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An Investigation of Warm Mix Asphalt Design and Construction

Stacy G. Williams, Annette M. Porter

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by

Stacy G. Williams, Ph.D., P.E.
Director, CTTP
Research Associate Professor
Department of Civil Engineering
University of Arkansas

Annette M. Porter, M.S.
Department of Civil Engineering
University of Arkansas

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1. Introduction

Warm mix asphalt is a relatively new technology in which additives are used to enable asphalt mixtures to be produced and compacted at reduced temperatures. This reduction in temperature saves the producer money while lessening the impact on the environment by using less energy. In addition, fewer toxic emissions are emitted by warm mix than hot mix, and mixtures are more workable, creating the potential for increased pavement performance. However, many aspects of warm mix asphalt are not well understood at this time.

The availability of new warm mix processes has exploded over the past few years, and it is unclear how the use of these technologies will actually affect the performance of warm mix asphalt. With so many new products on the market, a standard method of evaluating various WMA processes must be created which will enable any additive to be evaluated for potential use in a warm mix asphalt project. In order for this new technology to be practical for implementation, a better understanding of how the warm mix additives affect the properties of the mixture is necessary.

2. Problem Statement

Warm Mix Asphalt (WMA) has been an important development in asphalt pavement technology. WMA is produced in a manner similar to traditional hot mix asphalt (HMA), but production temperatures can be reduced by as much as 100°F. Additives or processes are used to reduce the effective viscosity of the binder at a given temperature. Thus, the aggregate particles can be adequately coated and the workability of the mat can be improved at more comfortable handling temperatures. The reduction in mix temperature reduces the cost of production and may increase the life of the pavement. Current AHTD specifications do not include provisions for the use of WMA. Therefore, if WMA is found to be a viable technology for the production of asphalt pavements in Arkansas, provisions for the design, verification and construction of WMA will need to be incorporated into AHTD Standard Specifications to allow its use.

3. Background

Warm Mix Asphalt (WMA) is a new and exciting concept in transportation engineering; it is very similar to hot mix asphalt except that it incorporates additives and/or processes so that it can be produced at lower temperatures, allowing for an energy reduction between 20 and 75 percent (Dristjansdottir, et al, 2007). In addition to the reduction in energy usage, WMA produces fewer emissions and increases workability. Many researchers believe that warm mix asphalt pavements will experience an increased service life, a reduction in thermal segregation of the mat, a reduction in dust production, and a higher level of compaction (Chowdhury and Button, 2008).

WMA is made possible through the use of processes or additives which may include foaming products or processes, chemical agents, or organic wax products. These technologies work by reducing the effective viscosity of the binder, allowing the binder to coat the aggregate particles and the mixture to be placed and compacted at lower temperatures. More than 20 warm mix technologies exist at this time, and more are being developed, although the pace of development has recently declined. Some examples of categories and types of the most popular U.S. warm mix technologies are summarized in Table 1. Some of these technologies have been studied extensively and others have not.

Table 1: Warm Mix Asphalt Technologies

Process / Product Type	Product Name
Foaming Additives	Advera
	Aspha-Min
Foaming Processes	Astec Double Barrel Green
	Low-Energy Asphalt (LEA)
	WAM-Foam
	AquaBlack
Chemical Additives	Evotherm
	CECA Base Arkema
	Rediset WMX
	REVIX
Wax Additives	Sasobit / Sasol Wax
	Rediset (Akzonobel)

The idea of reducing asphalt production temperatures is not new. In 1956, foamed bitumen was produced using steam, and foamed asphalt technologies have been investigated for a number of uses since that time. Since that time, waxes were used as viscosity modifiers in Germany, and the primary concepts of modern warm mix technologies then developed in Europe (Zaumanis, 2010). In the mid-1990's, WMA solutions gained a great deal of European attention in response to the Kyoto Agreement, which actively encouraged European nations to commit to a significant reduction in greenhouse gasses and carbon footprint. It also included accounting requirements for CO_2 emissions. Thus, whenever two options were given at the same price, the more environmentally responsible option was required to be chosen. These regulations were the motivation for the development of much of the warm mix technology, and spurred the intensity of product development for reducing asphalt production temperatures. In 1995, Shell Global Solution in Petit Couronne, France, teamed with Kolo-Veidekke ASA in Oslo, Norway to develop WAM-Foam. Demonstration projects using WAM-Foam began as early as 1999 (Cervarich, 2003).

The development of organic additives for warm mix asphalt in Germany also began in the mid-1990's. Two types of organic additives were developed at that time: synthetic paraffin waxes and low-molecular-weight ester compounds. The goal of these additives was to produce low temperature mixes which had equivalent resistance to fatigue and deformation as well as comparable workability to that of hot mix. Aspha-min, a synthetic zeolite, was also developed in Germany by Eurovia Services GmbH. In Germany, some asphalt mixes were typically produced at 450 °F (mixtures known as mastic asphalt, or 'Gussasphalt'), and the Aspha-min product was able to reduce the temperature to a typical range of 266 – 293 °F. At least 8 test sections were constructed prior to 2003 and no difference in performance from hot mix was reported (Cervarich, 2003).

In 1997, the Bitumen Forum was formed in Germany to provide research on asphalt fume hazards and take measures toward controlling these hazards. The forum included representatives from a variety of institutions and organizations and its formation was encouraged by the Federal Ministry for Work and Social Services. This group has taken great interest in WMA due to its reduced fume emission. The Bitumen Forum promotes warm mix by providing information online. It lists a number of successful applications of warm mix in Germany. A container storage space in Hoechst industrial park near Frankfurt was paved with WMA in 1997. After nine years, it was still performing well in spite of extreme static loading. Also in 1997, WMA was successfully used to re-surface a roadway at the Gruenewald bridge to avoid damaging a temperature sensitive surface coating. The German Bitumen Forum continually collected and updated information concerning WMA in order to promote worker safety and environmental responsibility (German Bitumen Forum, 2006).

In 2003, an article was produced by the National Asphalt Pavement Association (NAPA) describing WMA as a new technology in Europe. At that time, there were three technologies: Aspha-min, WAM-Foam, and organic additives (Cervarich, 2003). The main concern with the use of WMA technology in the United States centered around its compatibility with mix designs, equipment, climatic conditions, and work practices in the U.S., because the methods of producing asphalt vary from place to place. In 2007, a group of asphalt experts from the U.S. conducted a tour of practices, known as the European Scan Tour. This group visited Belgium, France, Germany, and Norway in order to better understand and evaluate what had already been developed and tested in Europe. (D'Angelo et al, 2008).

Based on information gathered during the European Scan Tour, it was expected that WMA could be produced anywhere from 35 to 100 degrees lower than HMA without adverse effects. This would allow for longer haul distances without sacrificing workability, extend the paving season into cooler weather without losing density, increase compactability, and enable a higher percentage of reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) to be used in the mix. Burner fuel savings were estimated at 11 to 35 percent, and fuel savings predicted to approach 50 percent for processes that do not heat the aggregates above the boiling point of water. WMA met all aspects of sustainability: economic development, social development, and environmental protection. WMA also allowed for a 35 to 50 percent reduction in asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs). Data showed typical reductions in other toxic fumes as follows (D'Angelo et al., 2008):

- 40 percent reductions in CO_2 and SO_2
- 50 percent reduction in volatile organic compounds (VOCs)
- 10 to 30 percent reduction in CO
- 60 to 70 percent reduction in nitrous oxides (NO_x), and
- 20 to 25 percent reduction in dust

A summary of the information obtained by the European Scan Tour group is given in Table 2 (D'Angelo et al., 2008).

Table 2. Summary of European WMA Products from European Scan Tour (D'Angelo et. al, 2008)

WMA Process	Company	Additive	Production Temperature (at plant)	Use Reported in	Approx. Total Tonnage Produced as of 2008
Organic (Wax) Additives- Added to binder or mix					
Sasobit (Fischer-Tropsch wax)	Sasol	Yes, in Germany added on average at 2.5% by weight of binder; lower doses, 1.0-1.5%, used in U.S.	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266 to 338 °F), depending on binder stiffness	Germany and 20 other countries	>10 million tons worldwide
Asphaltan-B (Montan wax)	Romonta	Yes, in Germany added on average at 2.5% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	Germany	Unknown
Licomont BS 100 (additive)	Clariant	Yes, about 3% by weight of binder	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–38 °F), depending on binder stiffness	Germany	>322,500 square meters since 1994
3E LT or Ecoflex (proprietary)	Colas	Yes	Varies, 30–40 C° (54–72 F°) drop from HMA	France	Unknown
Foaming Processes					
Aspha-min (zeolite)	Eurovia and MHI	Yes, about 0.3% by total weight of mix	Varies, 20–30 C°Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	France, Germany, and U.S.	About 300,000 tons
ECOMAC (cold mix warmed before laying)	Screg	Yes (unknown type/quantity)	Placed at about 45 °C (113 °F)	France	Some trials
LEA, also EBE and EBT (foaming from portion of aggregate fraction)	LEACO, Fairco, and EIFFAGE Travaux Publics	Yes, 0.2-0.5% by weight of binder of a coating and adhesion agent	<100 °C (212 °F)	France, Spain, Italy, and U.S.	>100,000 tons
LEAB® (direct foam with binder additive)	BAM	Yes, added at 0.1% by weight of binder to stabilize foam, aid in coating, and promote adhesion	90 °C (194 °F)	Netherlands	Seven commercial projects

LT Asphalt (foamed asphalt with addition of hygroscopic filler to maintain workability)	Nynas	Yes, added 0.5-1.0% of a hygroscopic filler	90 °C (194 °F)	Netherlands and Italy	Unknown
Emerging U.S. Technologies					
WAM-Foam (soft binder coating followed by foamed hard binder)	Kolo Veidekke, Shell Bitumen (patent rights worldwide except U.S.), and BP (patent rights U.S.)	Not necessary; a surfactant may be added to aid in the foaming of certain binders and an antistripping agent may be added to the soft binder	110-120 °C (230-248 °F)	France and Norway, also Canada, Italy, Luxembourg, Netherlands, Sweden, Switzerland, and U.K.	>60,000 tons
Evotherm (hot aggregate coated with emulsion)	Mead-Westvaco	Yes	85-115 °C (185-239 °F)	France, Canada, China, South Africa, and U.S.	>17,000 tons
Double Barrel Green	Astec	Not necessary; an antistripping agent may be added similar to normal HMA	115-135 °C (240-275 °F)	U.S.	>4,000 tons
Advera (zeolite)	PQ Corporation	Yes, about 0.25% by total weight of mix	Varies, 20–30 C° (36–54 F°) drop from HMA. German guideline recommends 130–170 °C (266–338 °F), depending on binder stiffness	U.S.	>10,000 tons
	Mathy Construction	Dilute surfactant	110 °C (230 °F)	U.S.	trial sections only

Based on lab and short term field performance data observed during the tour, WMA mixes showed equal or superior performance to HMA. The main difference between asphalt in Europe and asphalt in the U.S. which may require special attention involves the aggregate. The tour group noticed that European aggregates tended to have lower water absorption (1 to 2 percent) than aggregates in the U.S. (up to 5 percent). This higher absorption found in the U.S. aggregate could lead to residual water in the aggregate throughout the mixing process of WMA, and this could negatively impact the performance of the pavement. (D'Angelo et al, 2008).

After completing the tour, the following recommendations were made for development of warm mix asphalt in the United States. First, an approval system for new WMA technologies should be developed based on performance testing, supplemented by field trials. Next, best practices for handling and storing aggregates should be established to minimize moisture content and to adjust the burner. Finally, field trials need to be performed with higher traffic in conjunction with controls for a period of at least three years (D'Angelo et al, 2008).

While warm mix asphalt promised great advances in environmental stewardship, it was important to carefully investigate the actual types and quantities of emissions produced by WMA mixes as compared to hot mix asphalt mixtures because not all WMA additives act similarly. In a study published in 2011

(Farshidi, et al., 2011), the University of California Pavement Research Center (UCPRC) developed a simplified testing procedure which could be used along with conventional methods for testing asphalt emissions. This new procedure also allows for a direct comparison of emissions from the pavement surfaces of different mixtures during construction. Emissions were captured in a portable chamber which measures emissions before compaction, immediately after compaction, and two hours after compaction. The exact compounds which compose the emissions are identified using gas chromatography mass spectrometry (GC-MS). In this study, reactive organic gases were measured and compared for three rubberized HMA controls, and seven rubberized WMA sections of a test track. Two mix designs were used and produced at two different asphalt plants; both mix designs met Caltrans specifications for a standard 12.5mm asphalt rubber, gap-graded Type-1 R-HMA. For the WMA mixtures, not adjustments were made to the mix design. The results of this study showed that the type of warm mix asphalt technology, the temperature, and the level of compaction all influenced the emission output. According to the study, not all warm mix asphalt mixtures had reduced emissions. In some cases, the warm mixes observed in this study had higher concentrations of emissions than the hot mixes. Therefore, the effect of warm mix additives on emissions of a mixture cannot be generalized, but must be considered individually for specific additives (Farshidi et al., 2011).

Description of Warm Mix Asphalt Additives / Processes

As mentioned previously, a number of warm mix additives have been developed, and new technologies are emerging rapidly. The main categories of additives are foaming additives, foaming processes, chemical additives, and wax additives. Examples of products and processes within each of these categories are described below.

<u>Advera®</u>

Advera® is produced by PQ Corporation and is a foaming technology composed of an aluminosilicate or hydrated zeolite powder. Zeolites contain hollow spaces which may hold cations such as sodium or calcium or cation groups such as water molecules. Zeolites can gain or lose water without damaging their structures. By releasing water, they expand the volume of the binder which causes a foaming effect, increasing workability and aggregate coating at lower temperatures.

Advera functions by releasing moisture over time. During compaction, the steam is compressed out of the mix and any remaining moisture is reabsorbed by the Advera and bound in place where it acts like mineral filler. The manufacturer claims that Advera may be added to existing HMA mix designs without altering PG grade, and the paving temperature may be reduced by 50-70 °F. The use of Advera is expected to reduce emissions up to 60 percent and may be added at rates of up to 0.25 percent by weight (PQ Corporation, 2009).

<u>Aspha-Min®</u>

Aspha-Min® zeolite is distributed by Eurovia Services GmbH, a subsidiary of the VINCI Group. Eurovia recommends that Aspha-Min be added at a rate of 0.3 percent by mass of mix. This should allow for a 54 °F reduction, and should work with any type of binder, recycled asphalt, and any aggregate used by the hot mix industry. No changes to mix designs are need when using Aspha-Min because it is a zeolite (Hurley and Prowell, 2005A).

Low Energy Asphalt

McConnaughay is the producer of the LEA method, which requires only the coarse aggregate to be heated to approximately 150 degrees C. A coating and adhesion additive is added to the binder in the asphalt supply line at a rate of 0.5% by weight of binder. The modified binder is then added to the hot, coarse aggregate. Once the coarse aggregate is coated, the fine aggregate is added in a wet and ambient condition so that the water will evaporate and cause foaming in the asphalt at a mixing temperature of 90 to 100 degrees C (194 to 212 degrees F). The fine aggregate has a moisture content of 3 to 4%. This process requires significant plant modifications; a volumetric pump and feed line are necessary for adding the coating and adhesion additive to the binder. Another cold feed bin is required to go into the RAP collar to feed the fine aggregate into the plant (Middleton and Forfylow, 2009, Perkins, 2009).

Double Barrel Green®

Double Barrel Green® system is distributed by Astec Industries, Inc. This product uses a special apparatus which injects microscopic water bubbles at a rate of one pound per ton of mix into the binder in order to foam the binder to approximately 18 times its original volume. No chemicals are used in this process, and the manufacturer claims that the foaming process allows a drop of about 50 °F during production. The apparatus may be used with an Astec Double Barrel® drum mixer/dryer or may be added as a retrofit to existing equipment (Astec Industries, Inc., 2009B, Middleton and Forfylow, 2009).

WAM-Foam

WAM-Foam is distributed by the Shell Bitumen Company. Foaming processes such as WAM-Foam work by injecting steam into binder in order to reduce its viscosity. When water evaporates, it expands by a factor of 1,673. The WAM-Foam process has two binder components: a soft and a hard foamed binder. These binder components are added at certain stages of production to enable a reduction in mixing temperature. Because of its use of two binder components, WAM-Foam requires asphalt binder addition in two stages. The soft binder is mixed with the aggregate at 100 to 120 °C (212 to 248 °F); then, the hard asphalt binder and water are foamed into the mix at a rate of 2 to 5 percent by weight of binder. This process requires the addition of a binder injection line and a foaming unit for the hard binder (Middleton and Forfylow, 2009).

AQUABlack™

AQUABlack™ is a foaming process by Maxam Equipment, Inc. This product utilized a "Microbubble™" foaming technology that injects bubbles at 1000 psi into the binder so that the bubbles will stay in the mix until it is compacted. The AQUABlack™ system comes pre-assembled for quick and easy retrofitting. Once installed, the operator sets maximum tons on a control panel, and the system calculates and sets the amount of water to inject into the binder. Due to the high pressure injection, the water-to-liquid-asphalt ratio during foaming is lower than that of other foaming processes (Maxam Equipment Inc., 2010).

<u>Evotherm®</u>

Evotherm® is a product of MeadWestvaco Corporation and is available in three forms: Evotherm ET (Emulsion Technology), Evotherm DAT (Dispersed Asphalt Technology), and Evotherm 3G (Third Generation). Evotherm ET is a water-based emulsion having a high asphalt content that allows for a temperature reduction of greater than 100 °F. Evotherm DAT is a concentrated solution which is injected into the binder at the mix plant and allows a temperature reduction of 85-100 °F. Evotherm 3G is the latest Evotherm® technology; it is a water-free foam which is added to the binder at the mix plant or at the asphalt terminal. The producers claim that the use of Evotherm 3G can allow temperature reductions ranging from 60-85 °F. In addition, emissions may be reduced as follows: 46 percent reduction in CO_2, 63 percent reduction in CO, 30 percent reduction in VOC, 34 percent reduction in PM, 58 percent reduction in NO_x, and 81 percent reduction in SO_x (MWV Evotherm, 2009).

<u>Sasobit®</u>

Sasobit® is a wax additive produced by Sasol Wax, made from natural gas using the Fisher Tropsch polymerization process. Its melting point is between 185 and 239 °F. It comes in 20 kg bags or 600 kg super sacks in the following forms: prill (5 mm diameter), small prill (1 mm diameter), and flaked (3 mm chips). Sasobit can be added to the binder and/or the mix. If added to the mix, the Sasobit should be blown into the asphalt stream before the asphalt reaches the aggregate. This can be accomplished using a Sasobit injection machine available from Hi-Tech Asphalt Solutions. Sasobit can also be added directly to the drum or molten and added in-line with the binder. When mixing Sasobit with binder, a normal paddle mixer can be used; a high shear mixer is not necessary. The Sasobit binder will remain homogenized for storage for several weeks. The recommended dosage is 1.5 percent Sasobit by weight of binder. If RAP is used, the percent of binder in the RAP should be considered in the formula (Valley, 2007).

The manufacturer recommends producing warm mix asphalt starting at 50 °F below the normal control mix temperature; the dropping another 10 to 25 °F depending on the mix and comfort level of the plant operator. The target bag house temperature should be at least 200 °F, depending on air flow and percent water. Lower temperatures might cause clogging or water vapor build up. This makes minimum plant operating temperatures between 250 and 270 °F (Valley, 2007).

When Sasobit is added at 1.5 to 2 percent, it affects the binder grading by increasing the upper end 4 to 6 degrees and lowering the lower end 3 to 9 degrees, effectively increasing overall binder performance. The change in the lower end is offset by the lack of oxidation due to the lower production temperatures. Another advantage of Sasobit is that it allows as much as 35 to 45 percent RAP in the mixture while still achieving density at lower paving temperatures (Valley, 2007).

Associated Costs

One consideration when selecting additives is the life-cycle cost. Of the additives and processes currently available, WAM-foam is among the cheapest per ton of mix when initial costs are not considered (Button, et al, 2007). However, its initial costs are high because it requires plan modifications costing $50,000 to $70,000. This high initial investment cost is true of other foaming processes such as LEA and Double Barrel Green as well (Middleton and Forfylow, 2009). Double Barrel Green requires no material costs after the initial plan modification of about $75,000 (Button et al, 2007). Evotherm, Sasobit, and Aspha-Min have the lowest initial investment costs, but they have a higher mix production cost due to the recurring cost of the additives (Middleton and Forfylow, 2009). Sasobit is cheaper per ton than Aspha-Min and Evotherm (Button et al, 2007). Table 3 breaks down the costs of several common additives.

Table 3. Summary of Costs Associated with WMA Technologies (Middleton and Forfylow, 2009)

Economic Component	WMA Technology					
	Evotherm	Sasobit	Aspha-min, Advera	Low Energy Asphalt (LEA)	WAM Foam	Double Barrel Green
Equipment modification or installation costs	$1,000-$5,000	$5,000-$40,000	$5,000-$40,000	$75,000-$100,000	$60,000-$85,000	$100,000-$120,000
Royalties	None	None	None	N/A	$15,000 first year/$5,000 per plant/$0.35/ft	None
Cost of material	$35-$50 premium on binder	$1.75/kg	$1.35/kg	None	$75 premium on soft binder	None
Recommended additive dosage rate	30% water/ 70% AC	1.5%-3% by weight of binder	0.3% by weight of mix	0.5% coating additive by weight of binder	3% weight of binder	2% water to binder
Approximate increased cost of mix per ton	$3.50-$4.00	$2.00-$3.00	$3.60-$4.00	$0.50-$1.00 (depending on use of coating additive)	$0.27-$0.35 royalty	None

An additional source has cited costs of typical additives and processes that are somewhat lower (TRB Webinar, 2010). The additional cost per ton of mix is now $1.25 to $2.00 for Advera, $2.25 to $3.00 for Sasobit, and $2.00 to $2.75 for Evotherm 3G. It is anticipated that as warm mix technologies continue to gain popularity and become more established, costs may continue to decrease. Foaming processes are typically not associated with a price per ton since those processes involve a one-time plant modification cost.

Mechanistic-Empirical Design Guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is a great development for both designing and modeling pavements. This guide requires a much more extensive list of inputs than previous design guides. While this program is the most thorough guide available, it does not directly address WMA. To further complicate the task of modeling WMA using the MEPDG, the effects of warm mix additives on mixture properties, such as air voids and dynamic modulus, are uncertain. It is important to understand how this design guide operates because it is already being implemented throughout the United States and will eventually be the primary pavement design method. Hopefully, as more research is conducted to understand how warm mix additives affect the properties of a mixture, warm mix asphalt pavements may be modeled using the MEPDG without problems or concerns of inaccuracy.

The inputs of the MEPDG are divided into traffic, climate, and material properties. Within the material properties section of the inputs, there are three sub-sections: Asphalt Mix, Asphalt Binder, and Asphalt General. The Asphalt Mix sub-section requires information pertaining to gradation. The Asphalt Binder sub-section allows the user to select a binder grade and a grading method (Superpave binder grading, conventional viscosity grading, or conventional penetration grading). The Asphalt General sub-section includes gravimetric properties of the mix design, volumetric properties of the structure as built, Poisson's Ratio, and thermal properties. The gravimetric properties include reference temperature, binder content by weight, optimum binder content, and the design air voids used to select the optimum binder content. The volumetric properties include effective binder content, air voids, and total unit weight. The thermal properties include thermal conductivity and heat capacity.

Of all of the material inputs required, one of the most important properties is the dynamic modulus (E*). The dynamic modulus is the ratio of the maximum peak to peak stress over the axial strain during sinusoidal loading. E* describes material characteristics and incorporates the effects of time and temperature on material response and is used in material response models to predict stresses, strains, and deflections. Because the binder used in asphalt mixtures is viscoelastic, the dynamic modulus is a very complex property. A number of factors affect the dynamic modulus of binder and asphalt mixtures, including duration and rate of loading, mix properties, and more. The type of binder and the level of aging affects the dynamic modulus value such that as stiffness increases, E* increases. The aggregate type and gradation are also important factors; will-graded mixes have higher dynamic modulus values, and as NMAS increases, E* increases (Tran and Hall, 2005). Mallela and Glover agree that the dynamic modulus is sensitive to NMAS, but add that it is not sensitive to phase angle (Mallela and Glover, 2009). Gravimetric and volumetric properties affect the dynamic modulus as well, in that percent binder and percent air voids are inversely related to the value of E* (Tran and Hall, 2005).

A number of devices may be used to determine E*, including the Rotational Viscometer, Dynamic Shear Rheometer, Bending Beam Rheometer, and the Direct Tension Tester. In 1972, a standard test method was created (ASTM D 3497-79). This method was later refined under NCHRP Project 9-19, and AASHTO 62-07 became the standard method for determining dynamic modulus of hot mix asphalt mixtures. In this method, a sinusoidal axial compressive stress is applied at a constant temperature and constant frequency. The applied stress and recoverable axial strain are recorded. This procedure is repeated for a range of temperatures and frequencies. The typical temperatures at which the test is performed are 14, 40, 70, 100, and 130 °F. The frequencies used are 25, 5, 1, 0.5, and 0.1 Hz (Tran and Hall, 2005). In the past few years, this standard has been further modified, with the Asphalt Mixture Performance Tester (AMPT) becoming the newest device for performing dynamic modulus testing. This device was developed under National Cooperative Highway Research Program (NCHRP) projects 9-19 and 9-29, and the associated procedure for using this device to determine dynamic modulus was introduced as Provisional AASHTO method TP-79.

For Level 1 designs, the MEPDG requires the most detailed inputs, and recommends that HMA dynamic modulus testing in the laboratory follow the guidelines described in the NCHRP 1-28A report. The MEPDG requires values of dynamic modulus for three different testing temperatures at three corresponding loading frequencies. Level 1 data also requires the asphalt binder complex shear modulus and phase angle tests (AASHTO T 315) which are used to develop the HMA E* master curve (Mallela and Glover, 2009). Levels 2 designs provide for a less detailed knowledge of input values, and require HMA gradation, air voids, volumetric binder content, and binder type because these are the inputs to prediction equations for dynamic modulus. Level 3 requires only HMA aggregate gradation, binder type, air voids, and total unit weight in order to predict E*, and estimates of how this value varies with temperature are generated.

4. Literature Review

Warm Mix Asphalt additives and processes are not only used to achieve temperature reductions, but can also be used as a compaction aid. Because mixtures containing these additives have a reduced effective viscosity and a temperature closer to ambient temperatures, the mixture will compact more easily and will remain workable for longer periods of time. This is especially useful when asphalt mix must be hauled long distances or when asphalt is being placed during the end of the paving season when the weather is cold. These additives may make it possible to achieve desired pavement densities under difficult conditions, thus enabling the contractor to meet quality control specifications.

Some experts believe that using a warm mix additive requires no change to the mix design or to the mixing process other than adding the additive and reducing the temperature. However, other research has indicated significant differences in design and performance when warm mix technologies are incorporated. Still others question whether the reduction in temperature or the presence of the additive will introduce problems which require some change in procedure. Thus, further research is needed in order to determine how warm mix additives affect hot mix asphalt designs and how the design and production of warm mix may need to be altered.

The additives and the reduction in temperature experienced during production of warm mix asphalt may significantly affect the performance of the pavement. The biggest concerns for performance are increased susceptibility to rutting or moisture damage. Other concerns exist relating to the actual production of WMA. Many question whether the aggregate gets heated enough to eliminate all of the moisture when producing warm mix asphalt, and whether this moisture would negatively impact the performance of the asphalt. Another concern is related to the binder properties. Because warm mix asphalt is produced and paved at lower temperatures, the binder ages less, which could result in lower levels of oxidation and binder hardening/cracking. Thus, many researchers have supposed that the initial reduction in binder aging will increase the service life (Chowdhury and Button, 2008). However, recent studies have shown that roads paved with warm mix asphalt experience more rapid binder aging after paving and may “catch up” to the level of aging of binder in comparable hot mix asphalt pavements. The comprehensive effects of binder aging in warm mix asphalt are unknown at this time. Many studies are under way both in the lab and in the field in order to better understand the differences between hot mix asphalt and warm mix asphalt and whether any issues with warm mix asphalt need to be addressed.

A number of opinions exist on the proper procedures for using warm mix asphalt additives in order to achieve optimum performance. The manufacturer of each additive typically provides unique instructions for additive usage. Some instructions, such as those for Evotherm 3G, are extremely thorough, specifying even the brand of mixer, length of time, and depth of vortex required for proper blending of the additive into the asphalt binder. Other instructions, such as those for Advera, are vague and provide no details about proper technique. Regardless of the level of detail provided by the manufacturer, many questions remain. One significant concern is how changes in the mixing and compacting temperatures will affect the performance of the pavement.

Temperature Reductions

One of the most intriguing features of WMA is its capacity to generate significant reductions in temperature. However, significant variations have been reported regarding the most appropriate and achievable reductions. When comparing WAM-Foam, Aspha-Min, Sasobit, and Evotherm, one researcher found that WAM-Foam allows for the greatest temperature reduction followed by Evotherm (Button et al., 2007). Additives which allow greater temperature reductions will be more effective in achieving lower energy consumption and production costs; however, further research will be necessary to determine if a limit on temperature reduction is necessary to prevent problems such as thermal cracking and whether the manufacturers' recommended temperature reductions truly provide optimum performance. Some studies have found that optimum performance cannot be achieved in conjunction with temperature reductions as large as those recommended by the additive manufacturers, though it is noted that many of the manufacturer recommendations are based on optimal conditions. For instance, the manufacturer of the Double Barrel Green system recommends a temperature reduction of 50 °C. However, a study of a contractor's experience in Canada found that a temperature reduction of only 20 to 35 °C is advisable (Middleton and Forfylow, 2009).

In another study, WMA mixtures containing Aspha-Min were examined at temperatures of 300 °F, 265 °F, 230 °F, and 190 °F. Although the manufacturer's instructions recommend a temperature reduction of 54 °F, the product was shown to improve compaction at temperatures as low as 190 °F, however the rutting potential increased as the production temperature decreased (Hurley and Prowell, 2005A). A field section was then placed using a temperature reduction of 35 °F from HMA temperatures, and no difference in field performance was noted between the HMA and WMA sections.

The manufacturer of Evotherm recommends reducing the temperature by 60 to 85 °F, although it is recommended that field compaction should dictate the compaction temperature for each specific situation. In a study of Evotherm, compaction was improved at temperatures as low as 190 °F, while also increasing the resilient modulus of the mixture. As temperature reductions increased, rutting susceptibility also increased, probably due to the decreased aging of the binder. However, rutting susceptibility was not as sensitive to temperature changes as other additives (Hurley and Prowell, 2006).

It has also been recommended that the binder grade may be increased for WMA mixes if greater temperature reductions are desired. This "bump" may be successful in offsetting the potential increase in rutting susceptibility (Perkins, 2009). It is clear that further research on advisable temperature reductions for optimum constructability and performance is needed for all additives which are to be used in actual construction.

Performance

To many, WMA appears similar enough to HMA that many producers and research report no need for changes to mix designs or the mixing process (other than the addition of the WMA technique and temperature reduction). However, research must verify this conclusion by determining if and how warm mix additives affect hot mix asphalt designs and how the design and production of WMA may need to be altered so that adequate mixture performance can be ensured. Many studies are under way both in the lab and in the field in order to better understand the differences between hot mix asphalt and warm mix asphalt and whether any issues with warm mix asphalt need to be addressed.

Laboratory Performance

In addition to the questions of susceptibility to moisture damage and sensitivity to changes in production temperature, a number of other questions have been raised concerning WMA over the past years. In order to answer these questions, extensive research has been conducted, and a number of testing methods and procedures have become common for many WMA research projects.

During the initial European Scan tour, many laboratory tests were underway. In France, laboratory tests commonly included gyratory tests for workability and estimation of field compaction, wheel-tracking tests, Duirez tests for moisture resistance, and fatigue tests. According to these studies, the use of warm mix additives improved the workability of asphalt. The rutting resistance and fatigue of warm mix pavements did not display any significant difference from that of HMA (D'Angelo, et al. 2008).

Most laboratory tests for warm mix asphalt conducted in the United States have used a limestone aggregate and a granite aggregate and one or two types of binder (most commonly PG 64-22). Warm mix experiments have typically included most or all of the following tests on the asphalt samples: volumetric properties, compactability, resilient modulus, rutting resistance, moisture sensitivity, dust proportion, creep, and fatigue. Research conducted by the National Center for Asphalt Technology (NCAT) used four mixing temperatures ranging from 190 to 300 °F, which encompasses the typical range used by other researchers (Hurley and Prowell, 2006).

NCAT Studies

In the United States, many of the early WMA studies were conducted to evaluate specific WMA technologies. In a 2005 study conducted for the National Center for Asphalt Technology (NCAT), the effect of Sasobit on both granite and limestone mixes was examined using binder grades PG 64-22 and PG58-28 (Hurley and Prowell, 2005B). From these two binder grades, three different versions of Sasobit® modified binders were developed. The first type was produced by adding 2.5 percent Sasobit® to the PG 58-28 binder to produce a PG 64-22 binder. A second type was produced by adding 4 percent Sasoflex® to the PG 58-28, resulting in a PG 70-22. Sasoflex® is Sasobit with an added polymer and a proprietary cross-linking agent called Sasolink® (Glaregroup.com, 2011). The third binder type was produced from the addition of 4 percent Sasoflex® to the base PG 64-22, resulting in a PG 76-22 binder. After conducting volumetric tests, densification tests, resilient modulus tests, rutting tests, and moisture sensitivity tests, it was determined that Sasobit lowered the air voids in the mix and improved compactability at temperatures as low as 190 °F. Sasoflex improved compactability at temperatures as low as 230 °F. Sasobit did not affect resilient modulus but caused lower indirect tensile strengths. For samples containing Sasobit, the rutting potential increased as the compaction temperature decreased, but these samples showed less sensitivity than the hot mix control specimens as temperatures decreased. According to this report, if moisture sensitivity is too high, AKZO Nobel Magnabond can be used as an effective anti-stripping agent.

In another NCAT study, warm mix asphalt mixtures containing Aspha-min, two aggregates (granite and limestone) and two asphalt binders (PG 64-22 and 58-28) were examined (Hurley and Prowell, 2005). The mix design replicated a 12.5 mm coarse-graded crushed granite mix produced by Hubbard Construction in Orlando, Florida. The same gradation was used for the limestone mix. The design number of gyrations, $N_{design,}$ was set at 125 gyrations. Once the mix designs were verified at 300 °F, they were re-evaluated at 265 °F, 230 °F, and 190 °F. For reference, the manufacturer of Aspha-min recommends a temperature reduction of 54 °F from the normal hot mix temperature.

Ten samples per mix were made for short-term and long-term mix aging per AASHTO 312 using PG 64-22 binder. Indirect tensile strength was measured. To simulate actual mixing process of a typical drum plant, a bucket mixer was used to make the Tensile Strength Ratio test samples. Before the aggregate was combined with binder, 3 percent water was added to the absorption value of each aggregate before heating in order to evaluate moisture susceptibility. This process simulated conditions that could occur if the moisture in the zeolite did not completely evaporate during mixing.

Based on the results of this study, Aspha-min was determined to improve the compactability of mixes at temperatures as low as 190 °F, and a statistical analysis of the data showed an average reduction in air voids of 0.65 percent. Samples containing Aspha-min did not have increased rutting potential when compared to hot mix samples and paved at the same temperatures; however, samples containing Aspha-min did have increased rutting potential as the mixing and compacting temperatures decreased, possibly because of the decreased aging of the binder. Aspha-min did not significantly affect the resilient modulus, but did increase the potential for moisture damage as shown by tensile strength ratio and Hamburg tests. The use of hydrated lime was suggested as a solution for this problem. In addition to the laboratory exercises performed in this study, a field test was conducted where a mix containing Aspha-min was paved 35 °F lower than a control mix without Aspha-min; a year later, the mix containing Aspha-min had no more moisture damage than the control.

Relative to the effects of Aspha-min on binder grade, it was recommended that if the mixing temperature is greater than 275 °F, the same binder grade may be used; otherwise, a one-grade increase or the use of hydrated lime may counteract tendencies toward increased rutting susceptibility. It was suggested that tensile strength ratio tests be conducted at field production temperatures, and if the test results are not as desired, hydrated lime may be added to the mix to combat stripping and increase the tensile strength ratio. It was also stated that more research was needed to evaluate field performance, selection of optimum binder content, and binder grade selection.

In 2006, an additional study was conducted by NCAT to evaluate the performance of Evotherm in a granite mix and in a limestone mix (Hurley and Prowell, 2006). Binder grades PG 64-22 and 76-22 were used for this experiment. All samples were compacted to 125 design gyrations and the temperature was varied, compacting at 300 °F, 265 °F, 230 °F, and 190 °F. Volumetric testing was performed, as well as resilient modulus, APA rutting, moisture sensitivity, and strength change over time.

This study showed that the use of Evotherm caused a reduction in air voids, and the optimum binder content may be reduced (although this would negate the increase in compaction). The reduction in air voids was achieved at temperature reductions as high as 190 °F. Also, at a given temperature and binder content, Evotherm increased the resilient modulus of the mix. Evotherm generated a decrease in rutting potential at the same temperature, and an increase in rutting potential at decreased temperatures when compared with the hot mix asphalt controls. This is probably due to decreased aging of the binder. Although, in this experiment, mixes with Evotherm showed less sensitivity to rutting when experiencing a temperature decrease than did the control mixes. Indirect tensile strengths for Evotherm mixes were lower in some cases, but APA and Hamburg tests yielded results indicating good rutting resistance for these mixes. The original Evotherm formula showed stripping problems with the limestone aggregate, but the new formula (Evotherm 3G) increased tensile strength and eliminated visual stripping for the limestone aggregate.

The manufacturer of Evotherm recommends reducing the temperature 60-85 °F. Based on the results of this 2006 study, it was recommended that the following minimum temperatures be maintained when using Evotherm: 265 °F for mixing, and 230 °F for compacting. If lower temperatures are desired, the binder grade should be increased by one grade. Field compaction should ultimately dictate the minimum compaction temperature in a specific situation. Also, it was recommended that moisture sensitivity testing be performed at the field production temperature.

Additional Laboratory Studies

A number of other studies have been performed to evaluate the performance of various warm mix technologies, and to provide insight into the potential long-term performance of WMA based on laboratory performance measures.

In a Virginia study, two trial sections containing Sasobit were evaluated based on compactibility, volumetric properties, moisture susceptibility, rutting resistance, and fatigue performance (Diefenderfer and Hearon, 2008). The mixing and compacting temperatures as well as the aging periods were also altered and compared. The long-term performance of the test sections was modeled using the Mechanistic-Empirical Pavement Design Guide (MEPDG).

The first mixture was a Superpave 9.5 mm NMAS surface mix with PG 64-22. Morelife 3300 antistrip was used at a rate of 0.5 percent by weight of binder. The aggregate was composed of granite and siltstone. The only changes for the WMA were the addition of Sasobit and the reduction of mixing and compacting temperatures. Sasobit was added at 1.5 percent by weight of binder. The binder content did not change. The second mixture was a Superpave 12.5 mm MNAS surface mix using GP 64-22 and hydrated lime as an antistripping agent. The aggregate was limestone and gravel. The only changes were the addition of 1.5 percent Sasobit and the reduction of mixing and compacting temperatures.

For the first mix type, specimens were produced at the plant and in the laboratory. The WMA produced in the laboratory was compacted at temperatures of 230 °F, 265 °F, and 300 °F. Samples were also produced in the laboratory containing entrapped moisture. The second mix type was produced in the plant only.

Test results showed no significant differences in the volumetric properties of HMA and WMA. The in-place compaction of all mixes was also similar. The results of moisture damage testing by AASHTO T 283 did not show any trends toward moisture susceptibility, but there seemed to be a positive effect from the aging of the WMA. The WMA produced with entrapped moisture did show increased moisture damage when the aggregates were not fully dried during mixing; this was mitigated by oven-drying the aggregates before testing. The Hamburg wheel-track test showed similar performance from HMA and WMA.

In 2008, a study was conducted which investigated the long term effects of Sasobit and Aspha-min on binder and mix properties (Ghandi, 2008). In this study, indirect tensile strength (ITS), resilient modulus, and rut depth by the Asphalt Pavement Analyzer (APA) of HMA mixes were compared with WMA mixes. Two aggregates, two binders, and two additives (control, Aspha-min, and Sasobit) were used. The following characteristics were examined:

- the effects of temperature on viscosity as measured in rotational viscometer
- the effects of time on viscosity by measuring after addition of additives at 30, 60, and 90 minutes
- the effects of additives on complex modulus (G*) and phase angle of binders
- the effects of additives on creep response, creep recovery, flow, frequency sweep, and temperature sweep of binder as evaluated by running 96 dynamic shear rheometer tests
- the effects of additives on low temperature stiffness and m-value of binders evaulated by running 24 bending beam rheometer tests
- the effects of aging of binders with additives by conducting rolling thin film oven test at two different temperatures after simulating long term aging in a pressure aging vessel
- the effects of aging as measured by putting samples in oven for 120 hrs at 185 °F
- indirect tensile strength
- resilient modulus
- APA rut depths

This study showed that Sasobit was capable of reducing the viscosity of binders at 135 - 120 °C. Sasobit also improved mid-temperature creep response, creep recovery, complex modulus, and rutting resistance. When aged in the laboratory, samples containing Sasobit had similar rutting depth, TSR, and resilient modulus values as the aged hot mix asphalt control samples. Sasobit increased the viscosity of binders at 140 °F, increased the complex modulus and phase angle, increased stiffness at 140 °F, and increased stiffness and resistance to deformation at mid-range temperatures. After aging, binders containing Sasobit show decreased viscosity. When using Fourier Transform Infrared Spectroscopy (FTIR) and Gel Permeation Chromatography (GPC), binders containing Sasobit did not age more than the control binders. Samples containing Sasobit did display an increased tendency toward low temperature cracking with age.

Aspha-min did not affect viscosity in the same range as Sasobit (153 – 120 °C). Like Sasobit, Aspha-min improved mid-temperature creep response, creep recovery, and complex modulus. Aspha-min, however, reduced the dynamic modulus value. When aged, samples containing Aspha-min show similar rutting depth and TSR values as their controls. Aspha-min did not alter the viscosity of the binder at 275 °F or 248 °F but after 60-990 minutes, the viscosity was much higher than the base binder due to the addition of fine solids. After rolling thin film oven (RTFO) aging, binders containing Aspha-min had much higher viscosities than unmodified binders. Aspha-min did not influence fatigue resistance but did have higher creep stiffness values.

In another study on Aspha-min, the performance of WMA containing Aspha-min was evaluated by means of the MEPDG (Goh, et al, 2007). A mixture with a NMAS of 12.5 mm and PG 64-28 was used. Three mixes were tested: a control, a warm mix with 0.3 percent Aspha-min, and a warm mix with 0.5 percent Aspha-min. The control was compacted at 288F while the other two mixes were compacted at 212 °F and 248 °F. The dynamic modulus (E*) test was conducted and the results were entered into the MEPDG. The results show that Aspha-min does not affect the dynamic modulus; furthermore, the Aspha-min warm mixes actually showed decreased rutting potential.

According to the NCAT study (Hurley and Prowell 2005B), Sasobit lowers the air voids in the mix and improves compactability at temperatures as low as 190 °F, and Sasoflex improves compactability at temperatures as low as 230 °F. However, the 2008 study by Diefenderfer and Hearon found that Sasobit caused no significant differences in the volumetric properties of a mixture when compared with hot mix. In addition, the in-place compaction of warm mixes containing Sasobit was the same as hot mix.

Another discrepancy in these three studies exists concerning the effect of Sasobit on strength and rutting potential. According to the 2005 NCAT study, Sasobit casued lower indirect tensile strengths, and the rutting potential increased as the compaction temperature decreased (Hurley and Prowell, 2005). However, the 2008 study by Gandhi stated that when aged in the laboratory, samples containing Sasobit have similar rutting depth and TSR values as the aged hot mix asphalt control samples. The Virginia study agreed, stating that the Hamburg wheel-tracking test showed similar performance for the hot and warm mixes (Diefenderfer and Hearon, 2008). These studies do agree that samples containing Sasobit have similar resilient modulus values as HMA (Hurley and Prowell, 2005, Gandhi, 2008).

According to the study by Diefenderfer and Hearon, the results of TSR testing did not show any trends for moisture susceptibility but displayed a positive effect from the aging of the WMA. The WMA produced with entrapped moisture did show increased moisture damage when the aggregates were not fully dried during mixing; this was mitigated by oven-drying the aggregates before testing. The 2005 NCAT report stated that if moisture sensitivity is too high, AKZO Nobel Magnabond is an effective anti-stripping agent (Hurley and Prowell, 2005).

The 2008 study showed that Sasobit reduced the viscosity of binders at 135 to 120 °C. Sasobit also improved mid-temperature creep response, creep recovery, complex modulus, and rutting resistance. Sasobit increased the viscosity of binders at 140 °F, increased the complex modulus and phase angle, increased stiffness at 140 °F, and increased stiffness and resistance to deformation at mid-range temperatures. After aging, binders containing Sasobit showed decreased viscosity. Based on information gathered through Fourier transform infrared spectroscopy (FTIR) and Gel Permeation Chromatography (GPC), binders containing Sasobit did not age more than other binders. Also, samples containing Sasobit did show an increased tendency toward low temperature cracking with age (Gandhi, 2008).

Additional concerns have been raised regarding the true mechanism by which WMA is able to affect compaction. Although the increased compactability is often discussed in terms of viscosity, a better term may be workability. Recent work has investigated a new test method for quantifying the workability/compactability of various warm mix additives which were preblended into binder at various percentages (Bennert, et al, 2010). Conventional tests and compaction data used for HMA are insensitive to the effect of additives and dosage rates and to compactability; therefore, a new test, called the Lubricity Test, was developed. The Lubricity Test is sensitive to dosage rate and additive and ranks favorably with other mixture tests. The Lubricity Test is based on Thin-Film Rheology. Dynamic shear rheometers measure asphalt properties at a film thickness of 1000 microns, but this is much thicker than the film coating aggregates within an asphalt mixture. Therefore, this test studies film thicknesses as small as 25 microns. For this study, PG 76-22 was blended with three different warm mix asphalt additives (Evotherm 3G, Rediset, and Sasobit) at varying dosages. These additives were blended at 385F for one hour on a low shear mixer. Binder workability was measured using the following tests: rotational viscosity (AASHTO T316), Casola Method (NCHRP Project 9-39), and Lubricity Test (the new method).

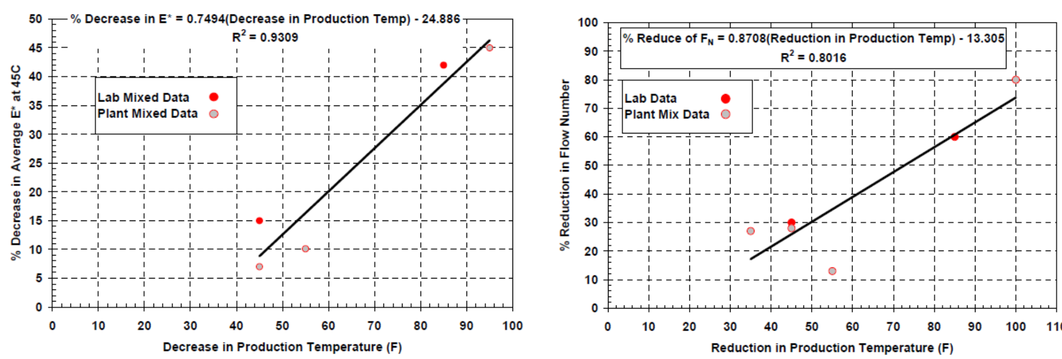
Based on the results of this study, Evotherm 3G and Rediset caused a slight decrease in the high temperature PG grade, while Sasobit caused a slight increase in the high temperature grade. The non-recoverable creep compliance and percent recovery also changed somewhat. At temperatures above 250 °F, all of the binder/mixture behavior was similar among the different samples, but below 220 °F, some of the mixtures containing additives showed less workability/compactability. When considering the addition of an additive, one should investigate the additive's ability to maintain its effectiveness at lower temperatures. These tests showed that 2.0 percent Rediset and 0.6 percent Evotherm 3G performed the best, and 1.5 percent Sasobit worked well.

In a 2011 study (Bennert, et al., 2011) the impact of production temperature on the performance of WMA mixtures was evaluated. The measured responses focused on rutting potential and fatigue cracking due to reduced aging of the binder and stripping potential due to aggregates retaining moisture. For this study, three WMA additives (Evotherm 3G, Rediset, and Sasobit) were added to PG 76-22 binder at varying dosage rates, mixed in the laboratory at various temperatures, and the following tests were conducted: Dynamic Modulus, Repeated Load (Flow Number), and dry Hamburg Wheel

Tracking. Then various mixtures, including two aggregate types, were treated with moisture and tested using the Hamburg Wheel Tracking and Tensile Strength Ratio tests.

The results of this study showed that the stiffness of a WMA mixture was reduced at high temperatures, but showed minimal change at lower temperatures. However, the amount of change in stiffness varied depending on the warm mix additive used. Therefore, the additive used should be considered when specifying allowable mixing temperature ranges to achieve desired performance. A Percent Reduction methodology which utilizes the Flow Number test was recommended for specifying a minimum production temperature. This would ensure mixture stability and allow for the use of various warm mix technologies, RAP, RAS, and volumetric and production specific properties (Bennert, et al., 2011)

The Percent Reduction methodology works as follows: first, the Flow Number characteristics of the HMA are determined. Then, the general or specific relationships, such as those shown in Figure 1 would be used to estimate the allowable temperature reduction to avoid potential rutting problems. As an example, assume that a HMA mixture designed for traffic between 10 and 30 million ESALs had a Flow Number of 250 cycles. Based on the results of NCHRP Project 9-33, a minimum Flow Number for that traffic level is 190 cycles, resulting in a 24 percent reduction from the hot mix value. Figure 1 is used to correlate this percent reduction to a reduction in production temperature of about 40 °F. The Percent Reduction method could be used for Dynamic Modulus instead of Flow Number, but minimum specifications for Dynamic Modulus are not currently available (Bennert, et al., 2011).



(a) – Dynamic Modulus (E*) (b) – Flow Number

Figure 1. Percent Reduction in Mixture Performance vs. Reduction in Production (Mixing) Temperature (Bennert, et al., 2011)

This study also showed that moisture in the aggregates has a significant effect on the moisture damage susceptibility of warm mix asphalt, and aggregates with higher absorptive capacity are more problematic than aggregates with lower absorptive capacity. Better stockpile management and/or the addition of anti-stripping agents should be adopted to minimize the potential for moisture damage with warm mix asphalt mixtures (Bennert et al., 2011)

Moisture Damage

Moisture damage occurs when the bond is broken between asphalt binder and aggregate. As previously mentioned, moisture damage, or stripping, is of concern for WMA mixtures because the lower production temperatures may not allow complete aggregate drying prior to mixing. Traditionally, moisture damage is tested according to AASHTO T283, also known as the Lottman test, by conducting an indirect tensile strength test. The tensile strength ratio (TSR) is the value used to evaluate strength retention after a sample has been conditioned. TSR is the ratio of the strength retained after one freeze-thaw cycle compared to a dry, unconditioned sample.

One study tested moisture damage in WMA mixtures that used moist aggregates (Xiao et al., 2009). Indirect tensile strength, tensile strength ratio, deformation, and toughness tests were conducted to identify susceptibility to moisture. Moisture contents of 0 percent and 0.5 percent by weight of dry mass of aggregate were used with two additives (Aspha-min and Sasobit). One binder grade (PG 64-22) and three aggregate sources (two granite and one schist) were used.

A preliminary study was conducted to simulate moist aggregate in the field. Moisture contents of 0.5, 1, and 1.5 percent were tested. This study showed that only about 0.5 percent moisture content could realistically be achieved after the aggregate has been heated to warm mix temperatures. To use moist aggregate for this study, 3 percent by weight of aggregate of hot water (60 to 70 °C) was added to completely dried aggregate which was at a temperature of 160 – 165 °C. The water was blended into the aggregate by hand for 30 seconds before mixing. This achieved an aggregate condition of about 0.5 percent moisture with a temperature of 121 – 127 °C because most of the water evaporated.

The results of this study showed that the warm mix additives did not have a negative effect on tensile strength; moisture content affected the tensile strength but additives did not. There was no difference in the performance of wet HMA and of wet WMA. However, Aspha-min required an anti-strip additive to perform equally well. Without the hydrated lime, some of the Aspha-min samples failed. Adding hydrated lime increased the deformation resistance of all mixtures. It seems that the decrease in indirect tensile strength caused by moisture can be offset by the addition of hydrated lime. It should also be noted that mixtures using Sasobit showed less deformation than mixtures without additive.

Although the AASHTO T283 method has widely been accepted as the standard test method for assessing moisture damage, this method has several shortcomings. It does not always correctly predict the moisture sensitivity of mixtures as compared to field performance, and specimen diameter can significantly affect test results such that 100 mm (4 in.) and 150 mm (6 in) diameter specimens yield different results (Kandhal and Rickards, 2001). Variations in conditioning can result in a wide range of levels of saturation, which can greatly affect tensile strength and stripping, and it has been argued that a cyclic load can better simulate pumping due to traffic better than a constant load rate. Finally, because the test is so long, shortened versions of the test are often used, and this can yield different results than would be obtained if all of the steps were followed.

As a result, a study was conducted to evaluate the variables associated with moisture-conditioning procedures (Kringos and Scarpas, 2009). This investigation was performed by means of microscale finite element analysis which utilizes the computer-aided pavement analyses in three dimensions (CAPA 3-D). This method allows for more exact results because of the level of detail used to examine the samples. For example, the typical method for calculating air voids does not consider outside pores. In this study, the outside pores were included by using an X-ray scan of the specimens. On average, the X-ray computed air voids was 1.8% higher than the conventional air void calculation. The use of finite element analysis showed great promise as a precise method for calculating moisture damage for a mix.

Another method being considered for ascertaining a mixture's susceptibility is the dynamic modulus (E*) test, which is conducted according to AASHTO TP62-03. This test has gained popularity because the dynamic modulus can be used as a simple performance test indicator and is also a major input into the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*.

The primary purpose one research project was to determine whether the dynamic modulus test could replace the indirect tensile strength test (Nadkarni, et al., 2009). An advantage of the dynamic modulus test is that it is non-destructive, so the same test specimen may be tested both before and after moisture conditioning. Four types of HMA mixtures were used in this investigation: conventional dense-graded asphalt concrete (AC), asphalt rubber asphalt concrete (ARAC) that was gap graded, asphalt rubber friction course (ARFC) that was open graded, and dense-graded AR mixtures. Each mixture was sampled from the field during construction and compacted in the laboratory. When conducting E* tests, the percent of retained stiffness, known as the E* stiffness ratio or ESR, was determined. Results of TSR and ESR for the same mixtures were compared, and no statistically significant difference was found between these two measurements. Furthermore, no significant difference was found between the ESR values for a given project and mix type obtained at the various frequencies; therefore, an average ESR for the range of frequencies may be used.

According to this report, the TSR values for open-graded mixes should be investigated for consistency rather than a pass-fail threshold because of issues of deformation of the sample due to its open-graded nature rather than the effects of conditioning. Also, flow of moisture may be too high and wrapping the specimen in plastic wrap prevents water from leaving the specimen.

Although the research project did not specifically investigate Warm Mix Asphalt applications, an investigation of this methodology for characterizing the moisture susceptibility of WMA seems to be warranted.

Another study (Katicha, 2010) investigated the possibility of using the dynamic modulus as a quality measure of HMA, especially related to rutting. While this study focused on HMA, the methods could also be applicable for studying WMA. In this study, and effective reduced frequency was determined such that the HMA dynamic modulus best correlated with the MEPDG-calculated HMA rutting for eight climatic conditions. This reduced frequency did not coincide with the modified Witczak effective temperature-frequency equation. Instead of subdividing the HMA layer as suggested by Witczak, this study used a single effective temperature-frequency combination for the entire HMA layer. To determine effective reduced frequency, dynamic modulus master curves were selected at a reference temperature of 70 °F with different shapes (different rates of change as a function of reduced frequency). The MEPDG was run for all master curves and a nonlinear least squares procedure was used to determine the best fit for the parameters (Katicha et al., 2010).

The HMA layer thickness was found to have a negligible effect on the reduced frequency. The HMA rutting calculated using the effective reduced frequency was comparable to the MEPDG-calculated HMA rutting. The average difference was 7.5 percent and the maximum difference was 23 percent, which is very good considering the variability associated with actual rutting measurements taken in the field. Using the effective reduced frequency can save time and money, especially for quality control. It allows fewer testing temperatures (one test at a single temperature instead of three test temperatures). They dynamic modulus has been recommended for use as a performance test to determine rutting and fatigue cracking performance (Katicha et al., 2010).

Another 2010 study evaluated the workability/compactibility of various warm mix additives which were pre-blended into binder at various percentages. Because conventional tests and compaction data used for HMA are insensitive to the effect of additives, dosage rates, and compactability, a new 'Lubricity Test' was developed. The Lubricity Test is based on Thin-Film Rheology. Dynamic Shear Rheometers measure asphalt properties at a film thickness of 1000 microns, but this is much thicker than the film coatings on aggregates within an asphalt mixture. Therefore, this test studied film thicknesses as small as 25 microns. For this study, PG 76-22 binder was blended with three different warm mix additives (Evotherm 3G, Rediset, and Sasobit) at varying dosages using a low shear mixer. Binder workability was measured using the following tests: rotational viscosity (AASHTO T 316), the Casola Method (NCHRP Project 9-39), and the Lubricity Test. The Lubricity Test was shown to be sensitive to dosage rate and additive type, and ranked favorably with other mixture tests (Bennert et al., 2010).

Based on the results of the study, Evotherm 3G and Rediset cause a slight decrease in the high temperature PG grade, while Sasobit causes a slight increase. The non-recoverable creep compliance and percent recovery also changed somewhat. At temperatures above 250 °F, all of the binder/mixture behavior was similar among the different samples, but below 220 °F, some of the mixtures containing additives showed less workability/compactability. When considering the addition of an additive, one should investigate the additive's ability to maintain its effectiveness at lower temperatures. These tests showed that 2 percent Rediset and 0.5 percent Evotherm 3G performed the best, and 1.5 percent Sasobit worked well (Bennert et al., 2010).

The lubricity test procedure involves the use of coefficient of friction to measure the effectiveness of warm mix additives to increase workability at lower temperatures. Additional work was done to investigate the sensitivity of the lubricity test to binder grade and temperature, and to evaluate the significance of the binder coefficient of friction to the workability of a mixture.The lubricity test uses a value called the Construction Force Index which is the summation of shear forces from N = 2 gyrations to the gyration corresponding to 92 percent of the maximum theoretical specific gravity (G_{mm}). This value was used to evaluate mixture workability in the lubricity test (Hanz et al., 2011).

When evaluating the effects of warm mix asphalt additives on the workability of binder, certain properties were temperature dependent. The coefficient of friction was significant in the predictive model for Construction Force Index at lower temperatures, but at higher temperatures this property became less important. However, the presence of binder modification had a significant effect on the lubricity test at all temperatures. While this study did not include foaming additives and only used laboratory compacted specimens, the results clearly reflected that the workability of a mixture was not simply based on binder content and viscosity. The mechanisms were complex and temperature dependent, and the lubricity test correlated a variety of parameters with the viscosity to allow for a better understanding of the factors that controlled asphalt mixture workability (Hanz, et al., 2011).

While a number of studies have investigated the effects of warm mix additives on the binder properties, the compactability of mixtures, and the rutting potential of mixtures at high temperatures, much less research has been conducted to evaluate the low temperature performance of warm mix asphalt pavements. In a 2011 study, the low temperature fracture characteristics of WMA were evaluated. Dense-graded 13-mm nominal maximum aggregate size mixtures were produced using a liquid-form Evotherm and a solid form wax blended with a PG 64-22 binder. Beam samples were produced and tested for fracture toughness (K_{IC}) at -20 °C using a 3-point bending beam test. Based on the results of this study, the viscosity of the binder was decreased by 25-33 percent at 115 °C when the additives were introduced, and the high-temperautre grade was increased from 64 to 70 or 76. In addition, the fracture toughness of WMA was equal to or higher than that of HMA for low temperatures, indicating better performance for WMA at low temperatures (Yoo et al., 2011).

Foaming Processes

Most of the published research regarding laboratory studies of warm mix asphalt technologies includes a product or additive that can easily be incorporated in the laboratory. Foaming processes, however, are not as easy to mimic in the laboratory due to the inherent differences in laboratory and field production of asphalt mixes.

A Canadian study examined a contractor's experience with using the Double Barrel Green process to produce warm mix asphalt (Middleton and Forfylow, 2009). For this study, four mix designs were prepared based on the Marshall mix design method: a virgin mix, a mix with 15 percent RAP addition, a mix with 15 percent RAP and 5 percent Manufactured Shingle Modifier (MSM) addition, and a mix with 50 percent RAP addition. All of the designs used an 80/100A penetration grade asphalt binder, which is similar to a performance graded PG 64-22 binder. Laboratory tests of the samples included recovery asphalt binder characteristics, mixture rutting susceptibility, mixture stiffness, and moisture susceptibility.

It was found that by using the Double Barrel Green process, the binder did not harden as much as with conventional methods, and additions of RAP (up to 15 percent) did not significantly alter the binder properties. At higher RAP percentages, binder stiffening became noticeable. The higher percentages of RAP showed improved rutting resistance, although none of the warm mix asphalt samples showed moisture susceptibility. Only the hot mix control mix displayed moisture damage susceptibility. In terms of temperature reduction, the manufacturer of Double Barrel Green recommends a temperature reduction of 122 degrees F (50 degrees C). However, this study found that a temperature reduction of 68 to 95 degrees F (20-35 degrees C) was more reasonable.

In general, studies have demonstrated that manufacturer's suggestions for allowable temperature reduction when using their products are more of an optimistic guideline than a proven rule. Some manufacturer's recommendations, such as those for Evotherm, seem to be accurate. But others, such as the recommendations for Double Barrel Green, may be overly optimistic and may lead to performance or constructability issues. Some researchers suggest that problems caused by temperature reductions can be overcome by grade bumping or by using hydrated lime to reduce potential for stripping and increase the tensile strength ratio (Hurley and Prowell, 2005). Other researchers suggest that Morelife 3300 antistrip may be added at a rate of 0.5% by weight of binder (Diefenderfer and Hearon, 2008), or AKZO Nobel Magnabond could be added as an anti-stripping agent (Hurley and Prowell, 2005). It is clear that further research on advisable temperature reductions for optimum constructability and performance is needed for all additives which are to be used in actual construction.

NCHRP Project 09-43

One of the largest research efforts regarding WMA was Project 09-43 under the National Cooperative Highway Research Program (NCHRP). This study focused on the mix design issues relating to WMA (Bonaquist, 2011). In this study, several primary conclusions were developed. First, the volumetric properties of HMA and WMA were essentially the same when the corresponding HMA mixtures had binder absorption values of 1.0 percent or less. However, the performance characteristics of those mixes could exhibit dramatic differences. Binder grade was also investigated, and it was concluded that the same binder grades should be used for HMA and WMA because only the extremely low production temperatures affected the stiffness of the recovered binders, but that the low temperature grade of the binder could see minor improvements. Binder grade bumping could be used to improve the rutting resistance of some mixes produced at very low temperatures.

Coating and compactability were also given much attention, and several devices were used to measure compactability. But, rather than recommending a particular device for measuring compactability, a procedure was proposed, which requires specimens of the WMA to be mixed and compacted at the target WMA temperatures, and then again at 54 °F (30°C) less than the target temperatures. Then, the number of gyrations to achieve 92 percent density is calculated for each temperature, and acceptable compactability is defined such that the lower temperature could result in no more than a 25 percent increase in number of gyrations. Laboratory mixing times were suggested, and AASHTO T 195 was recommended for assessing coating with a 95 percent minimum recommended value. All mixes in this study were prepared using a planetary mixer with a wire whip, though it was acknowledged that bucket mixers are more common. Thus, some changes could be necessary for laboratories using a bucket mixer.

Moisture damage was determined to be a potential issue for WMA mixes. In almost 80 percent of the mixes tested, tensile strength ratio decreased when the mixture was converted to WMA. In no case was the tensile strength improved for the WMA, unless anti-stripping agents were used. AASHTO T 283 was recommended as the test method for determining moisture sensitivity. Rutting resistance was evaluated using the flow number test using a 2 hour short-term conditioning at the compaction temperature, and the WMA mixes were found to be more susceptible to rutting.

In summary, it was determined that the volumetric properties of WMA mixes were similar to that of HMA mixes, but that the rutting susceptibility and moisture sensitivity were greater. Steps must be taken during the mixture design process to assess the performance of the WMA, though different aging techniques may be more appropriate for WMA. A draft appendix to AASHTO R 35 was included in the report (Bonaquist, 2011).

<u>Field Performance</u>
A number of field tests were observed during the European Scan Tour. In Norway, poor performance was found in some sections, but the problems were not directly attributed to the WMA. Six pavements containing WAM-Foam were observed. These pavements experienced traffic ranging from 3,500 to 25,000 vehicles per day. Four of the pavements were dense-graded and two were stone-matrix asphalt. All six pavements were in good condition. At the time of the tour, WMA pavements were being observed which had been paved along with a hot mix control section. During construction, the following field data was recorded: mix temperature, emissions data, mix samples, and initial profiles. Over the course of five years, the sections were monitored for transverse profile, layer thickness, and surface condition. After five years, the warm mix pavements were performing as well or better than the hot mix control sections (D'Angelo et al., 2008).

One of the earliest field demonstrations in the U.S. was conducted on Hall Street in St. Louis, Missouri. In this project, Evotherm, Sasobit, and Aspha-min were used, and it was the first time in the U.S. that all three technologies were included in a side-by-side comparison. All three products were viewed as successful, with significant temperature reductions and an overall savings of about $0.33 in fuel costs per ton of asphalt produced. One of the most prominent outcomes of this effort was that WMA was viewed as a solution for bumps created by heat expansion when joint sealants are exposed to typical HMA overlay temperatures (MacDonald, 2006).

In 2008, a demonstration project was conducted along California's State Route 1 (Kuennen, 2009). This roadway runs through remote terrain and requires long haul distances taking 3 to 4 hours. The demonstration project used WMA containing Evotherm. Due to concerns about rutting, laboratory and Heavy Vehicle Simulator tests were performed in 2007, and no rutting tendencies were evident. For the demonstration project, both dense-graded and open-graded warm mixes were used. The dense-graded portion was placed where flooding was likely. This mix used PG 64-16 binder and aggregate meeting CalTrans's ½-inch top-size grading. The open-graded section used a polymer-modified PG 58-34 binder, liquid antistrip, and aggregate meeting the 1/2 –inch grading. Mix workability was reportedly improved, and thus, the WMA was considered a success (Kuennen, 2009).

During the same year, about 55,000 tons of WMA were placed as an overlay on a four-lane section north of Saginaw, Texas in the Fort Worth District (Duval, 2009). This project was approximately 5 miles in length and had a 2007 traffic count of 24,100 vpd with 20 percent trucks. Previous hot mix overlays tended to heave and crack because the old crack sealant would expand when the heat of the HMA overlay was placed, as described in the Hall Street demonstration. Therefore, a WMA overlay was used to avoid this problem. The mix was designed using standard TxDOT HMA mix design procedures, and Evotherm was added. The base course was a fine-graded Type B mix containing PG 64-22 and 20 percent RAP, while the surface course was a Type D mix that contained PG 76-22 binder and 100 percent virgin aggregates. During production, the base course was mixed at temperatures as low as 220 °F, and the surface course as low as 235 °F. These temperatures resulted in stack emission reductions of 20 percent in terms of VOCs. Traditional pavers and rollers were used, and the air void requirements for in-place densities were successfully achieved with four passes of the double-drum vibratory steel wheel roller (Duval, 2009).

The following year, two separate field studies were conducted using the Astec Double Barrel Green® system for a mix containing RAP. The first documented Canadian experience in placing four WMA mixes with PG 64-22 binder varying percentages of RAP, and the second took place in Indio, California where two demonstration projects were placed to compare HMA and WMA (Middleton and Forfylow, 2009, Wielinski, et al., 2009). The experiences were similar, with the HMA mixtures displaying slightly better laboratory performance than the WMA mixtures. However, there were no significant differences noted in the early field performance comparisons.

In the Canadian study, the mixes were designed using the Marshall mix design method, and laboratory testing included the recovered asphalt binder characteristics, rutting, stiffness, and moisture susceptibility (Middleton and Forfylow, 2009). The results demonstrated that the WMA mixes did not experience the typical binder hardening from oxidation, although greater percentages of RAP did increase the effects of binder stiffening. Rutting resistance was increased with increased RAP content, although the difference was not significant. Only the virgin mix displayed moisture susceptibility. In terms of emissions and energy savings, there were overall reductions of 10 percent for CO_2, CO, and NO_x, and there was a slight increase in sulphur dioxide. The production temperature for the WMA mixes was 41 °C, resulting in a 24 percent reduction in energy consumption and a savings of $0.76 per metric ton based on a natural gas price of $9.50 (Middleton and Forfylow, 2009).

The second study took place in Indio, California, where two demonstration projects were placed to compare HMA and WMA. No modifications were made to the mix design when creating the WMA. The HMA plant discharge target temperature was 330 °F, while the WMA target temperature was 275 °F. The HMA and WMA sections were compacted in the same way, using 2-inch lifts and a steel drum roller for breakdown compaction and a tandem steel drum and pneumatic roller for intermediate and finish compaction. When sampling the cold-feed aggregates, moisture contents were consistent between the

HMA and WMA samples, ranging from 1.1 to 1.7 percent. Moisture contents of the WMA and HMA mixtures were similar ranging from 0.02 to 0.6 percent for the HMA mixtures, and 0.06 to 0.08 percent for the WMA mixtures. Cores were taken from each test site and tested for in-place density. Based on the results, the WMA displayed better density results for the same compactive effort. Moisture susceptibility testing was performed according to AASHTO T 283. Neither mix was a good performer, with the WMA having TSR values approximately 10 percent lower than the HMA control. Rutting was acceptable in both mixes, with the WMA displaying slightly larger rut depths. In terms of field performance, the initial performance of the HMA and WMA sections were similar, indicating successful placement of WMA (Wielinski, et al., 2009).

Similar results have been observed for other pavements using the Double Barrel Green® system. Pavements using this technology tend to have marginal moisture susceptibility, but may have improved performance if an anti-stripping agent is used. The density of the test specimens tended to be lower than desired, but improved rolling techniques could solve this problem. Laboratory samples tend to show high air voids, which could be lowered by making adjustments to the asphalt content of the mixture (Astec Industries, Inc., 2009A).

In a 2011 study, the performance of four field mixes was evaluated using WMA and HMA comparisons. Dynamic modulus, flow number, and moisture susceptibility were investigated as the parameters for evaluating performance. The warm mix technologies investigated were Evotherm 3G/Revix, Sasobit, and Double Barrel Green foaming. Both field-compacted and reheated field samples were used for the test specimens. Based on the results, only the Double Barrel Green foaming technology showed some improved characteristics over the HMA control. The tensile strength ratios obtained for the WMA samples indicated an increased susceptibility to moisture damage. Also, this study showed that laboratory-compacted field samples often performed better than field-compacted samples, indicating a discrepancy between the field and laboratory results (Buss, et al., 2011). This discrepancy should be taken into account when developing QC/QA specifications.

As warm mix asphalt has gained popularity, there have been many more field sections constructed. Also, the FHWA Every Day Counts (EDC) Initiative has actively encouraged an increase in the use of WMA in all 50 states. These construction sites have included locations all over the country, and have been used in applications ranging from parking lots to interstate roadways. While many field reports focus on density and incentive pay, or reductions in cost and fuel, one project in Delaware reported an increase in production rates of 18 percent. This increase was attributed to the ability of the WMA additive to easily and quickly coat the aggregates (Dolan, 2012).

<u>Discrepancies Between Field and Laboratory Performance</u>

A number of studies have been conducted in the laboratory, and a number of studies have been conducted in the field; however, when similar mix designs are simulated in the laboratory and constructed in the field, different results are often observed (Buss et al., 2011). This is problematic, because laboratory tests are designed to simulate what happens in the field. Many researchers have suggested that one possible cause for this discrepancy is that the aggregate used in WMA samples does not get heated enough to evaporate all of the moisture; however, when the samples are produced in the laboratory, standard procedures do allow this moisture to evaporate. Some researchers point to shortcomings in various testing procedures as cause for the discrepancies. Therefore, a number of studies have been conducted to try and better simulate true field conditions.

A study was presented in 2009 which tested moisture damage in WMA mixtures that used moist aggregate (Xiao et al., 2009). Indirect tensile strength, tensile strength ratio, deformation, and toughness tests were conducted to identify susceptibility to moisture-related distress. Moisture contents of 0.0 and 0.5 percent by weight of dry aggregate mass were used with Aspha-Min and Sasobit WMA mixes containing three aggregate sources. These moisture percentages were used because a preliminary study indicated that only about 0.5 percent moisture would realistically be achieved after the aggregate had been heated to warm mix temperatures. To produce the moist aggregate condition, 3 percent by weight of aggregate of hot water was added to completely dried aggregate, which was at a temperature of 160 – 165 °C. The water was blended into the aggregate by hand for 30 seconds immediately prior to mixing. This process resulted in the desired 0.5 percent moisture within the sample having a resulting temperature of 121 – 127 °C after evaporation had occurred (Xiao, et al., 2009).

The results of this study demonstrated that the moisture content did, in fact, affect tensile strength, but the additives did not. In addition, there was no difference in the performance of wet HMA and wet WMA. However, Aspha-Min required an anti-stripping agent (hydrated lime) in order to generate equivalent performance. It was also noted that the Sasobit samples exhibited less deformation than mixtures without an additive (Xiao et al., 2009).

The AASHTO T 283 method does not always correctly predict moisture sensitivity of mixtures experienced in the field (Kringos and Scarpas, 2009). Furthermore, discrepancies may arise between 4-inch and 6-inch diameter test specimens. Conditioning can result in a wide range of saturation levels, which significantly affects tensile strength and stripping performance. The use of finite element analysis has been demonstrated to show promise for providing a relatively precise method for calculating the moisture susceptibility of an asphalt mixture (Kringos and Scarpas, 2009).

Another factor that could explain discrepancies between field and laboratory performance is the lack of determination of an appropriate curing time. According to one researcher, no curing time is necessary for warm mixes containing additives which do not employ moisture to operate; however, mixes with additives which employ moisture may require a curing time in order to expel moisture remaining in the mix (Button et al., 2007). According to Maccarrone et al. (1994), such samples can be cured for three days at 140°F in order to achieve similar moduli as samples taken after 12 months. According to the results of NCHRP Project 09-43 study, a 2-hour short term aging period is recommended for mix design work. However, further research was recommended to determine the appropriate aging conditions for performance testing. Currently, AASHTO R30 requires 4 hours of conditioning at 275 °F, which is not appropriate for WMA since the compaction temperature of most WMA mixes is less than 275 °F (Bonaquist, 2011).

Specifications

During the European Scan Tour, American experts learned of the various specifications already in place in Europe. For example, the Norwegian Public Roads Administration allows warm mix asphalt to be used as long as it meets all of the applicable specifications of hot mix asphalt. A five year materials and workmanship warranty is required also.

In Germany, the constituent materials of asphalt must be approved either by European standard, European technical approval, or specifications based on demonstrable history of acceptable performance both in the laboratory and in the field. Sasobit, Romontan-B, Lincomont BS 100, and Aspha-min have been studied and observed in field test sections in order to meet the constituent material requirement. In 2006, the information from these observations was compiled into a bulletin of recommendations and references for the use of warm mix asphalt. This was a great step towards developing a warm mix asphalt standard.

In France, in order for a new technology to become certified, a contractor and the road directorate as represented by SETRA (Service of Technical Studies of the Roads and Expressways) must both fund the evaluation, starting with laboratory evaluation and then field trials. Then guidance papers are prepared for use of the product, and ultimately the product is incorporated into existing standards or new standards are produced. Trial sections along with controls are constructed, each at least 500 meters long, and these sections are monitored for at least three years. If the sections perform successfully, then certification is granted. In 2007, Aspha-min zeolite was certified.

In 2009, the Montana Department of Transportation's Office of Research Programs published the results of a survey of state DOT specifications for the use of warm mix asphalt (Perkins, 2009). Based on this survey, several states either did not have specifications, were in the process of developing specifications, or used current hot mix asphalt specifications for warm mix applications. The following states have standards which are detailed below.

<u>Alabama</u>
All procedures in the state specifications which apply to hot mix asphalt also apply to warm mix asphalt. Alabama defines warm mix asphalt as having mix temperatures ranging from 215 to 280F. The state has an approved list of processes which may be used for producing warm mix asphalt, and use of an anti-stripping agent is required. Higher percentages of RAP (up to 35 percent) are allowed for warm mix asphalt pavements than for hot mix pavements.

<u>Arkansas</u>
Arkansas currently allows the use of WMA, and requires the contractor to determine production temperatures. However, these temperatures may be adjusted according to the recommendations of the WMA additive/process manufacturer. It is also recommended that best practices be used to limit

the moisture content of aggregates prior to introduction into the drying or mixer drum. The placement temperature of WMA is not allowed to be less than 220 °F.

California

The warm mix specifications are based on the hot mix asphalt specifications but also provide for tests that ensure correct dosage rates of the additives. Only Advera, Evotherm, and Sasobit are approved for use in California.

Florida

Florida is using an interim specification for warm mix asphalt that allows for paving at lower temperatures than are specified for hot mix asphalt. The specification allows Aspha-Min, Double Barrel Green, Evotherm, and Aqua Foam to be used on the basis that these technologies are recognized processes with successful project demonstrations nationally and internationally.

Idaho

The specification does not allow any technology that alters the performance grade of the binder. It also suggests that field produced loose mixes be allowed to cool and be reheated before laboratory compaction.

Indiana

This specification allows QC/QA hot mix asphalt to be produced as warm mix asphalt by using a water-injection foaming device for ESAL categories 1 (<300,000 ESALs), 2 (300,000 to <3,000,000 ESALs), and 3 (3,000,000 to <10,000,000 ESALs) mixtures. The minimum plant discharge temperature for hot mix as well as warm mix asphalts must be reported. A maximum of 25 percent RAP or 5 percent Asphalt Roofing Shingles (ARS) by mass of the total mixture may be allowed for warm mix asphalts of ESAL categories 1, 2, and 3, excluding ESAL category 3 surface mixtures.

Iowa

Warm mix asphalt may be used on a project-specific basis through contract modifications which specify the type of technology that will be used as well as laboratory compaction and placement temperatures. The manufacturer’s recommendations are to be followed when using the technology.

Maine

Maine has a special provision which includes warm mix asphalt additives as possible materials in the composition of mixtures. The specification mandates that additives should be incorporated in the manner and at the dosage rate recommended by the manufacturer. The specification describes four possible forms of additive, including: organic, synthetic zeolite, chemical, and other product/processes such as foaming.

Ohio

Ohio specifies a list of requirements for the equipment to be used to produce warm mix asphalt. Among the requirements are 1) demonstrable stability and 2) effectiveness in other DOT projects. The requirements also limit warm mix technologies to water-based foaming technologies. Higher RAP percentages are allowed for warm mix asphalts than for hot mix asphalts.

Pennsylvania

Pennsylvania has special provision specifications for base and surface course warm mix asphalt. Only approved technologies may be used, including: Advera, Double Barrel Green, Evotherm, Green Machine, Low Energy Asphalt, Rediset WMX, Sasobit, and Warm Mix Asphalt System. A Paving Operation QC Plan is necessary, along with a technical representative from the warm mix asphalt manufacturer who must be present during both production and placement of the asphalt.

Texas

The specification for warm mix asphalt came from an amendment to the traditional specification for dense-graded hot mix asphalt. This specification defines warm mix asphalt as containing additives or processes that allow for a reduction in production and placement temperatures. Contractors may use warm mix asphalt as long as the plans do not show otherwise, and contractors must use warm mix asphalt if shown on the plans. The warm mix asphalt must be produced between 215F and 275F when shown on the plans, and must be produced between 215F and 350F when not shown on the plans. The Department has an approved list of additives which is maintained by the Construction Division, and contractors are to use approved additives unless otherwise directed.

Virginia

The department maintains a list of approved additives and processes which may be used, including: AQUABlack, Double Barrel Green, Evotherm ET, Sasobit, and Ultrafoam GX. As other products are evaluated, they may be added to the list. The evaluation process includes independent test data which supports the product, mix designs, and a trial section. For conformance testing, the mixture's properties are determined after allowing the mixture to cool to 100F or less and then reheating it. The tensile strength ratio must be at least 0.6 according to AASHTO T283 testing procedures to ensure adequate stripping resistance. Initial production is limited to 500 tons per day to ensure that the engineer is able to examine the process control at the mixing plant, placement procedures, surface appearance, compaction patterns, and correlation to nuclear density tests.

Washington

This specification acknowledges warm mix asphalt technologies and allows contractors to submit for approval of the technology that they wish to use.

5. Project Objectives

The overall objective of this project was to evaluate readily available WMA technologies and to develop the provisions necessary to incorporate WMA into AHTD Standard Specifications. Specific objectives included performing a comprehensive literature search, followed by an evaluation of WMA mixtures, including the following items.

- Investigate various processes available for the production of WMA. Initially, the basic technologies developed for WMA production included organic additives, chemical additives, and foaming processes. While these basic types of technologies still exist, the number of WMA products has grown significantly and continues to change. Thus, a decision was necessary regarding which products to include in the research. Information found in the available literature was used to determine which of the available products would be included in the project.
- Assess WMA mixture design parameters. The primary focus of this objective was to determine the differences in HMA and WMA mixture characteristics, design procedures, and which design and performance parameters were the most significantly affected by these differences.
- Evaluate the sensitivity of WMA mixes with respect to performance. Because of the inherent differences in the production of HMA and WMA, the ultimate performance of WMA was believed to be a key factor in determining the desirability of WMA. Particular factors of interest included differences in cooling rates, curing times, and binder aging, and how those differences affected mixture rutting, stripping, and strength characteristics.
- Develop specific recommendations regarding the inclusion of WMA in the AHTD Standard Specification. The most important step in accomplishing the goals of the project were to formalize the results in to a concise set of recommendations for the specifics of implementing WMA in Arkansas, including draft specification language for incorporating the WMA process into the typical bituminous pavement mix design and approval process.

6. Research Approach and Discussion

In this study, HMA and WMA comparisons were made in order to discover what factors were most significant to the production of each, specifically targeting the differences in the two types of asphalt mixtures. The primary goal was to identify the features of WMA that would need to be addressed in a specification in order to successfully implement WMA use in the state of Arkansas.

WMA Product Selection

In order to begin the research process, a literature search was conducted to determine which of the many WMA products would be included in the study. Because there were many to choose from, it was decided that the products having the greatest accessibility to contractors in Arkansas should be included, and that a product from each general category of the WMA technologies should be selected.

The WMA technologies fall into 3 basic categories: 1) chemical additives, 2) organic additives, and 3) foaming techniques. The foaming techniques may be either additives such as zeolites, or may be comprised of water injection processes. Of the available options, the following products were selected:

- Evotherm®3G, Formula J-1 (by MeadWestvaco Corporation)
- Advera® (by PQ Corporation)
- Sasobit® (by Sasol Wax North America Corporation, Inc.)

All three of the products chosen were additives. No foaming processes were included, based on two factors. First, it was believed that contractors in the state of Arkansas might be somewhat reluctant to invest in a plant modification required for the plant foaming techniques, and would prefer to try WMA technologies in a manner that would represent a less significant commitment. Second, at the time the research project began, neither the AHTD nor the University of Arkansas laboratories possessed a laboratory foaming device. Thus, there was no mechanism available for replicating this type of foaming process in the laboratory for a thorough evaluation.

HMA Mix Designs

Two aggregate sources were chosen for inclusion in the study, as shown in Figure 2. The first was a limestone (LS) source typical of the northwestern portion of Arkansas (APAC Central's Sharps Quarry). The second was a syenite (SY) aggregate source found in the central portion of the state (Granite Mountain Quarries).

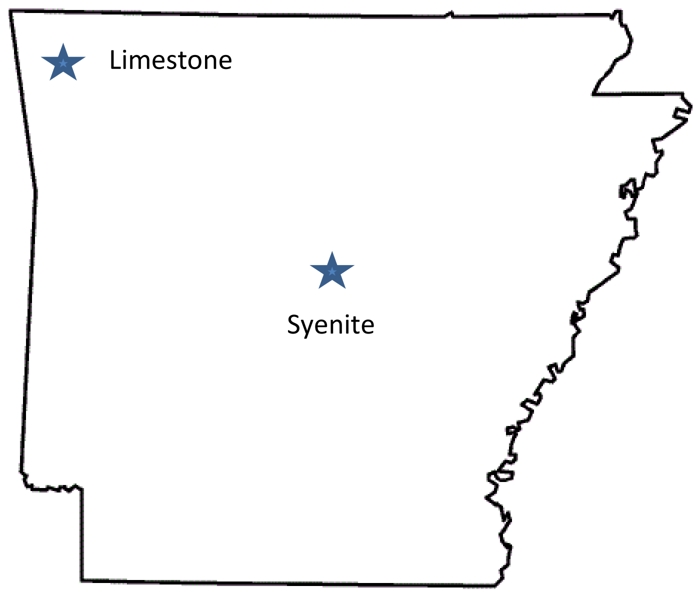


Figure 2. Location of Aggregate Sources

For each aggregate source, six HMA mixture designs were established. These mix designs represented two nominal maximum aggregate sizes (12.5mm and 25.0mm) and three combinations of binder grade and design gyration level (PG 64-22 / N_{des} = 75 gyrations, PG 70-22 / N_{des} = 100 gyrations, and PG 76-22 / N_{des} = 125 gyrations). The binder grade and compactive effort factors were interrelated in order to best represent typical mixture design parameters. A summary of the limestone mix designs is given in Table 4, and the syenite designs are shown in Table 5.

Table 4. Limestone Mix Design Summary

	Limestone					
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Job Mix Formula (%)						
1-1/2" Limestone	0	0	0	33	20	25
¾" Sandstone	31	31	31	0	0	0
½" Limestone	17	22	20	13	30	35
Coarse Lime	0	15	23	0	0	0
Avoca Lime	23	12	0	32	29	20
Asphalt Grit	29	20	26	22	21	20
Blend Gradation						
% Passing						
1-1/2"	100	100	100	100	100	100
1"	100	100	100	93	96	95
¾"	100	100	100	84	90	88
½"	91	91	91	71	82	78
3/8"	77	75	77	67	76	70
No. 4	51	47	49	51	50	41
No. 8	31	28	29	32	30	24
No. 16	19	18	17	20	19	15
No. 30	12	12	11	13	13	10
No. 50	8	9	8	9	9	7
No. 100	7	7	6	7	7	5
No. 200	4.9	5.0	4.6	5.3	5.4	4.3
Binder Content (%)	6.0	5.6	5.8	5.0	4.7	5.4
Air Voids (%)	4.5	4.5	4.0	4.5	4.5	4.2
VMA (%)	14.3	14.6	14.9	12.9	12.8	13.0
VFA (%)	68.4	69.2	73.0	65.2	64.9	69.2
Gsb	2.517	2.523	2.533	2.544	2.521	2.530
Gse	2.629	2.596	2.594	2.631	2.588	2.624
Max ThSpGr (G_{mm})	2.404	2.390	2.384	2.441	2.414	2.422
DP	1.13	1.11	0.93	1.41	1.46	1.07
Pbe (%)	4.5	4.0	4.6	3.7	3.1	4.1
Gb	1.028	1.023	1.029	1.028	1.023	1.031
G_{mm} at N_{ini} (%)	83.9	84.1	84.2	85.0	84.7	83.7
Mix Temp.	315F	320F	333F	315F	320F	333F
Compaction Temp.	293F	300F	315F	293F	300F	315F

Table 5. Syenite Mix Design Summary

	Syenite					
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Job Mix Formula (%)						
1-1/4" Syenite				35	35	37
¾" Syenite	50	45	45	35		
½" Syenite	25	25	15		25	24
Industrial Sand	15	20	29	20	30	32
Donna Fill	10	10	11	10	10	7
Blend Gradation						
% Passing						
1-1/2"	100	100	100	100	100	100
1"	100	100	100	99	99	99
¾"	100	100	100	90	90	90
½"	97	97	95	71	80	77
3/8"	89	90	88	61	71	68
No. 4	69	70	70	43	55	50
No. 8	48	49	51	33	40	36
No. 16	34	35	37	25	30	26
No. 30	25	25	28	20	23	19
No. 50	16	16	18	13	15	12
No. 100	10	10	11	8	9	6
No. 200	4.9	4.8	6.0	5.1	5.0	4.1
Binder Content (%)	4.9	4.8	4.8	4.1	4.0	4.4
Air Voids (%)	4.5	4.5	4.0	4.5	4.5	4.0
VMA (%)	14.8	14.7	14.3	13.1	12.7	13.2
VFA (%)	68.9	68.2	70.0	67.1	63.9	68.6
Gsb	2.596	2.595	2.564	2.606	2.599	2.605
Gse	2.618	2.616	2.583	2.623	2.630	2.634
Max ThSpGr (G_{mm})	2.434	2.436	2.409	2.466	2.476	2.466
DP	1.07	1.08	1.33	1.32	1.42	1.03
Pbe (%)	4.4	4.3	4.0	3.7	3.6	4.0
Gb	1.031	1.031	1.031	1.031	1.031	1.031
G_{mm} at N_{ini} (%)	87.4	87.3	88.0	88.1	88.4	87.8
Mix Temp.	315F	320F	330F	315F	320F	330F
Compaction Temp.	295F	300F	315F	295F	300F	315F

Next, the HMA designs were modified to create corresponding WMA designs. For each, manufacturer's instructions were consulted for determining the proper methods for incorporating the warm mix additive.

<u>Evotherm®</u>

The Evotherm 3G product was pre-blended with each of the three binders in half-gallon increments according to detailed manufacturer's directions. Each binder was heated until pourable (266 °F) in a 1-gallon can. Next, the Evotherm additive was measured at a rate of 0.5 percent by weight of binder, and added to the binder using a pipette. Then, the container of binder was placed on a hot plate under an overhead mechanical stirrer (a drill press with a paint paddle attachment), shown in Figure 3, and stirred at a relatively low speed for 30 minutes. The speed was adjusted to create the recommended ½ inch vortex. After stirring, the binder was cooled to room temperature, then sealed and stored until needed for mixing.

Figure 3. Pre-Blending Evotherm 3G with Binder

For mixing WMA samples, the manufacturer's instruction specified the use of a Hobart A120 mixer with a beater paddle and mixing bowl. However, this equipment did not appear to thoroughly mix the aggregates with the binder, and did not consistently provide a homogeneous mixture. A bucket mixer was used in subsequent trials and was successful at generating a consistent mix. Therefore, the bucket mixer was used for the remainder of the project. Prior to mixing, the treated binder and aggregates were heated to the target mixing temperature, and mixing was performed in the same manner as a typical HMA sample. In most cases, complete coating was achieved after a mixing time of 90 to 120 seconds. However, at lower mixing temperatures, a longer mixing period was required to effectively coat the aggregate particles. After mixing, all samples were aged at the target compaction temperature for two hours, and then compaction was performed according to AASHTO T 312.

Advera®

Advera is a foaming additive, and depends primarily upon the release of chemically bound water from the zeolite structure. Manufacturer's instructions indicate that it is important to incorporate the Advera product with the binder prior to mixing with aggregates in order for the zeolite to become well blended with the oil, and that the zeolite should not simply be added as a part of the aggregate blend. No guidance was presented regarding the mechanism for mixing, so the binder for each sample was pre-blended individually as a part of the sample mixing process using a beaker and spatula, as shown in Figure 4. However, this step had to be performed immediately prior to mixing with the aggregate blend so that the effects of the foaming process would not be diminished. According to PQ Corporation, the foam produced during is sustained during the production process; however, once the moisture is lost, the foaming effects are no longer present. Thus, if a sample must be reheated, WMA temperatures are no longer applicable and HMA temperatures must be used. This implies a finite time frame for the micro-foaming action, but a specific length of time was not stated.

Figure 4. Addition of Advera During the Mixing Process

In this project, Advera was added at the recommended dosage rate of 0.25 percent by weight of the asphalt mixture. This presented some difficulties in that the amount of Advera changed with changes in sample weight. Also, residual material was present in the beaker each time the binder and Advera were mixed, meaning that a slight overage of binder was necessary to make sure that the proper amount would be able to be scraped from the beaker and into the sample. Additionally, the beaker had to be cleaned between the mixing of each sample in order to prevent contamination. Another difficulty with mixing Advera in the laboratory was that while pre-blending with the binder, the temperature of the binder was difficult to control, creating additional variability in the production temperature for the mixing process.

<u>Sasobit®</u>

The Sasobit® used in this project was in pastille form, and was pre-blended with each binder using the mechanical stirring procedure similar to that of the Evotherm product. Sasobit, shown in Figure 5, was added at a rate of 1.5 percent by weight of the binder, and was stirred for a period of 10 to 20 minutes. According to the Sasol company representative, when Sasobit is added to binder that is above the melting point of Sasobit (i.e., above 212 °F), the Sasobit remains in dilution for a long period of time, and there is no concern of the product 'settling out' or deteriorating while in storage. The only caution was that the pellets should be added slowly, allowing them to disperse readily into the binder, rather than introducing them in a clump. Subsequent WMA mixing procedures were performed as typical for HMA.

Figure 5. Sasobit Pre-Blending Process

Temperature Reduction

One of the first questions was to examine the amount of temperature reduction that could be reasonably achieved for each of the additives. It was believed that the process of mix design for the WMA mixes would be basically the same as that for the HMA mixes, except that the added factor of temperature would constitute an additional confounding dimension of the design process. To start, each of the 12.5 mm HMA mixes was generated with the WMA additive using a series of temperature reductions to determine the sensitivity of each to temperature, and to identify the lowest practical mixing temperature that could be achieved. Temperature reductions were performed in terms of the number of degrees less than the stated HMA temperatures, which was based on binder grade. Twenty degree increments were used, including 40, 60, 80, and 100 °F less than HMA temperatures. Specimens were compacted using the Pine G2 gyratory compactor according to AASHTO T 312, bulk specific gravity was determined according to AASHTO T 166, and the maximum theoretical specific gravity test was performed according to AASHTO T 209. Calculations were then performed for air voids (AV), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and percent compaction at $N_{initial}$ (%D@N_{ini}).

The purpose of this analysis was to determine how much temperature reduction could be achieved while using each of the selected additives without causing significant changes in the mixture properties (as compared to HMA). WMA technologies are designed to allow for improved compactability, but this effect can serve to either 1) reduce the production temperature of the mix, or 2) serve as a compaction aid. Thus, a balance of the two goals must be considered based on the conditions for the project. If used primarily to reduce production temperatures, the benefits of energy savings and emission reductions will be the most prevalent. However, WMA used as a compaction aid can allow for longer haul times and increased mixture workability and compaction, which can translate to confidence in meeting specification requirements and achieving potential pay incentives.

The determination of optimum temperature reduction was based on volumetric properties of the samples as well as ease of mixing. If the temperature was reduced too much, the binder clumped to itself and did not properly coat the aggregate, as shown in Figure 6. Initially, the binder was heated to the same temperature as the aggregate for the temperature trials. However, this became problematic for samples containing Advera because the Advera was not added to the binder until the mixing process began. This required additional mixing time and resulted in cooling prior to the binder being mixed with the aggregates. Therefore, for these samples, the binder was heated to normal hot mix temperatures while the aggregate was only heated to the reduced temperatures. This allowed for adequate pouring, stirring, and mixing of the binder with the additive, during which time the effective temperature of the binder was reduced.

It was determined that although the reduction in temperature of a binder during mixing may at times be limited by its ability to properly coat the aggregate, it could be possible to reduce the aggregate temperature more significantly than that of the binder so that the overall temperature of the mixture was reduced while still allowing the binder to flow adequately. Thus, for some mixes, the mixing temperatures of the aggregates and binders were different. For these mixes, a proportional 'composite' mixing temperature was calculated to generate an overall WMA mixing temperature.

Figure 6. Binder Clumping when Maximum Temperature Reduction was Exceeded.

For each mixture, a series of temperature reductions was analyzed. Initially, a temperature reduction of approximately 40 °F from HMA temperatures was attempted. The mixing process generated adequate coatings more quickly for the Evotherm and Sasobit mixes than the Advera, so greater temperature reductions were possible for those additives. For each mix, temperature reductions were increased until adequate coating could no longer be achieved within a reasonable length of mixing time (approximately 90 – 120 seconds). For each additive, temperature reductions were selected for comparison, such that the temperature range was able to capture the maximum temperature reduction that would achieve adequate coatings and a homogeneous mixture. A summary of volumetric properties for each series of temperature reductions is shown in Tables 6 and 7. In these tables, mixing and compaction temperatures are given for each mixture. When aggregate and binder temperatures differed, a composite mixing temperature is shown.

Table 6. Average Values for Temperature Sensitivity – Limestone Mixes

			Average Volumetric Data Values			
Mix Design	Additive	Reduction from HMA Mix Temp/Compact Temp (°F)	%AV	%VMA	%VFA	$\%G_{mm}$ @N_{ini}
LS 64-22	ADV	36 / 40	5.4	15.6	65.5	83.7
		55 / 60	4.4	14.8	70.3	84.6
		73 / 80	4.6	15.1	69.5	84.6
	EVO	67 / 43	5.0	15.4	67.5	84.1
		87 / 63	4.5	15.1	70.3	84.4
		107 / 83	5.2	15.5	66.7	83.8
	SAS	58 / 60	5.7	15.6	64.0	83.5
		78 / 80	5.0	15.3	67.2	85.6
		98 / 100	5.4	16.1	66.3	83.8
LS 70-22	ADV	49 / 40	4.6	14.6	68.8	84.2
		68 / 60	5.5	15.0	63.4	83.4
		87 / 80	4.9	14.4	65.9	84.2
	EVO	72 / 48	4.0	13.8	70.9	84.4
		92 / 68	3.3	13.1	75.0	85.0
		112 / 88	4.3	13.8	69.1	84.2
	SAS	72 / 60	3.7	13.5	72.2	84.6
		92 / 80	4.1	13.6	70.0	84.5
		112 / 100	5.8	15.1	61.8	82.9
LS 76-22	ADV	21 / 20	6.0	16.0	62.6	83.3
		40 / 40	4.7	15.4	69.6	84.4
		58 / 60	4.1	14.6	71.8	84.9
	EVO	85 / 61	3.4	14.1	75.5	84.9
		105 / 81	3.3	14.1	76.7	85.1
		125 / 101	2.7	14.4	81.4	85.7
	SAS	62 / 60	3.3	13.8	76.2	85.0
		82 / 80	4.7	15.2	69.4	83.7
		102 / 100	4.3	14.4	69.8	84.1

Table 7. Average Values for Temperature Sensitivity – Syenite Mixes

			Average Volumetric Data Values			
Mix Design	Additive	Reduction from HMA Mix Temp/Compact Temp (°F)	%AV	%VMA	%VFA	$\%G_{mm}$ @N_{ini}
SY 64-22	ADV	40 / 40	6.1	16.2	62.1	86.3
		60 / 60	6.3	16.3	61.4	86.2
		80 / 80	6.3	16.3	61.2	86.1
	EVO	67 / 43	6.4	16.2	60.7	86.9
		87 / 63	5.5	15.5	64.3	87.1
		107 / 83	6.5	16.6	60.6	85.3
	SAS	60 / 60	6.7	16.6	59.9	85.8
		80 / 80	7.0	16.7	58.4	83.9
		100 / 100	6.8	16.7	59.3	85.6
SY 70-22	ADV	40 / 40	5.8	15.9	63.8	86.7
		60 / 60	6.0	16.0	62.6	86.3
		80 / 80	6.1	15.9	61.1	86.1
	EVO	72 / 48	6.0	15.8	61.8	87.1
		92 / 68	5.0	15.1	67.0	87.3
		112 / 88	7.0	16.6	58.0	86.1
	SAS	60 / 60	6.1	15.9	61.5	86.4
		80 / 80	6.6	16.3	59.4	85.6
		100 / 100	6.0	16.0	62.1	86.1
SY 76-22	ADV	22 / 20	5.6	14.3	61.0	87.0
		42 / 40	5.1	14.0	63.7	87.4
		62 / 60	5.5	14.2	61.6	86.9
	EVO	62 / 41	4.1	13.5	69.5	88.5
		82 / 61	4.9	14.0	65.0	88.0
		102 / 81	4.7	13.6	65.1	88.0
		122 / 101	5.1	14.1	64.1	87.7
	SAS	62 / 60	4.8	13.9	65.8	87.7
		82 / 80	5.3	14.2	63.1	87.1
		102 / 100	5.4	14.2	62.1	87.2

Next, a graphical analysis of the temperature data was prepared in order to discover the sensitivity of volumetric properties to changes in temperature, associated with each WMA additive. The graphs for Advera are presented in Figures 7 - 10, those for Evotherm are shown in Figures 11 - 14, and those for Sasobit in Figures 15 - 18.

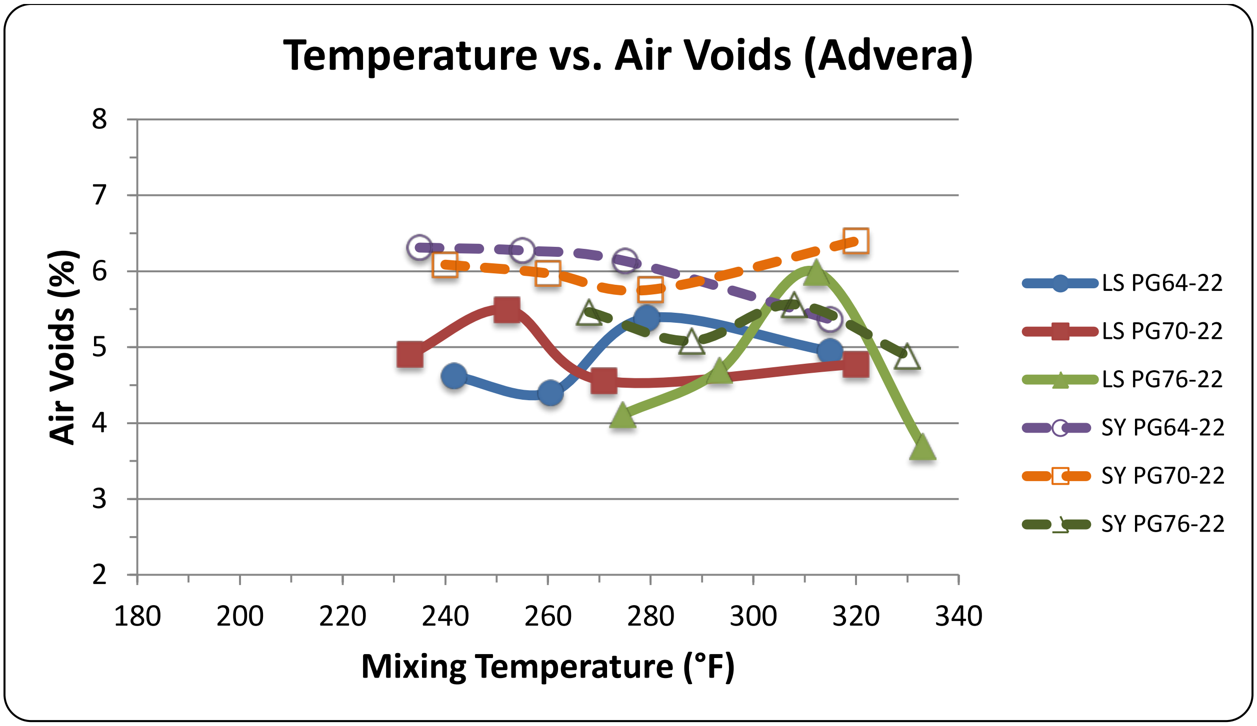


Figure 7. Advera – Relationship of Mixing Temperature and Air Voids

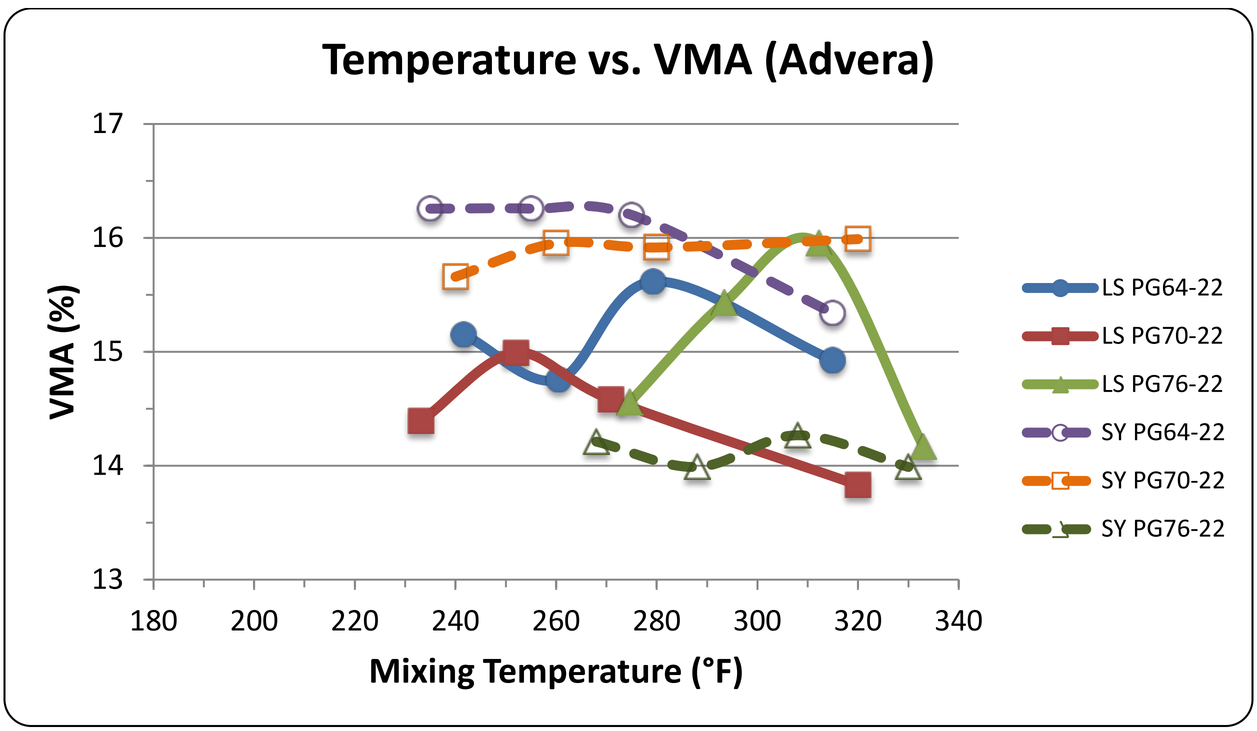


Figure 8. Advera – Relationship of Mixing Temperature and Voids in the Mineral Aggregate (VMA)

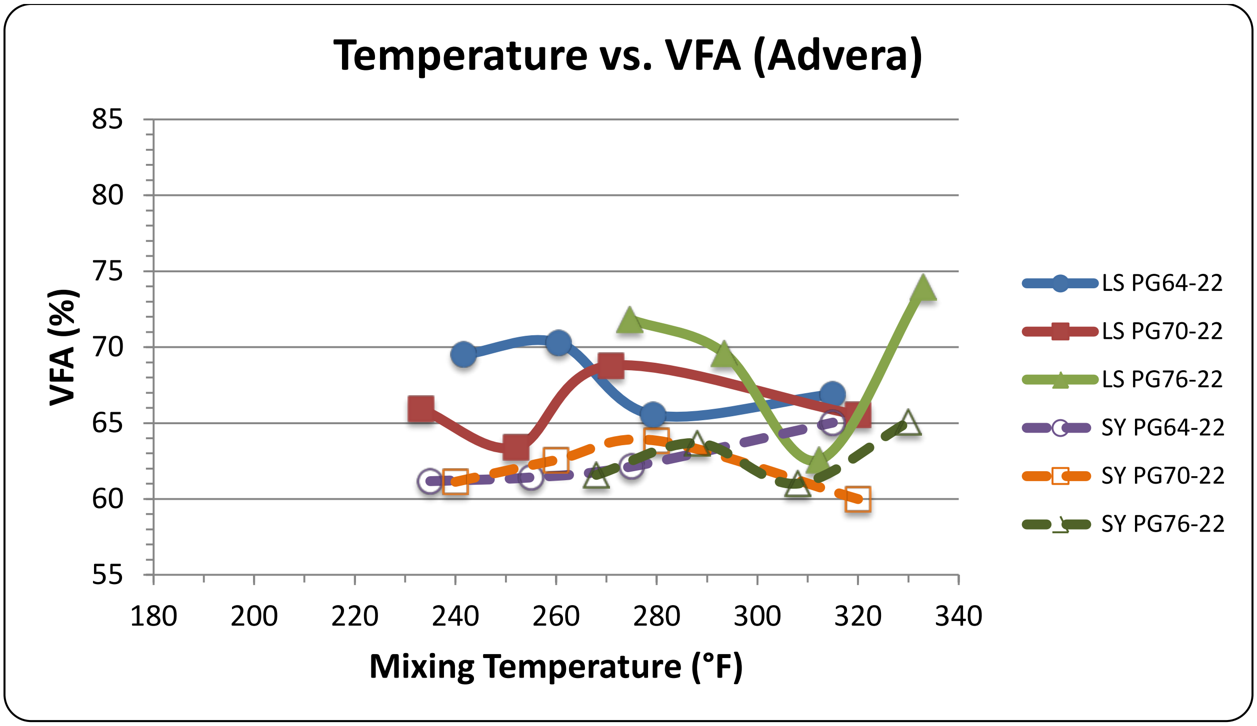


Figure 9. Advera – Relationship of Mixing Temperature and Voids Filled with Asphalt (VFA)

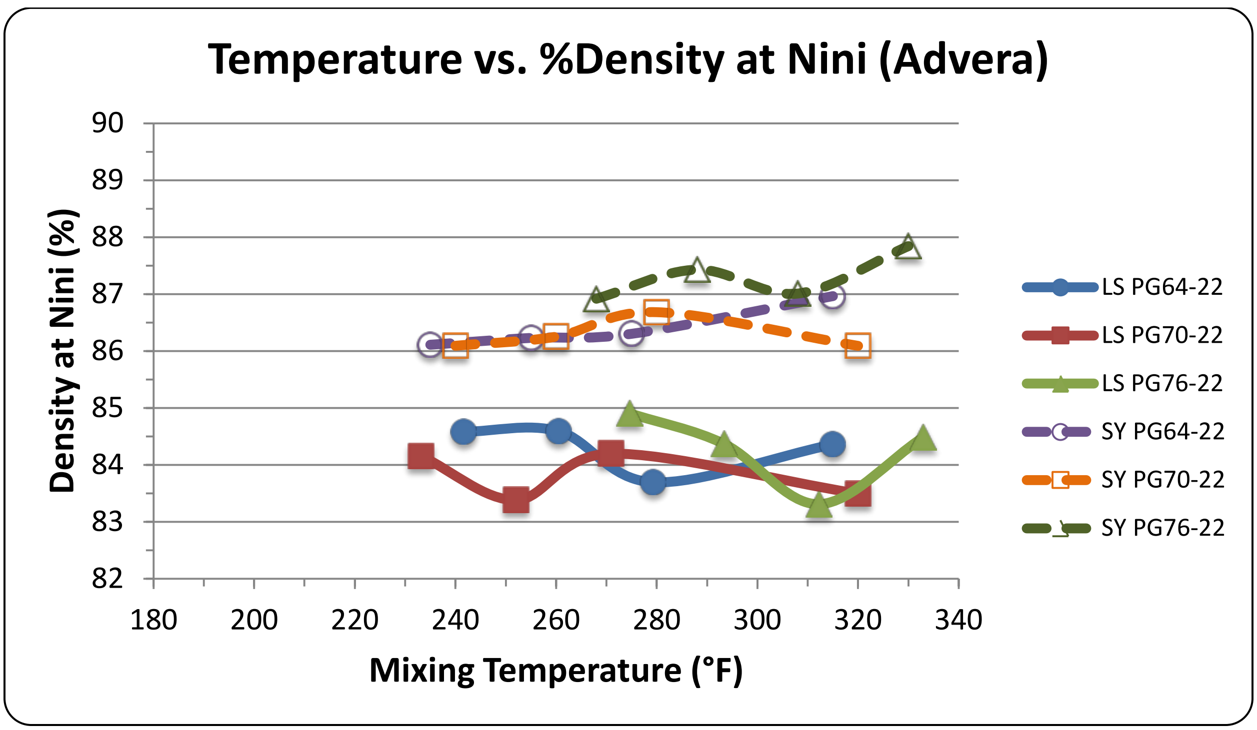


Figure 10. Advera – Relationship of Mixing Temperature and % Density at $N_{initial}$ Gyrations

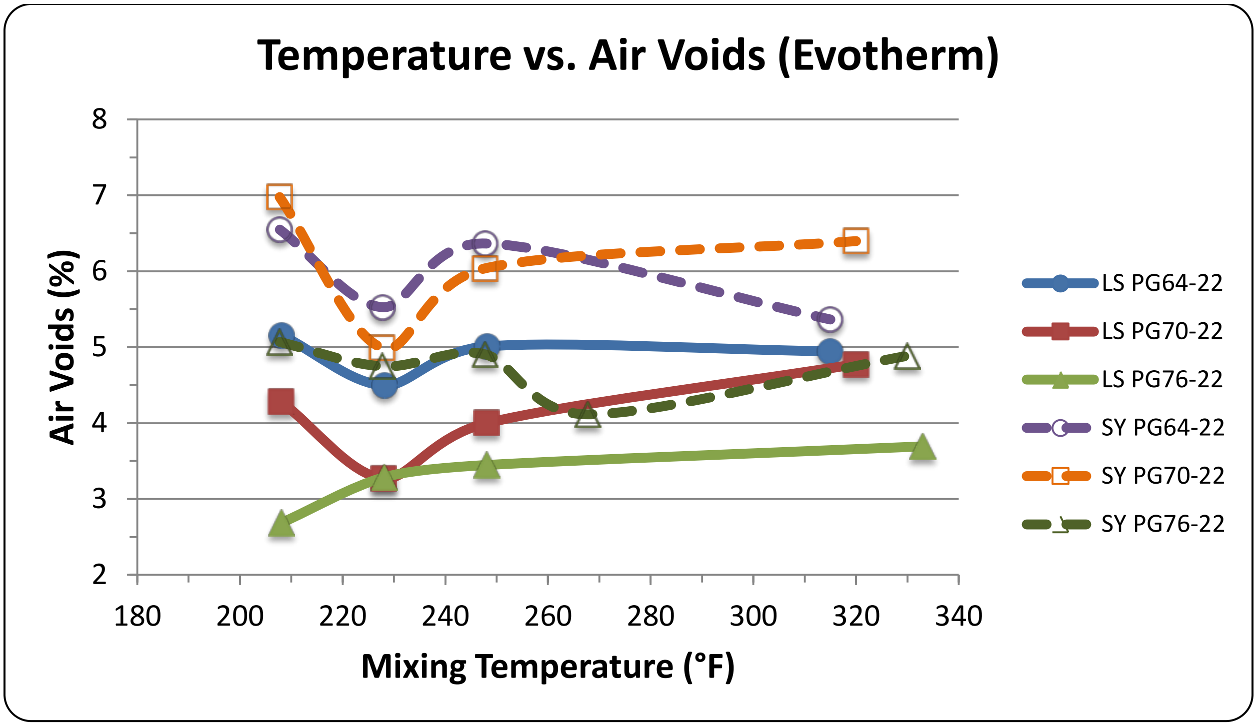


Figure 11. Evotherm – Relationship of Mixing Temperature and Air Voids

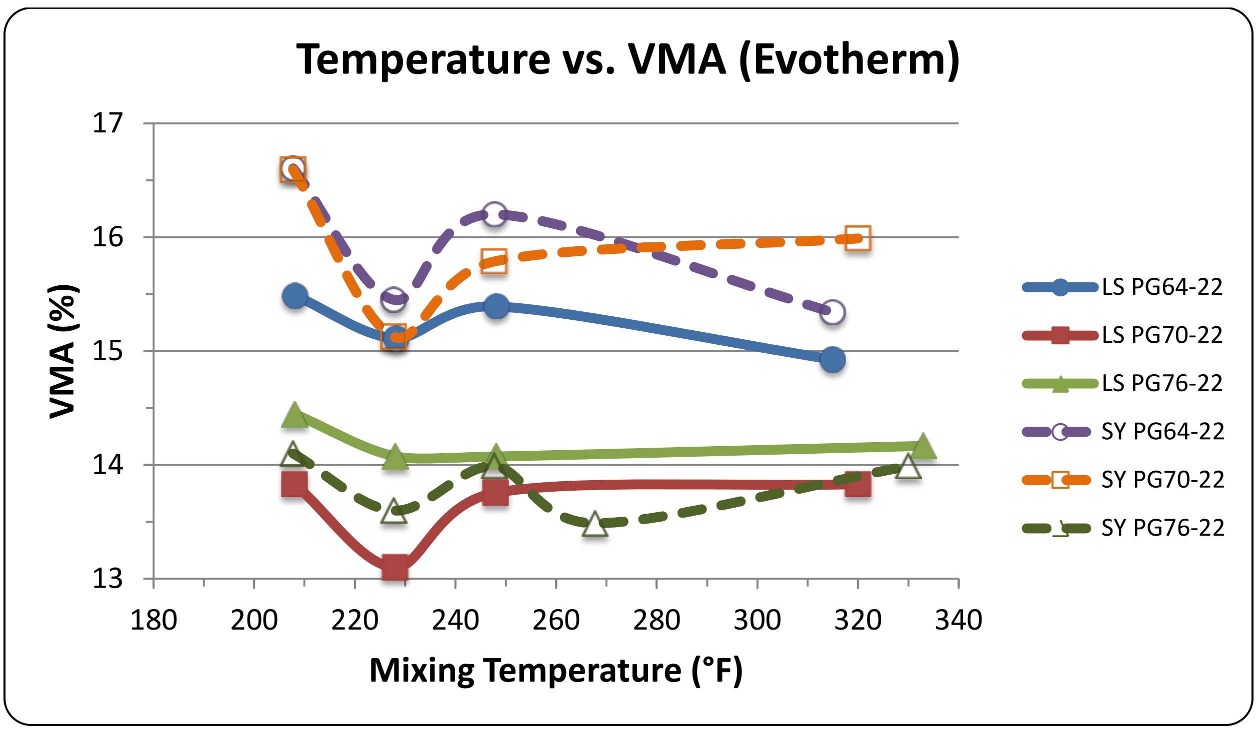


Figure 12. Evotherm – Relationship of Mixing Temperature and Voids in the Mineral Aggregate (VMA)

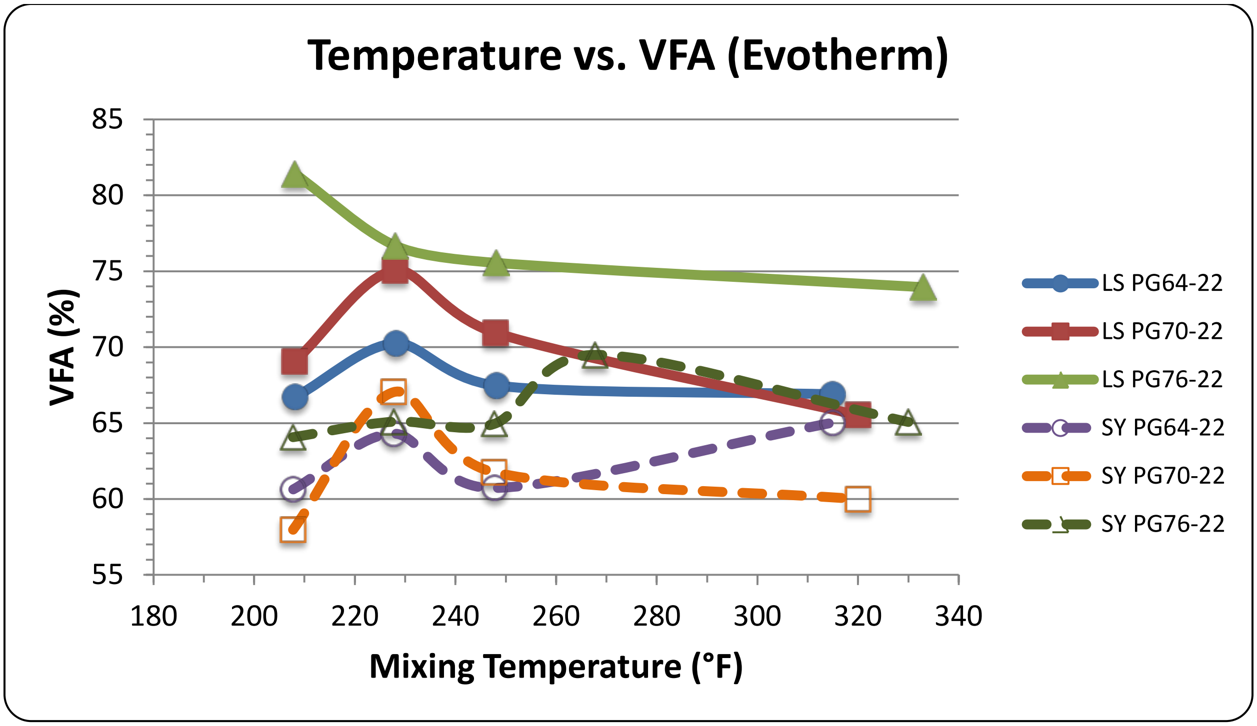


Figure 13. Evotherm – Relationship of Mixing Temperature and Voids Filled with Asphalt (VFA)

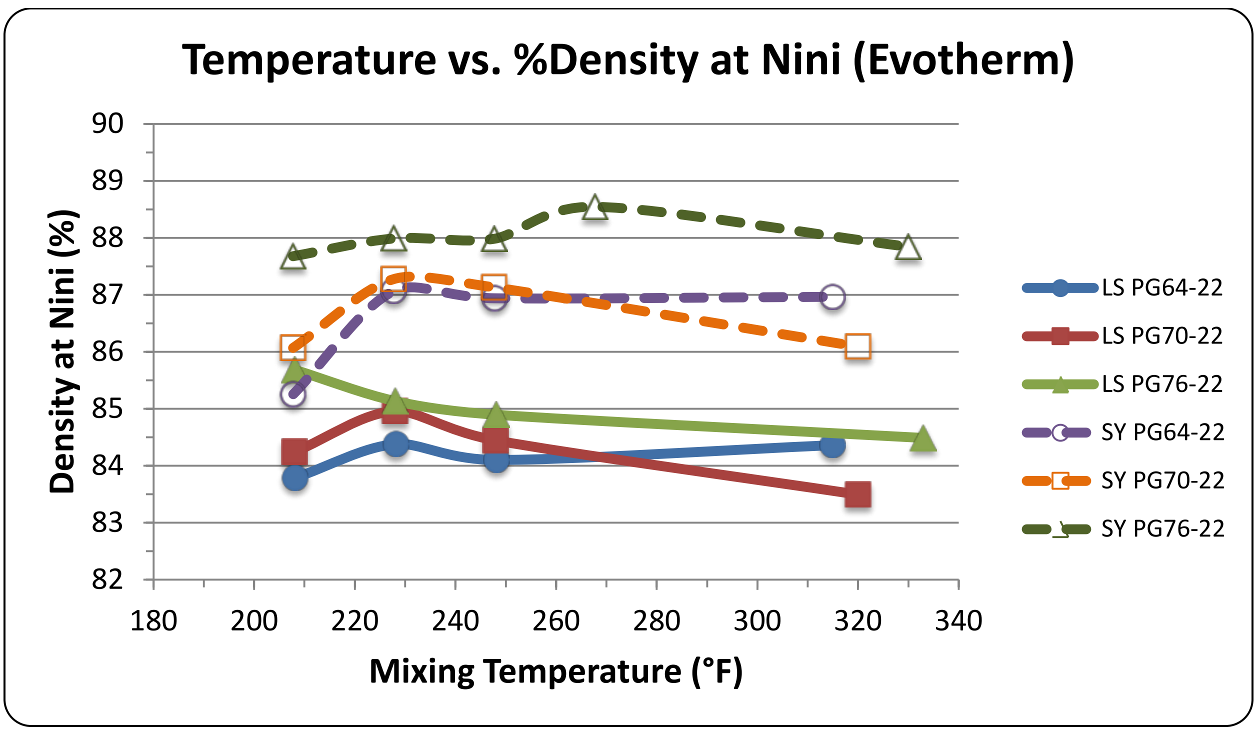


Figure 14. Evotherm – Relationship of Mixing Temperature and % Density at $N_{initial}$ Gyrations

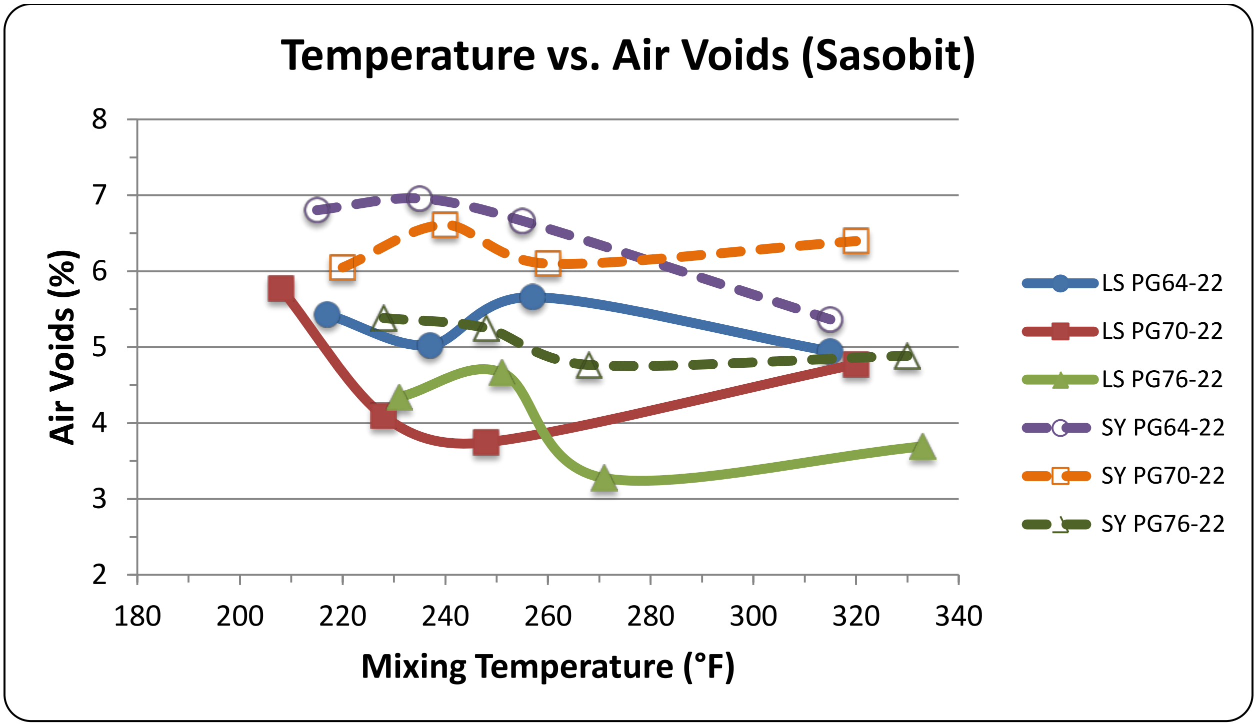


Figure 15. Sasobit – Relationship of Mixing Temperature and Air Voids

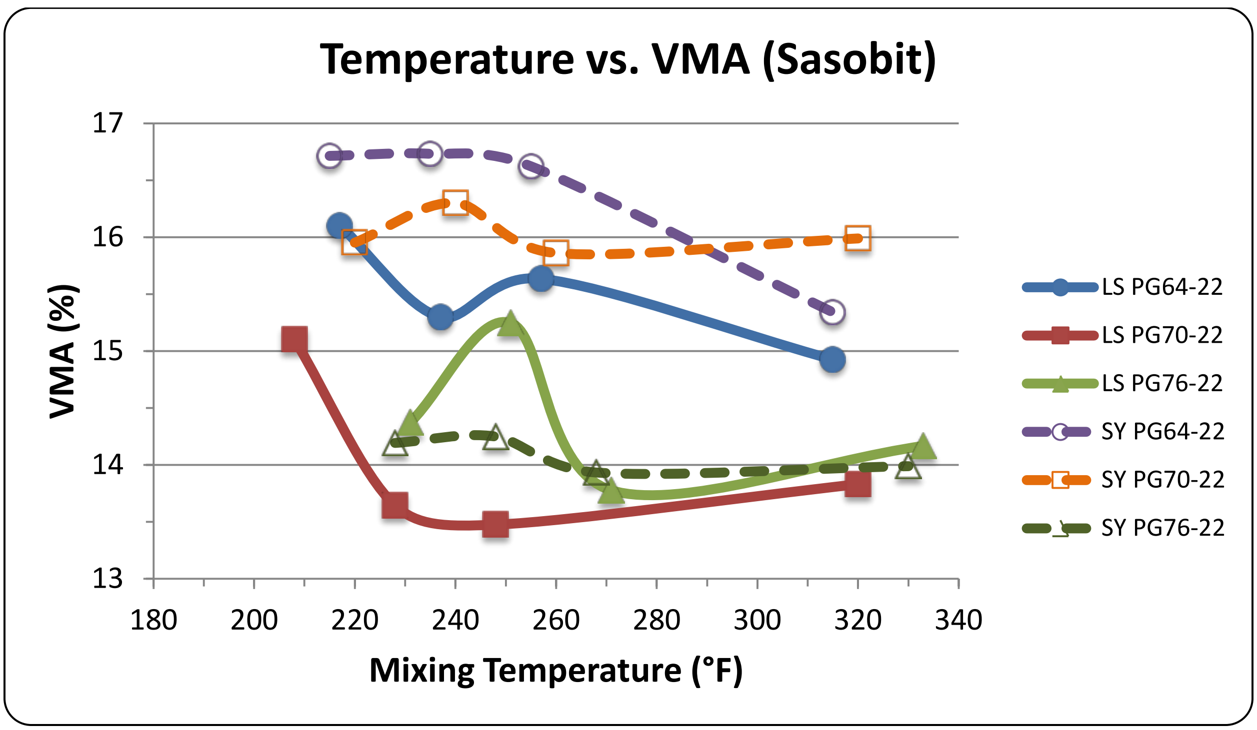


Figure 16. Sasobit – Relationship of Mixing Temperature and Voids in the Mineral Aggregate (VMA)

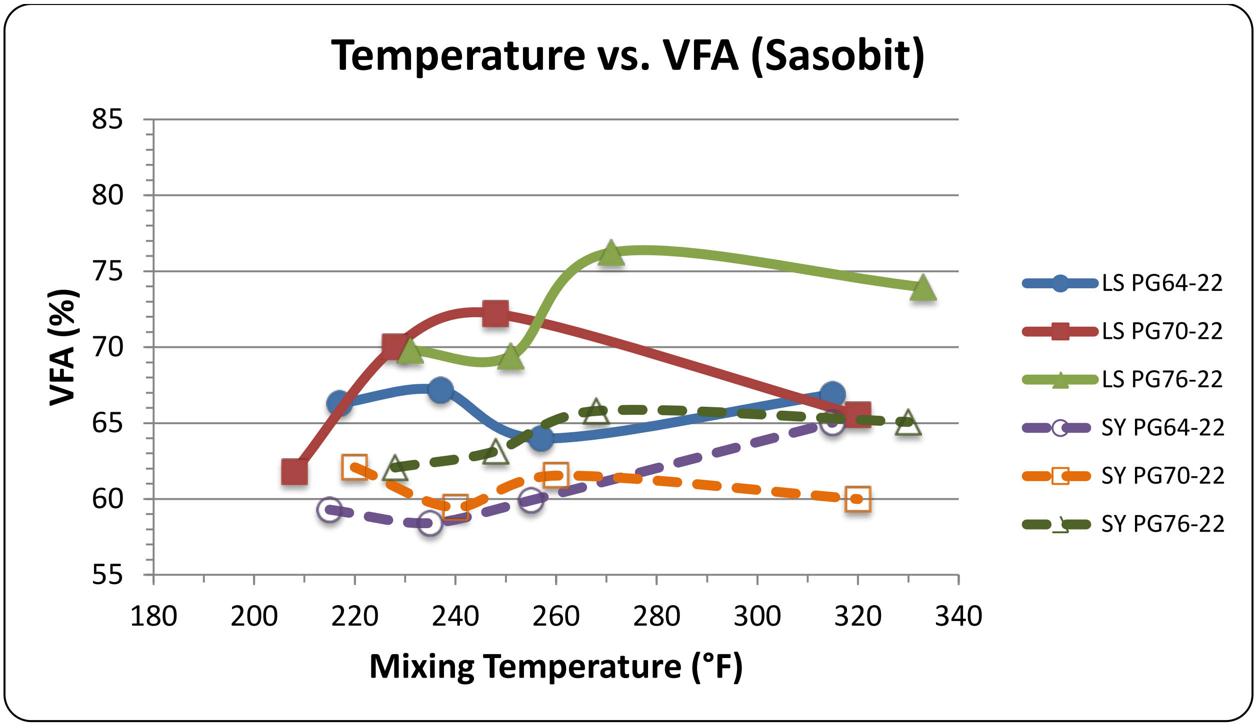


Figure 17. Sasobit – Relationship of Mixing Temperature and Voids Filled with Asphalt (VFA)

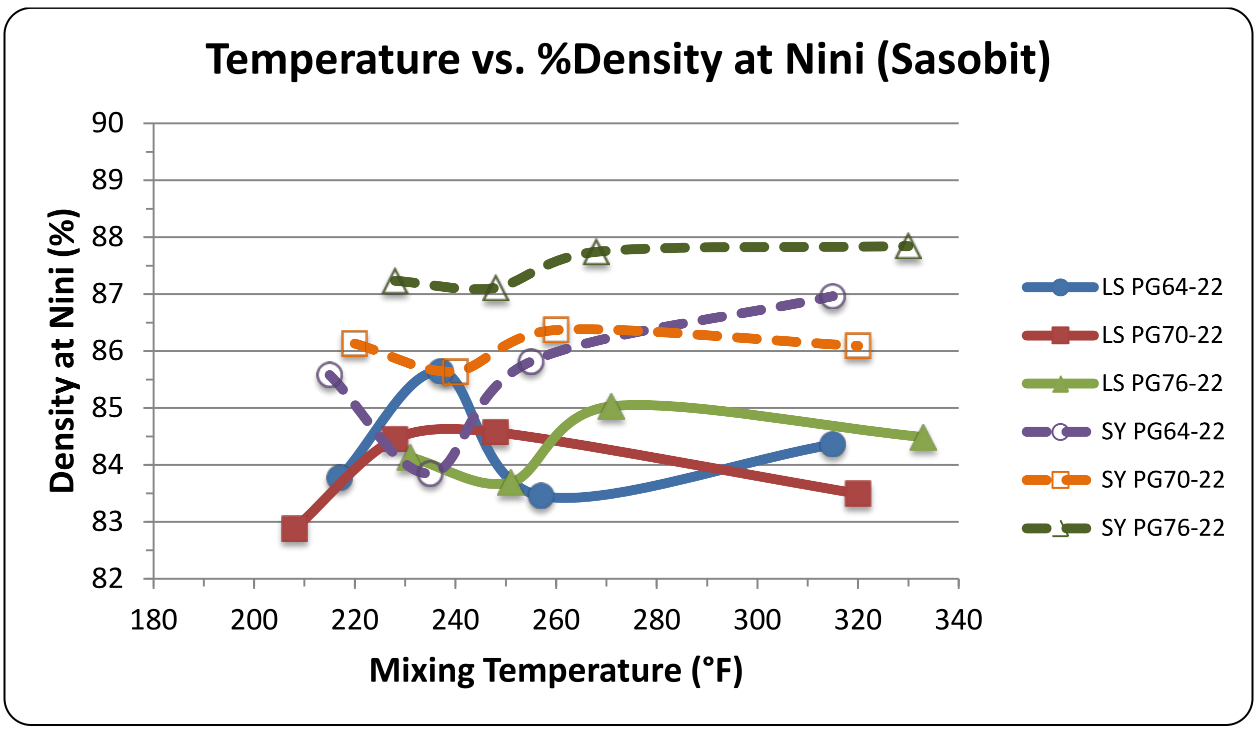


Figure 18. Sasobit – Relationship of Mixing Temperature and % Density at $N_{initial}$ Gyrations

The logical expectation is that as the temperature of the mixtures decreases, the workability of the mixture will also decrease, leading to an increase in air voids with decreasing temperature. However, if the warm mix additives are capable of providing adequate workability at decreased temperatures, this change could be less noticeable when warm mix additives are used. According to the preceding figures, mixtures containing the Advera additive did not provide consistent trends with respect to changes in volumetric properties. As the temperature of the mixture decreased, air voids sometimes increased, and sometimes decreased. The VMA values were also erratic, with the changes in VMA being heavily dependent upon the mixture type. Values for VFA and %Density at $N_{initial}$ were also variable, although the values for the syenite mixes were more consistent overall than those for the limestone mixes. It was believed that the difficulty in the mixing process for this additive could have significantly affected the consistency of test results. Due to this uncertainty and the ability to coat the aggregates at the lower temperatures, a temperature reduction of 40 °F was selected as the optimum value for the Advera mixes. This temperature reduction was based primarily on the ability of the binder to coat the aggregates at the given temperature. At temperature reductions greater than 40 °F, proper binder coatings were more difficult to achieve, resulting in a practical limit for the temperature of mixtures containing the Advera additive.

For the Evotherm mixes, there was relatively little change in air voids for mixing temperatures as low as approximately 250°F. As the mixing temperature decreased to approximately 230 °F, air voids for all mixes actually decreased, indicating the relative ease with which the mixes could be handled at that temperature. Further decreases in temperature, however, created an increase in air voids, and proper coating became more difficult to achieve. Similar trends were noted for VMA, VFA, and %Density at $N_{initial}$, suggesting that the benefits of the Evotherm additive reached maximum effectiveness at approximately 230 °F, or at about 80 °F below hot mix production temperatures.

The Sasobit mixes displayed similar trends in that air voids, VMA, VFA, and %Density at $N_{initial}$ values were relatively consistent as production temperatures decreased to 60 °F below HMA production temperatures. Only the PG 64-22 mixes showed an immediate increase in air voids as the temperature decreased, suggesting that the Sasobit product may be more effective with polymer modified asphalt binders. As temperatures dropped further, volumetric properties became more erratic, with increases in air voids indicating less workability. For these reasons, an optimum reduction in temperature of approximately 60 °F was selected for the Sasobit mixes. A summary of the optimum temperature selections for each additive and mixture is given in Table 8.

Table 8. Summary of Optimum Temperatures for Mixtures with WMA Additives

Mixture	Additive	Mixing Temperatures			Compaction Temperature of the Mixture
		Binder	Aggregate	Composite	
LS PG64-22	ADV	315	268	271	255
	EVO	262	226	228	222
	SAS	257	257	257	235
LS PG70-22	ADV	320	278	280	260
	EVO	262	226	228	222
	SAS	248	248	248	240
LS PG76-22	ADV	333	291	293	273
	EVO	262	226	228	222
	SAS	271	271	271	253
SY PG64-22	ADV	315	273	275	255
	EVO	262	226	228	222
	SAS	255	255	255	235
SY PG70-22	ADV	320	278	280	260
	EVO	262	226	228	222
	SAS	260	260	260	240
SY PG76-22	ADV	330	286	288	273
	EVO	262	226	228	222
	SAS	268	268	268	253

To more thoroughly assess the data, a statistical analysis (analysis of variance, or ANOVA) was performed for each additive to assess the significance of temperature reductions on the volumetric properties, as well as any interacting effects of binder grade and temperature reduction. Aggregate type served as a blocking factor. All analyses were performed using statistically robust procedures including checks for normally distributed residuals and constant variance, and a 95 percent level of significance was assigned as the determination of significance. A summary of results for the Advera mixes is given in Table 9, such that p-values less than 0.05 (bold) indicate a statistically significant difference.

Table 9. Statistical Results for Temperature Analysis of Advera

Factors/Interactions	P-values for Responses			
	AV	VMA	VFA	$\%G_{mm}$ at N_{ini}
Aggregate Type	**<0.0001**	0.0872	**<0.0001**	**<0.0001**
Temperature Reduction	0.0796	0.1690	0.2140	0.3331
PG Grade	**0.0097**	**0.0048**	0.0527	**0.0008**
PG*Temp Reduction	**0.0382**	0.9494	**0.0039**	**0.0355**

Aggregate type was largely significant, as was PG Grade. This is reasonable given the relationship of each to the volumetric properties. Temperature reduction was not significant for any of the volumetric parameters. However, there was a significant interaction evident for temperature reduction and PG Grade. This interaction is shown in Figure 19, which displays the air void levels for HMA, and the 1st, 2nd, and 3rd temperature reductions. For the PG 64-22 and PG 76-22 mixes, the resulting air voids when Advera was included were, on average, higher than that for the HMA mix. Some reduction was noted for the 1st temperature reduction of the PG 70-22 mix. It was also noted that the magnitude of the differences in air voids was greater for the polymer-modified binders than for the unmodified binder, meaning that the polymer-modified binders were more sensitive to the additive, and could realize a more significant change in air voids when the additive was included.

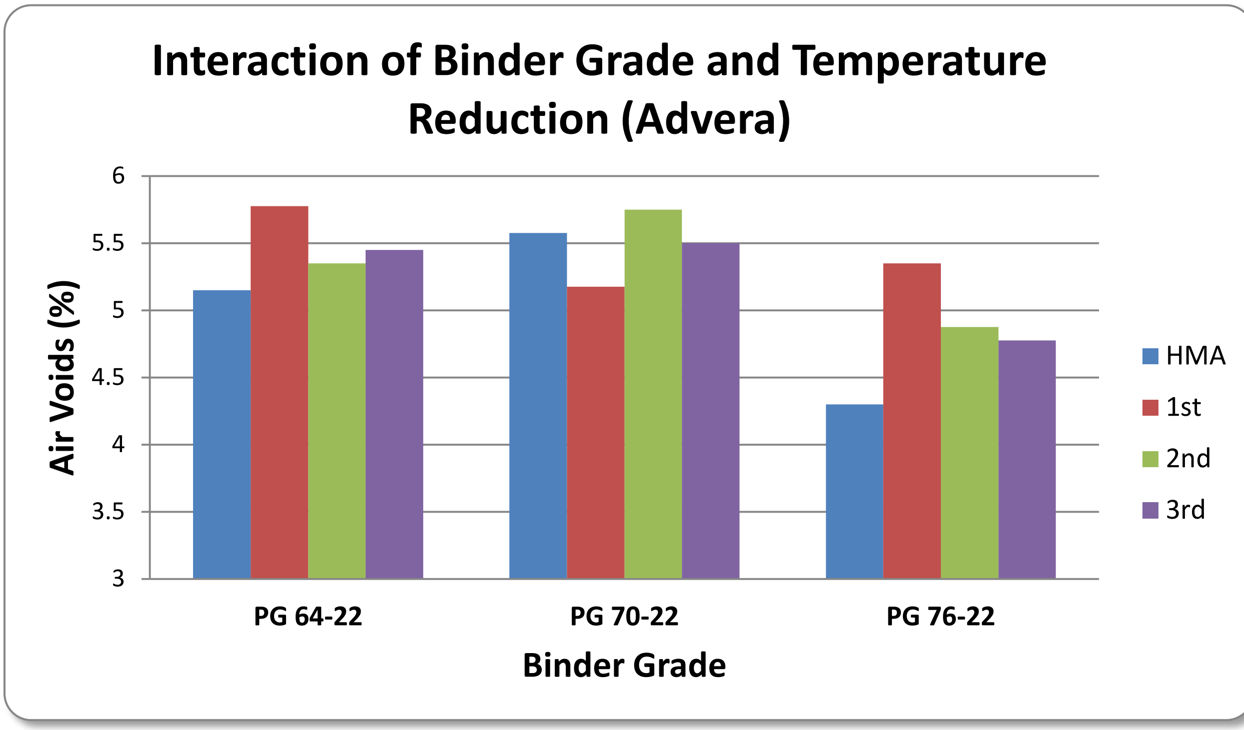


Figure 19. Advera – Interaction for Effects of Binder Grade and Temperature Reduction on Air Voids

The ANOVA results for the Evotherm mixtures are given in Table 10, and statistically significant results are shown in bold type. Aggregate type was significant for all response variables, as was PG Grade. However, PG Grade was included in significant interactions for air voids and VFA responses. The air voids interaction of PG Grade and Temperature Reduction is shown in Figure 20.

Table 10. Statistical Results for Temperature Analysis of Evotherm 3G

Factors/Interactions	P-values for Responses			
	AV	VMA	VFA	%G_{mm} at N_{ini}
Aggregate Type	<0.0001	<0.0001	<0.0001	<0.0001
Temperature Reduction	0.0017	0.0721	0.0065	0.0360
PG Grade	<0.0001	<0.0001	<0.0001	<0.0001
PG*Temp Reduction	0.0070	0.8000	0.0126	0.0740

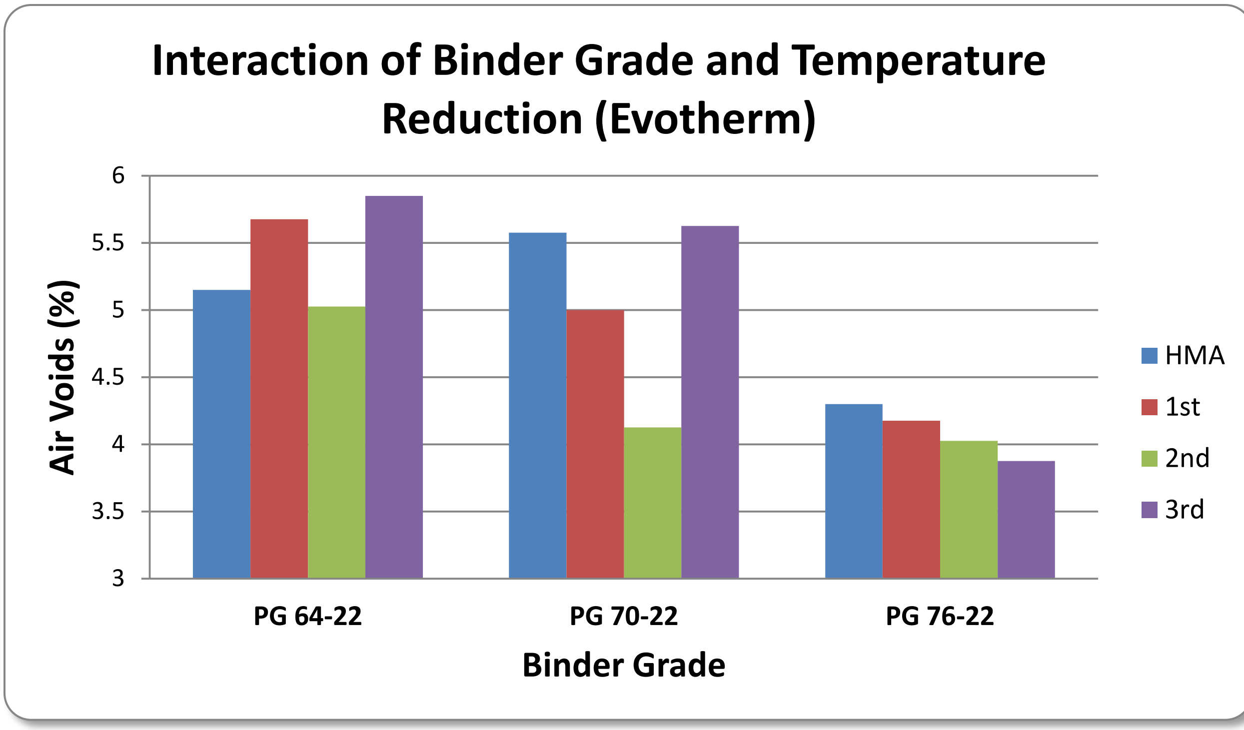


Figure 20. Evotherm – Interaction for Effects of Binder Grade and Temperature Reduction on Air Voids

From the interaction graph, it is seen that in general, air void content decreased as binder grade increased. For the PG 64-22 and PG 70-22 binder grades, the 2nd temperature reduction displayed reduced air voids and the 3rd temperature reduction showed increased air voids. However, for the PG 76-22 binder, air voids continued to decrease as the temperature decreased. This suggests that the more highly modified binders may be most compatible with the Evotherm product. Additionally, the magnitudes of the differences in air voids for the PG 70-22 binder appeared more exaggerated, indicating that the PG 70-22 could be more sensitive to changes in temperature than the other binder grades.

The same type of analysis was performed for the Sasobit mixtures, and the results are given in Table 11. PG Grade was significant for all responses, while temperature reduction was only significant for percent air voids and VFA. Although the interaction of PG Grade and Temperature reduction was not significant for air voids, the p-value could be considered marginal, and the interaction graph is given in Figure 21. While the PG 70-22 and PG 76-22 binders show a reduction in air voids for the first temperature reduction, the PG 64-22 binder does not, again indicating that the polymer modified binders may gain more benefit from the warm mix additives than the non-modified binders.

Table 11. Statistical Results for Temperature Analysis of Sasobit

Factors/Interactions	P-values for Responses			
	AV	VMA	VFA	%G_{mm} at N_{ini}
Aggregate Type	<0.0001	0.0001	<0.0001	<0.0001
Temperature Reduction	0.0075	0.0673	0.0117	0.4187
PG Grade	<0.0001	<0.0001	<0.0001	0.0184
PG*Temp Reduction	0.0776	0.3568	0.0181	0.6989

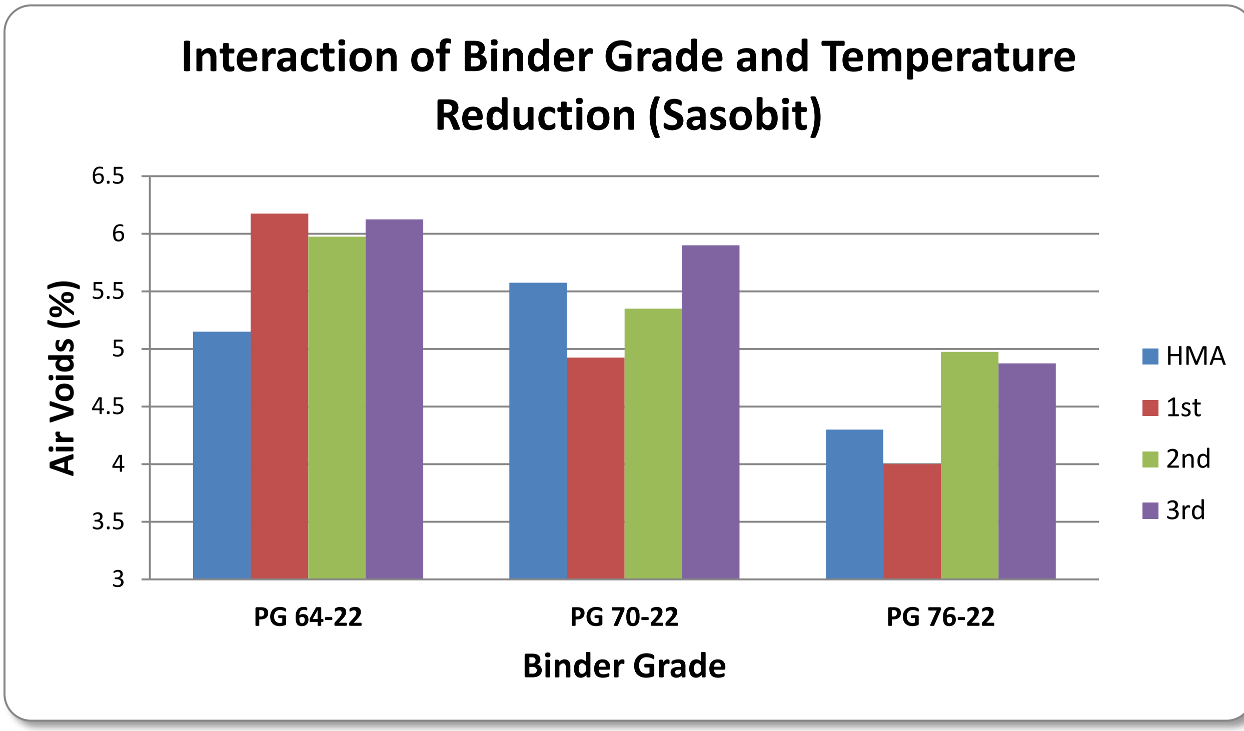


Figure 21. Sasobit – Interaction for Effects of Binder Grade and Temperature Reduction on Air Voids

In general, the percent air voids decreased as binder grade increased. This indicates that higher binder grades may achieve improved compactability. For the Evotherm additive in particular, the PG 76-22 binder experienced greater actual temperature reductions than the other binder grades, so the air void contents were expected to be higher for samples containing this binder. Since the air voids were actually lower, this indicates that the higher binder grades benefitted more from Evotherm than lower binder grades. Overall, the benefits realized by each warm mix additive can be expected to vary according to the additive, chosen temperature reduction, and binder grade. Thus, the target production temperature should be determined for each individual mix design. Also, since the mixing temperatures of the aggregate and binder do not necessarily have to be the same, it is important to specify these parameters for each mix design.

Comparisons of Hot Mix and Warm Mix

The purpose of this set of comparisons was to determine how sensitive a mixture is to the addition of a WMA additive, and to assess whether or not any additional compactability provided by the additives could generate a reduction in required binder content for a mix. If the optimum binder content could be reduced, then an additional potential savings could exist, reducing the cost of oil – the most expensive component – in a mixture.

Once the optimum temperatures for the warm mix designs were identified, the volumetric properties of the warm mixes were compared to those of the hot mixes. The properties of the warm mix asphalt mixtures at their optimum production temperatures are summarized in Tables 12 through 14.

The most informative volumetric parameter to identify potential savings in binder content is air voids. As binder content increases, air void content decreases. Thus, if the air void content decreases significantly when the WMA technology is incorporated, then a reduction in binder content (with associated savings) may be warranted. In Table 15, the effect (increase or decrease) on percent air voids is indicated for each mixture when the WMA additive was incorporated at the optimum temperature reduction.

Table 12. Mixture Properties at Optimum Temperature for Advera Mixes

Limestone with Advera						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Binder Content (%)	6.0	5.6	5.8	5.0	4.7	5.4
Air Voids (%)	5.4	4.6	4.7	4.0	5.7	4.2
VMA (%)	15.6	14.6	15.4	12.6	12.6	13.1
VFA (%)	65.5	68.8	69.6	68.3	54.8	68.1
Gsb	2.517	2.523	2.533	2.544	2.521	2.53
Gse	2.603	2.598	2.599	2.629	2.633	2.632
Max Sp. Gr. (Gmm)	2.383	2.392	2.386	2.438	2.452	2.426
DP	1	1.1	1	1.4	1.77	1.1
Pbe (%)	4.7	4.6	5.1	3.768	3.052	3.918
Gb	1.026	1.024	1.023	1.026	1.024	1.023
Height at N_{des}	123.0	121.2	121.9	118.3	118.7	119.5
Gmm at N_{ini}	83.7	84.2	84.4	85.4	83.7	83.5
Mix Temp. – Binder	315	320	333	315	320	333
Mix Temp. - Aggregate	268	278	291	268	278	291
Composite Mix Temp.	271	280	293	271	280	293
Compaction Temp.	255	260	273	255	260	273
Syenite with Advera						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
Ndes	75	100	125	75	100	125
Binder Content (%)	4.9	4.8	4.8	4.1	4.0	3.9
Air Voids (%)	6.1	5.8	5.1	4.3	5.7	3.85
VMA (%)	16.2	15.9	14.0	13.2	14.6	13.1
VFA (%)	62.2	63.9	63.7	67.3	60.9	70.2
Gsb	2.596	2.595	2.564	2.606	2.599	2.605
Gse	2.621	2.613	2.623	2.624	2.603	2.634
Max Sp. Gr. (Gmm)	2.437	2.432	2.441	2.466	2.452	2.463
DP	0.9	1.1	1.5	1.33	1.27	1.03
Pbe (%)	4.548	4.537	3.944	3.847	3.936	3.993
Gb	1.026	1.026	1.023	1.026	1.024	1.023
Height at Ndes	118.7	118.1	116.75	115.4	115.2	114.4
Gmm at Nini	86.3	86.7	87.5	88.05	87	88.2
Mix Temp. – Binder	315	320	330	315	320	330
Mix Temp. - Aggregate	273	278	286	273	278	286
Composite Mix Temp.	275	280	288	275	280	288
Compaction Temp.	255	260	273	255	260	273

Table 13. Mixture Properties at Optimum Temperature for Evotherm Mixes

Limestone with Evotherm						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Binder Content (%)	6.0	5.6	5.8	5.0	4.7	5.4
Air Voids (%)	4.6	3.2	3.4	4.0	5.4	4.1
VMA (%)	15.1	13.1	14.1	12.6	12.8	13.6
VFA (%)	69.5	75.4	76.1	68.6	57.6	70.3
Gsb	2.517	2.523	2.533	2.544	2.521	2.53
Gse	2.603	2.608	2.605	2.627	2.619	2.608
Max Sp. Gr. (Gmm)	2.383	2.4	2.391	2.437	2.44	2.407
DP	1	1.2	1	1.4	1.66	1.01
Pbe (%)	4.736	4.353	4.742	3.785	3.257	4.251
Gb	1.026	1.024	1.023	1.026	1.024	1.023
Height at N_{des}	122.2	119.1	120.2	117	118.8	120.4
Gmm at N_{ini}	84.3	85	2.391	85.9	83.5	83.9
Mix Temp. – Binder	262	262	262	262	262	262
Mix Temp. - Aggregate	226	226	226	226	226	226
Composite Mix Temp.	228	228	228	228	228	228
Compaction Temp.	222	222	222	222	222	222
Syenite with Evotherm						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Binder Content (%)	4.9	4.8	4.8	4.1	4	4.4
Air Voids (%)	5.3	5	4.7	4.9	5.7	4
VMA (%)	15.5	15.1	13.6	13.4	13.5	13.3
VFA (%)	65.5	67	65.1	63.2	57.8	69.7
Gsb	2.596	2.595	2.564	2.606	2.599	2.605
Gse	2.624	2.617	2.627	2.634	2.64	2.631
Max ThSpGr (Gmm)	2.438	2.417	2.443	2.475	2.483	2.461
DP	1.1	1.1	1.5	1.38	1.46	1.02
Pbe (%)	4.496	4.485	3.892	3.696	3.415	4.027
Gb	1.026	1.024	1.023	1.026	1.024	1.023
Height at N_{des}	117	116.8	115.7	115.35	114.85	115
Gmm at N_{ini}	87.2	87.3	88	87.8	87.4	88.2
Mix Temp. – Binder	262	262	262	262	262	262
Mix Temp. - Aggregate	226	226	226	226	226	226
Composite Mix Temp.	228	228	228	228	228	228
Compaction Temp.	222	222	222	222	222	222

Table 14. Mixture Properties at Optimum Temperature for Sasobit Mixes

Limestone with Sasobit						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
Ndes	75	100	125	75	100	125
Binder Content (%)	6.0	5.6	5.8	5.0	4.7	5.4
Air Voids (%)	5.7	3.8	3.3	4.1	5.4	4.5
VMA (%)	15.6	13.5	13.8	12.5	12.6	13.7
VFA (%)	63.7	72.1	76.2	67.4	57.6	67
Gsb	2.517	2.523	2.533	2.544	2.521	2.53
Gse	2.618	2.612	2.613	2.633	2.621	2.621
Max ThSpGr (Gmm)	2.395	2.403	2.397	2.442	2.442	2.417
DP	1.08	1.17	0.99	1.43	1.68	1.06
Pbe (%)	4.52	4.3	4.635	3.699	3.223	4.075
Gb	1.026	1.024	1.023	1.026	1.024	1.023
Height at Ndes	122.7	119.5	119.3	117.6	119.1	118.9
Gmm at Nini	83.4	84.6	85.0	85.7	83.4	83.3
Mix Temp. – Binder	257	260	271	257	260	271
Mix Temp. - Aggregate	257	260	271	257	260	271
Composite Mix Temp.	257	260	271	257	260	271
Compaction Temp.	235	240	253	235	240	253
Syenite with Sasobit						
NMAS	12.5mm	12.5mm	12.5mm	25.0mm	25.0mm	25.0mm
Binder Grade	PG 64-22	PG 70-22	PG 76-22	PG 64-22	PG 70-22	PG 76-22
N_{des}	75	100	125	75	100	125
Binder Content (%)	4.9	4.8	4.8	4.1	4.0	4.4
Air Voids (%)	6.7	6.1	4.8	4.7	5.4	4.3
VMA (%)	16.6	15.9	13.9	13.3	13.4	13.4
VFA (%)	59.8	61.4	65.8	64.9	59.8	68
Gsb	2.596	2.595	2.564	2.606	2.599	2.605
Gse	2.625	2.627	2.616	2.631	2.634	2.637
Max Sp. Gr. (Gmm)	2.439	2.443	2.434	2.472	2.478	2.466
DP	1.09	1.10	1.48	1.36	1.43	1.04
Pbe (%)	4.478	4.347	4.047	3.747	3.498	3.943
Gb	1.026	1.024	1.023	1.026	1.024	1.023
Height at N_{des}	118.7	118.2	116.6	115.8	115.0	114.9
Gmm at N_{ini}	85.8	86.4	87.7	88.0	87.6	87.7
Mix Temp. – Binder	255	260	268	255	260	268
Mix Temp. - Aggregate	255	260	268	255	260	268
Composite Mix Temp.	255	260	268	255	260	268
Compaction Temp.	235	240	253	235	240	253

Table 15. Change in Air Voids (%) Resulting from Incorporation of WMA Additive

		12.5mm Mixes			25.0mm Mixes		
Additive	Aggregate	PG 64-22	PG 70-22	PG76-22	PG 64-22	PG 70-22	PG 76-22
ADV	LS	↓ 0.4	↑ 0.2	↑ 1.0	↑ 0.2	↑ 1.3	↑ 0.8
	SY	↑ 0.6	↓ 0.4	↑ 0.2	↑ 0.2	↑ 1.0	↓ 0.6
EVO	LS	↓ 0.3	↓ 1.6	↓ 0.3	↑ 0.2	↑ 1.0	↑ 0.7
	SY	↓ 0.3	↓ 1.2	↓ 0.2	↑ 0.8	↑ 1.0	↓ 0.5
SAS	LS	↑ 0.8	↓ 1.0	↓ 0.4	↑ 0.3	↑ 1.0	↑ 1.1
	SY	↑ 1.1	↓ 0.3	↓ 0.1	↑ 0.6	↑ 0.7	↓ 0.2

In Table 15, the change in air voids content after adding the WMA technology is indicated. An up arrow indicates that the air voids increased, and a down arrow indicates that the air voids decreased. The mixes in which the WMA additive created a significant decrease in air voids are denoted with a green down arrow, those in which the additive created a significant increase in air voids are denoted with a red up arrow, and those in which the additive did not generate a significant change are denoted with a yellow arrow. Because a change of approximately 0.3 percent in air voids generally coincides with a 0.1 percent change in binder content, changes of less than 0.3 percent air voids were considered insignificant.

For the 12.5mm mixes, air voids decreased significantly for more than half of the mixes, most notably for the PG70-22 mixes. The 1.6 percent reduction in air voids for the 12.5mm Limestone PG70-22 mix with Evotherm corresponds to a potential reduction in binder content of approximately 0.5 percent, which is a significant savings. The 12.5mm Syenite PG70-22 mix with Evotherm would generate a binder savings of approximately 0.4 percent. For the 25.0mm mixes, however, air voids decreased significantly for only 2 of the 18 mixes; all decreases being associated with PG 76-22 binders. This suggests that the 12.5mm mixes are more accepting of the increased workability offered by the WMA additives, and that the coarser aggregate structure of the 25.0mm mixes can be more difficult to compact, even with the inclusion of the additives. As previously stated, WMA additives appear to benefit polymer-modified binders more than non-modified ones, particularly for the Evotherm and Sasobit additives. Trends were inconsistent for the Advera mixes.

Of the warm mix additives tested, Evotherm (followed by Sasobit) allowed for the greatest reduction in temperature with adequate homogeneity and ease of mixing. The laboratory mixing method for Advera likely contributed to the inconsistent results obtained for these samples. In general, the results obtained from each of the warm mix samples did not always follow intuitive thought. This reinforces the importance of including details concerning the specific additive when designing warm mix asphalt mixtures.

Next, the volumetric properties of optimum binder content (Pb_{opt}), effective binder content (Pbe), and dust proportion (DP) were investigated through statistical comparisons. A data summary is provided in Table 16. Then a paired t-test was used to compare the HMA and WMA equivalents for each of these properties, and the results are shown in Table 17.

Table 16. Summary Data for Optimum Binder Content, Effective Binder Content, and Dust Proportion

				Pb_{opt}		Pbe		DP	
Agg	PG	NMAS	Additive	HMA	WMA	HMA	WMA	HMA	WMA
LS	64	12.5	ADV	6	6	4.5	4.7	1.13	1
LS	70	12.5	ADV	5.6	5.8	4	4.6	1.11	1.1
LS	76	12.5	ADV	5.8	6.1	4.6	5.1	0.93	0.9
SY	64	12.5	ADV	4.9	5.5	4.4	5.2	1.07	0.9
SY	70	12.5	ADV	4.8	5.2	4.3	4.9	1.08	1
SY	76	12.5	ADV	4.8	5.2	4	4.3	1.33	1.4
LS	64	25	ADV	5	5.7	3.7	4.5	1.41	1.2
LS	70	25	ADV	4.7	5.4	3.1	3.8	1.46	1.4
LS	76	25	ADV	5.4	5.4	4.1	3.9	1.07	1.1
SY	64	25	ADV	4.1	4	3.7	3.7	1.32	1.4
SY	70	25	ADV	4	4.5	3.6	4	1.42	1.3
SY	76	25	ADV	4.4	4.4	4	4	1.03	1
LS	64	12.5	EVO	6	6	4.5	4.7	1.13	1
LS	70	12.5	EVO	5.6	5.1	4	3.8	1.11	1.3
LS	76	12.5	EVO	5.8	5.3	4.6	4.2	0.93	1.1
SY	64	12.5	EVO	4.9	4.9	4.4	4.5	1.07	1.1
SY	70	12.5	EVO	4.8	5	4.3	4.7	1.08	1
SY	76	12.5	EVO	4.8	5.3	4	4.4	1.33	1.4
LS	64	25	EVO	5	4.8	3.7	3.6	1.41	1.5
LS	70	25	EVO	4.7	5.4	3.1	4	1.46	1.4
LS	76	25	EVO	5.4	5.4	4.1	4.2	1.07	1
SY	64	25	EVO	4.1	4.2	3.7	3.8	1.32	1.3
SY	70	25	EVO	4	4.5	3.6	3.9	1.42	1.3
SY	76	25	EVO	4.4	4.4	4	4	1.03	1
LS	64	12.5	SAS	6	6.8	4.5	5.3	1.13	0.9
LS	70	12.5	SAS	5.6	5.4	4	4.1	1.11	1.2
LS	76	12.5	SAS	5.8	5.5	4.6	4.3	0.93	1.1
SY	64	12.5	SAS	4.9	5.4	4.4	5	1.07	1
SY	70	12.5	SAS	4.8	5.5	4.3	5.4	1.08	0.9
SY	76	12.5	SAS	4.8	5.05	4	4.3	1.33	1.4
LS	64	25	SAS	5	4.9	3.7	3.6	1.41	1.5
LS	70	25	SAS	4.7	5.1	3.1	3.6	1.46	1.5
LS	76	25	SAS	5.4	5.7	4.1	4.4	1.07	1
SY	64	25	SAS	4.1	4.1	3.7	3.7	1.32	1.4
SY	70	25	SAS	4	4.3	3.6	3.8	1.42	1.3
SY	76	25	SAS	4.4	4.5	4.0	4.0	1.03	1.0

Table 17. Paired t-test Results for Optimum Binder, Effective Binder, and Dust Proportion

	All Mixes					
	Pb_{opt}		Pbe		DP	
	P-value	Significant?	P-value	Significant?	P-value	Significant?
ADV	0.0034	Yes	0.0019	Yes	0.0615	No
EVO	0.5479	No	0.1485	No	0.9161	No
SAS	0.0415	Yes	0.0285	Yes	0.7143	No
	12.5mm Mixes Only					
	P-value	Significant?	P-value	Significant?	P-value	Significant?
ADV	0.0126	Yes	0.0025	Yes	0.1607	No
EVO	0.7683	No	0.5576	No	0.4659	No
SAS	0.1818	No	0.0894	No	0.7180	No

When the mixes were converted from HMA to WMA and all data were considered, the changes in optimum and effective binder content were significant for both the Advera and Sasobit mixes, but not for Evotherm. A statistically significant difference would be a great advantage if the optimum binder contents decreased with the change to WMA. However, for Advera, the average binder content for HMA was 4.96 percent, while that for WMA was 5.27 percent. For Sasobit, the significant increase was smaller, with an average binder content of 4.96 and 5.19 percent for the HMA and WMA mixes, respectively. When considering effective binder content, similar trends were noted in that significant increases in effective binder content were present for the Advera and Sasobit additives. No significant differences were present when comparing the dust proportion of HMA and WMA.

From the discussion of change in air voids when converting a mixture from HMA to WMA, it was noted that the 12.5 mm mixes saw more air void reductions than the 25.0mm mixtures. Therefore, the 12.5mm and 25.0mm mixtures could behave differently. A separate t-test was performed for each additive, including only the 12.5mm mixes. In this analysis, only the Advera additive produced a statistically significant change in optimum binder content. The average optimum binder contents were 5.32 and 5.63 for the HMA and WMA mixtures, respectively. Effective binder content was similar, with average values of 4.30 and 4.80 for HMA and WMA, respectively.

In practice, it is valuable to know that optimum binder content could increase when converting a mixture to WMA. One possibility for advertising warm mix is that the additional compactability of the warm mixes could allow the designer to reduce the optimum binder content for a mixture because this additional workability could substitute for the addition of binder, allowing the mixture to be produced at a lower cost. The amount of potential binder content reduction will likely depend on the additive used and the aggregate size, as well as the selected production temperature. In this study, Evotherm was the only additive that was consistently capable of not significantly increasing binder content requirements for a mixture, while also allowing for the greatest temperature reductions of the additives tested. Overall, WMA additives should not be expected to always generate significant savings in binder usage, though certain individual mixtures may benefit from this advantage.

Sensitivity of WMA to Changes in Binder Content

Another primary objective of this study was to examine the sensitivity of warm mix asphalt to changes in binder content as compared to hot mix asphalt. When hot mix asphalt is produced, binder content will experience some natural variation, but is expected to be maintained within a certain specification limit. In Arkansas, a tolerance of ±0.3 percent from the design value is allowed for Quality Control/Quality Assurance (QC/QA) testing. This limit is imposed because greater changes in binder content can significantly affect the volumetric properties and subsequent performance of the mix. Warm mix asphalt should behave similarly to hot mix asphalt; however, due to the variability in the temperatures, the sensitivity of WMA mixes to fluctuations in binder content could be greater. If WMA mixes are similar or less sensitive than HMA mixes, then the current QC/QA specification limits will be appropriate for WMA. However, if WMA mixes are more sensitive than HMA mixes to changes in binder content, then adjustments to the existing QC/QA specification may be necessary.

The sensitivity of warm mix asphalt to changes in binder content was evaluated by producing each mixture at the optimum binder content, at 0.5 percent below optimum binder content, and at 0.5 percent above optimum binder content. Each mixture was produced at its optimum temperature, as previously established, so that the only changes between samples were the intentional variations in binder content. The volumetric properties were established for each comparison, and used to determine whether WMA mixes were more or less sensitive to these changes than HMA mixes. The resulting data, including average values, is shown in Tables 18 through 21.

Table 18. Volumetric Properties for HMA Mixes at Varied Binder Content

Mix Design	Pb	%AV	VMA	VFA	Height @ N_{des}	G_{mm}@N_{ini}	DP	Pbe
12.5mm LS 64-22	opt - 0.5%	5.9	14.7	59.8	122	83	1.2	4
	opt	4.9	15	67	121.5	83.8	1.1	4.5
	opt + 0.5%	3.4	14.7	76.5	121	84.8	1	5
12.5mm LS 70-22	opt - 0.5%	6.2	14	56.1	119.9	82.4	1.4	3.5
	opt	4.8	13.9	65.35	119.6	83.5	1.3	4
	opt + 0.5%	3.9	14.1	72.5	118.3	84.2	1.1	4.5
12.5mm LS 76-22	opt - 0.5%	7.1	13.9	49.2	120.1	81.4	1.5	3
	opt	3.7	14.2	73.8	119.8	84.5	1	4.6
	opt + 0.5%	2.6	14.3	81.5	199.4	85.5	0.9	5.1
12.5mm SY 64-22	opt - 0.5%	8.4	17	50.7	120.4	83.8	1.2	3.9
	opt	5.6	15.4	63.95	117.4	86.8	1.1	4.4
	opt + 0.5%	5.7	16.7	65.7	119.4	85.7	1	4.9
12.5mm SY 70-22	opt - 0.5%	7.5	16	52.9	117.2	85.1	1.3	3.8
	opt	6.4	16	60.1	118.05	86.1	1.1	4.3
	opt + 0.5%	4.8	15.7	69.2	117.1	87.3	1	4.8
12.5mm SY 76-22	opt - 0.5%	6.6	14.5	54.6	117	86.4	1.7	3.5
	opt	4.9	14	65.2	116.6	87.9	1.5	4
	opt + 0.5%	3.5	13.8	74.6	116.3	89	1.3	4.5
25mm LS 64-22	opt - 0.5%	5.2	12.4	58	117	84.9	1.7	3.2
	opt	3.8	12.2	69.1	116.45	85.9	1.4	3.7
	opt + 0.5%	2.5	12.1	79.2	116.7	86.9	1.3	4.2
25mm LS 70-22	opt - 0.5%	6.3	12.1	48.3	117.8	82.6	2.1	2.6
	opt	4.45	11.5	61.55	117	84.2	1.7	3.1
	opt + 0.5%	3.4	11.7	70.8	117	84.9	1.5	3.6
25mm LS 76-22	opt - 0.5%	4.6	12.7	64.1	118	83.5	1.2	3.6
	opt	3.35	12.75	73.55	117.6	84.3	1	4.1
	opt + 0.5%	2.8	13.3	79.3	117.5	84.8	0.9	4.6
25mm SY 64-22	opt - 0.5%	5.7	13.2	56.4	115.5	87.1	1.6	3.2
	opt	4.1	12.75	67.8	114.85	88.45	1.4	3.7
	opt + 0.5%	2.6	12.5	79.4	113.2	89.8	1.2	4.2
25mm SY 70-22	opt - 0.5%	6.1	13.1	53.8	115.5	87.4	1.6	3.1
	opt	4.7	13	63.55	114.35	88.55	1.4	3.6
	opt + 0.5%	4.2	13.6	68.9	115.4	88.4	1.2	4.1
25mm SY 76-22	opt - 0.5%	5.6	13.5	58.9	114.7	87.2	1.2	3.5
	opt	4.45	13.65	67.3	115.35	87.9	1	4
	opt + 0.5%	2.8	13.2	79	115.3	89	0.9	4.5

Table 19. Volumetric Properties for Advera Mixes at Varied Binder Content

Mix Design	PB	%AV	VMA	VFA	Height @ N_{des}	G_{mm}@N_{ini}	DP	Pbe
12.5mm LS 64-22	opt - 0.5%	6.8	16	57.7	123.3	82.4	1.2	4.2
	opt	5.4	15.6	65.5	123.2	83.7	1	4.7
	opt + 0.5%	4.5	16	72.1	123.1	84.4	0.9	5.2
12.5mm LS 70-22	opt - 0.5%	5.9	14.7	59.6	121.7	83.1	1.3	4
	opt	4.6	14.6	68.75	121.4	84.2	1.1	4.5
	opt + 0.5%	3.7	14.7	75.2	121.9	84.6	1	5
12.5mm LS 76-22	opt - 0.5%	6.1	15.7	60.9	123.1	82.9	1.1	4.3
	opt	4.7	15.4	69.6	121.9	84.4	1	4.8
	opt + 0.5%	3.5	15.4	77.3	121.6	85	0.9	5.3
12.5mm SY 64-22	opt - 0.5%	8.2	17.2	52.3	120.7	84.4	1.2	4.1
	opt	6.2	16.2	62.2	118.7	86.3	1.1	4.5
	opt + 0.5%	4.8	16.3	70.3	118.6	87.6	1	5.1
12.5mm SY 70-22	opt - 0.5%	6.9	15.9	56.4	118.1	85.5	1.2	4
	opt	5.8	15.9	63.85	118.1	86.7	1.1	4.5
	opt + 0.5%	4.0	15.4	73.9	118.2	88	1	5
12.5mm SY 76-22	opt - 0.5%	7.1	14.8	52	117	85.9	1.7	3.4
	opt	5.1	14	63.8	116.8	87.5	1.5	3.9
	opt + 0.5%	3.6	13.8	73.6	116.4	88.6	1.4	4.4
25mm LS 64-22	opt - 0.5%	5.7	13.1	56.3	119.3	84.1	1.6	3.3
	opt	4	12.6	68.25	118.25	85.4	1.4	3.8
	opt + 0.5%	4.3	14	69	117.3	85.7	1.2	4.3
25mm LS 70-22	opt - 0.5%	7.9	13.5	41.7	119.5	81.3	2.1	2.5
	opt	5.7	12.6	54.6	118.7	83.15	1.8	3.1
	opt + 0.5%	4.8	12.9	62.4	118.9	83.7	1.5	3.6
25mm LS 76-22	opt - 0.5%	5.9	13.5	56.7	120.3	82.4	1.3	3.4
	opt	4.2	13.1	68.05	119.5	83.45	1.1	3.9
	opt + 0.5%	4.5	14.4	68.9	119	83.6	1	4.4
25mm SY 64-22	opt - 0.5%	5.9	13.5	56.5	115.8	86.9	1.5	3.3
	opt	4.3	13.15	67.3	115.4	88.05	1.3	3.8
	opt + 0.5%	2.9	12.9	77.9	114.8	89.1	1.2	4.4
25mm SY 70-22	opt - 0.5%	7.9	15.5	49.2	115.9	85.5	1.5	3.4
	opt	5.7	14.6	60.85	115.2	87	1.3	3.9
	opt + 0.5%	4.8	14.9	67.5	114.2	87.8	1.1	4.4
25mm SY 76-22	opt - 0.5%	5.4	13.4	59.9	114.9	87.1	1.2	3.5
	opt	3.85	13.1	70.55	114.35	88.2	1	4.0
	opt + 0.5%	2.1	12.6	83.4	113.6	89.8	0.9	4.5

Table 20. Volumetric Properties for Evotherm Mixes at Varied Binder Content

Mix Design	PB	%AV	VMA	VFA	Height @ N_{des}	$G_{mm}@N_{ini}$	DP	Pbe
12.5mm LS 64-22	opt - 0.5%	5.6	14.9	62.6	116.1	82.9	1.2	4.2
	opt	4.5	15.1	70.25	122.2	84.4	1	4.7
	opt + 0.5%	3.9	15.5	75	116	84.5	0.9	5.2
12.5mm LS 70-22	opt - 0.5%	4.6	13.2	65.6	119.5	84.1	1.3	3.8
	opt	3.3	13.1	75.05	119.1	85	1.2	4.4
	opt + 0.5%	2.2	13.2	83.5	113.1	85.4	1	4.9
12.5mm LS 76-22	opt - 0.5%	4.6	14.1	67.6	120.1	84.2	1.1	4.2
	opt	3.3	14.2	76.7	120.2	85.1	1	4.7
	opt + 0.5%	3.0	14.8	79.8	114.2	84.8	0.9	5.3
12.5mm SY 64-22	opt - 0.5%	7.1	16	55.6	118.4	85.9	1.2	4
	opt	5.5	15.5	64.35	117	87.1	1.1	4.5
	opt + 0.5%	5.6	15.7	64.1	117.7	86.6	1.1	4.5
12.5mm SY 70-22	opt - 0.5%	7.1	16	55.4	118.2	85.7	1.2	4
	opt	5.0	15.2	67.05	116.8	87.3	1.1	4.5
	opt + 0.5%	4.0	15.3	73.8	111.2	87.6	1	5
12.5mm SY 76-22	opt - 0.5%	6.8	14.4	52.6	117.3	86.1	1.8	3.4
	opt	4.9	14	64.95	113.2	88	1.5	3.9
	opt + 0.5%	4	14.1	71.2	117.3	88.4	1.4	4.4
25mm LS 64-22	opt - 0.5%	5.5	13	57.3	117.8	84.7	1.6	3.3
	opt	4	12.6	68.6	116.95	85.9	1.4	3.8
	opt + 0.5%	2.9	12.8	77	117.4	86.8	1.2	4.3
25mm LS 70-22	opt - 0.5%	7	13.1	46.7	119.9	82.2	2	2.7
	opt	5.4	12.75	57.6	118.75	83.45	1.7	3.3
	opt + 0.5%	4.3	12.9	66.3	118.8	84.2	1.4	3.8
25mm LS 76-22	opt - 0.5%	4.9	13.3	63.4	119.4	83.5	1.2	3.7
	opt	4.2	13.7	69.8	120.6	83.6	1	4.3
	opt + 0.5%	2.6	13.4	80.9	119.1	85.7	0.9	4.8
25mm SY 64-22	opt - 0.5%	6.5	13.8	52.8	116.6	86.3	1.6	3.2
	opt	4.95	13.4	63.3	115.35	87.8	1.4	3.7
	opt + 0.5%	3.3	13	74.7	114.7	89.1	1.2	4.2
25mm SY 70-22	opt - 0.5%	6.7	13.3	49.8	114.9	86.5	1.7	2.9
	opt	5.7	13.55	57.8	114.85	87.4	1.5	3.4
	opt + 0.5%	4.5	13.5	66.4	115	88.1	1.3	3.9
25mm SY 76-22	opt - 0.5%	5.9	14	57.6	116.2	86.5	1.2	3.5
	opt	4.05	13.35	69.7	114.95	88.15	1.0	4.0
	opt + 0.5%	2.7	13.2	79.8	115.6	89.5	0.9	4.5

Table 21. Volumetric Properties for Sasobit Mixes at Varied Binder Content

Mix Design	PB	%AV	VMA	VFA	Height @ N_{des}	G_{mm}@N_{ini}	DP	Pbe
12.5mm LS 64-22	opt - 0.5%	7.4	16.2	54.1	124.4	81.9	1.2	4.0
	opt	5.7	15.65	63.85	122.7	83.45	1.1	4.5
	opt + 0.5%	4.9	16	69.5	123.1	83.8	1.0	5.0
12.5mm LS 70-22	opt - 0.5%	5.9	14.4	58.8	121.1	82.7	1.3	3.8
	opt	3.8	13.5	72.1	119.5	84.6	1.2	4.3
	opt + 0.5%	2.7	14.4	81.2	120.7	85.3	1.0	5.2
12.5mm LS 76-22	opt - 0.5%	5.5	14.7	62.8	120.3	83	1.1	4.1
	opt	3.3	13.8	76.25	119.25	85	1.0	4.6
	opt + 0.5%	3.1	14.7	79.1	119.8	85.2	0.9	5.1
12.5mm SY 64-22	opt - 0.5%	8.3	17.1	51.1	119.6	84.5	1.2	4.0
	opt	6.7	16.6	59.8	118.7	85.8	1.1	4.5
	opt + 0.5%	4.6	15.8	71	118	87.6	1.0	5.0
12.5mm SY 70-22	opt - 0.5%	7.8	16.4	52.1	118.6	84.8	1.2	3.8
	opt	6.2	15.9	61.5	118.2	86.4	1.1	4.3
	opt + 0.5%	4.8	15.8	69.4	117.7	87.3	1.0	4.9
12.5mm SY 76-22	opt - 0.5%	6.5	14.5	54.8	117	86.2	1.7	3.5
	opt	4.8	14.0	65.8	116.6	87.7	1.5	4.0
	opt + 0.5%	3.3	13.6	76	116.3	89	1.3	4.5
25mm LS 64-22	opt - 0.5%	5.9	13.1	55	117.8	84.2	1.7	3.2
	opt	4.1	12.55	67.35	117.6	85.7	1.4	3.7
	opt + 0.5%	2.7	12.3	78.3	116.4	87	1.3	4.2
25mm LS 70-22	opt - 0.5%	7.1	13.2	46	119.2	82	2.0	2.7
	opt	5.35	12.65	57.6	119.05	83.4	1.7	3.2
	opt + 0.5%	4.3	12.7	66.3	117.8	84.2	1.5	3.7
25mm LS 76-22	opt - 0.5%	5.8	13.8	57.8	119.5	82.4	1.2	3.6
	opt	4.55	13.75	66.95	118.85	83.35	1.1	4.1
	opt + 0.5%	3.6	14	74.1	118.6	84.3	0.9	4.6
25mm SY 64-22	opt - 0.5%	6.3	13.7	53.7	115.7	86.7	1.6	3.2
	opt	4.7	13.3	64.9	115.8	88	1.4	3.7
	opt + 0.5%	3.3	13.1	74.9	114.9	89.2	1.2	4.2
25mm SY 70-22	opt - 0.5%	7.1	13.9	48.9	115.3	86.1	1.7	3.0
	opt	5.35	13.4	59.8	115	87.6	1.4	3.5
	opt + 0.5%	4.1	13.3	69.2	115.1	88.6	1.3	4.0
25mm SY 76-22	opt - 0.5%	5.3	13.2	60	114.6	87.2	1.2	3.4
	opt	4.25	13.4	68.05	114.85	87.65	1.0	3.9
	opt + 0.5%	2.7	13	79.3	114.5	89.4	0.9	4.4

In order to compare sensitivity of HMA and WMA to changes in binder content, the data was next shown graphically. Comparisons were made for the volumetric properties of air voids, VMA, VFA, and %Density @ $N_{initial}$. Figures 22 through 33 illustrate the comparison for each mix design.

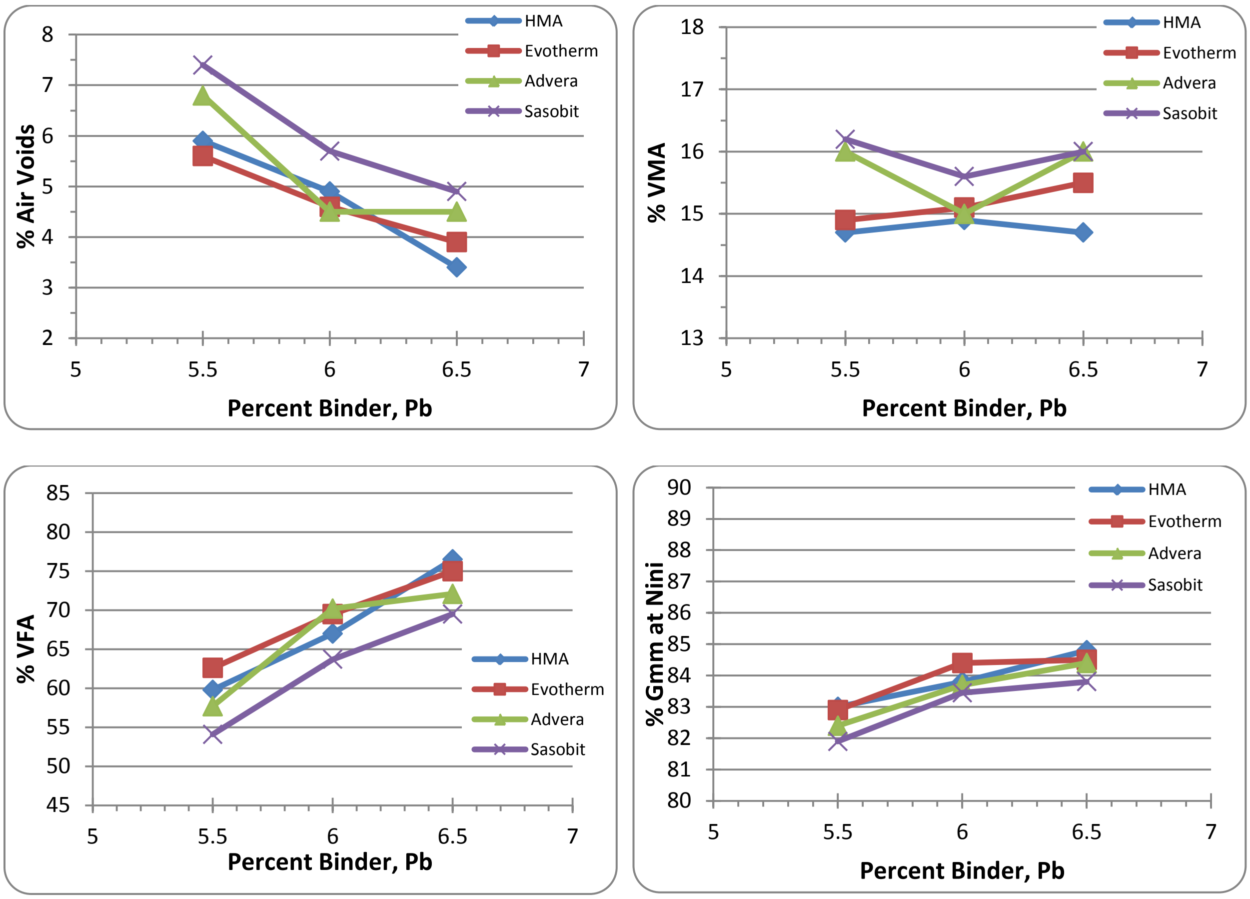


Figure 22. Sensitivity of Volumetrics to Binder Content Changes – LS 12.5mm PG 64-22

Figure 22 shows that in general, the 12.5mm limestone warm mixes containing PG 64-22 had similar sensitivity to changes in binder content as the hot mixes. The slopes of the lines in the graph represent sensitivity, in that the steeper the slope of the line, the more sensitive the volumetric property is to changes in binder content. For percent air voids and VFA, all of the warm mixes had similar or slightly reduced sensitivity to changes in binder content. The Advera results showed slightly more erratic behavior, which was also seen in previous analyses. Changes to VMA were somewhat more sensitive for the WMA mixes, and did not consistently follow the same trend as the HMA mix.

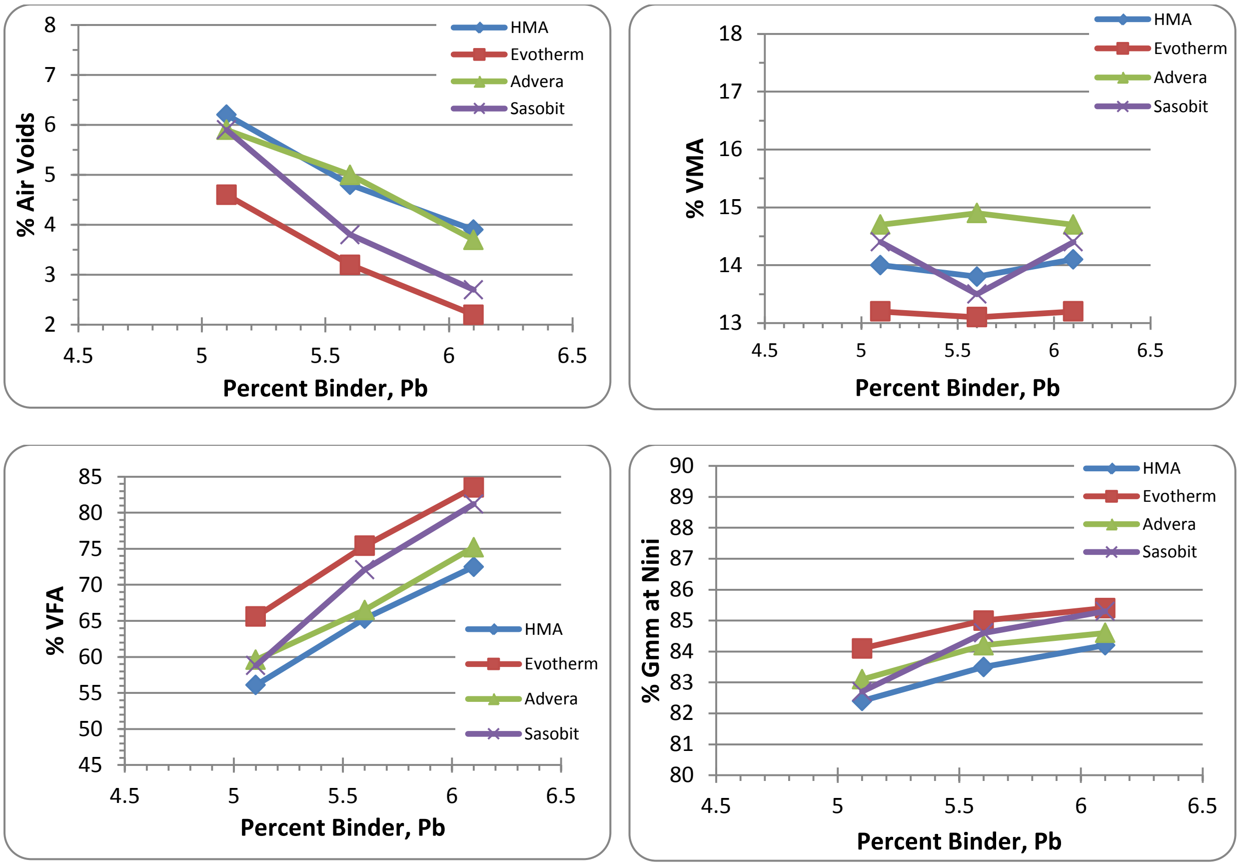


Figure 23. Sensitivity of Volumetrics to Binder Content Changes – LS 12.5mm PG 70-22

Figure 23 demonstrates that the sensitivity of 12.5mm limestone mixtures with PG 70-22 containing WMA additives is very similar to that of the corresponding HMA mix. The slopes of the lines are similar, however, the relative position of the lines for air voids do exhibit some differences of practical significance. The Advera mixes were very similar to the HMA, while Sasobit mixes showed improved compaction (i.e., lower air voids). The Evotherm mixes have the lowest air void contents, supporting the claim that Evotherm is an effective compaction aid. Some differences were also evident for VMA, though no meaningful relationships were noted. In general, all volumetric properties were similar in sensitivity with respect to change in binder content.

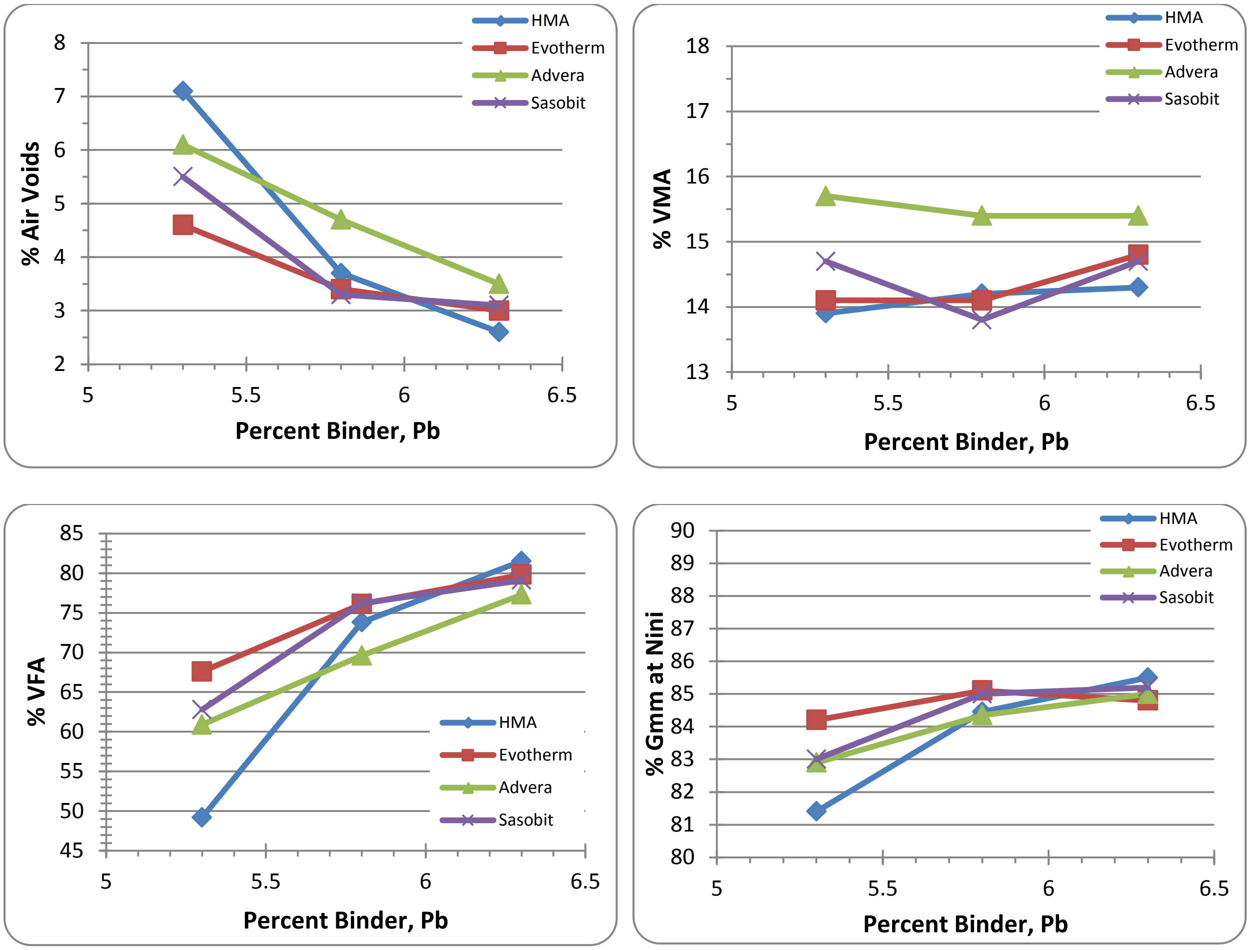


Figure 24. Sensitivity of Volumetrics to Binder Content Changes – LS 12.5mm PG 76-22

In Figure 24, it is demonstrated that the sensitivity of 12.5mm limestone mixtures with PG 76-22 containing WMA additives is also fairly similar to that of the corresponding HMA mix, although the HMA lines are generally steeper, meaning that the WMA mixes are less sensitive to changes in binder content. The Advera mix tends to differ from HMA more significantly than the other WMA mixes, especially for the VMA. One notable feature is that the WMA mixes, particularly the Evotherm mixes, were able to achieve increased compaction levels at binder contents below the optimum. This suggests that design binder contents for some mixes could be reduced slightly, still providing adequate compaction at a given temperature.

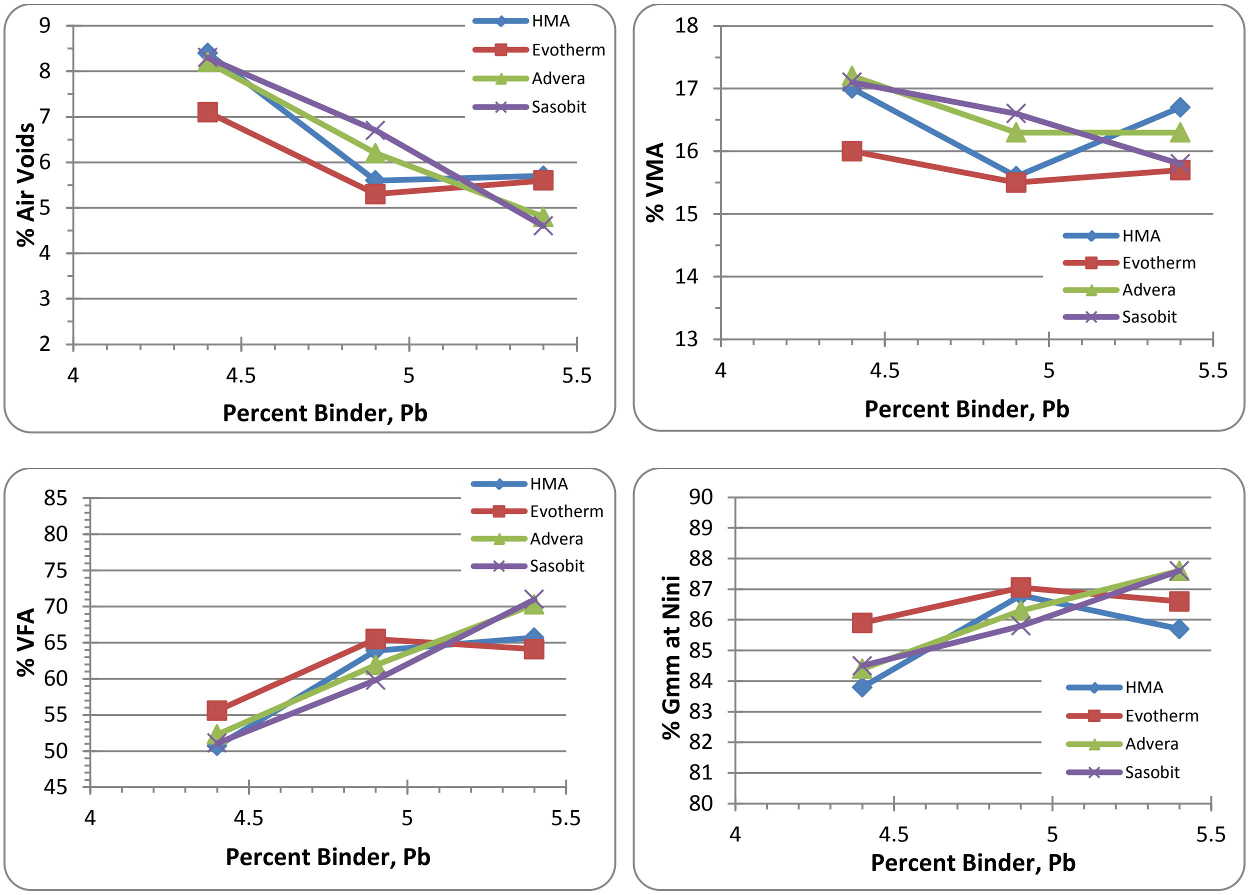


Figure 25. Sensitivity of Volumetrics to Binder Content Changes – SY 12.5mm PG 64-22

For the 12.5mm syenite mix with PG 64-22, shown in Figure 25, the HMA and Evotherm mixes were most similar, although the Advera and Sasobit mixes appeared slightly more sensitive at the upper end of the binder content range. VMA seemed to be most affected by changes in binder content. Even though the sensitivity of the Evotherm and HMA mixes were similar, the Evotherm mixes were best able to achieve increased compaction levels, providing air void contents less than that of the HMA mix.

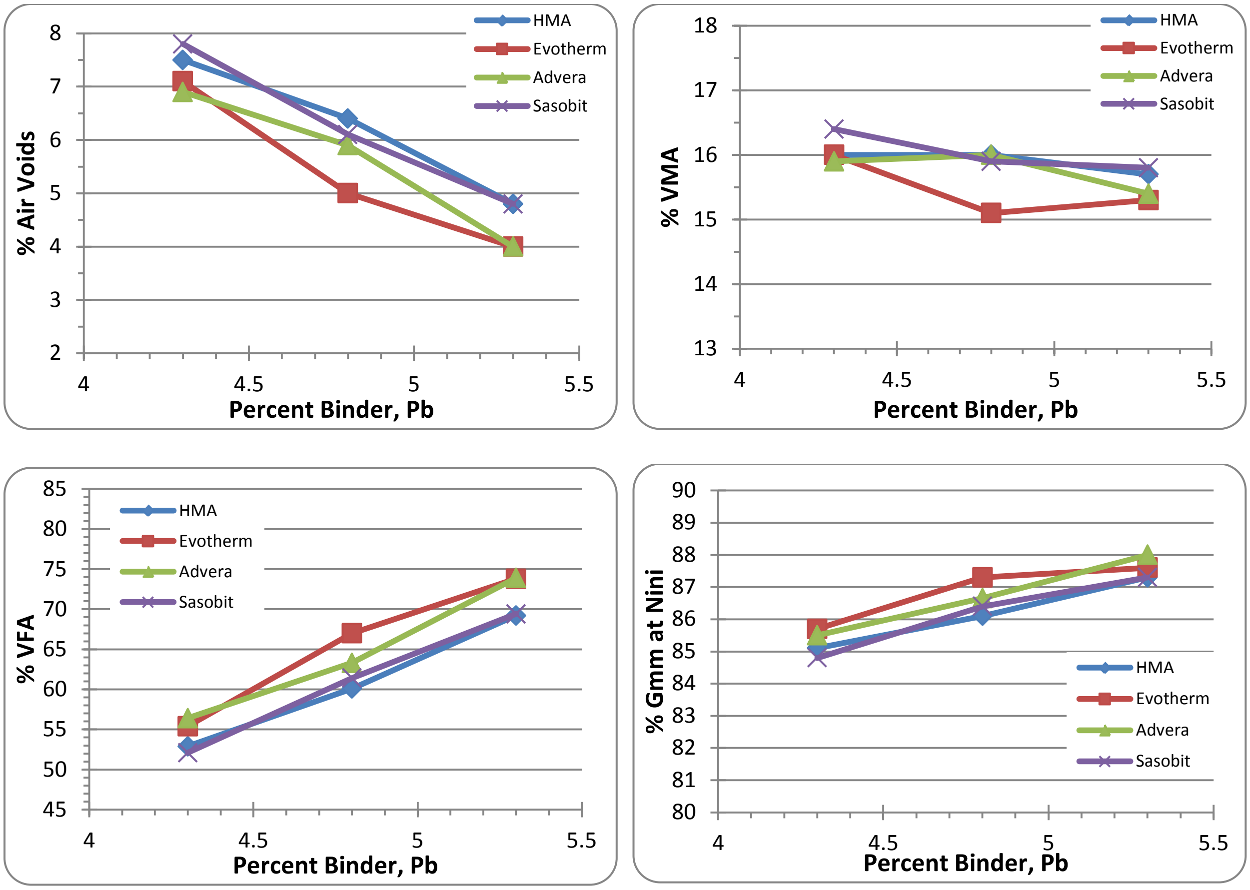


Figure 26. Sensitivity of Volumetrics to Binder Content Changes – SY 12.5mm PG 70-22

The 12.5mm syenite mixes with PG 70-22 are shown in Figure 26. The slopes of the lines for air voids, VFA, and percent density at $N_{initial}$ were very similar, indicating that the WMA mixes were no more sensitive than the HMA mix to changes in binder content. VMA was the only parameter with evident differences, such that the Evotherm mix showed a lower VMA value at the optimum binder content.

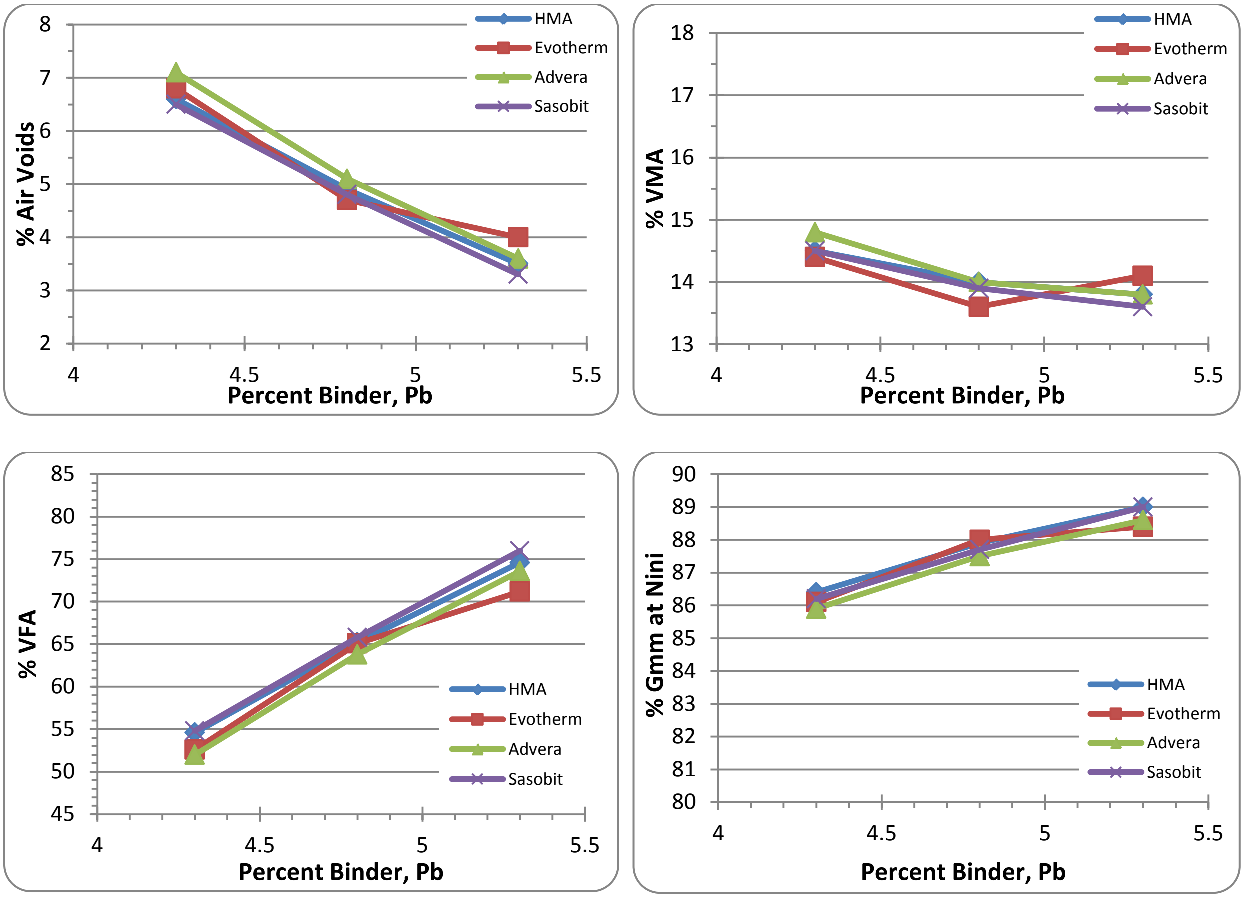


Figure 27. Sensitivity of Volumetrics to Binder Content Changes – SY 12.5mm PG 76-22

Figure 27 displays the comparative sensitivity of the WMA and HMA mixtures for the 12.5mm syenite mix design containing PG 76-22 binder. The HMA, Advera, and Sasobit mixes are very similar, and the volumetric properties of the Evotherm mix were slightly less sensitive to changes in binder content than the other mixes.

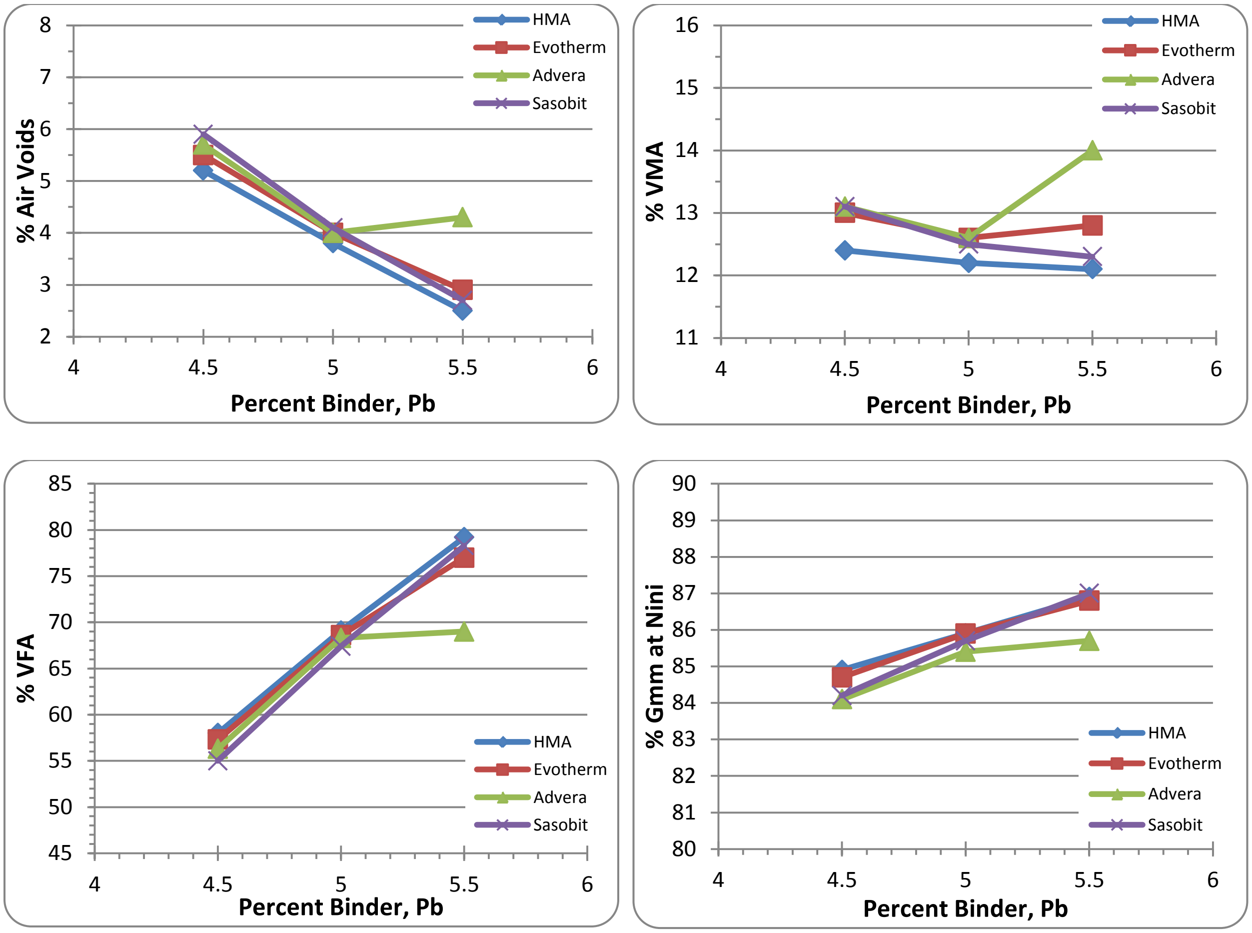


Figure 28. Sensitivity of Volumetrics to Binder Content Changes – LS 25.0mm PG 64-22

Figure 28 displays the relationships of volumetric properties and binder content for the 25.0mm limestone mixes containing PG 64-22 binder. The slopes of the lines were largely similar, indicating the sensitivity of the WMA mixes is similar to that of the HMA mix. The magnitudes of the values also fell close together, showing that the addition of the WMA additives did not significantly affect the volumetric properties of the mixtures. The only exception was the Advera mix at the higher binder content, which displayed less compaction, greater air voids, higher VMA, and lower VFA.

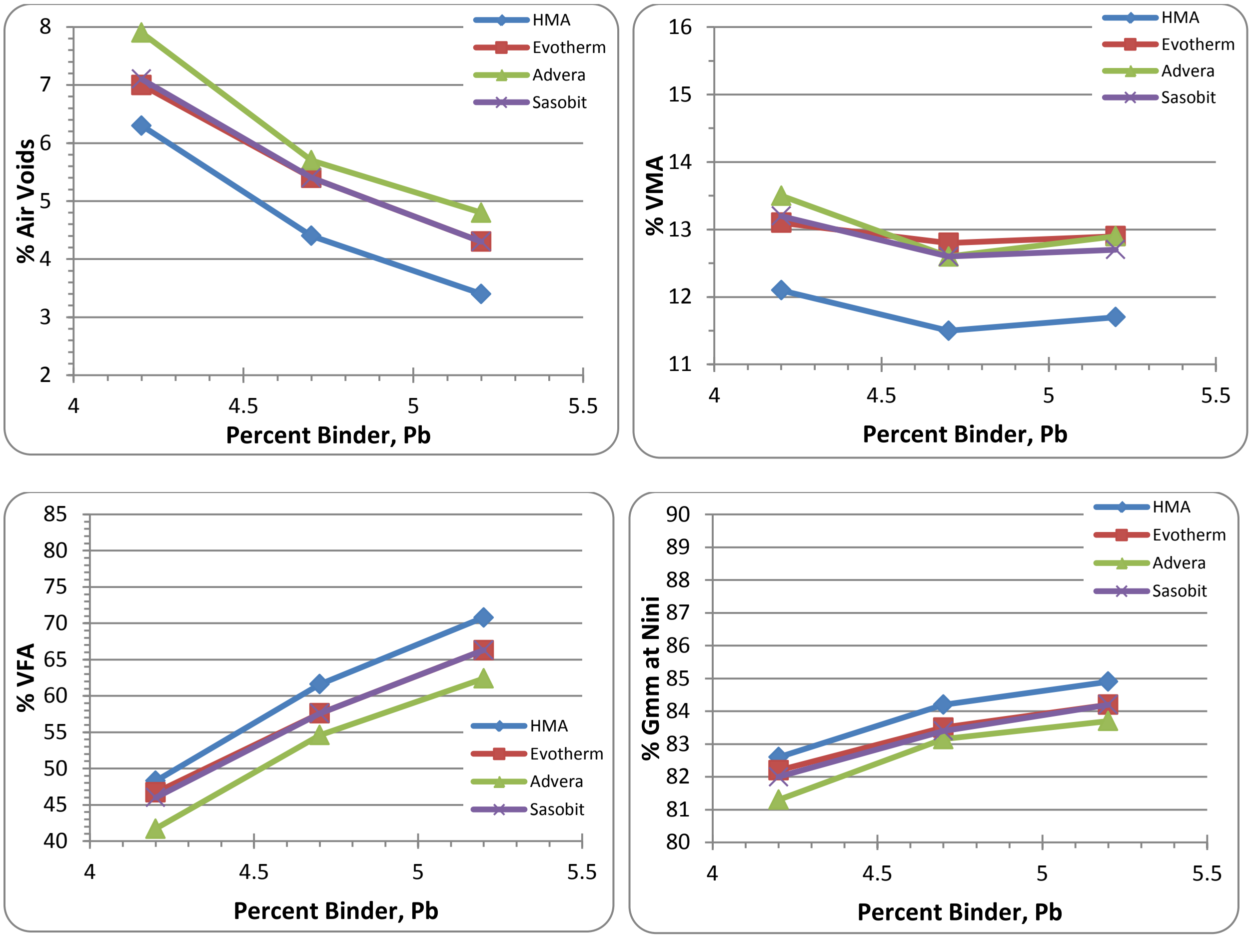


Figure 29. Sensitivity of Volumetrics to Binder Content Changes – LS 25.0mm PG 70-22

The 25.0mm limestone mixture comparisons for PG 70-22 are shown in Figure 29. In these comparisons, the Evotherm and Sasobit mixes appeared almost identical. The Advera mixture showed the least amount of compaction (i.e., greatest air voids), and the HMA mix displayed the greatest amount of compaction (i.e., least air voids). The VMA level was also the least for the HMA mix. Overall, the WMA alternatives for this mixture did not provide additional compactability, but were no more sensitive to changes in binder content than the HMA counterpart.

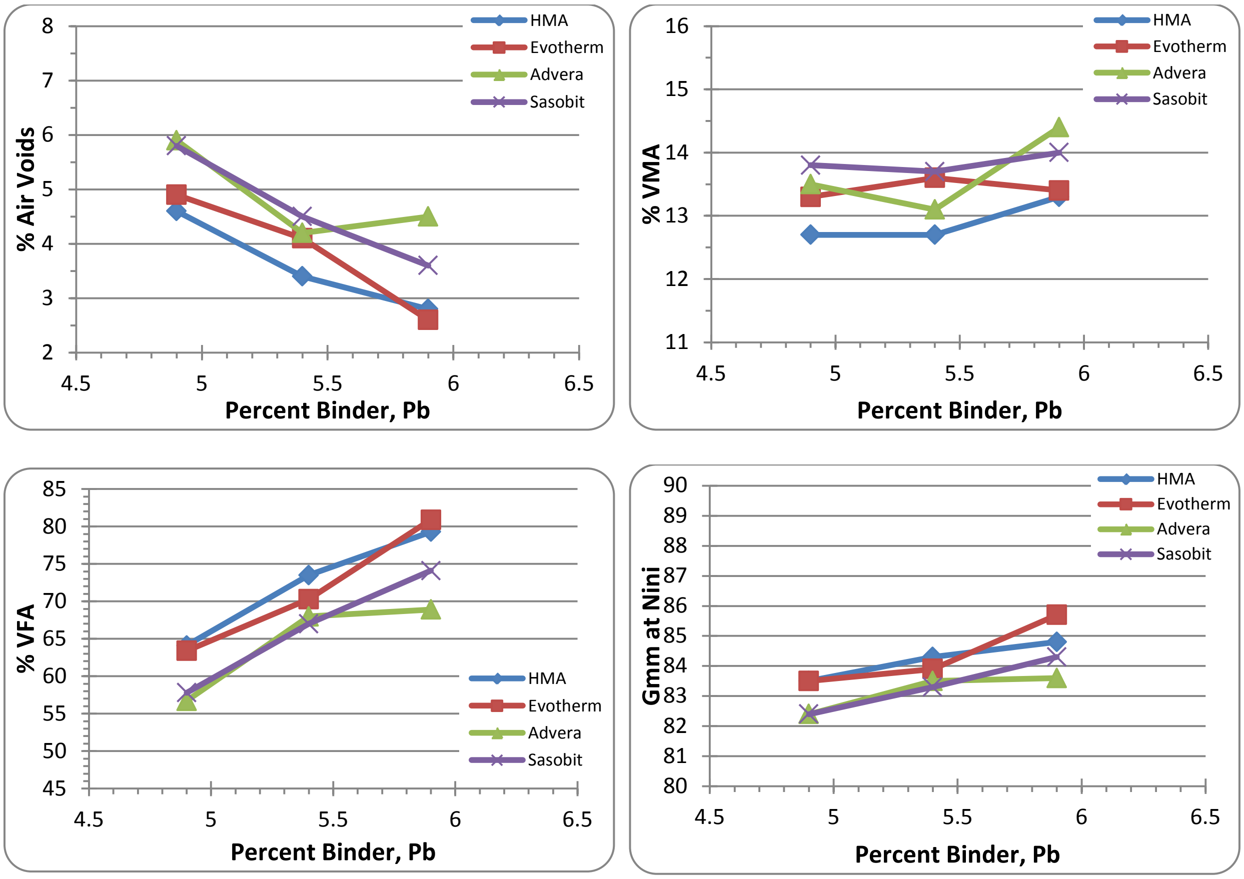


Figure 30. Sensitivity of Volumetrics to Binder Content Changes – LS 25.0mm PG 76-22

For the 25.0mm limestone mixes with PG 76-22 binder, shown in Figure 30, all mixes were fairly similar, with the Evotherm mixture appearing most similar to the HMA mixture. The Advera mix did not provide a consistent trend with respect to volumetrics as binder content increased, and the Evotherm mix appeared slightly more sensitive to binder content changes than the HMA mix. Again, the HMA mix experienced the greatest overall level of compactability.

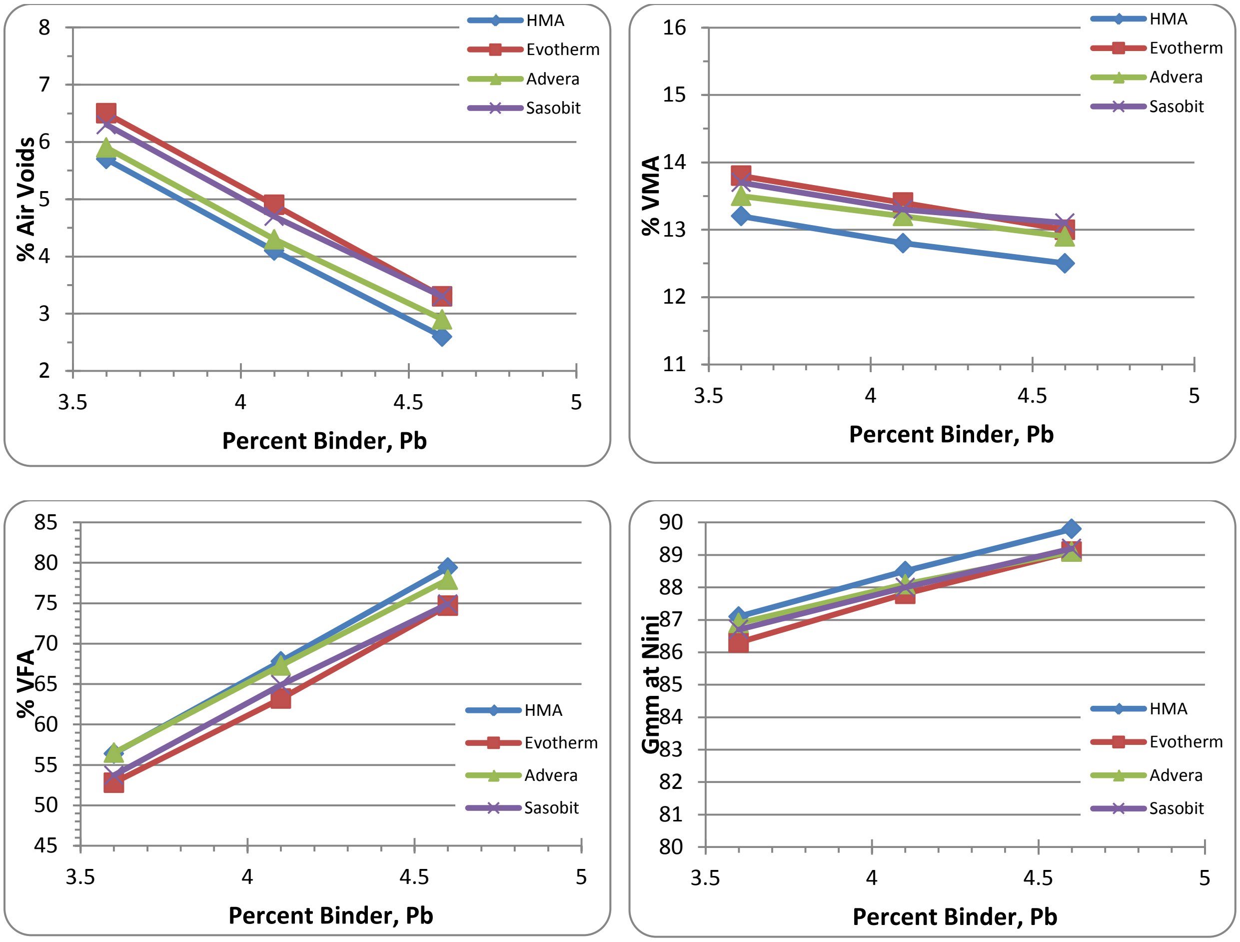


Figure 31. Sensitivity of Volumetrics to Binder Content Changes – SY 25.0mm PG 64-22

Figure 31 shows the comparisons for the 25.0mm syenite mixtures containing PG 64-22. These relationships are very similar for all mixes, both in sensitivity and magnitude. Though all mixes appeared similar, the Advera and HMA were the closest match, while the Evotherm and Sasobit mixes were nearly identical. The comparisons for this mixture provide no indication that WMA mixes are any more sensitive to changes in binder content than the HMA mix.

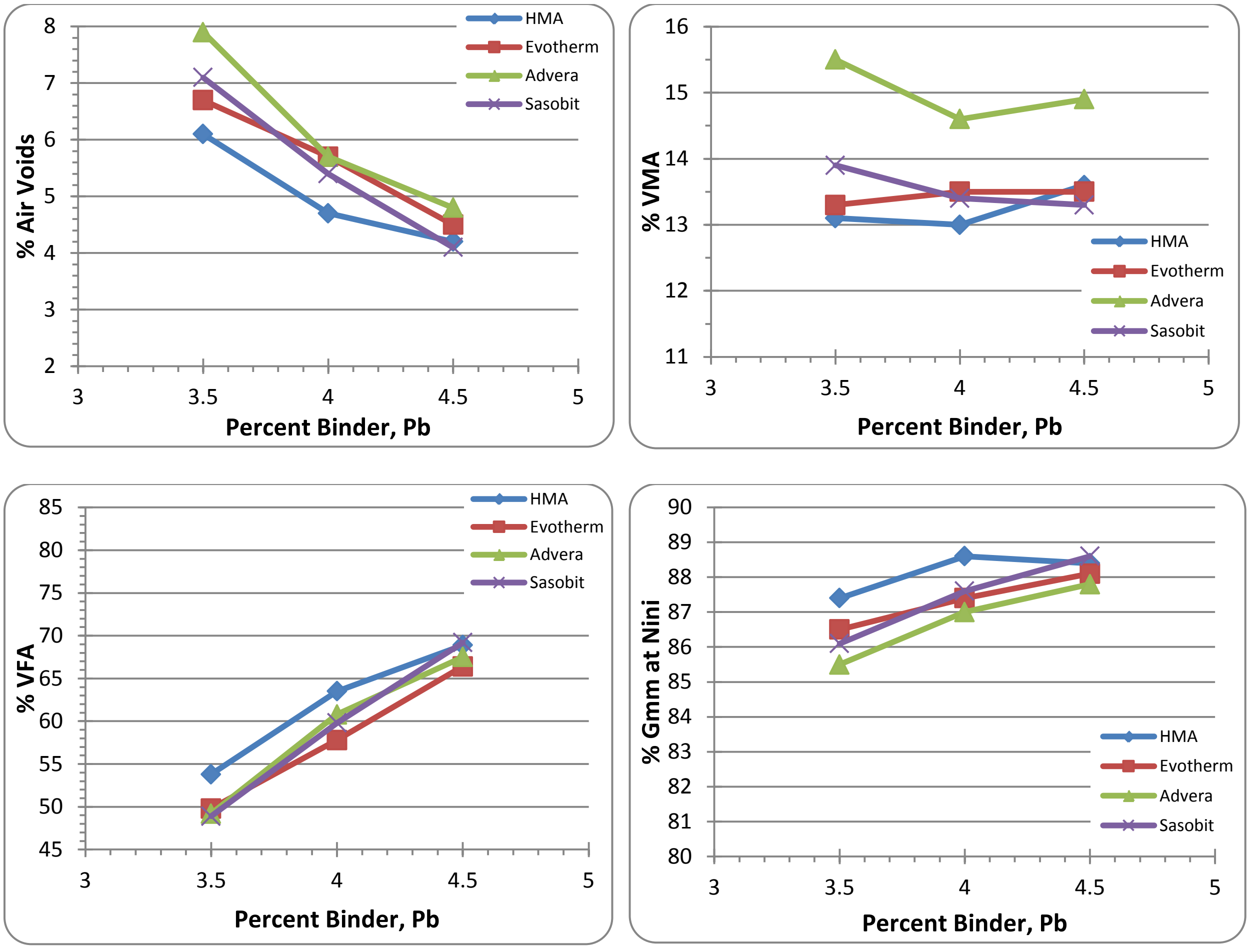


Figure 32. Sensitivity of Volumetrics to Binder Content Changes – SY 25.0mm PG 70-22

In Figure 32, the comparisons for the 25.0mm syenite mixtures with PG 70-22 are given. Again the sensitivity of the WMA and HMA mixtures appeared similar, with no cause for concern regarding any additional sensitivity to binder content changes when a mixture is converted from HMA to WMA. For this design, the HMA appeared slightly more compactible than the WMA mixes, as evidenced by the lower air void contents. The Advera mixture generated higher VMA values than the other mixes, but appeared no more sensitive to changes in binder content than the other mixes.

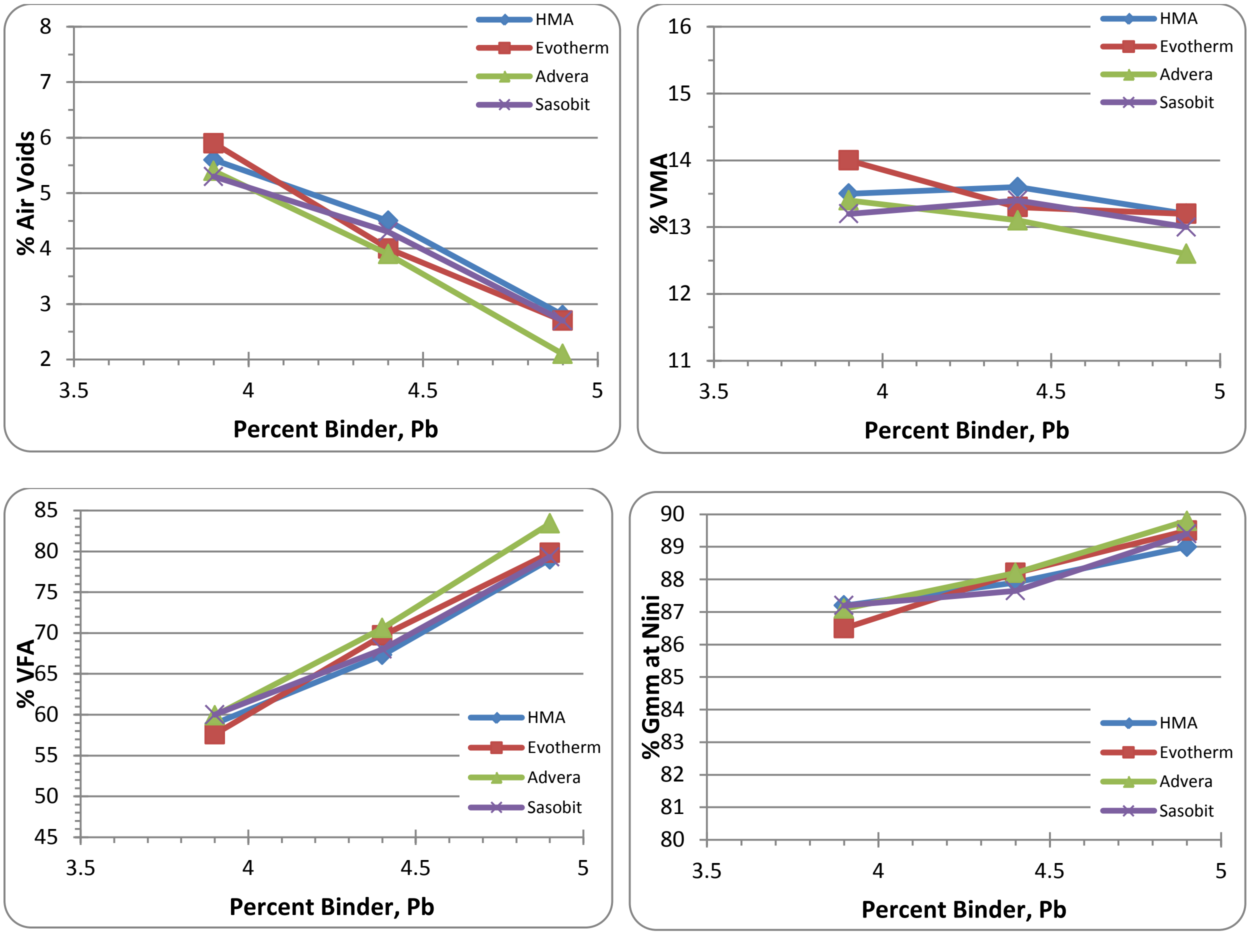


Figure 33. Sensitivity of Volumetrics to Binder Content Changes – SY 25.0mm PG 76-22

For the PG 76-22 25.0mm syenite mixes, Figure 33 shows that both the magnitudes and the sensitivity of the volumetric properties of the WMA mixes were similar to that of the HMA mix. The Sasobit mixture appeared to be most similar to the HMA mix, though all comparisons were very close. While none of the WMA additives generated additional compactability, all were able to generate similar compaction levels at reduced temperatures.

Next, the sensitivity data was further examined to discover whether the apparent differences in the data were statistically significant. To ensure that intentional changes were compared fairly among the various mixtures, a series of t-tests were conducted to determine if the changes in volumetric properties resulting from changes in binder content were significantly different from the warm mixes than the hot mixes. The values used for this analysis were calculated by subtracting the values at optimum binder content from the values obtained at the 0.5 percent below and the 0.5 percent above optimum binder content. These changes in volumetric properties were calculated for each warm mix and for the hot mix control mixes, and each WMA mixture was compared separately to its corresponding HMA mix using paired t-tests. The results of the analyses are shown in Table 22, including the F-values, P-values, and indication of significance. This analysis showed that the changes in volumetric properties which resulted from binder content variations were not statistically different. This was true for all combinations of aggregate type, aggregate size, and binder grade. Therefore, the specifications currently in place for the quality control and quality assurance of HMA are believed to be adequate for WMA mixtures. No specification changes are necessary.

Table 22. T-Test Results for Sensitivity to Changes in Binder Content

Response	Additive	F calc	F crit	P-value	Significant Difference from HMA?
AV (%)	ADV	-0.3394	2.0687	0.7374	no
	EVO	1.1551	2.0687	0.2599	no
	SAS	0.1496	2.0687	0.8824	no
VMA (%)	ADV	-1.5980	2.0687	0.1237	no
	EVO	0.0777	2.0687	0.9388	no
	SAS	-0.5593	2.0687	0.9388	no
VFA (%)	ADV	-0.0601	2.0687	0.9526	no
	EVO	-0.2496	2.0687	0.8052	no
	SAS	-0.6928	2.0687	0.4954	no
$\%G_{mm}$ at N_{ini}	ADV	-1.5878	2.0687	0.1260	no
	EVO	-0.1652	2.0687	0.8702	no
	SAS	-0.8561	2.0687	1.7139	no
DP	ADV	1.3280	2.0687	1.7139	no
	EVO	0.9166	2.0687	0.3689	no
	SAS	1.6828	2.0687	0.1059	no
Pbe	ADV	-1.1273	2.0687	0.2712	no
	EVO	-0.4524	2.0687	0.6552	no
	SAS	-1.6968	2.0687	0.1032	no

Overall, the sensitivity of WMA mixtures was very similar to or slightly less sensitive than that of the HMA mixes, and in some cases appeared identical. For the 12.5mm mixes, there were several instances in which the WMA mixes showed increased compactability over the HMA mix, particularly for the PG 70-22 and PG 76-22 binders, with the Evotherm additive typically being the most effective compaction aid. For the 25.0mm mixes, changes in binder content affected the WMA volumetric properties in much the same way as the HMA properties, and in many cases the actual values were very similar. When differences existed, the HMA often displayed more compactability than the warm mixes. Thus, warm mix additives may be more effective for 12.5mm mixtures than for 25.0mm mixtures. In terms of binder grade, compactability increased for 12.5mm mixes as binder grade increased. However for the 25.0mm mixes, the WMA additives appeared to work more efficiently with the lower binder grades.

Rutting and Stripping Susceptibility

Rutting and stripping are major concerns for warm mixes because they have less pre-oxidation due the reduced production temperatures. This results in a softer binder that may be more susceptible to rutting and stripping. For the analyses of rutting and stripping susceptibility, the original optimum percent binder was used; however, for some samples, the warm mix additives altered the volumetric properties enough to reduce the actual optimum binder content. For samples where the difference was significant, samples were also produced at the reduced binder content. No anti-stripping agents were used for any of the samples.

Samples for ERSA, the Evaluator of Rutting and Stripping in Asphalt, were prepared to a 75mm height, having 7 ± 1 percent air voids. Duplicate ERSA tests were run for each mixture type and additive combination. The results of an ERSA test, as previously described, provide insight into the process of sample deterioration, and the point during the test at which this deterioration is dominated by moisture damage (i.e., stripping inflection point). Although the graphical results of an ERSA test can clearly indicate the presence of stripping, this distress can also be detected visually at the completion of the test. Figure 34 illustrates the differences in appearance of samples with and without stripping.

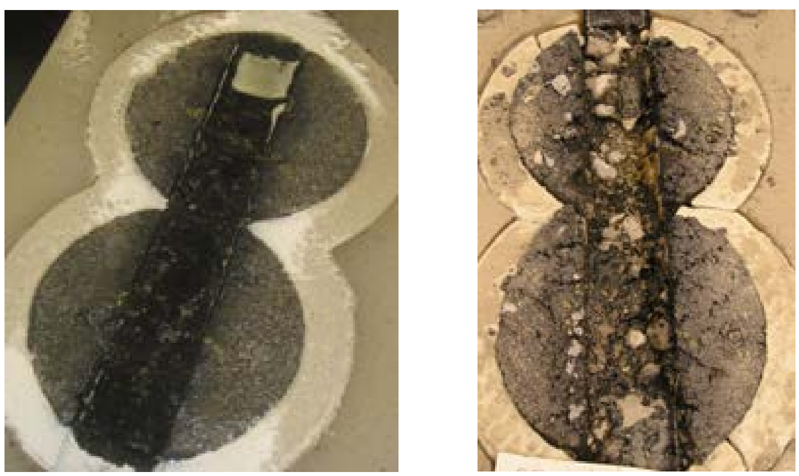


Figure 34. Samples tested in ERSA: no stripping evident on left, stripping evident on right

The corresponding graphical results are given in Figures 35 and 36, with Figure 35 representing the samples with no stripping, and Figure 36 representing the sample that did exhibit stripping. The rutting and stripping slopes are indicated on each figure.

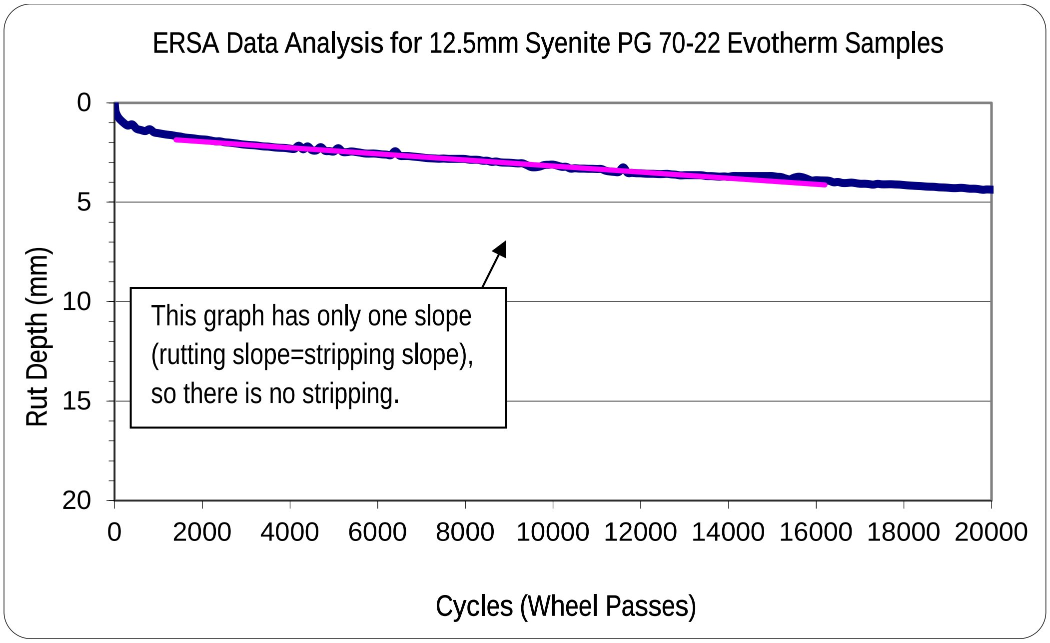


Figure 35. Resulting ERSA Data: No Stripping Evident

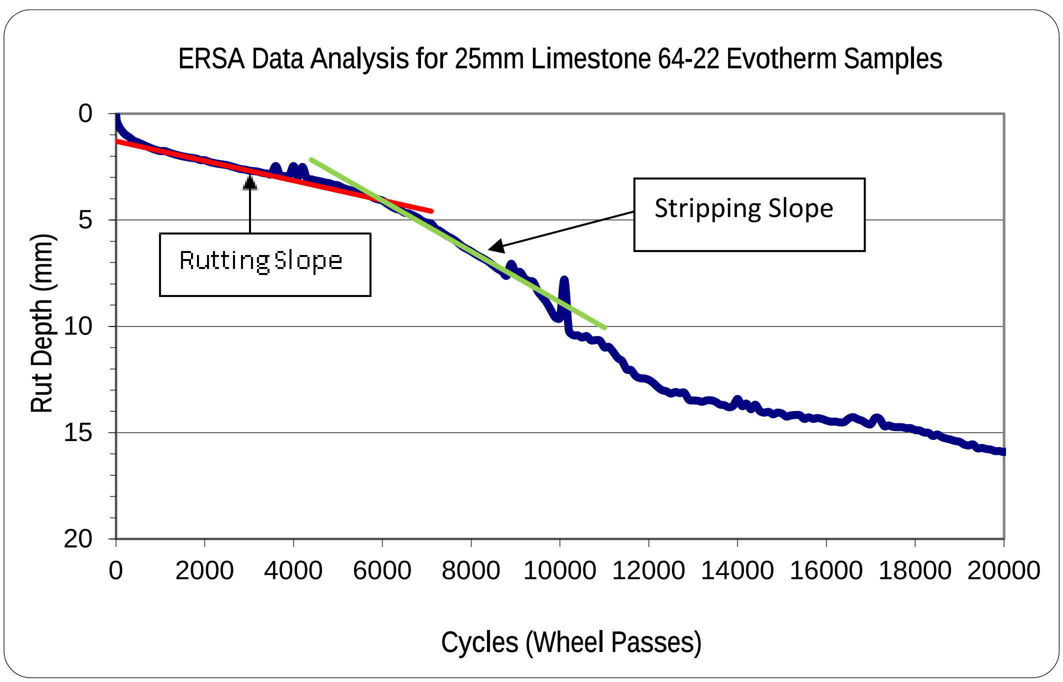


Figure 36. Resulting ERSA Data: Stripping Evident

The following data was collected from ERSA and used to conduct a series of multi-factor ANOVA tests: rut depth at 10,000 cycles, rut depth at 20,000 cycles, rutting slope, stripping slope, stripping inflection point (SIP). An additional response was also collected, which was the number of cycles to maximum rut depth. The results obtained from ERSA, as well as the results of the statistical analyses are presented in the following sections.

Tables 23 and 24 provide the average results for the ERSA tests for the 12.5mm and 25.0mm mixtures, respectively. Note that specimens that did not strip are marked with an asterisk. For analysis purposes, these specimens were assigned a value of 40,000.

Table 23. ERSA Results for 12.5mm Mixtures

		Values for Responses					
Mix Design	Additive	Rut Depth at 10,000 Cycles	Rut Depth at 20,000 Cycles	Rutting Slope	Stripping Slope	SIP	# Cycles to Max Rut Depth
12.5mm LS 64-22	HMA	11.4	22.0	1641	836	10143	20300
	ADV	25.1	29.2	363	571	4549	15200
	EVO	19.3	20.5	1027	323	5182	14150
	SAS	22.9	23.0	330	330	6601	9300
12.5mm LS 70-22	HMA	9.7	12.2	1539	4565	5462	17850
	ADV	18.0	21.8	797	596	22445	15150
	EVO	18.0	19.2	682	331	4929	12750
	SAS	16.2	20.0	916	566	23441	14200
12.5mm LS 76-22	HMA	5.3	7.0	3035	4345	20389	17800
	ADV	6.1	17.9	2780	2267	24964	18700
	EVO	13.3	18.4	1201	552	6312	17600
	SAS	7.5	14.6	1749	2188	23078	19850
12.5mm SY 64-22	HMA	5.0	10.1	4716	4716	27872	20350
	ADV	20.9	21.1	1108	240	3532	9300
	EVO	20.7	20.8	494	158	2314	11400
	SAS	21.3	21.3	641	329	3522	8300
12.5mm SY 70-22	HMA	7.8	12.1	2198	830	7400	20500
	ADV	20.9	21.0	2109	341	3789	8850
	EVO	3.2	4.9	6170	6170	40000	20500
	SAS	14.0	19.6	1329	771	21740	15450
12.5mm SY 76-22	HMA	3.7	5.3	3948	6205	22000	19950
	ADV	13.0	19.6	1538	509	3325	18700
	EVO	11.6	15.2	1312	2089	7194	20350
	SAS	11.2	18.2	2026	467	5053	19350

Table 24. ERSA Results for 25.0mm Mixtures

		Values for Responses					
Mix Design	Additive	Rut Depth at 10,000 Cycles	Rut Depth at 20,000 Cycles	Rutting Slope	Stripping Slope	SIP	# Cycles to Max Rut Depth
25mm LS 64-22	HMA	15.9	20.1	883	2140	8760	19950
	ADV	14.8	18.2	488	278	2425	16450
	EVO	11.6	15.8	2438	3891	5140	15300
	SAS	14.2	22.5	904	565	4731	12000
25mm LS 70-22	HMA	4.5	18.4	1042	431	13963	20400
	ADV	17.7	17.7	429	253	352	4100
	EVO	8.0	20.0	1045	2496	4743	7000
	SAS	17.7	22.0	849	742	4598	14750
25mm LS 76-22	HMA	4.8	9.8	2199	2199	40000	20400
	ADV	13.4	21.1	951	855	2894	20500
	EVO	8.9	18.7	1640	490	6329	18300
	SAS	7.0	20.0	1987	748	9083	19000
25mm SY 64-22	HMA	7.9	18.6	1852	1852	25732	20450
	ADV	25.7	25.7	492	353	1243	8000
	EVO	13.4	21.5	1711	670	5725	16750
	SAS	21.3	21.3	641	329	3522	8300
25mm SY 70-22	HMA	7.9	11.9	1855	1855	22840	18200
	ADV	17.7	17.7	429	253	352	4100
	EVO	2.7	7.3	3276	3276	40000	18700
	SAS	7.3	8.0	3159	1347	6553	20500
25mm SY 76-22	HMA	2.8	4.1	3387	7460	20619	19650
	ADV	16.9	18.9	1401	459	2284	15200
	EVO	5.1	7.3	2834	2834	40000	20400
	SAS	5.0	8.8	2529	2529	40000	20350

Next, the results of all ERSA testing are shown graphically in Figures 37 through 48, in which all mixes (HMA and WMA) for a given mixture design are plotted on a single graph. The following conclusions were made from the graphs.

<u>12.5mm Limestone PG 64-22</u>

Figure 37 shows that none of the mixes performed well, although the hot mix samples performed better than the warm mix samples. Of the warm mixes tested, the samples containing Evotherm performed best, and were most similar to the HMA mix.

12.5mm Limestone PG 70-22

Figure 38 shows that the warm mixes did not perform as well as the hot mixes. Of the warm mixes tested, the samples containing Sasobit performed best. All of the warm mixes exhibited stripping, and may have benefitted from an anti-stripping agent.

12.5mm Limestone PG 76-22

From Figure 39, it is evident that the HMA samples were the best performers, exhibiting no stripping slope, while all of the WMA samples did strip, with the Evotherm mix having the earliest onset of stripping failure.

12.5mm Syenite PG 64-22

In Figure 40, the HMA samples are again proven to be the best performers, while all of the WMA mixes exhibited severe stripping failures. Of all of the HMA / WMA comparisons, this mix design was one of the most sever examples of the potential detrimental effects of the incorporation of a WMA additive.

12.5mm Syenite PG 70-22

In the comparison illustrated in Figure 41, the Evotherm mixture performed better than the HMA mixture. This presents confirmation that WMA mixtures can be successfully designed to meet both target volumetric and performance parameters. Though Evotherm served to improve the performance of this mix design, the other WMA additives did not. This further supports the belief that each mixture design should be tested in the laboratory with the specific additive incorporated during design, and that performance testing should be completed prior to mix design approval.

12.5mm Syenite PG 76-22

Figure 42 provides another comparison in which the warm mixes did not perform as well as the hot mix, though they did not strip as quickly as some of the other mix designs. Again, an anti-stripping agent could be beneficial in aiding the performance of the WMA mixes.

25.0mm Limestone PG 64-22

In Figure 43, it is shown that all of the mixes performed similarly, with early evidence of stripping failures. Overall, the Evotherm mix showed slightly better performance, though this mixture would have still failure most design requirements for rutting.

25.0mm Limestone PG 70-22

The next comparison, shown in Figure 44, indicated that the HMA mix was the best performer in the group, while the Advera was the poorest performer. The Evotherm samples appeared to offer promising results, however sample roughness became severe during the early stages of the test, causing the test to terminate prematurely.

<u>25.0mm Limestone PG 76-22</u>

In the comparison shown in Figure 45, there was more uniformity among mixture performance. The HMA mixture was shown to be the best performer, though the rutting slopes of the Evotherm and Sasobit mixes had similar rutting slopes. Moisture sensitivity, however, caused the stripping slopes to be steeper for the WMA mixes.

<u>25.0mm Syenite PG 64-22</u>

In Figure 46, the HMA and Evotherm mixes performed very similarly at the beginning of the test, but diverged as stripping began to dominate the deterioration of the Evotherm samples. The Advera and Sasobit samples performed similarly as well, both experiencing stripping failures early in the test.

<u>25.0mm Syenite PG 70-22</u>

Figure 47 demonstrates an atypical comparison in that the Evotherm mix clearly outperformed the HMA mix. The HMA and Sasobit mixes were very similar, exhibiting mediocre performance, while the Advera sample failed early in the testing process. It is interesting to note that the other case in which the Evotherm mix demonstrated better performance than the HMA mix was also for the combination of the syenite aggregate source and the PG 70-22 binder. Thus, there is further evidence that a WMA additive cannot simply be incorporated into a HMA design with any assurance of acceptable performance. Each combination of materials must be tested individually in order to determine the anticipated performance for that particular mixture.

<u>25.0mm Syenite PG 76-22</u>

In contrast, Figure 48 provides a comparison of a mix design in which all of the mixes performed well, with the Evotherm and Sasobit mixes performing similarly to the HMA. An exception was noted for the Advera mix. In fact, the Advera was the only mixture of the four that exhibited stripping at all.

Overall, the warm mixes performed as well as the hot mix, for some designs, but failed quickly for other designs. Thorough testing of a mixture with a warm mix additive is recommended in order to prevent premature failures. Further investigation into the use of WMA with anti-stripping agents is also warranted.

The warm mixes containing Evotherm generally performed better than those containing Advera or Sasobit, especially for the PG 70-22 binder / syenite aggregate combination. In some cases the Evotherm provided greater rutting and stripping resistance than the HMA mix, though this was not the case for the other WMA additives.

Samples containing Sasobit performed similarly to Evotherm for many of the mixes. In a few cases, Sasobit showed potential for performance comparable to hot mix, but an anti-stripping agent would likely be necessary to realize this potential. Most samples containing Advera stripped quickly, so mixes containing this additive should be properly scrutinized before acceptance.

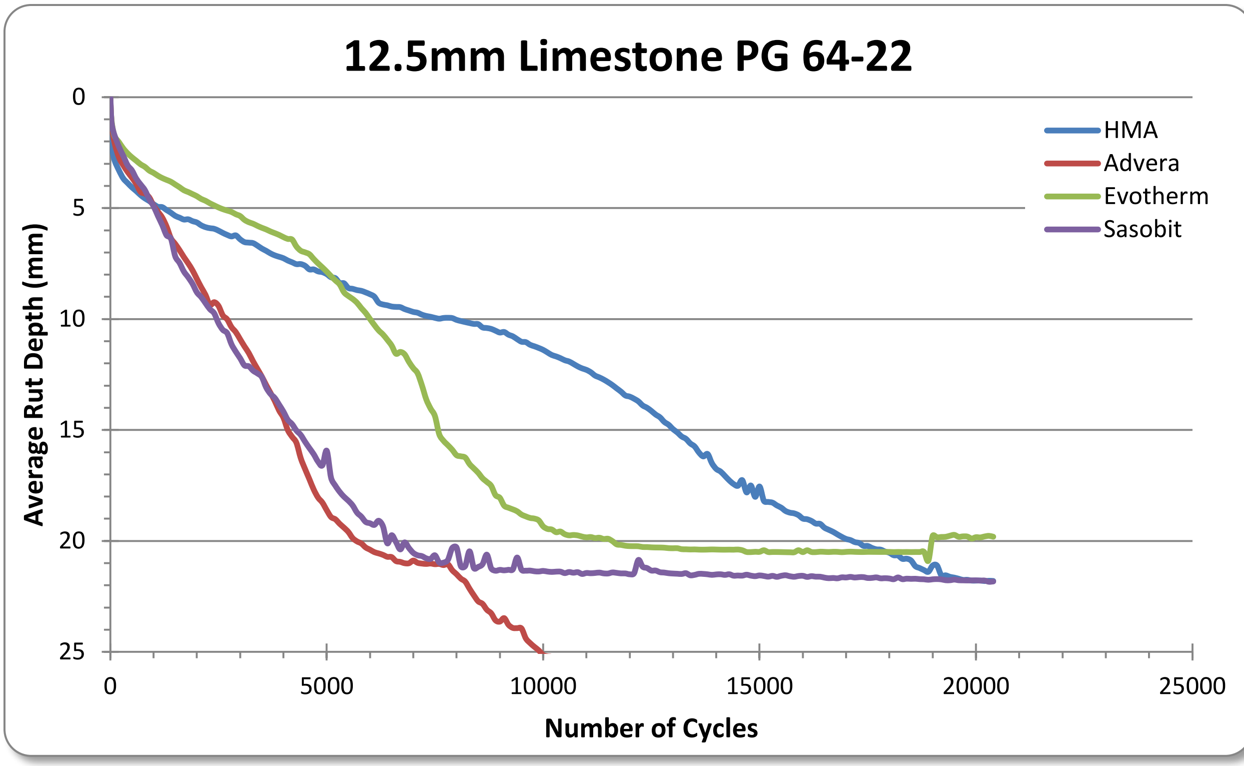


Figure 37. ERSA Results for All 12.5mm Limestone Mixes Containing PG 64-22

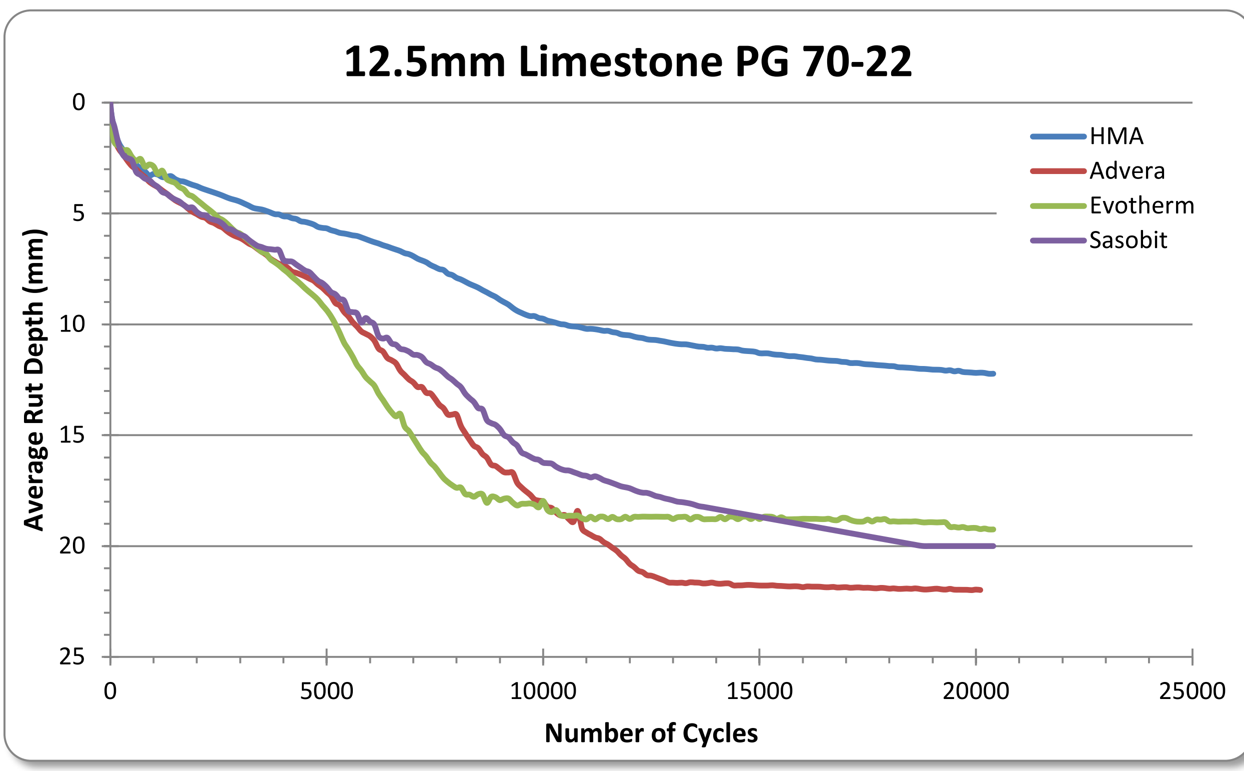


Figure 38. ERSA Results for All 12.5mm Limestone Mixes Containing PG 70-22

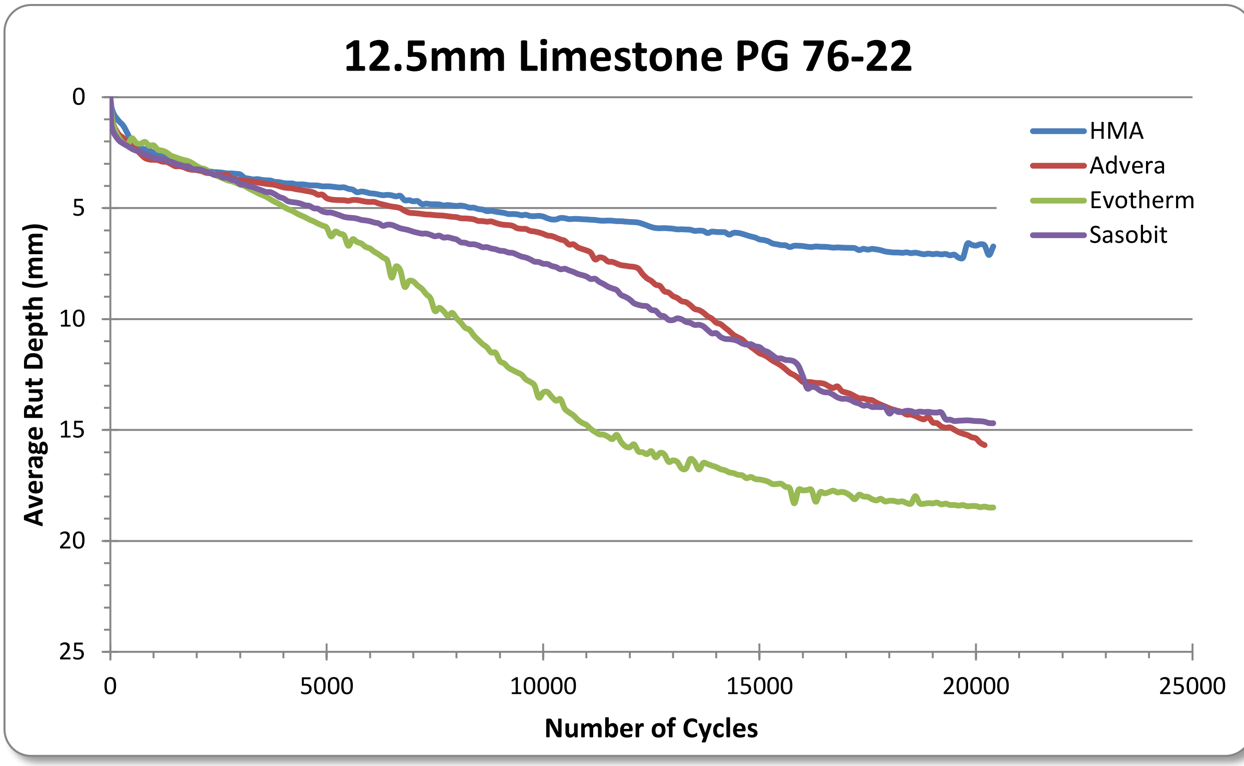


Figure 39. ERSA Results for All 12.5mm Limestone Mixes Containing PG 76-22

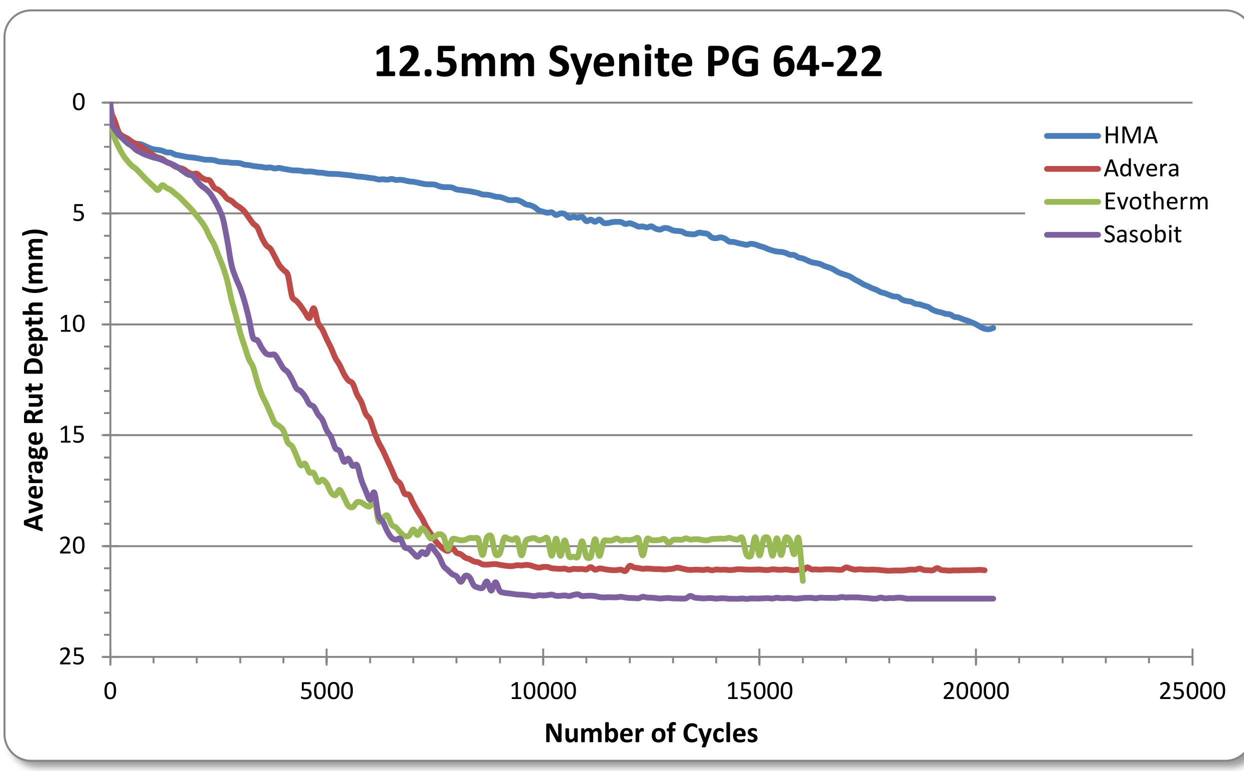


Figure 40. ERSA Results for All 12.5mm Syenite Mixes Containing PG 64-22

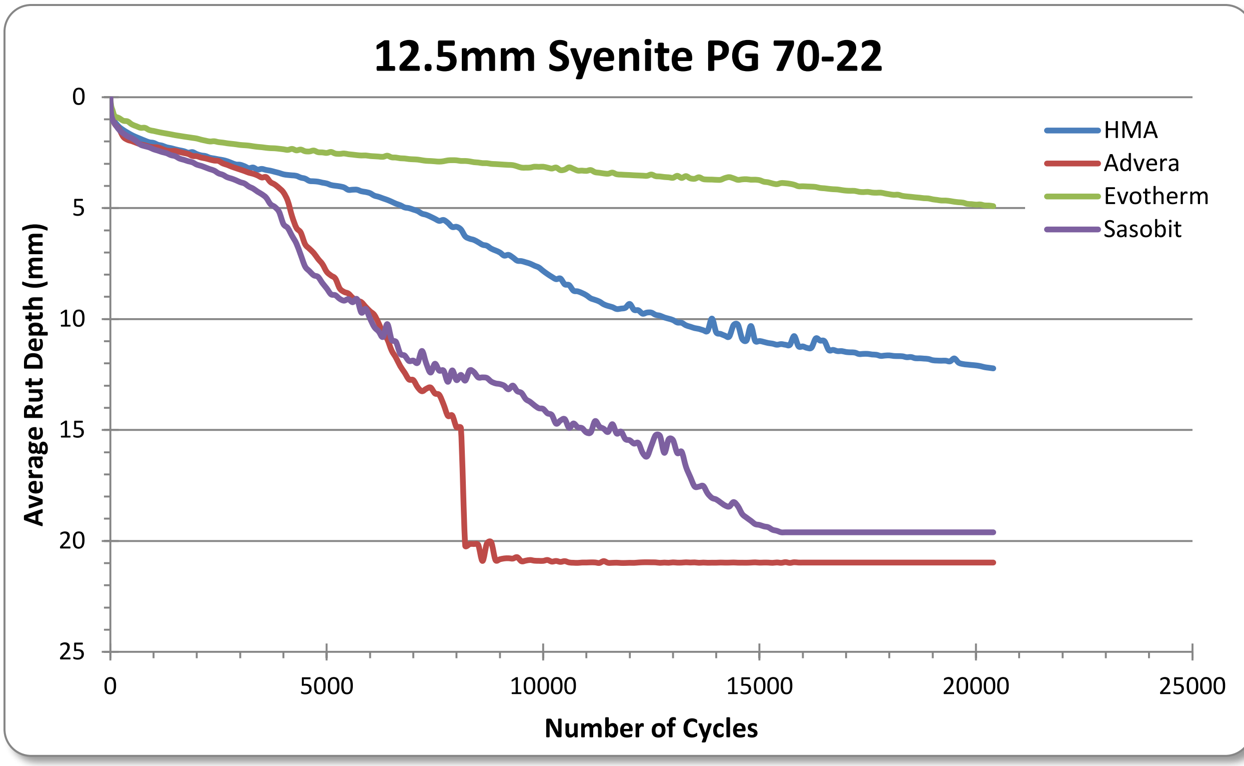


Figure 41. ERSA Results for All 12.5mm Syenite Mixes Containing PG 70-22

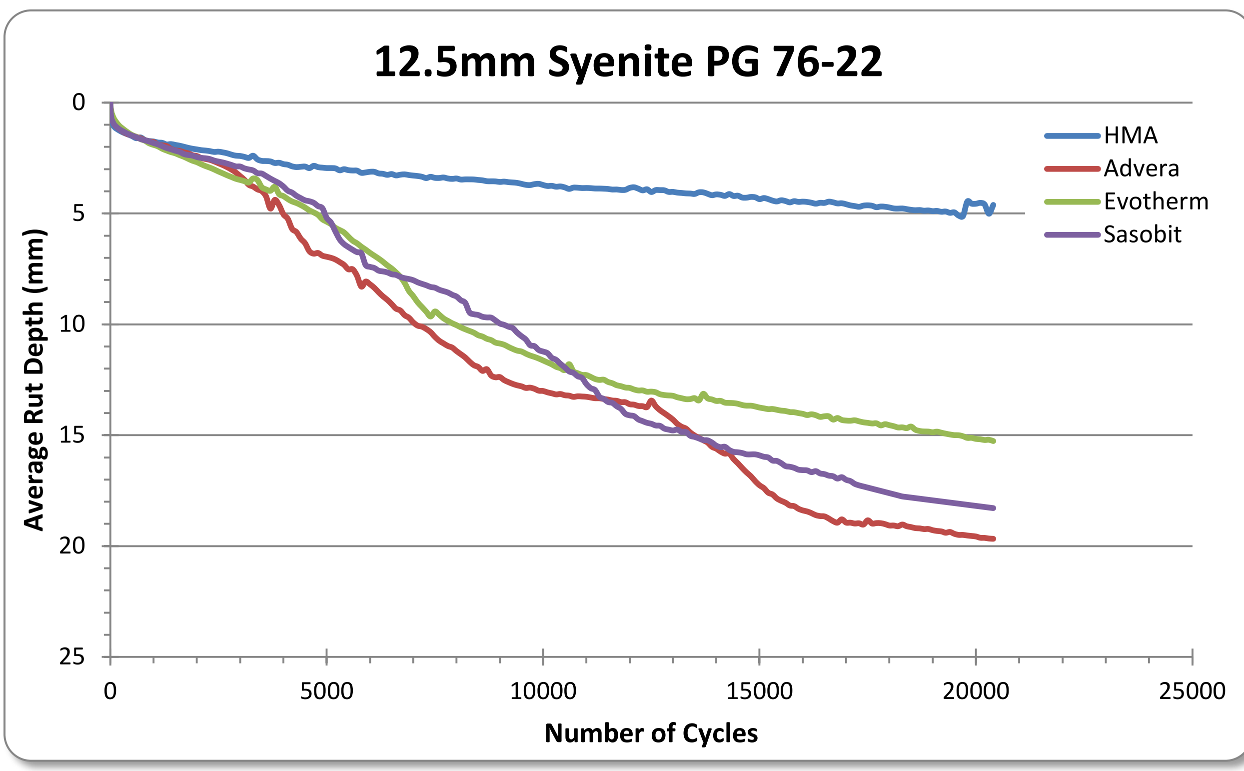


Figure 42. ERSA Results for All 12.5mm Syenite Mixes Containing PG 76-22

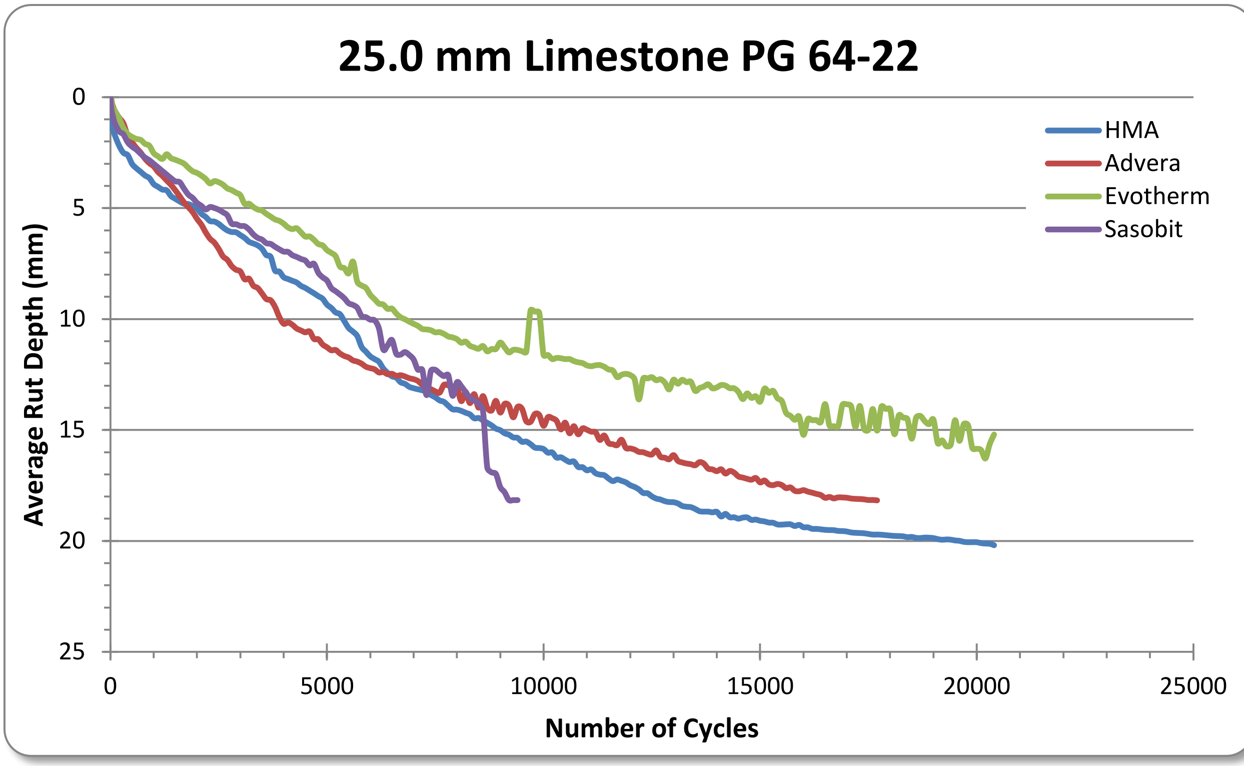


Figure 43. ERSA Results for All 25.0mm Limestone Mixes Containing PG 64-22

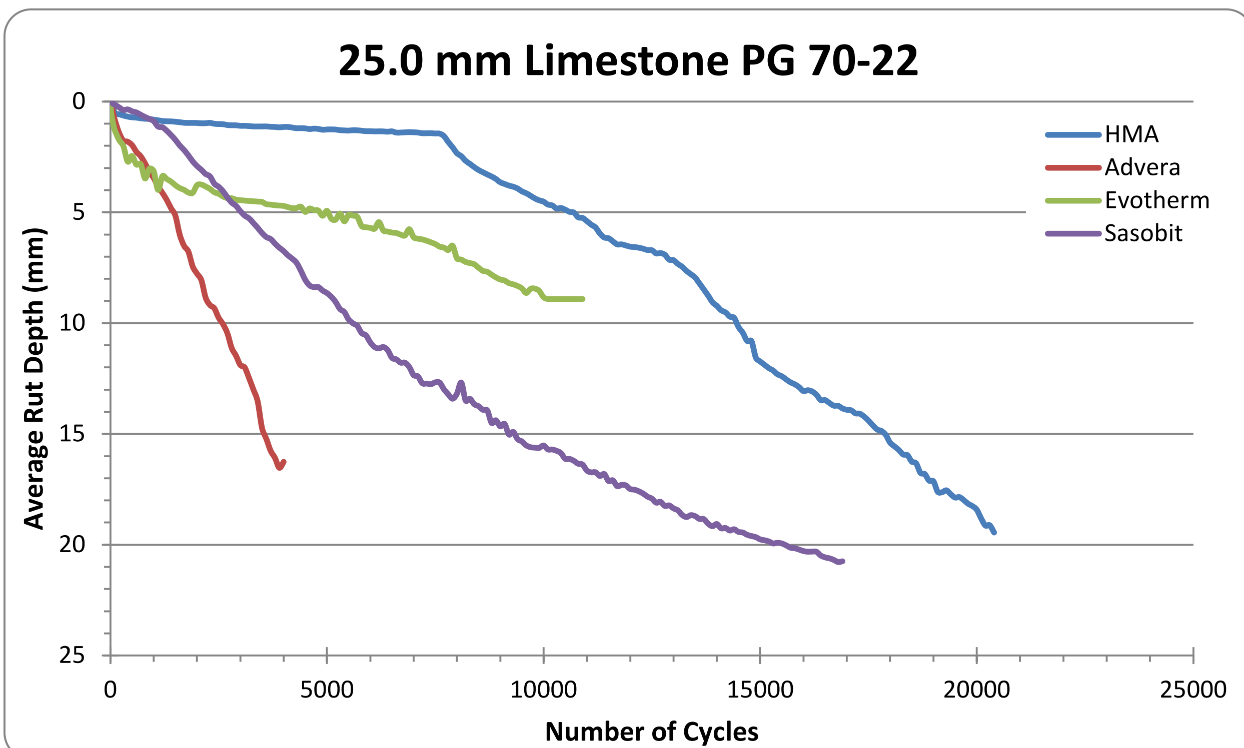


Figure 44. ERSA Results for All 25.0mm Limestone Mixes Containing PG 70-22

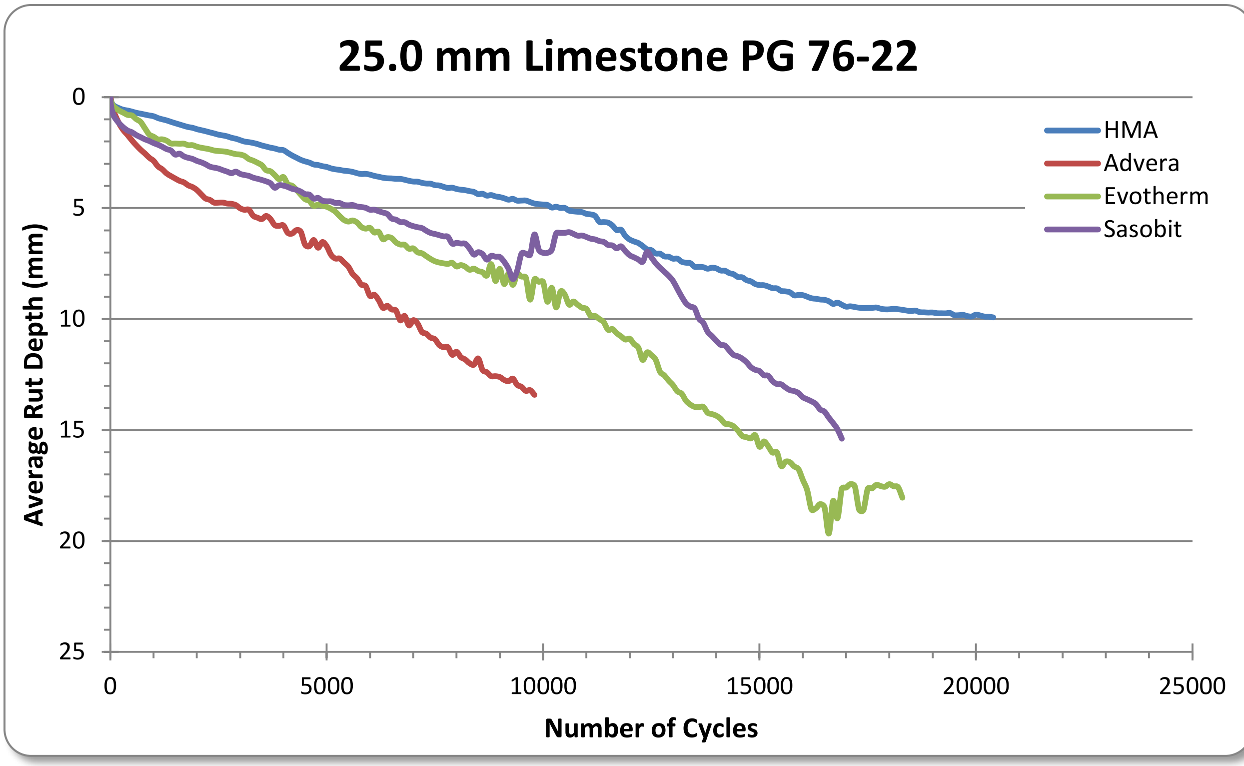


Figure 45. ERSA Results for All 25.0mm Limestone Mixes Containing PG 76-22

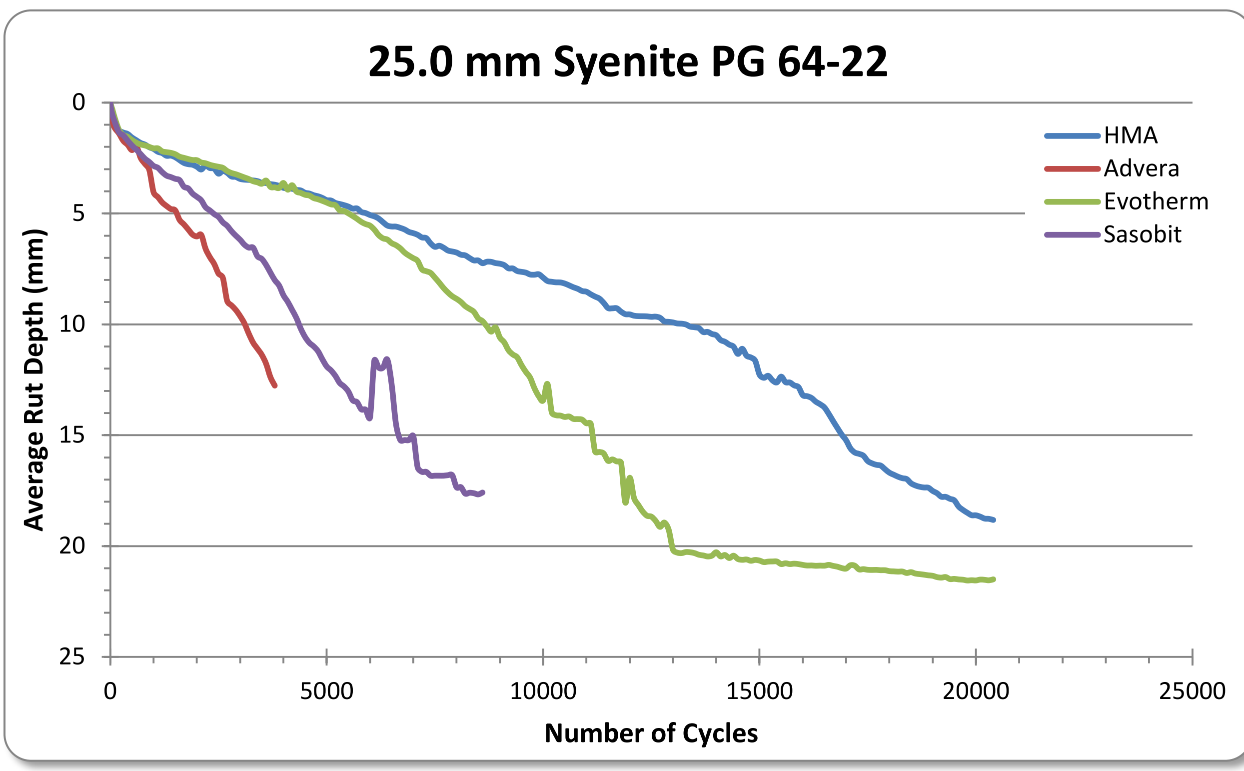


Figure 46. ERSA Results for All 25.0mm Syenite Mixes Containing PG 64-22

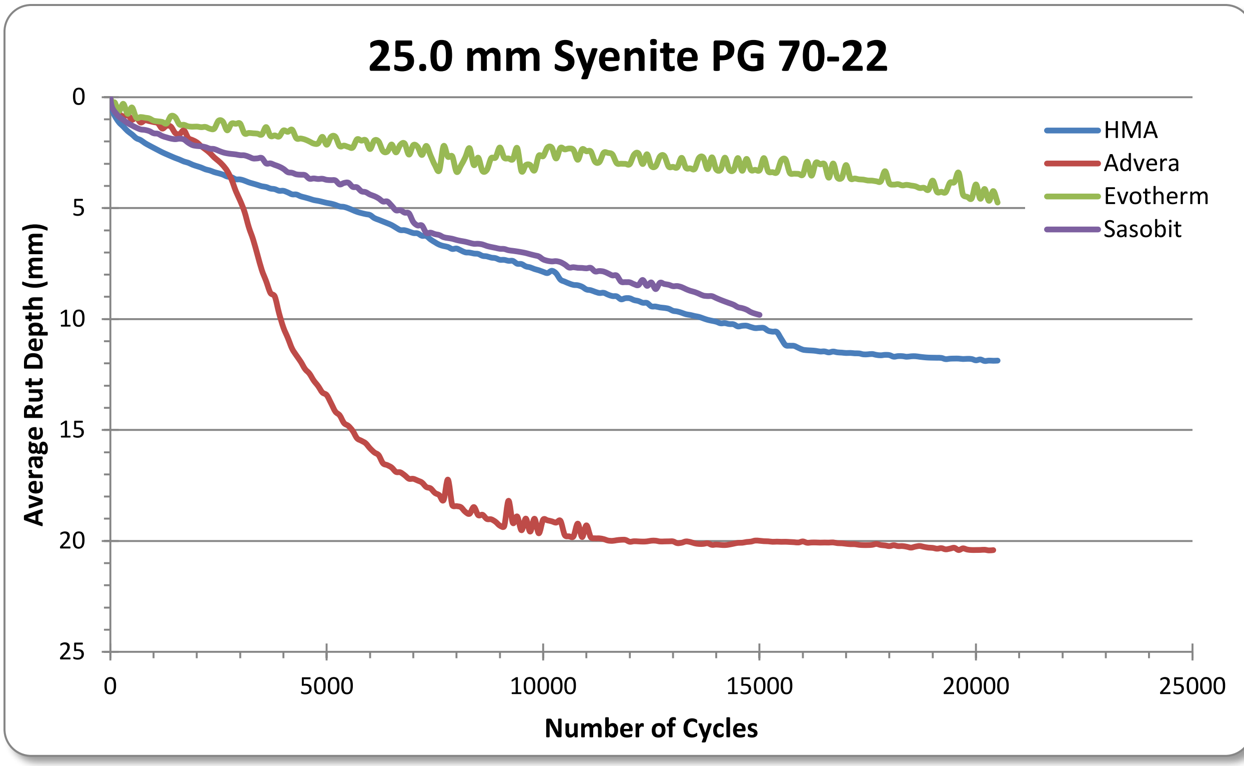


Figure 47. ERSA Results for All 25.0mm Syenite Mixes Containing PG 70-22

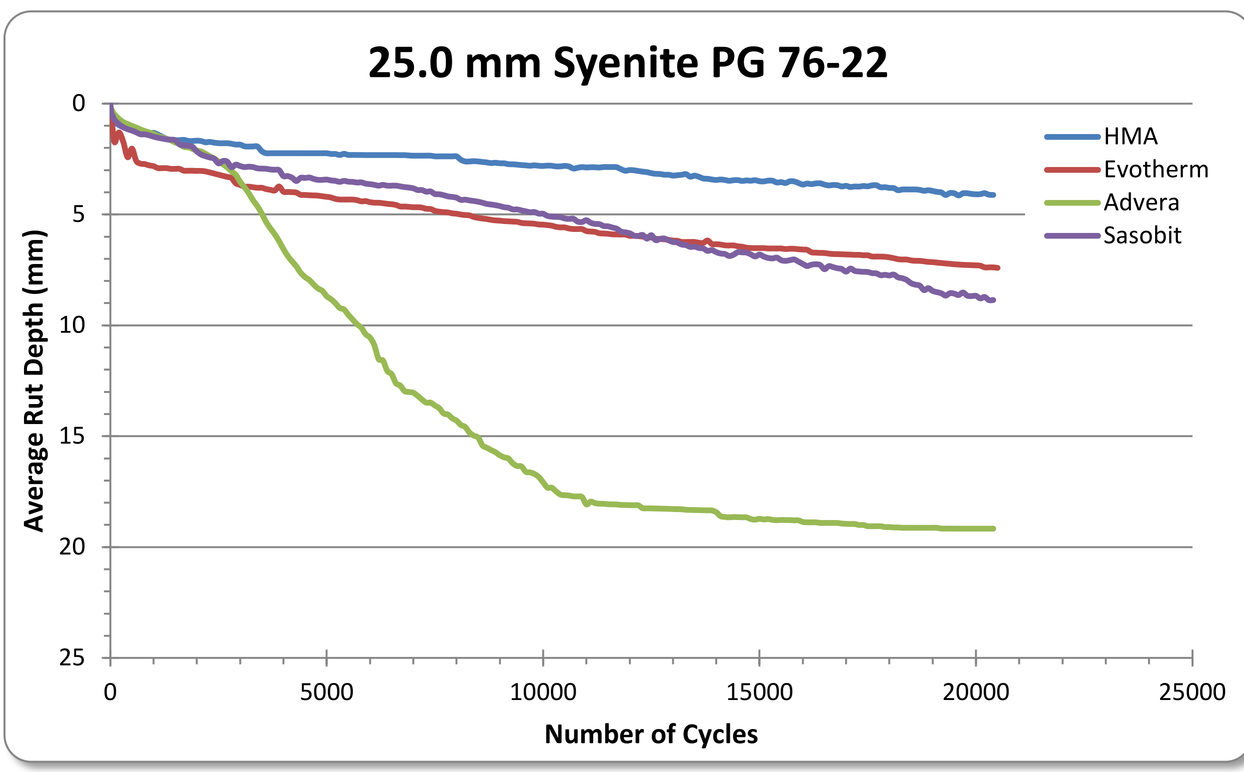


Figure 48. ERSA Results for All 25.0mm Syenite Mixes Containing PG 76-22

Statistical Analysis

Next, a multi-factor ANOVA was performed in order to determine what factors were most significant to the rutting and stripping performance of the mixes, and whether any significant relationships could be determined. The results of the ANOVA for all responses are shown in Table 25. Significant factors and interactions (i.e., p-values less than alpha=0.05) are displayed in **bold** type.

Table 25. ANOVA Results for ERSA Testing

	P-values for Responses					
Factors & Interactions	Rut Depth at 10,000 Cycles	Rut Depth at 20,000 Cycles	Rutting Slope	Stripping Slope	SIP	#Cycles to Max Rut Depth
Aggregate Type	0.1936	**0.0002**	**0.0003**	0.1162	0.1447	0.4245
NMAS	**0.014**	0.3469	0.4127	0.0827	0.8582	0.8659
PG	**<.0001**	**<.0001**	**0.0113**	0.1004	**0.023**	**<.0001**
NMAS*PG	0.4219	0.9802	0.859	0.0681	0.3146	0.3802
Additive	**<.0001**	**<.0001**	**0.0024**	0.0565	**0.0252**	**<.0001**
NMAS*Additive	0.0544	0.2678	0.0867	**0.0438**	0.2062	0.7515
PG*Additive	0.0608	0.0582	0.0683	**0.0112**	0.2355	**0.0013**
NMAS*PG*Additive	0.3452	0.8010	0.2156	**0.011**	0.5025	0.6591

Aggregate type was treated as a blocking factor, as differences in aggregate type were inherent to the experiment. Even so, aggregate type was only significant for the responses of Rut Depth at 20,000 Cycles and Rutting Slope.

With the exception of Stripping Slope and Number of Cycles to Maximum Rut Depth, there were no significant interactions for any of the response, meaning that individual factors could be examined separately. Due to significant interactions, Stripping Slope and # Cycles to Max Rut Depth are considered separately.

NMAS. NMAS was significant for Rut Depth at 10,000 Cycles. The average response for the 12.5mm mixes was 13.64, while that of the 25.0mm mixes was 11.38. Thus, the larger aggregate size provided better performance, which is reasonable since larger aggregates are generally believed to provide more strength than smaller aggregates.

PG Grade. PG Grade significantly affected Rut Depth at 10,000 cycles, Rut Depth at 20,000 Cycles, Rutting Slope, Stripping Inflection Point, and Number of Cycles to Maximum Rut Depth. These results are summarized in Table 26, which provides the results of means testing for the factor PG Grade. Mean values connected by a solid bar underline were not considered to have a statistically significant difference. For each response, the difference in performance between the PG 64-22 and PG 76-22 binders was statistically significant, regardless of Additive (HMA, Advera, Evotherm, or Sasobit) or NMAS (12.5mm or 25.0mm). Overall, the polymer-modified binders provided better performance than their non-modified counterparts. This is consistent with similar comparisons involving only HMA mixtures.

Table 26. Means Summary for PG Grade Factor in ERSA Testing

	Average Values for Each Response		
	PG 64-22	PG 70-22	PG 76-22
Rut Depth @ 10,000 Cycles	16.78	12.09	8.66
Rut Depth @ 20,000 Cycles	20.56	16.04	14.06
Rutting Slope	1274	1782	2157
Stripping Slope	Interaction	Interaction	Interaction
Stripping Inflection Point	7591	14057	17095
#Cycles to Max. Rut	Interaction	Interaction	Interaction

Additive. Additive type played a significant role in the rutting and stripping behavior of the mixes. This factor was statistically significant either as a main effect, or as part of a significant interaction, for all response variables. A summary of results is given in Table 27, in which the additives connected by a solid bar underline did not display statistically significant differences.

Table 27. Means Summary for Additive Type Factor in ERSA Testing

	Average Values for Each Response			
	HMA	Evotherm	Sasobit	Advera
Rut Depth @ 10,000 Cycles	7.22	11.33	14.19	17.30
Rut Depth @ 20,000 Cycles	12.64	15.53	18.65	20.73
Rutting Slope	2358	1986	1452	1155
Stripping Slope	Interaction	Interaction	Interaction	Interaction
Stripping Inflection Point	18765	13989	12551	6352
#Cycles to Max. Rut	Interaction	Interaction	Interaction	Interaction

For each response not included in an interaction, rutting and stripping performance ranked consistently with HMA having the best performance, followed Evotherm, Sasobit, and Advera, respectively. For Rut Depth at 10,000 cycles, there was a clear delineation of performance, with all additives generating performance that was significantly separated. Rut Depth at 20,000 cycles also generated a fair amount of data separation, with only Sasobit and Advera having rut depths. For Rutting Slope and Stripping Inflection Point, however, there was a considerable amount of data overlap, suggesting that the variability associated with each additive may have masked some of the differences.

Stripping Slope. For stripping slope, the three primary factors of NMAS, binder grade, and additive type showed significant interaction. Figure 49 illustrates this interaction, with the 12.5mm data shown in left graph and the 25.0mm data shown in the right graph.

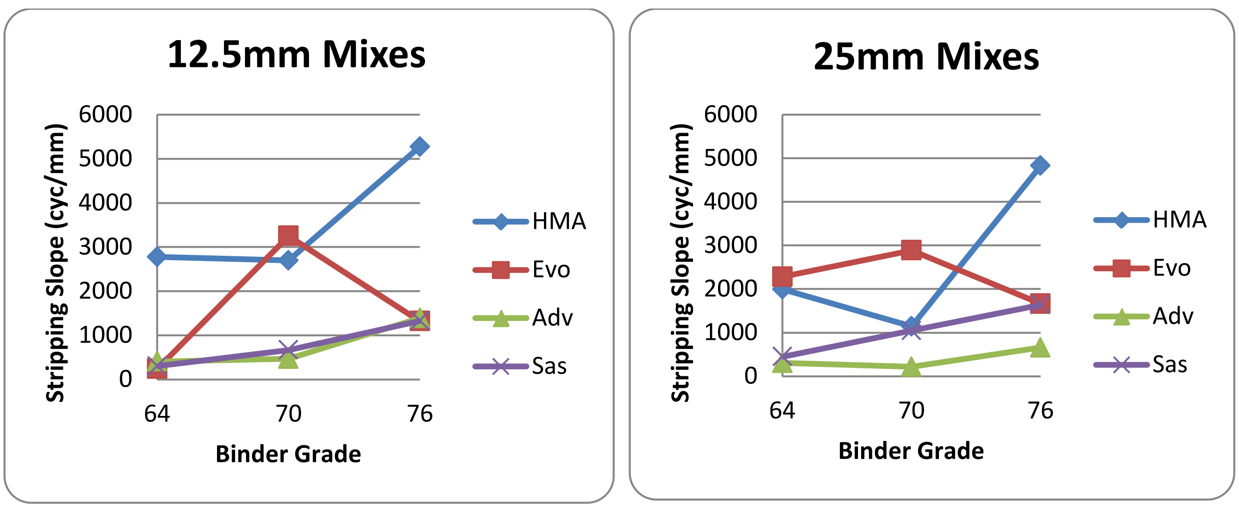


Figure 49. Interaction Plots for Effects of NMAS, Binder Grade, and Additive on Stripping Slope

In general, the HMA mixes had a higher stripping slope (i.e., better performance) than the warm mixes, with the exception of the Evotherm mix with PG 70-22 in the 12.5mm mixes, and for both the PG 64-22 and PG 70-22 in the 25.0mm mixes. Evotherm was the only warm mix additive which surpassed the quality of hot mix ast certain binder grades. HMA performance appeared much better for the PG 76-22 than any of the WMA additives. Sasobit and Advera exhibited similar performance, with the Sasobit performing slightly better for the 25.0mm mixes with PG 76-22. Overall, the mixes showed improved performance with increasing binder grade.

Number of Cycles to Maximum Rut Depth. This factor was sensitive to changes in PG grade and additive type, with interaction present. The interaction is shown in Figure 50.

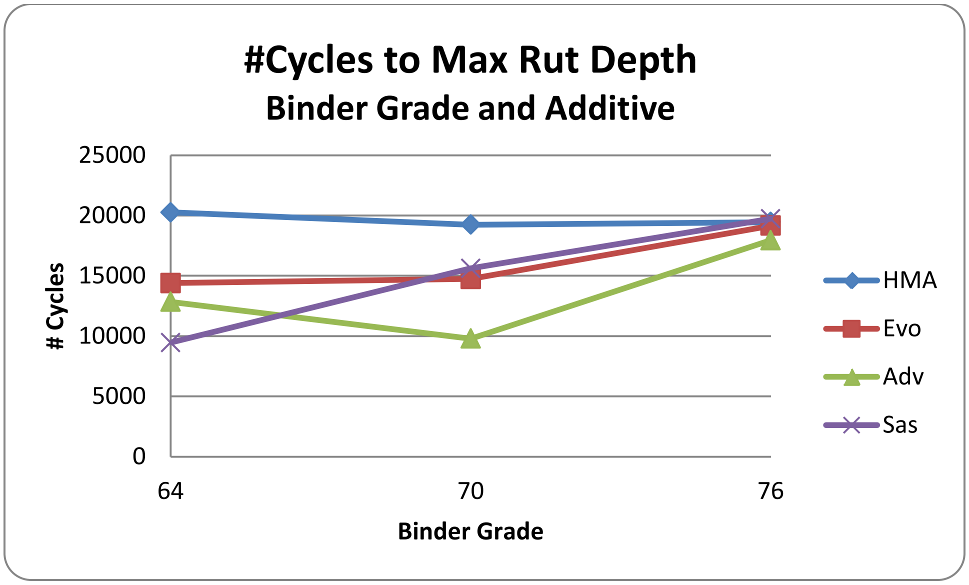


Figure 50. Interaction Plot for Effects of Binder Grade and Additive on #Cycles to Max Rut Depth

This interaction shows that the hot mixes were consistently ranked as the best performers, typically reaching the maximum rut depth late in the test (i.e., near 20,000 cycles). WMA performance improved for mixes containing PG 76-22, but the samples with lower binder grades sometimes reached a terminal rut depth as early as 10,000 cycles. Evotherm and Advera were less sensitive to changes between PG 64-22 and PG 70-22, and all WMA additives showed improvements between PG 70-22 and PG 76-22. Sasobit displayed consistent improvement as binder grade increased.

In general, the rutting and stripping performance of the warm mixes does give cause for concern, as the rutting and stripping performance were often significantly poorer than that of the HMA mixes, especially for the lower binder grades. In the industry, concerns have been raised regarding the lower WMA temperatures and their potential to reduce the amount of aging of binders during production, resulting in a "softer" mix. Additional concerns have arisen from the fear that the reduced temperatures during production could also result in aggregates not being completely dried, creating additional susceptibility to moisture damage. In this study, all mixes were prepared with dry aggregates, so the additional concerns of moisture in the aggregate are not represented. However, significant issues with rutting and stripping have been demonstrated for these warm mixes, simply due to the addition of the WMA additive. It is likely that moisture trapped in the aggregate pores would only serve to worsen the performance.

<u>Design Binder Content Reductions</u>

It was previously noted that in some cases, the air voids generated by incorporating a WMA additive into a mix design were decreased significantly enough that a reduction in the design binder content could be warranted. Because WMA is designed to improve the workability of the mixture, this type of change seems reasonable, though the magnitude of the change must be balanced with the desired temperature reduction for the mix. There is some concern that if the optimum binder content decreased but no change was made to the design in order to accommodate this change, the rutting and stripping potential of the mix could become exaggerated.

For most of the mix designs used in this study, no significant change in binder content (i.e., 0.3 percent or more) was warranted when the WMA technology was incorporated. However, for mixtures that show a decrease in optimum binder content for warm mixes, reducing the binder content could represent a potential source of savings, while also improving the mixture's resistance to rutting or stripping.

In this study, three mixtures were identified to allow for a reduction in binder content, including:

- 12.5mm Limestone, PG 70-22 with Evotherm,
- 12.5mm Limestone, PG 70-22 with Sasobit, and
- 12.5mm Limestone, PG 76-22 with Sasobit.

These three mixtures were produced at the original HMA design binder content, as well as the revised optimum binder content in order to determine whether a significant difference in rutting and/or stripping performance would be demonstrated. Figures 51, 52, and 53 show the results of these comparisons. Average values are shown.

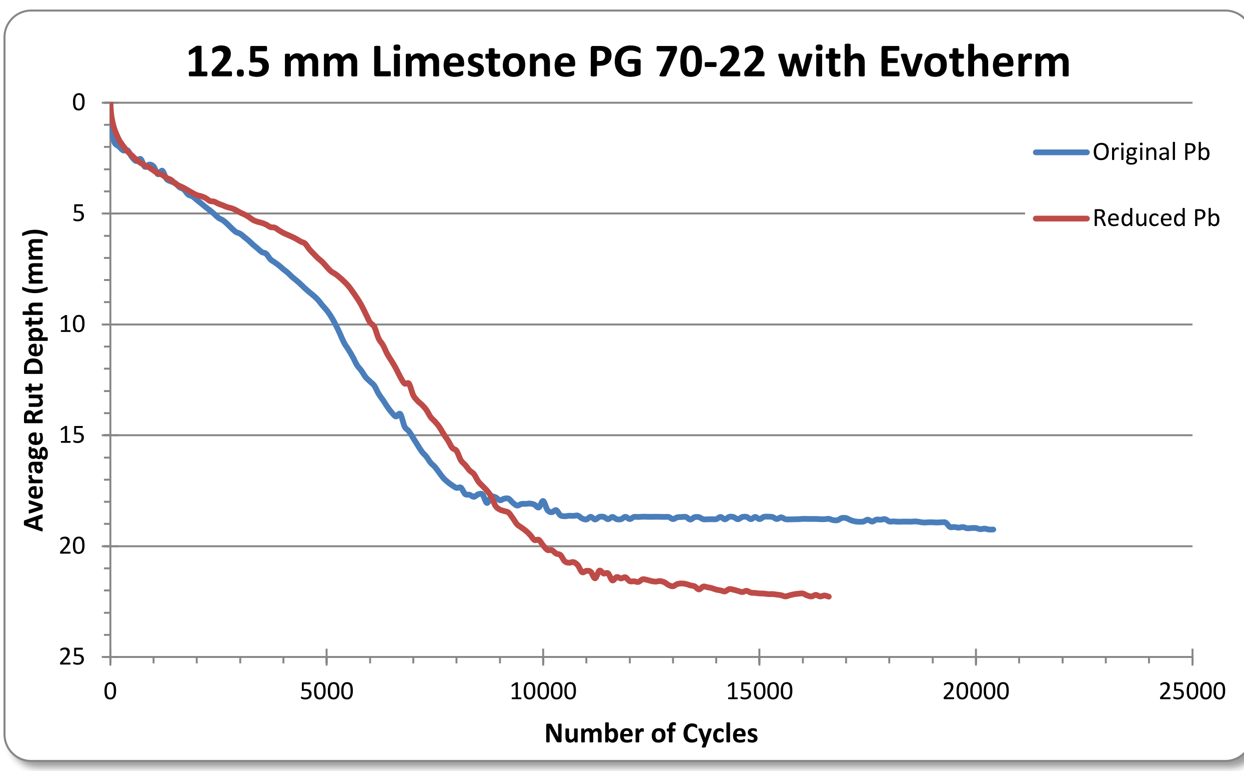


Figure 51. ERSA Results for 12.5mm Limestone Mix, PG 70-22, Evotherm with Design Pb Reduction

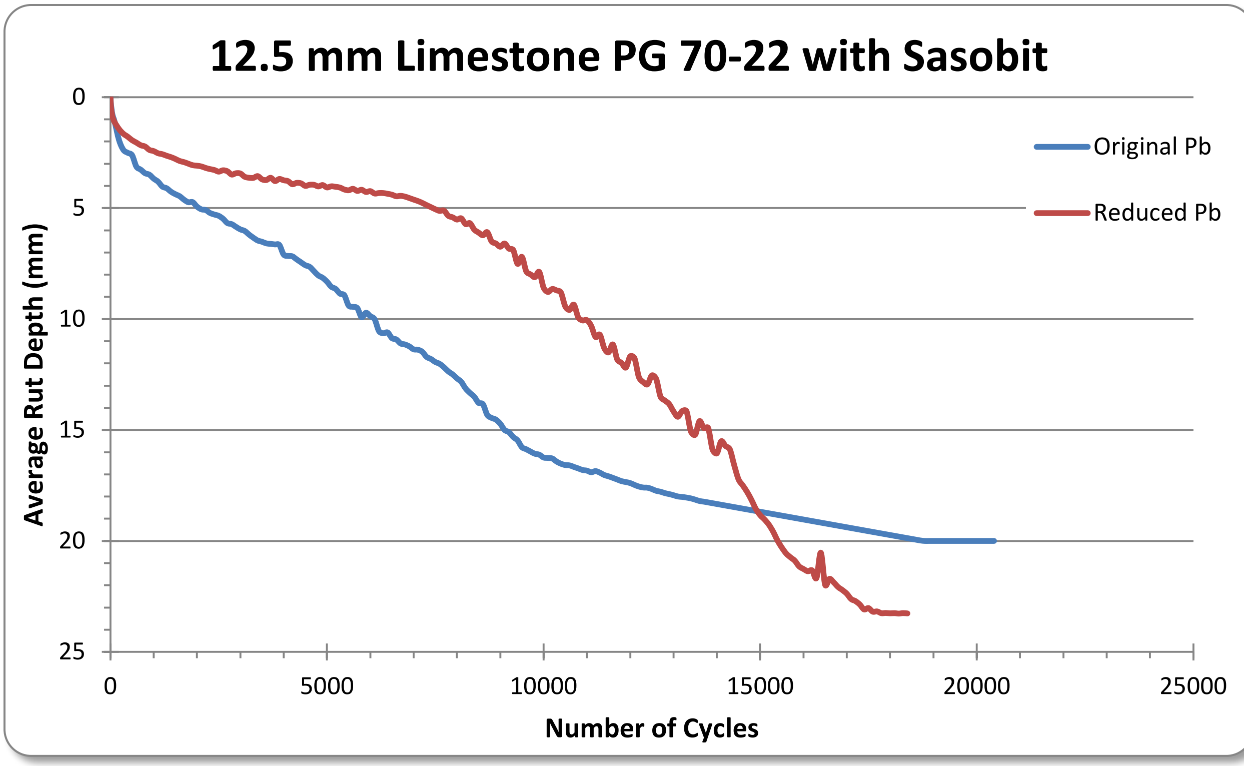


Figure 52. ERSA Results for 12.5mm Limestone Mix, PG 70-22, Sasobit with Design Pb Reduction

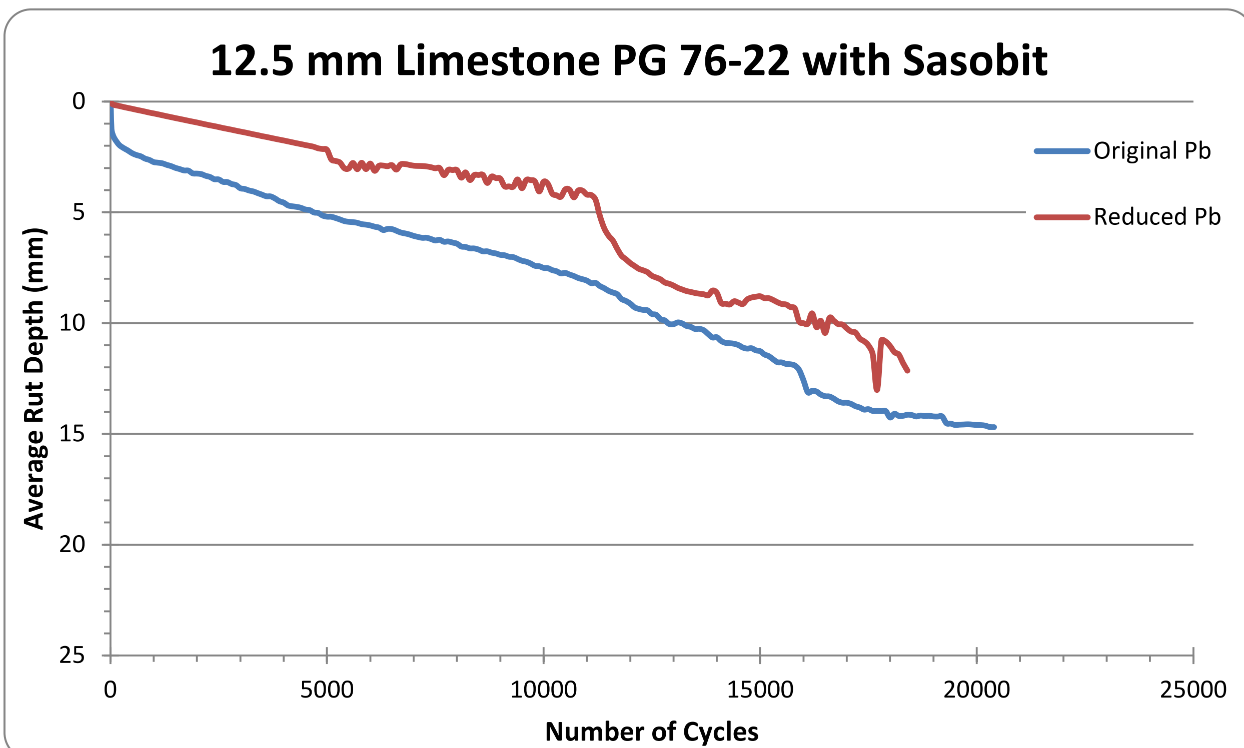


Figure 53. ERSA Results for 12.5mm Limestone Mix, PG 76-22, Sasobit with Design Pb Reduction

For all three of the mixes examined, reducing the binder content did appear to improve the performance of each mixture slightly, though these improvements were not necessarily significant from a practical standpoint. The encouraging feature of these comparisons was that rutting and stripping performance were consistently improved for all cases.

Rutting Performance by the Asphalt Pavement Analyzer

Additional rutting tests were performed for selected mixes using the Asphalt Pavement Analyzer (APA), and these tests were performed by AHTD's Materials Division. The APA is shown in Figure 54, along with rutted samples after testing. The APA test method, performed according to AHTD Test Method 480, is used in the current AHTD specification, which requires a maximum rut at 8000 cycles of 8.000 mm for 50 and 75 design gyration (N_{des}) mixes, a maximum of 5.000 mm for 100 and 125 design gyration (N_{des}) mixes. In this study, these limits correspond with a maximum rut depth of 8.000 mm for the PG 64-22 binder grades, and 5.000 mm for the PG 70-22 and PG 76-22 binder grades.

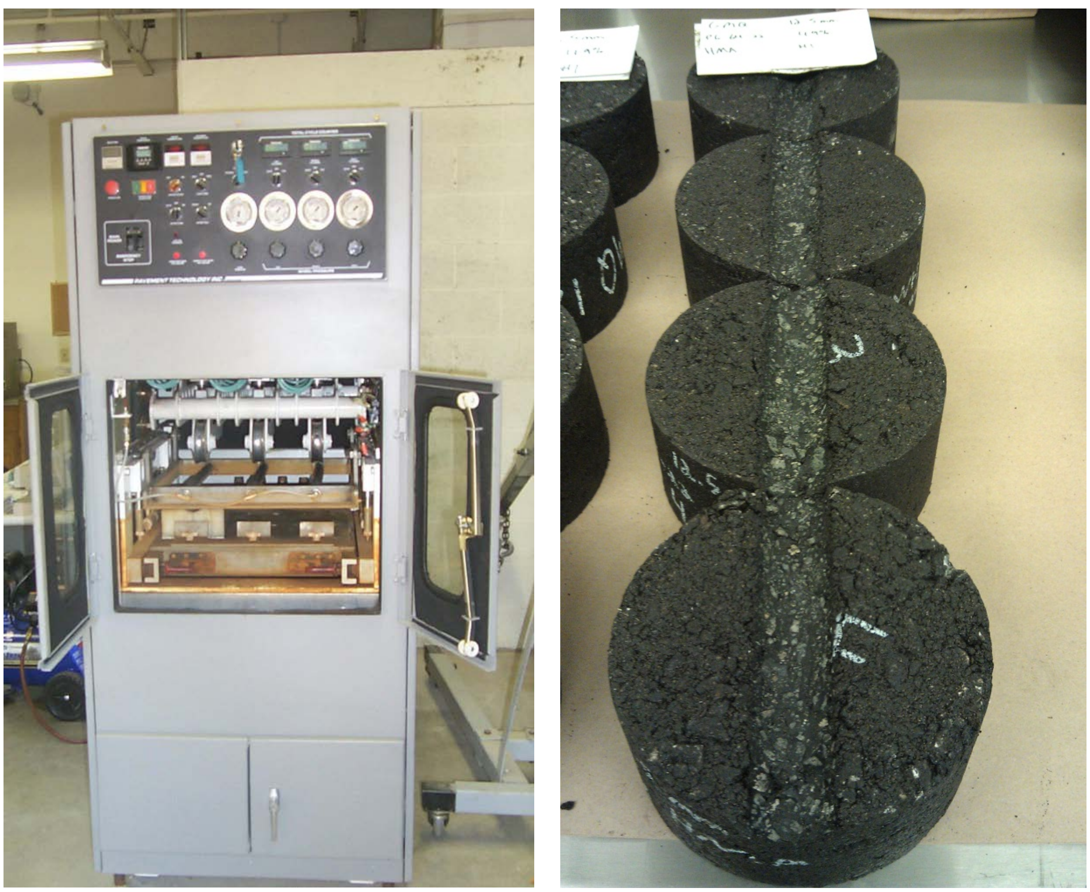


Figure 54. Asphalt Pavement Analyzer (left) and Samples after APA Testing (right)

A subset of the mixtures was selected for this portion of the testing, designed to include a range of mix design features and performance levels. Because the Advera mixes had consistently been ranked as the poorest performers, these mixes were omitted from further investigation. The subset chosen for APA testing included the following mixes:

- 12.5mm Limestone PG 76-22 (HMA, Evotherm, Sasobit)
    - In ERSA, this mix was a fair performer. The HMA mix performed better than the WMA mixes, but Evotherm and Sasobit were very similar.
- 12.5mm Syenite PG 64-22 (HMA, Evotherm, Sasobit)
    - In ERSA, this mix showed drastic differences between the HMA and WMA mixes. The HMA performed fairly well, but all three WMA mixes stripped quickly and reached a terminal rut depth by 10,000 cycles.
- 25.0mm Limestone PG 70-22 (HMA, Evotherm, Sasobit)
    - In ERSA, this mix was not a good performer, and the WMA mixes were not as resistant to rutting as the HMA mix. The Evotherm mix provided better performance than the Sasobit mix.
- 25.0mm Syenite PG 70-22 (HMA, Evotherm, Sasobit)
    - In ERSA, this mix was a fairly good performer, with the Sasobit and HMA mixes performing very similarly. The Evotherm mix was the best performer, clearly exhibiting less rutting than the HMA mix.

Table 28 contains a summary of results, including average rut depth and rate of rutting at 100 cycles, 4000 cycles, and 8000 cycles. Mixes failing the AHTD mix design criteria are shown in bold type. Summary graphs are shown in Figures 55 through 58.

Table 28. Summary of APA Data – Average Values

Aggregate	NMAS	PG Grade	Additive	Rut Depth @ 100 Cycles	Rut Depth @ 4000 Cycles	Rut Depth @ 8000 Cycles
LS	12.5	PG 76-22	HMA	0.739	3.020	3.681
			Evotherm	0.835	3.618	4.379
			Sasobit	1.484	4.984	6.688
	25.0	PG 70-22	HMA	0.360	2.333	2.790
			Evotherm	0.454	3.050	3.645
			Sasobit	0.315	1.993	2.496
SY	12.5	PG 64-22	HMA	1.308	5.633	6.777
			Evotherm	1.530	6.148	7.612
			Sasobit	1.048	4.588	5.562
	25.0	PG 70-22	HMA	0.494	3.404	4.224
			Evotherm	0.689	4.261	5.098
			Sasobit	0.451	2.085	2.603

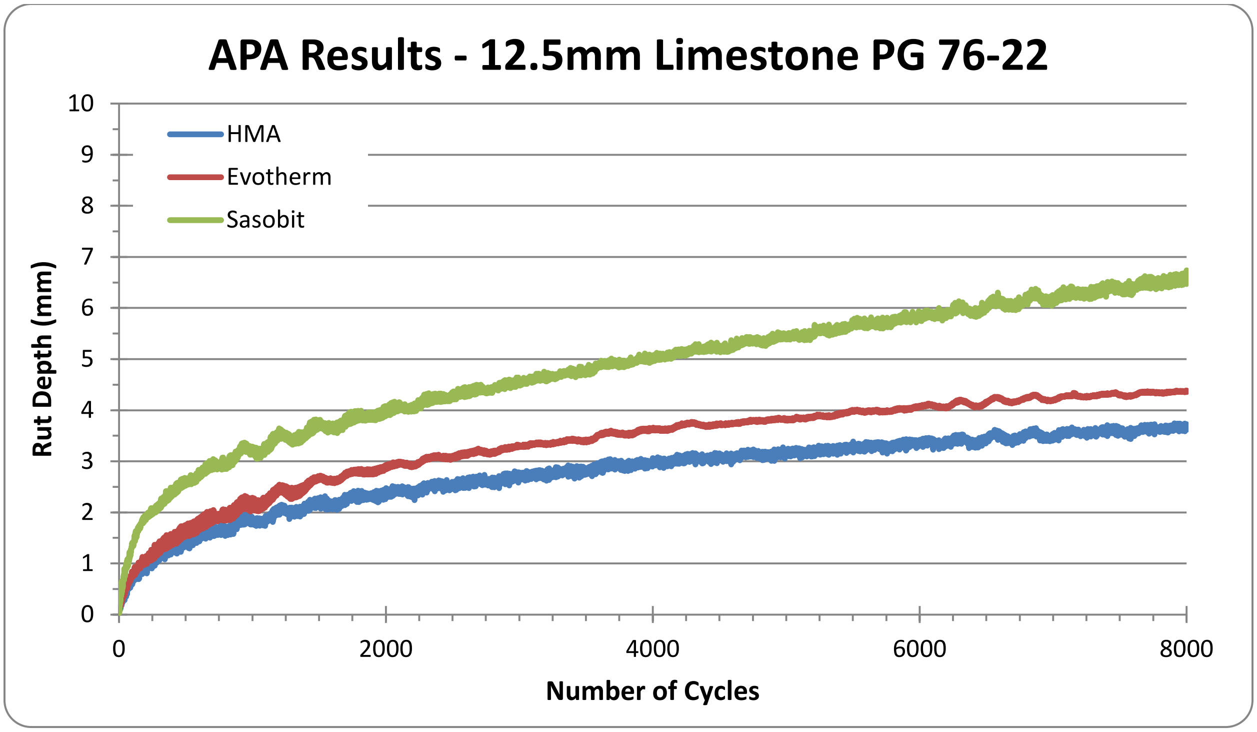


Figure 55. Average APA Results for 12.5mm Limestone Mix, PG 76-22

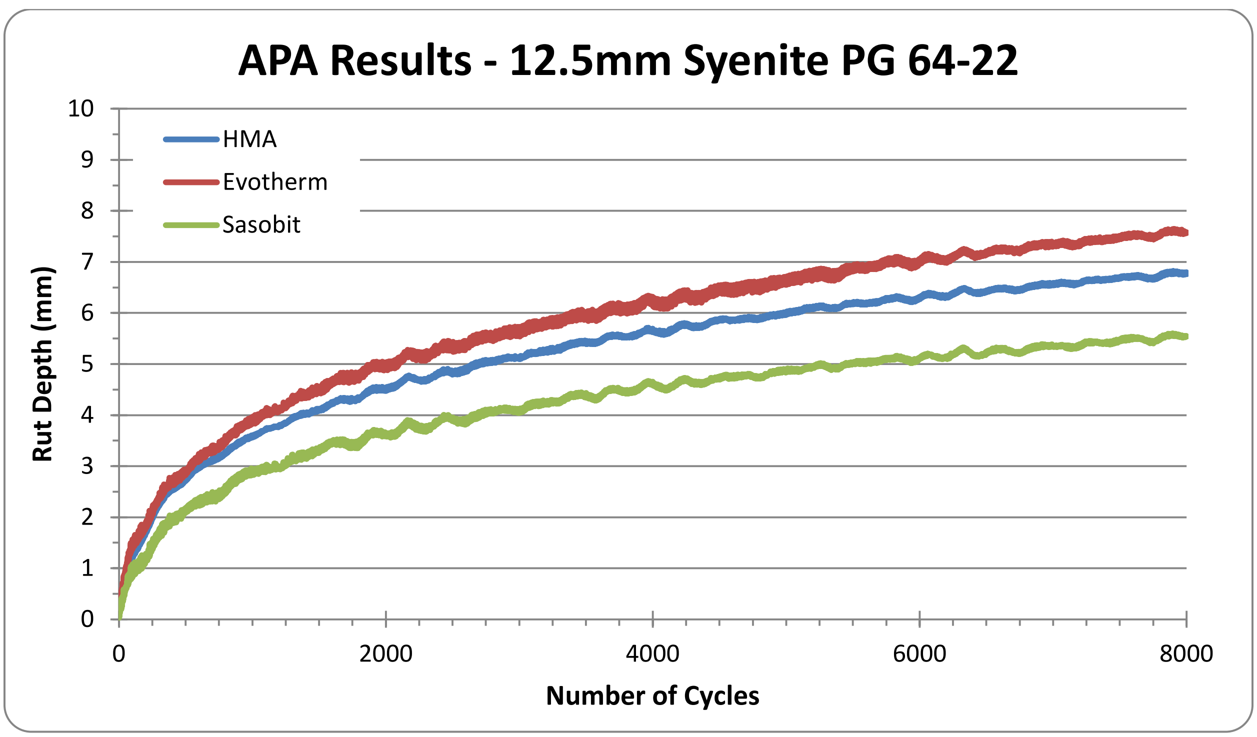


Figure 56. Average APA Results for 12.5mm Syenite Mix, PG 64-22

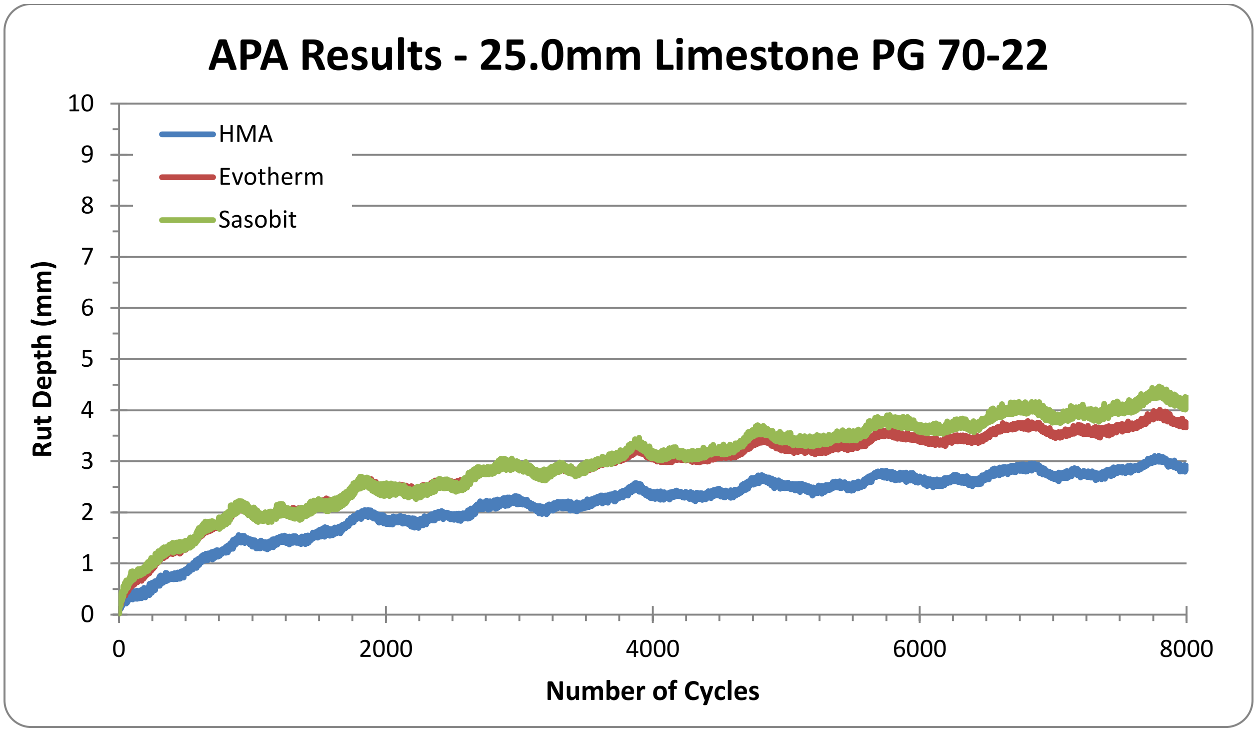


Figure 57. Average APA Results for 25.0mm Limestone Mix, PG 70-22

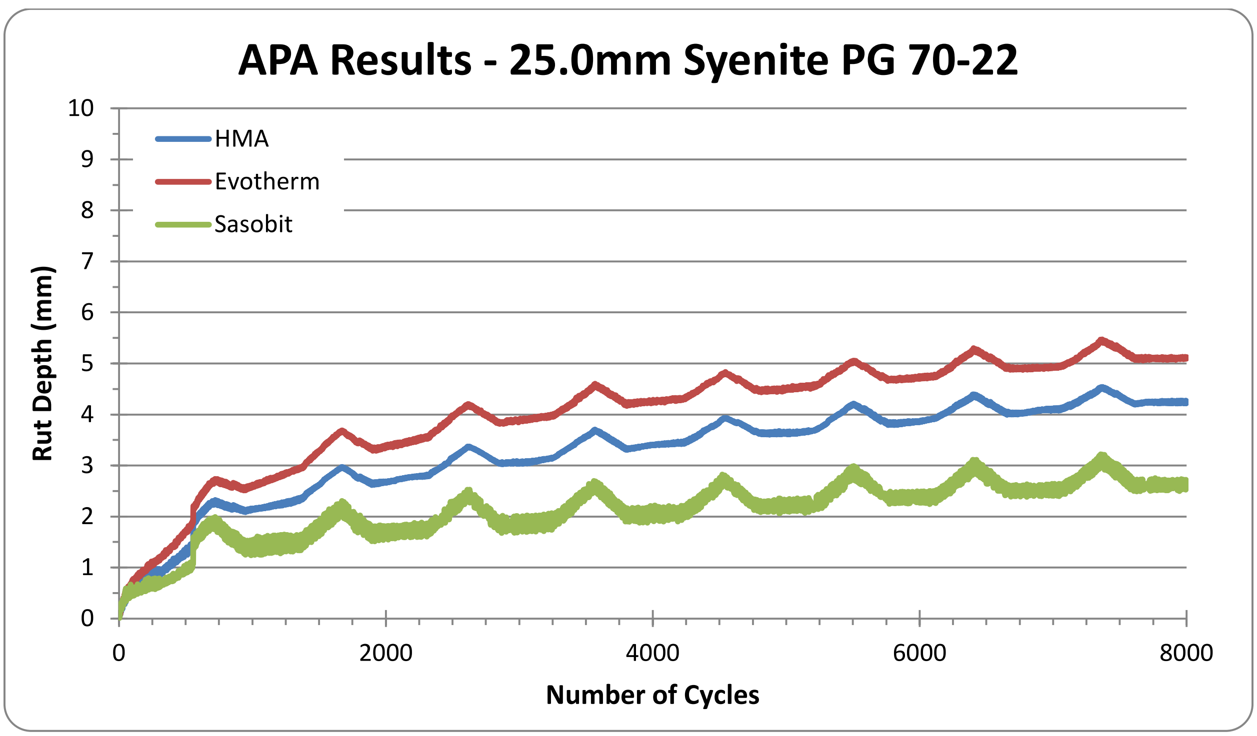


Figure 58. Average APA Results for 25.0mm Syenite Mix, PG 70-22

It is immediately evident that the rut depths resulting from the APA test are much lower than that of the ERSA test. This is reasonable because the two tests employ different testing parameters. Most significantly, the ERSA test is more severe because it uses a steel wheel and the samples are tested in the submerged condition. Although the APA test is conducted at a higher temperature of 64 °C, it is a dry test, and the test specimens are contacted directly by a pressurized rubber hose rather than the actual loaded wheel. Thus, similar results were not necessarily expected for the two tests.

For the 12.5mm limestone mix design, the HMA mix was the best performer, followed by Evotherm and Sasobit. The 25.0mm limestone mix design was similar in that the HMA mix displayed performance superior to that of the WMA mixes, though there was less differentiation between the 25.0mm mixes. For both syenite mix designs, the Sasobit mixes were the best performers, followed by the HMA mixes, and then the Evotherm mixes.

Interestingly, only two of the mixes failed the AHTD mix design specification for APA rut depth: the 12.5mm limestone PG 76-22 with Sasobit, and the 25.0mm syenite PG 70-22 with Evotherm. Additionally, the results of the ERSA and APA tests were not consistent with each other. The Sasobit mix failing the APA test was a fair performer in the ERSA test, and the Evotherm mix failing the APA test was one of the best performers in the ERSA test. The 12.5mm syenite mixture that quickly failed in the ERSA test was deemed acceptable by the APA test. Clearly, the failure mechanisms employed by each of these tests are quite different. Given the numerous accounts in the literature stating that field performance is typically better than laboratory rutting performance, the APA test results are likely the more realistic of the two. However, it is noted that a dry test provides information on rutting, but does not address stripping potential.

Moisture Damage Testing by AASHTO T 283

Further testing was performed to assess an alternative method for determining moisture damage susceptibility. AASHTO T 283, or the modified Lottman test, is a common test procedure for determining the relative performance of a given mixture, and compares the indirect tensile strength of specimens subjected to vacuum saturation and an unconditioned control set. The primary response is the Tensile Strength Ratio (TSR) value, which is usually required to be a minimum of 0.80. Visual assessments are also included as a part of the method and require the technician to assign a visual stripping rating, such that a minimum rating of 0 indicates no visible stripping, and a maximum rating of 5 indicates severe stripping. Although AHTD requires a modified version of this test method (AHTD Test Method 455), the T 283 was used as there is more literature available relating to this method.

In this experiment, the same subset of mixture used in the APA testing was used. These mixes encompassed a range of performance and mixture parameters, and included the HMA, Evotherm, and Sasobit mixes for each design. Table 29 provides a summary of data from the T 283 testing, and includes visual ratings for the conditioned and unconditioned sample sets, maximum load values for the conditioned and unconditioned samples sets, and the TSR value for each mix.

Table 29. Summary of Moisture Damage (T 283) Data – Average Values

Mixture	Additive	Conditioned Visual Rating	Unconditioned Visual Rating	Conditioned Load (lbs)	Unconditioned Load (lbs)	TSR
12.5mm LS PG 76-22	HMA	0.8	0.7	3583	5067	0.78
	Evo	5.0	1.7	2217	4025	0.55
	Sas	3.0	2.2	2517	3850	0.66
25mm LS PG 70-22	HMA	2.8	2.3	3717	5650	0.66
	Evo	5.0	4.0	2817	4858	0.58
	Sas	5.0	3.5	2367	4275	0.55
12.5mm SY PG 64-22	HMA	2.5	1	2910	6142	0.47
	Evo	4	1.5	3250	4700	0.69
	Sas	4.5	1	1817	4683	0.39
25mm SY PG 70-22	HMA	1.5	0.5	6050	7500	0.81
	Evo	1.7	1.5	4450	5400	0.82
	Sas	2.5	1.3	3600	4983	0.72

For the mixes with polymer modified binders, the HMA mixes performed better than the WMA mixes. According to the typical specification limit for this method, only two mixes would have been deemed acceptable: the 25.0mm syenite HMA mix with PG 70-22, and the 25.0mm syenite Evotherm mix with PG 70-22. For the unconditioned specimens from all mix designs, the maximum load values of the HMA were higher than those of the corresponding Evotherm and Sasobit mixes. This was also true for the conditioned specimens, with the single exception of the 25.0mm syenite mix, in which the Evotherm mixture was stronger than the HMA mixture.

The 25.0mm syenite mix with PG 70-22 was the best-performing mix design of the group. The visual ratings for the conditioned samples of this mix design were very low compared to samples from other mixes, and the Evotherm samples had a better rating than the Sasobit samples. In addition, the TSR values were higher for these samples than for the other mixes, and the load ratings for conditioned and unconditioned samples were higher than the other mixes. The excellent performance of these samples can be seen in Figures 59 and 60, which show the conditioned and unconditioned samples with Evotherm. Neither of these specimens showed significant moisture damage, and the conditioned sample appeared comparable to the unconditioned sample.

Figure 59: Conditioned Sample, 25mm Syenite PG 70-22 with Evotherm

Figure 60: Unconditioned Sample, 25mm Syenite PG 70-22 with Evotherm

The second ranking HMA mix was the 12.5mm limestone mix with PG 76-22. The HMA mix for this design had a TSR of 0.78, which was close to the 0.80 threshold. However, the WMA mixes did not perform as well, with the Sasobit mix demonstrating greater stripping resistance than the Evotherm mix. The samples containing Evotherm displayed noticeable stripping, as did the Sasobit samples. The unconditioned load of the Evotherm mix was greater than that of the Sasobit mix, though. The conditioned and unconditioned Evotherm samples from this mix design are shown in Figures 61 and 62. It is important to note that the white spots are a result of broken aggregate particles. This is not stripping, though weak aggregate particles can certainly be detrimental to mixture strength. Stripping is evidenced by the separation of the aggregate particles and the binder films, and typically presents as an aggregate particle having a brownish tint, which is the remainder of the binder film that has stripped away.

Figure 61: Conditioned Sample, 12.5mm Limestone, PG 76-22 with Evotherm

Figure 62: Unconditioned Sample, 12.5mm Limestone PG 76-22 with Evotherm

The 25.0mm limestone mix with PG 70-22 did not perform very well (TSR = 0.66), but the performance of the Evotherm and Sasobit mixes was only slightly poorer (TSR = 0.58 and 0.55, respectively). Figures 63 and 64 show an unconditioned sample and a conditioned sample containing Evotherm. Evidence of moisture damage can be observed in the conditioned sample.

Figure 63: Conditioned Sample, 25mm MCA 70-22 with Evotherm

Figure 64: Unconditioned Sample, 25mm MCA 70-22 with Evotherm

The poorest ranking HMA mixture in the T 283 testing set was the 12.5mm syenite mix with PG 64-22 binder. The results from this testing agreed with the ERSA testing in that all mixes, with or without WMA additives, were poor performers. By visual inspection, there was some evidence of stripping in the unconditioned specimens, which should not happen. However, this reveals the nature of the lack of and adequate bond between the aggregate particles and the binder coatings. The Evotherm comparison of conditioned and unconditioned samples is shown in Figures 65 and 66.

Figure 65: Conditioned Sample, 12.5mm GMQ 64-22 with Evotherm

Figure 66: Unconditioned Sample, 12.5mm GMQ 64-22 with Evotherm

The purpose of the moisture damage testing was to have a second method of evaluating the mixtures' susceptibility to stripping in order to either support or dispute the findings from the ERSA and APA tests. Therefore, the four mixes were ranked with respect to performance of the HMA mixes according to the ERSA, APA, and T 283 testing. The results of these rankings are shown in Table 30.

Table 30. Rankings by Various Rutting and Moisture Susceptibility Test Methods (HMA)

		Mix Design			
		25.0mm SY PG 70-22	12.5mm LS PG 76-22	25.0mm LS PG 70-22	12.5mm SY PG 64-22
ERSA	Rut Depth @ 10,000 Cycles	4	3	1	2
	Rut Depth @ 20,000 Cycles	3	1	4	2
	Rutting Slope	3	2	4	1
	Stripping Slope	3	2	4	1
	Stripping Inflection Point	2	3	4	1
	#Cycles to Max. Rut	3	4	1	2
	Overall ERSA Rating	3	1	4	2
APA	Rut Depth at 4000 Cycles	3	2	1	4
	Rut Depth at 8000 Cycles	3	2	1	4
	Overall APA Rating	3	2	1	4
T 283	Conditioned Visual Rating	2	1	4	3
	Unconditioned Visual Rating	1	2	4	3
	Conditioned Max. Load	1	3	2	4
	Unconditioned Max. Load	1	4	3	2
	TSR	1	2	3	4
	Overall T 283 Rating	1	2	3	4

According to the rankings of the HMA mixes, none of the test methods provided similar rankings. This is reasonable because each method incorporates a different measure of performance. The T 283 test measures strength change as a results of moisture damage, whereas the APA test measures rutting and is performed in the dry condition. ERSA incorporates a bit of both, combining a measure of rutting with performance in the wet condition. According to ERSA, the 25.0mm limestone was the poorest performer, though the APA ranked it as best. The T 283 test also ranked it poorly, suggesting that the primary failure mechanism is related more to moisture damage than rutting susceptibility. The 25.0mm syenite mix was ranked poorly by the ERSA and APA methods, but was the best performer according to the T 283 method. Thus, this mix could be more prone to rutting than moisture damage. All three test methods identified the 12.5mm limestone mix as one of the better performers.

Next, the same 4 mix designs were ranked using the Evotherm samples. These results are shown in Table 31. In this comparison, again, there was no clear consensus among the various test methods. The ERSA and T 283 methods ranked the 25.0mm syenite mix as the top performer, while the APA test resulted in a lower rank. The 12.5mm syenite was the worst performer according to the APA and ERSA tests, but performed fairly well in the T 283 test. The lower binder grade of this mix could have been somewhat responsible for the susceptibility to rutting.

Table 31. Rankings by Various Rutting and Moisture Susceptibility Test Methods (Evotherm)

		Mix Design			
		25.0mm SY PG 70-22	12.5mm LS PG 76-22	25.0mm LS PG 70-22	12.5mm SY PG 64-22
ERSA	Rut Depth @ 10,000 Cycles	1	3	2	4
	Rut Depth @ 20,000 Cycles	1	2	3	4
	Rutting Slope	1	2	3	4
	Stripping Slope	1	3	2	4
	Stripping Inflection Point	1	2	4	3
	#Cycles to Max. Rut	1	2	3	4
	Overall ERSA Rating	1	2	3	4
APA	Rut Depth at 4000 Cycles	3	2	1	4
	Rut Depth at 8000 Cycles	3	2	1	4
	Overall APA Rating	3	2	1	4
T 283	Conditioned Visual Rating	1	3	4	2
	Unconditioned Visual Rating	1	3	4	2
	Conditioned Max. Load	1	4	3	2
	Unconditioned Max. Load	1	4	2	3
	TSR	1	4	3	2
	Overall T 283 Rating	1	4	3	2

Finally, the rankings for the Sasobit mixes are shown in Table 32. Slightly better agreement was achieved in this data set, in that all three test methods agreed that the 25.0mm syenite mix was one of the best, and the 12.5mm syenite mix was one of the worst. It is likely that binder grade was the predominant factor in this difference. The 12.5mm limestone mix was one of the better performers by ERSA and T 283, but did not perform well by the APA method. Again, this suggests that there could be greater concern for moisture susceptibility than rutting susceptibility for this mix.

Table 32. Rankings by Various Rutting and Moisture Susceptibility Test Methods (Sasobit)

		Mix Design			
		25.0mm SY PG 70-22	12.5mm LS PG 76-22	25.0mm LS PG 70-22	12.5mm SY PG 64-22
ERSA	Rut Depth @ 10,000 Cycles	1	3	2	4
	Rut Depth @ 20,000 Cycles	1	2	4	3
	Rutting Slope	1	2	3	4
	Stripping Slope	1	3	2	4
	Stripping Inflection Point	2	1	3	4
	#Cycles to Max. Rut	1	2	3	4
	Overall ERSA Rating	1	2	3	4
APA	Rut Depth at 4000 Cycles	2	4	1	3
	Rut Depth at 8000 Cycles	2	4	1	3
	Overall APA Rating	2	4	1	3
T 283	Conditioned Visual Rating	1	2	4	3
	Unconditioned Visual Rating	2	3	4	1
	Conditioned Max. Load	1	2	3	4
	Unconditioned Max. Load	1	4	3	2
	TSR	1	2	3	4
	Overall T 283 Rating	1	2	4	3

Conclusions from Performance Testing

Overall, the performance of HMA and WMA mixes were different, such that performance decreased with the addition of a WMA additive. Although the various test methods provided different rankings as to the relative performance of selected mixes, there were also differences in the mixtures and the failure mechanisms by which the mixes were evaluated. Thus, it is important to require tests that will assess both rutting and stripping susceptibility.

The most important finding from the performance testing is that HMA and WMA mixes can exhibit very different performance characteristics, even when the only change is the incorporation of the WMA additive. Thus, it is critical that all laboratory volumetric and performance testing be conducted on specimens that include the WMA additive. It is not safe to assume that if a design performs well as HMA, then it will also perform well as WMA.

Mixture Aging

One question relating to the performance of WMA is the relative effects of aging and how the aging of WMA compares to that of HMA. Because WMA experiences less extensive aging (i.e., binder oxidation) during production, it is expected that the resulting mixture behavior is affected by the 'softer' binder characteristics. To investigate this issue, four mix designs were selected (the same subset as was used in the moisture damage evaluation), including:

- 12.5mm limestone, PG 76-22 (HMA, Evotherm, and Sasobit)
- 25.0mm limestone, PG 70-22 (HMA, Evotherm, and Sasobit)
- 12.5mm syenite, PG 64-22 (HMA, Evotherm, and Sasobit)
- 25.0mm syenite, PG 70-22 (HMA, Evotherm, and Sasobit)

Multiple sets of specimens of each HMA mix were compacted in the laboratory to a target air void content of approximately 7 percent, and replicate specimens were then compacted for the mixes containing the Evotherm and Sasobit additives, using the same compactive effort as that used to achieve 7 percent in the HMA samples. Three aging times were used, including no additional aging, 24 hours, and 48 hours. Aging was performed on the loose mix at compaction temperature, and then the samples were compacted using the given compactive effort. A short-term aging period of 2 hours at compaction temperature was used for all specimens.

In order to assess the relative performance, two features were measured: the air voids of each specimen, and the maximum load in indirect tension using the Modified Lottman breaking head. The load testing setup is shown in Figure 67.

Figure 67. Load Testing in Indirect Tension Using the Modified Lottman Breaking Head

A summary of data from this testing plan is given in Table 33, and graphical representations are shown in Figures 68 through 71. Figures 68 and 69 show the measured air void contents, and Figures 70 and 71 provide the strength relationships.

Table 33. Summary of Aging Data – Air Voids and Strength

Aggregate	NMAS	PG Grade	Additive	Additional Aging (hrs)	Air Voids (%)	Strength (lb)
Limestone	12.5mm	PG 76-22	HMA	0	7.4	6790
				24	9.2	6690
				48	12.2	1422
			Evotherm	0	6.8	5600
				24	7.2	7914
				48	6.9	7810
			Sasobit	0	7.7	3220
				24	8.2	5240
				48	8.0	5690
Limestone	25.0mm	PG 70-22	HMA	0	8.4	5730
				24	7.7	7030
				48	9.5	2420
			Evotherm	0	9.2	4350
				24	9.2	6820
				48	9.1	6790
			Sasobit	0	9.1	4950
				24	8.9	7350
				48	8.9	8180
Syenite	12.5mm	PG 64-22	HMA	0	6.5	6790
				24	10.0	9100
				48	10.7	4250
			Evotherm	0	10.4	4430
				24	10.4	6500
				48	10.3	6600
			Sasobit	0	6.2	6110
				24	7.5	8530
				48	7.4	8270
Syenite	25.0mm	PG 70-22	HMA	0	6.5	8180
				24	8.3	10300
				48	10.9	4130
			Evotherm	0	7.3	6640
				24	7.4	8050
				48	7.1	9332
			Sasobit	0	6.9	6230
				24	7.3	7510
				48	7.6	8840

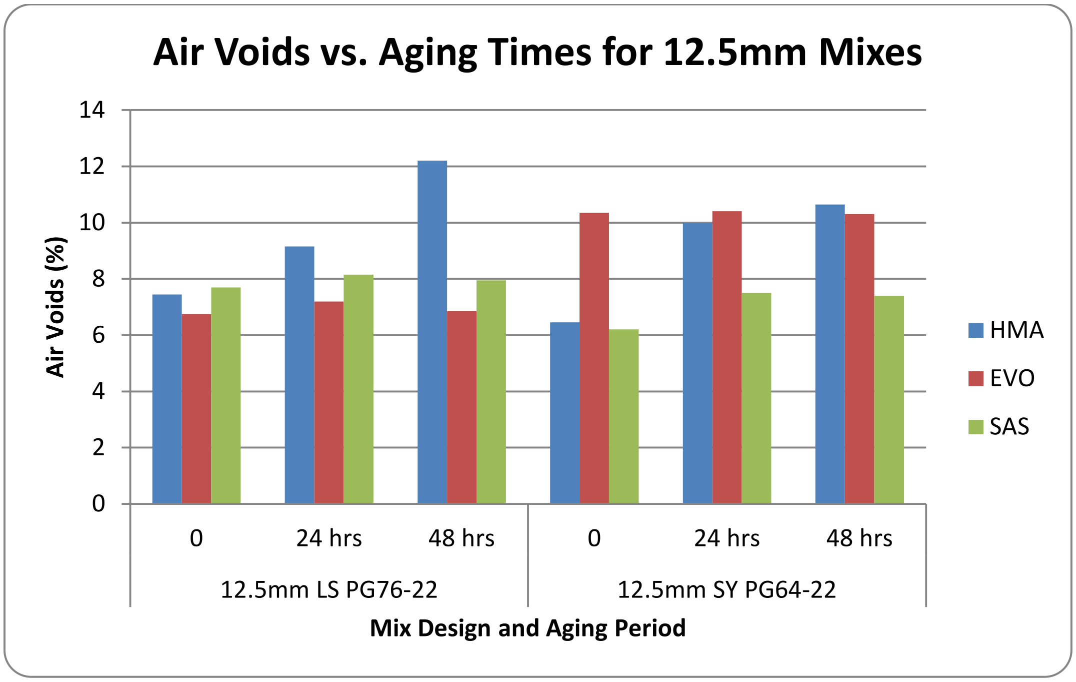


Figure 68. Aging Study – Air Voids vs. Aging Times for 12.5mm Mixes

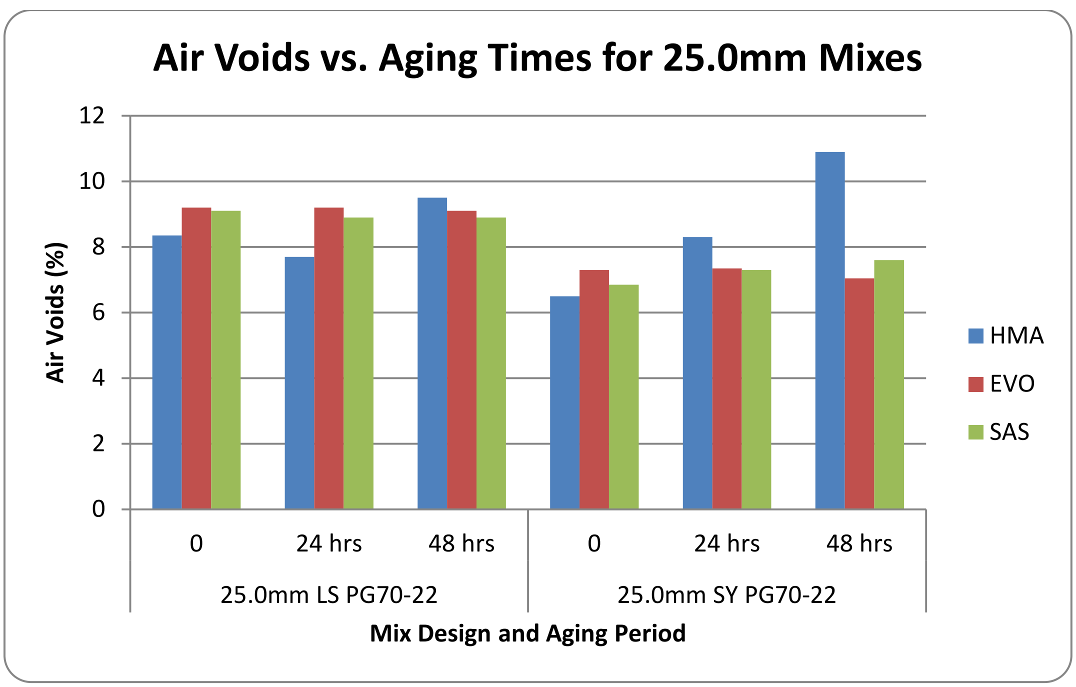


Figure 69. Aging Study – Air Voids vs. Aging Times for 25.0mm Mixes

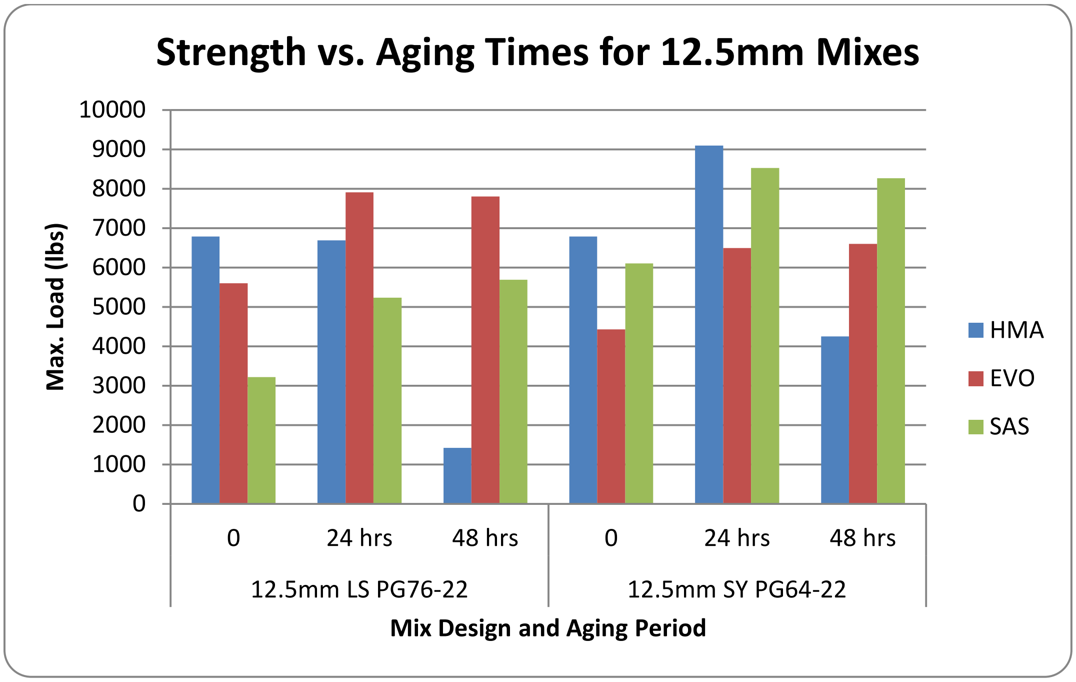


Figure 70. Aging Study – Strength vs. Aging Times for 12.5mm Mixes

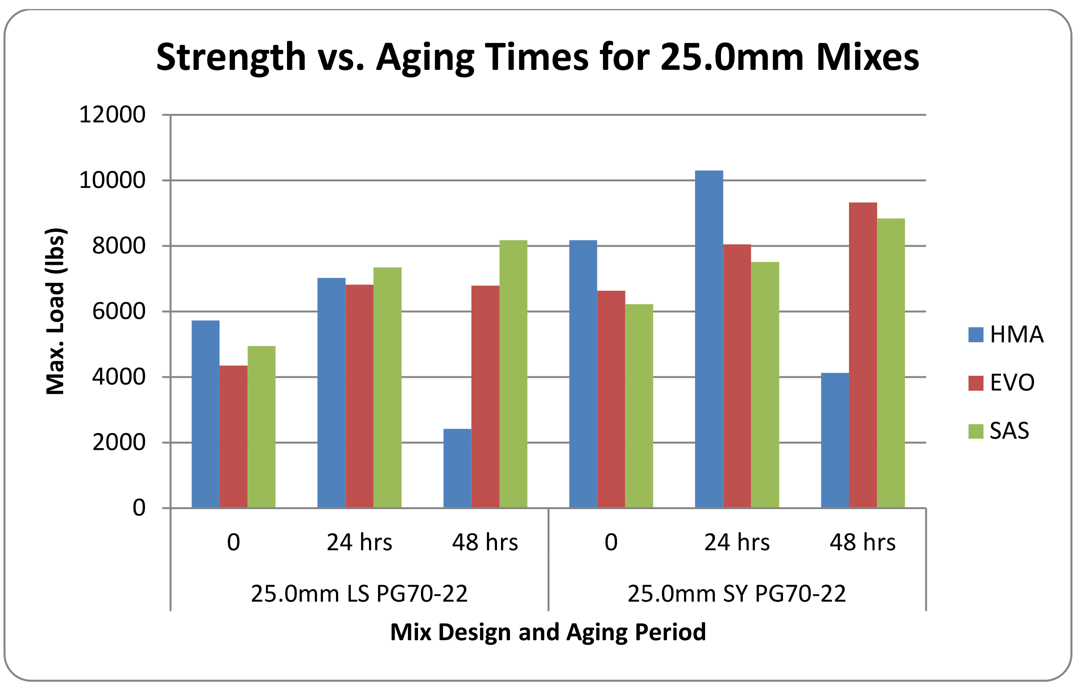


Figure 71. Aging Study – Strength vs. Aging Times for 25.0mm Mixes

For the HMA mixes, air voids tended to increase as aging time increased, while the air voids of the WMA mixes remained relatively constant. Air voids for the Evotherm mixes tended to be very consistent, though they did not always match the target air void levels for any aging period. Specifically, the 12.5mm syenite and the 25.0mm limestone mixes with Evotherm contained 10 and 9 percent air voids, respectively. This suggests that the compactability of the WMA mixes can be maintained even after long periods of additional aging (i.e., up to 48 hours), and that the volumetric properties do not change considerably. This supports the notion that haul times can be increased for WMA mixes, provided the temperature of the mixture is properly controlled.

The relationship of Air Voids and Tensile Strength is shown in Figure 72, with each additive type displayed separately. The linear relationship of decreasing strength with increasing air voids for the HMA was visually evident, having an R^2 value of approximately 40 percent. The relationships for the Evotherm and Sasobit mixes were not as consistent. However, the air voids in the WMA mixes were not as sensitive to changes in aging time, so it was expected that these relationships would contain less definition.

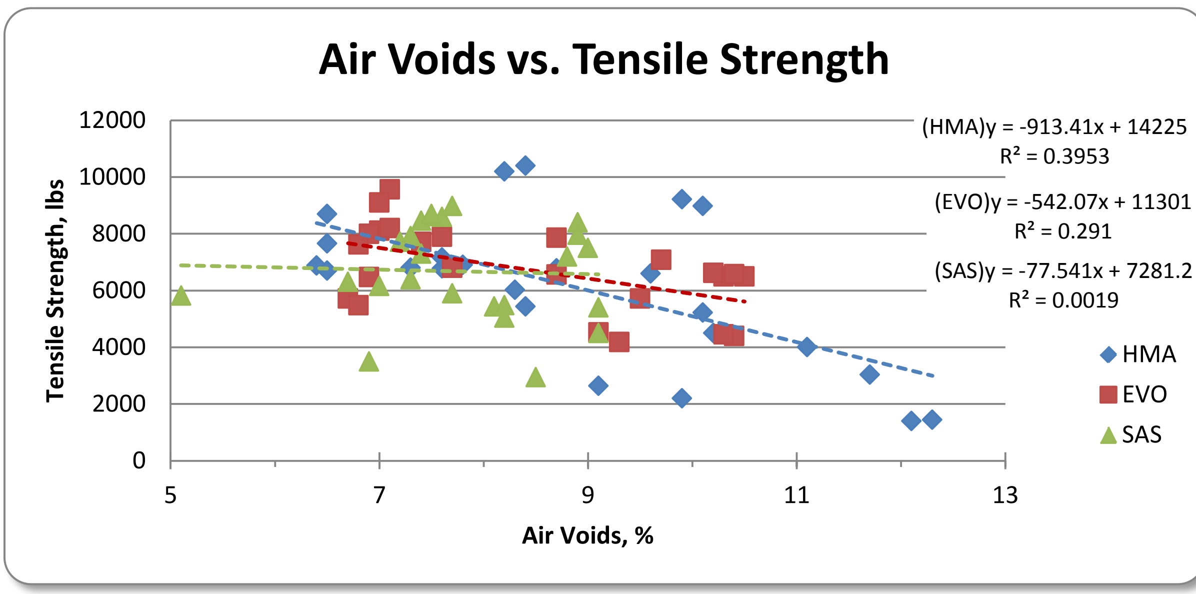


Figure 72. Relationship of Air Voids and Strength for HMA, Evotherm, and Sasobit

In terms of the effects of aging on strength, the HMA samples gained or maintained strength during the first 24 hours of additional aging, but then lost strength at the 48 hour aging time. The WMA samples, however, gained strength as the aging process continued. This was true for both the 12.5mm and 25.0mm mixes. It is probable that the increase in air voids for the HMA samples was primarily responsible for the strength loss, because a less compacted specimen should be expected to have less strength. A more tightly compacted specimen, however, would be better able to maintain strength levels. Specifically, the HMA samples that had been aged for 48 hours all had air voids in excess of 9 percent, which coincided with the lower strength levels. Even the WMA samples with high air void contents (12.5mm syenite with Evotherm, 25.0mm limestone with Evotherm, and 25.0mm limestone with Sasobit), the strength increased with aging time. Thus, it was concluded that aging of WMA is beneficial, while that for HMA is detrimental.

Cooling Rate of Warm Mixes

Because warm mix asphalt is produced at a lower temperature, it is supposed that warm mix pavements may be opened to traffic sooner than hot mix pavements. In addition, it is theorized that warm mix asphalt cools at a slower rate because it starts at a temperature closer to the ambient temperature, which allows for longer haul distances and extended paving seasons. In order to investigate these theories, the surface temperature of laboratory-produced hot mix and warm mix samples was monitored over time and recorded using an infrared thermometer for triplicate samples of a subset of mix designs. Two mix designs were chosen, representing only surface mixes with PG 70-22 binders. This combination was chosen because the majority of asphalt surface mixes in the state of Arkansas are 12.5mm mixes with PG 70-22 binders. The mix designs used included:

- 12.5mm limestone, PG 70-22 (HMA, Evotherm, and Sasobit)
- 12.5mm syenite, PG 70-22 (HMA, Evotherm, and Sasobit)

The side and top temperatures of each specimen were measured and recorded, until the average temperature reached 100 °F. This sequence was performed for specimens placed outdoors in varying ambient conditions in order to simulate the cooling rate in each situation. Ambient temperatures represented a range of typical temperatures in the state of Arkansas, such that 50, 70, and 90 °F were included. Other weather descriptors such as sunny, cloudy, and breezy were also included in the data. The average results are shown in Table 34. Cooling curves are given in Figures 73 through 82.

Table 34. Cooling Rate and Time to Reach 100 °F

Mix Design	Ambient Temperature, °F	Ambient Conditions	Additive	Time to Reach 100 °F, min.	Cooling Rate, degrees/min.
12.5mm LS PG70-22	50	Sunny with breeze	HMA	80	1.753
			EVO	60	1.775
			SAS	60	1.800
		Cloudy, no breeze	HMA	110	1.351
			EVO	100	1.013
			SAS	100	1.115
	70	Cloudy with breeze	HMA	80	1.909
			EVO	70	1.329
			SAS	60	1.994
		Cloudy, no breeze	HMA	140	1.113
			EVO	120	0.910
			SAS	120	0.971
	90	Cloudy, light breeze	HMA	110	1.079
			EVO	110	0.965
			SAS	130	0.951
12.5mm SY PG70-22	50	Sunny with breeze	HMA	110	1.325
			EVO	90	0.917
			SAS	40	1.206
		Cloudy, no breeze	HMA	120	1.325
			EVO	90	0.864
			SAS	100	0.940
	70	Cloudy with breeze	HMA	70	1.871
			EVO	60	1.609
			SAS	60	1.267
		Cloudy, no breeze	HMA	140	0.890
			EVO	130	0.807
			SAS	110	0.898
	90	Cloudy, light breeze	HMA	200	0.459
			EVO	170	0.493
			SAS	180	0.445

In general, the HMA mixes cool at a faster rate than the WMA, but the WMA mixes reached a temperature of 100 °F more quickly than the HMA. This is consistent with the literature, which states that the slower cooling rate of WMA allows for longer haul times, while the quicker cooling to a target temperature allows for the new pavement to be opened to traffic sooner. As ambient temperature decreased, the cooling rate increased, due to the greater difference in the sample and ambient temperatures. For the ambient temperature of 70 °F, a direct comparison could be made for breezy conditions and no wind. When a breeze was blowing, the rate of cooling was approximately twice that of samples with no breeze. The average time required for the HMA samples to cool to 100 °F was 114 minutes, while that for the Evotherm and Sasobit mixes was 100 and 96 minutes, respectively. This suggests that if the laboratory-compacted specimens cool in a manner similar to that of a field mix, a WMA section could be opened to traffic approximately 15 to 20 minutes sooner than a HMA section.

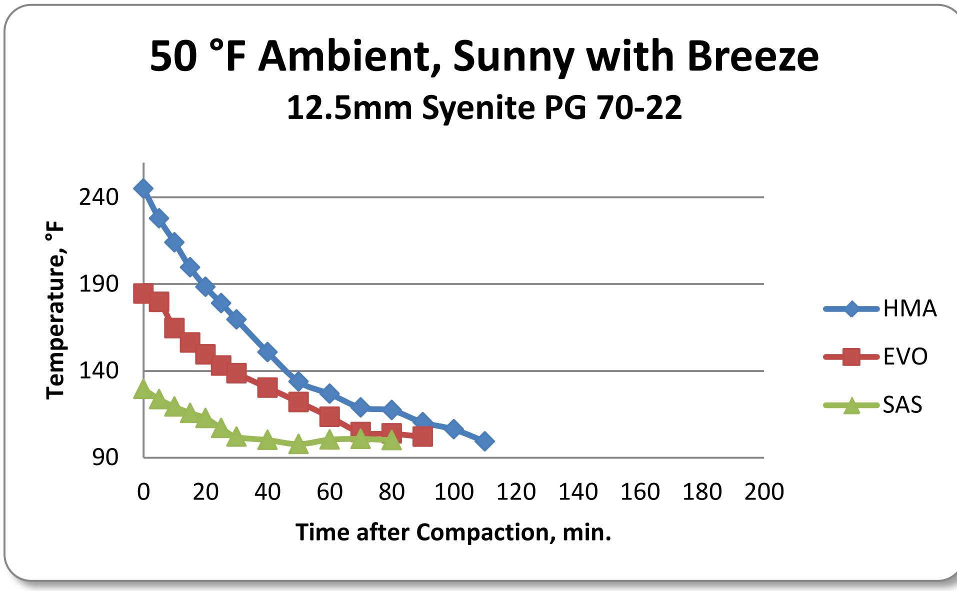


Figure 73. Cooling Curves for Syenite Mixes, 50 °F Ambient, Sunny with Breeze

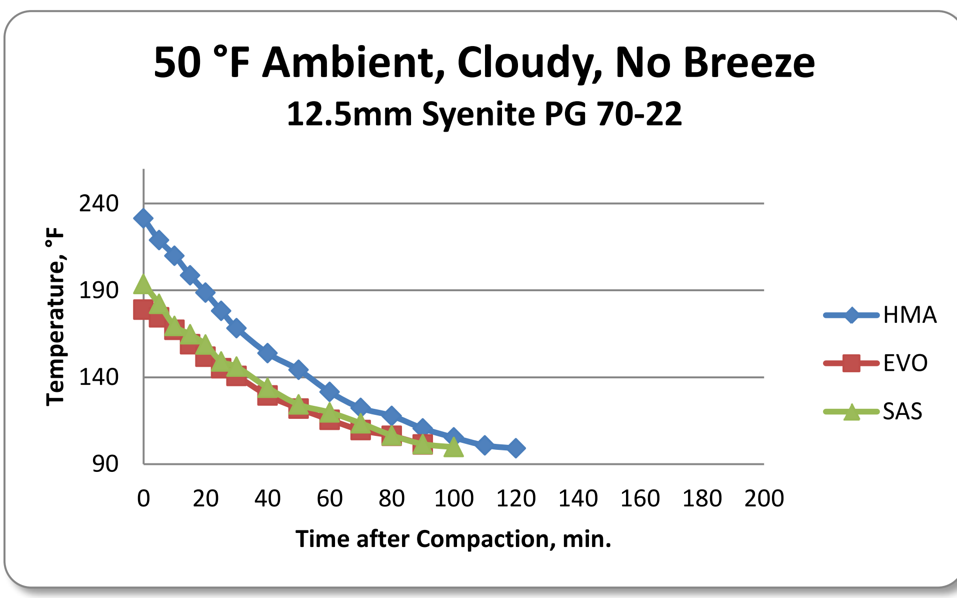


Figure 74. Cooling Curves for Syenite Mixes, 50 °F Ambient, Cloudy, No Breeze

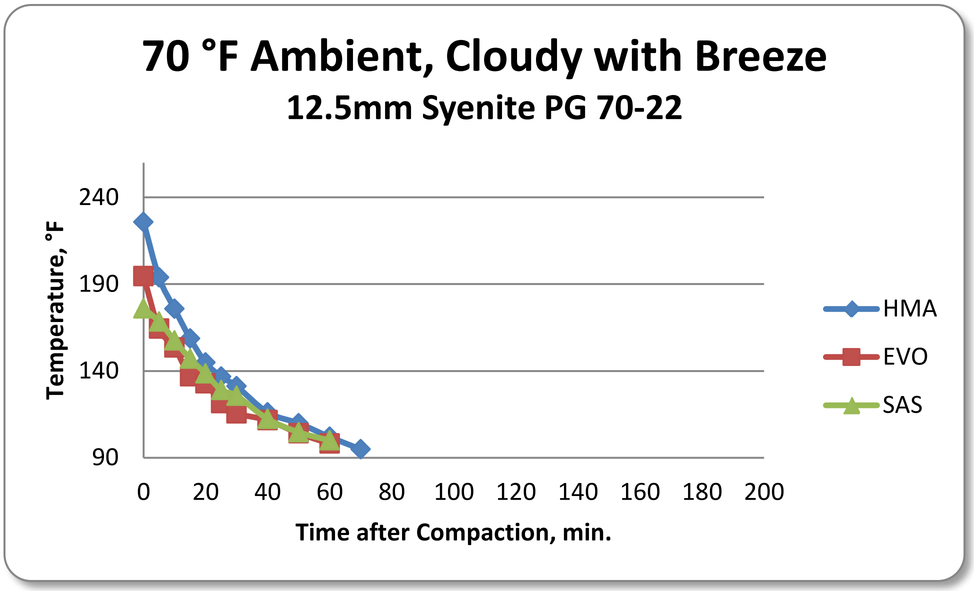


Figure 75. Cooling Curves for Syenite Mixes, 70 °F Ambient, Cloudy with a Breeze

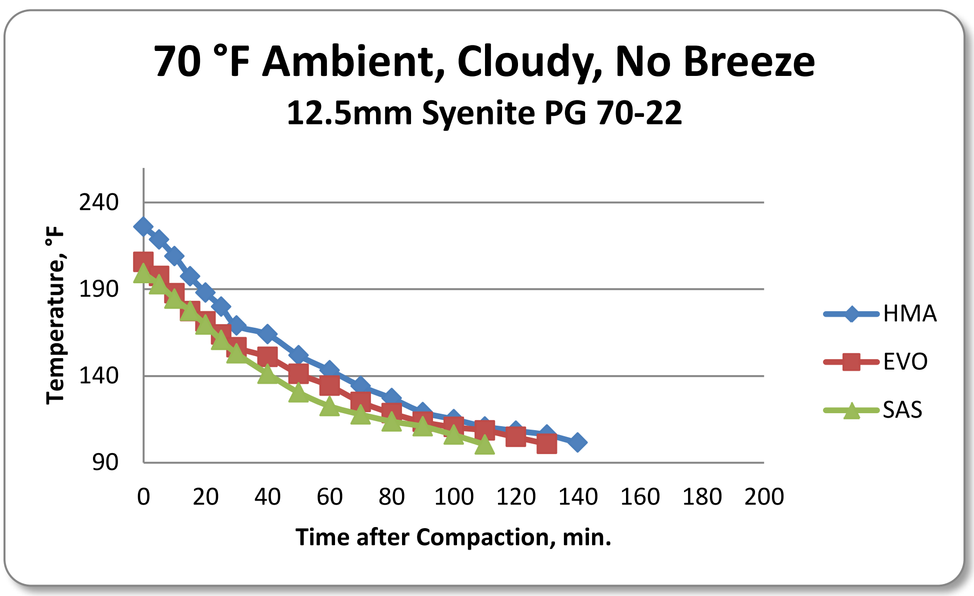


Figure 76. Cooling Curves for Syenite Mixes, 70 °F Ambient, Cloudy, No Breeze

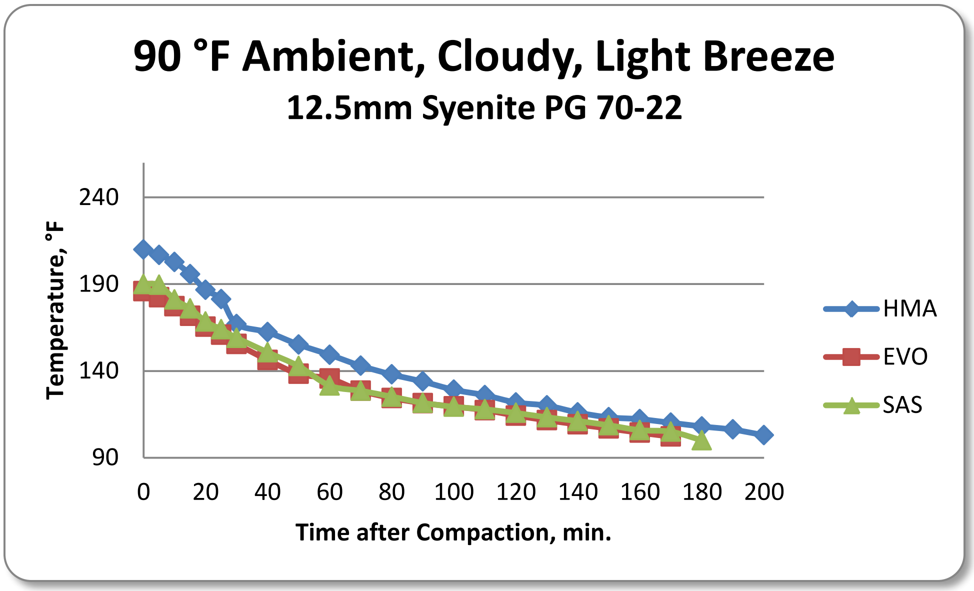


Figure 77. Cooling Curves for Syenite Mixes, 90 °F Ambient, Cloudy, Light Breeze

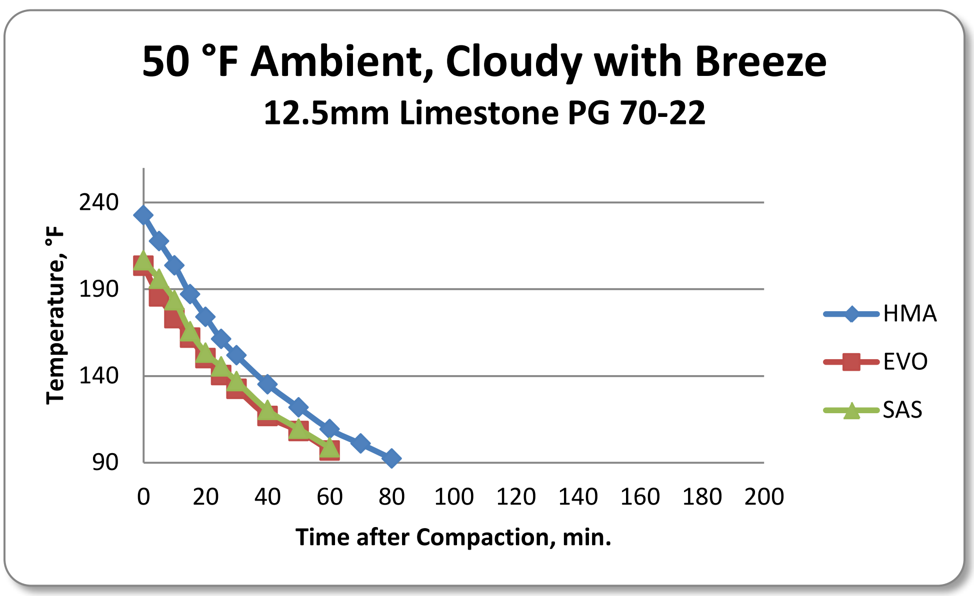


Figure 78. Cooling Curves for Limestone Mixes, 50 °F Ambient, Cloudy with a Breeze

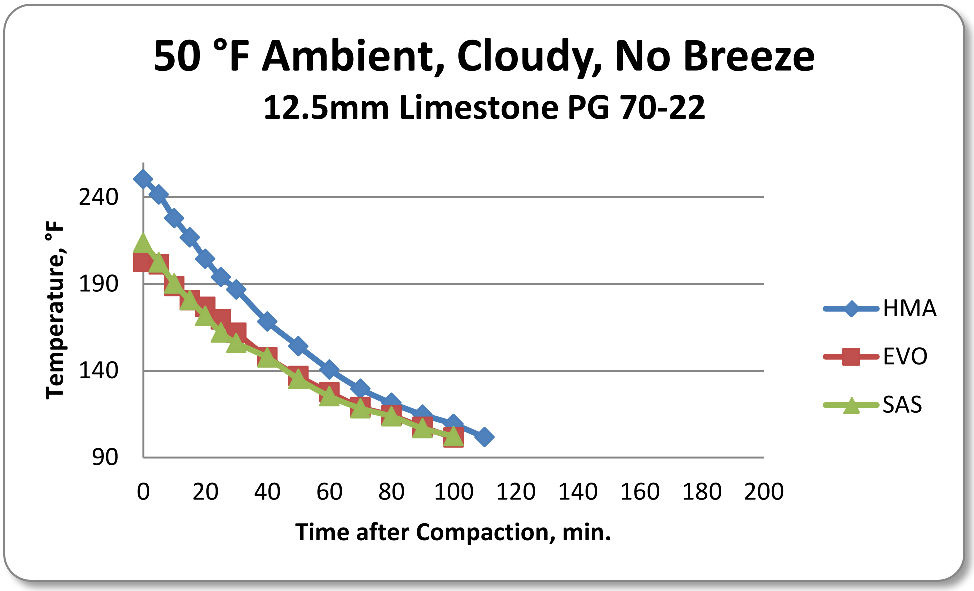


Figure 79. Cooling Curves for Limestone Mixes, 50 °F Ambient, Cloudy, No Breeze

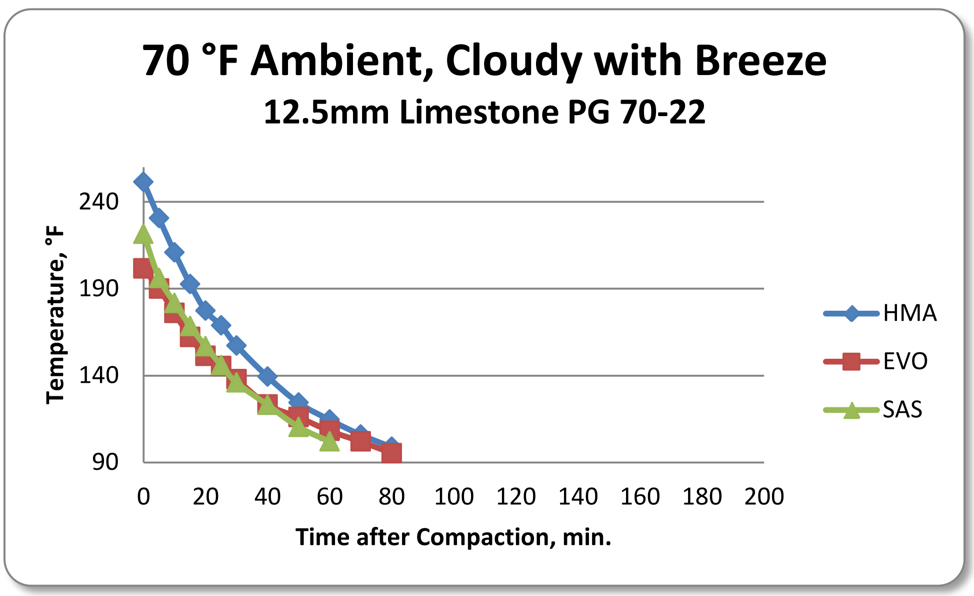


Figure 80. Cooling Curves for Limestone Mixes, 70 °F Ambient, Cloudy with a Breeze

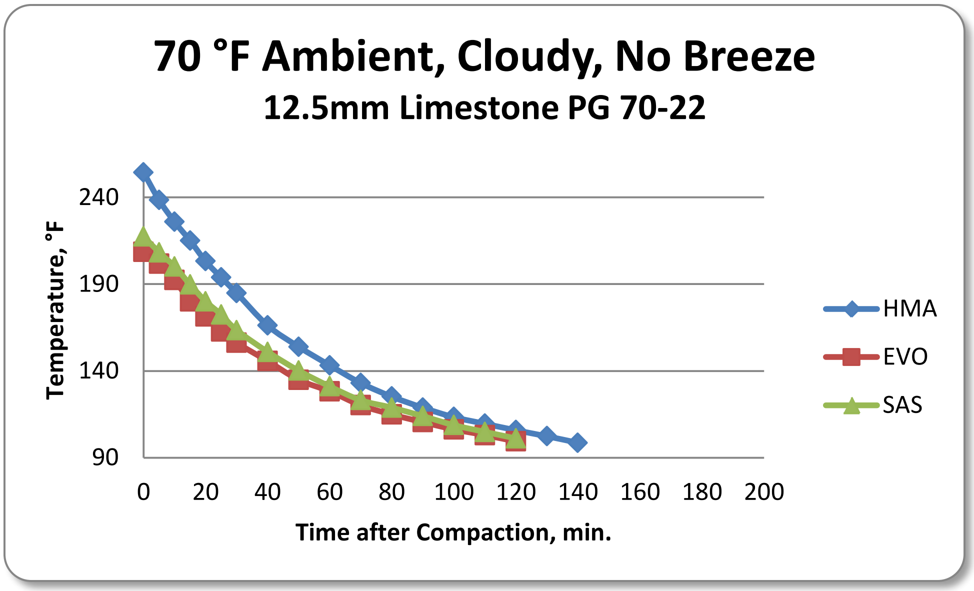


Figure 81. Cooling Curves for Limestone Mixes, 70 °F Ambient, Cloudy, No Breeze

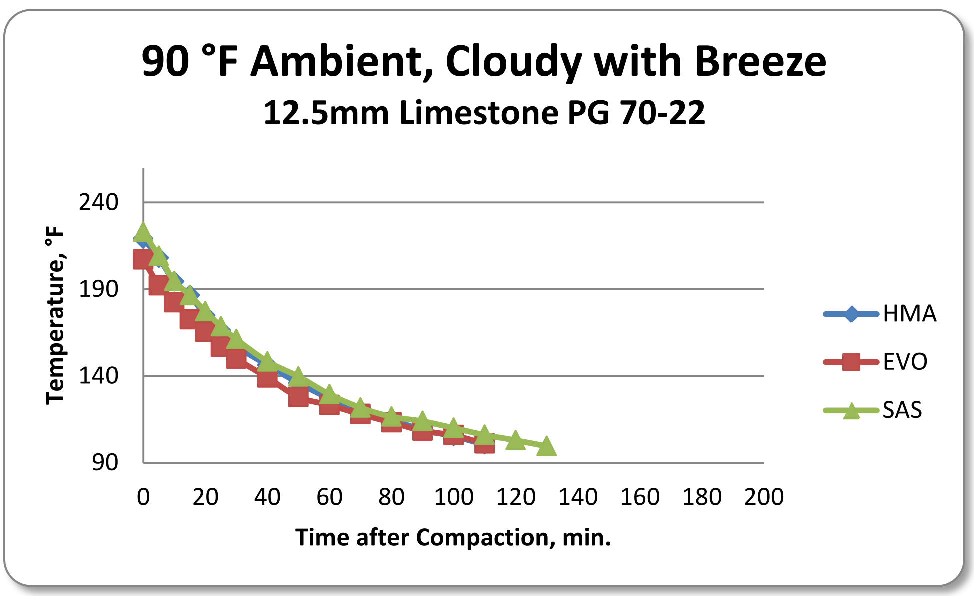


Figure 82. Cooling Curves for Limestone Mixes, 90 °F Ambient, Cloudy, Light Breeze

Next, the strength of samples that had been cooled in each condition was tested for strength in indirect tension. Each mix was tested for the maximum load it could withstand at the time it had cooled to 140 °F. Then additional samples were tested at the time they reached 100 °F. The goal of this effort was to determine if HMA and WMA specimens behaved differently. From the previous analyses (rutting and aging studies), it was shown that the WMA specimens were not as strong as comparable HMA specimens, and that the WMA mixes exhibited 'softer' behavior. This was shown again in the cooling study, as seen in Figures 83 and 84, although the strengths increased as the temperature approached ambient temperature. The results were fairly consistent for all ambient temperature conditions, in that the strengths were low (approximately 500 lbs) for the HMA and WMA mixes when the specimens had only cooled to 140 °F, but were considerably stronger when the specimen temperature reached 100 °F. At 100 °F, however, the strength gain in the HMA specimens was greater than that of the WMA mixes. Often times, a new mat is opened to traffic when the pavement's surface temperature has reached 120 °F and there is no apparent tenderness in the mat. Because the WMA mixes have a lesser strength than HMA, a newly paved WMA mat should be observed carefully before opening to traffic. The mat temperature of a WMA should cool as much as possible in order to ensure the greatest amount of strength.

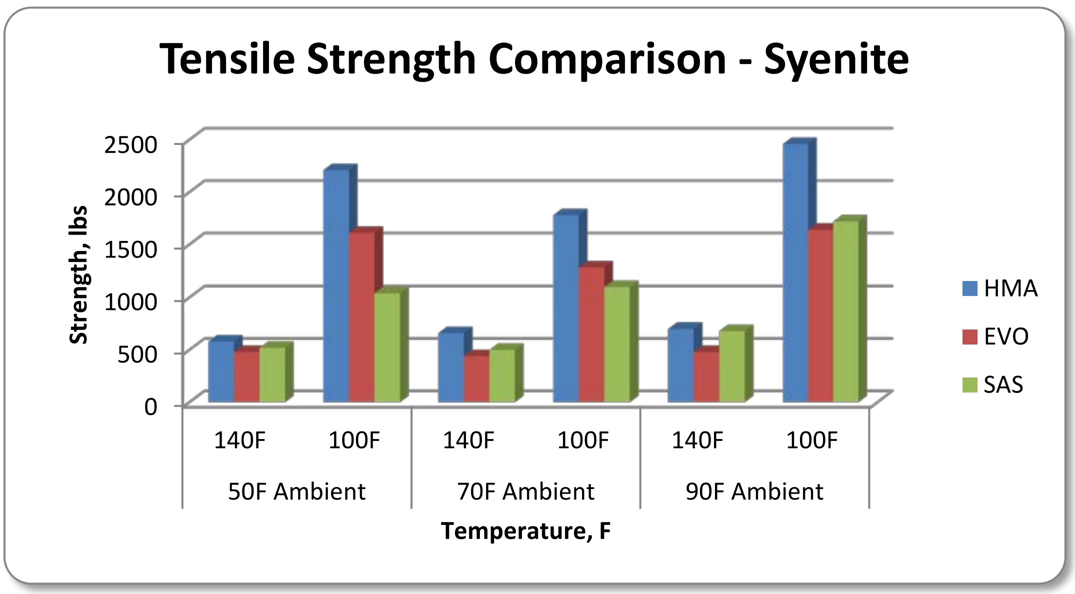


Figure 83. Tensile Strength Comparison for the 12.5mm Syenite Mix – PG 70-22

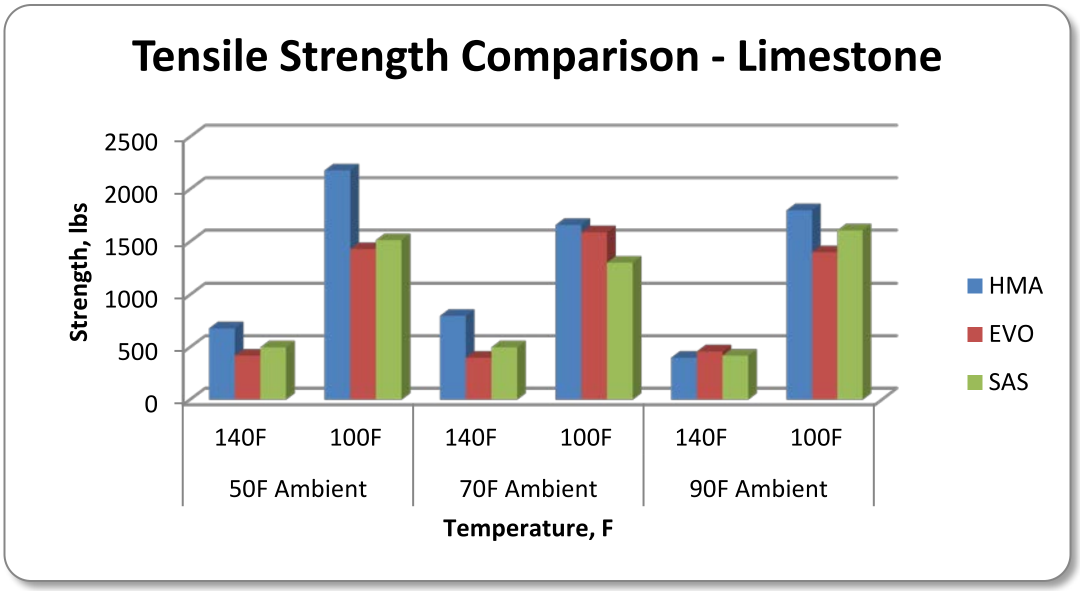


Figure 84. Tensile Strength Comparison for the 12.5mm Limestone Mix – PG 70-22

A paired t-test was performed in order to determine whether the cooling rates of HMA and WMA were similar. The results confirmed that the cooling rates of the HMA were greater than that of either WMA mix (p-values of 0.003 and 0.027), but the Evotherm and Sasobit cooling rates were similar (p-value of 0.147). It is believed that although the cooling rates of the HMA differed from that of the WMA, these differences are primarily related to the temperature differentials and not the actual WMA technology.

To compare the relative cooling rates of laboratory-compacted specimens of that with field cooling rates, temperature data was collected from a warm mix paving project. The project was placed on a sunny day with a light breeze, with ambient temperatures of approximately 60 °F. The WMA mixture was produced using the AquaBlack plant foaming mechanism, and was placed as a 2-inch lift over a 7.5-inch crushed stone base. Readings were taken using an infrared thermometer to measure the surface temperature of the mat at 3 different locations on two sections of the mat. The results are shown in Figures 85 and 86. In each graph, there are sections of data that do not follow a steady trend. During these times, rollers were actively compacting the mat, which affected the temperature readings. The times of the breakdown and finish rolling are denoted by a shaded box.

The cooling rate for Section 1 (not including the first 5 minutes) was 1.667 degrees/minute, while that for Section 2 was 1.526 degrees/minute. These values are most consistent with the HMA cooling rates found in the laboratory cooling data. However, it is evident that the rate of cooling is heavily influenced by the rolling operations. For both sections, the mat temperature leveled out at a fairly steady temperature at the completion of finish rolling. But, Section 2 took a greater amount of time to reach the steady temperature. The finish rolling was completed within 40 minutes for Section 1, while Section 2 required more than an hour to complete. Thus, the amount of time needed to open a new WMA mat to traffic may be dominated by the time required for finish rolling rather than the cooling rate of the mix.

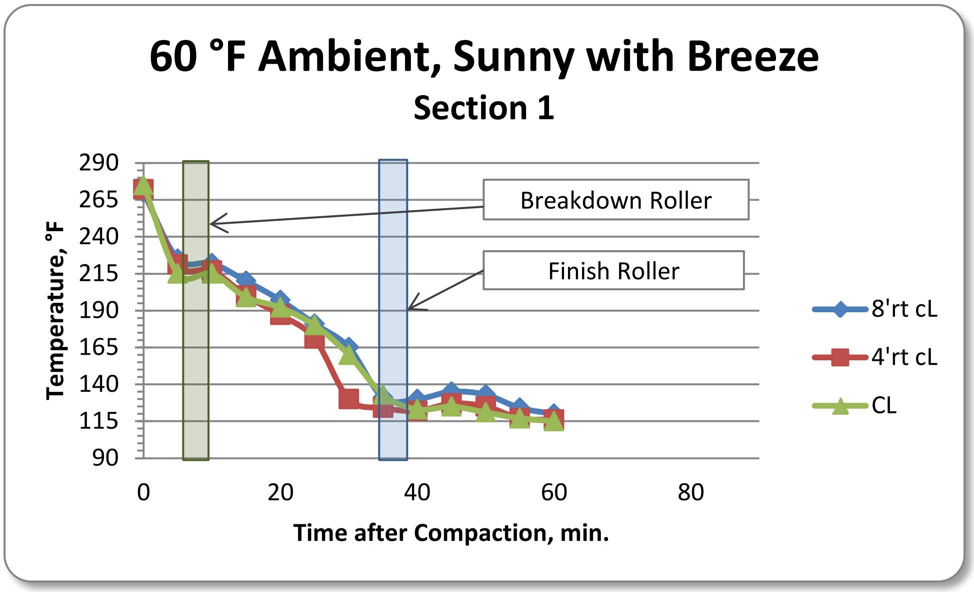


Figure 85. Cooling Curve for Field Section 1

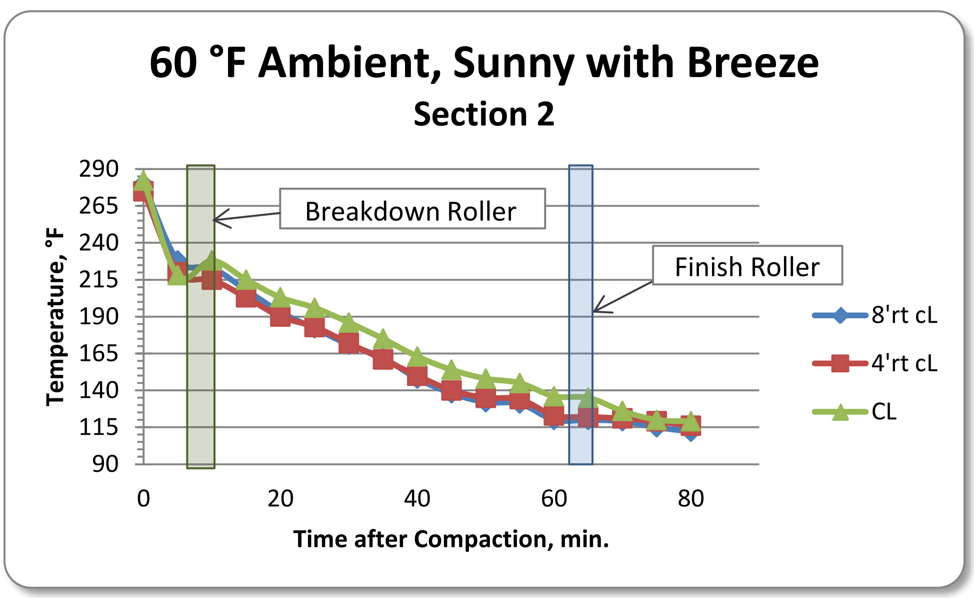


Figure 86. Cooling Curve for Field Section 2

Field Projects

During the course of the research some field sites were available for evaluation. The earliest was a demonstration project was performed using Evotherm, and then a few projects in the southwest portion of Arkansas were completed using the Astec Double Barrel Green plant foaming system. Later projects utilized Evotherm products and plant-foaming techniques, including the Astec system and Maxam's AquaBlack system.

Fualkner County Demonstration

The first field section using WMA was project SA2362 near Vilonia in Faulkner County, Arkansas, in which an Evotherm WMA section was placed in conjunction with a control section of HMA. This project was constructed in the summer of 2008, and contained 0.5% Evotherm 3G with a PG 67-22 binder. For the WMA section, the mix temperatures ranged from 230 to 250 °F, representing a decrease from HMA temperatures of at least 50 °F. No particular problems were noted during construction and field densities were acceptable, yielding percent compaction values for the WMA section of 92.7, 93.4, 92.9, and 93.0 percent. After three years in service, the WMA section appeared to be performing well, and had a darker, or 'richer' appearance than the HMA section, indicating a lesser degree of aging. There were some isolated areas of cracking and edge failures with rutting, most likely caused by the severe flooding in the spring of 2011. Photos from each section are shown in Figures 87 and 88.

Figure 87. Faulkner County Warm Mix Section After 3 Years in Service

Figure 88. Faulkner County Hot Mix Section After 3 Years in Service

Texarkana

Multiple projects were completed in the southwest portion of the state, including Job # 030341, Job # 030370, and Job # S10307. The Astec foaming system was used on two of the projects, which included both PG 70-22 and PG 76-22 binders. The PG 76-22 binder was produced at temperatures ranging from 250 to 275 °F, and placed at temperatures ranging from 240 to 270 °F, representing temperature reductions of approximately 60 °F. The Evotherm mix was produced at temperatures of 260 to 270 °F, and placed at 235 to 250 °F using PG 70-22, representing a decrease of about 50 to 60 degrees. Reported density data revealed no difficulties with field densities. Field compaction values were 92.7, 93.4, and 93.1 percent, clearly meeting the specification minimum of 92 percent.

Clay County

In September 2009, a warm mix project was constructed in the northeastern portion of Arkansas. This project utilized the AquaBlack plant foaming system, achieving temperature reductions of approximately 30 °F. Density data for this project was favorable, resulting in values of 93.6, 92.5, 92.8, 95.4, 91.3, 93.3, 94.7, and 93.7 percent.

<u>Fayetteville</u>

The City of Fayetteville, Arkansas used warm mix on a paving project during July of 2010. In this project, binder and surface mixes were placed on Township Avenue, as shown in Figure 89. These mixes contained Evotherm 3G, and were produced at temperatures approximately 50 to 60 °F less than that of HMA. The binder mix was approximately 280 °F at the time of initial compaction, and there were difficulties in compacting the mix because it was tender and prone to shoving. As a result, the mix was allowed to cool to approximately 235 °F, and rolling operations were successfully completed. Density results ranged from 92.5 to 95.7 percent. When the surface mix was placed, trucks arrived at the job during the morning, but unforeseen difficulties in preparing the paving surface required the trucks to wait for a considerable length of time before discharging into the paver hopper. No field density data was available for the surface mix, though no difficulties were noted during compaction and the pavement is still performing well to date.

Samples of the surface mix were obtained from the plant and brought back to the laboratory for testing air void content. The average value of the samples compacted on the day of production was 4.2 percent. Additional mix was allowed to age for three weeks at room temperature, then reheated and compacted. The average air void content for these samples was 4.9 percent, indicating that some aging had, in fact occurred, causing an increase in air voids.

Figure 89. Fayetteville Warm Mix Section Under Construction

Northwest Arkansas

Another warm mix project in Northwest Arkansas was completed in 2011 on Hwy. 21, north of Hwy. 412. This mix was produced using a PG 64-22 binder with the AquaBlack plant foaming technology. The target mixing temperature was 300 °F and the compaction temperature was 270 °F, which did not represent a significant reduction in production temperatures. However, the primary reason for using WMA on this project was that the haul time from the plant to the site was approximately one hour. It was believed that the slower cooling rate of WMA would benefit these conditions.

Field densities were collected, resulting in the following data.

Table 35. Field Density Data from Hwy. 21 Project

	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Lot 6
Sublot 1	91.7	93.2	91.7	91.6	91.3	91.6
Sublot 2	93.6	93.5	90.8	92.6	91.9	92.5
Sublot 3	93.4	92.2	94.0	92.5	92.5	92.3
Sublot 4	91.9	93.2	93.4	91.6	95.6	N/A
Average	92.6	93.0	92.5	92.1	92.8	92.1

Mix was also sampled from this project by the research team, compacted in the laboratory, then tested for air voids. This process was repeated for sample sets aged in the oven at compaction temperature for 8 hours, 24 hours, 48 hours, and 7 days. The average air voids resulting from each aging time is given in Table 36. A sharp increase in air voids occurred between the 24-hour and 48-hour aging periods, meaning that the benefits of warm mix could, in a sense, 'expire', somewhere in that timeframe. The literature has indicated difficulties in determining an appropriate laboratory aging time that would simulate field aging, though it has also been said that while field warm mixes appear less aged early on, they do tend to catch-up to their HMA counterparts over time. Though further research is needed on this topic, the 24 to 48 hour laboratory aging range could represent the point at which this 'catching up' happens.

Table 36. Average Air Voids for Various Aging Times

Aging Time	0 hrs	8 hrs	24 hrs	48 hrs	7 days
Average Air Voids, %	5.5	6.6	6.6	9.6	12.8

Reclaimed Asphalt Pavement (RAP)

Because WMA contains binders that are less aged, they tend to exhibit softer behavior, which has been demonstrated in this project. Binders in RAP, however, are much more aged and exhibit stiffer behavior. Questions have been raised regarding the applicability of using RAP in WMA mixes. Successful combinations of these materials have been demonstrated, such that the softer properties of the WMA binders tend to balance the stiffer characteristics of the RAP binders. The primary concern associated with WMA/RAP mixes is that the WMA mix will not be heated adequately to activate the binder in the RAP, and therefore not fully realizing the economic advantages of binder savings from using RAP. WMA/RAP combinations were not specifically investigated in this project, however the results of the NCHRP study did include topics concerning RAP. It was determined that RAP and WMA binders do mix at WMA temperatures, but that the production temperatures must be maintained for a sufficient length of time to allow this mixing. The draft appendix to AASHTO T 35 recommended that the planned field compaction temperature for WMA exceed the high temperature grade of the RAP binder, which would assist in ensuring that acceptable binder mixing is able to occur.

CONCLUSIONS AND RECOMMENDATIONS

This project included a thorough review of warm mix asphalt mix designs and properties, and specifically investigated the sensitivity of warm mix additives to temperature and binder content fluctuations. Three additives were used (Advera, Evotherm, and Sasobit) in a variety of mix designs representing two aggregate types (limestone and syenite), two aggregate sizes (12.5mm and 25.0mm), and three binder grades (PG 64-22, PG 70-22, and PG 76-22). Performance was assessed with respect to rutting susceptibility, moisture susceptibility, cooling rate, and aging conditions.

Mixture Design Using Additives

Different additive generate different allowable levels of temperature reduction. Thus, the additive must be included during the WMA mix design process (i.e., do not simply "plug in" an additive to an existing HMA mix design). Mix designs should be developed by determining an aggregate blend using traditional mix design procedures, and then adding the WMA technology and reducing the temperature to the desired level; then determining the optimum binder content, as well as other volumetric design properties. Temperatures (mixing and compacting) should be considered a primary mix design parameter. The amount of temperature reduction should be based on economic considerations, the ability of the additive to successfully coat the aggregate particles at that temperature while achieving the desired volumetric properties, and the expected time between mixing and compacting (i.e., proximity of the plant to the jobsite).

In this project, each additive was incorporated into the mixtures according to manufacturer's recommendations. However, the level of detail varied greatly among the various sets of instructions. Because of the inherent differences in working with various additives, it is recommended that AHTD require the following information from contractors requesting approval of a warm mix design using additives:

- Product Information
  - Mix Design Technology / name of additive
  - Name of Company providing the additive
  - Description of how the additive will be incorporated during production (i.e., pre-blended with binder, separate injection port, as an aggregate, etc.)
- Laboratory Preparation Method
  - Is the additive incorporated during sample mixing?
  - Is the additive pre-blended and stored?
  - Is the additive blended by manually or mechanically?
  - Is any special equipment required for blending?
  - At what temperature is the additive blended?
  - How much stirring time is required?
  - What is the shelf life of the binder with pre-blended additives?
  - Dosage rate of the Additive
    - Percent by weight of binder?

        - Percent by weight of mix?
    - Mixing temperature of the aggregate
    - Mixing temperature of the binder
    - Length of mixing time
    - Compaction temperature of the mixture
- Target Production Temperatures
    - Target temperature of mixture components during production
        - Aggregates
        - Binder
        - Additive (depending upon blending method)
    - Target compaction temperature

<u>Temperature</u>

The temperature sensitivity of WMA varied by additive, and optimum temperature reductions were established for each additive based on coating quality and consistency of volumetric properties. The optimal temperature reduction for Advera was 40 °F, the optimal reduction for Evotherm was 80 °F, and the optimal reduction for the Sasobit mixes was 60 °F.

The Evotherm was least affected by temperature reductions, followed by the Sasobit. The Advera mixes did not generate consistent trends with respect to volumetric properties when the mix temperature was reduced. For the Evotherm mixes, the changes in volumetric properties were most significant for the PG 70-22 binder grade. For the Sasobit mixes, the PG 70-22 and PG 76-22 binders were most sensitive to changes in temperature. Thus, the benefits realized by these WMA additives may be more significant for polymer-modified binders than for a non-modified binder, such as PG 64-22.

When WMA mixes were compared to HMA mixes, it was found that the WMA additives did not always generate the desired or expected result. In some cases, the incorporation of the WMA additive (at the optimal WMA temperature) generated a decrease in air voids, as desired and expected, but sometimes caused an increase in air voids. Overall, the additives were more effective for the 12.5mm mixes than the 25.0mm mixes, particularly for the polymer-modified binders. The unmodified binder was slightly more effective for the 25.0mm mixes. In some cases, the addition of the WMA component allowed for a decrease in design binder content, but in others required additional binder. Thus, each mix design must be evaluated specifically, incorporating the additive during the design stage. While WMA additives do offer the potential advantages of reduced production temperatures, longer haul times, and binder content reductions, they also add another dimension to the design process with associated confounding effects. Therefore, the WMA additive must be included in the entire design process.

Temperature is an important feature of the WMA design process because it represents an additional confounding factor in the overall design process. Greater the temperature reductions result in greater the economic benefits, so the most efficient use of the additives should involve maximizing the temperature reduction. Thus For the additives tested in this study, the WMA mixes appeared less sensitive than HMA mixes to changes in temperature, and volumetric properties were relatively unaffected until the temperature reached a lower 'threshold' in which the mixes were difficult to compact. The NCHRP study (9-43) defined workability as the ratio of the number of gyrations required to achieve 92% density when compacted at design WMA temperature to the number of gyrations required to achieve 92% density when compacted at 30 °C (54 °F) lower than the design WMA temperature, and recommended a maximum ratio of 1.25. While this certainly addresses the workability concept, this requirement could force the warm mix design temperatures to be a bit higher, possibly offering a greater level of consistency in volumetrics, though not necessarily maximizing the abilities of the warm mix additives. Further study is recommended for the workability ratio concept.

Binder Content

Binder content of a mixture is certainly important to the design of the mix, but is also a critical component of the quality control / quality assurance process. Fluctuations in binder content were evaluated to determine whether the WMA mixes were more sensitive than HMA to changes in binder content, and whether current QC/QA specifications would be appropriate for WMA mixes. Overall, the sensitivity of WMA was similar or less than that of the HMA mixes, meaning that no changes to current QC/QA specifications are warranted.

Rutting and Stripping

Because warm mixes do not experience the high temperatures that promote binder aging, WMA additives are believed to soften a binder, which could also affect the stiffness, or rutting resistance, of a mixture. In addition, the lower temperatures may not be effective at completely drying the aggregates during production, leading to moisture damage susceptibility. Wheel track testing and moisture damage testing was performed for each of the mixtures to determine whether the WMA mixes were more susceptible to these distresses.

In most cases, the WMA mixes were less resistant to rutting and stripping than the HMA mixes, and in some cases, the difference was quite distinct. It is important to include the WMA additive for laboratory tests that are used in the acceptance of a mix design, and to recognize that significant differences in performance may occur when a WMA additive is incorporated. Tests for both rutting and stripping susceptibility are recommended for inclusion in mix design specifications.

Although WMA and HMA mixes have not performed similarly in the laboratory, field data has shown many WMA mixes to perform as well as HMA mixes (at least in the short term). Thus, no changes are recommended to current specification limits for APA testing (according to AHTD Test Method 480) and moisture damage testing (according to AHTD Test Method 455). Both methods should be used to evaluate WMA mix designs. The effect of this recommendation is that since WMA mixes may not perform as well as HMA in the laboratory, holding WMA mixes to the same standard as HMA may actually increase the reliability of anticipated WMA field performance.

Aging

Laboratory-compacted samples of HMA and WMA were subjected to various lengths of aging, then compacted and tested for air void content and indirect tensile strength. As aging time increased, the air void contents of the WMA samples did not increase significantly, but increased steadily for the HMA mixes. The strengths of the HMA samples were greater than those of the WMA samples, however the strengths of the WMA samples did increase with longer aging times. Because the air voids in the HMA samples increased with additional aging, HMA samples gained or maintained strength during the first 24 hours of additional aging, but then lost strength with additional aging, which corresponded with the highest air void levels. Overall, the aging process affected the air voids and strengths of the HMA mixes, but affected only the strength of the WMA samples.

Cooling Rate

The cooling rate of WMA was measured for laboratory-compacted specimens that were placed in a variety of ambient weather conditions. The ambient temperatures ranged from 50 °F to 90 °F, and varied in terms of sun, clouds, and wind. The WMA samples cooled at a slower rate than the HMA samples, but reached a target temperature more quickly. These differences in WMA and HMA were primarily attributed to the temperature differential, and not the WMA additives. The strengths of the samples were affected by temperature, in that the strengths increased as the temperature decreased. The HMA mixes displayed greater strengths than the WMA mixes. This suggested that perhaps greater attention should be given to ensuring that a target temperature is reached prior to opening the mat to traffic. Field data indicated that rolling operations can also have an impact on the cooling rate of the mat. No changes are recommended for construction procedures relating to WMA and opening to traffic, however, attention should be given to the stability of the mat under heavy loads. If the mat appears tender, regardless of temperature, heavy traffic should not be placed on it until further cooling has been achieved.

Aggregate Coating

Coating of the aggregates is of key importance for warm mix asphalt. Since the aggregates and binder temperatures are not as hot as those used in traditional HMA mixtures, aggregates may not acquire adequate coatings as quickly; inadequate coatings could pose a performance problem for WMA mixes. In general, as production temperature decreases, aggregates become more difficult to coat, and extended mixing times may be required to achieve proper coating. For this reason, the laboratory mixing time is recommended as an information item that should be required for mixture approval. In general, if the laboratory mixing time is no more than 90 – 120 seconds, then normal production speeds should be sufficient to allow enough time for thorough coatings. However, if the laboratory mixing times are longer, then production speeds may need to be limited in order to ensure that adequate coatings are generated during field production.

In this study, as temperatures were reduced, the WMA mixes were more difficult to mix, and often experienced 'binder clumping'. While this feature is difficult to quantify, it is reasonable that a mixture that clumps is likely to trap binder and fines into clumps and not properly coat the larger aggregate particles. Thus mixes that have clumps after 90 seconds of continuous mixing should not be approved, as they will not be homogeneous. In order to provide a quantifiable metric for aggregate coatings, it is recommended that AASHTO T 195 be required at a frequency of one test per sublot for quality control, and one test per lot for quality assurance. This method is a visual test of the coarse aggregate particles in a mix, and does not represent a significant commitment in terms of additional QC/QA testing effort and/or time. As recommended in the NCHRP report, the ratio of fully-coated particles to the total number of coarse particles should not be less than 0.95.

Production and Placement Temperatures

Production temperatures will vary, and are dependent upon a number of factors, including ambient temperature, wind conditions, and haul time. During production, mixture temperatures should not deviate significantly from those reported for the WMA design. Although the details of a project cannot truly be predicted, anticipated production conditions should be considered during the design (haul distance, time of year and expected ambient temperatures). It is recommended that the production and placement temperatures match the mixing and compacting temperatures stated on the mix design within ±20°F. When conditions differ significantly from those anticipated, these limits may be adjusted at the discretion of the Engineer, provided all QC/QA measures meet applicable tolerances. In some cases, (particularly if conditions have changed and the contractor is having difficulty with field control), the Engineer may recommend that a revised mix design should be submitted to the state lab for approval.

Note: Some mixtures are more sensitive to changes in temperature than others. This phenomenon is not necessarily limited to WMA mixes, but does seem to be mixture dependent. WMA mixes appear to be more sensitive to temperature changes when they approach the lower threshold of their temperature range. Extra measures may need to be taken if a particular mix is being produced near this lower threshold, or appears to be extra sensitive to such changes.

Quality Control / Quality Assurance

Current QC/QA procedures are largely adequate for WMA mixes. Based on the laboratory studies performed, WMA mixtures are no more sensitive to changes in binder content than traditional HMA mixes. Thus, existing HMA QC/QA specification limits are appropriate for WMA mixtures. It is recommended that a temperature reporting requirement be added to the information submitted with QC/QA reports. This data should be used for information only, and should include actual plant (production temperature), as well as the compaction temperature. Plant temperature should be added to the acceptance test report. Compaction temperatures (i.e., temperature behind the screed) are already taken and evaluated for the Materials Transfer Device, as per the Gold Book, section 409.04(b). Temperature should not be included as a pay item, but would serve as justification for the Engineer to require process changes when necessary.

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