing |
| Sample ID: | ARB with 0.5% Sasobit (Low Target) |
| AMEC Lab No.: | 1341359 |
| Date Received: | 05-31-2012 |
| Sample Date: | 05-31-2012 |
| Sample Type: | Submittal |

| Tests on Original Asphalt-Rubber | | | |
|---|---|---|---|
| Viscosity, 350°F, Pa.s | (1) | Report | 2.0 |
| Viscosity, 325°F, Pa.s | (1) | Report | 2.8 |
| Viscosity, 300°F, Pa.s | (1) | Report | 3.5 |
| Viscosity, 275°F, Pa.s | (1) | Report | 6.0 |
| Viscosity, 250°F, Pa.s | (1) | Report | 8.5 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 07-24-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | |
| | | Sample ID: | ARB with 0.5% Sasobit (Low Target) | | | | |
| | | AMEC Lab No.: | 1341359 | | | | |
| | | Date Received: | 05-31-2012 | | | | |
| | | Sample Date: | 05-31-2012 | | | | |
| | | Sample Type: | Submittal | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 24 | 24 | 24 | 25 | 26 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 67 | 66 | 67 | 66 | 67 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 34 | 34 | 33 | 34 | 32 |
| Dynamic Shear, G*/sinδ, kPa (2mm GA | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 4.14 | 4.55 | 3.85 | 3.60 | 4.16 |
| 82°C | | | 2.44 | 2.59 | 2.31 | 2.01 | 2.42 |
| 88°C | | | 1.36 | 1.54 | 1.45 | 1.21 | 1.45 |
| Pass / Fail Temperature, °C | | Report | 91.2 | 93.0 | 92.8 | 90.3 | 92.3 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 08-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | |
|---|---|---|---|
| | | Project No.: | Product Testing |
| | | Sample ID: | ARB with 1.5% Sasobit (Target) |
| | | AMEC Lab No.: | 1341360 |
| | | Date Received: | 05-31-2012 |
| | | Sample Date: | 05-31-2012 |
| | | Sample Type: | Submittal |
| Tests on Original Asphalt-Rubber | | | |
| Viscosity, 350°F, Pa.s | (1) | Report | 2.0 |
| Viscosity, 325°F, Pa.s | (1) | Report | 2.5 |
| Viscosity, 300°F, Pa.s | (1) | Report | 3.5 |
| Viscosity, 275°F, Pa.s | (1) | Report | 5.5 |
| Viscosity, 250°F, Pa.s | (1) | Report | 8.0 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 07-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | |
| | | Sample ID: | ARB with 1.5% Sasobit (Target) | | | | |
| | | AMEC Lab No.: | 1341360 | | | | |
| | | Date Received: | 05-31-2012 | | | | |
| | | Sample Date: | 05-31-2012 | | | | |
| | | Sample Type: | Submittal | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 1.9 | 2.0 | 2.0 | 2.1 | 2.0 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 22 | 23 | 23 | 22 | 22 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 72 | 73 | 72 | 72 | 76 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 33 | 34 | 35 | 34 | 35 |
| | | | | | | | |
| Dynamic Shear, G*/sinδ, kPa (2mm GAI | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 4.42 | 4.51 | 4.81 | 4.97 | 5.32 |
| 82°C | | | 2.57 | 2.59 | 2.78 | 2.94 | 3.04 |
| 88°C | | | 1.55 | 1.52 | 1.68 | 1.71 | 1.77 |
| Pass / Fail Temperature, °C | | Report | 93.2 | 92.7 | 94.1 | 94.0 | 94.3 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149 |
| Project Name: | Warm Mix Study | Date Reported: | 08-30-2013 |
| | | Material: | Asphalt-Rubber Binder |

| | | | |
|---|---|---|---|
| | | Project No.: | Product Testing |
| | | Sample ID: | ARB with 3.0% Sasobit (High Target) |
| | | AMEC Lab No.: | 1341361 |
| | | Date Received: | 05-31-2012 |
| | | Sample Date: | 05-31-2012 |
| | | Sample Type: | Submittal |
| Tests on Original Asphalt-Rubber | | | |
| Viscosity, 350°F, Pa.s | (1) | Report | 1.9 |
| Viscosity, 325°F, Pa.s | (1) | Report | 2.4 |
| Viscosity, 300°F, Pa.s | (1) | Report | 3.1 |
| Viscosity, 275°F, Pa.s | (1) | Report | 5.4 |
| Viscosity, 250°F, Pa.s | (1) | Report | 7.8 |

Remarks:

*(1) Viscosity was determined with a Rion Handheld Viscotester model VT-04 using a No. 1 rotor.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | |
|---|---|
| Client: ADOT | AMEC Job No.: 19-2012-2149 |
| Project Name: Warm Mix Study | Date Reported: 07-30-2013 |
| | Material: Asphalt-Rubber Binder |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | |
| | | Sample ID: | ARB with 3.0% Sasobit (High Target) | | | | |
| | | AMEC Lab No.: | 1341361 | | | | |
| | | Date Received: | 05-31-2012 | | | | |
| | | Sample Date: | 05-31-2012 | | | | |
| | | Sample Type: | Submittal | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 1.9 | 1.9 | 1.9 | 2.0 | 1.8 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 21 | 23 | 21 | 21 | 21 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 89 | 89 | 90 | 90 | 90 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 31 | 31 | 31 | 33 | 33 |
| Dynamic Shear, G*/sinδ, kPa (2mm GA | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 5.37 | 5.01 | 5.12 | 5.81 | 6.12 |
| 82°C | | | 2.98 | 2.79 | 2.87 | 3.31 | 3.45 |
| 88°C | | | 1.74 | 1.52 | 1.64 | 1.97 | 2.03 |
| Pass / Fail Temperature, °C | | Report | 94.2 | 92.2 | 93.3 | 95.8 | 96.0 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Sam W. Huddleston, Bituminous Laboratory Manager

# Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149.04 |
| Project Name: | Warm Mix Study | Date Reported: | 12-16-2014 |
| | | Material: | Asphalt-Rubber Binder |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Project No.: | Product Testing | | | | | |
| | | Sample ID: | ARB with EVOTHERM | | | | | |
| | | AMEC Lab No.: | 1443150 | | | | | |
| | | Date Received: | 12-05-2014 | | | | | |
| | | Sample Date: | 09-24-2014 | | | | | |
| | | Sample Type: | Submittal | | | | | |
| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 | |
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 2.3 | 2.5 | 2.4 | 2.3 | 2.0 | |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 33 | 31 | 31 | 32 | 32 | |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 65 | 66 | 67 | 66 | 65 | |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 42 | 46 | 46 | 47 | 46 | |
| Dynamic Shear, G*/sinδ, kPa (2mm GAP)( | AASHTO T315 | | | | | | | |
| 76°C | | 1.00 min. | 3.85 | 3.60 | 4.56 | 3.66 | 4.38 | |
| 82°C | | | 2.24 | 2.13 | 2.72 | 2.11 | 2.46 | |
| 88°C | | | 1.38 | 1.20 | 1.69 | 1.32 | 1.52 | |
| Pass / Fail Temperature, °C | | Report | 92.4 | 89.9 | 95.9 | 91.5 | 93.2 | |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Brian A. Waterbury, Bituminous Laboratory Manager

## Asphalt Classification Summary

amec

| | | | |
|---|---|---|---|
| Client: | ADOT | AMEC Job No.: | 19-2012-2149.04 |
| Project Name: | Warm Mix Study | Date Reported: | 12-16-2014 |
| | | Material: | Asphalt-Rubber Binder |

| | |
|---|---|
| Project No.: | Product Testing |
| Sample ID: | As Received ARB with No Additives |
| AMEC Lab No.: | 1443151 |
| Date Received: | 12-05-2014 |
| Sample Date: | 09-24-2014 |
| Sample Type: | Submittal |

| Tests on Original Asphalt-Rubber | | | 60 | 90 | 240 | 360 | 1440 |
|---|---|---|---|---|---|---|---|
| Viscosity, 350°F, Pa.s | | 1.5-4.0 | 2.5 | 2.8 | 2.7 | 2.4 | 2.2 |
| Penetration, 39.2°F,200g., 60sec., 0.10 mm | ASTM D5 | 10 min. | 35 | 35 | 39 | 40 | 41 |
| Ring and Ball Softening Point, °C | ASTM D36 | 57 min. | 64 | 66 | 63 | 62 | 62 |
| Resilience, 77°F, % | ASTM D5329 | 25 min. | 42 | 39 | 38 | 36 | 35 |
| | | | | | | | |
| Dynamic Shear, G*/sinδ, kPa (2mm GAP)( | AASHTO T315 | | | | | | |
| 76°C | | 1.00 min. | 3.56 | 4.27 | 3.41 | 3.12 | 3.90 |
| 82°C | | | 2.04 | 2.50 | 2.07 | 1.92 | 2.42 |
| 88°C | | | 1.31 | 1.57 | 1.28 | 1.14 | 1.58 |
| Pass / Fail Temperature, °C | | Report | 91.9 | 94.9 | 91.1 | 89.5 | 95.6 |

Remarks:

*(1) Due to the granular sizing of the crumb rubber in the asphalt rubber sample, inconsistencies with DSR data may occur.*

*Specifications refer to ADOT Specifications.*

Reviewed By:

Brian A. Waterbury, Bituminous Laboratory Manager

**APPENDIX B: AR-ACFC LAB TEST DATA**

**Laboratory Draindown Test Data**

**Table B - 1. Percentage of Draindown – Set 1**

| | Additive | | | | | |
|---|---|---|---|---|---|---|
| | Evotherm | | Sasobit | | Advera | |
| | 275° F | 325° F | 275° F | 325° F | 275° F | 325° F |
| No Additive | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Below Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.02 |
| At Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Above Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.02 |

**Table B - 2. Percentage of Draindown – Set 2**

| | Additive | | | | | |
|---|---|---|---|---|---|---|
| | Evotherm | | Sasobit | | Advera | |
| | 275° F | 325° F | 275° F | 325° F | 275° F | 325° F |
| No Additive | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.01 |
| Below Target | 0.0 | 0.01 | 0.0 | 0.01 | 0.0 | 0.02 |
| At Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Above Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table B - 3. Percentage of Draindown – Set 3**

| | Additive | | | | | |
|---|---|---|---|---|---|---|
| | Evotherm | | Sasobit | | Advera | |
| | 275° F | 325° F | 275° F | 325° F | 275° F | 325° F |
| No Additive | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Below Target | 0.0 | 0.01 | 0.0 | 0.0 | 0.0 | 0.01 |
| At Target | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.01 |
| Above Target | 0.0 | 0.0 | 0.0 | 0.01 | 0.01 | 0.01 |

**Laboratory Durability Test Data**

**Table B - 4. Percent Loss – Cantabro – Set 1**

| **Evotherm** | **Unaged (%)** | | | | **Aged (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.98 | 0.70 | 0.51 | 0.73 | 45.62 | 47.44 | 51.80 | 48.29 |
| Below Target | 0.87 | 0.87 | 2.71 | 1.48 | 37.68 | Damaged | 45.06 | 41.37 |
| At Target | 2.32 | 2.85 | 2.38 | 2.52 | 31.29 | 26.09 | 35.34 | 30.91 |
| Above Target | 0.26 | 0.36 | 0.19 | 0.27 | 31.26 | 29.43 | 28.55 | 29.75 |
| | | | | | | | | |
| **Sasobit** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.98 | 0.70 | 0.51 | 0.73 | 45.62 | 47.44 | 51.80 | 48.29 |
| Below Target | 0.52 | 0.40 | 0.72 | 0.55 | 45.19 | 46.18 | 44.10 | 45.16 |
| At Target | 2.17 | 1.53 | 1.44 | 1.71 | 38.84 | 47.21 | 42.64 | 42.90 |
| Above Target | 0.43 | 0.33 | 0.77 | 0.51 | 43.25 | 46.20 | 47.19 | 45.55 |
| | | | | | | | | |
| **Advera** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.98 | 0.70 | 0.51 | 0.73 | 45.62 | 47.44 | 51.80 | 48.29 |
| Below Target | 0.55 | 0.42 | 0.87 | 0.61 | 24.30 | 17.48 | 25.63 | 22.47 |
| At Target | 0.59 | 0.67 | 0.64 | 0.63 | 20.78 | 23.34 | 23.54 | 22.55 |
| Above Target | 0.46 | 0.59 | 0.28 | 0.44 | 17.75 | 16.27 | 16.68 | 16.90 |

**Table B - 5. Cantabro – Percent Loss – Set 2**

| **Evotherm** | **Unaged (%)** | | | | **Aged (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.27 | 0.25 | 0.44 | 0.32 | 34.92 | 37.66 | 32.90 | 35.16 |
| Below Target | 1.07 | 0.62 | 1.11 | 0.94 | 43.37 | 54.30 | 47.20 | 48.32 |
| At Target | 1.66 | 0.42 | 2.29 | 1.46 | 46.49 | 32.35 | 36.99 | 38.61 |
| Above Target | 0.66 | 0.78 | 0.82 | 0.75 | 50.75 | 43.72 | 39.49 | 44.32 |
| | | | | | | | | |
| **Sasobit** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.27 | 0.25 | 0.44 | 0.32 | 34.92 | 37.66 | 32.90 | 35.16 |
| Below Target | 1.07 | 0.62 | 1.11 | 0.94 | 43.23 | 45.06 | 43.07 | 43.79 |
| At Target | 1.12 | 1.46 | 1.46 | 1.34 | 34.53 | 38.28 | 35.53 | 36.11 |
| Above Target | 0.64 | 0.55 | 0.32 | 0.51 | 49.30 | 44.00 | 48.87 | 47.39 |
| | | | | | | | | |
| **Advera** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.27 | 0.25 | 0.44 | 0.32 | 34.92 | 37.66 | 32.90 | 35.16 |
| Below Target | 1.01 | 0.84 | 0.52 | 0.79 | 30.83 | 32.65 | 33.93 | 32.47 |
| At Target | 1.17 | 1.06 | 0.53 | 0.92 | 24.88 | 21.69 | 19.15 | 21.91 |
| Above Target | 0.73 | 0.50 | 0.79 | 0.67 | 35.90 | 30.46 | 31.12 | 32.50 |

**Table B - 6. Percent Loss – Cantabro – Set 3**

| **Evotherm** | **Unaged (%)** | | | | **Aged (%)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.33 | 1.49 | 0.23 | 0.68 | 31.73 | 33.01 | 32.30 | 32.35 |
| Below Target | 1.24 | 0.93 | 0.92 | 1.03 | 51.57 | 48.37 | 47.63 | 49.19 |
| At Target | 0.60 | 1.13 | 1.28 | 1.00 | 41.00 | 37.03 | 37.09 | 38.37 |
| Above Target | 0.98 | 0.70 | 0.90 | 0.86 | 37.01 | 54.72 | 42.96 | 44.90 |
| | | | | | | | | |
| **Sasobit** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.33 | 1.49 | 0.23 | 0.68 | 31.73 | 33.01 | 32.30 | 32.35 |
| Below Target | 1.66 | 1.05 | 1.10 | 1.27 | 42.08 | 38.09 | 41.86 | 40.68 |
| At Target | 1.28 | 1.09 | 1.46 | 1.29 | 38.36 | 42.10 | 38.56 | 39.67 |
| Above Target | 0.43 | 0.55 | 0.67 | 0.55 | 47.30 | 49.11 | 47.72 | 48.04 |
| | | | | | | | | |
| **Advera** | **Unaged (%)** | | | | **Aged (%)** | | | |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** |
| No Additive | 0.33 | 1.49 | 0.23 | 0.68 | 31.73 | 33.01 | 32.30 | 32.35 |
| Below Target | 0.52 | 0.30 | 1.11 | 0.64 | 27.38 | 34.20 | 29.14 | 30.24 |
| At Target | 1.02 | 0.72 | 1.21 | 0.98 | 19.71 | 22.29 | 20.94 | 20.98 |
| Above Target | 0.82 | 0.57 | 0.77 | 0.72 | 34.68 | 29.88 | 30.04 | 31.53 |

**Laboratory Moisture Susceptibility Lab Test Data**

**Table B - 7. Moisture Susceptibility Set 1**

| **Evotherm** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
|---|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 39 | 41 | 39 | 40 | 17 | 19 | 26 | 21 | 52 |
| Below Target | 33 | 33 | 37 | 34 | 20 | 19 | 19 | 19 | 56 |
| At Target | 36 | 41 | 41 | 39 | 18 | 21 | 24 | 21 | 53 |
| Above Target | 32 | 30 | 30 | 31 | 24 | 22 | 22 | 23 | 75 |
| | | | | | | | | | |
| **Sasobit** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 39 | 41 | 39 | 40 | 17 | 19 | 26 | 21 | 52 |
| Below Target | 34 | 45 | 46 | 42 | 23 | 25 | 27 | 25 | 60 |
| At Target | 37 | 40 | 39 | 39 | 22 | 23 | 24 | 23 | 59 |
| Above Target | 41 | 40 | 44 | 42 | 26 | 30 | 28 | 28 | 68 |
| | | | | | | | | | |
| **Advera** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 39 | 41 | 39 | 40 | 17 | 19 | 26 | 21 | 52 |
| Below Target | 38 | 42 | 41 | 40 | 16 | 17 | 18 | 17 | 42 |
| At Target | 42 | 44 | 45 | 43 | 19 | 22 | 22 | 21 | 48 |
| Above Target | 49 | 49 | 55 | 51 | 28 | 27 | 27 | 27 | 53 |

**Table B - 8. Moisture Susceptibility Set 2**

| Evotherm | Unconditioned (psi) | | | | Conditioned (psi) | | | | Ratio |
|---|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 41 | 33 | 35 | 36 | 14 | 15 | 17 | 16 | 43 |
| Below Target | 49 | 39 | 45 | 45 | 25 | 24 | 24 | 24 | 54 |
| At Target | 35 | 36 | 37 | 36 | 16 | 19 | 18 | 18 | 49 |
| Above Target | 30 | 35 | 36 | 24 | 16 | 16 | 16 | 16 | 47 |
| | | | | | | | | | |
| **Sasobit** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 41 | 33 | 35 | 36 | 14 | 15 | 17 | 16 | 43 |
| Below Target | 31 | 40 | 42 | 38 | 23 | 21 | 20 | 21 | 57 |
| At Target | 36 | 37 | 35 | 36 | 25 | 23 | 22 | 23 | 64 |
| Above Target | 30 | 32 | 33 | 32 | 21 | 23 | 20 | 21 | 66 |
| | | | | | | | | | |
| **Advera** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 41 | 33 | 35 | 36 | 14 | 15 | 17 | 16 | 43 |
| Below Target | 39 | 41 | 37 | 39 | 16 | 19 | 16 | 17 | 43 |
| At Target | 36 | 42 | 40 | 39 | 16 | 18 | 19 | 18 | 45 |
| Above Target | 38 | 39 | 39 | 39 | 15 | 17 | 17 | 16 | 42 |

**Table B - 9. Moisture Susceptibility Set 3**

| Evotherm | Unconditioned (psi) | | | | Conditioned (psi) | | | | Ratio |
|---|---|---|---|---|---|---|---|---|---|
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 33 | 40 | 33 | 35 | 17 | 17 | 20 | 18 | 51 |
| Below Target | 40 | 41 | 44 | 42 | 24 | 22 | 20 | 22 | 53 |
| At Target | 35 | 36 | 37 | 36 | 16 | 16 | 16 | 36 | 47 |
| Above Target | 29 | 34 | 25 | 29 | 17 | 14 | 15 | 15 | 52 |
| | | | | | | | | | |
| **Sasobit** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 33 | 40 | 33 | 35 | 17 | 17 | 20 | 18 | 51 |
| Below Target | 36 | 31 | 38 | 35 | 20 | 19 | 23 | 21 | 59 |
| At Target | 37 | 37 | 37 | 37 | 21 | 25 | 22 | 23 | 62 |
| Above Target | 26 | 40 | 29 | 32 | 20 | 22 | 20 | 21 | 65 |
| | | | | | | | | | |
| **Advera** | **Unconditioned (psi)** | | | | **Conditioned (psi)** | | | | **Ratio** |
| **Specimen** | **1** | **2** | **3** | **Average** | **1** | **2** | **3** | **Average** | **%** |
| No Additive | 33 | 40 | 33 | 35 | 17 | 17 | 20 | 18 | 51 |
| Below Target | 35 | 38 | 41 | 38 | 17 | 17 | 16 | 17 | 44 |
| At Target | 58 | 60 | 48 | 55 | 23 | 28 | 26 | 25 | 46 |
| Above Target | 47 | 37 | 49 | 45 | 20 | 20 | 19 | 20 | 44 |

# APPENDIX C: FOAMED ASPHALT TEST PLOTS

**PG 64-22 Asphalt Binder**
**DATA**

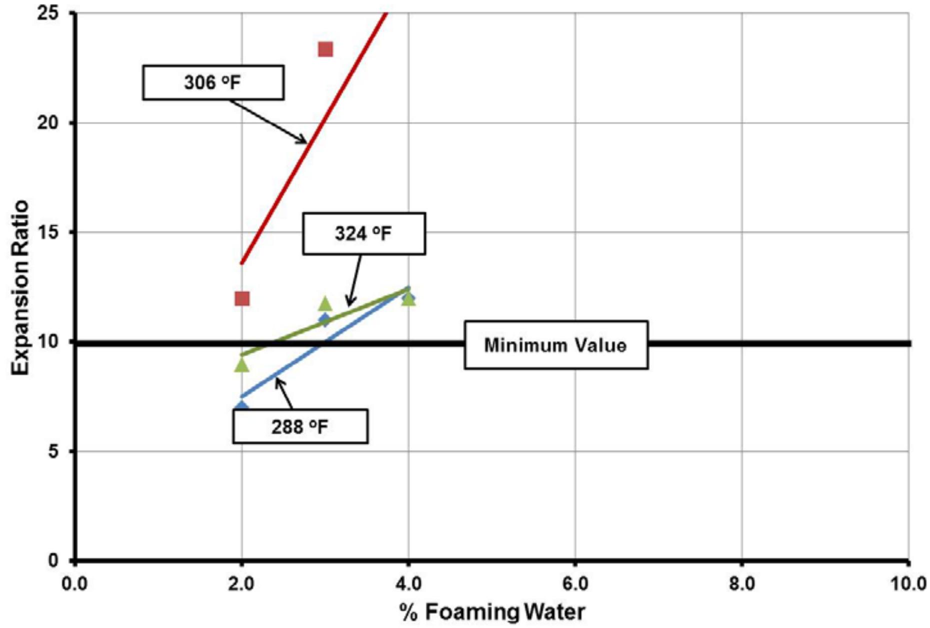


**Figure C - 1. PG 64-22 Expansion Ratio**

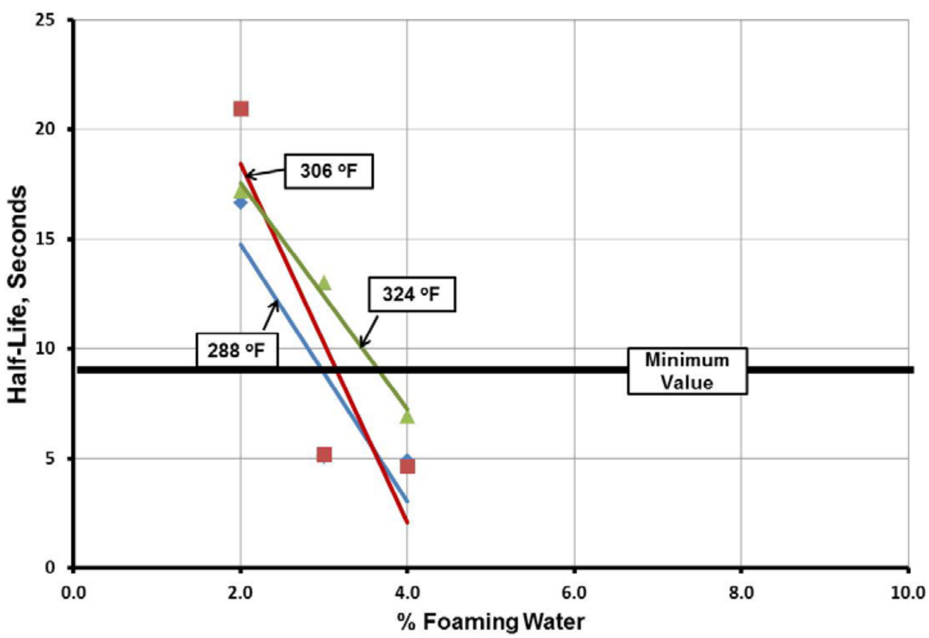


**Figure C - 2. PG 64-22 Half-Life**

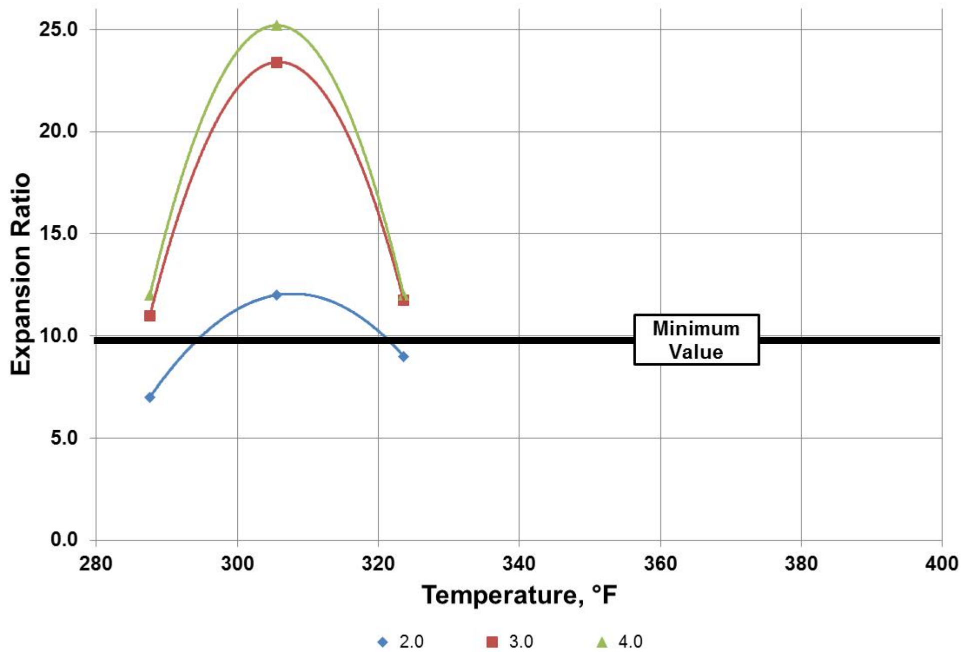


Figure C - 3. PG 64-22 Expansion vs. Temperature

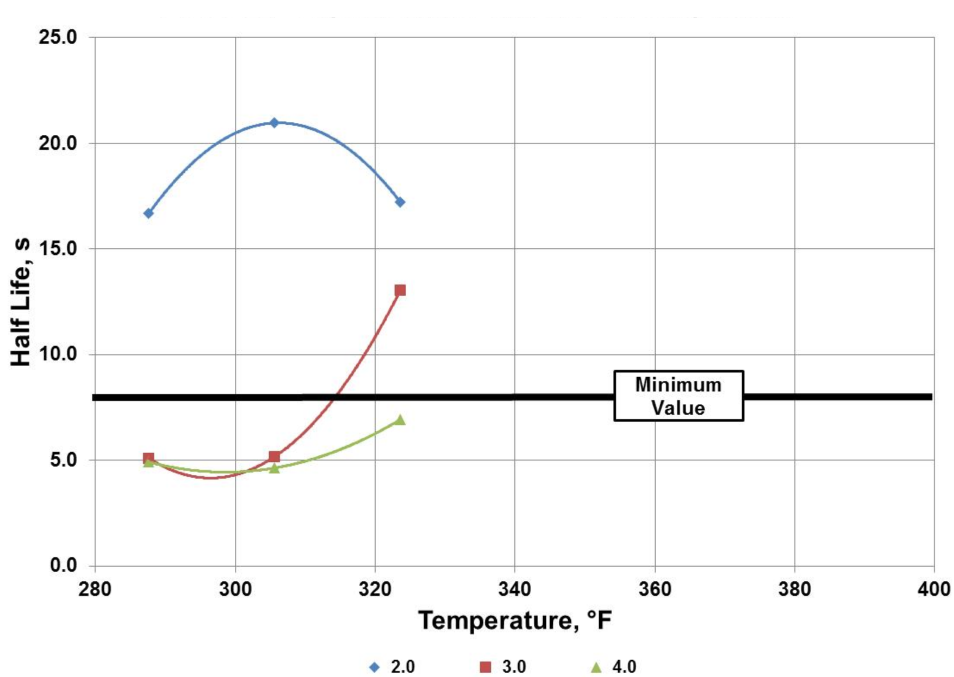


Figure C - 4. PG 64-22 Half-Life vs. Temperature

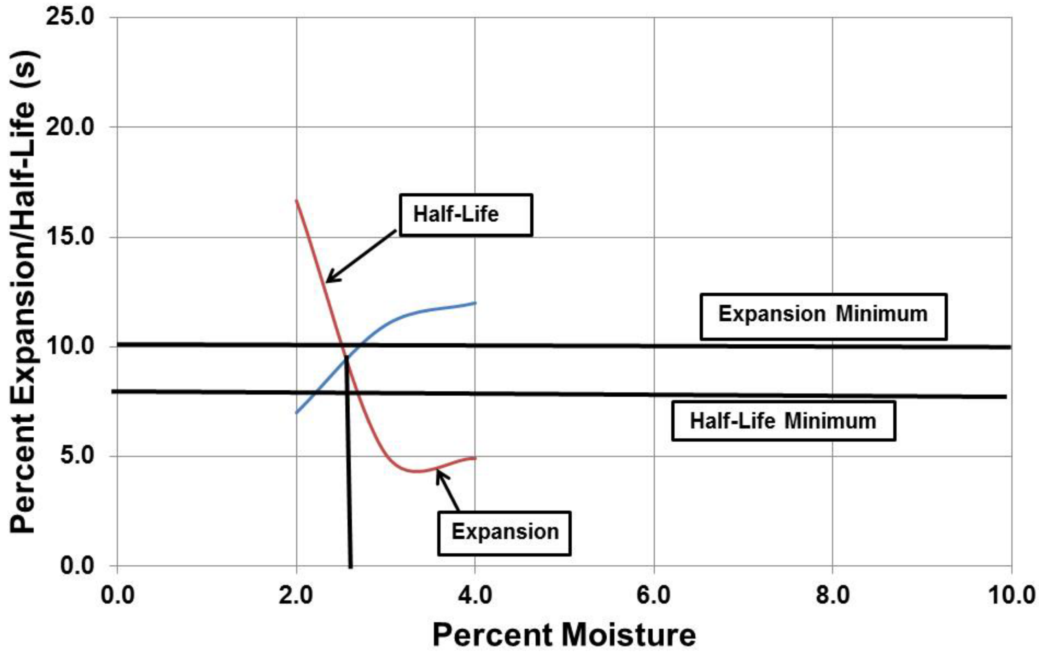


**Figure C - 5. PG 64-22 Expansion and Half-Life vs. Moisture (288$^{o}$ F)**

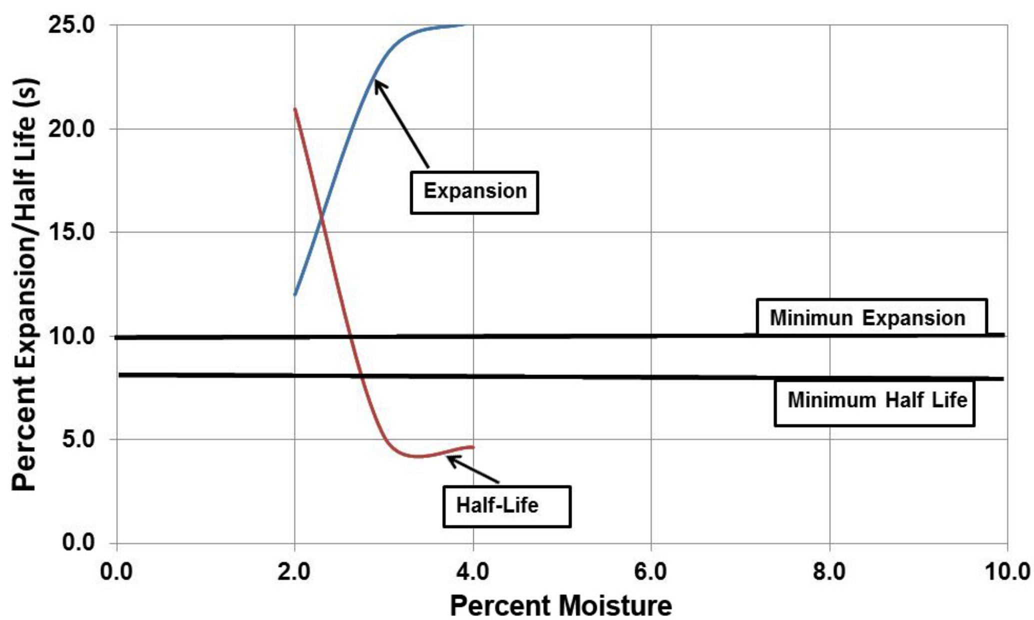


**Figure C - 6. PG 64-22 Expansion and Half-Life vs. Moisture (306$^{o}$ F)**

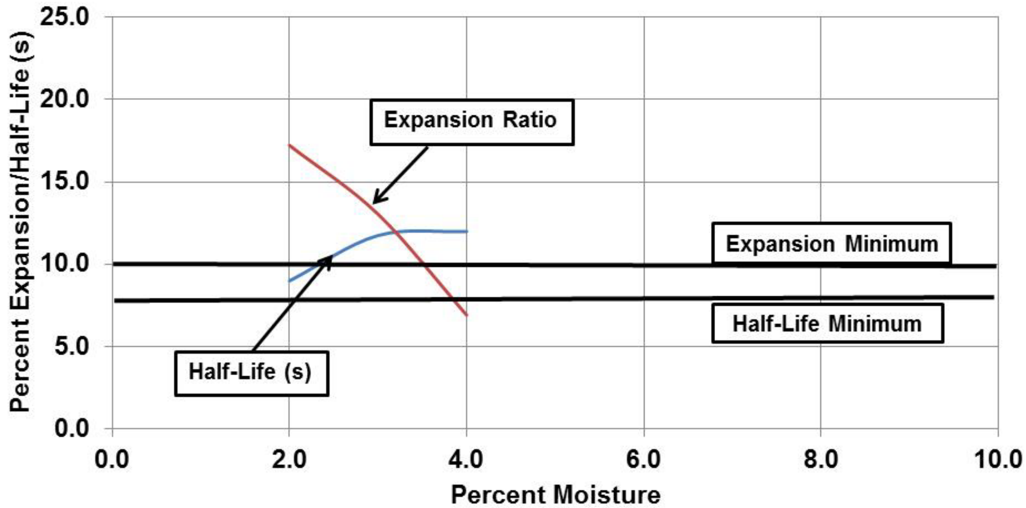


**Figure C - 7. PG 64-22 Expansion and Half-Life vs. Moisture (324$^{o}$ F)**

**PG 76-22 Asphalt Binder**
**DATA**

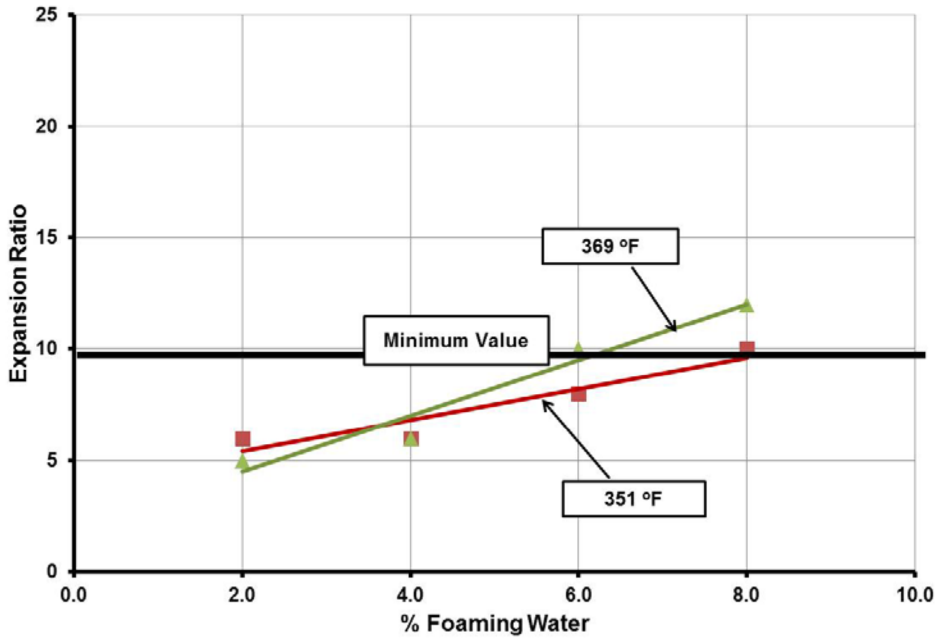


**Figure C - 8. PG 76 -22 Expansion Ratio**

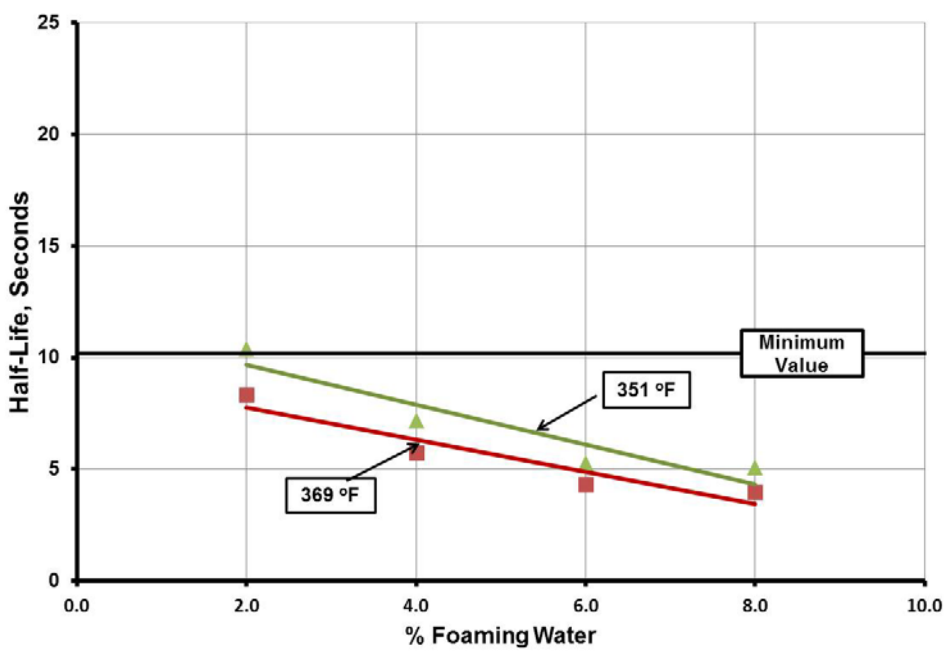


**Figure C - 9. PG 76-22 Half-Life**

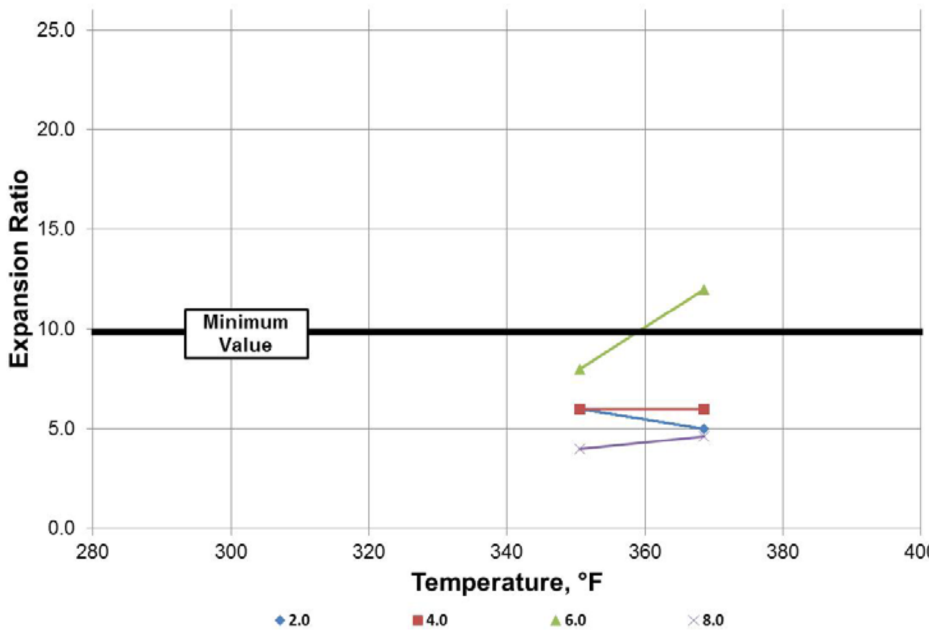


**Figure C - 10. PG 76-22 Expansion vs. Temperature**

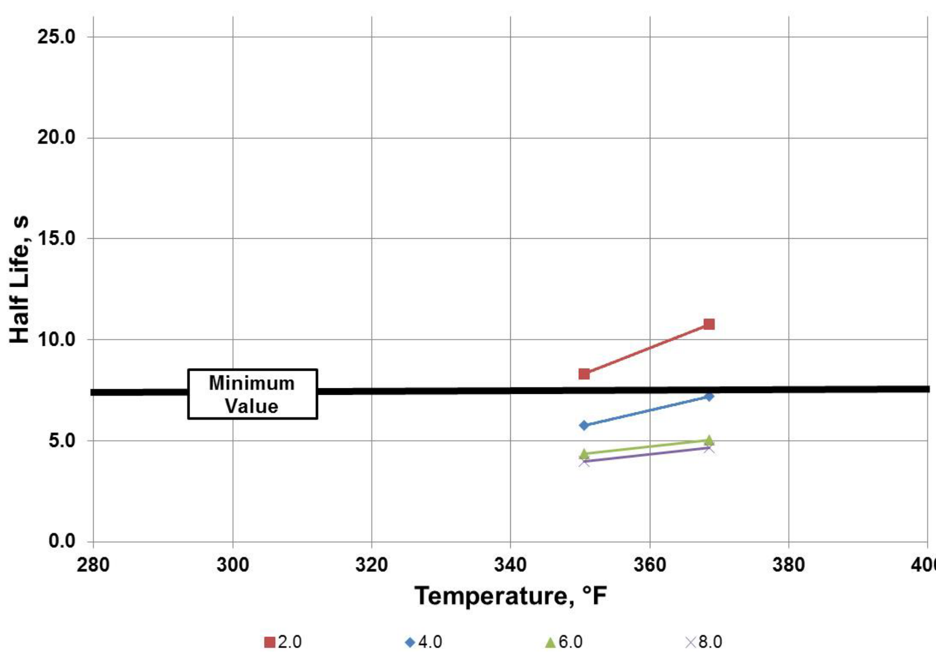


**Figure C - 11. PG 76-22 Half-Life vs. Temperature**

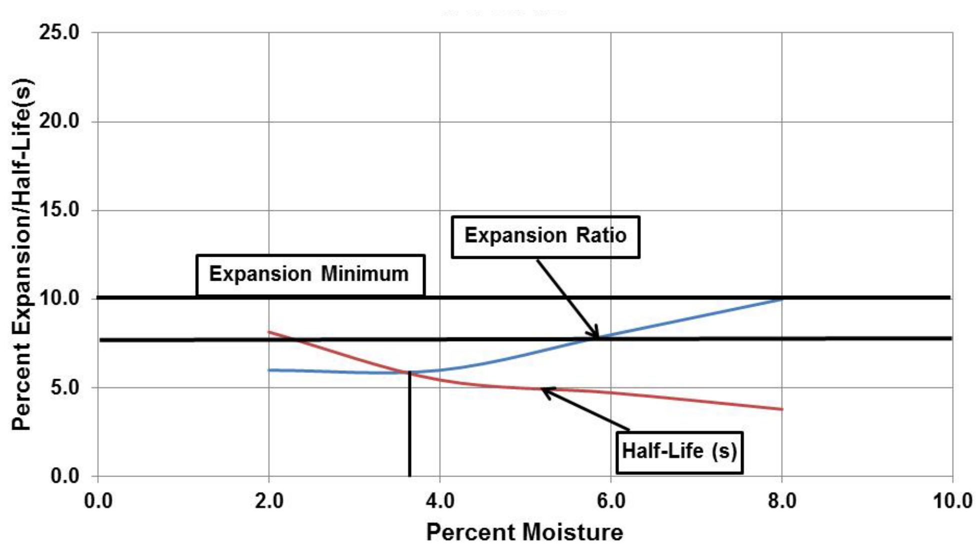


**Figure C - 12. PG 76-22 Expansion and Half-Life vs. Moisture (351°)**

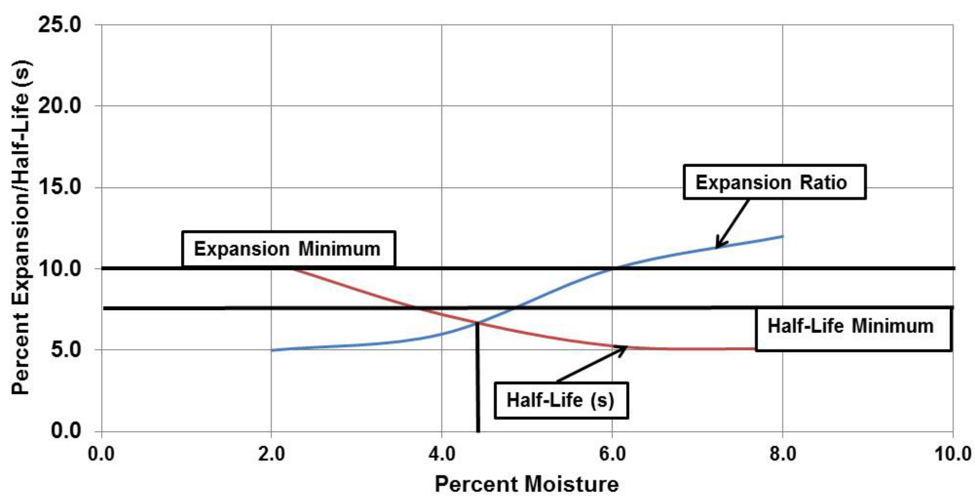


**Figure C - 13. PG 76-22 Expansion and Half-Life vs. Moisture (369°)**

**ARB – Rubberized Asphalt Binder**
**DATA**

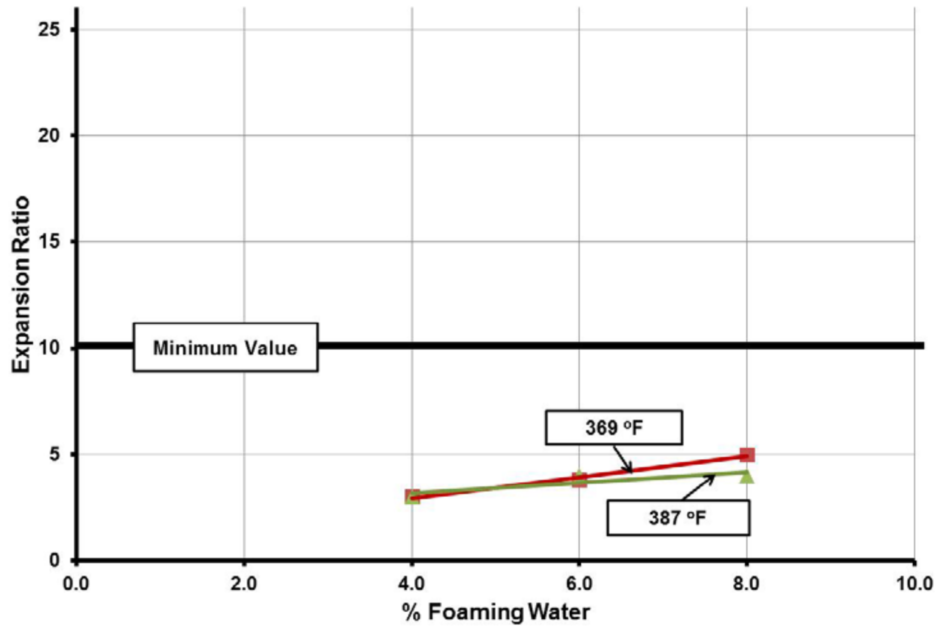


**Figure C - 14. Asphalt Rubber Expansion Ratio**

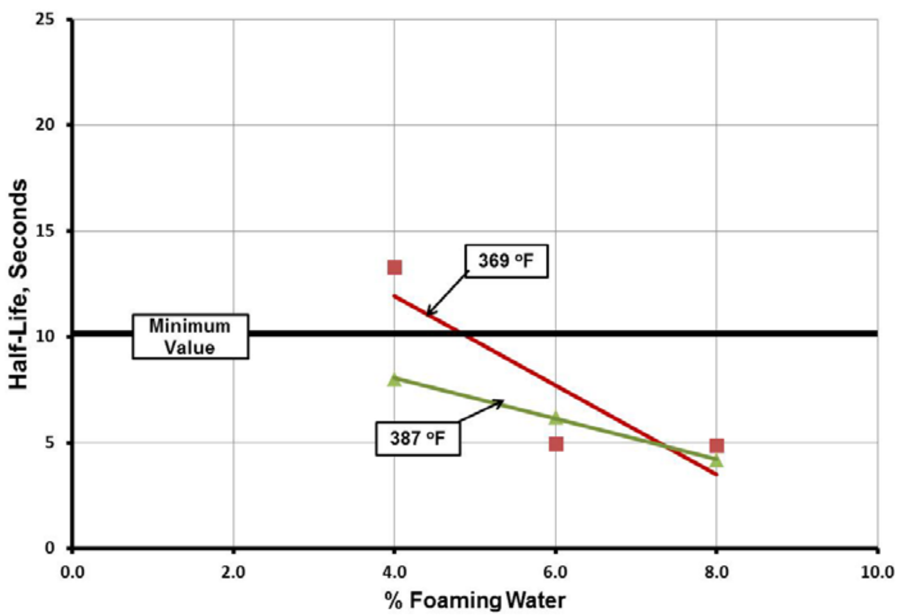


**Figure C - 15. Asphalt Rubber Half-Life**

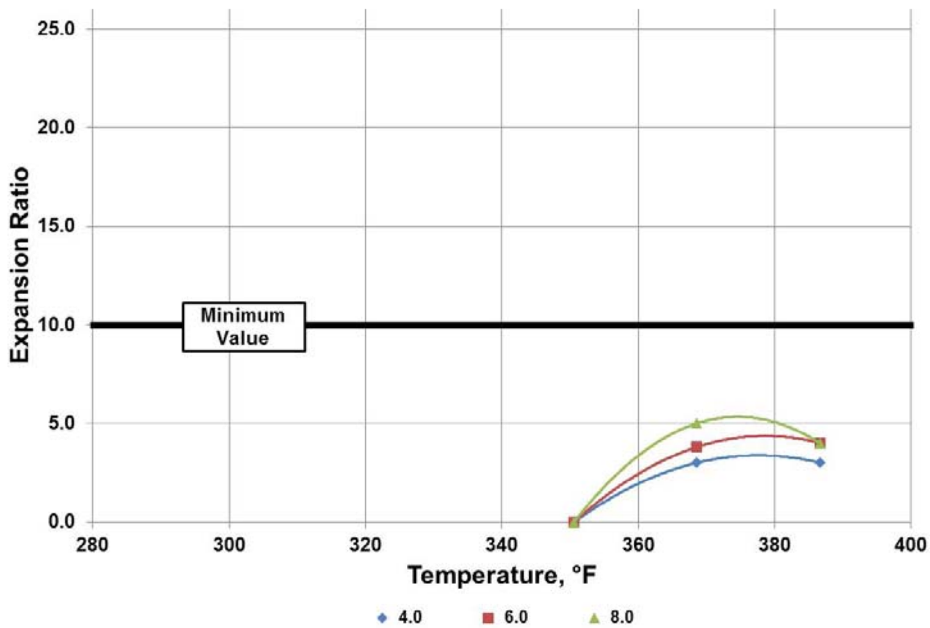


**Figure C - 16. Asphalt Rubber Expansion vs. Temperature**

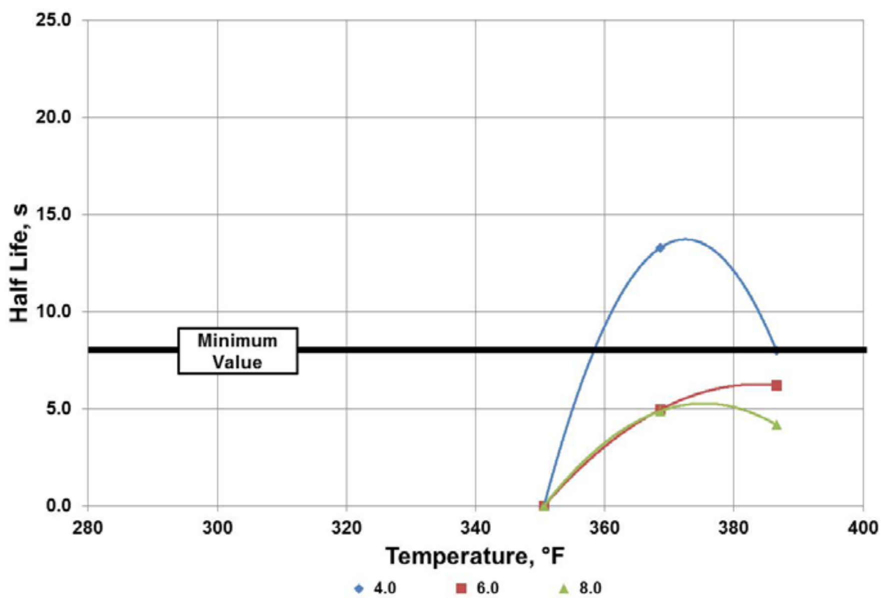


**Figure C - 17. Asphalt Rubber Half-Life vs. Temperature**

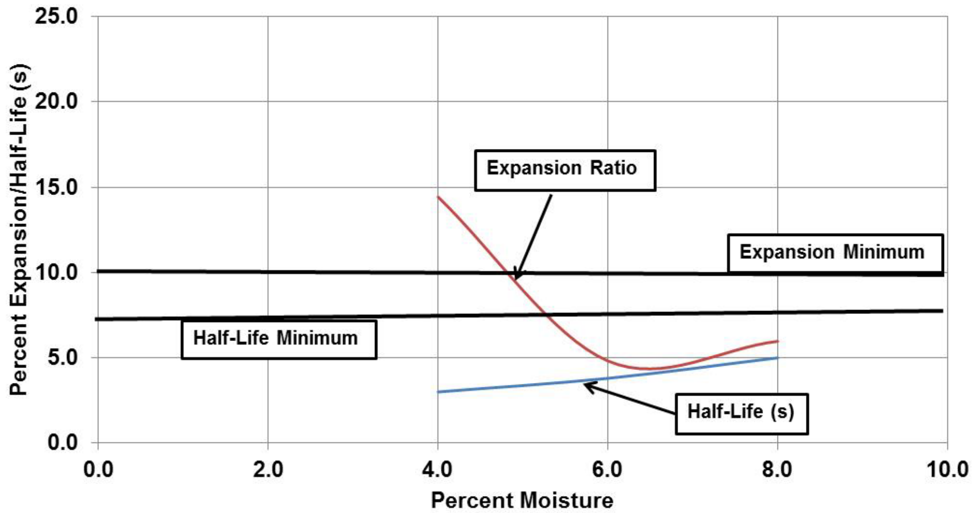


**Figure C - 18. Asphalt Rubber Expansion and Half-Life vs. Moisture (369°)**

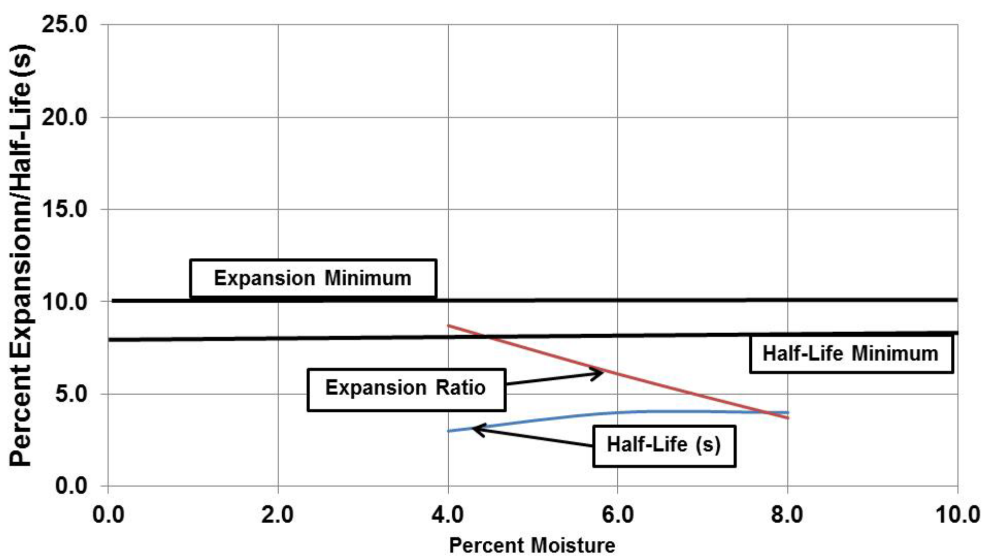


**Figure C - 19. Asphalt Rubber Expansion and Half-Life vs. Moisture (387°)**

## APPENDIX D: FIELD TEMPERATURE DATA

**Table D - 1. Field Temperature Data – Sasobit**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Warm Mix Additive Research Project** | | | | | | Project No.: | 19-2012-2146.04 |
| **Yavapai County** | | | | | | | |
| **Admixture: Sasobit** | | | | | | Placement Date: | 09/16/14 |
| **Location: South Bound Travel Lane** | | | | | | | |
| | | | | | | | |
| | Mix Temperatures | | | GPS | | | |
| Time | Windrow | Hopper | Mat | North | West | Station | Notes: |
| 10:15 | 173° | 179° | 235 | 34°31'45.7023" | 111°58'53.5995" | 4106+75 | Discharge Temp at Plant 290° |
| 10:30 | 233° | 261° | 252 | 34°31'26.0733" | 111°59'07.0985" | 4083+00 | 1st Load with Sasobit |
| 10:45 | 217° | 223° | 250 | | | 4081+75 | |
| 11:00 | 248° | 262° | 268 | | | 4069+29 | |
| 11:15 | 219° | 245° | 272 | | | 4056+76 | |
| 11:30 | 275° | 270° | 264 | 34°30'38.2834" | 111°59'43.1647" | | |
| 11:45 | 291° | 260° | 285 | | | 4031+76 | |
| 12:00 | 278° | 292° | 236 | 34°30'26.2875" | 111°59'51.8878" | | Clumping Developed |
| 12:15 | 273° | 266° | 283 | 34°30'10.4265" | 112°00'06.0432" | 4000+85 | Temp at Plant increase from 290° to 315° |
| 12:30 | 308° | 259° | 275 | | | | |
| 12:45 | 278° | 271° | 275 | 34°29'57.0755" | 112°00'14.9253" | | |
| 1:00 | 296° | 290° | 292 | 34°29'39.1012" | 112°00'22.1192" | | Increasing cloud cover |
| 1:15 | 305° | 291° | 281 | 34°29'38.6104" | 112°00'22.4265" | 3958+50 | |
| 1:30 | 254° | 198° | 282 | 34°29'27.9624" | 112°00'28.6530" | | |
| 1:45 | 268° | 279° | 284 | 34°29'11.4996" | 112°00'47.7285" | 3922+45 | |
| 2:00 | 312° | 236° | 277 | | | | |
| 2:15 | 282° | 265° | 272 | 34°28'54.2779" | 112°01'13.0678" | 3894+75 | Light rain - production halted |

## Table D - 2. Field Temperature Data – Advera

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Warm Mix Additive Research Project** | | | | | | Project No.: | 19-2012-2146.04 |
| **Yavapai County** | | | | | | | |
| **Admixture: Advera** | | | | | | Placement Date: | 09/18/14 |
| **Location: Southbound Travel Lane** | | | | | | | |
| | Mix Temperatures | | | GPS | | | |
| Time | Windrow | Hopper | Mat | North | West | Station | Notes: |
| 9:00 | 285° | 282° | | 34°28'54.2779" | 112°01'13.0678" | 3894+75 | Discharge temp at Plant- 315° |
| 9:15 | 278° | 239° | 279 | Problem with GPS Unit No coordinates available | | 3891+75 | |
| 9:30 | 249° | 275° | 301 | | | 3884+40 | |
| 9:45 | 281° | 248° | 278 | | | 3872+60 | |
| 10:00 | 281° | 246° | 282 | | | 3867+62 | |
| 10:15 | 306° | 258° | 273 | | | 3865+00 | |
| 10:30 | 305° | 238° | 275 | | | 3863+00 | |
| 10:45 | 302° | 260° | 297 | | | 3860+40 | |
| 11:00 | 307° | 238° | 293 | | | 3856+20 | |
| 11:15 | 298° | 276° | 282 | | | 3853+80 | |
| 11:30 | 266° | 198° | 275 | | | 3852+40 | |
| 11:45 | 302° | 238° | 274 | | | 3850+00 | 45 minute wait time with no obvious problems |
| 12:00 | 302° | 283° | 269 | | | 3846+30 | |
| 12:15 | 298° | 247° | 264 | | | 3842+00 | |
| 12:30 | 286° | 266° | 246 | | | 3838+20 | |
| 12:45 | 228° | 216° | 238 | | | 3836+40 | |
| 1:00 | 293° | 187° | 240 | | | 3832+70 | |
| 1:15 | 261° | 305° | 303 | | | 3828+00 | |
| 1:30 | 299° | 294° | 300 | | | 3816+00 | Temp drop at Plant from 315° to 305° |
| 1:45 | 286° | 275° | 281 | | | 3808+98 | |
| 2:00 | 296° | 280° | 281 | | | 3794+10 | |
| 2:15 | 294° | 282° | 286 | | | 3779+50 | |
| 2:30 | 299° | 288° | 281 | | | 3758+40 | |
| 2:45 | 282° | 290° | 280 | | | 3742+00 | Temp drop at Plant from 305° to 295° |
| 3:00 | 246° | 274° | 278 | | | 3734+40 | |
| 3:15 | 228° | 273° | 272 | | | 3723+25 | |
| 3:30 | 273° | 261° | 257 | | | 3715+20 | |
| 3:45 | 236° | 198° | 257 | | | 3708+90 | Increase of "clumps" were noted at roadway |
| 4:00 | 294° | 243° | 287 | | | 3696+50 | Temperature increased at Plant from 295° to 305° |
| 4:15 | 287° | 277° | 281 | | | 3677+40 | |
| 4:30 | 293° | 286° | 278 | | | 3666+00 | |
| 4:45 | 296° | 289° | 276 | | | 3652+30 | |
| 5:00 | 277° | 248° | 273 | | | 3635+40 | |
| 5:15 | 289° | 196° | 275 | | | 3621+10 | |
| 5:30 | 300° | 265° | 289 | | | 3611+80 | |
| 5:45 | 259° | 260° | 298 | | | 3592+50 | |
| 6:00 | 268° | 259° | 296 | | | 3577+00 | |
| 6:15 | N/A | 228° | 271 | 34°24'31.2640" | 112°04'116.1730" | 3576+45 | Last load with Advera |
| Note: | **Start and end points were located after GPS problem was resolved. No other coordinates were determined.** | | | | | | |

## Table D - 3. Field Temperature Data – Evotherm

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Warm Mix Additive Research Project** | | | | | | Project No.: | 19-2012-2146.04 |
| **Yavapai County** | | | | | | | |
| **Admixture: Evotherm** | | | | | | Placement Date: | 09/24/14 |
| **Location: Northbound Lane** | | | | | | | |
| | | | | | | | |
| | Mix Temperatures | | | GPS | | | |
| Time | Windrow | Hopper | Mat | North | West | Station | Notes: |
| 10:15 | 265° | 239° | 284 | 34°24'31.0223" | 112°04'14.3778" | 3576+90 | Plant discharge temperature 310° |
| 10:30 | 280° | 257° | 296 | 34°24'36.3381" | 112°04'12.6158" | 3582+55 | Start Point Evotherm Additive 9/24/14 |
| 10:45 | 310° | 285° | 289 | 34°24'46.9823" | 112°04'05.8198" | 3595+00 | |
| 11:00 | 287° | 291° | 301 | | | | |
| 11:15 | 305° | 301° | 296 | | | | |
| 11:30 | 306° | 259° | 301 | 34°25'09.3216" | 112°03'46.0452" | 3623+40 | |
| 11:45 | 290° | 283° | 280 | 34°25'15.9478" | 112°03'37.6296" | 3633+30 | |
| | | | | 34°25'16.5573" | 112°03'36.2680" | 3634+50 | Plant discharge temperature lowered to 300° |
| 12:00 | 297° | 232° | 281 | | | | |
| 12:15 | 286° | 277° | 272 | 34°25'17.0975" | 112°03'10.4800" | | Plant discharge temperature lowered to 290° |
| 12:30 | 265° | 246° | 273 | 34°25'17.8998" | 112°03'10.4563" | 3656+90 | |
| 12:45 | 275° | 204° | 281 | 34°25'17.6577" | 112°03'04.8129" | 3661+75 | |
| 1:00 | 289° | 275° | 258 | | | | |
| 1:15 | 275° | 263° | 278 | | | | |
| 1:30 | 277° | 275° | 279 | | | | |
| | | | | 34°25'33.9500" | 112°02'22.9502" | 3699+65 | Plant discharge temperature lowered to 280° |
| 1:45 | 269° | 259° | 242 | 34°25'42.3606" | 112°02'10.7636" | 3713+80 | |
| 2:00 | 275° | 271° | 248 | 34°26'04.3540" | 112°01'55.1035" | 3740+00 | |
| 2:15 | 283° | 269° | 274 | | | | |
| 2:30 | | 231° | 248 | 34°26'16.7504" | 112°01'52.0487" | 3752+75 | |
| | | | | 34°26'17.5788" | 112°01'52.0528" | 3753+70 | End Point Evotherm Additive 9/24/14 |
| | | | | | | | |
| Admixture: Evotherm | | | | | | Placement Date: | 09/25/14 |
| Location: Northbound Lane | | | | | | | |
| | | | | | | | |
| | | | | GPS | | | |
| Time | Windrow | | | North | West | Station | Notes: |
| 10:45 | 276° | | | 34°28'17.6118" | 112°01'22.0933" | 3880+00 | Plant discharge temperature lowered to 270° |
| 11:15 | 253° | | | 34°28'18.2782" | 112°01'15.2869" | 3898+20 | prior to arrival. |
| 11:30 | 250° | | | 34°28'48.2004" | 112°01'07.7481" | 3913+25 | End of Monitored Evotherm Additive Placement |