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Evaluation of Warm Asphalt Technology

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Submitted by

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16. Abstract

The concept and use of warm mix asphalt (WMA) is becoming more popular in the asphalt industry. The promise of reduced energy consumption, reduced emissions, and a more workable product is very appealing to an industry pressured by environmentalists with sustainability agendas and state agencies applying pay adjustments based on ride quality and pavement density. However, the use of WMA may come with some potential issues as well. Lower production temperatures may result in softer asphalt due to the reduced oxidative aging. Also, poorly dried aggregates may create issues of moisture damage.

To evaluate these issues, a research project was undertaken to evaluate the general performance of WMA and whether or not the NJDOT should begin its implementation. The research study was comprised of a lengthy laboratory investigation, as well as pilot projects produced at various asphalt plants. The research indicated that WMA did indeed aid in the compaction of asphalt mixtures, especially at lower production temperatures. In turn, the reduced production temperatures significantly reduced the emissions produced during asphalt production and placement. However, the research study did indicate that rutting potential and moisture damage susceptibility may be an issue with WMA if production temperatures drop too low, which would result in asphalt binders of a lesser oxidized (stiffened) condition and aggregates not fully dried. The lower production temperatures also negatively affected the blending between the RAP and virgin binders when evaluating the blending potential of higher recycled asphalt pavement (RAP) mixtures in WMA. However, WMA mixtures did show an improvement in the fatigue cracking resistance, most likely due to the decreased oxidation aging and asphalt binder absorption.

This pilot projects illustrated that the WMA, at lower production and compaction temperatures, can be compacted to field densities meeting the NJDOT requirements. Some of the WMA technologies were also found to lend themselves to specialized applications, like eliminating the use of fibers in gap-graded and open-graded asphalt mixtures. Based on the work conducted in the study, recommendations for future WMA implementation for the NJDOT are provided.

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INTRODUCTION

Warm mix asphalt refers to asphalt concrete mixtures that are produced at temperatures approximately 50 °F (28 °C) cooler than typically used in the production of hot mix asphalt. The goal of warm mix asphalt is to produce mixtures with similar strength, durability, and performance characteristics as hot mix asphalt using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including: lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing asphalt binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving.

Warm mix asphalt technologies were first introduced in Europe in the late 1990's as one measure to reduce greenhouse gas emissions. The National Asphalt Pavement Association has been instrumental in bringing these technologies into the United States with several demonstration projects being constructed since 2004. These projects have demonstrated the feasibility of using warm mix processes in the United States. Pavements have been successfully constructed using various warm mix processes with only minimal changes to equipment and quality control practices. These projects have served the important function of introducing warm mix asphalt to agency and contractor personnel, demonstrating the constructability of warm mix asphalt and providing data on energy usage and emissions. They also provide critically needed pavement sections for monitoring the performance of warm mix asphalt. Recently, a Warm Mix Asphalt Technical Working Group has been assembled to help guide future efforts to implement this technology.

One of the critical issues facing warm mix asphalt is the lack of a formal mixture design procedure. To date, properly designed hot mix asphalt concrete has served as the design for the warm mix projects constructed in the United Sates. If warm mix is to replace hot mix in the future, a laboratory mixture design procedure for warm mix asphalt must be established. Current efforts are underway under the National Cooperative Highway Research Program (NCHRP) 9-43, awarded to Advanced Asphalt Technologies (AAT). However, to date, New Jersey has had limited experience with the warm mix technology and its implications if premature adoption occurred.

OBJECTIVES

The objective of this project, *Warm Asphalt Technology*, is to evaluate the different facets of warm mix asphalt production and performance for future use by the New Jersey Department of Transportation (NJDOT). To accomplish this goal, a research effort was divided into tasks specifically designed to address the critical concerns of the NJDOT. First, a Feasibility Study was conducted by Rutgers University and provided to the NJDOT. The purpose of the Feasibility Study was to provide NJDOT with additional background information regarding warm mix asphalt (WMA) technologies, as well as general performance and use. After the Feasibility Study was complete, additional tasks were conducted to evaluate the general performance of WMA. These included:

- Effect of moist aggregates during WMA production;
- Compactability characteristics of WMA;
- Rutting potential of WMA;
- Effect of WMA additives and technologies on PG Grade;
- Blending potential of RAP and virgin binders under WMA production; and
- Evaluation of pilot projects produced and placed in the field.

PHASE 1 – FEASIBILITY STUDY

The use of warm mix asphalt (WMA) has been proposed to provide a multitude of benefits over conventional hot mix asphalt (HMA). Some of the claims many of the WMA technologies have made are:

- Overall increase in mixture workability at lower production and compaction temperatures
- Reduction in emissions at the plant and behind the paver;
- Reduction in energy costs
- Incorporating higher RAP content while maintaining workability and mixture adhesion
- Specific pavement rehabilitation uses

To help guide NJDOT into the use of WMA's, a research project was developed to look at various WMA additives/technologies, evaluate their potential use, provide recommendations for immediate implementation, and evaluate critical factors that need to be evaluated for the responsible implementation of the identified WMA additives/technologies. This "Feasibility Report" is aimed at identifying the current WMA additives/technologies and how they can be implemented by the NJDOT, while taking into account the practicality of the additive/technology during production.

The references within this study are primarily those recently collected by Brian Prowell and Graham Hurley of Advanced Materials Services, LLC, who was retained as a technical consultant on this project. A majority of these references can be found published in National Asphalt Pavement Association's (NAPA's) new publication "Warm Mix Asphalt – Best Practices 2008". Other peer-reviewed publications, such as the Transportation Research Record (TRR) and the Journal of the Association of Asphalt Paving Technologist (AAPT) were utilized as well. The Feasibility report also includes information gathered from interviews with industry members and representatives of other state agencies from Massachusetts, New York, and Pennsylvania.

Warm Mix Additives/Technologies

The following eight proprietary warm mix technologies were identified during the preparation of this report:

- **Aztec Double Barrel Green System.** The ASTEC Double Barrel Green WMA system uses a multi-nozzle foaming device to foam the hot mix asphalt. The device includes a manifold with a system of valves, mixing chambers, and nozzles. Each nozzle is computer controlled and can increase or decrease the number of nozzles needed to inject water into the mixing chamber based on the production rate. The Double Barrel Green system has been used predominantly in Tennessee. However, demonstration projects have also been conducted in Florida, Ohio and South Carolina.

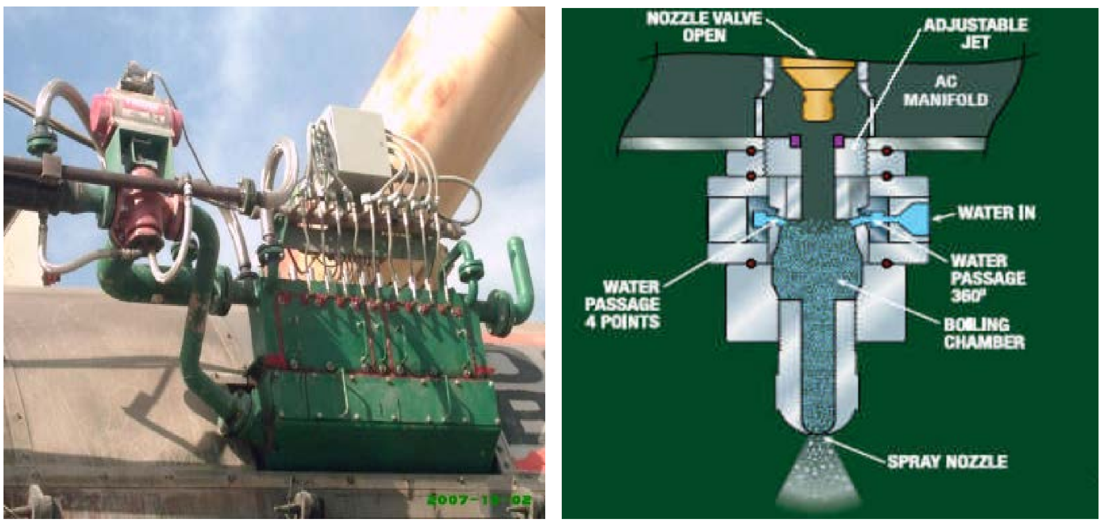


Figure 1. a) Astec Double Barrel Green Water Nozzle System and b) Schematic of Water Nozzle System

- **Evotherm.** Evotherm is a high residue emulsion that reportedly includes additives to improve coating, workability, and adhesion. The emulsion contains approximately 70 percent binder by weight and can be formulated using various binder grades. The water in the emulsion evaporates when it is mixed with the heated aggregates. Evotherm is the product of MeadWestvaco Corporation's Asphalt Innovations located in Charleston, South Carolina. It has been used in several demonstration projects in the United States that include the National Center for Asphalt Technology (NCAT) Test Track, San Antonio TX, St. Louis MO, and Nashville TN.

Figure 2. Evotherm Added to Drum (85% Water; 15% "Chemical Package")

- **Low Energy Asphalt (LEA).** LEA is a process where the coarse aggregate is heated to a high temperature, approximately 305 °F (150 °C), and coated with asphalt binder. Wet, fine aggregate and filler are then added, resulting in foaming of the asphalt binder and subsequent coating of the fine aggregate and filler. The discharge temperature of the mixture is approximately 195 °F (90 °C). Some of the water from the fine aggregate condenses in the mixture and improves the workability of the mixture. A surfactant is added to the binder to promote foaming and coating of the fine aggregate and filler. LEA is the product of FAIRCO of France. The main test trials in the US have occurred in NY State.

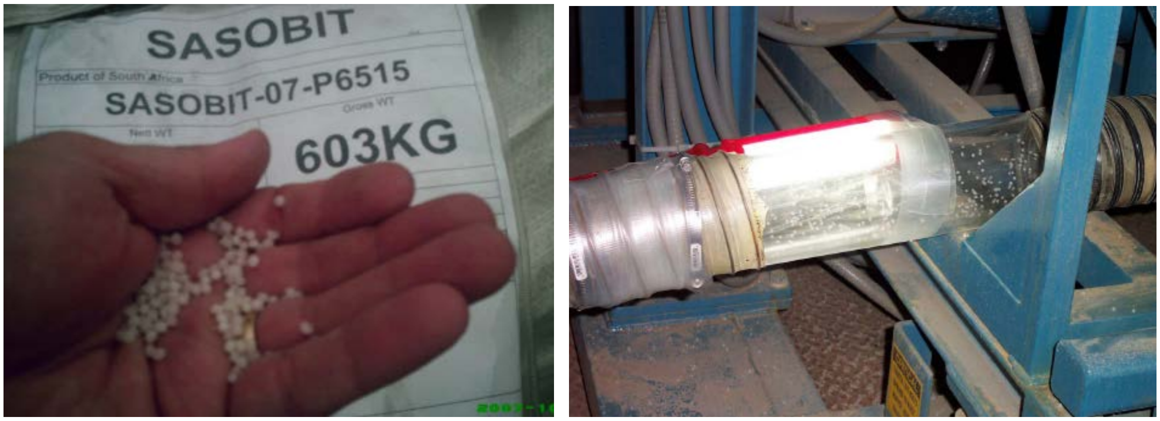
a) b)

Figure 3. a) Monitoring Addition of LEA Solution and b) Adding Water to Fine Aggregate Portion of Blend

- **Rediset WMX.** Rediset WMX combines cationic surface-active agents (surfactants) and rheology modifiers (organic additives) in a solid form. The surface-active agents improve the "wetting" of the aggregate surface by the asphalt, as well as provide an anti-stripping effect in the asphalt mixture. The surface active compounds enables coating of damp aggregate which could be encountered with lower drying temperatures. The Rediset WMX has only been used at one field demonstration to date, by Baldwin Contracting Company in California.

Figure 4. Rediset WMA Pellets

- **Sasobit.** Sasobit is a Fischer-Tropsch wax that is produced from coal gasification. Sasobit has a melting point around 212 °F (100 °C). The recommended dosage rate is 1.5 to 3 percent by weight of the binder. It can be blended with the binder or added in the mix plant. At temperatures above the melting point, Sasobit reduces the viscosity of the asphalt binder making it possible to produce asphalt concrete mixtures at lower temperatures. At temperatures below the melting point, Sasobit increases the stiffness of the binder. Sasobit is marketed in the United States by Sasol Wax Americas, Inc, Shelton, Connecticut. It has been used in several demonstration projects in the United States that include St. Louis MO, Mt. Hope NJ, Charles and Montgomery County MD, Yellowstone National Park, and Nashville TN.



a) b)

Figure 5 – a) Sasobit Pellets and b) Sasobit Being Blown into Drum Plant

- **Synthetic Zeolite.** Aspha-Min and Advera are synthetic zeolites, which is a mineral that has water trapped in its porous structure. The synthetic zeolite contains approximately 21 percent water by weight. It is added to the aggregate during warm mix production. When the temperature of the aggregate reaches approximately185 °F (85 °C), the water in synthetic zeolite begins to be released. This results in a foaming of the asphalt binder, which allows coating of the aggregate at a lower temperature. Aspha-Min® is the product of Aspha-Min GmbH of Germany , while Advera is the product of the PQ Corp. The recommended dosage rate is 0.2 to 0.3 percent by weight of the asphalt mixture. It has been used in several demonstration projects in the United States that include Orlando FL, Charlotte NC, St. Louis MO, Yellowstone National Park and Nashville TN.

a) b)

Figure 6. a) Advera type of Sythetic Zeolite and b) Feeding Port for Zeolite Into Drum Plant

- **WAM Foam**. WAM Foam (Warm Asphalt Mix Foam) is a two component binder system that uses a soft binder and a hard, foamed binder at different times during the mixing process. In the first stage, the soft binder is used to fully coat the aggregate. In the second stage, the hard binder is then foamed into the pre-coated aggregate. The combination of soft binder and foaming of the hard binder acts to lower the viscosity to provide the necessary workability. WAM-Foam is the product of a joint venture product between Shell International Petroleum Company Ltd., U.K., and Kolo-Veidekke, Norway. To date, it has not been used on any project in the United States, although there was a trial section conducted in Vancouver, Canada in 2007.

Figure 7. WAM Foam Expansion Chamber, Controls and Transfer Pipe

These seven proprietary technologies can be grouped into four general processes based on the underlying principles involved:

- **Foaming Agents/Additives.** Macroscopic foaming occurs as moisture is released from the additives/aggregates during the mixing process. Warm mix additives/technologies that fall under this category are Advera, Aspha-min, and LEA.

- **Plant Foaming.** Foaming of the asphalt occurs from the addition of water/compounds due to modifications in the plant production. In these technologies, the foaming can be directly attributed to the required plant modifications. The Astec Double Barrel Green and WAM Multi-component Binder Coating (WAM Foam) processes are examples of this type of warm mix technology.

- **Viscosity Reducers.** These additives significantly reduce the viscosity of the binder at mixing and compaction temperatures. Sasobit and Rediset WMX are technologies based on this process.

- **Emulsions.** Use of an emulsion as the asphalt binder. Evotherm is a technology based on this process.

Benefits and Uses of Warm Mix Asphalt

The use of warm mix asphalt (WMA) has been publicized as having a number of potential benefits to the asphalt industry. The following describes some of the benefits that are associated with the use of WMA.

<u>Used as a Compaction Aid</u>

Probably the biggest benefit in the use of WMA is that of an aid during compaction, with compacted field densities meeting non-warm mix asphalt mixtures at lower compaction temperatures. This covers a few different areas, such as; better compaction of stiffer mixes, better compaction in cold weather paving, and better compaction in difficult areas (i.e. – around manhole covers, inlets, etc.). Real life examples of WMA benefits are discussed below.

Compaction of Stiffer/Colder Mixes

Asphalt mixtures containing polymer-modified binders and/or higher percentages of RAP have been known to create problems in the field during compaction. Although higher stiffness in HMA is important to minimize rutting potential, there are occasions where the mix may become difficult to achieve air voids. It is well documented that higher air void levels in asphalt directly affects the material's performance (i.e. – higher levels of rutting and fatigue and thermal cracking), thereby negating the benefit of the polymer-modified asphalt. Warm mix asphalt can potentially aid in alleviating these compaction issues.

An example of this is from recent work conducted at Logan Airport in October 2007. The paving job included a deep mill, six to nine inches, and then paving with two lifts of intermediate course and a fuel resistance surface course mixture. The intermediate course consisted of:

- 19mm maximum aggregate size P401
- PG64-28 with 4% SBR Latex and 1% hydrated lime
- 18.5% RAP

The milling and paving was conducted on an alley way between two terminals where planes consisting back out and onto the taxiway. Due to the frequent traffic of planes, it was required that the full depth of the intermediate course be placed within a 24 hour period, and the surface course was required to be placed no later than six hours after the intermediate course was finished.

To accomplish this, Aggregate Industries used Sasobit to modify the mixture at the plant and produced the mixture 40^{o}F lower than normal production temperatures. This allowed the intermediate course lifts to cool down enough to be completed within the required 24 hour window, while staying within FAA specifications. The fuel resistance (FR) surface course mixture was shortly placed after the second lift of the intermediate course and the alley way opened up soon after that.

According to Aggregate Industry representatives, a job like this typically takes five days to complete. By using the warm mix concept, the project was completed in three days. Aggregate Industries also reported that the handwork required along the building area was also much easier to accomplish.

Cold Weather Paving

Figure 8 shows the FR surface course mixture at Logan Airport modeled in Multi-Cool program to determine the reduction in HMA lift temperature. According to representatives at Aggregate Industries, the air temperature during the night of paving was 38^{o}F with a wind speed of 25 mph. As the figure shows, even when the mixture was delivered to the site at 300^{o}F, the window to achieve compaction is very limited. By using a warm mix additive, the mixture viscosity is reduced increasing the time to achieve density in the field.

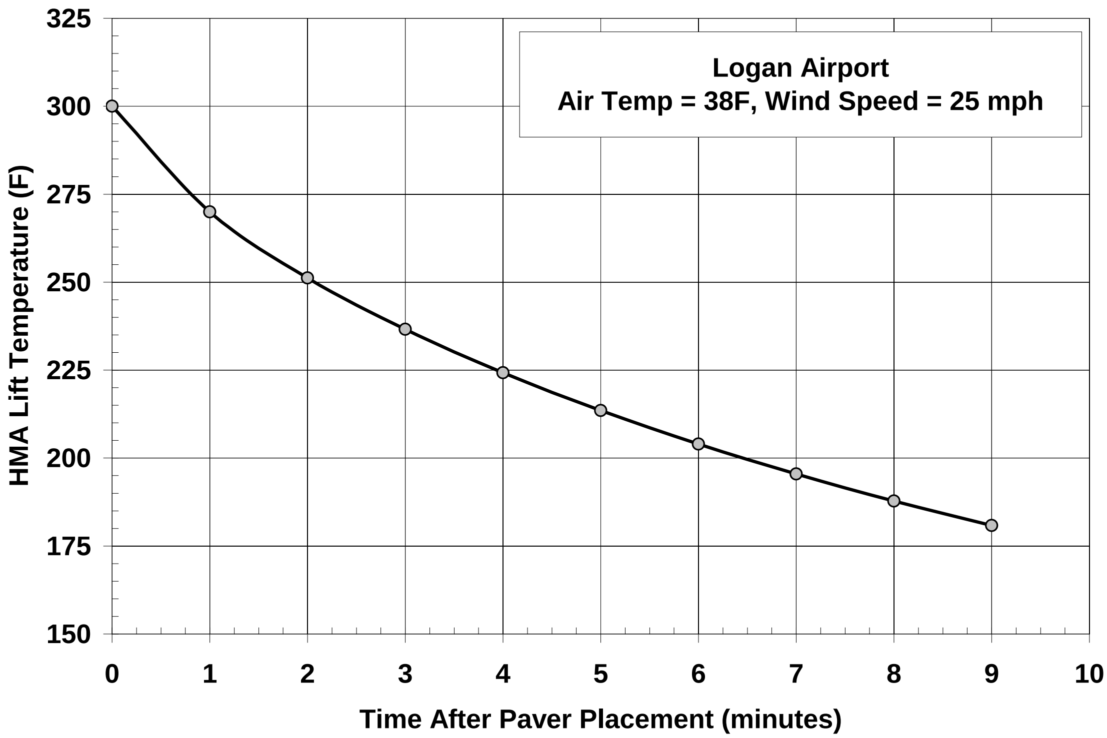


Figure 8. Reduction in HMA Lift Temperature as Modeled in MultiCool

Case studies were also presented during the European Scan Tour where, in Germany, paving was conducted with several different WMA technologies when ambient air temperatures were between 27 to 40^{o}F. In each case, better densities were achieved with the WMA compared to the HMA control sections with the same or fewer roller passes (Harnischfeger, 2007).

Longer Haul Distances and Times

Regarding the same benefit as "Cold Weather Paving", the reduced mixture viscosity (or increased mixture workability) can allow for increased haul distances/times by increasing the window to achieve compaction. Examples from the NAPA publication on Best Practices of Warm Mix Asphalt are summarized below (Prowell and Hurley, 2008);

- Sasobit modified HMA in Australia achieved compaction after a haul time of almost nine hours. The truck used during the trial was insulated.
- The manufacturer of WAM Foam, Kolo Veidekke, reported a pilot project where the WAM Foam modified HMA was stored in a silo for over 48 hours and still retained enough workability to be placed and compacted.
- The Evotherm test section compacted at the NCAT Test Track was stored overnight and then successfully placed and compacted.

Use of Higher Percentages of RAP

The use of WMA technologies has been reported to allow for the increased percentage of RAP in HMA mixtures. The WMA allows for the overall reduction in mixture viscosity, thereby providing a better opportunity to achieve density. If lower production temperatures are used, the liquid asphalt binder is aged less and thereby helps to compensate for the increased amounts of aged RAP binder. WMA work in the Netherlands has shown that RAP contents as high as 50% are commonly used. Field trials with Sasobit and Aspha-min were reported to have been used with 90 and 100% RAP in Germany. If increased RAP contents can consistently be produced and placed, the cost savings may help to compensate for the additional costs of the WMA technology used.

In New Jersey, an In-House demonstration conducted by the Oldcastle Materials at the Tilcon, Mt Hope facility used Sasobit preblended in a PG76-22 asphalt binder. Production temperatures were reduced to 245^{o}F while increasing RAP percentages to 30%. Tilcon representatives reported all field densities to have been below 7% air voids, while the paving crew clearly noted the reduction in emissions and heat from behind the paver.

Specific Pavement/Material Applications

Two examples are shown to illustrate the further potential of warm mix asphalt when production at lower temperatures is required:

The first example has been reported in two sources; LLM – Asphalt Technology Consulting (Michael and Layman, 2006), and the NAPA publication (Prowell and Hurley, 2008). The project revolved around a WMA field evaluation that took place in St. Louis, MO on a composite pavement. During the initial HMA overlay, transverse "bumps" occurred over the areas where the PCC transverse joint rubberized joint sealant had been placed (Figure 9). These types of transverse "bumps" commonly occur from both the rubberized sealant and trapped moisture being pulled upwards from the heat of the newly applied overlay.

Figure 9. Transverse "Bumps" in the Areas of Rubberized Joint Sealant

A publication by Michael and Layman (2006) described in detail the use of Sasobit on the project, while the NAPA publication briefly mentioned that different WMA additives/technologies were used (Sasobit, Aspha-min, and Evotherm). Both studies concluded that the use of WMA at compaction temperatures lower than 240^{o}F made a markedly improvement with respect to the transverse "bump" problem. Adequate density was achieved for the WMA sections, and the success of the project provided enough evidence for the contractor to petition the Missouri DOT to change other similar projects to WMA in order to minimize the potential for the transverse joint "bumps".

The second example is not as well documented, although the problem deals with emissions issues. In a recent National Institute of Occupational Safety and Health (NIOSH) study, HETA #2001-0536-2864, *Crumb-Rubber Modified Asphalt Paving: Occupational Exposures and Acute Health Effects*, NIOSH took personal breathing zones (PBZ) air samples on both the crumb rubber modified (CRM) and conventional (CONV) asphalt paving workers during their typical paving work day. NIOSH tested for:

- Total particulate (TP)
- Benzene soluble particulate (BSP)
- Polycyclic aromatic compounds (PAC)
- Organic sulfur-containing compounds (OSC)
- Benzothiazole.

What the NIOSH study found was that;

- PBZ exposures were usually higher during CRM asphalt paving
- The highest exposures were from jobs near the paver or asphalt delivery trucks
- Eye, nose, and throat irritation were symptoms most frequently reported by the workers.

In summary, the NIOSH study suggested that CRM exposures are potentially more hazardous than conventional asphalt exposures, and that exposure to asphalt fumes should be reduced whenever possible by the use of engineering and administrative controls. The potential use of WMA additives/technologies in conjunction with asphalt rubber mixtures could potentially allow for the reduction in the mixing temperatures of the asphalt rubber mix without causing workability issues in the field – keeping in mind that the rubber and the asphalt binder would still require to be blended at 350^{o}F to ensure proper modification. However, maintaining the temperature of the asphalt rubber mix at 350^{o}F, where there is obviously a greater potential for emissions issues, would not be needed in order to achieve field compaction. Therefore, the addition of WMA additives/technologies to asphalt rubber has two important benefits; 1) Potential reduction in emissions by allowing a decrease in production/compaction temperatures and 2) Maintaining workability of the asphalt rubber mixture.

Environmental Benefits of WMA

With maintaining workability while decreasing production and compaction temperatures, one of the biggest potential benefits of using Warm Mix Asphalt (WMA) is environmental. In particular, the reduction in temperatures is associated with reducing emissions, both at the plant and at the paver, as well as potential reduction is fuel costs during production.

Reduction in Emissions

With many state agencies, including NJDOT, using more polymer-modified asphalt to help in achieving longer pavement lives, many asphalt plants have been increasing their production temperatures to ensure proper workability and compaction that can be achieved in the field. However, elevated production temperatures at the plant are also associated with elevated levels of emissions at the plant and at the paver. Figure 10 shows asphalt emissions surrounding the paver and paver crew at the NJDOT Rt 38 Warm Mix project in July 2007. Production temperature of the 9.5H76 mix was 315^{o}F.

Preliminary results from various pilot projects in the United States have shown that the use of WMA can decrease the amount of recordable emission by sometimes up to 50%. For example:

- Barthel and Von Devivere (2003) showed that with the addition of Aspha-Min and a corresponding reduction in production temperatures of approximately 50^{o}F was able to reduce plant emissions by 75%

- Larsen et al. (2004) reported a reduction of 30% of CO_2 during a project using WAM-Foam. The authors also discussed a project in Norway where the use of
- WAM-Foam resulted in; 31% reduction in CO_2, 29% reduction in CO, and 62% reduction in NO_X
- Romier et al. (2006) reported a potential reduction in greenhouse gas of as much as 50% through the use of the LEA process

Figure 10. Emissions Behind the Paver on the NJDOT Rt. 38 Warm Mix Project

The Ohio DOT pilot project that evaluated Sasobit, Aspha-Min, and Evotherm provided a detailed assessment as to the potential reduction in emissions, both at the plant and behind the paver. Table 1 shows the emission test results from Stack Emissions Tests. The results for the Paver Emission Tests were evaluated using a newly accepted NIOSH test procedure for Total Particulates (TP), ***NIOSH Method 5024 for Total Particulates***, and are shown below:

- Evotherm WMA: 23% Reduction in TP
- Aspha-Min WMA: 33% Reduction in TP
- Sasobit WMA: 26% Reduction in TP

As shown in the results from the Ohio WMA Pilot Project, the use of WMA reduces greenhouse gas emissions from the plant stacks and also particulate emissions behind that paver where workers are most vulnerable.

Table 1 - Stack Emission Test Results from Ohio DOT WMA Test Trials

Mix Type	SO_2		NO_X		CO		VOC	
	(lb/hr)	% Change	(lb/hr)	% Change	(lb/hr)	% Change	(lb/hr)	% Change
Conventional HMA	0.24	N.A.	5.2	N.A.	63.1	N.A.	7.8	N.A.
Evothern WMA	0.37	54.2	5.1	-1.9	50.3	-20.3	20.2	159.0
Aspha-Min WMA	0.04	-83.3	3.6	-30.8	24	-62.0	2.9	-62.8
Sasobit WMA	0.04	-83.3	4.1	-21.2	23.2	-63.2	3.8	-51.3

Additional emissions data collected during the FHWA International Warm Mix Scanning Tour (D'Angelo et al., 2007) from the different European countries visited is shown in Table 2. The European results coincide with the emissions results recorded during the Ohio WMA Pilot Project.

Table 2 - Observed Percent Reduction in Emission with WMA (After D'Angelo et al., 2007)

Emission Parameter	Norway	Italy	Netherlands	France	Canada
CO_2	31.5	30 - 40	15 - 30	23	45.8
SO_2	N.A.	35	N.A.	18	41.2
VOC	N.A.	50	N.A.	19	N.A.
CO	28.5	10 - 30	N.A.	N.A.	63.1
NO_X	62.5	60 - 70	N.A.	18 [a]	58
Dust	54	25 - 55	N.A.	N.A.	N.A.

[a] – Reported as NO_2

Reduction in Energy and Fuel Consumption

Burner fuel consumption, or potential savings, during asphalt production will be a function of the following parameters:

- Drum/Batch Plant Temperature Setting;
- Moisture Content of Aggregate and RAP; and
- General Detail of the Plant's Design and Operation

Observations by Prowell and West (2005) have indicated that burner fuel usage is increased 10% for every 1% increase in aggregate/RAP moisture content. Therefore, fuel savings associated with lower production temperatures may end up being voided out by the need to increase drying times to ensure proper aggregate drying is achieved.

Lower mixture viscosity (higher workability) may also allow energy savings to come from other areas of the plant besides the burner fuel costs. For example, after the WMA mixture has been discharged from the drum, it is feed into the silos via a drag chain mechanism. If lower mixture viscosities were obtainable, amperage levels at these drag chains should decrease. The same could be said for asphalt binder pumps that feed the asphalt binder from the storage tanks into the mixer (drum or batch plant). WMA additives such as Sasobit and Rediset can be preblended at the refinery and pumped directly into the asphalt binder storage tanks. If the WMA additive was able to properly decrease the asphalt binder viscosity, there is potential to again achieve lower amperages at these pumps.

To date, accurate measurements of fuel and energy savings have been difficult to obtain, mainly due to plant fluctuations during smaller pilot-type projects. At the NJDOT Rt. 38 pilot project, both drag chain and asphalt binder pump amperages were recorded to try see if amperages indeed lowered. Table 3 (a) and (b) show the results to the control mix (no WMA) and the preblended Sasobit. The result indicate that no difference was found at the drag chain, and the amperage level at the binder pump slightly increased in the WMA mix at a production temperature of 270^{o}F. It should be noted that this project only used approximately one-half of the recommended Sasobit dosage and only 500 tons of mix were produced for each type.

Table 3 (a) - Plant Production Information for Control Mix (No WMA)

Time	Mix Discharge Temperature (F)	Production Rate	Asphalt Binder Pump Amperage	Drag Chain Motor Amperage
8:45 PM	315	250 ton/hr	35	50
9:15 PM	318	250 ton/hr	35	50
9:45 PM	313	250 ton/hr	35	50
10:15 PM	315	250 ton/hr	35	50

Table 3 (b) - Plant Production Information for WMA Mix (0.8% Sasobit Preblended per Weight of Binder)

Time	Mix Discharge Temperature (F)	Production Rate	Asphalt Binder Pump Amperage	Drag Chain Motor Amperage
10:45 PM	270	250 ton/hr	35	50
11:15 PM	270	250 ton/hr	35	55
11:45 PM	268	250 ton/hr	35	55
12:15 AM	272	250 ton/hr	35	55

According to Larry Michael (2008), to fully understand what type of energy savings could be obtained (from burner fuel and electrical consumption), the project should run a minimum of two to three full days to allow the plant operator to “tune” the plant to the mixture requirements. For most drum plants, this would equate to approximately a minimum of 2,500 tons of mix produced for one mix type at one production temperature. A majority of the WMA projects to date have not met these requirements.

To date, the only United States project that met these criteria was the recent paving through Yellowstone National Park. The project details are below (Neitzke, 2007):

- Approximately 7 lane miles of paving
- Placed in two 2" lifts
- Evaluated two WMA technologies and a control section
  - Advera (Zeolite)
  - Sasobit
- Over 28,000 tons of mix produced (1/3 of total tonnage per mixture)
- Binder Type – PG58-34
- 19mm Mix (designed using Hveem) – equivalent to 75 Gyrations
  - 5.3% asphalt
  - 1.0% hydrated lime
- Production Temperatures
  - Control – 325^{o}F
  - Advera – 275^{o}F (0.3% by weight of mix)
  - Sasobit – 275^{o}F (1.5% weight by binder)
- 90 minute haul time

Attempts were made to try and maintain a consistent roller pattern (compaction energy) for each mixture. The final roller pattern consisted of 7 passes of an Ingersoll Rand DD-130 vibratory compactor and 3 finishing passes with an Ingersoll Rand SD-77 compactor. Final density measurements of the different field mixtures were:

- Control - 93.2% of G_{mm} (6.8% air voids)
- Advera – 93.9% of G_{mm} (6.1% air voids)
- Sasobit – 93.4% of G_{mm} (6.6% air voids)

Based on the data collected at the plant, it was estimated that approximately 20% savings in fuel was achieved by using the WMA mixtures. However, it should be noted that even though the tonnages produced in the trial allowed to a good estimation of fuel savings, discussions with Larry Michael (2008) indicated that the temperatures at this plant were difficult to regulate and the plant supplemented their burner fuel with used motor oil. Under normal and consistent plant conditions, it is estimate that approximately 30% reduction in fuel costs may have been obtained.

According to the NAPA Publication (Prowell and Hurley, 2008), fuel savings reported on various WMA projects to date indicated burner fuel savings range from 20 to 35 percent. These percentages could be higher if "burner tuning" was completed to allow the burner to run at lower settings. Others have reported similar fuel consumption reductions:

- Barthel and Van Devivere (2003) reported that the use of Aspha-min, with a production temperature reduction between 54 to 63^{o}F resulted in a 30% reduction in energy consumption.

- Larsen et al., (2004) reported on energy consumption measurements made in Norway that resulted in a 40% decrease in diesel fuel during the production of WAM-Foam WMA.
- Although not based on actual measurements, Romier et al. (2006) indicated that heating energy for Low Energy Asphalt (LEA) is less than 50% of similar HMA.
- Two Evotherm trials conducted in Canada (Davidson, 2005a; Davidson, 2005b) dropped the production temperature of the WMA to 208^{o}F, resulting in energy savings of 33% and 55% for a plant using Natural Gas and the second plant burning oil, respectively. Although 208^{o}F production temperature is rather low, using production temperatures that have been consistent with most WMA test trials (240 to 260^{o}F) most likely would have resulted in fuel savings in the area reported by Prowell and Hurley (2007) of 20 to 35%.

Additive/Technology Specific Benefits

The benefits of WMA described earlier seem to be across the board for the various additives/technologies identified. However, there are also other benefits that pertain solely to individual additives/technologies that have been identified and not yet discussed. This section tries to identify “other” benefits of the various WMA additives/technologies specific to the respective technology.

Sasobit

In the course of Literature Review and NJDOT’s own use of WMA additive on the Rt 38 pilot project, Sasobit was found to provide a few additional benefits.

Ease of Use

One of the best additional benefits of Sasobit is that it can be preblended in the asphalt binder at the asphalt suppliers terminal, eliminating any need for additional equipment to be rented or purchased. However, it should be noted that depending on the time of the construction season, a terminal fee will most likely be charged that may range from $0 per liquid ton (during last season paving when needs for asphalt binder are limited) to $50 per liquid ton (during times of large demand for asphalt binder – this charge is a reflection of the preblending occupying a tank that otherwise would hold more commonly used asphalt binder). It should be noted that these tentative terminal fees were obtained from only one binder supplier during the course of this report.

Asphalt Binder Modification

In the numerous pilot projects involving Sasobit, the wax material was found to provide an increase in the high termperature PG grade, while causing minimal increase to the low PG grade. Having an additional increase in high PG grade may help to alleviate any issues with lower material stiffening due to reduced production temperatures. An example of this is from the WMA trials in Frisco, Colorado on I-70. At this trial, three WMA additives were used; Sasobit, Aspha-Min, and the synthetic Aspha-Min Advera.

The results of the binder test results on the extracted and recovered binder is shown in Table 4. The results show that the high temperature PG grade of the base asphalt was 58^{o}C, while after the addition of the Sasobit, the high PG grade bumped up to a 64^{o}C. Both of the other additives had minimum affect on the high PG grade.

Table 4 - PG Grade Results on Extracted and Recovered Binders from I-70, Frisco, CO

WMA Additive	M320 Continuous Grade (^{o}C)	M320 Performance Grade (^{o}C)
Base	59.9 – 30.3	58 – 28
Sasobit	64.2 – 29.2	64 – 28
Aspha-Min	61.1 – 30.9	58 – 28
Advera	60.7 – 30.4	58 – 28

Increased Adhesion in Mixture

Many have stated that higher RAP contents would be easier to achieve due to increased workability of the potentially stiffer mixture. Statements regarding the additional adhesive properties of Sasobit would also ensure proper bonding between the virgin materials and RAP. Although this would be very difficult to quantify, test results pertaining to interface bond strength (bond strength between the previous asphalt lift and the new WMA lift placed on top) have shown that Sasobit may indeed increase the adhesion between these lifts, even at lower production temperatures.

Only three test sections were found in the Literature Search that included bond strength testing; NJ Rt 38, St. Louis and Milwaukee test trials. Results of bond strength testing using the NCAT Bond Strength Tester (Figure 11) are shown in Table 5.

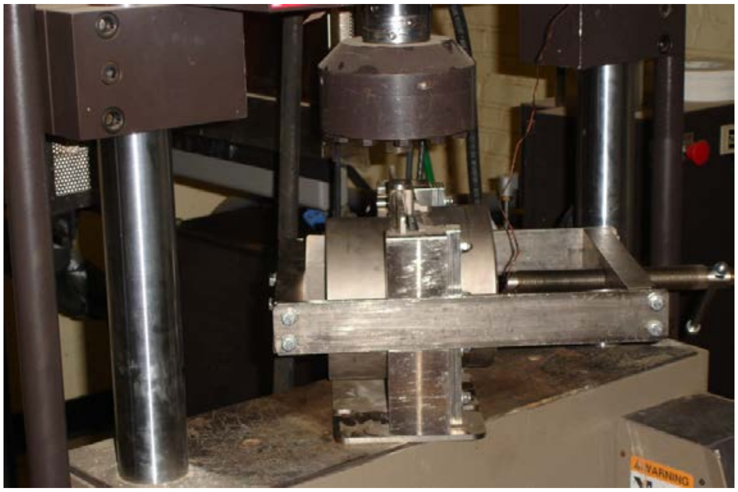


Figure 11. NCAT Bond Strength Test Device (Picture of Rutgers U. Unit)

Table 5 - Summary of Interface Bond Strength Tests

WMA Project Location	Overlay Lift Mixture and Laydown Temperature	Bond Strength
NJ Rt. 38	Normal HMA (9.5H76) (290^{o}F)	104.3 psi
	Sasobit Modified (290^{o}F)	172.9 psi
	Sasobit Modified (255^{o}F)	167.3 psi
St. Louis, MO	Normal HMA (9.5mm 70-22) (285^{o}F)	126.7 psi
	Sasobit Modified (240^{o}F)	151.2 psi
Milwaukee, WI	Normal HMA (12.5mm 64-28) (280 to 290^{o}F)	27.7 psi
	Sasobit Modified (230 to 240^{o}F)	133.5 psi
	Evotherm Modified (230 to 240^{o}F)	60.6 psi

<u>Rediset</u>

Ease of Use

Similar to Sasobit, Rediset can be preblended at the asphalt terminal prior to delivery to the asphalt plant. This eliminates any needs to purchase or rent additional equipment required to add the Rediset to the drum/batch plant.

Additional Anti-Strip Benefit

Being classified as a surfactant, Rediset has the additional benefit of being an anti-strip. With moisture sensitivity possibly being an issue with lower production temperatures, the additional anti-strip properties would be a tremendous benefit. Due to the relative "newness" to the industry, Rediset has yet to be implemented in a field trial. Only preliminary laboratory results exist, which were conducted at NCAT late 2007.

<u>Evotherm DAT</u>

Additional Anti-Strip Benefit

Similar to Rediset, Evotherm DAT contains a surfactant chemical that acts as an anti-strip.

Summary of WMA Benefits as Compared with HMA

The previous sections discussed in detail many of the benefits that have been reported when using WMA. It appears that the potential advantages of WMA over conventional HMA are tremendous, and can be summarized as follows:

- Significantly lower production and compaction temperatures;
- Reduction in greenhouse gases and emissions at the plant and behind the paver;
- Better workability with stiff mixes and during cold air temperatures results in;
    - Extending paving seasons;
    - Using higher RAP contents;
    - Extending haul and storage times;
    - Better workability of PMA;
    - Reduced potential for thermal segregation.
- Reduction in energy consumption (burner fuels and electrical levels at drag chain and binder pumps); and
- Improved working conditions for plant and paving crew.

Potential Hindrances in WMA Implementation

Although it appears that there are tremendous benefits for the wide spread adoption of WMA, inevitably it must overcome an industry that is very conservative and resistant to change. As noted by Button et al. (2007); "Generally speaking, the paving industry, as a whole, is slow to accept new technologies. For example, Superpave has been around for 11 years, and it is still not universally accepted by all state DOT's."

Another important aspect to overcome is the inevitable increase in costs. Reports have indicated that the use of WMA will increase the production costs of the asphalt mixture somewhere in the range of $2.00 to $4.00 per mix ton in a very competitive industry. However, this will be dependent of the additive/technology used, whether or not the asphalt plant is willing to purchase or rent required equipment, and possible license fees associated with different technologies. Other conditions the asphalt plant may need to consider is the use of an anti-strip based on historical aggregate issues and knowing lower production temperatures of WMA may not fully dry the aggregates prior to mixing. Some of these cost issues will be attempted to be answered in the upcoming sections for New Jersey conditions.

To date, performance records of WMA test sections has been limited. Initial reports have shown that the rutting resistances of WMA sections are performing in a similar manner to conventional HMA. Moisture damage has yet to be reported in any of the test trials, as well as no evidence of early cracking.

A number of state agency and federally funded research efforts have recently focused on trying to answer some of the more fundamental questions regarding the potential use and implementation of WMA. Some of the more pertinent questions related to WMA uses are:

- Because of lower mixing temperatures, does the WMA final product undergo less stiffening, and therefore, more prone to permanent deformation than conventional HMA of identical aggregate structure and asphalt binder grade? Will this result in state agencies adopting stiffer asphalt binders to counteract the lower degree in stiffening?
- Lower mixing temperatures will inevitably affect the amount of asphalt binder absorbed in the aggregates themselves, thereby increasing the effective asphalt content of the mixture. Will higher effective asphalt contents create rutting issues for softer binders and should this be taken into consideration during the mixture design phase?
- Lower production temperatures will most likely result in higher levels of residual moisture in the aggregates. If this is the case, will this inevitably result in moisture damage issues in the WMA pavements? Will the use of anti-strip additives be required for all WMA materials, thereby again increasing the overall cost of the WMA? Will state agencies using WMA require the asphalt suppliers to utilize better methods to keep aggregate moisture contents low (i.e. – paving under stockpiles, covering stockpiles, increasing mix times for greater heat exposure)?
- For quality control during production, there are essentially no cure time requirements prior to compacting specimens, sampled from the trucks, for volumetric assessment. Are these same procedures acceptable for WMA specimens, or is some cure time needed to allow moisture in certain WMA

mixtures to evaporate/cure? Should similar procedures be adopted during the mixture design phase?

Warm Mix Technology Costs – Analysis Scenario

Much of the research on WMA to date has concentrated on performance and environmental benefits. However, for implementation to truly be considered, the cost of the additive/technology must also be considered. The use of WMA adds cost to the asphalt mix. Cost comes from plant modifications/equipment needed to produce the WMA and any required additives and their freight costs. Other intangible costs, such as mark-up or risk are possible, but were not included in this analysis.

There are also a number of potential savings from the use of WMA. Fuel savings have been talked about the most, but there are other savings that are typically lost in a plant's overhead, such as emissions compliance and monitoring and worker health. Some WMA additives include anti-stripping agents as part of the additive (i.e. – Evotherm DAT and Rediset). The use of other WMA additives may necessitate the addition of or increased quantities of anti-stripping agents compared with HMA. For this analysis, it was assumed that those WMA additives/technologies which were not classified as including anti-stripping agents had to utilize an anti-strip. This increased the per Mix Ton cost by approximately $0.50. In the future, it may even be possible for asphalt plants to sell so-called carbon credits to other industries to offset part of the cost of the WMA.

To analyze the magnitude of the WMA additive/technology potential cost increases, two scenarios were developed to compare the cost of WMA technologies. The first scenario looked at the cost of WMA used on a limited basis and the second scenario looked at full implementation of WMA. In the first case, called Scenario #1, 5,000 tons of WMA will be produced in a 5-day period. A total of 15,000 tons of WMA are expected to be produced a year over a three year period. The production of the WMA was treated as discrete events, not back-to-back weeks for the purposes of assessing equipment rentals (and hence mobilization of specialty equipment like feeders). In the second case, called Scenario #2, it was assumed that all asphalt concrete would be produced as WMA. A production rate for the hypothesized asphalt plant of 350,000 tons per year was selected based on an average value as determined through phone interviews with the various Quality Control managers for a number of HMA plants located in New Jersey.

When a contractor purchases equipmen they expect a return on their investment. The Federal government allows capital recovery through depreciation, over a seven-year period. In addition, the contractor would most likely include some level of profit in their overhead based on this investment. In many cases, the scenario is somewhat different for specialty equipment required to produce a specific mix for a specific job or jobs. A specialty feeder, used to introduce a WMA additive probably falls into this category. Ideally, the contractor may like to recoup this investment on that particular job. That may be possible with a work order. However, for a low bid project, this will probably need to be spread out over three to four years in order for the contractor to actually get the job. A three year amortization period was selected for this example. If the contractor had not purchased a particular piece of equipment, they could have simply invested that money and would expect a return on their investment. The same holds true for the equipment, a contractor would hope to get more than their money back at the end of the three-year period. Twelve percent compounded interest was selected as a rate of return for this example.

A surface mix with 5 percent binder content was selected for calculating the addition rate of additives in both scenarios, where that addition rate is affected by the binder content. This is approximately the average binder content of surface mixes used in New Jersey. The 5 percent binder content was also used to assess the magnitude of the terminal fee used for the Rediset and Sasobit Terminal Blend calculations. The terminal fee determined for this cost analysis was an average for the paving season. Based on a phone conversation of a SemMaterials' representative, the cost of the terminal fee would most likely be higher during the peak production time (May through August) where the blending of the WMA additive would hold up a binder tank at the refinery. Meanwhile, the terminal fee would be less towards the end of the paving season, when most HMA suppliers have already completed their work for the year and the need for asphalt binder is limited. The project location selected was Trenton, NJ.

The various WMA suppliers were asked to provide cost estimates, including freight, for the two scenarios. It should be noted that these estimates are based on a single point in time for a single location. (It should be noted that not all of the WMA additive/technologies responded to email and phone messages, and therefore could not be included in the cost analysis). For instance, one of the suppliers has a warehouse in New Jersey, while another supplier's warehouse is half-way across the country. This significantly impacts the freight cost. Further, freight cost can vary widely with fuel costs. Freight costs would be expected to decrease with the complete implementation of WMA scenario (2), since material could be shipped in bulk, by rail. A number of the additives could be manually added to batch plants using melt bags.

The comparisons are shown in Table 6 and Figure 12. The cost analysis shows that for Scenario #1, which basically describes the infrequent use of WMA for a New Jersey asphalt supplier, the less expensive WMA additive/technology was the Evotherm DAT. As shown in Table 6, this technology also has the added benefit of including an anti-strip agent. The most costly WMA additive/technology determined was the Rediset material when blown into the drum plant with a feeder system.

For Scenario #2, which would model the complete implementation of WMA at a typical New Jersey drum plant facility, the Astec Double Barrel Green and the WAM-Foam WMA technologies were the least expensive. The most expensive WMA additive/technology when considering full implementation of WMA in New Jersey was the Rediset additive when it is terminally blended at the asphalt refinery.

Table 6 - Cost Estimates for WMA Additives/Technologies for Hypothetical Implementation in New Jersey (2008 Analysis)

Technology	Scenario	Equipment Purchase Cost	Equipment Rental and mobilization cost for one week	Additive cost per ton with freight	Anti-stripping agent deduct?	Estimated cost increase per ton
Advera	1	NA	$6,900	$2.01	No	$3.39
	2	$130,000	NA	$1.45	No	$1.62
Double Barrel Green	1	$90,000	NA	$0.00	No	$2.81
	2	$90,000	NA	$0.00	No	$0.12
Evotherm DAT	1	$3,500	NA	$2.25	Yes	$1.86
	2	$3,500	NA	$2.25	Yes	$1.75
Low Energy Asphalt	1	$72,000	NA	$0.88	Yes	$2.63
	2	$72,000	NA	$0.88	Yes	$0.48
Rediset Terminal Blend	1	NA	NA	$3.48	Yes	$2.98
	2	NA	NA	$3.48	Yes	$2.98
Rediset Blown into Plant	1	NA	$5,250	$2.85	Yes	$3.40
	2	$55,000	NA	$2.85	Yes	$2.42
Sasobit Terminal Blend	1	NA	NA	$2.88	No	$2.88
	2	NA	NA	$2.88	No	$2.88
Sasobit Blown into Plant	1	NA	$5,250	$2.28	No	$3.33
	2	$55,000	NA	$2.28	No	$2.35
WAM-Foam	1	$100,000	NA	$0.00	No	$3.12
	2	$100,000	NA	$0.00	No	$0.13

[1]Advera addition rate is 0.25 percent by total weight of mix (5 lbs per ton).
[2]Evotherm DAT addition rate is 0.25 percent by weight of binder.
[3]Rediset addition rate is 1.5 percent by weight of binder.
[4]Sasobit addition rate is 1.5 percent by weight of binder.
[5]Typical liquid anti-stripping additive addition rates are 0.25 to 0.50 percent by weight of binder.

Typical reported fuel savings are approximately 30 percent. This equates to slightly more than $1.00 per ton with current 2008 fuel prices.

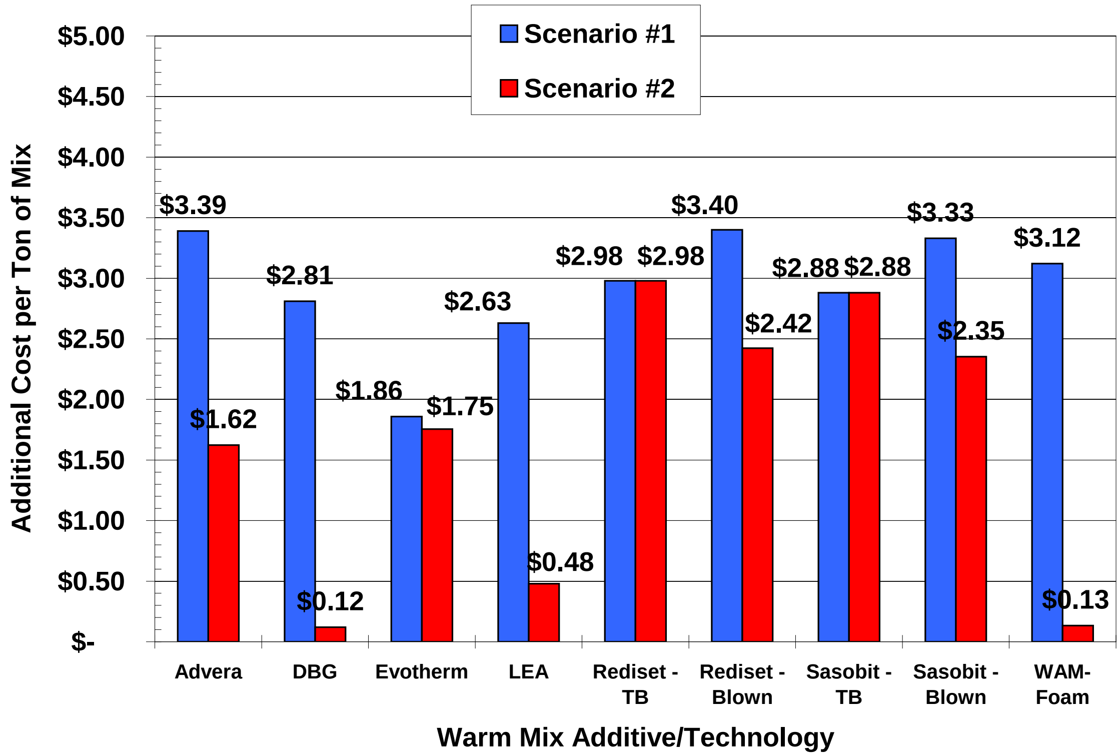


Figure 12. Summary of Cost Analysis for Different WMA Additives/Technologies for Hypothetical Implementation in New Jersey (TB – Terminal Blend; DBG – Double Barrel Green) (2008 Analysis)

Not included in the analysis is the potential difference in fuel savings among the different technologies. Typical reported fuel savings are approximately 30 percent. This equates to slightly more than $1.00 per ton with current 2008 fuel prices. Some technologies allow larger fuel savings.

Many of the suppliers offer special rates for demonstration projects. These rates may be less than those shown for Scenario #1. Although the same scenario was presented to each of the suppliers, some notes are appropriate in terms of the costs presented, particularly in the long-term. Freight costs may also change with increased production of WMA as suppliers establish more distribution points. A HMA design which does not require the addition of an anti-stripping agent may require one when produced as WMA due to the lower production temperatures and reduced aging of the binder.

<u>Long-Term Costs and Requirements</u>

The long-term equipment costs for the introduction of Advera include a feeder (similar to a fiber feeder), a storage silo, piping, bin activator, and tie into the plant controls. The storage silo would allow the zeolite to be shipped in bulk, which offers cost savings. A contractor may be able to use an existing silo or piping, which would further reduce cost.

The costs for the Double Barrel™ Green system include the cost of the unit and an estimate of the installation costs. Actual installation costs will vary with location due to the variance in travel costs. It should be noted that in its current form, the Double Barrel Green system can only be used on an Astec Double Barrel™ plant, which may limit its implementation in New Jersey.

The equipment costs for Evotherm DAT include a variable speed pump, flow meter, and necessary couplings, check valves, and ball valves. A 2-inch female NPT nipple will need to be welded onto the asphalt feed line for the coupling used to introduce the Evotherm DAT. The cost to tie the variable speed pump and flow meter directly into the plant controls is not believed to be included.

Several plant modifications are required to produce Low Energy Asphalt (LEA). The modifications differ for batch and drum plants. The minimum requirements are a stainless steel volumetric pump and mass flow meter to control the addition of the additive, moisture probe for the damp fine aggregate, and contact probe to measure the discharge temperature of the mix. All of this equipment is tied into a computer in the control house. Typically, an additional RAP feeder would be added to a drum plant or cold feed bin with a separate elevator for a batch plant to introduce the damp fine aggregate. The cost of the controls and an additional RAP feeder are included in the equipment costs. In a drum plant, a heated valve and extra asphalt line would typically be installed just before the asphalt line enters the drum. The second asphalt line would penetrate further into the drum to allow the coarse aggregate to be coated before the RAP collar where the damp fine aggregate would be introduced. The valve allows the plant to rapidly switch between producing HMA and WMA. The cost of this additional line and heated valve is not included in the equipment cost shown.

Rediset and Sasobit can both be introduced in the same manner. The products can be blended at the asphalt terminal or blown into the plant in pellet form. If Rediset or Sasobit are introduced at the asphalt terminal, there are costs associated with the use of blending and storage tanks, particularly when the terminal is busy. The addition of Rediset or Sasobit at the asphalt plant requires a feeder that controls the quantity of the additive with load cells and then pneumatically blows the additive into the plant. Many plants already have a line entering the mixing chamber for the introduction of fibers. This same line may be able to be used to introduce Rediset, Sasobit, or Advera. The line introduces the additive at the same point that the binder is added. A mixing box may be added to better incorporate the additive into the binder.

A major portion of the equipment costs associated with WAM Foam is for reprogramming the plant control systems. If the contractor had multiple plants with the same controls, this fee would only need to be paid once. A second asphalt line is also needed from the tank to either the pugmill or drum. A mass flow meter is used to control the addition of the hard binder on both batch and drum plants. A water line and foaming nozzle is also required. All of these costs are included in the estimate of the equipment costs. This assumes that the contractor already has two asphalt tanks in which to store the soft and hard binders. Additional tanks may be required if the contractor intends to run both HMA and WMA on a regular basis.

Summary of Feasibility Study

A Feasibility Study/Literature Review was conducted to evaluate how the NJDOT could more optimally use warm mix technology in their asphalt pavements. Technical papers and reports, as well as phone and email interviews with industry members were used to develop the study. The technical services of Brian Prowell from Advanced Material Services were also used to help develop the cost assessment portion of the study.

Based on the work conducted, the following conclusions can be drawn regarding NJDOT's potential use of warm mix technologies;

- The most apparent benefit for implementation in NJ is the use of WMA to aid in compaction issues. The use of polymer-modified asphalt, RAP, and cold weather paving all create compaction/workability issues frequently voiced by the NJ's asphalt industry. Although compaction issues seem to be less frequent during warm weather paving, utilizing WMA on projects that have a planned start date after October 1st may be viable. The need for increasing workability of asphalt mixtures may become even more of an issue as NJDOT moves in the direction to allow higher percentages of RAP in the mixtures.
- The second most apparent benefit for NJDOT would be the benefit to the environment and worker. Reduced production temperatures have clearly shown to dramatically reduce the visual and measured emissions at the plant and at the paver. This would be especially important as NJDOT continues to move forward with the use of asphalt rubber mixtures. With the continued pressure to become more "Green", NJDOT could utilize the WMA technologies to demonstrate their conviction on helping the environment and the workers of the asphalt industry.

The Feasibility Study/Literature Review has also shed some light as to the potential detriments that may come along during the initial implementation of warm mix technologies. Some of the prominent ones being:

- Costs – additional costs pertaining to the WMA will include such things as the warm mix additive, equipment rental/purchase, additional use of anti-strip agents. As shown in Table 6, the infrequent use of WMA (Scenario #1) would increase mix costs by $1.86 to $3.40 per mix ton. If full implementation were to be allowed (Scenario #2) and an asphalt supplier was to participate in the everyday production of warm mix asphalt, these additional costs could be as low as $0.12 to $0.50 additional per mix ton.
- Potential Stripping Issues – although to date stripping issues have yet to be reported on any of the warm mix asphalt project conducted in the United States, the use of lower production temperatures may not adequately drive off enough excess aggregate moisture. Therefore, the potential and most likely addition of anti-stripping agents may increase with implementation. Some WMA

technologies, such as Rediset, Evotherm, and LEA also have an anti-stripping component to their processes. Other ways of potentially reducing this issue would be to increase mixing times and/or promoting drier aggregate stockpiles (covers or paving under stockpiles to allow drainage).

- Potential Mixture Design Changes – any major modification to the HMA mixture may create a need to modify the mixture design. For quick and easy implementation, it would be hopeful that minor to no modifications would be required. However, due to lower production temperatures, issues such as the effect of higher aggregate moisture content and reduced asphalt binder aging and absorption, would need to be evaluated. Lower asphalt binder stiffening and/or lower asphalt binder absorption may induce mixture rutting.

Feasibility Study - Recommendations

Based on the work conducted, the following recommendations are provided for the future evaluation and implementation of Warm Mix Technologies;

- For immediate implementation, without requiring the asphalt supplier to modify or require any additional equipment, both Sasobit and Rediset additives can be used. Both additives can be preblended at the asphalt refinery and pumped directly into the asphalt suppliers current asphalt binder storage tanks. The use of Sasobit has shown to actually help increase the high PG grade of the asphalt binder while still maintaining mixture workability. Although little research has been conducted using the Rediset product, the limited work conducted to date has shown to provide an increase in mixture workability, while also providing an anti-strip property. If the asphalt supplier current has a fiber feeding system at their facility, the Advera product could also be used. The additional cost per mix ton for the Sasobit and Rediset additives to be preblended at the refinery would cost an additional $2.88 to $2.98 per mix ton.
- For the long term implementation, full cooperation with the asphalt industry would be required. Along with continuing the use of WMA products like Sasobit and Advera, the asphalt industry would be able to justify the added expenses of purchasing the required equipment to conduct the other types of technologies discussed earlier. However, the types of WMA that would be able to be provided to NJDOT would vary depending on the asphalt suppliers' current plant equipment. For example, the Astec Double Barrel Green system would only be applicable for those asphalt plants that currently utilize Astec equipment. Meanwhile, the LEA, WAM-Foam and Evotherm products, even though they require additional equipment, are more flexible with respect to modification to existing asphalt equipment. However, due to the counter-intuitive notion of applying addition water to the asphalt product, further performance monitoring of LEA and Astec Double Barrel Green system trial sections should be conducted to ensure potential future problems do not develop (i.e. – stripping).
- It is evident that further research regarding the effects of different WMA technologies on stripping and mixture performance need to be evaluated. Also, the effect of increased aggregate moisture on the mixing, compaction, and

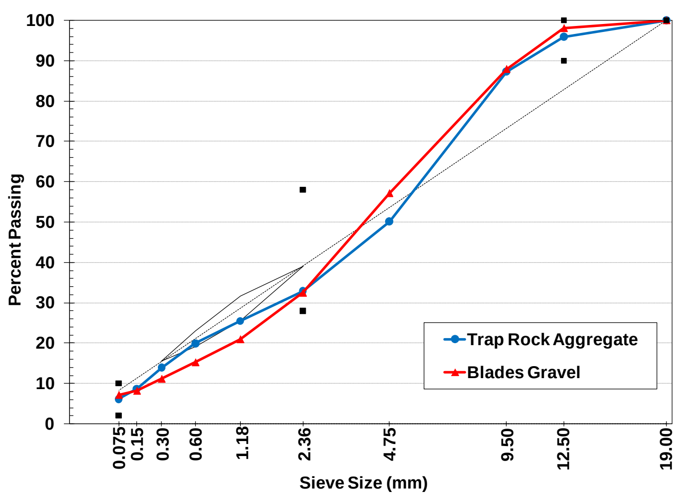
performance of HMA, due to reduction production temperatures, also needs to be further evaluated.

PHASE 2 – EFFECT OF MOIST AGGREGATES DURING WMA PRODUCTION

As discussed earlier in the Feasibility Study, residual moisture in the aggregate may initialize and/or accelerate moisture damage in the compacted asphalt mixture. Trapped moisture in the aggregate will limit asphalt binder absorption and be susceptible to freeze-thaw damage. To evaluate the potential for stripping in WMA when mixing temperatures are reduced and initial aggregate are moist, a modified asphalt mixing and moisture damage testing program was conducted.

Materials

For the moisture damage evaluation, two aggregate sources having different absorption properties were used. The first aggregate source, a Trap Rock aggregate, was supplied by Trap Rock Industries in Kingston, NJ and is a typical aggregate source in NJ. The Trap Rock aggregate blend used for the study had an absorption of 0.61%. The second aggregate source was a gravel from New York State. Although this type of aggregate is not used in New Jersey, it resulted in a much higher absorption level to evaluate how aggregate absorption played a role in this moisture damage potential. The gravel used was from the Blades Construction gravel pits in Harnell, NY. The mixture design and job mix formula properties are shown in Figure 13.



	Trap Rock	Blades
Binder Content (%)	4.9%	6.4%
VMA (%)	14.9%	16.3%
G_{mm} (g/cm^3)	2.712	2.424
G_{sb} (g/cm^3)	2.91	2.616
Percent Passing		
19mm	100	100.0
12.5mm	95.9	98.0
9.5mm	87.3	87.9
4.75mm	50.1	57.2
2.36mm	32.9	32.5
1.18mm	25.5	21.0
0.6mm	19.9	15.3
0.3mm	13.9	11.2
0.15mm	8.7	8.2
0.075mm	6.2	7.2

Figure 13. Job Mix Formula Information for Moisture Damage Study

The moisture damage study consisted of the following test parameters:

- Two mixing temperatures: 315 and 270^{o}F;
- Three initial aggregate moisture contents: 0, 3, and 6%;
- Two aggregate blends: 0.61 and 1.47% aggregate absorption; and
- One asphalt binder grade: PG76-22.

Moisture Damage Testing Procedure

To evaluate the moisture damage potential, two different test procedures were used; 1) Tensile Strength Ratio, TSR (AASHTO T283) and 2) Hamburg Wheel Tracking (AASHTO T324). Each test procedure has been found to be an indicator of moisture damage potential of asphalt mixtures. A special mixture preparation and mixing procedure was used to simulate the production of HMA and WMA in a drum plant using moist aggregates. General procedures were as follows and were based on the early WMA research conducted by Hurley and Prowell (2005).

- Pre-wet aggregate blend with specified moisture content and placed in zip-loc bag to limit evaporation. Allow the pre-wetted aggregate blend to absorb the moisture for 24 hours (Figure 14).

Figure 14. Aggregate Blend Saturating

- After 24 hours, place the pre-wetted aggregate in laboratory bucket mixer. Begin rotation of the bucket and begin heating with a propane torch (Figure 15).

Figure 15. Heating and Mixing Aggregate Blend

- Take quick pauses in aggregate heating to monitor aggregate temperature with infrared temperature probe (Figure 16).

Figure 16. Monitoring Temperature of Aggregate Blend with Infrared Temperature Probe

- Continue heating until aggregate reaches predetermined mixing temperature. Once temperature achieved, add the heated asphalt binder and mix until fully coated.
- Condition for 2 hours at compaction temperature, which for this study was 15^{o}C lower than mixing temperature.

For the moisture damage study, the aggregates were heated to mixing temperatures of 315 and 270^{o}F. The aggregate blends were evaluated using the following moisture contents; 0%, 3%, and 6%. All mixtures evaluated in the moisture damage study used a polymer modified PG76-22 produced and supplied by NuStar Asphalt from Paulsboro, NJ. No warm mix additives were evaluated during this portion of the study.

Moisture Damage Test Results

Two test procedures were used to evaluate the moisture damage potential; Tensile Strength Ratio (AASHTO T283, *Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage)* and the Hamburg Wheel Tracking (AASHTO T324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)).*

Tables 7 and 8 show the results of the moisture damage testing. The test results from the Table 7 shows that all mixes would have failed an 80% TSR requirement except for when the aggregate blend has 0% moisture and mixed at 315^{o}F. Table 7 also clearly shows how the mixing temperature and initial aggregate moisture play a significant role in not just the TSR values, but also the tensile strengths. For both aggregate sources, as mixing temperature decreased and initial moisture content increased, there was a clear reduction in the TSR and indirect tensile strength for the mixes.

The same general conclusions can be made with the Hamburg Wheel Tracking tests (Table 8). However, based upon the published criteria by TxDOT when using a PG76-22 asphalt binder, only three sample types would have officially failed (a fourth sample achieved 12.22mm when the criteria is less than 12.5mm of rutting at 20,000 cycles). Three of these four test specimens were constructed with 6% initial moisture content and mixed at the 270^{o}F mixing temperature.

Table 7 – Moisture Damage Test Results Using AASHTO T283

Moisture Content of Aggregate Blend = 0.61% Trap Rock Aggregate				
Mixing Temp (F)	Moisture Content (%)	TSR	Tensile Strength (U)	Tensile Strength (C)
270	0	62.6	224.7	140.7
	3	52.0	195.8	123.3
	6	63.0	184.6	96.1
315	0	88.2	240.7	212.2
	3	64.0	217.7	139.3
	6	65.8	236.4	155.5

Moisture Content of Aggregate Blend = 1.47% Gravel Gravel				
Mixing Temp (F)	Moisture Content (%)	TSR	Tensile Strength (U)	Tensile Strength (C)
270	0	63.0	247.3	155.9
	3	38.7	157.2	90.4
	6	57.5	220.7	85.3
315	0	93.9	195.6	183.6
	3	63.2	227.3	143.5
	6	71.5	219.3	156.9

Table 8 – Moisture Damage Test Results for Hamburg Wheel Tracking Tests

Aggregate Type & Absorption	Mixing Temp (F)	Moisture Content (%)	Inflection Point (cycles)	Hamburg Rutting @ 10,000 Cycles	Hamburg Rutting @ 20,000 Cycles (mm)
Trap Rock 0.61% Absorption	270	0	9,908	3.14	8.12
		3	8,203	4.97	11.62
		6	10,133	6.72	>12.5
	315	0	11,763	2.96	6.89
		3	10,217	3.44	7.97
		6	13,675	3.25	9.41

Aggregate Type & Absorption	Mixing Temp (F)	Moisture Content (%)	Inflection Point (cycles)	Hamburg Rutting @ 10,000 Cycles	Hamburg Rutting @ 20,000 Cycles (mm)
Gravel 1.47% Absorption	270	0	6,343	8.11	8.67
		3	3,610	>12.5	>12.5
		6	3,335	>12.5	>12.5
	315	0	9,613	2.96	9.41
		3	9,370	3.84	10.12
		6	8,663	5.20	>12.5

Summary and Conclusions of Moisture Damage Study

The combination of reduced mixing temperatures and aggregate moisture clearly had a detrimental impact on the moisture damage characteristics of the asphalt mixtures. Additionally, when the aggregate blend absorption increases, it appears that a greater degree of moisture damage can be expected. To help in mitigating these issues, NJDOT may need to consider the following;

- Increased mixing and/or storage time of the WMA. By increasing the mixing time in the drum/batch plant, the aggregates would most likely achieve a dryer state. Also, increased storage time at elevated temperatures would accomplish, although to a lesser degree, a similar effect. However increased storage time would also increase the general stiffness of the asphalt mixture through additional oxidative aging of the asphalt binder.
- Modify flighting in drums. Realignment in the flighting in the asphalt drums may be required to maximize aggregate movement and drying capabilities. This will also retain the aggregates in the drum longer to promote longer drying times.
- Better aggregate stockpile management. Covering of stockpiles, paving in under stockpiles and placing stockpiles on sloped surfaces will help to keep aggregate stockpiles drier. Drier aggregates will not only promote better resistance to moisture damage, but they will also help to keep burner temperatures lower as aggregate moisture is mainly responsible to for burner temperature selection.
- Enforce use of anti-strips. If plant/production modifications are not being followed or are met with a larger resistance from the industry, the enforcement of anti-strip agents would need to be required. Some additives like Rediset and Evotherm 3G already include an anti-strip in their chemical package. However, other technologies, like the foaming systems, do not.

PHASE 3 – ASSESSMENT OF WORKABILITY AND COMPACTABILITY OF WMA

Objective

With the increasing desire to use warm mix asphalt, it would be helpful if a procedure/method was available to evaluate the workability/compactability of asphalt mixtures modified with the multitude of warm mix processes/additives currently available. To further evaluate this concept, a research study was conducted to evaluate;

- The potential use of asphalt binder tests to look at ranking the workability/compactability of asphalt binders modified with warm mix additives
- The potential use of asphalt mixture tests to look at ranking the workability/compactability of warm mix asphalt mixtures
- The potential recommendation of a test procedure to evaluate and rank workability/compactability of asphalt mixtures modified with warm mix asphalt technologies.

Asphalt Binder and Mixture Properties

The asphalt binders evaluated in the study consisted of a PG76-22 manufactured by NuStar Asphalt, Baltimore Maryland facility. The binder was produced in two stages; a SBS concentrate (11 to 13%) was produced and then let down to the final PG 76-22. The binder was cured until total florescence was achieved. The cured binder was sampled from the finished production tank and the warm mix technology was produced in the laboratory under controlled conditions. The three warm mix technologies (Evotherm 3G, Rediset, and Sasobit) at varying dosage rates were blended at 385^{o}F for 1 hour on a low shear mixer. Table 9 contains the asphalt binders used in the study and their respective general properties.

Table 9 – Asphalt Binders and Their Respective Properties

Binder Type	PG Continuous Grade	Viscosity (Pa-s)		Elastic Recovery (%)	MSCR @ 64C	
		135 C	165 C		% Rec	Jnr
PG76-22	80.8 - 24.52	1.33	0.335	76	33.8	0.452
+ 0.6% 3G	78.9 - 25.00	1.262	0.34	78	24.1	0.521
+ 0.5% Sasobit	81.1 - 23.88	1.335	0.335	86	34.8	0.430
+ 1.0% Sasobit	81.4 - 22.91	1.29	0.308	85	37.2	0.376
+ 1.5% Sasobit	82.2 - 22.00	1.262	0.403	70	37.7	0.351
+ 1.0% Rediset	79.6 - 24.00	1.29	0.31	75	33.8	0.450
+ 2.0% Rediset	78.0 - 24.59	1.137	0.278	73	27.9	0.594

The asphalt binder tests show that minimal changes occurred in the PG76-22 asphalt binder as a result of the preblended warm mix additives. In some cases, the high temperature PG grade slightly decreased (Evotherm 3G and Rediset) while slight increases in high temperature PG grade were found in others (Sasobit). The non-recoverable creep compliance (J_{nr}) and percent recovery (% Rec), determined at 3,200 Pa, from the Multiple Stress Creep Recovery Test (AASHTO TP70) were also found to change slightly due to the dosage rates of the preblended warm mix additives. These changes were in agreement with the changes to the high temperature PG grade (i.e. – increase in J_{nr} for Evotherm 3G and Rediset and decrease in J_{nr} for Sasobit).

Each of the asphalt binders were used to construct a 12.5mm, coarse graded, Superpave mixture. The aggregates used were a Trap Rock aggregate from central New Jersey. The asphalt mixture design properties are shown in Figure 17. The mix design was developed to represent a typical surface course mixture for New Jersey materials.

Binder Content (%)	4.9%
VMA (%)	14.9%
G_{mm} (g/cm^3)	2.712
G_{sb} (g/cm^3)	2.91
Percent Passing	
19mm	100
12.5mm	95.9
9.5mm	87.3
4.75mm	50.1
2.36mm	32.9
1.18mm	25.5
0.6mm	19.9
0.3mm	13.9
0.15mm	8.7
0.075mm	6.2

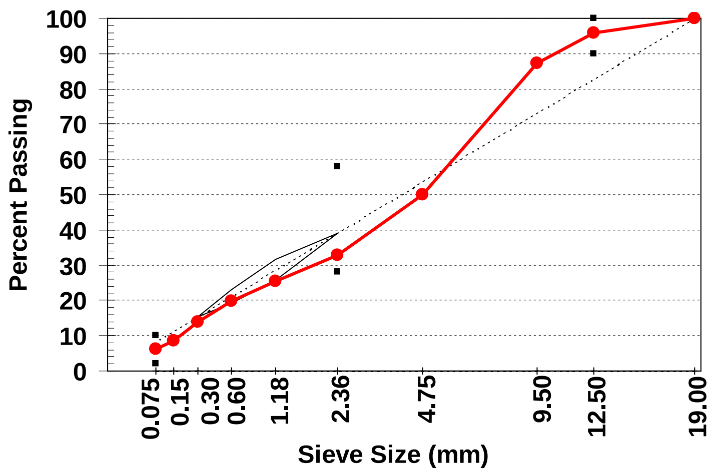


Figure 17. Mixture Design Properties

Laboratory Workability and Compactability Testing

The asphalt binders preblended with the different warm mix additives were evaluated under both asphalt binder related tests and also asphalt mixture tests. By utilizing the preblended asphalt binders, it allowed for the direct comparison of workability/compactability rankings between the asphalt binder and mixtures tests. However, it should be noted that most of the additives evaluated can also be introduced during the asphalt mixing process. Varying the dosage rates provided a means of evaluating the ranking validity (i.e. – generally better workability as Sasobit and Rediset dosages increase).

Asphalt Binder Tests

A number of asphalt binder workability/compactability type tests were conducted in order to access their potential for indexing and ranking the workability of warm mix asphalt and additives. The asphalt binder tests evaluated were as follows:
Rotational Viscosity (AASHTO T316, *Viscosity Determination of Asphalt Binder Using Rotational Viscometer)* for determining mixing and compaction temperatures;

Casola Method (NCHRP Project 9-39, Procedure for Determining Mixing and Compaction Temperatures of Asphalt Binders in Hot Mix Asphalt); and
Lubricity Test.

Rotational Viscosity – Mixing and Compaction Temperatures

The rotational viscometer was used to determine equi-viscous temperature ranges for mixing and compaction following AASHTO T316, *Viscosity Determination of Asphalt Binder Using Rotational Viscometer*. The calculated mixing and compaction temperatures for the preblended asphalt binders are shown in Table 10. The mixing and compaction temperatures seem to be unrealistic for warm mix applications. All of the preblended binders were classified as having mixing temperatures higher than 300°F (148.9°C) and compaction temperatures higher than 287°F (141.7°C).

Table 10 – Mixing and Compaction Temperatures Determined via Rotational Viscosity and Casola Method

Binder Type	Mixing Temps (°F)		Compaction Temps (°F)		Casola Method Temperatures	
	High	Low	High	Low	Mixing (°F)	Compaction (°F)
76-22	321.0	311.5	301.1	293.4	322	285
+ 0.6% 3G	323.2	313.2	302.3	294.2	322	285
+ 0.5% Sasobit	320.9	311.4	301.1	293.4	329	290
+ 1.0% Sasobit	316.6	307.6	297.8	290.5	325	287
+ 1.5% Sasobit	336.5	324.6	311.7	302.1	332	293
+ 1.0% Rediset	317.0	307.9	298.0	290.7	324	286
+ 2.0% Rediset	313.1	304.1	294.3	287.1	323	285

Casola Method (NCHRP Project 9-39)

The equi-viscous concept of the rotational viscosity works well for neat or unmodified asphalt binders. However, the resulting mixing and compaction temperatures for modified asphalt binders can be excessive and not representative of actual field conditions. The main goal of NCHRP Project 9-39, *Procedure for Determining Mixing and Compaction Temperatures of Asphalt Binders in Hot Mix Asphalt*, was to identify and develop a laboratory procedure that could be used to determine "reasonable" mixing and compaction temperatures for both unmodified and modified asphalt binders. One of the major outcomes of the study is the Casola Method. The Casola Method uses the dynamic shear rheometer to determine the mixing and compaction temperatures of asphalt binders. The concept is based on the observation that visco-elastic behavior of asphalt binders at routine PG grading temperatures is a relative indicator of handling and mixing temperatures. In general, the Casola Method procedure is as follows:

- Conduct a frequency sweep using 3 to 5 temperatures in the dynamic shear rheometer;
- Construct a Phase Angle Master Curve;
- Determine the frequency where the phase angle (δ) = 86°; and

- Calculate the mixing and compaction temperatures using the simple relationships of the following regression models.

$$\text{Mixing Temperature (ºF)} = 325\omega^{-0.0135} \quad (1)$$

$$\textit{Compaction Temperature (ºF)} = 287\omega^{-0.012} \quad (2)$$

where,

ω = the frequency in rad/s for the phase angle of 86 degrees as reported from the master curve.

The test results for the Casola Method are shown in Table 10. The test results of the Casola Method are comparable with that of the Rotational Viscosity shown earlier. As with the rotational viscosity, the mixing and compaction temperatures do not represent observed mixing and compaction temperatures commonly associated with the plant production of warm mix asphalt.

Lubricity Test

The Lubricity Test is based on concept of Thin-Film Rheology. The dynamic shear rheometer (DSR) uses an asphalt thickness, or film, of 1000 microns during typical testing (PG Grading, Casola Method, etc.). However, this film thickness does not truly represent the actual film thickness between aggregates during field or laboratory compaction. Therefore, research conducted by Mathy Technology and Engineering Services [10] began evaluating the steady state flow of asphalt binders in the DSR at film thicknesses less than 500 microns, and as low as 25 micros, in an effort to better simulate realistic film thicknesses.

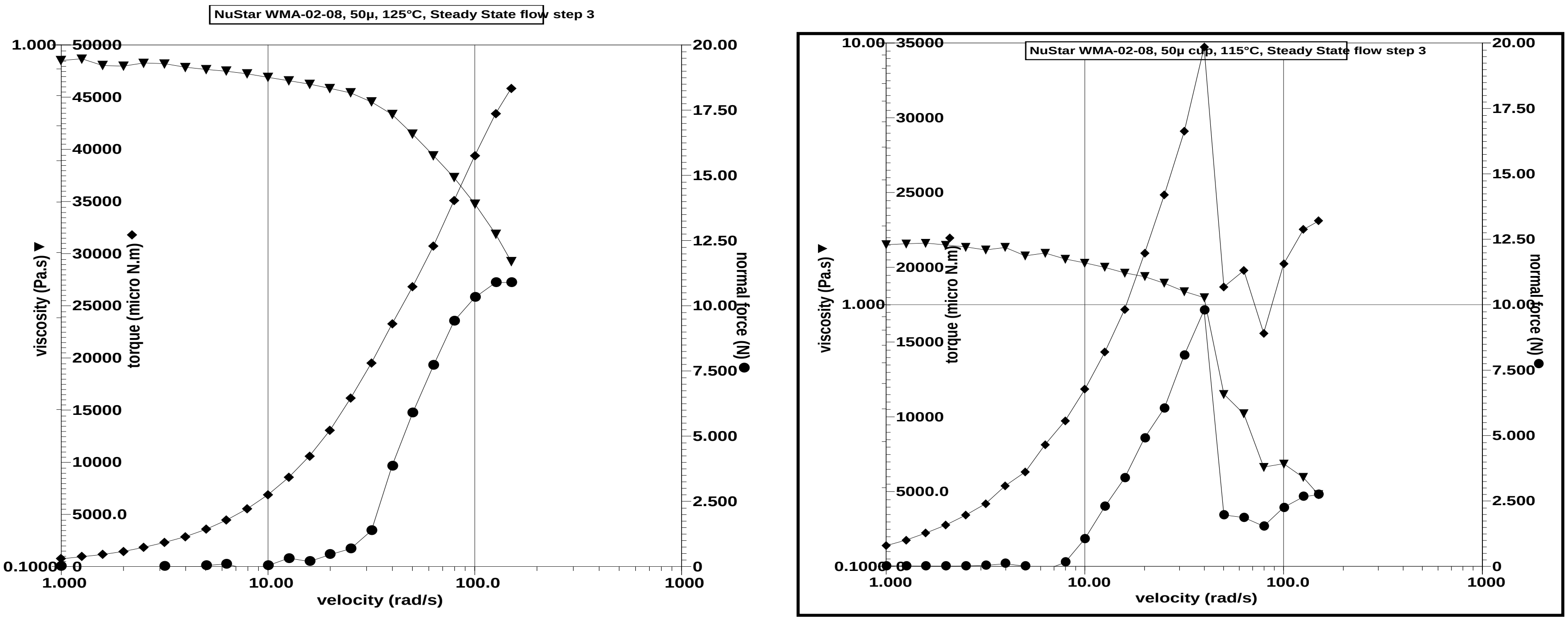
In the test procedure, the binder sample is loaded into the cup (Figure 18a) and brought to the initial gap thickness (Figure 18b). For screening purposes, 4 test gaps are used on the same sample for a single temperature. The initial gap is set at 500µm and the steady shear test is performed at rotational speeds of 1 to 150 radians/sec. Following this test a squeeze flow test is programmed at the same temperature in which the gap is reduced by 400 µm at a gap closure speed of 10 µm/sec; the final gap after this adjustment being 100 µm. It has been found that incorporating the squeeze flow test step enables automation of all 4 test steps without having to open the machine and with no need for operator involvement or further temperature conditioning steps as the temperature is never allowed to change. The same rotational speed sequence is performed at the 100 µm gap and subsequent steps following the same routine enables performance of the steady shear flow test at final gap height of 50 µm and 25 µm.

(a) (b)

Figure 18. Lubricity Test Setup a) Loading Asphalt Binder Pat in Bottom Cup Platen; b) Lowering Top Platen to 100 Microns

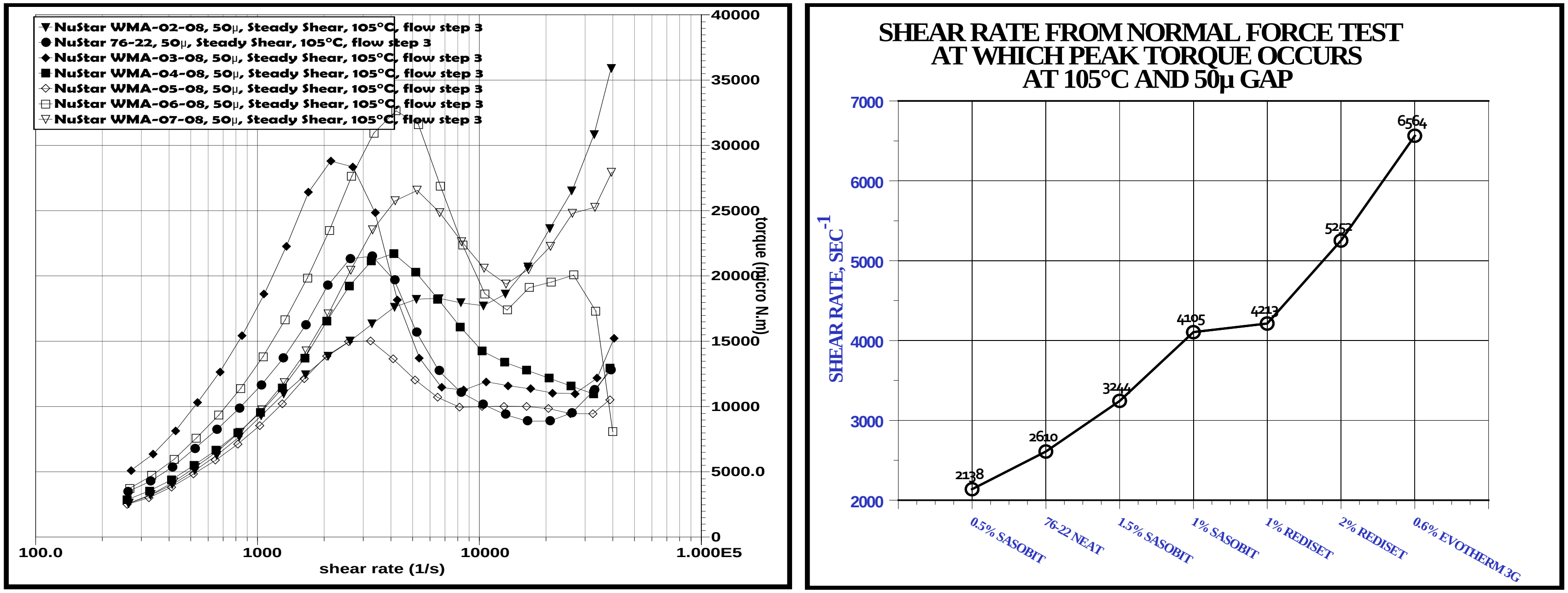
The data that is collected during a test is rotational speed (in radians/sec), viscosity (in Pa·s), normal force (in Newtons) and torque (in micro or milli newton meters). A typical test outcome is shown in Figures 19a and b. Figure 19a shows the result at 125°C for the Evotherm 3G treated PG 76-22. As the rotational speed increases the normal force exerted by the binder increases along with the resultant torque. The viscosity decreases exponetially with increasing rotational speed and the normal force reaches a peak value. When the temperature is decreased to 115°C (Figure 19b), there is a sharp breakpoint in the viscosity plot and sharp drop in the normal force and torque after achieving a maximum value. This occurs with most binders at some temperature and rotational speed and appears to be related to the upper plate slipping with respect to the binder sample on the stationary bottom plate at some rotational speed. Two factors affecting warm mix binder performance appear to be the magnitude of rotational speed or shear rate that can be sustained before this slippage occurs and the magnitude of normal force produced by the binder at that shear rate.

In Figure 20a the torque achieved at increasing shear rates for the 50 µm gap thin film rheology test at 105°C (221°F) is shown. The plots shown in Figure 20a have been smoothed by the TA Advantage software to aid in viewing the data. For each binder except for the 76-22 + Evotherm 3G there is a maximum value of torque followed by a decline in the torque as shear rate increases. Because of the low temperature of this test, for a PG 76-22 binder the peak torque values occur at relatively low shear rates compared to the results viewed at warmer temperatures. For simiplicity the initial maximum torque value is plotted in Figure 20b. The basis underlying the plot in Figure 4b is that greater the shear rate that can be sustained before peak is achieved, the more workable the mixture should be. If it is possible with a given warm mix additive to achieve a higher shear rate before the torque drag on DSR plates increases and peaks, the more readily the warm mix additive will achieve the internal friction reduction in the mixing and compacting process that we believe is necessary for successful warm mix production and construction. The data beyond the peak is most likely inaccurate as the film between the plates has, we believe, fractured and the measured torque values are



(a) (b)

Figure 19. Typical Data Output from Lubricity Test; a) Test Conducted at 257°F (125°C); b) Test Conducted at 239°F (115°C)



(a) **(b)**

Figure 20. Final Test Results of Lubricity Test; a) Torque vs Shear Rate at 221°F (105°C) and 50 micron Gap; b) Shear Rate from Normal Force Test at 221°F (105°C) and 50 μm Gap

inaccurate. Possible exceptions are the data shown for WMA-07-08 (2% Rediset) and WMA-02-08 (0.6% Evotherm 3G). For both of those additives there is a further increase in torque as the shear rates become very high.

Asphalt Mixture Tests

Each of the asphalt binders previously studied were mixed with the Trap Rock aggregates to construct a 12.5 mm Superpave mixture that was evaluated for workability/compactability. Three different devices/test methods were used; 1) Asphalt Workability Device, 2) Marshall Compaction; and 3) Gyratory Compaction.

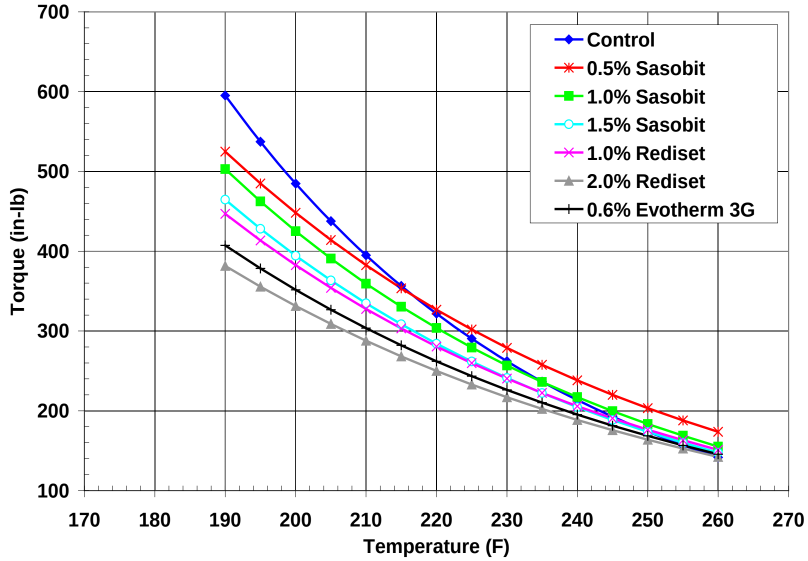
Asphalt Workability Device (AWD)

As discussed earlier, the bucket mixer type device has most often been utilized to measure the general workability of asphalt mixtures, and therefore, can be assumed to be a “baseline” for all comparisons. The workability of the mixtures was measured using a prototype HMA workability device developed at the University of Massachusetts Dartmouth (Figure 21). The Asphalt Workability Device (AWD) operates on the torque measurement principles that have been established in previous work. The AWD rotates loose HMA mixture at a constant speed (15 rpm for this study) in a bucket and separately records the resultant torque exerted on a fixed, pug mill style paddle shaft embedded into the mixture. Concurrently the surface and internal temperatures of the mixture are recorded. As the mixture cools in ambient conditions, the torque exerted on the shaft increases thereby giving an indication of the workability of the mixture at different temperatures. Based on the raw torque versus temperature data collected from the AWD, a best fit model in the form of an exponential line are fit to the data. These models are then utilized to develop a model curve plotted over the actual temperature range in which the torque data was collected. Mixtures exhibiting lower torque values are considered more workable.

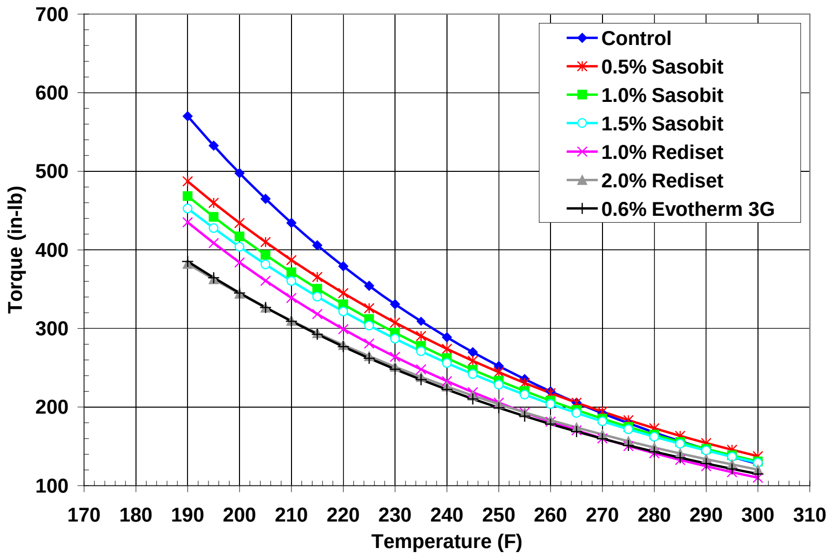
In the study, the control mixture (PG76-22) and the control mixture with different types and dosages of warm mix additives were mixed and conditioned at two different sets of temperatures. Two sets of temperatures were used to determine if any differences in workability due to lower production/mixing temperatures could be observed. The first set of mixtures were mixed at 320°F and then conditioned for two hours at 300°F before the commencement of workability testing. The second set of mixtures were mixed at 270°F and then conditioned for two hours at 260°F before workability testing.

The fitted workability models for each set of mixtures are presented in Figures 22a and b. Based on the two figures, it was observed that the greatest difference in torque between the control and mixtures containing WMA occurred at temperatures lower than those normally associated with typical HMA mixture production. For the first set of mixtures mixed at 320°F and conditioned at 300°F, the relative differences in torque measurements started to occur at approximately 240°F. Similarly, for the mixtures mixed at 270°F and conditioned at 260°F, the relative differences in torque measurements started to occur at approximately 230°F for the majority of WMA mixtures. The figures also suggest that the relative ranking of workability is reasonable where the control PG76-22 achieved the highest torque values while increasing the dosage rates of the different warm mix additives resulted in lower torque values.

Figure 21. Asphalt Workability Device Developed by the University of Massachusetts, Dartmouth



(a)



(b)

Figure 22. Asphalt Workability Device (AWD) Torque vs Temperature Curves; a) 260^{o}F (132^{o}C) Starting Temperature; b) 300^{o}F (149^{o}C) Starting Temperature

Marshall Compactor

The Marshall Compactor was also used to evaluate the general workability/compactability of warm mix asphalt. The Marshall Compactor applies a pseudo, constant energy to the asphalt mixtures during compaction through a constant weight, dropped from a constant height at a predetermined number of drops. However, it is well known that the resultant, compacted density of Marshall samples are sensitive to mixture compaction temperature, which in turn, is analogous to workability/compactability. As the mixture cools, the viscosity of the asphalt binder and mixture increases resisting the compactive force of the Marshall Compaction. Therefore, by varying the compaction temperature of different mixtures while applying the identical number of compactive blows, asphalt mixtures with higher levels of workability/compactability should result in higher densities (i.e. – lower air voids).

For the Marshall Compactor work, the asphalt mixtures were mixed at temperatures 15°F higher than the targeted compaction temperature. This was in an effort to simulate typical temperature drops associated with plant production temperatures and laydown temperatures in the field. The temperatures used in the study were as follows:

- Mixing Temperature = 315°F; Compaction Temperature = 300°F
- Mixing Temperature = 270°F; Compaction Temperature = 255°F
- Mixing Temperature = 230°F; Compaction Temperature = 215°F

Prior to compaction, the asphalt mixtures were conditioned for 2 hours at their respective compaction temperature. After the conditioning period, the asphalt mixtures were transferred into the Marshall Compaction molds and compacted to 75 blows per side in accordance with AASHTO T245, *Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus*. Once the samples had cooled, the compacted air voids of the asphalt mixtures were determined. Similar to the Asphalt Workability Device, a best fit model in the form of an exponential line was used to fit the data. These models were then utilized to develop a model curve plotted over temperature and compacted air voids. Mixtures exhibiting lower air void values at lower compaction temperatures are considered more workable and compactable.

The results for the Marshall Compactor tests are shown in Figure 23a and b. Figure 23a show the measured air voids at each of the compaction temperatures while Figure 23b shows the resultant exponential lines used to fit the data. The test results are very comparable to the Asphalt Workability Device in that the ranking is reasonable at temperatures below 260°F. The test results indicate that the untreated PG76-22 would result in the highest air void level using the same compaction energy, while the asphalt mixtures modified with the 2.0% Rediset and 1.5% Sasobit would result in the lowest air void level. The test results also show that as dosage rates of the Rediset and Sasobit warm mix additives increase, the general workability/compactability of the asphalt mixtures increased.

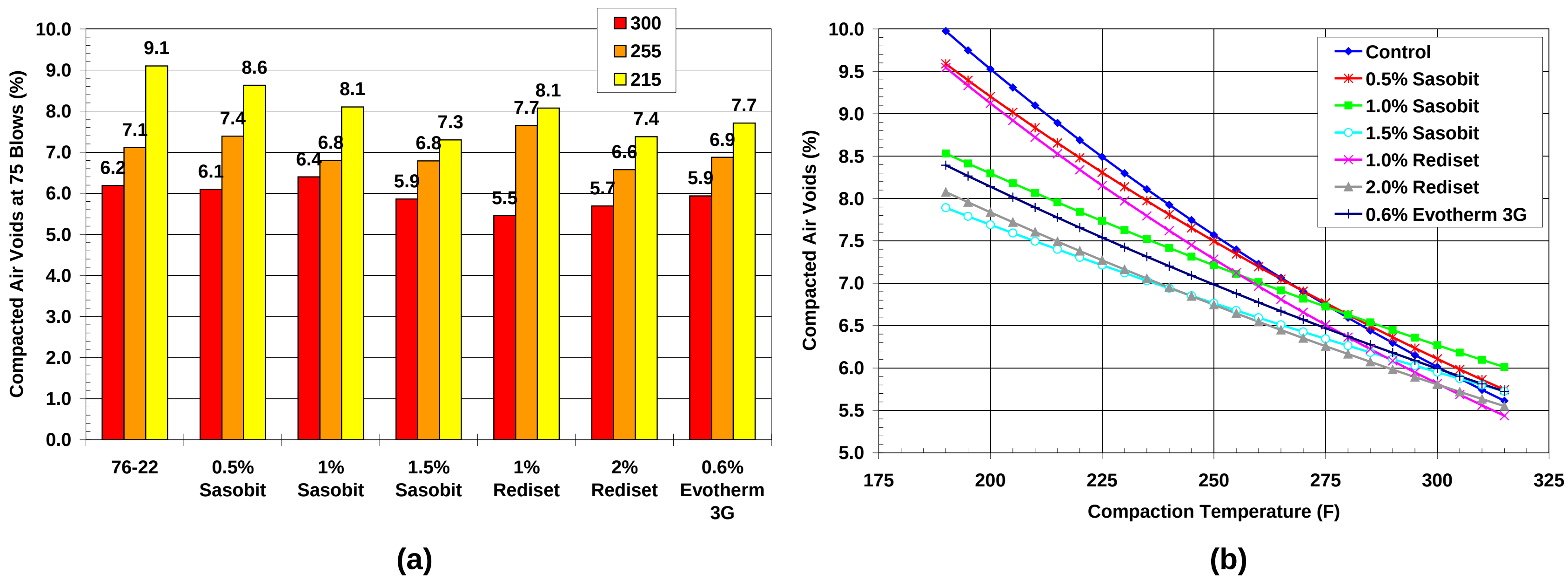


Figure 23. Marshall Compactor Results; a) Compacted Air Voids for Different Mixes; b) Exponential Fit of Compacted Air Voids vs Compaction Temperature

Gyratory Compactor

Historically, the gyratory compactor has been labeled as not being as sensitive to compaction temperature as the Marshall compactor, especially in the general ranges of typical production temperatures. However, with respect to evaluating compactability of asphalt mixtures, the gyratory compactor has the ability to measure density during compaction. Therefore, the gyratory compactor was evaluated to determine if workability/compactability rankings could be developed for warm mix asphalt mixtures. The gyratory compactor was used in two different manners. In the first set of tests, the gyratory compactor was used to compact the different asphalt mixtures to 100 gyrations at different compaction temperatures and then the respective specimen densities were measured and compared. This approach is identical in concept to the Marshall compactor tests. In the second set of tests, the gyratory compactor was set to compact to a standard density of approximately 7% air voids by compacting a predetermined weight (3,200 grams ± 5 grams) to a predetermined height of 77 mm. Using the initial and final heights along with the number of gyrations required to achieve the final height of 77 mm, the compaction rate (mm/gyration) of the different asphalt mixtures and compaction temperatures were determined. Higher compaction rates would indicate that the asphalt mixture compacted more quickly and would be more workable and compactable.

The test results for the gyratory compactor investigations are shown in Figures 24a and b. As shown in Figure 24a, the results of the 100 gyration compaction tests show minimal differences between the different asphalt mixtures and compaction temperatures at the 300°F and 260°F compaction temperatures. This was expected and confirms the general assumption that the gyratory compactor is not very sensitive to changes in compaction temperature. Although, it should be noted that the Evotherm 3G modified mixture resulted in air void levels approximately 1% lower than the average. At the 215°F compaction temperature, the air voids of the compacted samples did increase but not to the extent of the baseline PG76-22 asphalt mixture. Unfortunately, there was an unreasonable trend in the warm mix modified samples as lower dosage rates of Sasobit appeared to be more compactable.

Figure 24b shows the gyratory compactor results when evaluating the resultant compaction rate when compacting to a known density. An unusual trend in the data for all of the asphalt mixtures shows that the compaction rate decreased at the 260°F compaction temperature and then increased at the 215°F compaction temperature. This occurred for all of the asphalt mixtures evaluated. One would expect better compaction rates at the 260°F compaction temperature, even when warm mix additives are being used. Similar results were observed by Hurley and Prowell (2005) when using a vibratory compactor device. Prowell (2010) believes that this may be due to the general aging of the asphalt binder that occurs. At 265°F, the asphalt binder still undergoes aging/stiffening that is commonly overcome at 300°F simply due to a generally lower asphalt binder viscosity from elevated temperatures. At 215°F, the aging of the asphalt binder is less and allows for better compactive properties,

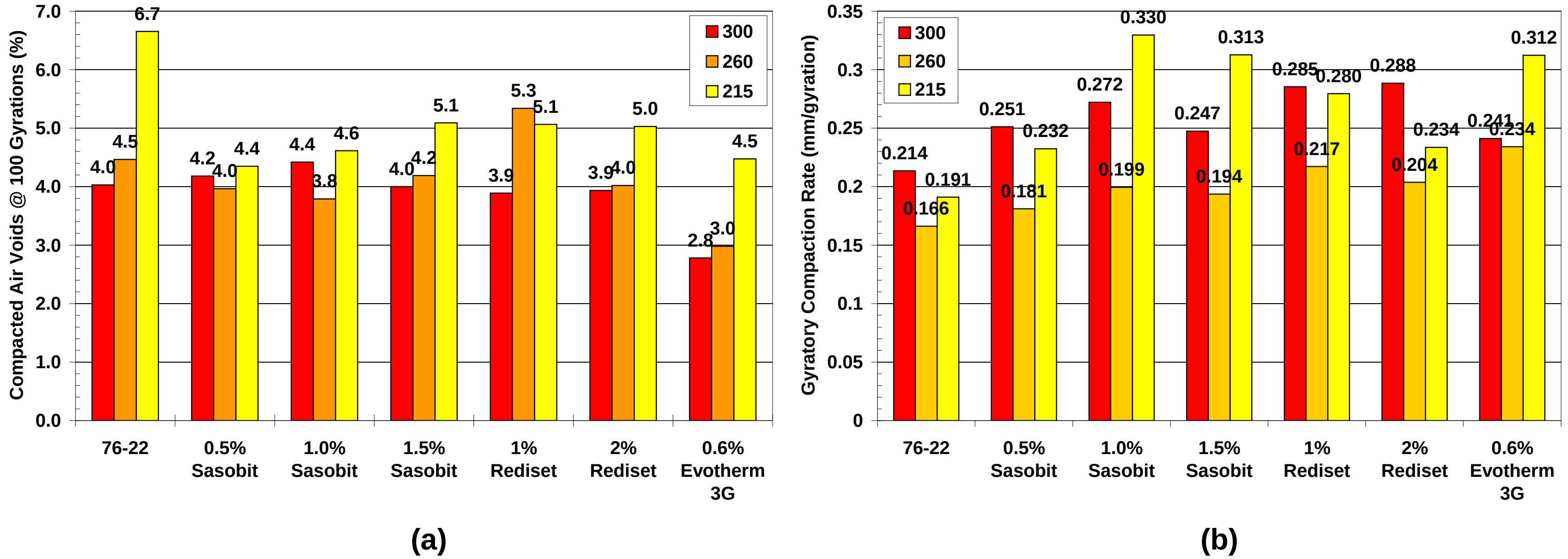


Figure 24. Gyratory Compactor Results; a) Compacted to Predetermined Effort of 100 Gyrations; b) Compacted to Predetermined Density of 7% Air Voids

especially when modified with warm mix additives. The general ranking for the compaction rate was more reasonable than the 100 gyration compaction with the PG76-22 mixture showing the lowest compaction rates, but there were still some discrepancies as shown by 1% Rediset and 1% Sasobit resulting in large compaction rates than 2% Rediset and 1.5% Sasobit, respectively.

General Discussion on Workability Results

Three different asphalt binder tests and three different asphalt mixture tests were used to evaluate the relative workability/compactability of different warm mix additives preblended in a PG76-22 asphalt binder. Each test method/parameter provides a general ranking of the workability/compactability of the different warm mix asphalt mixtures. It should be noted that although some of the asphalt binder test procedures did not provide mixing and compaction temperatures commonly observed during warm mix asphalt production (i.e. – Rotational Viscosity and Casola Method), the procedures did provide a general ranking of the mixing/compaction temperatures which is an indicator of the general workability/compactability.

When establishing the final rankings of warm mix additives/test procedures, it is important to note that as the different asphalt binders and mixes cool, there is substantial variation in the rate at which temperature impacts the indicator of performance. At temperatures of 250^{o}F and higher, the asphalt binder/mixture behavior is rather closely grouped, as shown in Figures 22 and 23. However, as the temperature drops to temperatures of 220^{o}F and lower, some additives exhibit a noticeable increase in the resistance to workability/compaction. Therefore, it is important to identify the ability of warm mix asphalt to maintain its effectiveness as the temperature decreases. Although specifications may be able to dictate the temperatures at which mixes should be produced, once the asphalt mixture leaves the plant, haul times and weather can raise havoc with final compaction temperatures. Therefore, any test method used to provide a general ranking of warm mix workability/compactability should be done so over a range of reducing, lower temperatures to assess the “sustainability” of workability/compactability over that lower temperature range.

Summary of Workability Test Procedure Results

Three asphalt binder test procedures were used to recommend mixing and compaction temperatures (Rotational Viscosity and Casola Method) and low temperature workability (Lubricity Test). The general rankings of the asphalt binder tests are shown Table 11. The rankings of the Rotational Viscosity and Casola Method were not rational as the test procedures should have ranked the PG76-22 the worst (i.e. – value of 7). It should also be noted that both the Rotational Viscosity and Casola Method provided unrealistically high mixing and compaction temperatures, not commonly associated with warm mix asphalt production. Meanwhile, the Lubricity Test provided a rational ranking of the additives where the PG76-22 was rated low (second worst) and the workability increased with increasing dosage rate.

Three asphalt mixture test procedures were also evaluated to determine the general workability/compactability of the different warm mix modified mixtures. The general rankings are again shown in Table 11. It should be noted that only the compaction rate from the gyratory compactor was used for rankings. The results of the mixture tests show that the Asphalt Workability Device torque measurements and Marshall Compactor density rankings compared favorably with one another, with the Lubricity Test and Asphalt Workability Device showing almost identical rankings of the warm mix modified mixtures. From an additive perspective, the rankings for different methods/tests indicate the 2% Rediset and 0.6% Evotherm 3G were the best performers with the 1.5% Sasobit showing up favorably on some of the tabulations.

Table 11 – Final Test Procedure Ranking of Warm Mix Additives

Binder Type	Rotational Viscosity	Casola Method	Lubricity Test @ 221°F	Asphalt Workability Device @ 215°F	Marshall Compactor @ 215°F	Gyratory Compaction Rate @ 215°F
PG76-22	5	1	6	7	7	7
+ 0.6% 3G	6	1	1	2	3	3
+ 0.5% Sasobit	4	5	7	6	6	6
+ 1.0% Sasobit	2	4	5	5	4	1
+ 1.5% Sasobit	7	6	4	4	1	2
+ 1.0% Rediset	3	3	3	3	5	4
+ 2.0% Rediset	1	2	2	1	2	5

1 – Best; 7 - Worst

Summary and Conclusions for Workability Assessment

In the presented study, different warm mix additives at different dosage rates were preblended in the identical PG76-22 asphalt binder and evaluated for workability/compactability. Based on the data and information gathered during the study, the following conclusions were made:

- Both the Rotational Viscosity and Casola Method resulted in unrealistically, high mixing and compaction temperatures. This is most likely due to some of the additives not influencing the general viscosity properties of the asphalt binder (i.e. – Evotherm 3G), as well as the Casola Method artificially restricting the minimum mixing and compaction temperature attainable due to the equations used in their respective calculations (Equations 1 and 2). Future revisions of the Casola Method equations may be required for the application of asphalt binders modified with warm mix additives.
- The Lubricity Test for asphalt binders compared favorably to the Asphalt Workability Device and the Marshall Compactor mixture tests with respect to ranking the workability/compactability of the asphalt binders. This is most likely due to the fact that the Lubricity test simulates more realistic film thicknesses (50 μm) when compared to conventional asphalt binder test procedures (i.e. – Rotational Viscosity and Casola Method via the Dynamic Shear Rheometer). Therefore, it is proposed that the Lubricity Test can be used for warm mix additive selection and dosage rate determination when preblended with asphalt binders. The testing can be accomplished during the warm mix asphalt mix design phase, as well as possibly a QC tool during mixture production.
- The gyratory compactor seemed to be somewhat insensitive at compaction temperatures between 300 and 255^{o}F, as shown in the compacted densities. However, when comparing the compaction rate data, there was a clear difference in the rate of compaction as defined by the height per gyration (mm/gyration) to achieve a specified density. Similar results were found in earlier studies at the National Center for Asphalt Technology work with the vibratory compactor. Unfortunately, the rankings of the gyratory compaction rate were not reasonable with 1% Rediset and 1% Sasobit providing better workability/compactability than 2% Rediset and 1.5% Sasobit, respectively.
- The Marshall Compaction method and the Asphalt Workability Device provided rankings of asphalt mixture workability that were consistent with field observations and rational thinking. This indicates that the Marshall Compaction procedure proposed in the study may be used to evaluate different warm mix additives and dosage rates during the warm mix asphalt mixture design phase. Further refinement to expedite the Marshall Compaction procedure would be required for use as a production QC tool.
- Although it was not the main goal of the study, general rankings of the warm mix additives, with respect to workability/compactability, can be concluded. Overall, the asphalt mixtures using the 2% Rediset and 0.6% Evotherm 3G provided the best workability/compactabality, with the 1.5% Sasobit resulting in higher rankings in some of the different test methods.

PHASE 4 – RUTTING POTENTIAL OF WARM MIX ASPHALT

The term warm mix asphalt (WMA) refers to technologies and systems that allow for the substantial reduction in production and compaction temperatures of hot mix asphalt. The original intent of utilizing WMA was to provide better workability and compaction of asphalt mixtures. In turn, a better compacted asphalt pavement should also enhance its general performance. It is well known that asphalt pavements compacted to better densities often have superior fatigue and rutting performance. A thorough analysis of this can be found in detail in NCHRP Report 567, *Volumetric Requirements for Superpave Mix Design*.

The implementation and use of WMA may create potential issues as well. The reduced oxidative aging of the asphalt binder during production may increase the asphalt's susceptibility to rutting. A number of laboratory studies have indicated that the testing conducted on hot mix asphalt (HMA) and warm mix asphalt (WMA) using identical materials and mixture designs resulted in the WMA achieving a lower resistance to permanent deformation than the HMA specimens. A number of laboratory studies have clearly indicated that for a majority of WMA additives/technologies, a decrease in rutting resistance is observed. Recent work under NCHRP Project 9-43, *Mix Design Practices for Warm Mix Asphalt*, has indicated that a reduction in production temperature of approximately30^{o}C (54^{o}F) can reduce the high temperature PG grade by 3^{o}C, or one half of the high temperature grade (Bonaquist, 2009). A lower high temperature PG grade, in combination with increased effective asphalt contents due to lower asphalt absorption, would create asphalt mixtures that may be more prone to rutting.

Asphalt Binder and Mixture Properties

The asphalt binder and mixture design properties used in the study were identical to those shown earlier in Figure 17 and Table 10.

Permanent Deformation Testing

Asphalt mixture performance tests were conducted on asphalt mixtures produced in the laboratory. The asphalt mixture was produced and conditioned at different temperatures following the sequencing below:

- Mixing Temperature = 325 to 335^{o}F; Condition and Compaction Temperature = 310 to 320^{o}F;
- Mixing Temperature = 265 to 275^{o}F; Condition and Compaction Temperature = 250 to 260^{o}F; and
- Mixing Temperature = 225 to 235^{o}F; Condition and Compaction Temperature = 210 to 225^{o}F

After mixing, all loose material was conditioned for 2 hours at the compaction temperature specified above. All performance testing was conducted on samples targeted for densities between 6 to 7% air voids.

Mixture Stiffness

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79*, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The data was collected at three temperatures; 4, 20, and 45^{o}C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz.

The collected modulus values of the varying temperatures and loading frequencies were used to develop Dynamic Modulus master stiffness curves and temperature shift factors using numerical optimization of Equations 3 and 4. The reference temperature used for the generation of the master curves and the shift factors was 20^{o}C.

$$\log|E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log \omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \quad (3)$$

where:

$|E^*|$ = dynamic modulus, psi
ω_r = reduced frequency, Hz
Max = limiting maximum modulus, psi
δ, β, and γ = fitting parameters

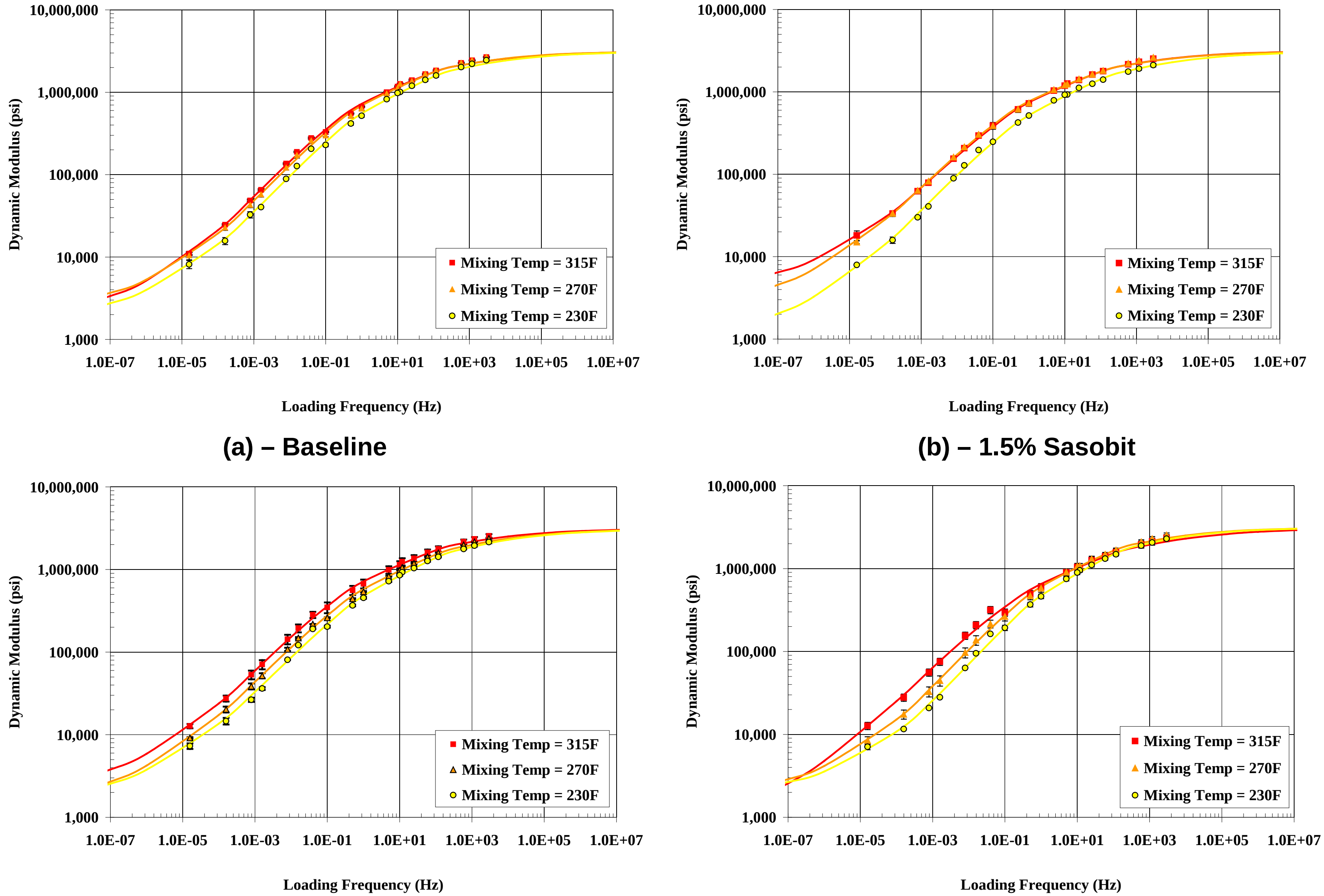
$$\log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (4)$$

where:

a(T) = shift factor at temperature T
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

Master stiffness curves for the baseline (no WMA additive) and the WMA additives blended at manufacturer's recommendation dosages are shown in Figure 25. There is an obvious decrease in mixture stiffness as the mixing temperature decreased, especially at the higher temperatures, regardless of WMA additive and dosage rate.

To further evaluate the general change in mixture performance, the dynamic modulus measured at each test temperature was averaged and compared to average dynamic modulus at the reduced temperatures. The resultant plots are shown in Figure 26. In Figure 26a, it is observed that minimal changes occur at the 4^{o}C test temperature until the mixing temperatures are reduced to 230^{o}F. And even at that temperature, there is only a 14% reduction in mixture stiffness, which would be beneficial in reducing the cracking potential of the asphalt mixture. At the 20^{o}C test temperature (Figure 26b), only a 5% reduction in modulus was found when reducing the mixing temperature to



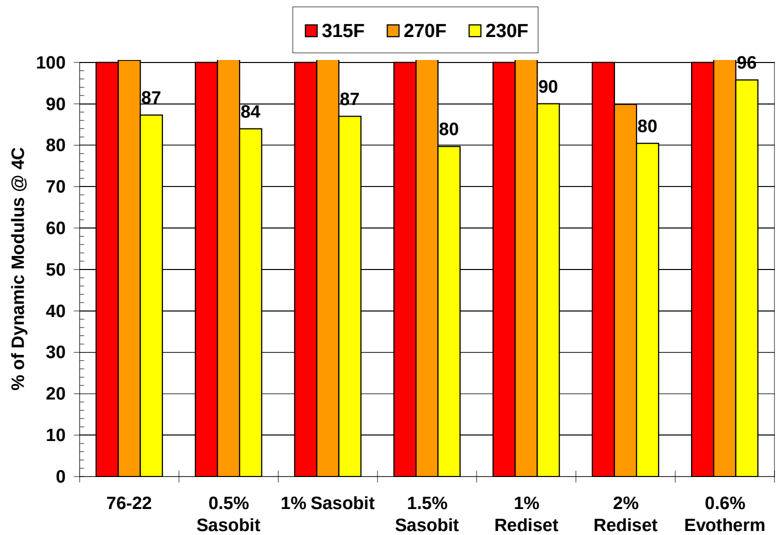
(a) – Baseline

(b) – 1.5% Sasobit

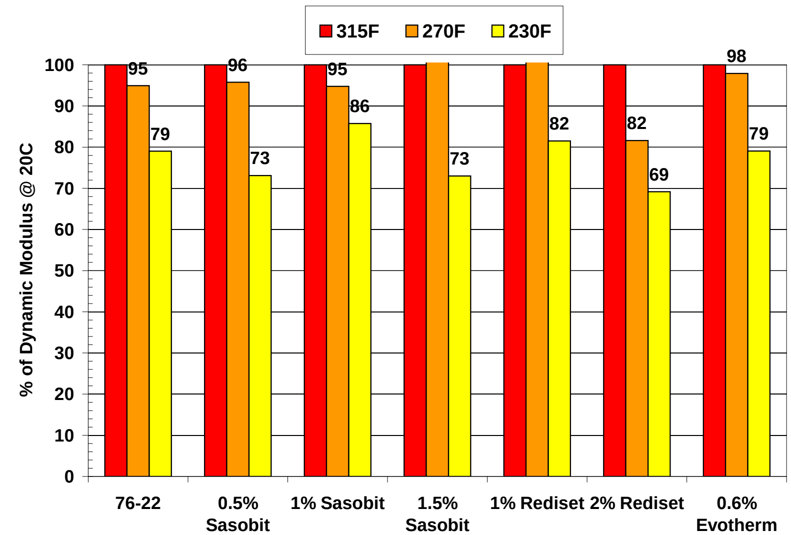
(c) – 2.0% Rediset

(d) – 0.6% Evotherm

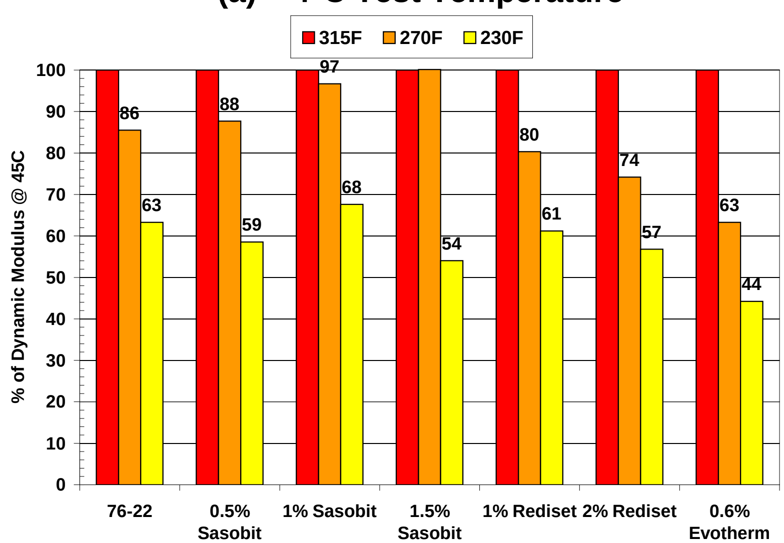
Figure 25. Master Stiffness Curves of HMA and WMA Mixtures at Varying Mixing and Compaction Temperatures



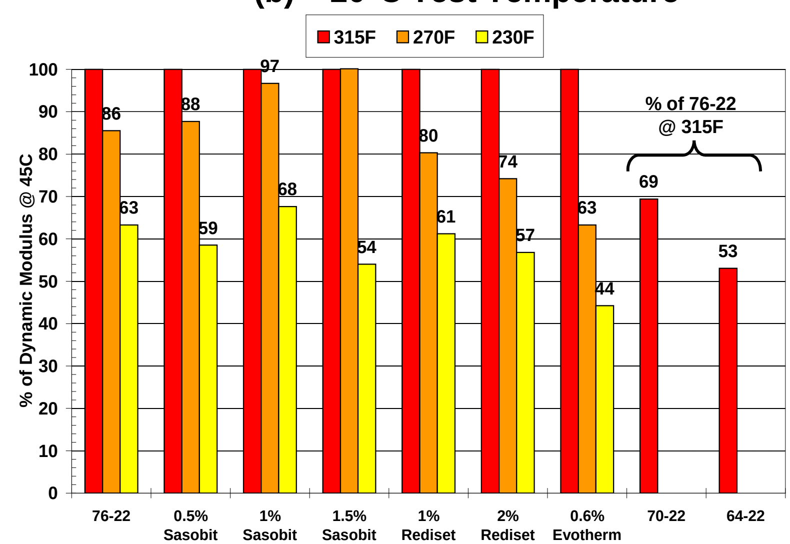
(a) – 4^{o}C Test Temperature



(b) – 20^{o}C Test Temperature



(c) – 45^{o}C Test Temperature



(d) – 45^{o}C Test Temperature

Figure 26. Reduction in Average Dynamic Modulus at Different Test Temperatures and Mixing Temperatures

270°F and a 23% reduction in modulus when reducing the mixing temperature to 230°F. A larger reduction in mixture modulus was found at the 45°C test temperature (Figure 26c), where a 16% reduction in modulus occurred at the 270°F and a 42% reduction in modulus occurred at the 230°F test temperature. Additional testing was conducted using a PG70-22 and PG64-22 using the identical test procedure, although the asphalt mixtures were only mixed at 315°F. The purpose of this was to compare the reduction on modulus of the PG76-22 asphalt binder with the various WMA additives to the PG70-22 and PG64-22 and determine if a particular drop in mixing temperature corresponded to a reduction in PG grade. Minimal differences were found at the 4 and 20°C. However, at the 45°C test temperature, the reduction in dynamic modulus at the lower mixing temperatures began to look similar to the lower PG grade binders (Figure 26d).

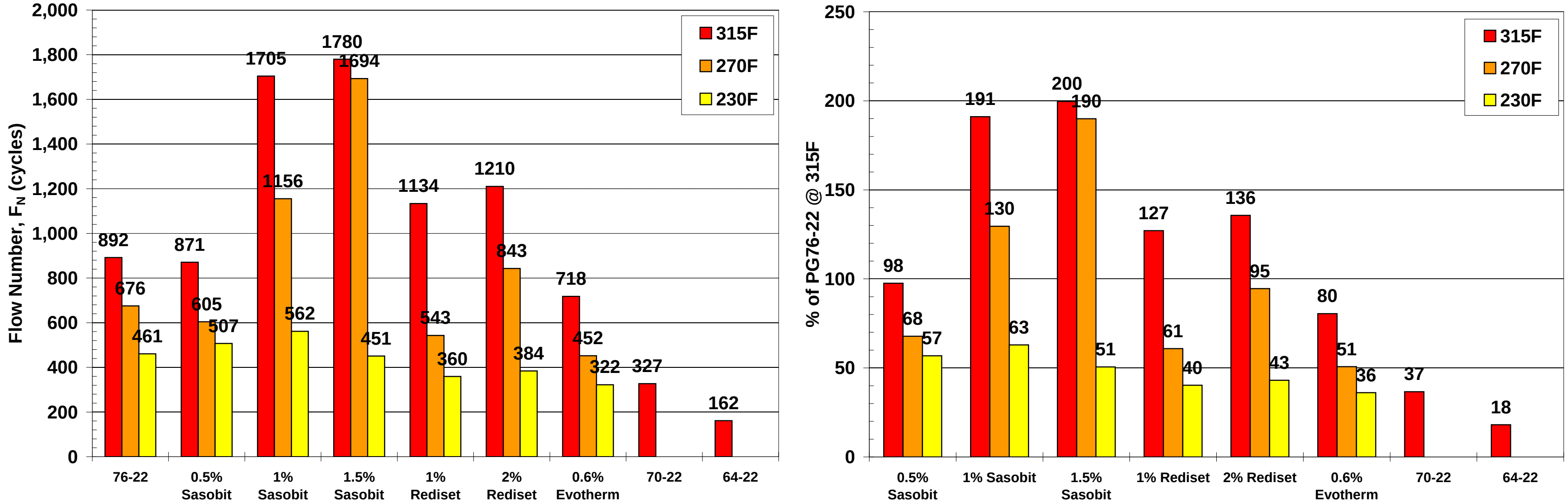
On average, the dynamic modulus test results indicated that a 30 to 35% reduction in dynamic modulus at 45°C is equivalent to dropping from a PG76-22 to a PG70-22. Meanwhile, a 45 to 50% reduction in dynamic modulus is approximately equivalent to reducing the PG grade from a PG76-22 to a PG64-22.

Repeated Load (Flow Number)

Repeated load permanent deformation testing was measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79*, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 54.4°C, which corresponds to New Jersey's average 50% reliability high pavement temperature at a depth of 25 mm according the LTPPBind 3.1 software. These testing parameters (temperature and applied stress) conform to the recommendations currently proposed in NCHRP Project 9-33, *A Mix Design Manual for Hot Mix Asphalt*. Testing was conducted until a permanent vertical strain of 5% or 10,000 cycles was obtained.

The Flow Number results for the mixtures are shown in Figure 27. The test results in Figure 27a clearly show that most of the WMA additives, when at normal mixing temperatures (315°F) actually increase the Flow Number. However, as the mixing temperature decreased, the Flow Number decreased as well, except for the Sasobit WMA which was able to maintain Flow Number values at the 270°F mixing temperature at the 1.0% and 1.5% dosage rates. The Flow Number results of the PG70-22 and PG64-22, mixed at normal HMA temperatures, had significantly lower Flow Number values, although the PG70-22 results were similar to the different WMA mixtures at 230°F mixing temperature.

Figure 27b illustrates the percent of Flow Number when compared to the PG76-22 (baseline) mixture at a mixing temperature of 315°F. The test results indicate that a 60% reduction in the Flow Number equates to approximately a one grade drop in PG grade (from a PG76-22 to a PG70-22). An 80% reduction equated to dropping the PG grade from a PG76-22 to a PG64-22.



(a) – Measured Flow Number Values **(b) Percent of PG76-22 @ 315^{o}F Mixing Temperature**

Figure 27. Flow Number Test Results

Hamburg Wheel Tracking

Hamburg Wheel Tracking tests were conducted in accordance with AASHTO T324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. Test specimens, compacted between 6.0 to 7.0% air voids, were conditioned for 4 hours and tested dry at a test temperature of 50°C. Testing was conducted until 20,000 cycles or until 12.5mm of rut depth was reached. The test results are shown in Figure 28. Since many of the baseline mixes went out past 20,000 cycles before achieving 12.5mm of rutting, a percent reduction could not be accurately determined. However, Figure 28 clearly indicates that as the mixing temperature decreases, so does the resistance to permanent deformation in the dry Hamburg Wheel Tracking.

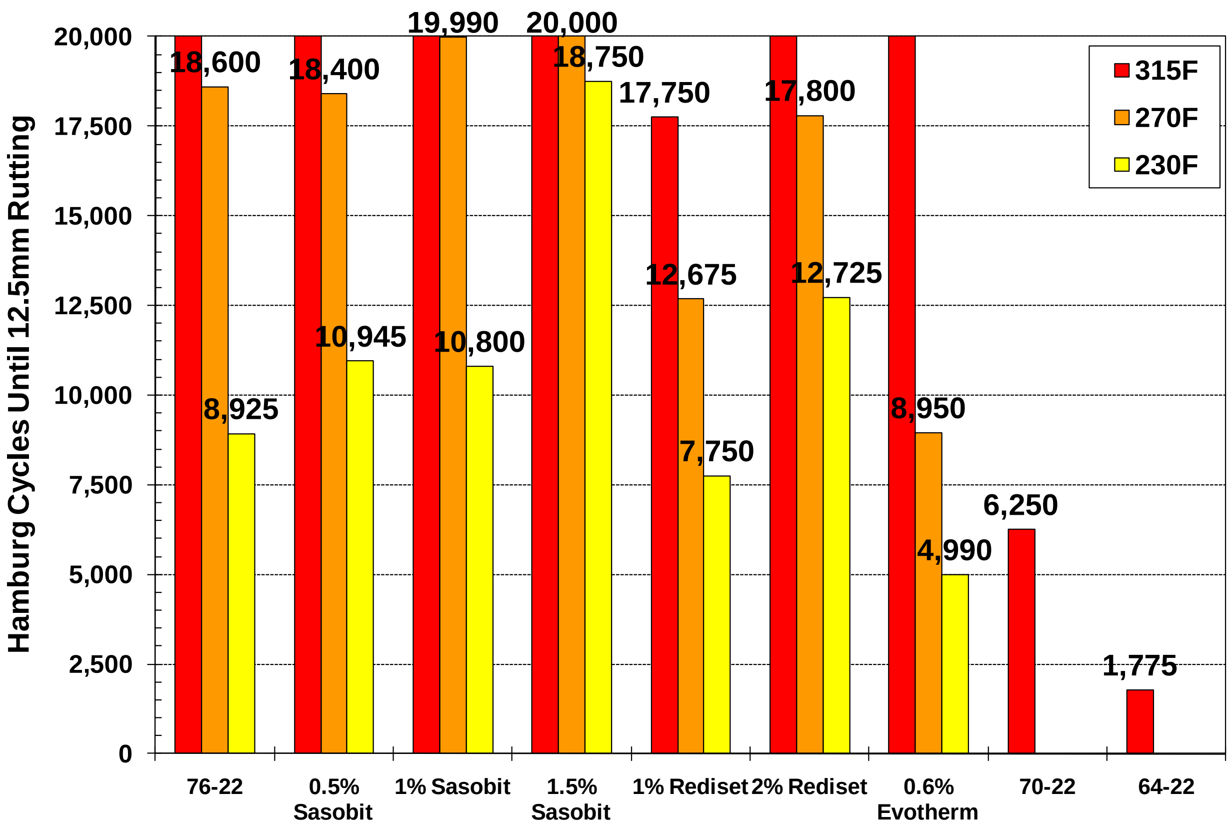


Figure 28. Dry Hamburg Wheel Tracking Results

Summary of High Temperature Performance

The high temperature performance of HMA and WMA mixtures were evaluated to determine their response as mixing temperature decreased from normal (315°F) to temperatures representing warm mix asphalt (270 and 230°F). It is evident from the test data that the mixture stiffness and resistance to permanent deformation decreases as mixing temperature decreases, although it is not proportional for all WMA additives. For example, the 1.0 and 1.5% Sasobit mixtures achieved high temperature stiffness and permanent deformation performance that exceeded the baseline mixture even when mixing temperatures were reduced to 270^{o}F. Therefore, to ensure mixture stability is not a problem, state agencies may need to specify minimum production temperatures to ensure rutting is not an issue. However, as the test data suggests, mixture performance will vary depending on the WMA additive employed and dosage rate used.

The high temperature test data developed in the study also indicates that test procedures like the AMPT can be used to prescreen the mixture to suggest minimum mixing (production) temperatures are not exceeded where stability problems may occur. Figure 29 shows the percent reduction of the E* at 45^{o}C (Figure 29a) and reduction of Flow Number at 54^{o}C (Figure 29b) due to the reduction in production temperature. The laboratory data developed during this study was averaged for all mixes for plotting purposes and is compared to field data collected from New Jersey and New York field projects conducted by the authors (discussed in further detail later in the report). The trendlines shown in the figures clearly show a reduction in both the mixture stiffness at 45^{o}C and Flow Number at 54^{o}C for the mixtures tested. The test data also suggests that a 35% reduction in dynamic modulus at 45^{o}C and 60% reduction in Flow Number essentially drop the performance of the asphalt mixture equivalent to one performance grade. Based on the trendlines shown in Figure 29, this would correspond with reduction in temperature of approximately 80 to 85^{o}F and illustrates that an allowable percent reduction in mixture performance can be used as guidance when specifying minimum production temperatures of WMA to ensure stability.

Under NCHRP Project 9-33, *A Mixture Design Manual for HMA*, a Flow Number criteria is established to minimize rutting potential of asphalt mixtures and is shown in Table 12. The Flow Number criteria in Table 12 can be used in conjunction with a Percent Reduction methodology to ensure the rutting performance of WMA mixtures does not become detrimental. A general methodology would be as follows:

1. Determine Flow Number characteristics of HMA or WMA at normal production temperatures (i.e. – 315F or above)
2. Use general relationship shown in Figure 29, or state specific developed relationship, to estimate allowable reduction of production temperature before potential rutting issues.

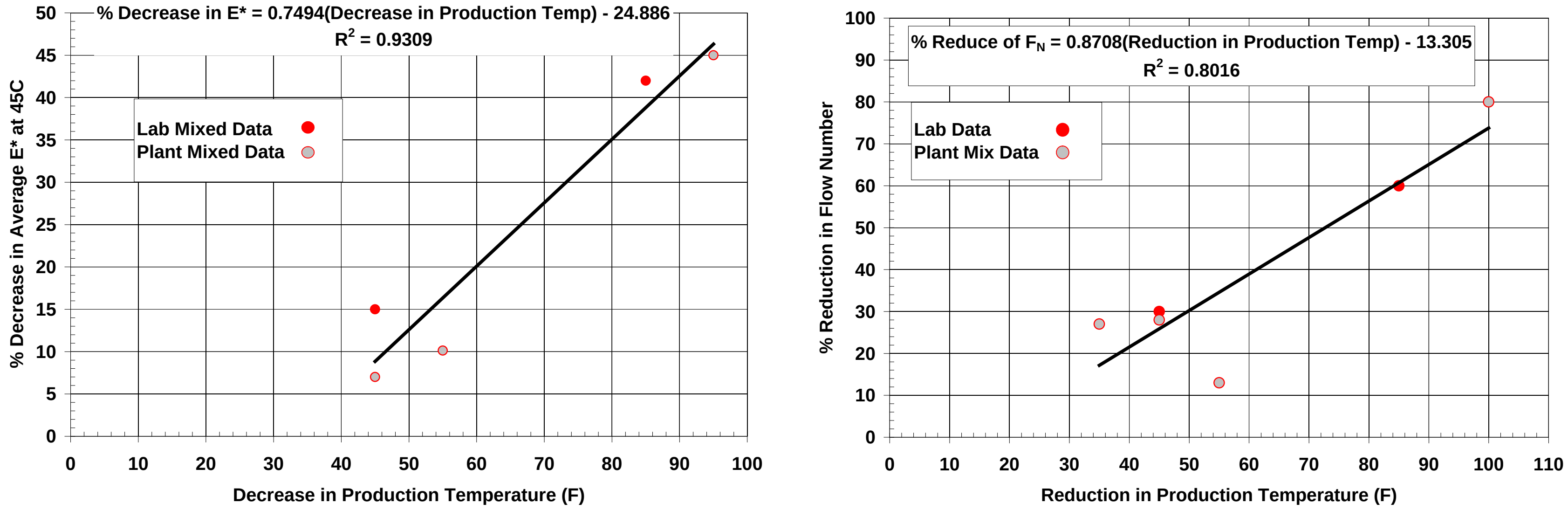
For example, a WMA mixture (with or without RAP, foamed or additive, etc.) is designed for 10 to <30 Million ESALs and produced at normal production temperatures, resulting in a Flow Number of 250 cycles. For this traffic level, based on NCHRP 9-33, a minimum Flow Number of 190 cycles is recommended. This results in a Percent Reduction of 24% from the HMA value of 250 cycles [(250-190)/150]x100. Using Figure 29b, it is recommended not to reduce the production temperature by more than approximately 40^{o}F. The same methodology could also be used for dynamic modulus test results, although current minimum specifications are not available.

Table 12 – Flow Number Specifications

Traffic Level, *Million ESALs*	Minimum Flow Number, *Cycles*
	NCHRP 9-33 Recommended
< 3	---
3 to < 10	53
10 to < 30	190
> 30	740

Overall, the permanent deformation testing clearly indicates that asphalt mixtures will undergo a reduction in mixture stiffness at high temperatures due to the lower production temperatures associated with warm mix asphalt. Based on the results generated in the study, it would appear that asphalt binders typically used by the New Jersey Department of Transportation (NJDOT) will undergo a one performance grade reduction when production temperatures are reduced by approximately 80^{o}F (i.e. – normal production temperature = 325^{o}F; warm mix asphalt production = 245^{o}F). Based on this phenomenon, the following are recommended:

1. The NJDOT should restrict the drop in normal production temperature to 50 to 60^{o}F. This drop in temperature would still provide a reduction in energy consumption and emissions, while still providing enough oxidative aging.
2. If an asphalt supplier/contractor would like to reduce production temperatures lower than 80^{o}F, a “bump” in the high temperature performance grade of the asphalt binder should be required to ensure rutting resistance of the asphalt mixture is maintained.



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

Figure 29. Percent Reduction in Mixture Performance vs Reduction in Production (Mixing) Temperature

General Fatigue Performance of WMA

Although it would appear that the production of warm mix asphalt (WMA) may result in asphalt mixtures are have a greater potential for permanent deformation, in theory, the production of WMA may actually result in a more fatigue resistant asphalt mixture. It is hypothesized that the reduction in production temperature may help to increase the asphalt mixture's fatigue performance by:

1. Reducing oxidative aging of base asphalt binder – The asphalt binder continues to oxidize and stiffen under elevated temperatures. However, with WMA, the reduced production temperatures may help to minimize the oxidative aging/stiffening of the asphalt binder, resulting in lower binder stiffness.
2. Reduces polymer degradation at higher mixing and compaction temperatures – higher production temperatures have been known to possibly breakdown the polymer networks in the asphalt binder. Therefore, lower production temperatures would have a better chance of maintaining the polymer networking and reinforcement.
3. Reduces asphalt binder absorption – The reduced production temperature generally increases the asphalt binder's viscosity, which in turn limits the amount of asphalt binder absorbed in the aggregates of the asphalt mixture (Figure 30). Lower absorption results in an increase in the effective asphalt binder content, which has been known to increase the general fatigue resistance and durability.

<u>Overlay Tester (TxDOT Tex-248-F)</u>

For this study, the Overlay Tester was used to measure the fatigue resistance of the WMA mixtures. The Overlay Tester, described by Zhou and Scullion (2005), has shown to provide an excellent correlation to field cracking for both composite pavements as well as flexible pavements. Figure 30 shows a picture of the Overlay Tester used in this study. Sample preparation and test parameters used in this study followed that of TxDOT Tex-248-F testing specifications. These include:

- 25^{o}C (77^{o}F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in Initial Load.

The test results for the Overlay Tester testing are shown in Figure 31. The test results shown in Figure 31 clearly indicate that the reduction in mixing temperatures increases the fatigue resistance of the WMA mixtures. Figure 31 also shows that not all WMA additives result in similar fatigue resistance. The test data suggests that WMA additives like Rediset and Evotherm may actually help in increasing the fatigue resistance while Sasobit appears to have little effect.

Figure 30. Overlay Tester Used in Study

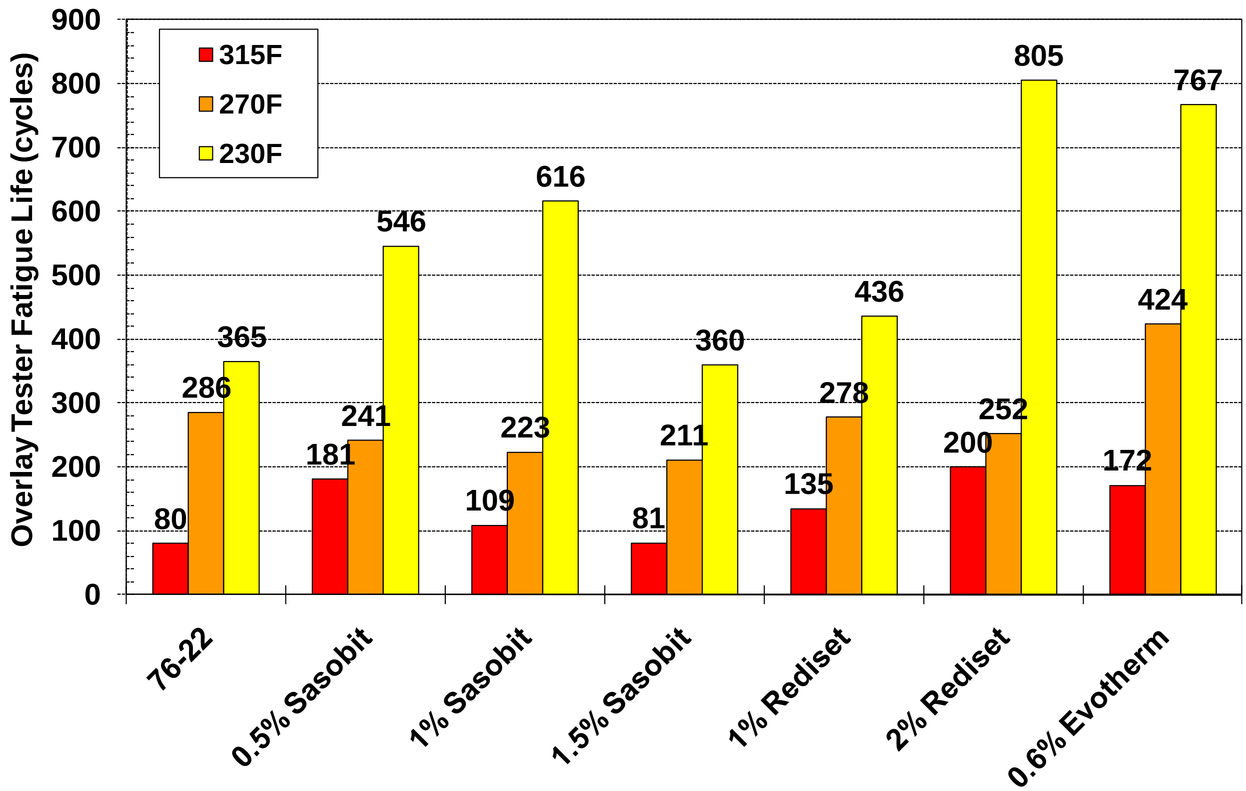


Figure 31. Overlay Tester Results for HMA and WMA Mixtures at Varying Mixing Temperatures

It should be noted that typically fatigue cracking is a pavement distress that occurs later in the pavement's life, and generally results after some period of aging. The magnitude of differences shown in Figure 31 may not be as severe after a few years of aging and service life. However, in areas where reflective cracking in composite pavements is an issue and cracking typically initiates within the first few years after placement, Figure 31 would suggest a definite benefit in using WMA.

PHASE 5 – CHANGE IN ASPHALT BINDER GRADE DUE TO WMA MODIFICATION

Throughout the research study, asphalt mixtures produced in the laboratory and also during the field trials, were sampled for not only mixture testing, but also to determine what happens to asphalt binder performance grade during WMA production. As mentioned earlier, it is hypothesized that the warm mix asphalt production process may modify the asphalt binder performance grade due to the reduction in oxidative aging and possible reduction in polymer degradation from excessive heating. To evaluate if this does take place, hot mix asphalt and warm mix asphalt were sampled and brought back to the laboratory for extraction, recovery, and performance grading.

Rowan University was subcontracted to conduct the extraction, recovery, and performance grading of the asphalt binders. The asphalt binders were extracted and recovered in accordance with AASHTO T319, *Quantitative Extraction and Recovery of Binders from Asphalt Mixtures.* This method of asphalt binder extraction and recovery was developed by researchers from WRI during the Strategic Highway Research Program (SHRP), and is recommended for use in conjunction with physical or chemical property testing of the recovered binders. The continuous PG grade of the recovered binders was compared to assess the general degree of aging that occurs due to changes in production temperatures.

The results of the extraction, recovery, and PG grading are shown in Table 13. Five different WMA research efforts were evaluated during Phase 5; two laboratory efforts and three plant produced (field) efforts. Unfortunately, the test results were inconclusive as to the general trend in asphalt binder performance grade and contradicted some expected results. For example, the Rt 18 SMA with a PG76-22 also contained Sasobit, which is known to increase the asphalt binder stiffness. When evaluating the asphalt binder from the mixture produced at 310^{o}F, the resultant PG grade was a PG70-28, which is a grade lower than the original PG grade of the asphalt binder used (PG76-22). Then, when the mixture was produced at 270^{o}F, 40^{o}F lower than the previous production temperature, the PG grade increased back to the original grade of PG76-22. Similar conflicting results can also be seen in the test results from the Laboratory Moisture Sensitivity mixtures and the I78 Evotherm project. However, the results of the I78 project may be skewed due to the addition of RAP in the asphalt mixture.

Table 13 – Extracted, Recovered, and Resultant Performance Grade of HMA and WMA Asphalt Binders

Project	Original PG Grade Used	Mixing Procedure	Continuous Grade After Extraction/Recovery	PG Grade After Extraction/Recovery
Laboratory Rutting and Fatigue Performance of WMA	PG76-22	Lab Mixed at 315F and conditioned for 2 hours at 300F	PG89.15-26.8 (23.6) PG85.54-29.92	PG88-22 PG82-28
		Lab Mixed at 270F and conditioned for 2 hours at 250F	PG80.99-28.27 (28.4)	PG76-28
		Lab Mixed at 245F and conditioned for 2 hours at 230F	PG81.4-27.09 (20.3)	PG76-22
Laboratory Moisture Sensitivity Performance of WMA with Wet and Dry Aggregates	PG76-22	Lab Mixed at 315F and conditioned for 2 hours at 300F (0% Moisture)	PG82.08-27.66 (20.3)	PG82-22
		Lab Mixed at 315F and conditioned for 2 hours at 300F (3% Moisture)	PG82.96-27.76 (20.6)	PG82-22
		Lab Mixed at 315F and conditioned for 2 hours at 300F (6% Moisture)	PG85.04-26.6 (23.9)	PG82-22
		Lab Mixed at 270F and conditioned for 2 hours at 250F (0% Moisture)	PG88.95-26.08 (22.5)	PG88-22
		Lab Mixed at 270F and conditioned for 2 hours at 250F (3% Moisture)	PG84.15-27.15 (21.4)	PG82-22
		Lab Mixed at 270F and conditioned for 2 hours at 250F (6% Moisture)	PG80.54-27.8 (19.6)	PG76-22
Rt 38 - Sasobit used at 0.8% with reduced SBS polymer to produce "compactable" PG76-22 - 15% RAP	PG76-22	Plant Produced at 315F - Normal PG76-22 Binder + 15% RAP	PG80.54-27.82 (19.6)	PG76-22
		Plant Produced at 315F - Sasobit modified PG76-22 Binder + 15% RAP	PG75.04-27.24 (18.2)	PG70-22
		Plant Produced at 270F - Normal PG76-22 Binder + 15% RAP	PG80.87-23.21 (21.8)	PG76-22
I78 - 0.6% Evotherm with SBS modified PG76-22 + 25% RAP	PG76-22	Plant Produced at 315F - Normal PG76-22 Binder + 25% RAP	PG83.75-27.52 (19.57) PG88.74 - (25.1)	PG82-22 PG88-
		Plant Produced at 290F - 0.6% Evotherm in PG76-22 + 25% RAP	PG82.75-29.08 (21.9)	PG82-28
		Plant Produced at 270F - 0.6% Evotherm in PG76-22 + 25% RAP	PG78.86-29.95 (17.3) PG81.94- (20.3)	PG76-28 PG76-
Rt 18 - 1.5% Sasobit PG76-22 in SMA - No RAP	PG76-22	Plant Produced at 310F - Sasobit Modified PG76-22 Binder + 0% RAP	PG72.75-30.24	PG70-28
		Plant Produced at 270F - Sasobit Modified PG76-22 Binder + 0% RAP	PG80.06-26.83 (20.2)	PG76-22

PHASE 6 – DOES BLENDING OF RAP AND VIRGIN WMA OCCUR?

One of the major concerns with the incorporation of RAP in hot mix asphalt is the degree of blending between the virgin asphalt binder and the asphalt binder on the RAP aggregate (i.e. – oxidized binder). A lack of blending creates an under-asphalted condition as a lack of RAP binder is mobilized resulting in the virgin asphalt binder coating the oxidized binder on the RAP aggregate, as well as the virgin aggregate. This ultimately reduces the film thickness on the virgin aggregates, reducing the mixtures durability and fatigue resistance. This reduction in fatigue resistance has been verified by Bennert (2009) on a number of NJDOT projects incorporating higher percentages of RAP (up to 25%) in the surface course (Figure 32). Recent work conducted by Rowan University (Mehta, 2009) has indicated that the expected range of working or mobilized RAP binder is probably between 50 to 80%. However, it should be noted that the degree of blending is a function of the type of asphalt plant (i.e. – mixing conditions), production temperature, time of exposure at elevated temperatures, and stiffness of the RAP asphalt binder. With production temperature and time of exposure at elevated temperatures being critical factors in the degree of blending between the RAP and virgin asphalt binders, it is logical to assume that a reduction in production temperature, as is done with warm mix asphalt, may further reduce the degree of blending.

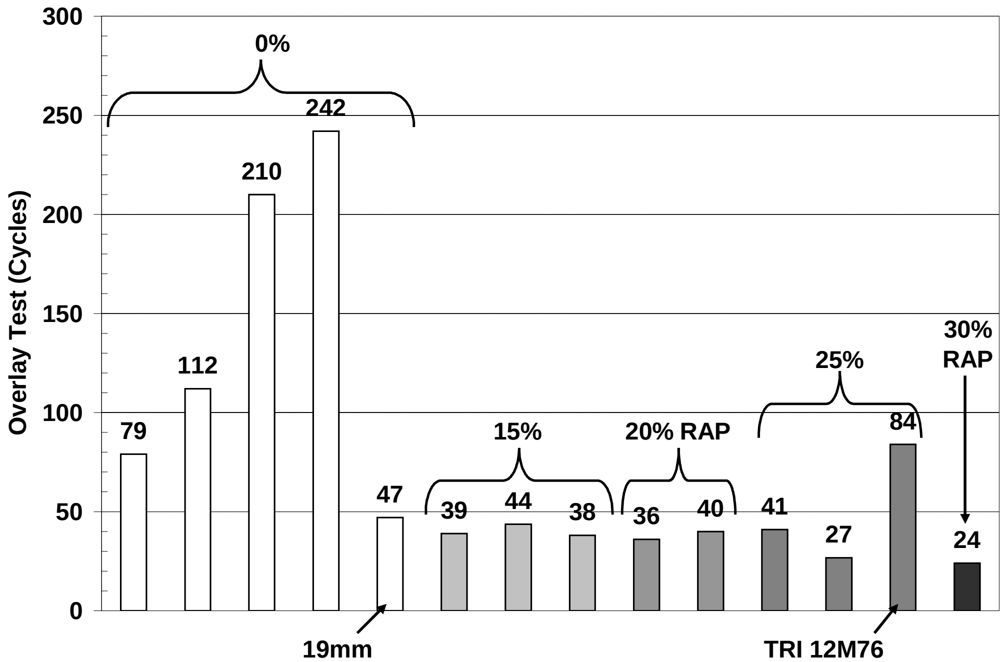


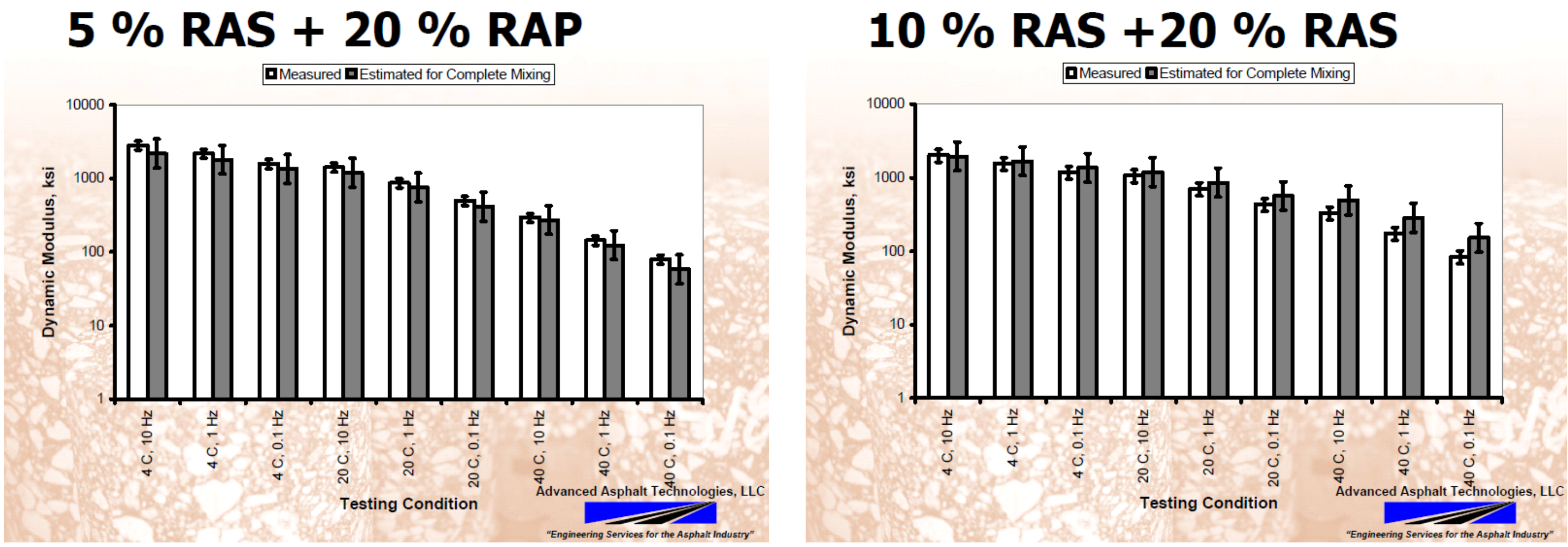
Figure 32. Fatigue Life of RAP Asphalt Mixtures Measured in the Overlay Tester

Since the degree of the blending between the RAP and virgin binders requires evaluation through the final mixture properties, as extraction and recovery would artificially blend the two asphalt binders together, Bonaquist (2005, 2009) and later Bennert and Dongre (2010), have utilized the dynamic modulus test and dynamic modulus prediction equations to estimate the degree of blending that occurs during mixing. A detailed explanation can be found in Bennert and Dongre (2010), however, a brief outline of the procedure is below.

1. Determine the dynamic modulus of the asphalt mixture using the Asphalt Mixture Performance Tester (AMPT);
2. After testing, extract and recover the asphalt binder from the tested specimens or identical material;
3. Test the recovered asphalt binder for the shear modulus (G*) over a range of temperatures and loading frequencies that are similar to the AMPT mixture testing;
4. Use the Hirsch Model (Christensen, et al., 2003) to predict the dynamic modulus of the asphalt mixture based on 100% blending – this is accomplished by using the G* values from the extracted and recovered asphalt binders; and
5. Compare the measured dynamic modulus to the predicted dynamic modulus. If the results are reasonably close, then it can be concluded that full blending between the RAP and the virgin asphalt binders occurred. The further the results are away from one another, the lesser degree of blending has actually occurred.

An example of this methodology is shown below from Bonaquist (2009). The testing was conducted from plant produced material containing recycled asphalt shingles (RAS) and RAP. The premise of the work was that the contractor wanted to use 20% RAP and then also wanted to know how much RAS could be added as well before blending became an issue. In Figure 33a, it is clear that the predicted and measured modulus values compare favorably and therefore could be assumed that blending is occurring. However, when the contractor tried producing the mixture with 10% RAS (Figure 33b), it is clear that the predicted and measured value begin to separate away from one another, indicating the amount of blending between the recycled and virgin binders is limited.

The methodology described above was utilized on a few of the warm mix asphalt plant produced jobs evaluated during this study. Rutgers University conducted the dynamic modulus mixture testing and overall analysis, while Rowan University conducted the extraction and recovery of the asphalt binders and also the shear modulus (G*) master curve testing.



(a) (b)

Figure 33. Examples of Blending Potential Analysis Using Bonaquist (2005, 2009) Procedure

NJ Rt. 38 – Sasobit

In July 2007, the New Jersey Department of Transportation (NJDOT) attempted a pilot project to determine if a "more compactable" PG76-22 asphalt binder could be designed using Sasobit to supplement styrene-butadiene-styrene (SBS) in modifying an asphalt binder to achieve a final performance grade of PG76-22. The "new" asphalt binder was produced at the NuStar Asphalt Refinery in Paulsboro, NJ and was used to produce a 9.5H76 + 15% RAP mixture that was being placed on NJ Rt. 38. It should be noted that the Sasobit was only added at 0.8% by weight of asphalt binder, which is approximately one half of the recommended dosage rate for true WMA applications.

Loose mix was sampled during production and brought back to the Rutgers Asphalt/Pavement Laboratory where it was reheated to compaction temperature (assumed to be 15^{o}F lower than the recorded production temperature) and compacted into the AMPT specimens. Additional specimens were compacted and delivered to Rowan University for extraction and recovery.

The blending analysis results for the NJ Rt 38 WMA are shown in Figures 34 and 35. Figure 34 shows the blending analysis for the "normal" production temperature of 315^{o}F. The comparison between the measured and predicted dynamic modulus indicate that this is a relatively good agreement between them, thus indicating blending of virgin and RAP binders are occurring. Figure 35 shows the blending analysis for the 270^{o}F production temperature. Again, the test results are somewhat comparable, although not as close as the normal production temperature data, especially at the higher test temperatures.

According to recommendations from Bonaquist (2010), blending is expected when the average difference between the measured and predicted results are within 20% of each other. The test results for the normal (315^{o}F) and 270^{o}F production temperatures resulted in differences that were 18% and 33%, respectively. This would suggest that for 15% RAP, a normal production temperature (i.e. – 315^{o}F or greater) should provide blending between the RAP and virgin asphalt binders. However, at a reduced production temperature of 270^{o}F, the blending of RAP and virgin asphalt binders may be an issue, as indicated in the comparisons in Figure 35.

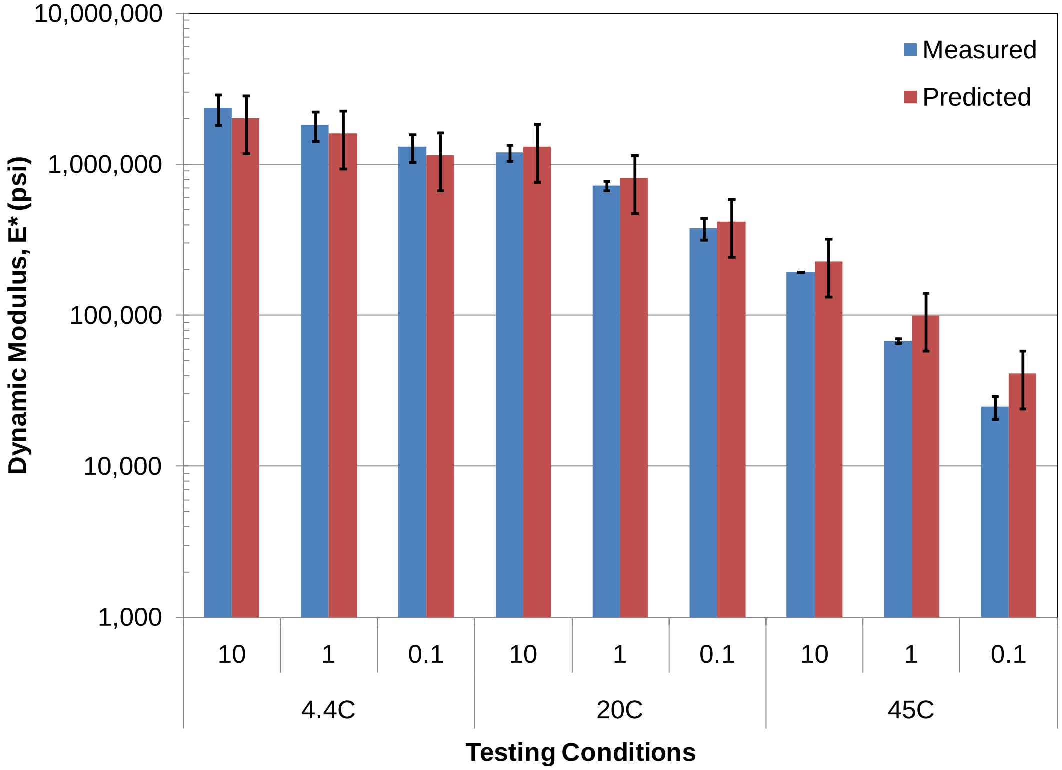


Figure 34. Blending Potential Analysis for NJ Rt 38 at 315^{o}F Production Temperatures

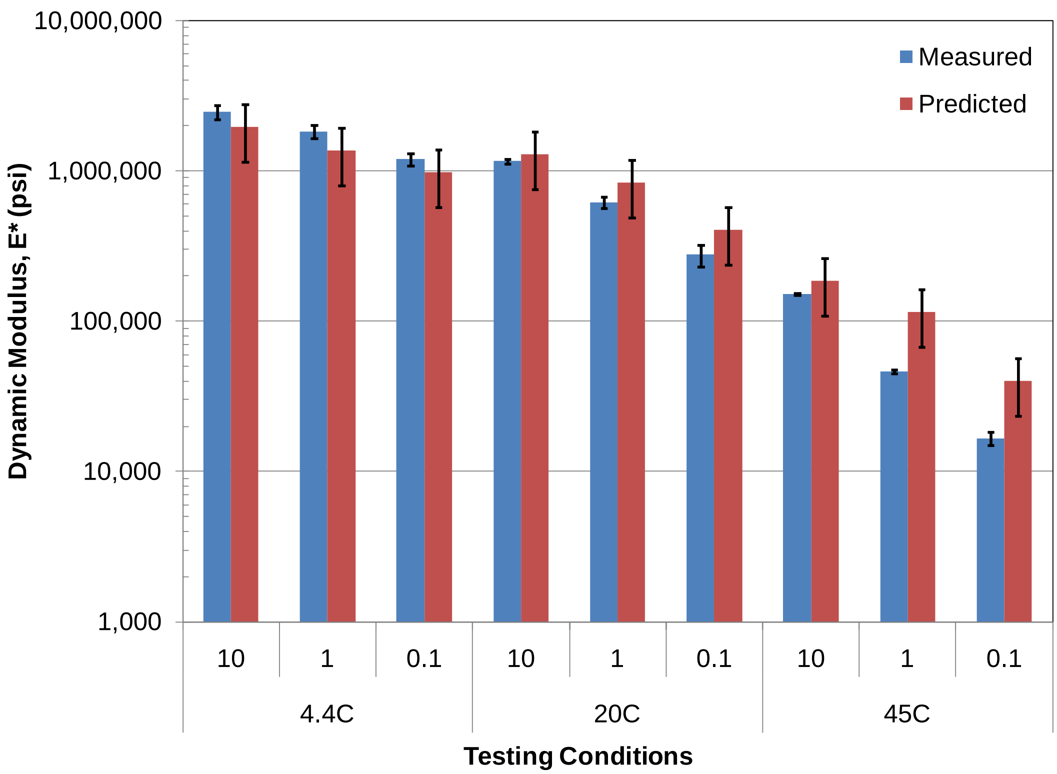


Figure 35. Blending Potential Analysis for NJ Rt 38 at 270^{o}F Production Temperatures

I78 – Evotherm 3G

In November 2008, Trap Rock Industries was placing an intermediate course prior to the application of an asphalt rubber open graded friction course (AR-OGFC) mix. The asphalt mixture evaluated was a 12.5H76 + 25% RAP. The PG76-22 asphalt binder was supplied by NuStar Asphalt Refinery and used 0.6% Evotherm 3G WMA additive, which was preblended in the asphalt binder at the refinery. Loose mix was sampled during production and brought back to the Rutgers Asphalt/Pavement Laboratory where it was reheated to compaction temperature (assumed to be 15^{o}F lower than the recorded production temperature) and compacted into the AMPT specimens. Additional specimens were compacted and delivered to Rowan University for extraction and recovery.

The blending analysis results for the I78 WMA are shown in Figures 36 and 37. Figure 36 contains the results of the mixture when produced at the "normal" production temperature of 315^{o}F. The results indicate that general blending seems to be occurring when comparing the lower temperature data but there is certainly a blending issue at the higher test temperature (45^{o}C) data.

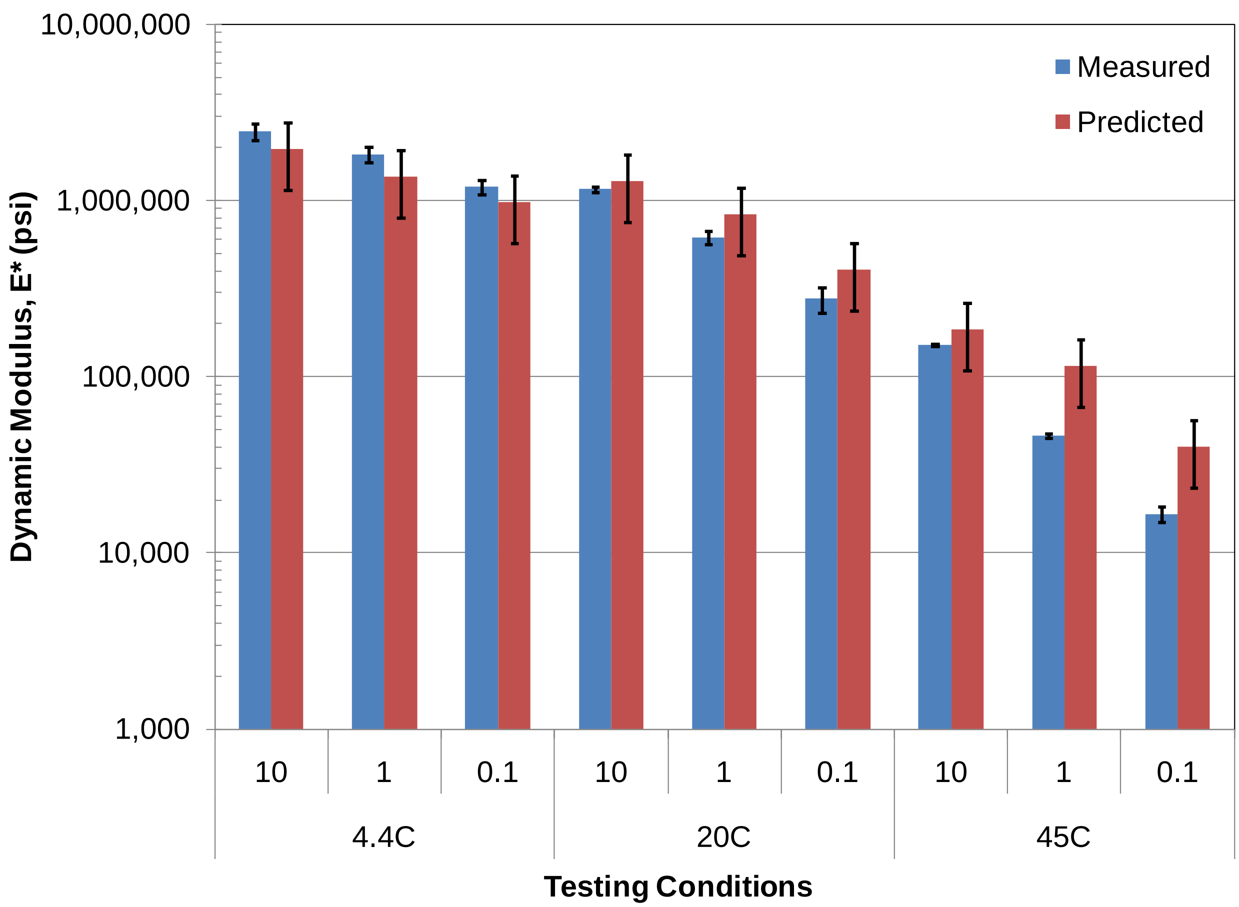


Figure 36. Blending Potential Analysis for I78 WMA at 315^{o}F Production Temperatures

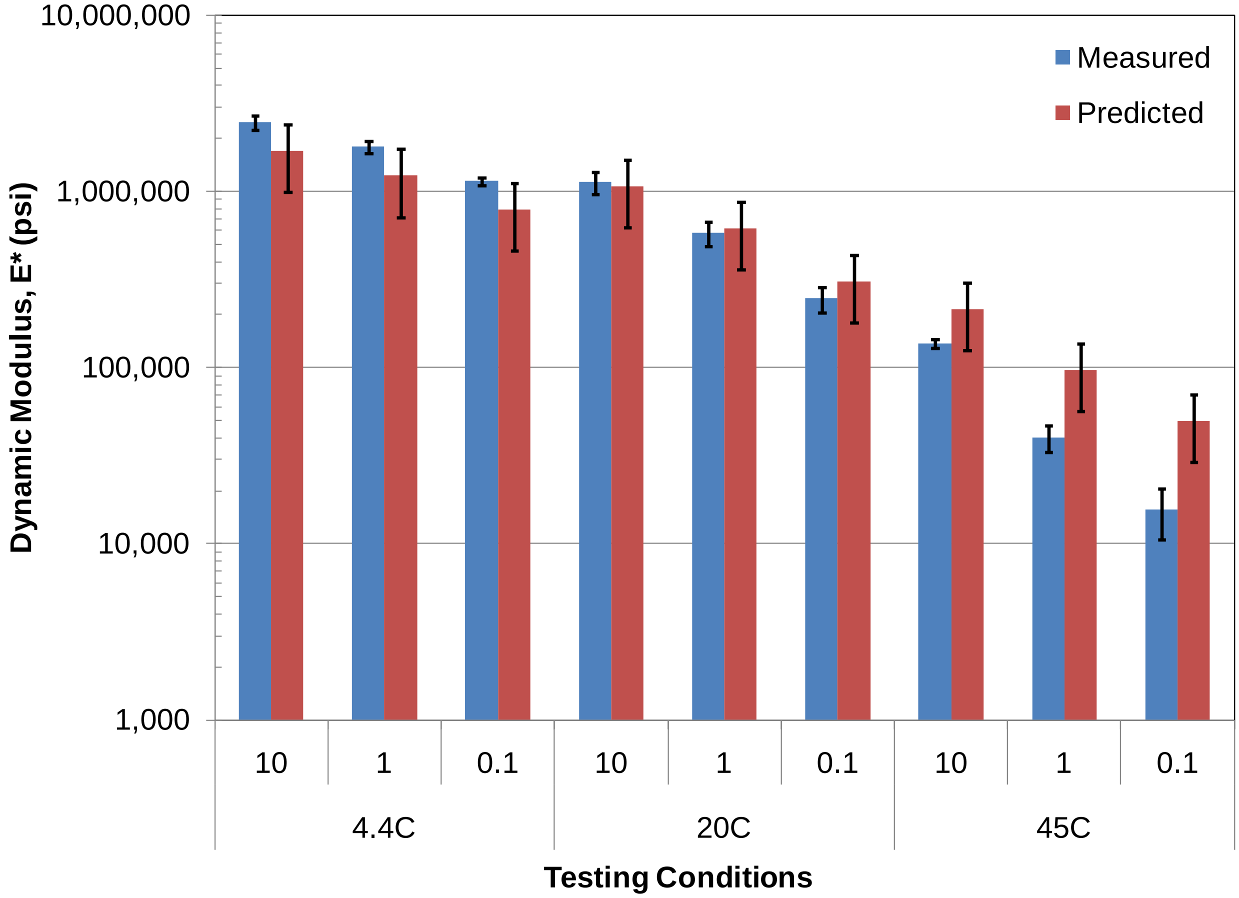


Figure 37. Blending Potential Analysis for I78 at 270^{o}F Production Temperature

The test results in Figure 37 show a similar trend to what was shown earlier in Figure 36, although the differences appear to be greater than when produced at normal production temperatures.

According to recommendations from Bonaquist (2010), blending is expected when the average difference between the measured and predicted results are within 20% of each other. The test results for the normal (315^{o}F) and 270^{o}F production temperatures resulted in differences that were 31% and 37%, respectively. This again would suggest that regardless of the production temperature evaluated, the addition of 25% RAP did not allow for full blending between the virgin and RAP asphalt binders.

Summary of RAP in WMA Blending Potential Analysis

A new methodology was evaluated to determine if blending between RAP and virgin asphalt binders occur during mixing at normal and reduced production temperatures associated with warm mix asphalt production. The procedure uses the measured and predicted dynamic modulus, where the predicted dynamic modulus is based on the Hirsch Model (Christensen et al., 2003) using measured shear modulus information from extracted and recovered asphalt binder to simulate 100% blending conditions.

Meanwhile, the dynamic modulus of the compacted asphalt mixture would represent the actual blending condition achieved, whether this is 100% or less.

In general, the test results indicated that blending appeared to be achievable at 15% RAP when produced at normal (315^{o}F) production temperatures. However, when test temperatures were reduced by 45^{o}F to a production temperature of 270^{o}F, the predicted and measured dynamic modulus values begin to deviate from one another, indicating that blending may be an issue. For the 25% RAP mixtures, there were clear differences between the measured and predicted dynamic modulus values, especially at the high test temperature. The data suggests that there may be issues with RAP and virgin binders blending at higher RAP contents and at reduced production temperatures associated with warm mix asphalt production.

PHASE 7 – WARM MIX ASPHALT PILOT STUDIES

During the course of the research project, Rutgers University attempted to arrange warm mix asphalt pilot studies where different technologies were used during actual field production project. In some cases, the pilot studies were evaluated extensively, such as I280 High Performance Thin Overlay (HPTO) WMA and the NYSDOT Low Emissions Asphalt (LEA) projects, while some projects were only used as observation/minimal testing (i.e. – NJ Rt 18 SMA, I78 AR-OGFC WMA). Test results and observations generated during these studies are described below.

NJ Rt 38 – Sasobit Pilot Project

The first pilot project conducted by the NJDOT was on NJ Rt 38 using a Sasobit modified 9.5M76 + 15% RAP mixture in the Summer of 2007. The mixture was produced by Trap Rock Industries at the Mt. Holly facility. Three different asphalt mixtures were evaluated on the project;

1. 9.5H76 + 15% RAP at normal production temperature (315^{o}F) – called Baseline mixture;
2. 9.5H76 + 15% RAP + 0.8% Sasobit at normal production temperature (315^{o}F);
3. 9.5H76 + 15% RAP + 0.8% Sasobit at 270^{o}F production temperature.

<u>Plant Production Data</u>

During production, amperages at the asphalt binder pump and drag chain were measured to determine if any differences between the Baseline and 270^{o}F warm mix asphalt could be observed. Table 14 shows the Baseline and WMA plant production data, respectively. The results indicate that while dropping the production temperature 45^{o}F and maintaining production rate, no differences were found at the asphalt binder pump with a slight increase in the amperage at the drag chain motor; from 50 to 55 amps. The increase in the drag chain amperage would suggest that the WMA mixture has slightly less workability than the normal production mix.

Table 14 – NJ Rt 38 Plant Production Data

Time	Mix Discharge Temperature (F)	Production Rate	Asphalt Binder Pump Amperage	Drag Chain Motor Amperage
8:45 PM	315	250 ton/hr	35	50
9:15 PM	318	250 ton/hr	35	50
9:45 PM	313	250 ton/hr	35	50
10:15 PM	315	250 ton/hr	35	50

- Average Storage Time was approximately 1 hours, 15 minutes

- Average temperature immediately behind paver was 290 to 300F

- Average pavement surface before paving was 80 to 85F

Time	Mix Discharge Temperature (F)	Production Rate	Asphalt Binder Pump Amperage	Drag Chain Motor Amperage
10:45 PM	270	250 ton/hr	35	50
11:15 PM	270	250 ton/hr	35	55
11:45 PM	268	250 ton/hr	35	55
12:15 AM	272	250 ton/hr	35	55

- Average Storage Time was approximately 2 hours, 15 minutes
(Storage Time for small 270F warm mix section was 45 minutes)

- Average temperature immediately behind paver was 250 to 260F

- Average pavement surface before paving was 80 to 85F

Collected Field Information and Observations

One of the major observations that was of interest was the potential decrease in emissions due to the decrease in production temperatures. At this time, warm mix asphalt was a relatively new concept in New Jersey and the promise of reducing emissions was enticing. Figure 38 shows a few pictures taken during field placement of the normal and WMA mixtures. Figures 38a and b clearly show emissions at the back of the paver and above the back of the dump truck. Meanwhile, in Figure 38c, no visual observation of emissions could be made at a production temperature of 270^{o}F. The photos clearly show a production temperature reduction of 45^{o}F can drastically reduce the emissions present from asphalt mixture production.

(a)

(b)

(c)

Figure 38. Photos of Field Duration on NJ Rt 38 WMA Pilot Project

Each of the three sections was extensively cored for compacted density and laboratory performance testing. Table 15 shows the final results of the compacted air voids and lift thickness measurements. Table 15 shows that on average, the compacted air voids for the normal production temperature were lower than for the 270^{o}F production temperature WMA. It should be noted that for this project, the dosage rate for the Sasobit was approximately one half that of the what is commonly recommended, which may have influenced the overall compaction of the 270^{o}F production temperature WMA.

Laboratory Evaluation of Loose Mix

Loose mix was sampled during production and brought back to the Rutgers Asphalt/Pavement Laboratory (RAPL) where it was reheated back to compaction temperature for specimen fabrication. Compaction temperature was assumed to be 15^{o}F lower than production temperature.

Tensile Strength Ratio (TSR)

Extracted field cores were evaluated for their tensile strength ratio (TSR) in accordance with AASHTO T283. The TSR results were as follows:

- Normal Production = 71.1%
- Normal Production with Sasobit = 80.2%
- 270^{o}F Production Temperature WMA = 55.9%

Pictures of the broken specimens are shown in Figure 39. It is evident from the pictures that the 270^{o}F WMA specimens shows more signs of stripping with broken aggregates and uncoated aggregate faces are along the fractured area than the other TSR specimens. Further investigation of the moisture content of the aggregate stockpiles indicate that the aggregate blend moisture content may have been excessive (greater than 4%) and may not have been fully dried at a production temperature of 270^{o}F (Table 16). Moisture content measurements of asphalt mixture, tested in accordance with AASHTO T255, indicated that the asphalt mixture had a moisture content between 0.04 to 0.05%. Historical information regarding the aggregates used confirms that they are not known to have had moisture damage problems in the past.

Additional TSR testing was also conducted on reheated loose mix compacted in the laboratory. The loose mix was reheated to compaction temperature, which was assumed to be 15^{o}F lower than production temperature. The final TSR results for the reheated loose mix were as follows:

- Normal Production = 97.1%
- Normal Production with Sasobit = 79.9%
- 270^{o}F Production Temperature WMA = 77.3%

The TSR testing on the reheated mix resulted in two out of the three mixes having an increase in TSR values, while the third remained constant. This indicates that the additional conditioning associated with reheating the loose mix helped in improving the TSR values.

Table 15 – Compacted Air Voids and Lift Thickness Measurements for NJ Rt 38 WMA Pilot Project

Mix Type	Sample ID	Air Voids (%)
9.5H76	25	5.40
	27	5.58
	28	6.22
	29	6.03
	31	8.12
	32	9.31
	33	6.51
	34	5.82
	36	9.33
	26 (BS)	5.46
	30 (BS)	5.90
	35 (BS)	7.73
	Average =	**6.78**
	Std Dev =	**1.46**
	1st Quartile:	5.76
	2nd Quartile:	6.13
	3rd Quartile:	7.83
	Inter-Quartile Range, IQR:	2.06
Outlier Limits (Quartiles)	**Min:**	**2.67**
	Max:	**10.92**
Outlier Limits (Std Dev)	**Min:**	**3.87**
	Max:	**9.69**

Mix Type	Sample ID	Air Voids (%)
W315	1	8.09
	2	8.16
	3	6.93
	5	5.87
	6	5.56
	8	7.35
	9	6.12
	11	6.56
	12	6.05
	4 (BS)	8.57
	7 (BS)	6.93
	10 (BS)	5.42
	Average =	**6.80**
	Std Dev =	**1.06**
	1st Quartile:	6.01
	2nd Quartile:	6.75
	3rd Quartile:	7.53
	Inter-Quartile Range, IQR:	1.53
Outlier Limits (Quartiles)	**Min:**	**3.72**
	Max:	**9.82**
Outlier Limits (Std Dev)	**Min:**	**4.68**
	Max:	**8.92**

Mix Type	Sample ID	Air Voids (%)
W270	13	7.54
	14	9.99
	15	6.99
	16	9.36
	17	8.56
	19	7.25
	20	6.28
	22	8.78
	24	5.74
	18 (BS)	6.37
	21 (BS)	6.53
	23 (BS)	7.77
	Average =	**7.60**
	Std Dev =	**1.33**
	1st Quartile:	6.49
	2nd Quartile:	7.40
	3rd Quartile:	8.62
	Inter-Quartile Range, IQR:	2.13
Outlier Limits (Quartiles)	**Min:**	**3.30**
	Max:	**11.81**
Outlier Limits (Std Dev)	**Min:**	**4.93**
	Max:	**10.26**

Sample ID	Ave. Production Temperature (F)[1]	Ave. Mix Temperature Prior to Compaction (F)[2]	Air Voids (AASHTO T166)				Core Thickness (mm)	
			Average	Std. Dev.	Maximum	Minimum	Average	Std. Dev.
Normal Mix	315	290 to 300	6.92	1.57	9.33	5.40	46.95	1.70
WMA 315	315	290 to 300	6.74	0.95	8.16	5.56	42.17	3.24
WMA 270	270	260 to 265	7.83	1.43	9.99	5.74	42.11	2.63

[1] - Measured at plant and recorded by Plant Operator

[2] - Measured Immediately Behind Paver and recorded by Tom Bennert

(a) – Normal Production

(b) – Normal Production with Sasobit

(c)

Figure 39. Photos of Conditioned TSR Specimens Showing Fractured Faces

Table 16 - Measured Moisture Contents of Aggregate Stockpiles at the Trap Rock Industries Mt. Holly Asphalt Plant

Aggregate Moisture Content			
Aggregate Type	Moisture Content (%)	% of Total Mix	Total Moisture by Mix Weight (%)
3/8" Stone	3.4	40.3	1.37
Natural Sand	4.5	11.9	0.54
Screenings	6.7	28.1	1.88
RAP	3.7	15.0	0.56
Binder	0	4.7	0.00
Total		100.0	4.34

Asphalt Pavement Analyzer (AASHTO TP63)

Collected loose mix was used to compact specimens for testing in the Asphalt Pavement Analyzer (APA) in accordance with AASHTO TP63. The test results are shown in Figure 40. On average, the 270°F WMA achieved the highest APA rutting, although the general range in sample rutting would indicate that all production temperatures were statistically equal.

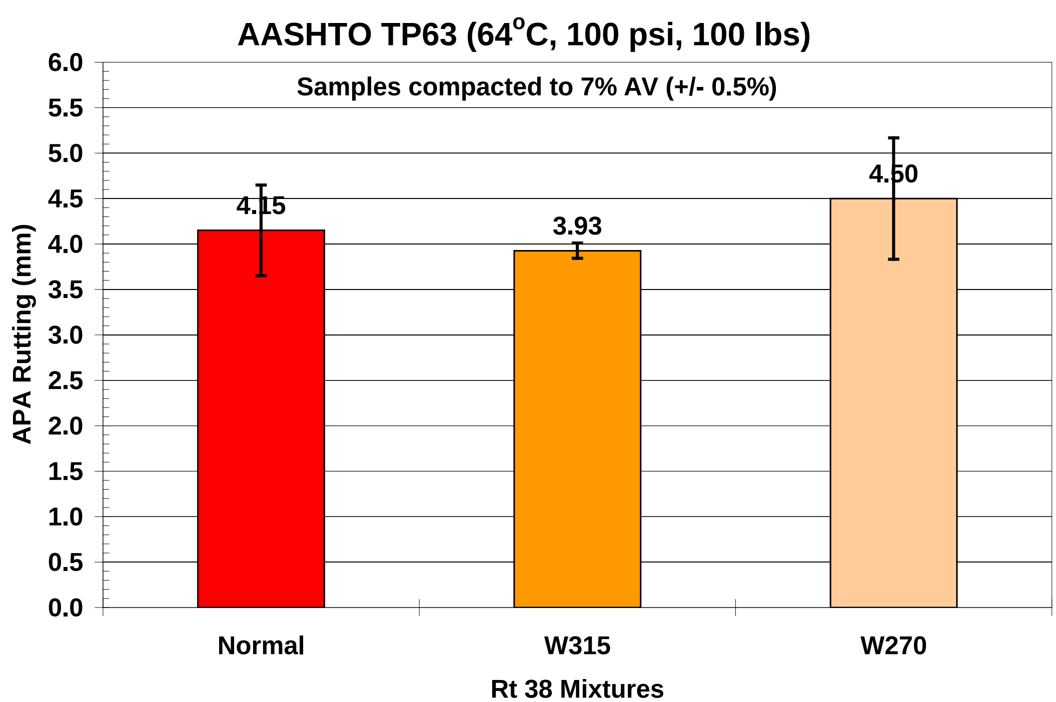


Figure 40. APA Test Results of NJ Rt 38 WMA

Overlay Tester (TxDOT Tex-248F)

The fatigue resistance of compacted loose mix specimens was evaluated in the Overlay Tester (Zhou and Scullion, 2005). The test results are shown in Figure 41. The fatigue results indicate that the average fatigue resistance is better for the 270°F WMA mixtures as opposed to the 315°F production temperature specimens. This indicates that asphalt mixtures produced at lower production temperatures (i.e. – warm mix asphalt) may provide greater fatigue resistance than when produced at normal production temperatures. This concept was further verified in the performance evaluation phase of this research report.

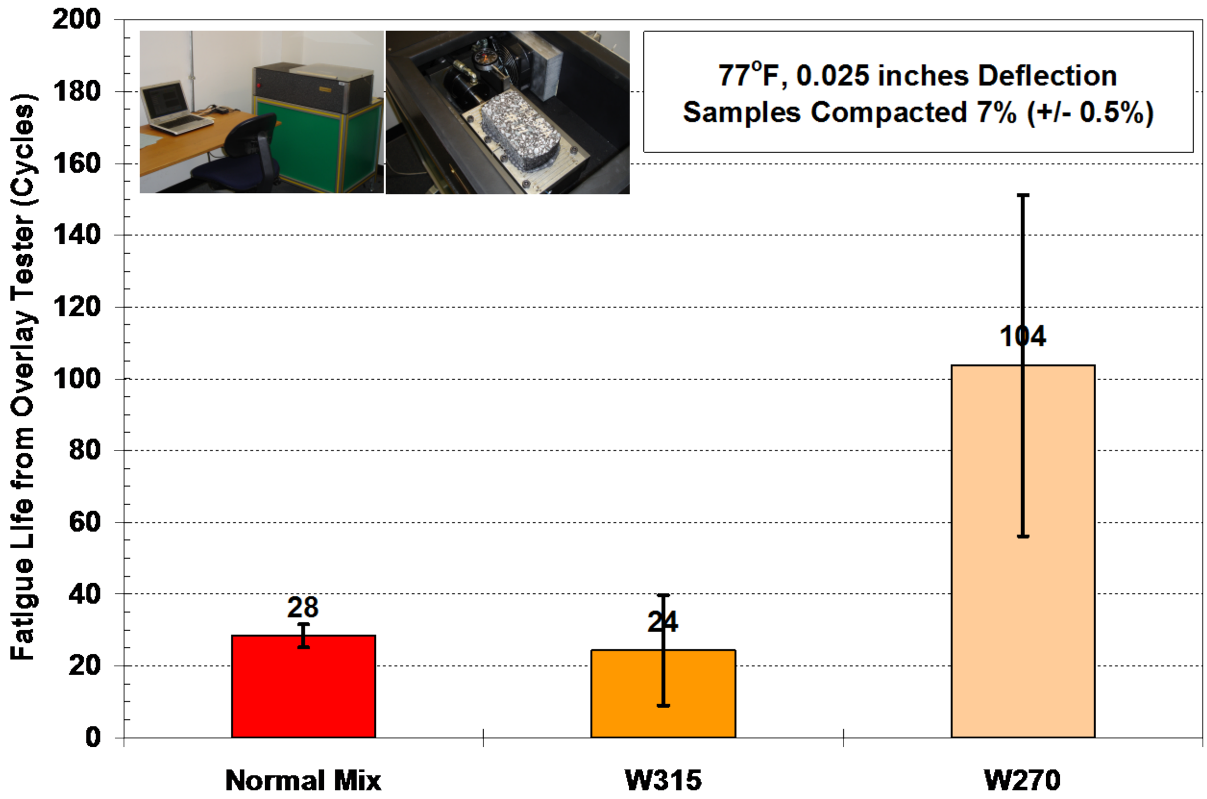


Figure 41. Overlay Tester Fatigue Cracking Results for NJ Rt 38 WMA Pilot Project

NJ Rt 18 – Stone Matrix Asphalt Modified with Sasobit

NJ Rt 18 (New Brunswick) was paved during May 2008 using a stone matrix asphalt (SMA) mixture. SMA mixtures have been known to be difficult to work with and compact due to the polymer-modified asphalt binder (PG76-22) and fibers required to limit draindown potential. To aid in contractors achieving required density requirements when placing SMA, a pilot project was established to look at the addition of Sasobit (preblended in the PG76-22 asphalt binder). Field observations were conducted by Robert Sauber and Robert Blight of NJDOT and Tom Bennert of Rutgers University. General observations and comments were as follows:

- Normal SMA production temperatures were 325^{o}F, while WMA SMA was produced around 275^{o}F.
- WMA SMA handled and compacted in a similar manner to normal production temperatures.
- Some areas were under 250^{o}F due to frequent paver stops without trucks feeding paving. These areas did witness tears in the mat due to the screed pulling the cooled mix.
- Laboratory compacted (gyratories) and field cores of both the normal and WMA sections resulted in similar densities.
- There was a clear reduction in emissions when using the 270^{o}F production temperature WMA when compared to the normal production temperature SMA.

NJ I78 – Evotherm 3G

NJ I78 was paved during November 2008 using a 12.5M76 + 25% RAP. The PG76-22 was produced at the NuStar Asphalt Refinery in Paulsboro, NJ where the Evotherm 3G product was preblended at a dosage rate of 0.6% by weight of asphalt binder. The material was placed as an intermediate lift, prior to the placement of an asphalt rubber OGFC (AR-OGFC) surface course.

<u>In-Place Field Core Density</u>

Field cores were extracted at three different time intervals; immediately after the mat cooled, 24 hours after paving, and seven (7) days after paving. The main idea behind this was to determine if the Evotherm 3G mix required a “curing” time. Four different production temperatures/mixes were evaluated in this work; 1) Normal mixture called Control, 2) WMA produced at 290^{o}F, 3) WMA produced at 270^{o}F, and 4) WMA produced at 240^{o}F. The 240^{o}F production temperature was not originally planned but occurred due to the plant operator dropping production temperature too quickly during the project.

Figure 42 shows the compacted air voids from the in-place cores. The results indicate that as production temperature decreases, on average, the compacted air voids increases. However, the 325 to 270^{o}F production temperature range did show minimal differences in the air voids of the field cores.

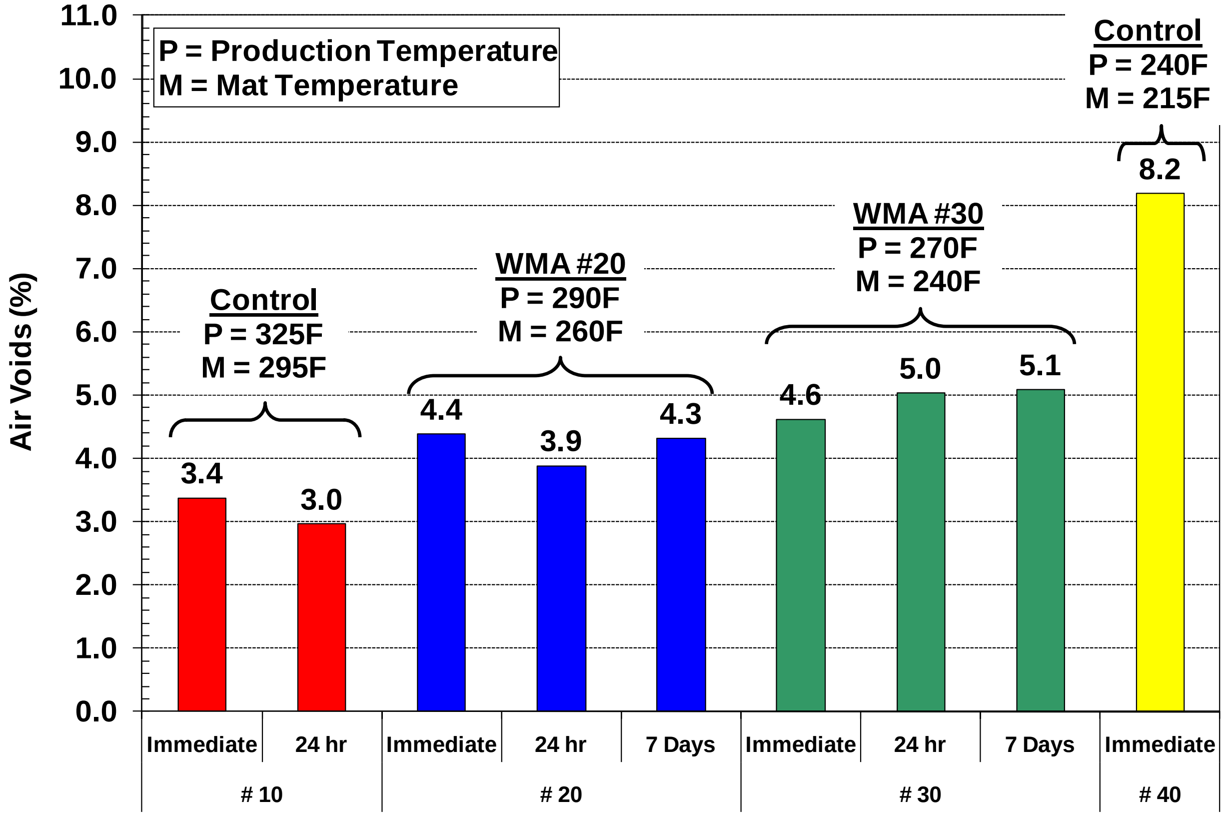


Figure 41. Compacted Air Voids from Extracted Field Cores on NJ I78 WMA Pilot Project

Mixture Performance Testing

Mixture performance testing was conducted on extracted field cores (Asphalt Pavement Analyzer and High Temperature Indirect Tensile Strength) and loose mixed compacted at the asphalt plant during QC testing (Overlay Tester).

Asphalt Pavement Analyzer (AASHTO TP63)

Asphalt Pavement Analyzer (APA) testing was conducted in accordance with AASHTO TP63. To test the thinner pavement lift, a full depth field core was trimmed to 77mm tall, allowing the testing of the 12.5M76 + 25% RAP mixture directly under the APA loading system. One thing that should be noted is that all specimens were tested at their in-place density. The resultant APA testing is shown in Figure 42.

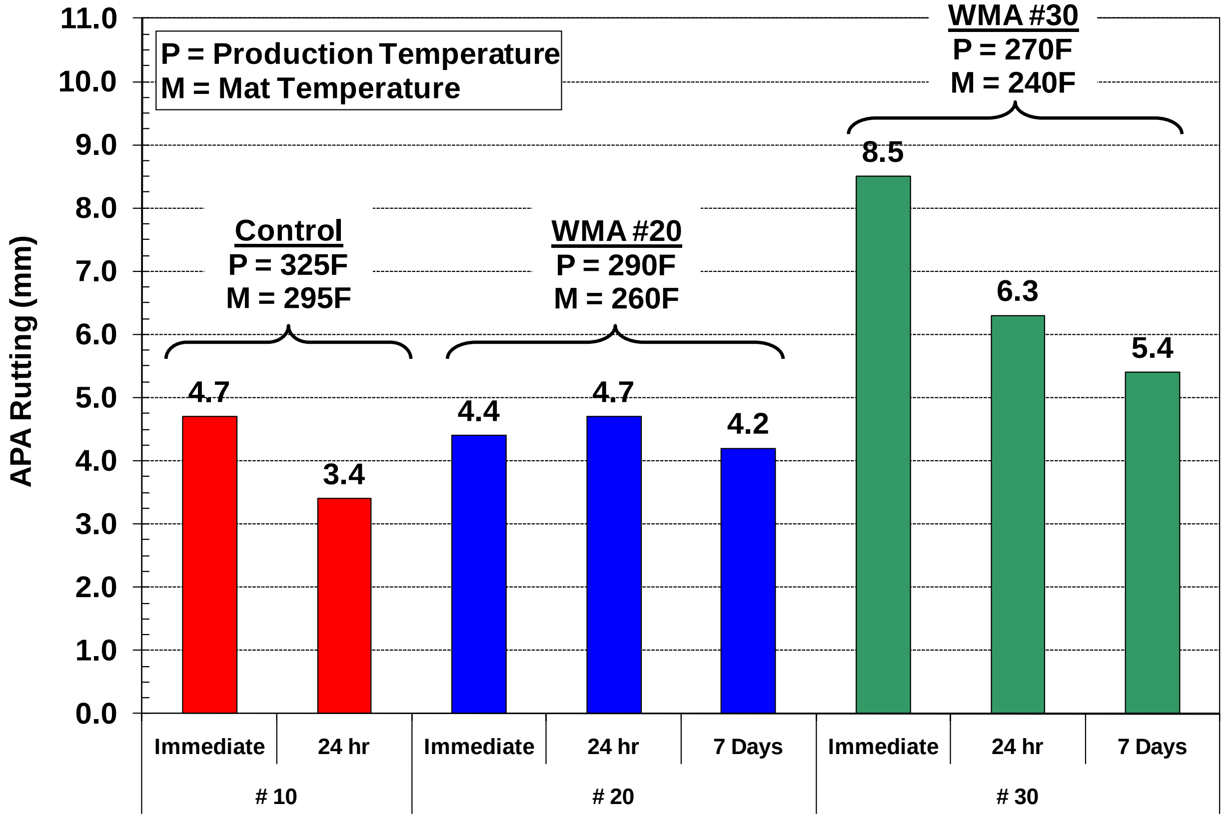


Figure 42. Asphalt Pavement Analyzer (APA) Test Results for NJ I78 WMA Pilot Project

The APA test results shown in Figure 42 indicate that little difference is found between the Control and 290oF production temperature WMA. However, as the test temperature decreased to 270^{o}F, the APA rutting increased, even though the compacted air voids of the mixtures within this temperature range were similar (Figure 41). The test data in Figure 42 also suggests that perhaps there is some "curing" that takes place at the lower test temperature WMA mixtures.

High Temperature Indirect Tensile Strength (HT/IDT)

High-temperature indirect tensile (HT/IDT) strength tests at high temperature, following procedures given in draft standard NCHRP Project 9-33, were conducted on extracted field cores. This is a simple test for evaluating rut resistance of HMA, and is also included in the Mix Design Manual. The NCHRP 9-33 recommended table of required HT/IDT values vs traffic is shown in Table 17 for comparing the HT/IDT results shown in Figure 43. The HT/IDT results showed a great sensitivity to production temperature than the APA test results. Figure 43 clearly indicates that as production temperature decreased, the HT/IDT strength also decreased. However, this reduction in HT/IDT strength can also be attributed to the compacted air voids, as shown in Figure 44. This indicates that if contractors used lower production temperatures (i.e. – WMA) and still do not achieve density, rutting potential will be a function of reduced stiffness and high air void content of the compacted mixtures.

Table 17 - High Temperature IDT Strength Minimum Requirements for Different Traffic Levels

Traffic Level, *Million ESALs*	HT/IDT Strength, *psi*
	NCHRP 9-33 Recommended
< 3	---
3 to < 10	30
10 to < 30	50
> 30	67

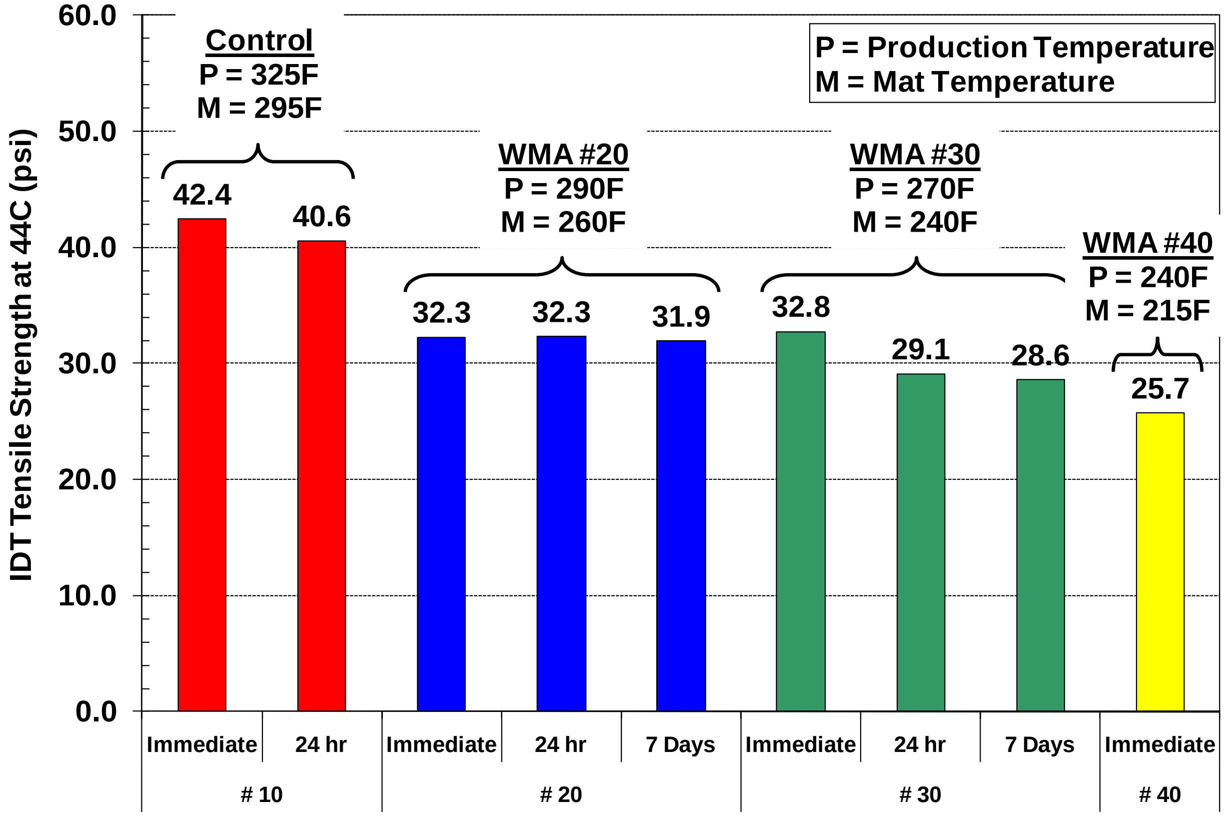


Figure 43. High Temperature IDT Strength Results for Extracted Field Cores for NJ I78 WMA Pilot Project

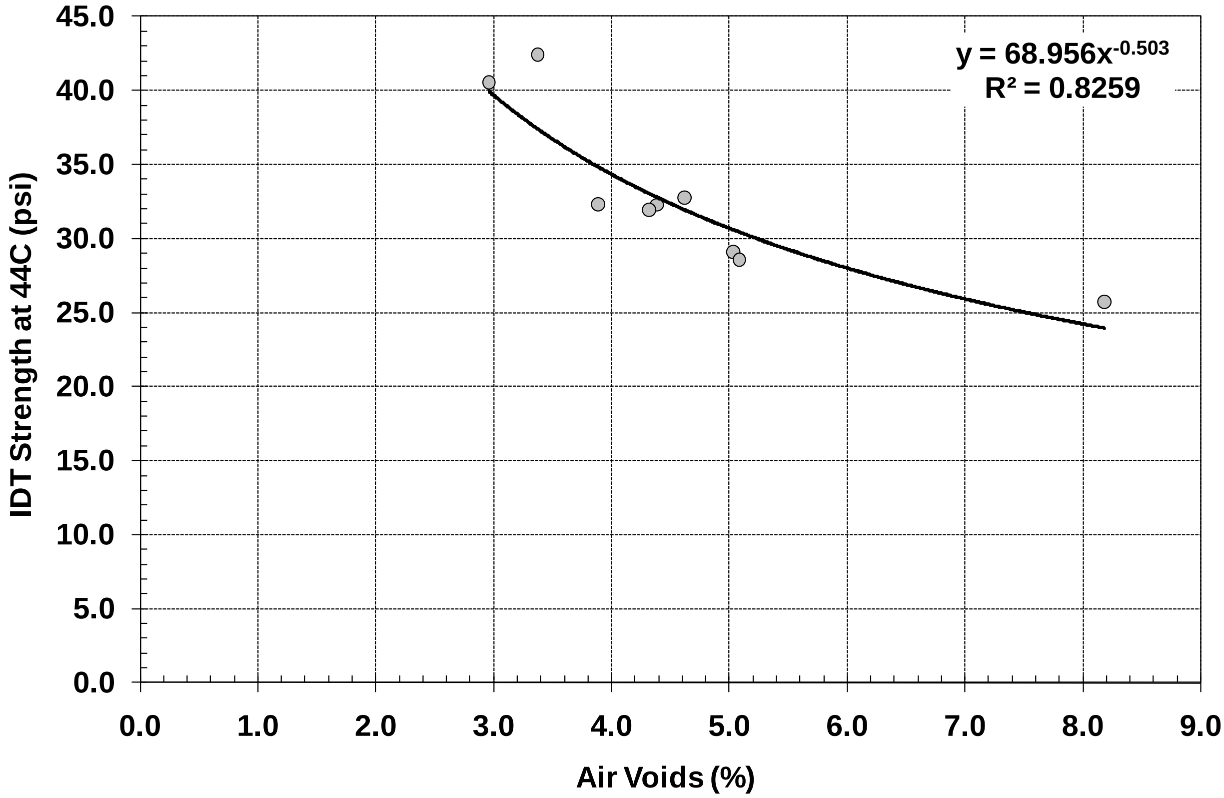


Figure 44. High Temperature IDT Strength vs Compacted Air Voids for NJ I78 WMA Pilot Study

Overlay Tester (TxDOT Tex-248F)

The Overlay Tester was used to evaluate the fatigue cracking potential of the different mixes. Testing was conducted on mixtures sampled and then immediately compacted, as well as samples that were conditioned in an oven for 2 hours prior to compaction. The test results are shown in Figure 45. The test results indicate that as the production temperature decreases, the fatigue resistance in the Overlay Tester increases. Similar results were found in previous sections of the report.

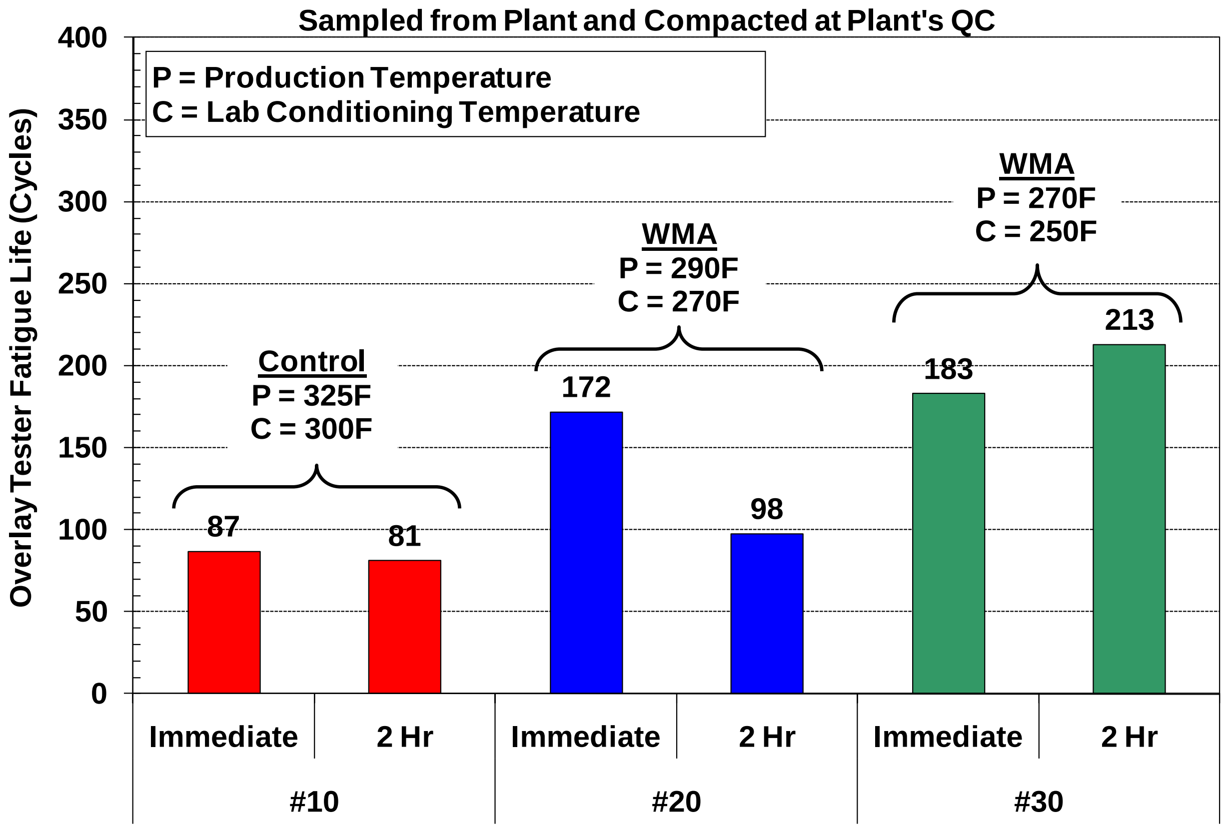


Figure 45. Overlay Tester Results for NJ I78 WMA Pilot Project Mixtures

NYSDOT – Low Emissions Asphalt

In April 2009, the NYSDOT conducted a research study to evaluate the mechanical properties of hot mix asphalt and warm mix asphalt produced using the Low Emissions Asphalt (LEA) process. The laboratory test specimens were produced from loose mix sampled at the asphalt plant and compacted to 170mm tall gyratory samples. Three different mixture types were produced for evaluation:

1. Normal – normal HMA mixture produced and compacted at normal temperatures
2. LEA with No RAP – warm mix asphalt produced with the LEA technology with no addition of RAP
3. LEA with RAP – warm mix asphalt produced with the LEA technology with the addition of RAP.

It was identified prior to the start of the project that the RAP content of the "Normal" mix and LEA with RAP mix was 15%.

Specimens were compacted to target air void levels of 3.5 and 7% to evaluate the influence of density on the mixture properties.

The performance-related laboratory testing included:

- Dynamic Modulus testing using the Simple Performance Tester (SPT);

- Repeated Load Permanent Deformation testing (Flow Number) using the Simple Performance Tester (SPT); and
- Overlay Tester.

<u>Mixture Stiffness – Dynamic Modulus (E*)</u>

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP62, *Standard Test Method for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*. The data was collected at three temperatures; 4, 20, and 35^oC using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz. Test specimens were tested in triplicate and averaged.

The collected modulus values of the varying temperatures and loading frequencies were used to develop Dynamic Modulus master stiffness curves and temperature shift factors using numerical optimization of Equations 5 and 6 (FHWA, 2007). The reference temperature used for the generation of the master curves and the shift factors was 20^oC.

$$\log|E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \quad (5)$$

where:

$|E^*|$ = dynamic modulus, psi
ω_r = reduced frequency, Hz
Max = limiting maximum modulus, psi
δ, β, and γ = fitting parameters

$$\log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad (6)$$

where:

a(T) = shift factor at temperature T
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

Dynamic Modulus (E*) at 7% Air Voids

The E* data was used to generate master stiffness curves in accordance with equations (5) and (6), shown earlier. The master stiffness curves for the three mix types at 7% air voids are shown in Figure 46. The figure shows that the "LEA - No RAP" achieved the lowest mixture stiffness of the three mixes tested, with approximately 25% of the mixture stiffness of the "Normal" mix at higher test temperatures (lower loading frequencies). The addition of RAP ("LEA – with RAP") increased the mixture stiffness of the “LEA – with RAP” by approximately 32%, with larger amounts occurring at higher temperatures (slower loading frequencies).

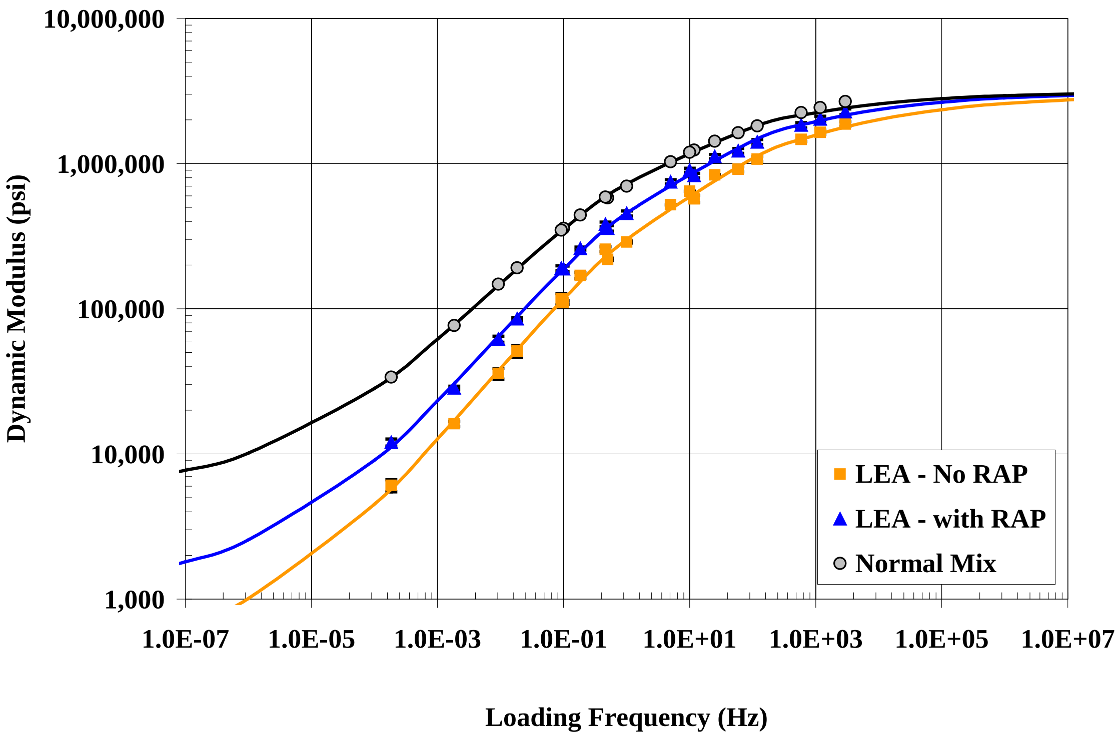


Figure 46. Master Stiffness Curves of Specimens Compacted to 7% Air Voids

Dynamic Modulus (E) at 3.5% Air Voids*

Similar to the 7% air void samples, master stiffness curves were generated for the three different mixes. However, different to the previous samples, these samples were compacted to a target air void level of 3.5%. The results are shown in Figure 47. The test results of the 3.5% air void specimens are very similar in magnitude and trend as the 7% air void specimens.

Influence of Density Level on Mixture Dynamic Modulus (E)*

Two different air void levels were evaluated using the dynamic modulus test procedure. Comparisons are shown in Figures 48 through 50. The test results show that minimal differences in modulus were measured at low and intermediate test temperatures (intermediate and higher loading frequencies) with larger differences (5 to 10%) measured at higher test temperatures (slower loading frequencies).

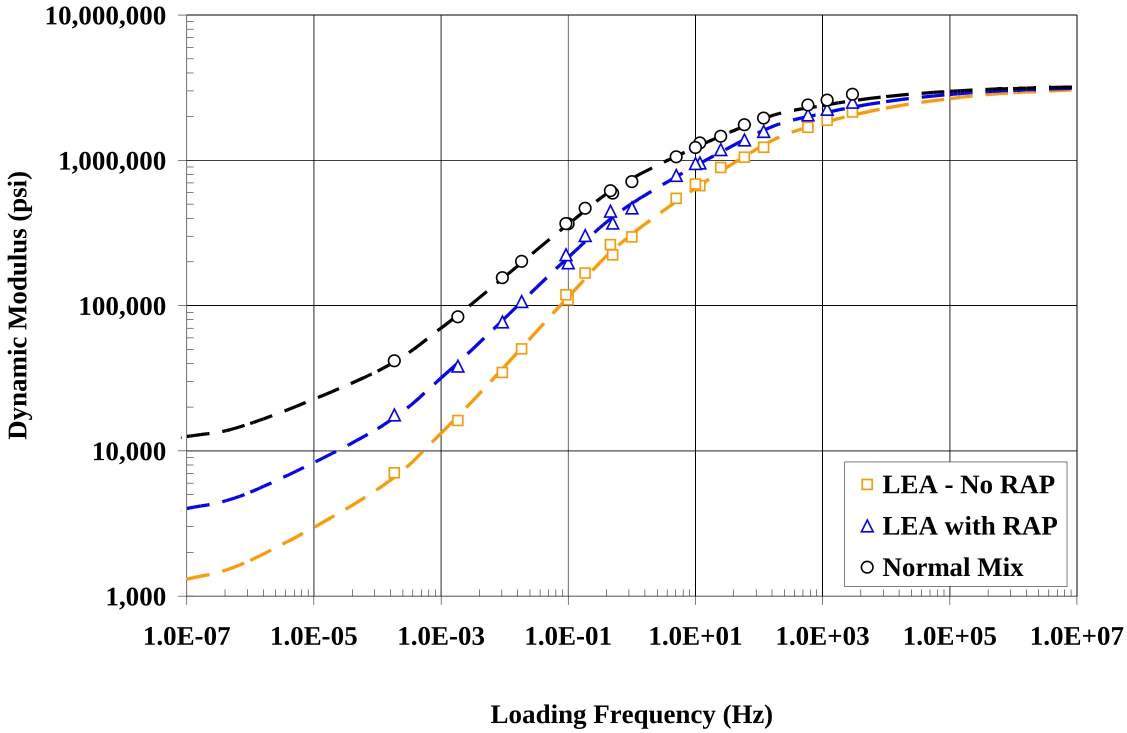


Figure 47. Master Stiffness Curves of Specimens Compacted to 3.5% Air Voids

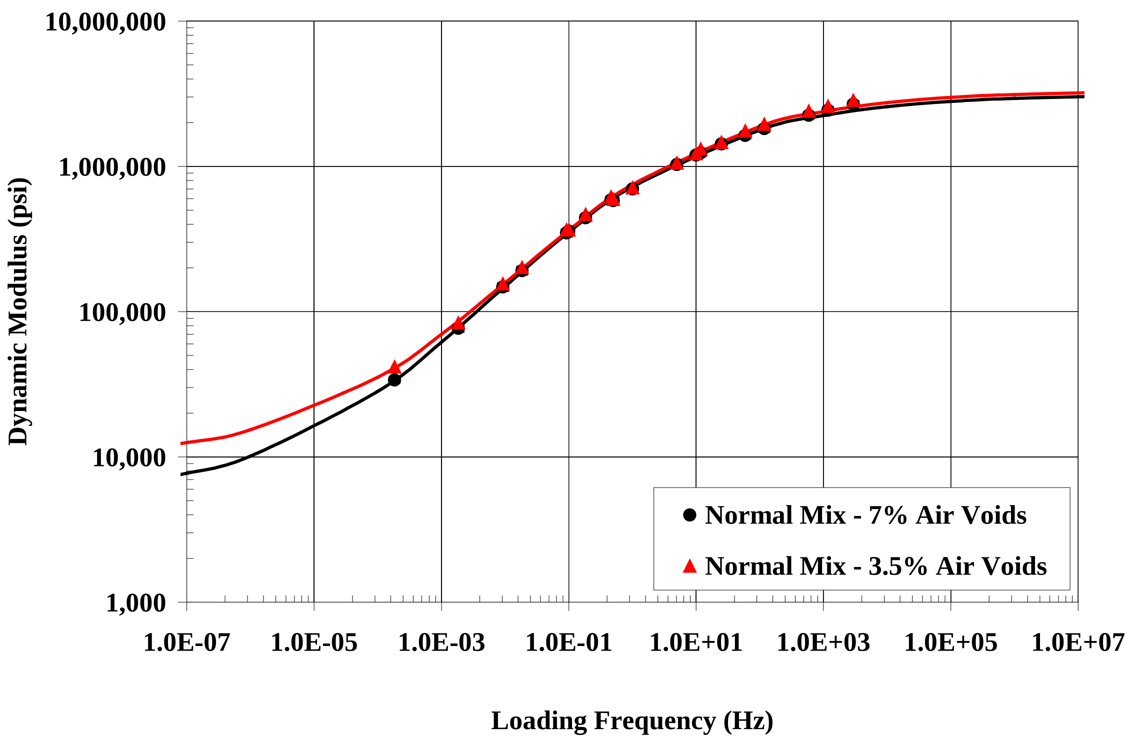


Figure 48. Master Stiffness Curves for "Normal" Mix with Different Air Void Levels

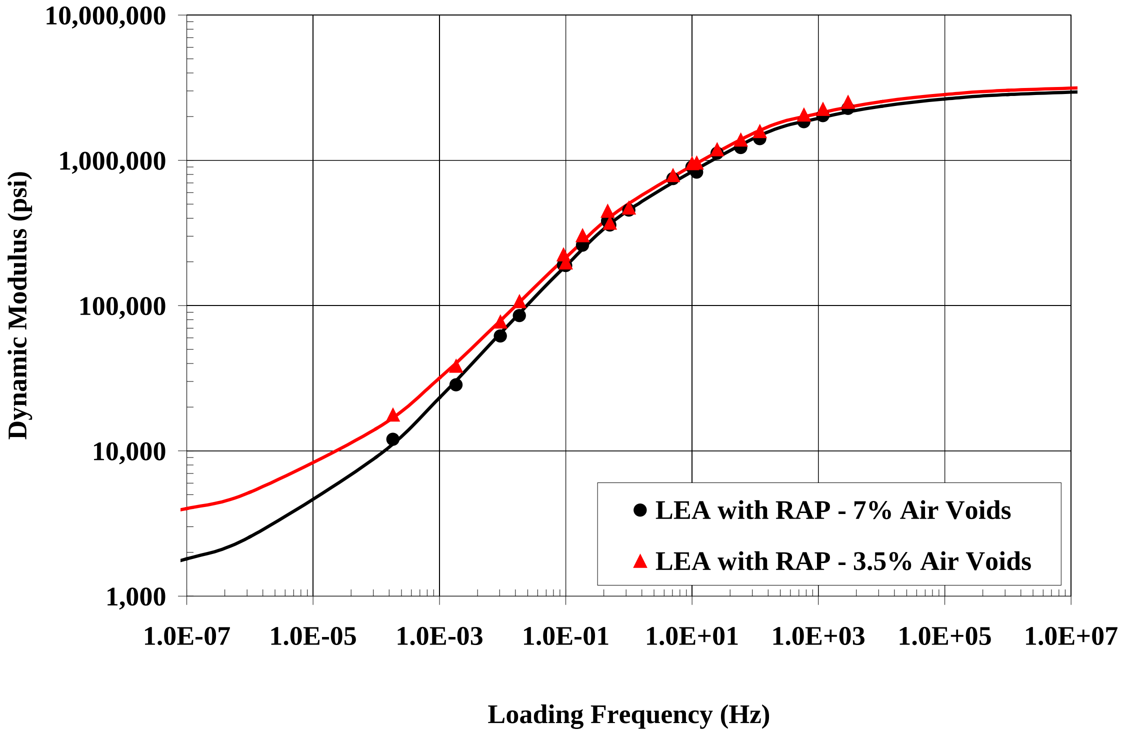


Figure 49. Master Stiffness Curves for "LEA – with RAP" Mix with Different Air Void Levels

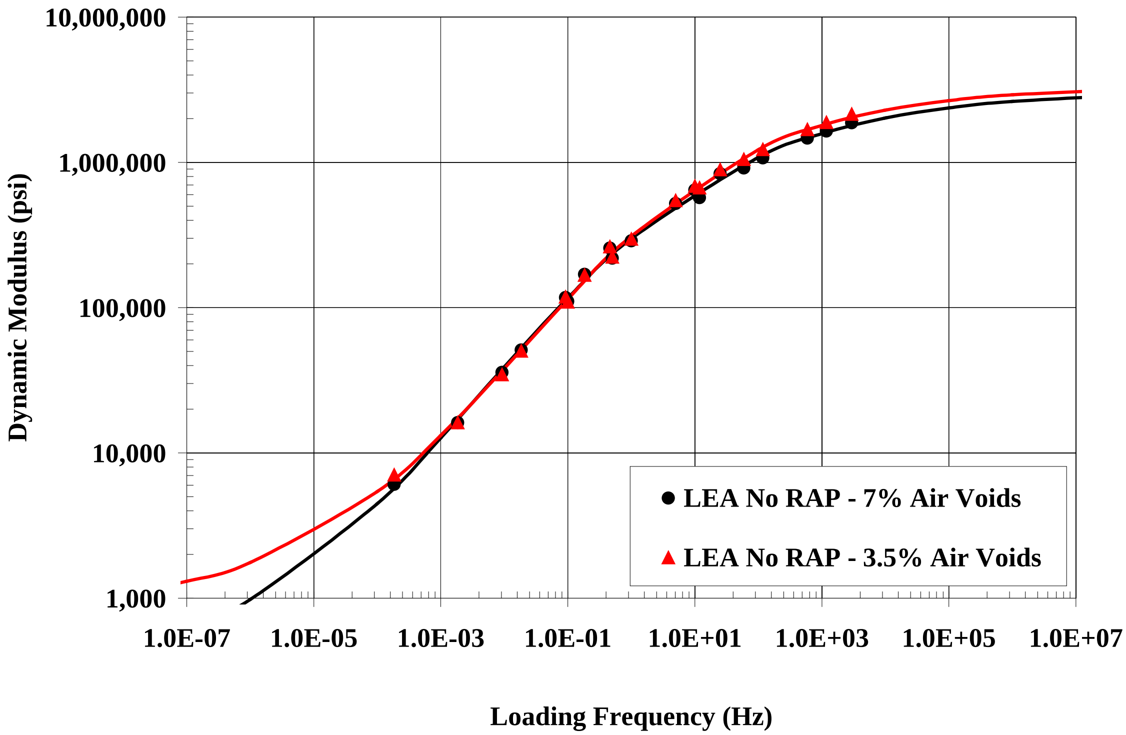


Figure 50. Master Stiffness Curves for "LEA – No RAP" Mix with Different Air Void Levels

Summary of Dynamic Modulus (E*) Testing

The dynamic modulus test results showed that;

1. Oxidation aging and additional asphalt binder absorption, occurring from the production temperature difference of approximately 80 to 90°F, significantly increased the HMA mixture stiffness. Higher oxidation aging and asphalt binder absorption occurs in hot mix asphalt than warm mix asphalt because;
   a. At higher production temperatures, the light oils in the asphalt binder start to "burn off". These lighter oils help to maintain the elasticity and crack resistance of asphalt binder. It is common practice to utilize extender oils in high RAP mixes, which is essentially replacing the light oils.
   b. At higher production temperatures, the asphalt binder has a lower viscosity which increases the mobility of the asphalt binder, which in turn, allows for greater penetration into the porous structure of the aggregates. At lower temperatures, the viscosity is higher and the liquid binder does not have the ability to flow as easily. Lower levels of asphalt binder absorption will increase the effective asphalt binder content and also help to increase the general fatigue resistance of the mix.

   The average difference in HMA mixture stiffness between the "Normal" mix and the "LEA with RAP" was approximately 34% higher, with the differences being as low as 13% at the low test temperature and as high as 61% at the high test temperature.
2. The addition of 15% RAP significantly increased the HMA mixture when using the LEA technology. The average difference in HMA mixture stiffness between the "LEA with RAP" and "LEA – No RAP" was approximately 34% higher, with the differences being as low as 16% at the low test temperature and as high as 55% at the high test temperature.
3. Of all of the factors, specimen density had the least amount of influence on the HMA mixture stiffness. On average, the difference in specimen density (3.5% to 7% air voids) resulted in an average difference of 8% in HMA mixture modulus with mixture stiffness increasing with decreasing air voids.

<u>TTI Overlay Tester (TxDOT Tex-248-F)</u>

The TTI Overlay Tester is a relatively new test method developed by the Texas Transportation Institute, TTI (German and Lytton, 1979; Zhou and Scullion, 2005). The test device simulates the expansion and contraction movements that occur in the joint/crack vicinity of PCC pavements. Although this test procedure is essentially a fatigue-type test, it currently represents the best method to truly simulate horizontal joint movements of PCC pavements in the laboratory.

Sample preparation and test parameters used in this study followed that of TxDOT Tex-248-F testing specifications. These include:

- 25°C (77°F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and

- Specimen failure defined as 93% reduction in Initial Load.

Recent work conducted by the TTI has shown that the test results of the Overlay Tester correlate very well to wheel path cracking, as compared to the measured wheel-path cracking at the FHWA's ALF facility (Zhou et al., 2007). The ALF provided an excellent tool for comparison since the pavement structure used in the comparison (Lanes 2 through 6) had the identical pavement structure, HMA thickness, testing temperature and loading conditions (speed and weight). Therefore, the only difference that could have caused a pavement failure was the mixtures themselves. Figure 51 shows the correlation generated between the Overlay Tester results (conducted on field cores) and the measured number of ALF loading passes until 50% of the wheel path area achieved fatigue cracking.

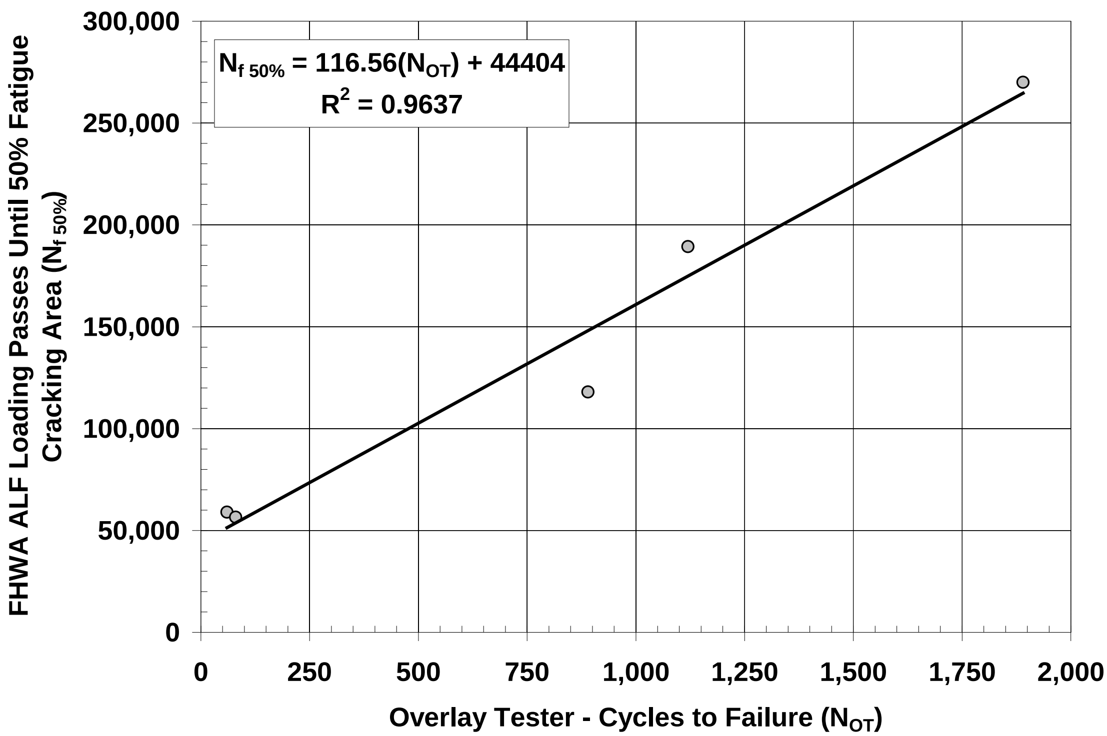
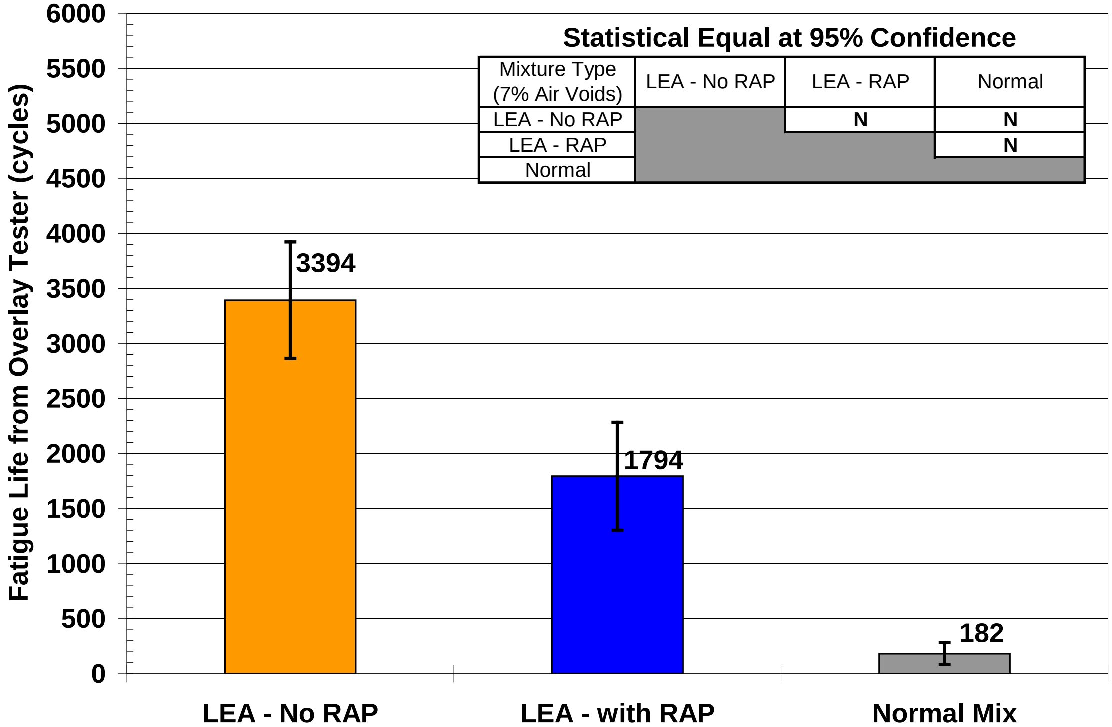


Figure 51. Correlation Between Overlay Tester Results and FHWA's ALF Fatigue Cracking

Overlay Tester Results at 7% Air Voids

Figure 52 shows the Overlay Tester results for the specimens compacted to a target density of 7% air voids. The results show that the "Normal" HMA mixture achieved the lowest number of Overlay Tester fatigue cycles, while the "LEA – No RAP" achieved the greatest number of Overlay Tester fatigue cycles.



Mixture Type (7% Air Voids)	LEA - No RAP	LEA - RAP	Normal
LEA - No RAP		N	N
LEA - RAP			N
Normal			

Figure 52. Overlay Tester Results for 7% Air Void Samples

Overlay Tester Results at 3.5% Air Voids

Figure 53 shows the Overlay Tester results for the specimens compacted to a target density of 3.5% air voids. The test results show an identical trend to the test results on the 7% air void samples, although the magnitude of the number of Overlay Tester fatigue cycles is greater for the 3.5% air void samples.

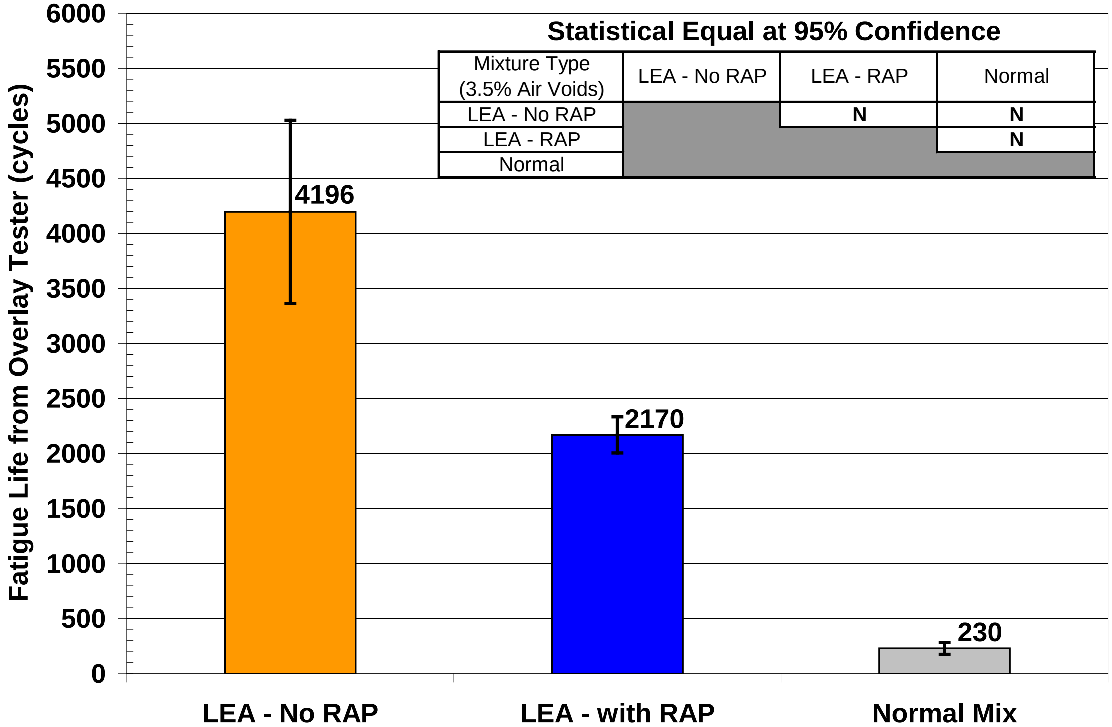


Figure 53. Overlay Tester Results for 3.5% Air Void Samples

Summary of Overlay Tester Testing

The Overlay Tester test results showed that;

1. Oxidation aging and additional asphalt binder absorption, occurring from the production temperature difference of approximately 80 to 90^{o}F, significantly decreased the HMA mixture fatigue cracking resistance. The Overlay Tester fatigue testing indicated that an order of magnitude increase (**10 times greater**) in fatigue life was achieved by using the LEA technology instead of "Normal" production temperatures. This was illustrated by comparing the number of fatigue life loading cycles of the "Normal" mix to the "LEA with RAP" samples.
2. The addition of RAP to the mixture decreased the fatigue life, as measured in the Overlay Tester, by approximately 50%. This is illustrated by comparing the "LEA – with RAP" mixture results to the "LEA – No RAP" test results.
3. The Overlay Tester results indicated that there was approximately a 20% reduction in fatigue life due to difference in air void level, with greater fatigue life be obtained with lower air void levels (3.5% versus 7% air voids).

Repeated Load Permanent Deformation – Flow Number (F_N)

Repeated Load Permanent Deformation tests were conducted in uniaxial compression following the procedures outlined in Appendix B of NCHRP Report 465, *Simple Performance Test for Superpave Mix Design* (Witczak et al., 2002). The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 50^{o}C, which, on average, corresponds to the 50 percent reliability, 7-day average maximum pavement temperature at a depth of 20 mm for New York State according the LTPPBind 3.0 software (FHWA, 2005). These testing parameters (temperature and applied stress) conform to the recommendations currently proposed in NCHRP Project 9-33, *A Mix Design Manual for Hot Mix Asphalt*. Testing was conducted until a permanent vertical strain of 5% or 10,000 cycles was obtained. The research conducted in NCHRP Report 465 showed that the Flow Number showed excellent correlation to rutting measured in field at the MnRoad, FHWA ALF, and WesTrack facilities. Therefore, the Flow Number has been identified as a HMA rutting performance indicator.

Flow Number Results of 7% Air Void Samples

The Repeated Load test results for the 7% air void samples are shown in Figure 54. The Flow Number results clearly indicate that the LEA produced mixtures are more prone to permanent deformation than the “Normal” mixture, even at 7% air voids. The test results also show that at an air void level of 7%, the addition of RAP in the LEA produced samples only slightly increased the mixture’s resistance to permanent deformation.

Flow Number Results of 3.5% Air Void Samples

The Repeated Load test results for the 3.5% air void samples are shown in Figure 55. Again, the Flow Number results indicated that the “Normal” mix achieved the highest Flow Number (i.e. - greatest resistance to permanent deformation), while the “LEA – No RAP” sample achieved the lowest Flow Number value (i.e. – more susceptible to permanent deformation). However, the test results of the 3.5% air voids also showed that the “LEA – with RAP” mix was far more comparable at 3.5% air voids than 7% air voids. This indicates that compacting to better densities can help to achieve better resistance to permanent deformation.

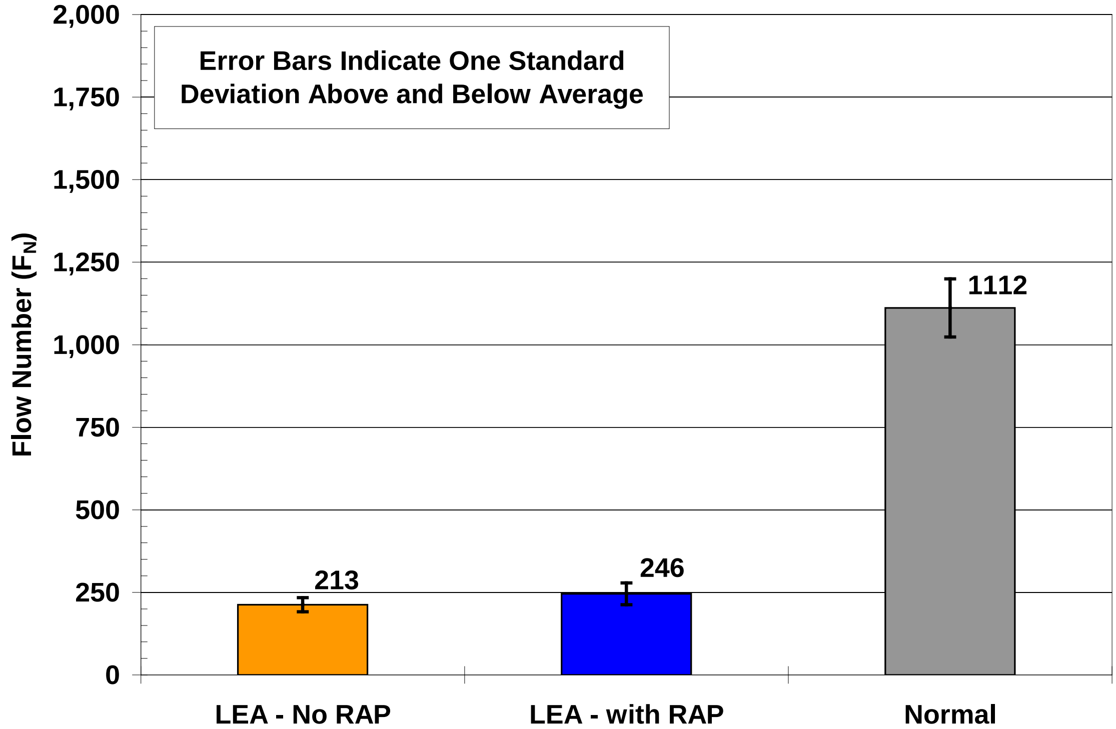


Figure 54. Flow Number Results of 7% Air Void Specimens

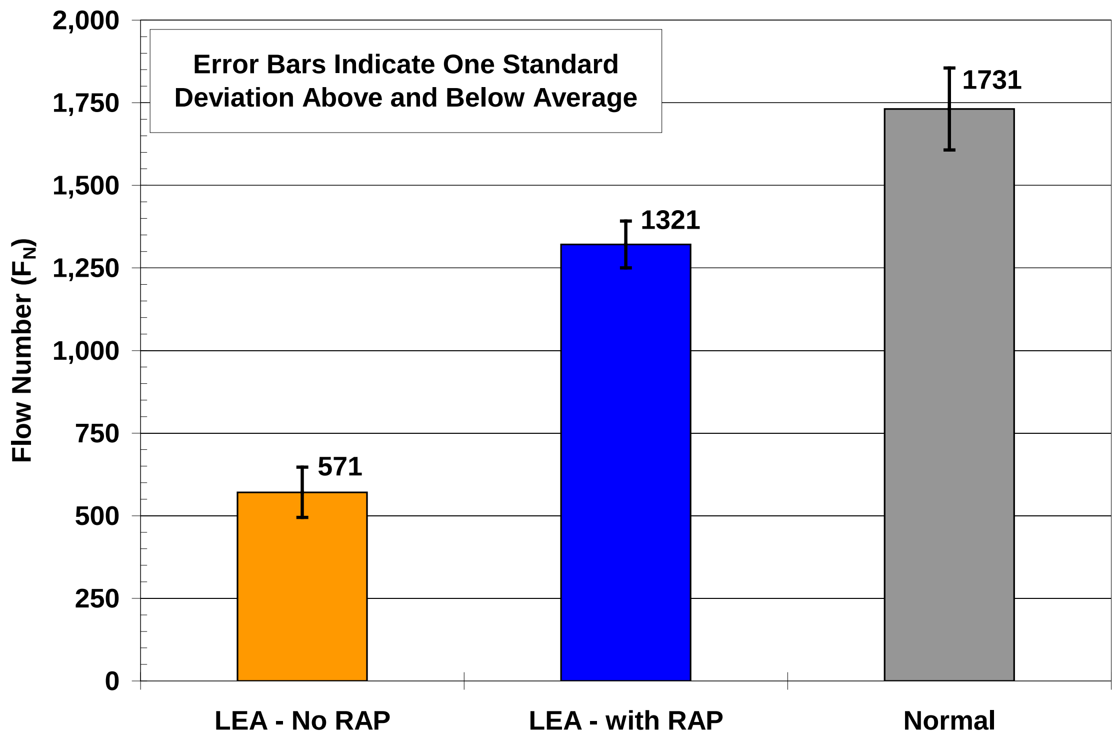


Figure 55. Flow Number Results of 3.5% Air Void Specimens

Summary of Repeated Load (Flow Number) Testing

The Repeated Load (Flow Number) testing showed that;

1. The “Normal” mix, produced at normal production temperatures, has a greater resistance to permanent deformation than either of the LEA produced mixtures. On average, the “Normal” mix achieved Flow Number values 62% higher than the LEA produced mixes, with a larger difference shown at the higher air voids.
2. The addition of RAP increased the permanent deformation resistance of the LEA produced mixtures, but had a more beneficial impact at 3.5% air voids than at 7% air voids. This shows that not only is mixture stiffness (modulus) at high temperatures important to resist permanent deformation, but so is the density at which the mixture is compacted. On average, achieving better density (going from 7% air voids to 3.5% air voids) increased the Flow Number by 60%, with more of an influence occurring in the lower modulus mixtures (LEA mixes).

Conclusions for NYSDOT LEA WMA Evaluation

Overall, the LEA produced mixtures had lower modulus, higher resistance to fatigue cracking, and lower resistance to permanent deformation than the conventionally produced HMA mixture (“Normal”). The addition of 15% RAP to the LEA produced mixture helped in increasing the high temperature modulus and resistance to permanent deformation. Although the addition of 15% RAP to the LEA mixture decreased its resistance to fatigue cracking, as measured in the Overlay Tester, the fatigue results were still an order of magnitude (10 times) greater than “Normal” mixture, indicating that the addition of RAP to LEA produced mixtures may be beneficial to its overall performance.

As expected, the mechanical properties of the mixtures were affected by the compacted density of the mixtures. Permanent deformation and fatigue cracking resistance increased as the air void level decreased from 7% to 3.5%, while mixture stiffness (modulus) only slightly increased.

NJ I78 Asphalt Rubber OGFC – Evotherm 3G

In August 2009, an asphalt rubber open graded friction course (AR-OGFC) was being placed on I78 by Stavola Company. Traditionally, due to the higher production temperatures associated with the production of asphalt rubber mixes, a large amount of emissions are commonly produced and found hovering around the paving train (Figure 56). To help eliminate this issue, a warm mix additive (Evotherm 3G) was preblended in the base asphalt binder to allow for lower production temperatures, thus lower amount of emissions around the paver.

To evaluate this concept, Rutgers University measured the emissions behind the paver using a portable air quality measuring device (Figure 57). The device was mounted onto the rear of the paver and recorded the emissions from the start of the night, where the contractor was still using conventional temperatures, through the use of the WMA.

Figure 56. Photo of Emissions Due to Paving an Asphalt Rubber OGFC Mixture

Figure 57. Portable Air Quality Measurement Device

An example of the recorded data is shown in Figure 58. The results clearly showed a tremendous decrease in the recorded emissions, as illustrated in Figure 58 (Hydrocarbons). The results indicated that at the peak of using the WMA, the hydrocarbon output was approximately 15 ppm. However, when the contractor brought the temperature of the mix back up to typical asphalt rubber production temperatures, the hydrocarbon output jumped to approximately 110 ppm.

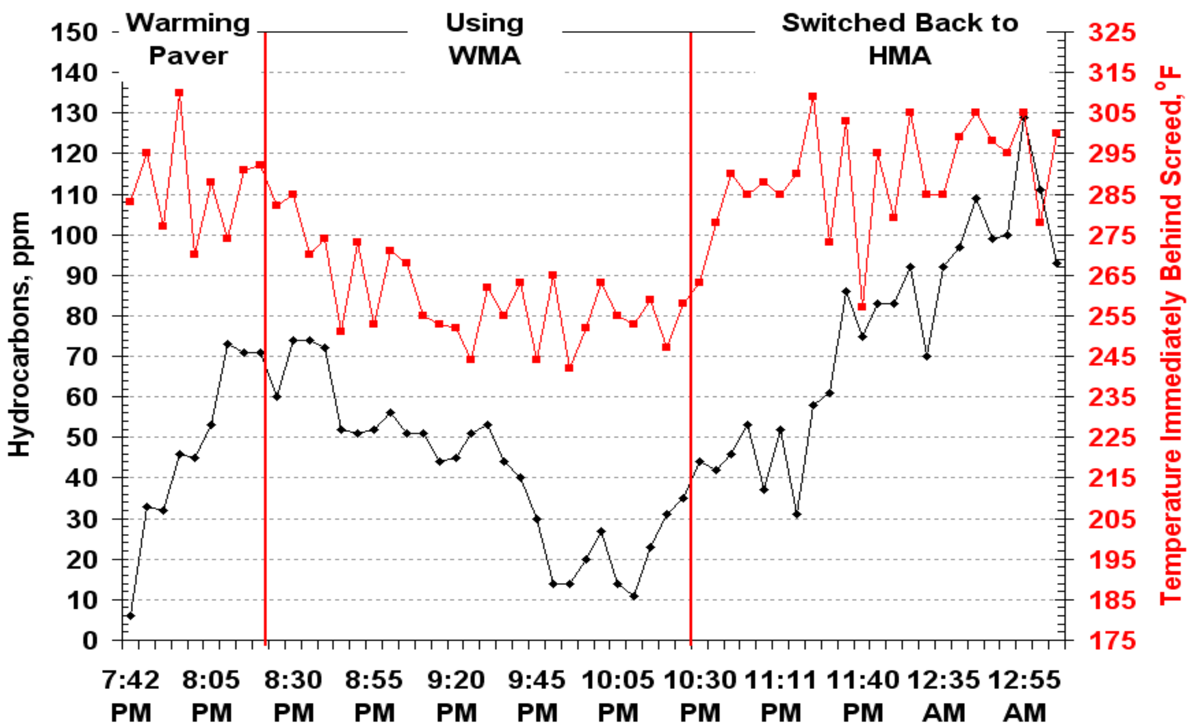


Figure 58. Recorded Emissions Behind the Paver During HMA and WMA Production

NJ Rt 1 Stone Matrix Asphalt – Evotherm 3G

In October 2009, Trap Rock Industries (TRI) was placing a stone matrix asphalt (SMA) mixture on NJ Rt 1. According to specifications, an SMA mixture is required to include cellulose fibers to mitigate draindown of the asphalt binder. Most asphalt suppliers and contractors dislike the use of fibers due to production and placement issues associated with homogeneous mixing. Therefore, Trap Rock Industries approached NJDOT with the possibility of using a warm mix additive to reduce production temperatures, thereby increasing the asphalt viscosity, and resisting draindown without the need of fibers.

To evaluate this concept, two asphalt mixtures were produced and placed on NJ Rt 1; a conventional SMA with fibers and a WMA SMA with no fibers. Laboratory testing, included draindown testing using virgin aggregates and binder, as well as the Asphalt Pavement Analyzer, Hamburg Wheel Tracking, Overlay Tester, and Dynamic Modulus were conducted on collected loose mix during plant production.

Draindown Tests (AASHTO T305)

Draindown testing was conducted on the SMA mixtures produced at the Rutgers Asphalt/Pavement Laboratory in accordance with AASHTO T305, *Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures*. A summary of the test results are shown in Table 18. Table 18 clearly indicates that as the mixing/test temperature decreases, so does the resultant asphalt binder draindown. It can be assumed that this is mainly due to an increase in the asphalt binder viscosity due to the reduction in temperature. To pass the NJDOT specifications, an asphalt mixture can not have more than 0.1% of draindown.

Table 18 - Summary of Draindown Results from Rt 1 WMA SMA with No Fibers

Mixture ID	Temperature (F)		Percent Draindown
	Mixing	Testing	
Normal SMA	325	325	0.08
WMA SMA #1 (No Fibers)	325	325	0.19
WMA SMA #2 (No Fibers)	290	290	0.08
WMA SMA #3 (No Fibers)	255	255	0.06

The above experiment was provided as evidence to the NJDOT that the use of a WMA additive, one that can provide lubrication during compaction while not influencing the viscosity properties of the asphalt binder, could be used in lieu of fibers to resist draindown in gap graded asphalt mixtures. During production, there were no reported issues with draindown and the contractor reported that the mixture compacted and rolled in a similar manner to the normal SMA produced on the job.

Mixture Stiffness – Dynamic Modulus (E*)

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP62, *Standard Test Method for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*. The data was collected at three temperatures; 4, 20, and 35^{o}C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz. Test specimens were tested in triplicate and averaged.

The collected modulus values of the varying temperatures and loading frequencies were used to develop Dynamic Modulus master stiffness curves, as described previously in this report. The master stiffness curves of the normal production and WMA produced SMA mixtures are shown in Figure 59. As expected, the normal production temperature SMA resulted in high stiffness properties than the WMA SMA with no fibers. The difference is most likely a combination of lower oxidative aging of the asphalt binder, as well as higher effective asphalt content in the WMA SMA mixture.

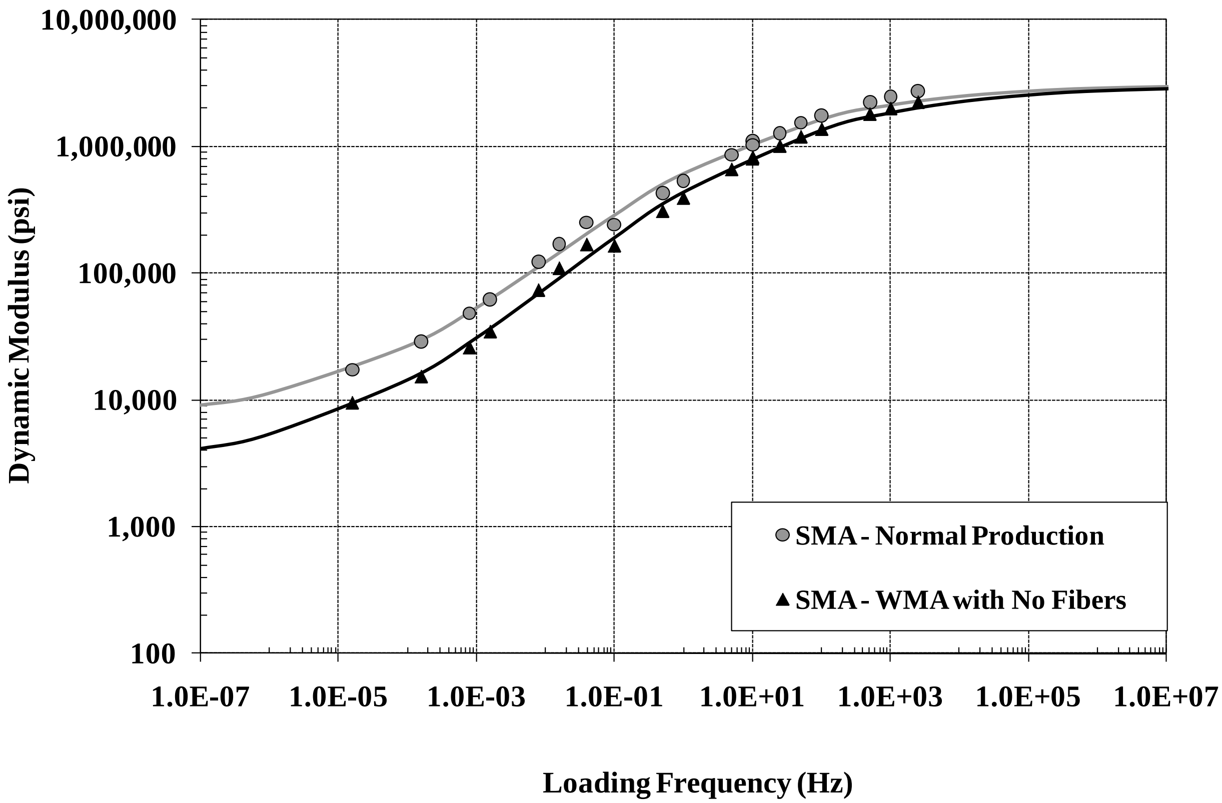


Figure 59. Master Stiffness Curves of Normal Production and WMA Production with No Fibers SMA

<u>Hamburg Wheel Track Test (AASHTO T324)</u>

Hamburg Wheel Track tests were conducted in accordance with AASHTO T324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. Test specimens, compacted between 5.5 to 6.5% air voids, were tested at a test temperature (water) of 50^oC.

The test results of the Hamburg Wheel Track testing are shown in Figure 60. The test results show that both mixtures are highly resistant to rutting and stripping when tested in the Hamburg device. Although the NJDOT does not have a requirement for the Hamburg test, the TxDOT specification is shown in Figure 60 as a general guide. The figure clearly indicates that both mixtures are well above the maximum Hamburg rutting. However, it should be noted that the WMA SMA mixture rutted slightly more in the Hamburg device than the normal production SMA.

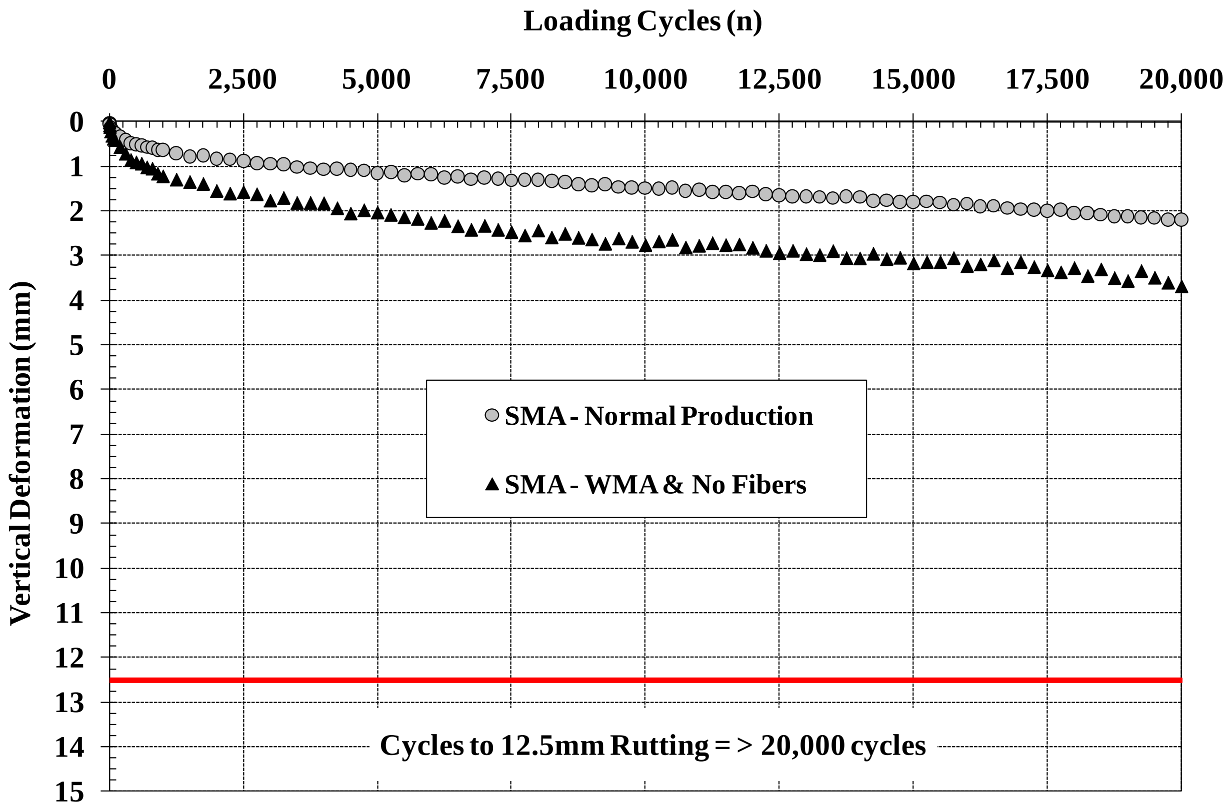


Figure 60. Hamburg Wheel Tracking Test Results for NJ Rt 1 SMA WMA Pilot Project

Overlay Tester (TxDOT Tex-248-F)

The Overlay Tester, described by Zhou and Scullion (2007), has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2007; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007). Sample preparation and test parameters used in this study followed that of TxDOT Tex-248-F testing specifications. These include:

- 25^{o}C (77^{o}F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in Initial Load.

The test results for the Overlay Tester testing are shown in Table 19. The Overlay Tester results show that the WMA SMA was able to achieve a fatigue life almost 10 times greater than the normal production SMA. Again, as indicated earlier, the fatigue resistance most likely increased due to an increase in effective asphalt content due to lesser asphalt binder absorption and reduced oxidative aging/stiffening of the asphalt binder.

Table 19 - Overlay Tester Results for NJ Rt 1 SMA Pilot Project

SMA - Normal Production			
Sample ID	**Temp (F)**	**Displacement (inches)**	**Fatigue Life (cycles)**
# 1	77 F	0.025"	2,126
# 2			2,425
# 3			1,458
Average (Trimmed Mean) =			**2,003**

SMA - WMA with No Fibers			
Sample ID	**Temp (F)**	**Displacement (inches)**	**Fatigue Life (cycles)**
# 1	77 F	0.025"	10,472
# 2			27,855
# 3			16,255
Average (Trimmed Mean) =			**18,194**

Conclusions from NJ Rt 1 WMA SMA Pilot Project

The evaluation of the NJ Rt 1 WMA SMA pilot project indicated that gap graded asphalt mixtures, which require the addition of cellulose fibers, can be successfully produced and compacted without the use of the cellulose fibers by reducing production temperatures to increase asphalt binder viscosity while using a WMA technology to provide workability and compactability.

The performance of the WMA SMA mixture generally showed similar performance to the other WMA mixtures evaluated in this study. The WMA SMA mixture had higher fatigue resistance, lower mixture stiffness and lower permanent deformation resistance than the normal production SMA.

NJ I280 WMA High Performance Thin Overlay (HPTO) – Evotherm 3G and Rediset

In November 2009, a high performance thin overlay (HPTO) mixture proposed to be placed on NJ I280. However, due to the paving time air temperatures, and the requirement of the PG76-22 asphalt binder, the contractor was worried about not achieving the compacted density requirements. Therefore, it was proposed to utilize a WMA additive, preblended in the asphalt binder, to aid in the cold weather paving of the HPTO.

The majority of the project utilized the Evotherm 3G additive to produce the WMA HPTO. However, a small section was produced using the Rediset additive as well. Loose mix was sampled during production and reheated and compacted at the Rutgers Asphalt Pavement Laboratory to provide performance specimens for evaluation. The loose mix was reheated to compaction temperature, which was approximately 270 to 280^{o}F, for all performance specimens tested.

Field Density from Field Cores

During production, the NJDOT collected field cores during normal QC practices. The results from the field cores were provided to the Rutgers Asphalt Pavement Laboratory (RAPL) for presentation purposes in this report. Testing conducted by NJDOT indicated that the average air voids of the Evotherm cores was 4.6%, while the average air voids for the Rediset cores was 5.7%. However, it should be noted that the number of cores collected for each mix was different; Evotherm = 35 cores; Rediset = 5 cores.

Dynamic Modulus (AASHTO TP79)

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79*, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The data was collected at three temperatures; 4, 20, and 45^{o}C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz. The test specimens were tested in duplicate and averaged for reporting and analysis. The final test specimens were prepared to final air void levels between 4.5 and 5.5%, which represent the average air void range found in the collected field cores.

Master stiffness curves of the two WMA High Performance Thin Overlay (WMA-HPTO) mixtures are shown in Figure 61. The master curves show that at the low temperatures (higher loading frequencies) the Rediset WMA-HPTO stiffness was slightly lower, while at the higher temperatures (lower loading frequencies) the Rediset WMA-HPTO stiffness was again slightly higher. However, the stiffness of the mixtures for each temperature and loading frequency were found to be statistically equal at a 95% confidence interval.

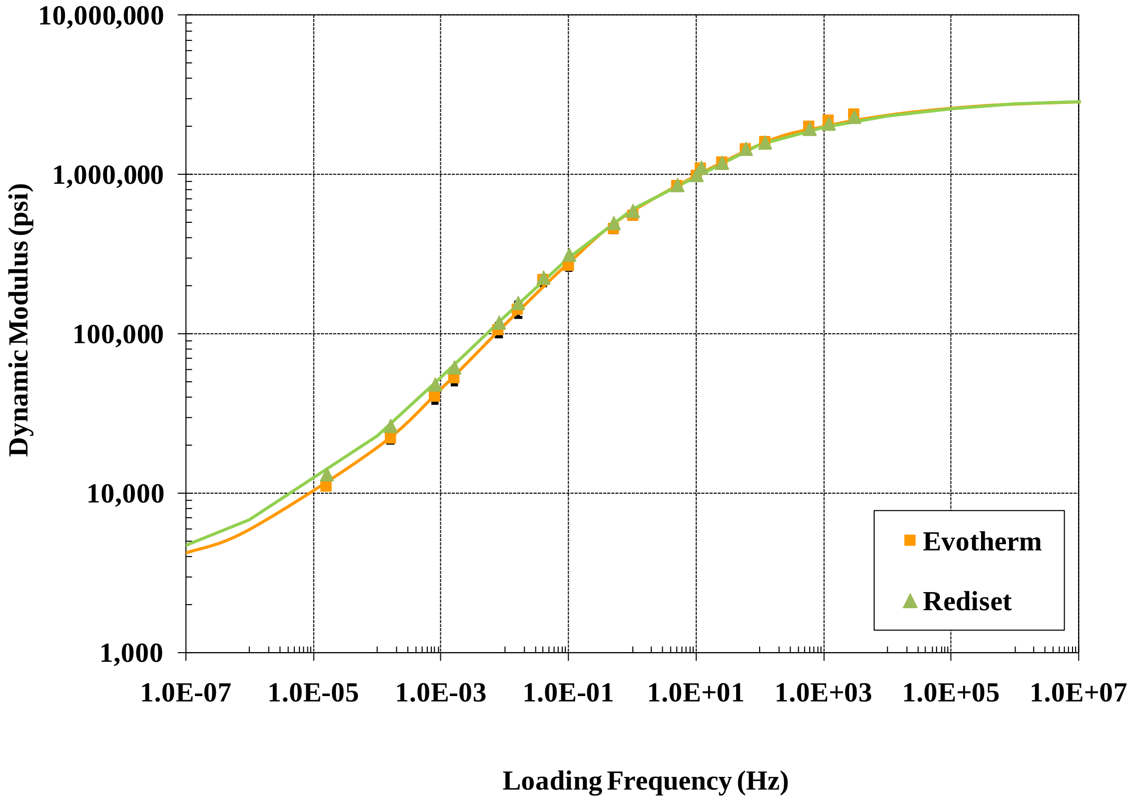


Figure 61. Dynamic Modulus Test Results of Evotherm and Rediset WMA-HPTO

Repeated Load Permanent Deformation – Flow Number (F_N)

Repeated Load permanent deformation testing was measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79*, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 54.4^{o}C. Testing was conducted until a permanent vertical strain of 5% or 10,000 cycles was obtained.

The test results for the Flow Number testing are shown in Table 20. The test results indicate that the Rediset WMA-HPTO achieved higher Flow Number values, meaning that Rediset WMA-HPTO mixtures should be more rut resistant in the field.

Table 20 - Repeated Load (Flow Number) Test Results for WMA-HPTO Mixes

Mix Type	Sample ID	Flow Number (cycles)	Cycles to Achieve 5% Strain
Evotherm WMA-HPTO	1	795	1,958
	2	539	1,644
	3	692	2,333
	Average	***675***	***1,978***
Rediset WMA-HPTO	1	1,256	3,311
	2	1,453	3,573
	3	1,489	3,859
	Average	***1,399***	***3,581***

Overlay Tester (TxDOT Tex-248-F)

Sample preparation and test parameters used in this study followed that of TxDOT Tex-248-F testing specifications. These include:

- 25^oC (77^oF) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in Initial Load.

The test results for the Overlay Tester testing are shown in Table 21. The test results indicate that the average fatigue life of the Evotherm WMA-HPTO was approximately twice as high as the Rediset WMA-HPTO. When evaluating the results statistically, it was found that the Evotherm results were statistically Not Equal to the Rediset results at a 95% confidence interval.

Hamburg Wheel Track Test (AASHTO T324)

Hamburg Wheel Track tests were conducted in accordance with AASHTO T324, *Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. Test specimens, compacted between 4.5 to 5.5% air voids, were tested at a test temperature (water) of 50^oC.

The test results of the Hamburg Wheel Track testing are shown in Figures 62 and 63. Figure 62 contains the test results of the Evotherm WMA-HPTO and Figure 63 contains the results of the Rediset WMA-HPTO. The test results between the two additives were conflicting. The Evotherm WMA-HPTO had a slightly higher Inflection Point (8,500 to 7,175 cycles, respectively) than the Rediset WMA-HPTO. Meanwhile, the Rediset WMA-HPTO had a slightly higher number of cycles until 12.5mm of rutting than the Evotherm WMA-HPTO (17,550 to 16,375 cycles, respectively).

Table 21 - Overlay Tester Results for Evotherm and Rediset WMA-HPTO

HPTO with Rediset			
Sample ID	**Temp (F)**	**Displacement (inches)**	**Fatigue Life**
# 1	77 F	0.025"	162
# 2			112
# 3			88
# 4			70
# 5			169
Average =			**120**
Standard Deviation =			**44**
Coefficient of Variation =			**37**

HPTO with Evotherm			
Sample ID	**Temp (F)**	**Displacement (inches)**	**Fatigue Life**
# 1	77 F	0.025"	293
# 2			236
# 3			289
# 4			173
# 5			244
Average =			**236**
Standard Deviation =			**48**
Coefficient of Variation =			**20**

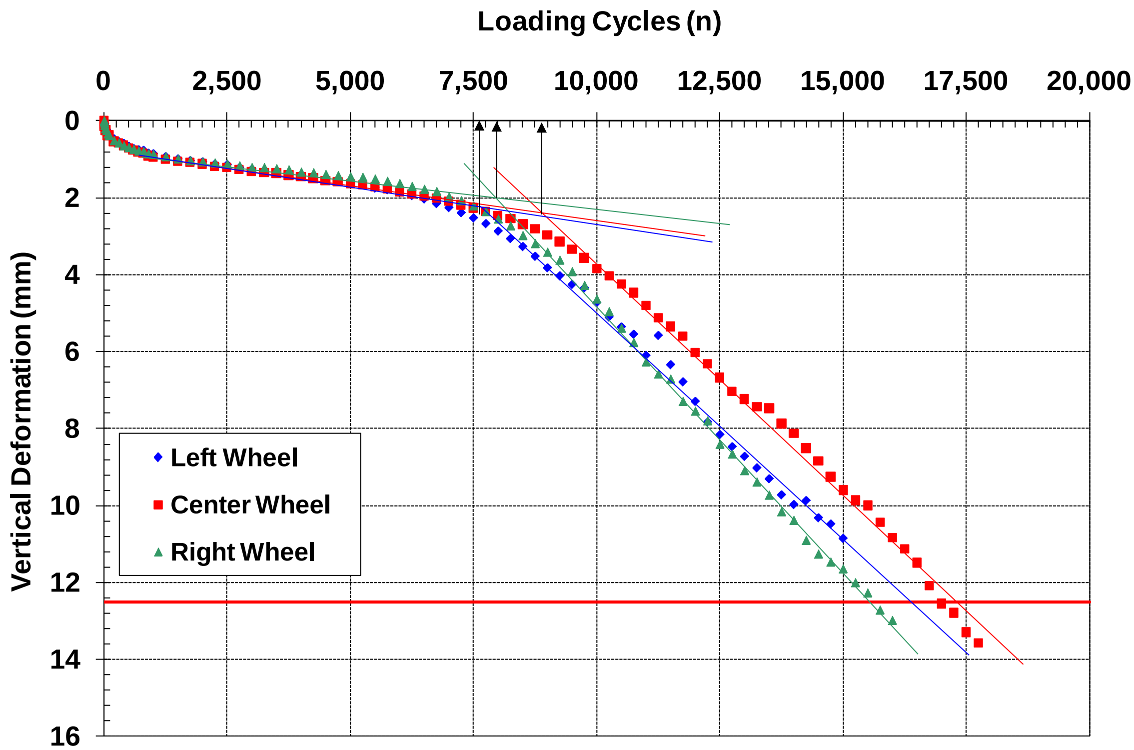


Figure 62. Hamburg Wheel Track Test Results for Evotherm WMA-HPTO

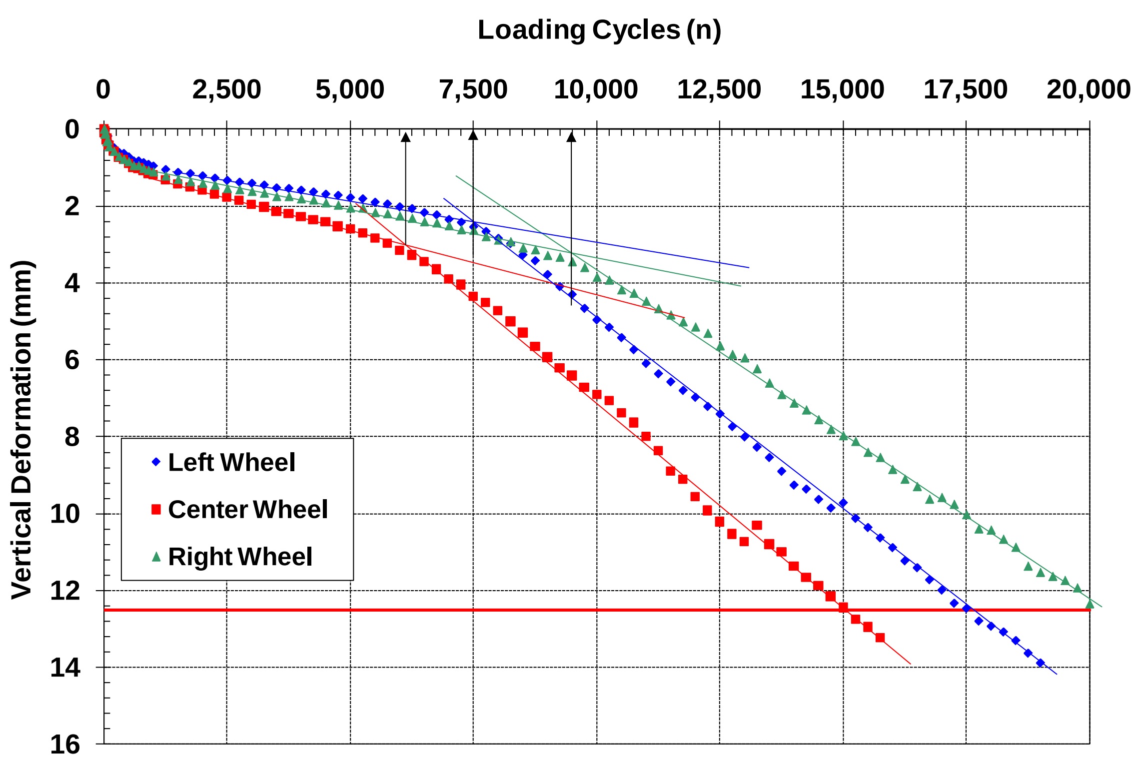


Figure 63. Hamburg Wheel Track Test Results for Rediset WMA-HPTO

Asphalt Pavement Analyzer (AASHTO TP63)

The Asphalt Pavement Analyzer (APA) was conducted in accordance with AASHTO TP63, *Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer (APA).* A hose pressure of 100 psi and a wheel load of 100 lb were used in the testing. A test temperature of 64°C was selected for testing to correspond with the base high temperature PG grade of New Jersey. Testing was continued until 8,000 loading cycles and APA rutting deformation was recorded at each cycle.

Prior to testing, each sample was heated for 6 hours (+/- 15 minutes) at the testing temperature to ensure temperature equilibrium within the test specimen was achieved. Testing started with 25 cycles used as a seating load to eliminate any sample movement during testing. After the 25 seating cycles completed, the data acquisition began sampling test information until a final 8,000 loading cycles was reached.

The APA test results for the Evotherm and Rediset WMA-HPTO are shown in Figure 64 and 65. On average, the test results indicate that Rediset WMA-HPTO had a slightly lower APA rutting than Evotherm WMA-HPTO. However, when evaluating the results statistically using a Student t-test, the APA rutting results were found to be statistically equal at a 95% confidence level.

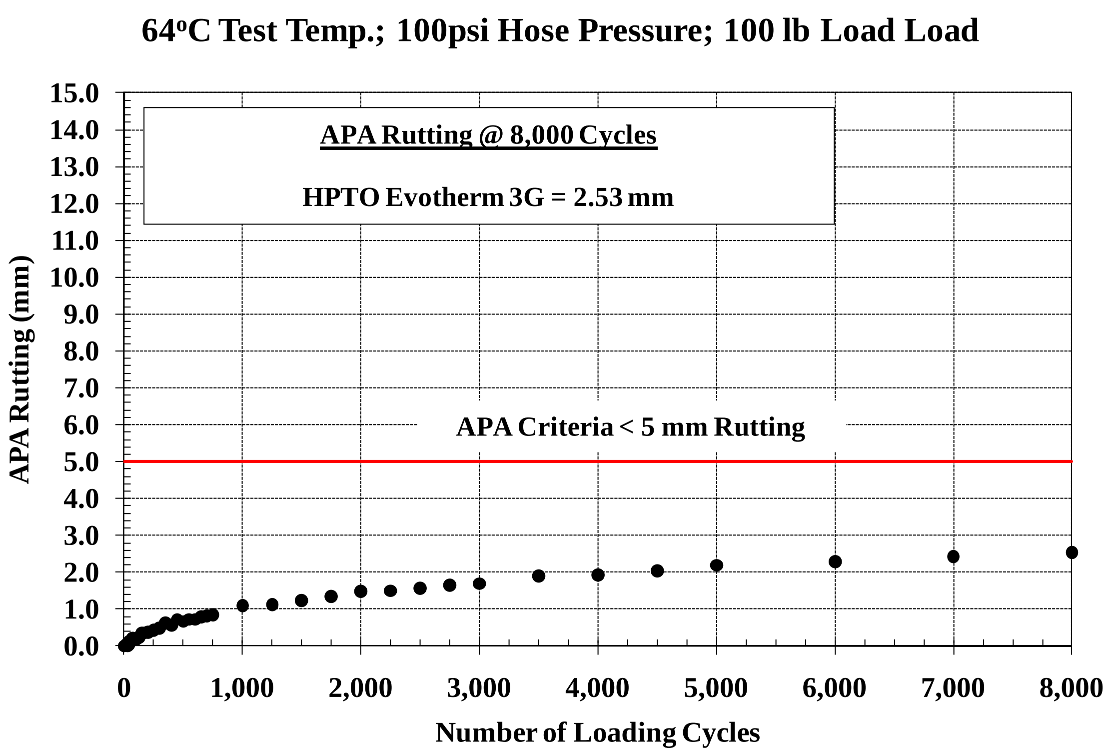


Figure 64. APA Rutting for Evotherm WMA-HPTO

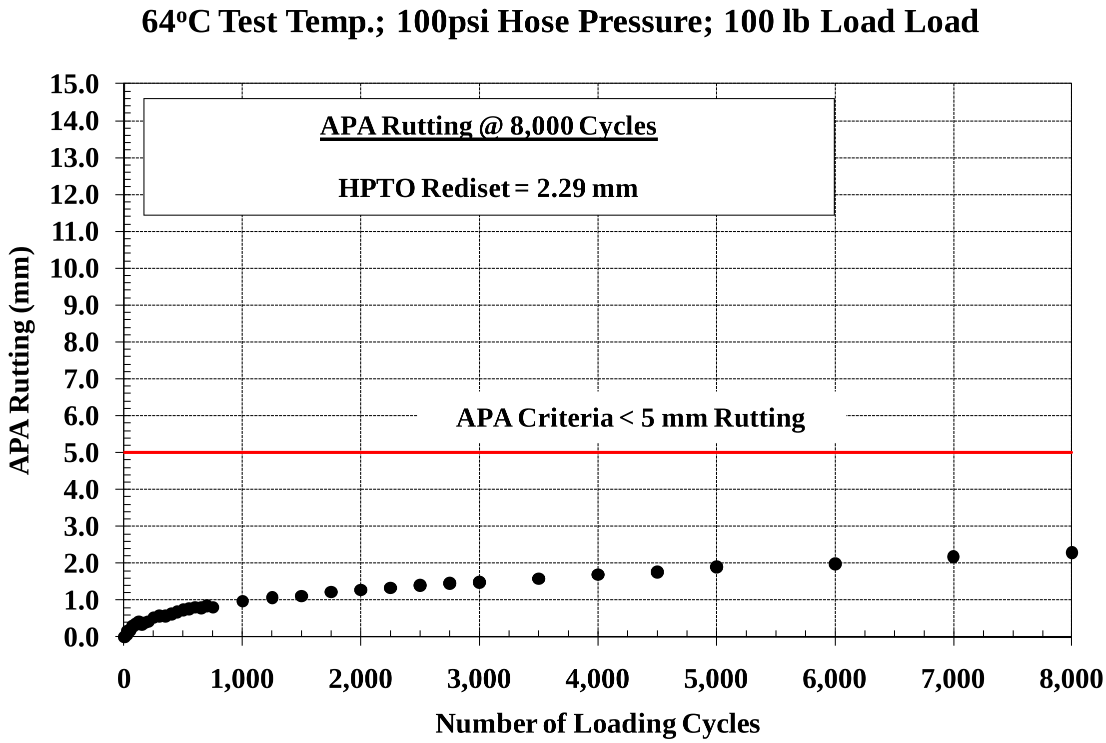


Figure 65. APA Rutting for Rediset WMA-HPTO

Tensile Strength Ratio, TSR (AASHTO T283)

The potential for moisture damage was evaluated using the Tensile Strength Ratio (TSR) in accordance with AASHTO T283, *Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*. However, it should be noted that the test specimens were not compacted to 6.5 to 7.5% air voids, as is specified in AASHTO T283. Since the compacted air voids of the HPTO is much lower, generally in the 4 to 5% range, it was determined that the compacted air voids of the test specimens should match those found in the field cores.

The final TSR results for the two WMA-HPTO mixes are shown in Table 22. The results indicate that both WMA-HPTO mixtures performed fairly well with respect to resisting moisture damage. However, the Rediset WMA-HPTO performed slightly better than the Evotherm WMA-HPTO mixture.

Table 22 - Tensile Strength Ratio (TSR) Test Results

Evotherm 3G HPTO			
Specimen Type	Indirect Tensile Strength		Average TSR (%)
	Dry	Conditioned	
AASHTO T283 Conditioned	161.2	145.8	***97.5%***
	155.8	160.6	
	158.5	157.2	
	158.5	***154.5***	

Rediset HPTO			
Specimen Type	Indirect Tensile Strength		Average TSR (%)
	Dry	Conditioned	
AASHTO T283 Conditioned	159.9	157.2	***104.4%***
	151.7	159.1	
	136.1	151.2	
	149.3	***155.8***	

Conclusions from NJ I280 WMA HPTO Pilot Project

Asphalt mixture characterization testing was conducted on two different warm mix asphalt technologies, Evotherm 3G and Rediset, which were incorporated into a NJDOT High Performance Thin Overlay (HPTO) mixture. The mixtures were produced through the asphalt plant and loose mix sampled prior to leaving the plant. The loose mix was brought back to the Rutgers Asphalt Pavement Laboratory (RAPL), where the material was reheated to compaction temperature and then compacted into performance samples. The testing of the performance samples indicated;

- The Rediset WMA-HPTO had a slightly higher stiffness at intermediate and higher temperatures, while also achieving lower stiffness at low temperatures.
- The rutting resistance testing of the mixtures indicated that the Rediset WMA-HPTO mixture was more resistant to permanent deformation than the Evotherm 3G WMA-HPTO. Testing in the Asphalt Mixture Performance Tester (AMPT) for Flow Number showed that the Rediset WMA-HPTO achieved higher number of cycles than the Evotherm mixture. Meanwhile, in the Asphalt Pavement Analyzer (APA), the Rediset WMA-HPTO had lower rutting than the Evotherm WMA-HPTO.
- The fatigue cracking resistance testing of the mixtures indicated that the Evotherm 3G WMA-HPTO was more resistant to fatigue cracking than the Rediset WMA-HPTO. Testing in the Overlay Tester indicated that the Evotherm WMA-HPTO achieved almost twice the number of cycles to fatigue cracking than the Rediset WMA-HPTO.
- Moisture damage testing showed conflicting results. In the Hamburg Wheel Track testing, the Evotherm WMA-HPTO achieved more cycles prior to the on-

set of the Inflection Point (or point of stripping), while the Rediset WMA-HPTO achieved more cycles until 12.5mm of rutting was achieved. Meanwhile, TSR results showed both mixtures had a relatively low potential for moisture damage, with the Rediset WMA-HPTO achieving a slightly better TSR value than the Evotherm WMA-HPTO.

CONCLUSIONS AND RECOMMENDATIONS

An extensive study was undertaken to begin to evaluate and understand the general performance of warm mix asphalt (WMA). The study comprised of a scoping study, to laboratory characterization and evaluation, to pilot projects produced and placed in the field. Based on the work conducted in this study, the following conclusions can be drawn:

- A number of WMA technologies currently exist that range from chemical packages, organic waxes, and foaming type systems. However, based on the scoping study evaluation, it was determined that the NJDOT would best benefit from these technologies when utilizing them as compaction aids (i.e. – increasing compactability of asphalt mixtures) and to reduce emissions during production and placement of asphalt mixtures.
- One of the possible issues with the adoption of WMA is that the reduced production temperatures associated with production may not thoroughly dry the aggregate blend, which could lead to moisture damage/stripping issues. Laboratory work conducted in this study demonstrated that moist aggregates heated at reduced mixing temperatures will be more prone to moisture damage than dry aggregates, as evaluated with the tensile strength ratio (TSR) and Hamburg Wheel Tracking device. The reheating of loose mix from plant produced projects performed differently regarding moisture damage than when testing was conducted on cores. This is most likely due to additional aging and drying that occurs during the reheating process. Care should be taken to accept any moisture susceptibility testing after this reheating process has occurred as it may skew the test results when evaluating WMA.
- Another potential issue with the adoption of WMA is that the reduced production temperatures may not stiffen/age the asphalt binder to the degree of hot mix asphalt. As a result, the WMA may not be as stiff and may be more susceptible to rutting. The laboratory testing conducted throughout the study did indeed show that WMA mixtures were less stiff, especially at high test temperatures. A detailed evaluation indicated that a drop of approximately 80^{o}F in production temperature will ultimately drop the high temperature PG one grade (i.e. – from a PG76 to a PG70). While the rutting potential of the WMA mixtures increased, the fatigue resistance of the WMA mixtures also increased. It is hypothesized that the lower production temperatures; 1) Reduce oxidative aging/stiffening of the base asphalt binder; 2) Reduce asphalt absorption, which increases the effective asphalt content of the asphalt mixture, and 3) Reduces polymer degradation associated with high temperatures. All of these would contribute to an increase in fatigue resistance, while the reduced oxidation aging and increased effective asphalt content would increase rutting potential.

- For acceptance testing, since the main issue of WMA appears to be a higher potential for rutting and moisture damage, it would be prudent for the NJDOT to evaluate a Percent Reduction methodology when evaluating rutting potential of WMA. The Percent Reduction methodology would simply limit the amount of decrease in laboratory rutting tests when compare normal production temperature asphalt mixture to the reduced temperature WMA mixture. As indicated earlier, mixture tests like the Flow Number test, which have performance criteria proposed in NCHRP Project 9-33, can be used as a guideline to limit the drop in production temperature so rutting would not be a problem. Moisture damage should be evaluated on each job on plant produced samples compacted at the asphalt plant's QC laboratory using the tensile strength ratio (TSR) test. This testing should continue to be conducted until the NJDOT feels comfortable with the stripping potential of WMA mixtures.
- To evaluate the general workability of WMA mixtures in the laboratory, a simple and effective test has been recommended based on the Marshall Compactor. The test procedure ranked the compactability/workability of the WMA mixtures the same as the torque-type device commonly associated with testing workability of mixtures. However, the benefit of the Marshall Compactor method is that a majority of state agencies and industry already has this equipment, thereby not requiring them to purchase a separate testing device.
- An assessment of the blending between the RAP and virgin asphalt binders during WMA production indicated that the degree of blending appears to be a function of the RAP content and the temperature at which the mixture is being produced at. At normal temperatures, the 15% RAP mixture showed relatively good blending while the 25% RAP mixture did not. When production temperatures were reduced to 270^{o}F, both RAP contents showed poorer blending characteristics. This evaluation was only based on testing two different mixtures and needs to be further evaluated using different WMA technologies, mixtures, and temperatures.

RECOMMENDATIONS FOR IMPLEMENTATION

The data generated during the study has indicated that warm mix asphalt (WMA) can move forward as an implementable technology for the NJDOT to aid in compaction while reducing the emissions associated with asphalt production and placement. In particular, the following WMA technologies, based on their historical use and experience gained in New Jersey, can be specified:

- Evotherm 3G
- Rediset
- Sasobit

Besides the experience gained in New Jersey, these three WMA technologies are appealing for the following reasons:

1. All three additives can be preblended in the asphalt binder relieving the need of additional equipment to incorporate these additives during the mixing process as the asphalt plant.

2. All three additives have potential to help with moisture damage when used at recommended dosage levels. Both the Evotherm 3G and Rediset products include an anti-strip agent into their chemical package while Sasobit generally stiffens the asphalt mixture making it less prone to stripping potential.

Although there are currently new WMA technologies on the market that have been advertised to perform similar to the above technologies (i.e. – SonneWarm, Cecabase, etc.), these additives were not available at the inception of the study and therefore could not be properly evaluated. Also, since none of the foamed technologies were evaluated, these too are not recommended yet. It is hopeful that the asphalt suppliers currently incorporating these foaming systems into their asphalt plants will approach the NJDOT for future evaluation.

For the QC acceptance of these products, until field history proves differently, it is recommended that the NJDOT evaluate their rutting potential using the Flow Number test and the moisture damage susceptibility using the tensile strength ratio (TSR) test. With much of the United States only having WMA down for a limited time, long term performance, especially stripping potential, is still questionable.

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