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16. Abstract

During the first half of this research study, TxDOT had only placed 1000 tons of warm mix asphalt (WMA) as part of a demonstration project. By the end of this three year study, TxDOT had placed more than 1,000,000 tons of WMA and allowed its use in all dense-graded mixtures through the implementation of a special provision 341---020. This research project was focused on evaluating all aspects of WMA and identifying the effects of WMA technologies on mixture design, lab performance characteristics, and field performance. An ongoing implementation study is underway to continue to monitor performance of WMA field sections.

Researchers found that WMA technologies improve the compactability of mixtures which can lead to a reduction in design asphalt content if incorporated in the mixture design process. Laboratory tests indicate that warm mix asphalt is initially less stiff than hot mix but stiffens considerably during the first year of service and with increases in laboratory oven curing time/temperature. Field performance of warm mix projects has, thus far, been comparable to hot mix projects. X-ray CT and ground penetrating radar testing indicate the uniformity of WMA construction may be better than that for hot mix construction.

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FIELD AND LABORATORY INVESTIGATION OF WARM MIX ASPHALT IN TEXAS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Joe Button (Texas, # 40874).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objectives of this report.

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Special appreciation is given to the TxDOT project director, Dale Rand, P.E., for providing technical guidance and assistance. Acknowledgement is given to the project monitoring committee for this research project: Mr. David Kopp, Mr. Darwin Lankford, Mr. Harry Bush, and Dr. German Claros. This portion of the research project was completed in cooperation with TxDOT and FHWA.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

INTRODUCTION

Warm mix asphalt (WMA) is generic term for a variety of technologies that allow the producers of hot mix asphalt (HMA) to lower the temperatures at which the material is mixed and placed on the road. Reductions of 50 to 100ºF have been documented. These temperature reductions

- Reduce fuel consumption;
- Enhance compaction;
- Allow for increase in haul distances; and
- Extend the paving season.

This research study was initiated by the Texas Department of Transportation (TxDOT) in 2006 to evaluate WMA as a new technology. Initially, a literature search was completed and published in 2007 as the first research report from this study (Button et al., 2007).

This report documents the results of a laboratory and field evaluation of different WMA technologies. The following materials were selected for the laboratory experiment:

- WMA Additives
  - Evotherm
  - Sasobit
  - Advera
- Aggregate Sources
  - Limestone
  - Sandstone

Mix designs were developed in the laboratory at 3 different mixing and compaction temperatures to evaluate the effects of the WMA additive on selection of asphalt content. The effects of WMA were also evaluated on the following performance properties

- Hamburg Wheel Tracking Test (HWTT);
- Overlay test;
- Resilient modulus;
- Mixture workability and compaction;
- Binder viscosity;
- Surface free energy analyses; and
- Fatigue analysis.

Investigations of field demonstration projects were conducted. Samples of the plant mixes were obtained during construction and lab-molded properties were determined. Field performance of the projects was evaluated after one year of service, and cores were taken and evaluated for the following:

- HWTT,
- Overlay test,
- Indirect tension, and
- Density.

Ground penetrating radar (GPR) was used to assess the uniformity of construction of WMA compared to HMA and X-ray computed tomography (CT) tests were conducted on field cores to evaluate the air void distribution. Falling weight deflectometer (FWD) testing was conducted on one of the WMA that was thick enough to be evaluated as a structural layer.

REVIEW OF RECENT FINDINGS

During the past five years, rising fuel costs and evermore stringent environmental regulations have generated increased interest in WMA technologies as a means for decreasing energy consumption and emissions associated with conventional HMA production and placement. As a result, there has been a meteoric increase in the development of WMA technologies and consequential research activities. Pertinent WMA research findings, published since this project produced Report 5597-1, "A Synthesis of Warm Mix Asphalt," (Button et al., 2007) are proffered.

Laboratory Testing

Although there is no standard measure of workability of asphalt paving mixtures, several researchers have developed empirical tests to measure workability of paving mixtures for comparative purposes. Some researchers have used workability tests in an attempt to determine which WMA technologies provide improved workability, what dosage of WMA additive provides optimum workability, and how the addition of reclaimed asphalt pavement (RAP) in WMA affects workability (Austerman et al., 2009a; Austerman et al., 2009b; Mogawer et al., 2009). As expected, higher quantities of RAP exhibited lower workability.

Bennert et al. (2010) concluded that their workability device and the Marshall compaction hammer ranked the general workability/compactability of the mixtures in a rational order and compared favorably to one another. However, they found that the Superpave gyratory compactor (SGC) was generally insensitive to workability/compactability. They further demonstrated that common asphalt binder tests conducted at conventional mixing and compaction temperatures were insensitive to the different WMA additives and dosage rates. Therefore, they evaluated asphalt binders using the Lubricity Test and found that it was not only sensitive to dosage rate and warm mix additive, but also the rankings compared favorably to compacted mixture tests.

Hanz et al. (2010) also studied the Lubricity Test. Using a lubricating fluids test method from the engine industry (ASTM D 5138, Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine), they developed an asphalt lubricity test using the dynamic shear rheometer (DSR). The new test measures coefficient of friction of binders at various temperatures, loading rates, and normal forces. They correlated lubricity measurements to workability, as defined by the compactive effort required to densify a mixture to 8 percent air voids. Testing was conducted at 195°F to 275°F and indicated a significant reduction in coefficient of friction by the WMA technologies they studied. They concluded that viscosity reduction is not the only mechanism that supports reduced production temperatures for WMAs.

Forfylow and Middleton (2008) and Reyes et al. (2009) evaluated the Double Barrel Green (DBG) process for producing WMA at 265 to 274°F in western Canada. Their evaluations included WMA containing various percentages of RAP and recycled asphalt shingles (RAS). Tensile strength ratios on core specimens and plant production specimens demonstrated that the DBG mixes were not susceptible to moisture damage. Mixtures containing up to 15 percent RAP, some also containing 5 percent RAS, performed similar to virgin WMA mixes; however, higher amounts of recycled materials significantly altered performance. Two years after construction, performance of all sections was good.

Xiao et al. (2010) concluded that rutting resistance of HMA and WMA mixtures (as measured using the Asphalt Pavement Analyzer [APA]) was more related to the aggregate type than to the WMA technology. Their mixtures containing Sasobit® additive yielded the lowest rut depths, while those containing Asphamin® and Evotherm® generally showed APA rutting characteristics similar to the control HMA mixture.

Based on Heavy Vehicle Simulator (HVS) testing, Jones et al. (2010) concluded that the use of any of three unnamed WMA technologies will not significantly influence rutting performance. Laboratory testing similarly indicated that the W MA technologies did not influence fatigue performance. Laboratory testing further indicated that all three mixes tested were potentially susceptible to moisture damage; however, they found no significant difference in the level of moisture sensitivity between the control HMA and the WMA mixtures.

Field Performance

Generally, those agencies that have constructed WMA field tests with corresponding HMA control sections have reported similar performance and no signs of distress, most readily admitting that the monitoring has been conducted for a few months to a few years (Aurilio and Michael, 2008; Wielinski et al., 2009; Hodo et al., 2009; Hurley et al., 2009; Mogawer et al., 2009; Hughes et al., 2009; Reyes et al., 2009; Manolis et al., 2008; Elshafey et al., 2009; Jones et al., 2010).

Researchers in the Province of New Brunswick, Canada conducted some successful (after one year) field trials using various WMA technologies (Evotherm emulsion and Evotherm 3G (Hughes et al., 2009). They reported the usual advantages associated with reduced mixing and compacting temperatures; but they also reported reduced segregation in the WMA, indicating that, although the WMA was very workable, it had a stiffer makeup than the corresponding HMA and thus held the mix together to reduce end-of-truckload segregation. Apparently related to this, several truck drivers remarked that the WMA seemed to be less sticky in the truck box tending to flow smoothly out of the box into the paver. Researchers further stated that the longitudinal joints in the WMA were tighter than those in the HMA.

Elshafey et al. (2009), in qualified statements, similarly reported that their *initial* performance data *suggested* that WMA provided better longitudinal joint performance than HMA. Specifically, after two years in service, the WMA section displayed approximately half of the longitudinal joint cracking as the corresponding HMA section. They attributed this improved performance of the WMA to the very consistent temperature of the newly-placed material (<18ºF variation) as compared to considerable variation (45 to 60°F) in the HMA section (measured by infrared cameras). In particular, the edges of the HMA were up to 60°F lower than the remainder of the material. Tighe et al. (2008) earlier reported that, in their field experiment, longitudinal joints for WMA and HMA performed equivalently.

HyperTherm is a non-aqueous liquid WMA additive from LaFarge. It can be pre-dosed or added in-line to the liquid asphalt. Manolis et al. (2008) reported that a project in the City of Ottawa, Canada included a 4.75 mm mix containing PG 58-28 binder modified with HyperTherm designed for a traffic level of 3 to 10 million equivalent single axle loads (ESALs) and placed at thickness of about 1 inch. The WMA was produced at about 247°F and compacted between 166 and 193°F. They reported that the pavement was performing acceptably after a few months in service. In another experiment, they used HyperTherm to demonstrate that WMA technology can be used to extend the paving season well into Canadian winter while paving at conventional HMA temperatures. They placed a 100 mm material on a frozen base at air temperatures ranging from 35°F down to 8°F. The paving crew commented that the mix was easy to work with. After four months, the pavement was performing acceptably.

Emissions and Energy Savings

Hassan (2009) conducted a generalized assessment of the life-cycle WMA technology as compared to a conventional HMA. He estimated that WMA provides a reduction of 24 percent in air pollution and a reduction of 18 percent on fossil fuel consumption. Overall, he estimated the use of WMA to provide a reduction of 15 percent on the environment impacts. WMA will, of course, not have a direct impact on the other three main production processes for HMA: aggregate production, asphalt refining, and transportation and construction processes.

Aurilio and Michael (2008) reported a fuel savings of 30 percent on a small Sasobit® project in Ottawa, Ontario.

Middleton and Forfylow (2009) reported a 10 percent reduction in carbon monoxide, carbon dioxide, and nitrogen oxides when WMA (Double Barrel Green process) was used in place of conventional HMA. The process also yielded a 24 percent reduction in energy consumption.

Xiao et al. (2009) deduced that the addition of 1.5 percent Sasobit® will generally allow for mixing and paving temperatures about 20°F to 55°F (depending on the mix and project) lower than those for conventional HMA. This resulted in CO_2 emission reductions of around 32 percent from direct reductions; plus, another 8 percent reduction from energy savings is possible. They estimated a joint reduction of about 40 percent.

Based on an industrial hygiene survey, Hurley et al. (2009) asserted that WMA reduced emissions at the paver, on average, 67 to 81 percent, based on total particulates and benzene-soluble matter for three WMA technologies (Asphamin ® zeolite, Sasobit®, and Evotherm™).

CHAPTER 2

EFFECT OF WARM MIX ASPHALT ADDITIVES ON DESIGN OF ITEM 340/341 TEXAS GYRATORY MIXTURES

WMA PROCESSES EVALUATED

To evaluate the effects of WM additives on TxDOT mixture designs, researchers selected three WMA additives that were being used to some extent in the U.S. at the time of this experiment:

- Evotherm,
- Sasobit, and
- Advera.

Evotherm

Evotherm was developed in the U.S. by MeadWestvaco Asphalt Innovations, Charleston, South Carolina (http://www.evotherm.com). Evotherm uses a chemical additive technology customized for aggregate compatibility. The Evotherm technology can be delivered in three different forms as described below.

1) Evotherm ET (Emulsion Technology) – a high asphalt cement (AC) content, water-based asphalt emulsion (~70 percent solids). Evotherm ET requires no plant modifications and simply replaces the liquid asphalt in the HMA design. Evotherm ET allows for temperature reductions greater than 100°F.
2) Evotherm DAT (Dispersed Asphalt Technology) – a concentrated solution of Evotherm additives in-line injected at the mix plant. Evotherm DAT allows for flexibility in switching between warm mix and hot mix production while lowering mix temperatures 85-100°F.

3) Evotherm 3G (Third Generation) – developed in partnership with Paragon Technical Services and Mathy Technology & Engineering, this water-free form of Evotherm is suitable for introducing the additives at the mix plant or asphalt terminal. Evotherm 3G generally lowers mix temperatures 60-85°F (33-45°C).

Each version is reported to contain the same Evotherm additives. For this laboratory study, the DAT process was used at a rate of 0.5% by weight of the asphalt binder. Figure 2.1 shows the product at the Lufkin field trials as delivered on site for injection into the mixture plant.

Figure 2.1. Evotherm DAT Solution as Delivered to Hot Mix Plant.

Sasobit

Sasobit (Figure 2.2) is a product of Sasol Wax (formerly Schumann Sasol) of South Africa. Sasobit is a Fischer-Tropsch (F-T) or synthetic wax that is created in the coal gasification process (http://www.sasolwax.com/www_sasobit_de.html). These organic waxes have longer chemical chain lengths and are different from petroleum or paraffin waxes (which are normally considered undesirable in asphalt). The longer chains help keep the wax in solution, and it reduces binder viscosity at typical asphalt production and compaction temperatures. Sasobit has been used as a compaction aid and a temperature reducer. The Sasobit process incorporates a low melting point organic additive that chemically changes the temperature-viscosity curve of the binder. Both of these additives melt at about 210°F and produce a reduction in the binder viscosity by providing liquids in the binder above their melting points. Blending 3 to 4 percent Sasobit by weight allows a reduction in production temperatures of 18°F to 54°F.

The manufacturer anticipates that in-line blending of melted Sasobit with the asphalt binder stream at the plant will be finalized in the near future, thus eliminating the current use of the Sasobit distributor at the plant. Direct blending of solid Sasobit at the plant is not recommended because it will not give a homogeneous distribution of Sasobit in the asphalt. Further, Sasobit allows incorporation of Styrene Butadiene Styrene (SBS) modifier using a special cross-linking agent termed Sasoflex. Either Sasobit or Sasoflex can be blended into hot binder at the blending plant without the need for high-shear blending.

Sasol emphasizes the difference between naturally occurring bituminous waxes and F-T waxes in terms of their structure and physical properties. The main difference is the much longer chain lengths and the fine crystalline structure of the F-T waxes. The predominant chain lengths of the hydrocarbons in Sasobit range from 40 to 115 carbon atoms; whereas, those in bituminous paraffin waxes range from about 25 to 50 carbon atom, yielding lower melting points than F-T waxes. The longer carbon chains in the F-T wax yield a higher melting point. However, the smaller crystalline structure of the F-T wax, as compared to bitumen paraffin waxes, reduces the brittleness at low pavement service temperatures.

Sasol states that the melting point of Sasobit is approximately 210°F and that it is completely soluble in asphalt at temperatures above 248°F. It reduces the binder viscosity and, thus, reportedly enables mix production temperatures to be reduced by 18°F to 54°F and improves compactability. At temperatures below its melting point, Sasobit forms a lattice structure in the asphalt binder that is the basis for the reported stability of asphalts that contain Sasobit. At service temperatures, Sasobit-modified mixes exhibit increased resistance to rutting.

Figure 2.2. Sasobit WMA Additive.

Advera

Advera (Figure 2.3) is supplied by PQ Corporation. It is a finely powdered synthetic zeolite (sodium aluminum silicate hydrate) that has been hydro-thermally crystallized. When Advera is added to the mix at the same time as the binder, water is released. This water release creates a foaming of the asphalt binder and, thereby, temporarily increases workability and enhances aggregate coating at lower temperatures. When it is heated above 185°F to 360°F, it gives up 21 percent water by mass, which microscopically foams the asphalt to aid coating of the aggregate. This foaming action of the liquid binder acts as a temporary asphalt volume extender and mixture lubricant, enabling the aggregate particles to be rapidly coated and the mix to be workable and compactable at temperatures significantly lower than those typically used for HMA. PQ Corporation states that the mix can be compacted until the temperature drops below 212°F.

PQ Corporation recommends the addition of 0.25 percent by weight of the mix, or 5 pounds of Advera WMA per ton of asphalt mix. Since Advera is an inorganic material (like aggregate), it does not change the performance grade of the asphalt binder. Advera WMA is manufactured in plants located in Jeffersonville, Indiana, USA and Augusta, Georgia, USA. It is available in bags, bulk bags (supersacks), and bulk delivery by truck and rail.

Figure 2.3. Advera WMA Additive.

MIX DESIGNS

The mixtures designed in this experiment meet the requirements for TxDOT Specification Item 340/341, *Dense-Graded Hot-Mix Asphalt*, Type C, according to Tex 204-F, Part 1 using the Texas Gyratory Compactor (TGC).

Two different mixture designs were obtained from TxDOT districts and then replicated in Texas Transportation Institute's (TTI's) laboratory. The mixture designs as obtained from the districts are shown in Appendix A. The aggregates used for these two mixture designs are of the following types:

- Vulcan Brownwood Limestone, and
- Delta Sandstone/Hanson Limestone.

The Brownwood limestone is a higher quality and less absorptive aggregate than the Hanson limestone and is typical of the aggregate types used in many parts of the state.

In the Austin and San Antonio areas of Texas, there are several limestone quarries which supply aggregate for HMA to many parts of the state. The Hanson limestone used in this laboratory study is very typical of the calcareous aggregates produced in this area. It is a relatively soft and somewhat absorptive limestone. It was blended with a higher quality, Class A aggregate (Sandstone) available from the same part of the state.

The aggregate compositions for the two mixtures are listed below in Table 2.1.

Table 2.1. Mixture Compositions.

Limestone Mix	Sandstone/Limestone Mix
90% Brownwood Limestone	25% Sandstone
10% Field Sand	61% Hanson Limestone
	14 % Field Sand
No lime or liquid antistrip	*No lime or liquid antistrip*

Appropriate quantities of the aggregates were obtained from the sources listed in Table 2.1, sieved into different size fractions, and then recombined to meet the gradation requirements shown in Table 2.2 that correspond to the mixture designs in Appendix A provided by local TxDOT districts. Note that both mixture designs do not contain any lime or liquid antistripping agent. Properties of the aggregates used are shown in Table 2.3.

Table 2.2. Mix Design Gradations.

Sieve Size	Limestone Mix (Brownwood), % Passing	Sandstone Mix, % Passing
7/8-in	100.0	100.0
5/8-in	98.7	98.8
3/8-in	77.5	74.9
No. 4	54.7	55.6
No. 10	37.1	36.6
No. 40	17.4	20.6
No. 80	5.8	7.1
No. 200	1.6	3.1

Table 2.3. Material Properties for the Aggregate Sources Used in Laboratory Study.

Material Property	Test Method	TxDOT Spec. Requirement for Dense-Graded Hot Mix Asphalt (Item 340/341)	Vulcan LS Brownwood Pit	Capital Aggregates Sandstone, Brownlee Pitt	Hanson Limestone, Servtex Pit
Los Angeles Abrasion, % loss *Evaluates the resistance of a coarse aggregate to degradation by abrasion and impact.*	Tex-410-A	40% max loss	25%[1]	21%[1]	28%[1]
Magnesium Sulfate Soundness, 5 cycles, % loss *Estimates the resistance of aggregate to weathering.*	Tex-411-A	30% max loss	8%[1]	13%[1]	20%[1]
Acid Insoluble Residue[2], % *Indicates the susceptibility of aggregate to polishing*	Tex-612-J	55% min for SAC A[2]	1%[1]	58%[1]?	1%[1]
MicroDeval, % loss *Measures resistance to abrasion and weathering.*	Tex-461-A	Used to determine need for soundness verification testing	12%[1]	13%[1]	20%[1]

[1] As reported in the TxDOT Bituminous Rated Source Quality Catalog.
[2] This test and minimum value is required for an aggregate to meet a Class A Surface Aggregate Classification (SAC) for the Wet Weather Accident Reduction Program. Not required for a B classification. The Delta Sandstone is a Class A aggregate, and both of the limestones are Class B.

The asphalt binder used to fabricate the laboratory mixture designs was obtained from Valero Energy Corporation in Corpus Christi, Texas, and both a PG 76-22 and PG 64-22 were included.

EXPERIMENT DESIGN

To evaluate the effect of the WMA additives on mixture design volumetrics, mixture designs were performed according to the experiment design shown in Table 2.4. The Brownwood aggregate was used for this experiment. WMA mixtures were designed at standard HMA mixing and compaction temperatures for the base asphalt. Designs were also performed for mixing and compaction temperatures 30ºF below standard and 60ºF below standard.

Table 2.5 shows the experiment design conducted to evaluate the results of HWTT for one WMA process (Evotherm) where optimum asphalt content was determined with and without the additive. Also, for the Evotherm process the curing condition normally used for the HMA (2 hrs at 250ºF) was evaluated at 275ºF at both 2 and 4 hours and compared to HMA.

Table 2.4. Experiment Design for Evaluation of Mixture Volumetrics.

Mixing and Compaction Temperatures	Mixture Type					
	PG 64-22 HMA	PG 64-22 WMA Advera	PG 64-22 WMA Sasobit	PG 64-22 WMA Evotherm	PG 76-22 HMA	PG 76-22 WMA Advera
Standard*	xxx	xxx	xxx	xxx	xxx	xxx
30ºF below Standard		xxx	xxx	xxx		xxx
60ºF below Standard		xxx	xxx	xxx		xxx

* Standard HMA Mixing and Compaction Temperatures according to TxDOT Test Procedure Tex-206-F.

Table 2.5. Evaluation of the Effect of Asphalt Content and Curing Conditions on HWTT (Evotherm WMA Process Only).

Curing Conditions	HMA at Optimum AC Content	WMA at HMA Optimum AC Content	WMA at TGC Optimum AC Content*
2 hrs Standard	xx	xx	xx
2 hrs at 275ºF		xx	
4 hrs at 275ºF	xx	xx	

*AC content was determined with the additive incorporated into the mix.

The experiment design shown in Table 2.6 was conducted to evaluate the effect of two different curing conditions on three WMA processes using the Brownwood Limestone aggregate for HWTT.

The experiment in Table 2.7 was conducted to evaluate three different WMA processes and two different aggregates. In this experiment, a two-hour cure at the compaction temperature was used.

Table 2.6. Evaluation of the Effect of Curing Conditions on Different WMA Mixtures (using Brownwood Limestone).

Curing Conditions	HMA	WMA Advera	WMA Sasobit	WMA Evotherm
2 hrs Standard	xx	xx	xx	xx
4 hrs at 275ºF	xx	xx	xx	xx

Table 2.7. Evaluation of the Effect of Aggregate on HWTT Response of Different WMA Mixtures.

Aggregate Type	HMA	WMA Advera	WMA Sasobit	WMA Evotherm
Limestone Mix	xx	xx	xx	xx
Sandstone Mix	xx	xx	xx	xx

WMA additives were obtained directly from the manufacturers, and technical representatives were contacted for their recommendations on quantity of additive and procedure for incorporating the additive into the laboratory mixtures. The Sasobit additive was blended with the asphalt at a rate of 3 percent by weight of the binder. The Advera additive was added to the hot aggregate at the same time as the binder was added at a rate of 0.5 percent by weight of the mix. The Evotherm DAT solution was added to the aggregate with the binder at a rate of 0.5 percent by weight of the binder. A technical representative from MeadWestvaco was onsite to instruct TTI technicians regarding how to incorporate the product in the mix. All mixes were produced at TTI's McNew Laboratory (Figure 2.4).

Figure 2.4. TTI Technicians Performing WMA Mixture Designs at TTI Laboratory.

All mixture designs were performed using the TGC (Figure 2.5), which had been calibrated for this research study by TxDOT personnel.

Figure 2.5. Compacting WMA Mixtures in the Texas Gyratory Compactor (TGC) at TTI.

EFFECT OF WMA ON SELECTION OF ASPHALT CONTENT FOR ITEM 340/341 USING TGC

HMA and WMA mixtures were designed according to Tex 206-F. Standard TxDOT mixing and compaction temperatures were used for the HMA mixtures as well as for the WMA mixtures: 325/300ºF for PG 76-22 and 290/250ºF for PG 64-22. In addition, WMA mixtures were designed at 30ºF below standard and at 60ºF below standard. These results are shown for the Advera/PG 64-22 mixes in Figure 2.6 and for the Advera/PG 76-22 mixtures in Figure 2.7. The Sasobit and Evothem WMA designs are shown in Figures 2.8 and 2.9, respectively.

As shown in Figures 2.6 through 2.9, the WMA additives improved the compactability of the mixtures. This result is true when standard HMA mixing and compaction temperatures were used as well as for temperatures at both 30 and 60ºF below standard. Item 340/341 requires the dense graded mixtures be designed at 4 percent air voids unless otherwise designated by the Engineer.

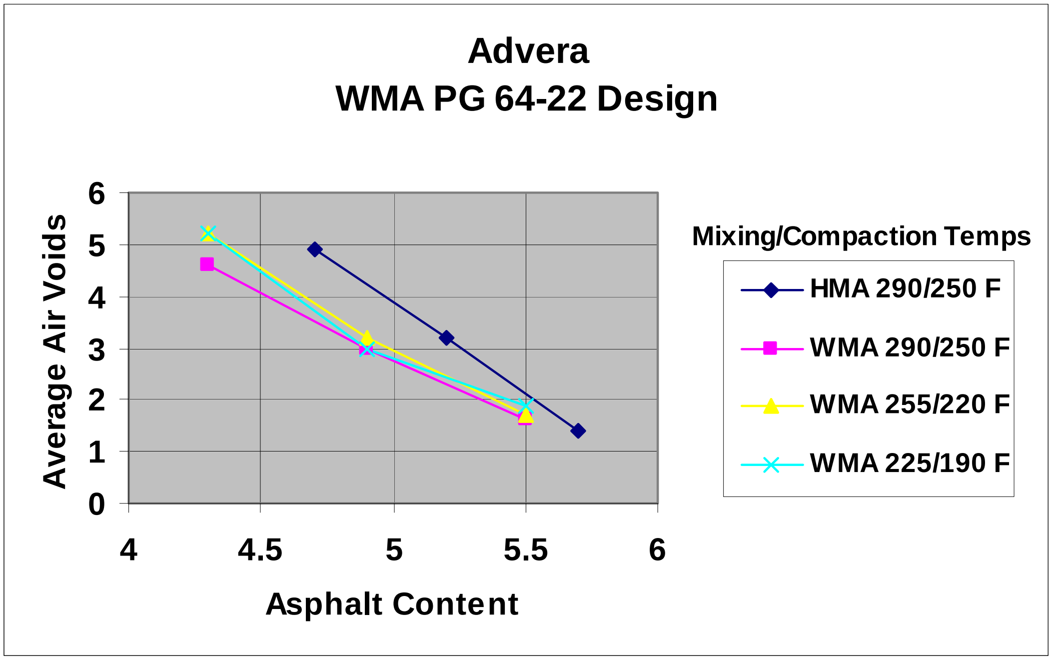


Figure 2.6. Effect of Mixing and Compaction Temperature on TGC Mixture Design Volumetrics for PG 64-22 Advera WMA.

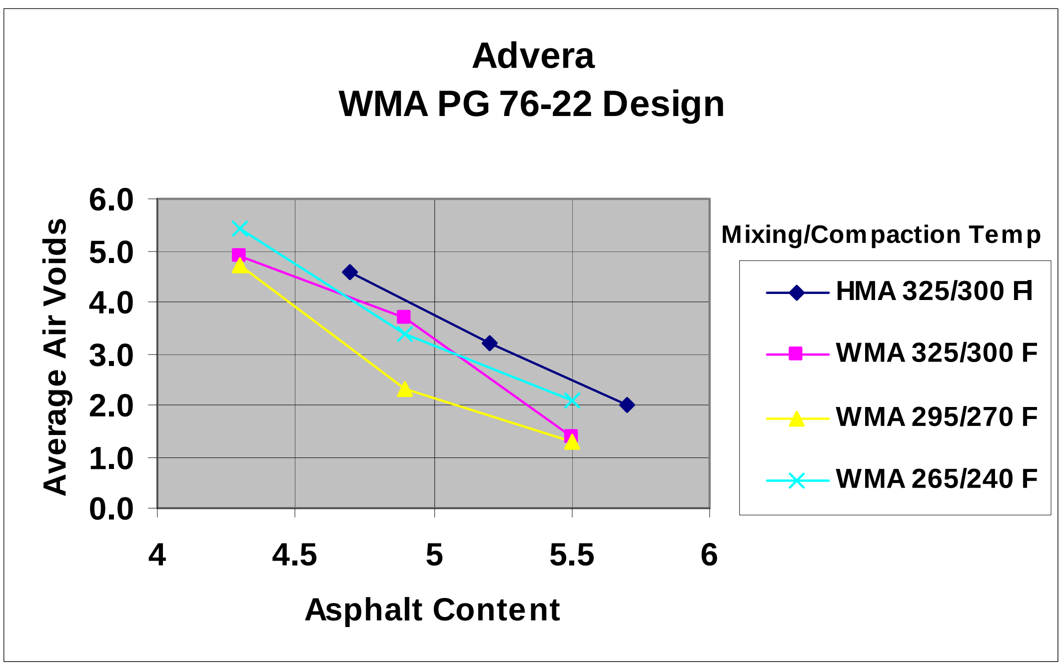


Figure 2.7. Effect of Mixing and Compaction Temperature on TGC Mixture Design Volumetrics for PG 76-22 Advera WMA.

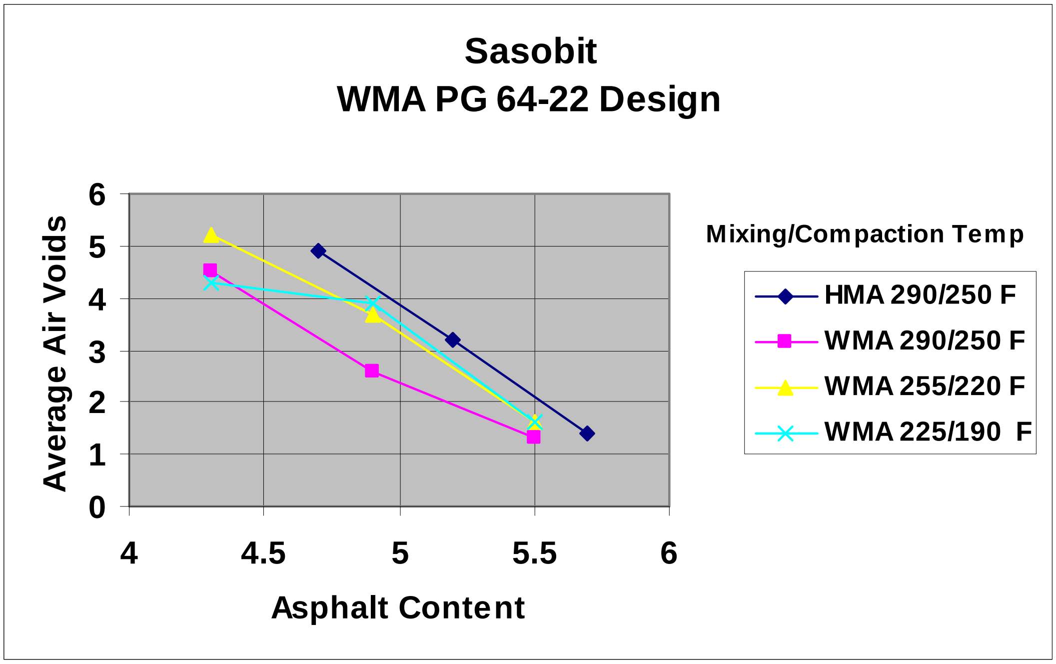


Figure 2.8. Effect of Mixing and Compaction Temperature on TGC Mixture Design Volumetrics for PG 64-22 Sasobit WMA.

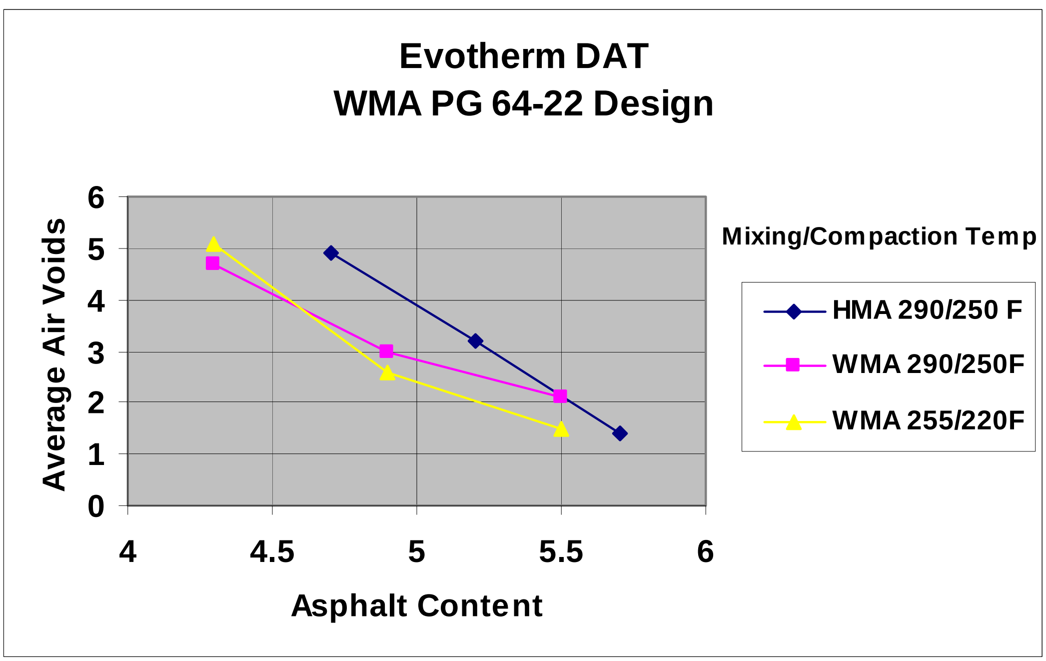


Figure 2.9. Effect of Mixing and Compaction Temperature on TGC Mixture Design Volumetrics for PG 64-22 Evotherm WMA.

Using the design curves shown in Figures 2.6 through 2.9, optimum asphalt content was determined at 4 percent air voids or 96 percent density. The optimum asphalt content for all of the PG 64-22 WMA mixtures compared to the HMA optimum AC content is shown in Figure 2.10. According to the results shown in Figure 2.10, if standard HMA mixing and compaction temperatures are used, the optimum asphalt content for all 3 types of WMA mixtures is decreased from 4.9 (for the HMA) to 4.5 percent (WMA mixtures), for a reduction in asphalt of 0.4 percentage points. This is a significant reduction in asphalt content that could have a negative effect on the long-term durability of these mixtures in the field. Even at lower mixing and compaction temperatures, the optimum asphalt content for the WMA mixtures is less than the HMA control mix.

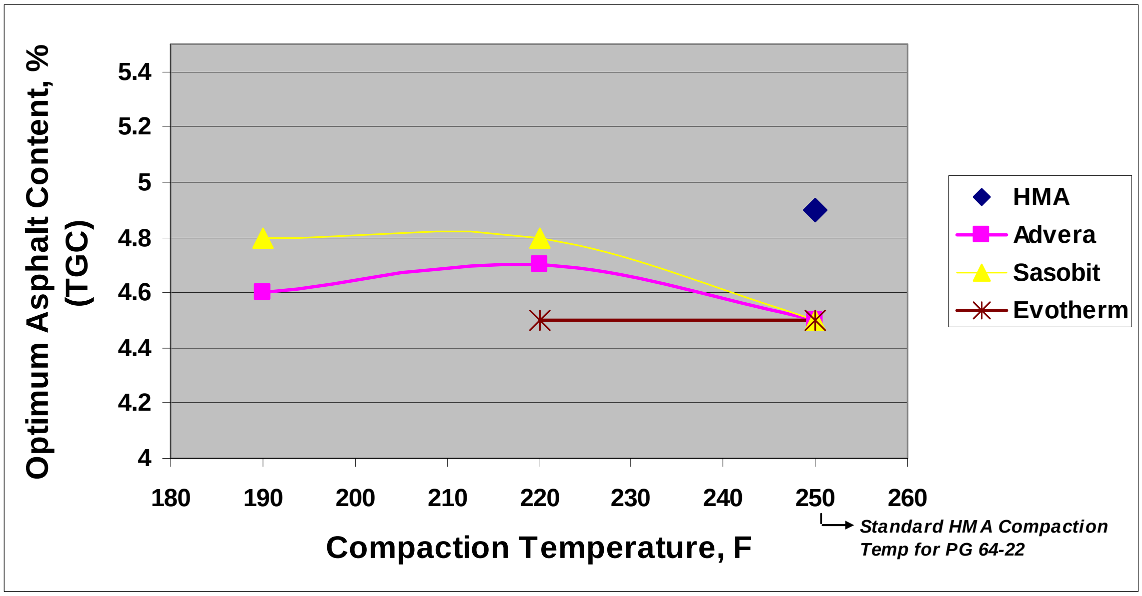


Figure 2.10. Effect of Mixing and Compaction Temperature on Optimum Asphalt Content for Different WMA and HMA using PG 64-22.

Figure 2.11 is an illustration of the effect of WMA additives on the optimum asphalt content for mixtures designed in the TGC.

HAMBURG WHEEL TRACKING TEST (HWTT) RESULTS

Acceptable performance in the HWTT is a specification requirement of Item 340/341 dense-graded mixtures. HMA and WMA mixtures were mixed, cured, and compacted under different conditions as described in the following. In addition, the influence of different aggregate types on WMA performance in the HWTT was evaluated. Hamburg samples were compacted and tested according to Tex 241-F (Figure 2.12) and Tex 242-F (Figure 2.13), respectively. At the time of this experiment, no provisions for WMA were incorporated in the test procedures.

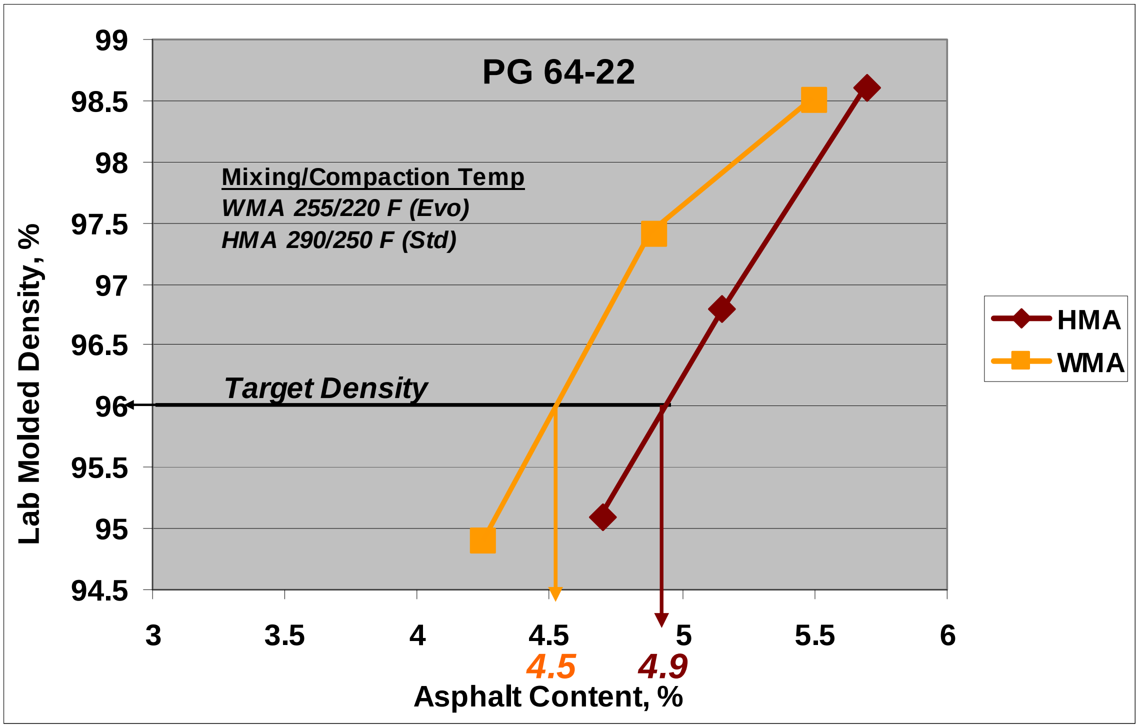


Figure 2.11. Effect of WMA Additive on Selection of Asphalt Content.

Figure 2.12 Compacting Hamburg Wheel Tracking Test (HWTT) Specimens in SGC.

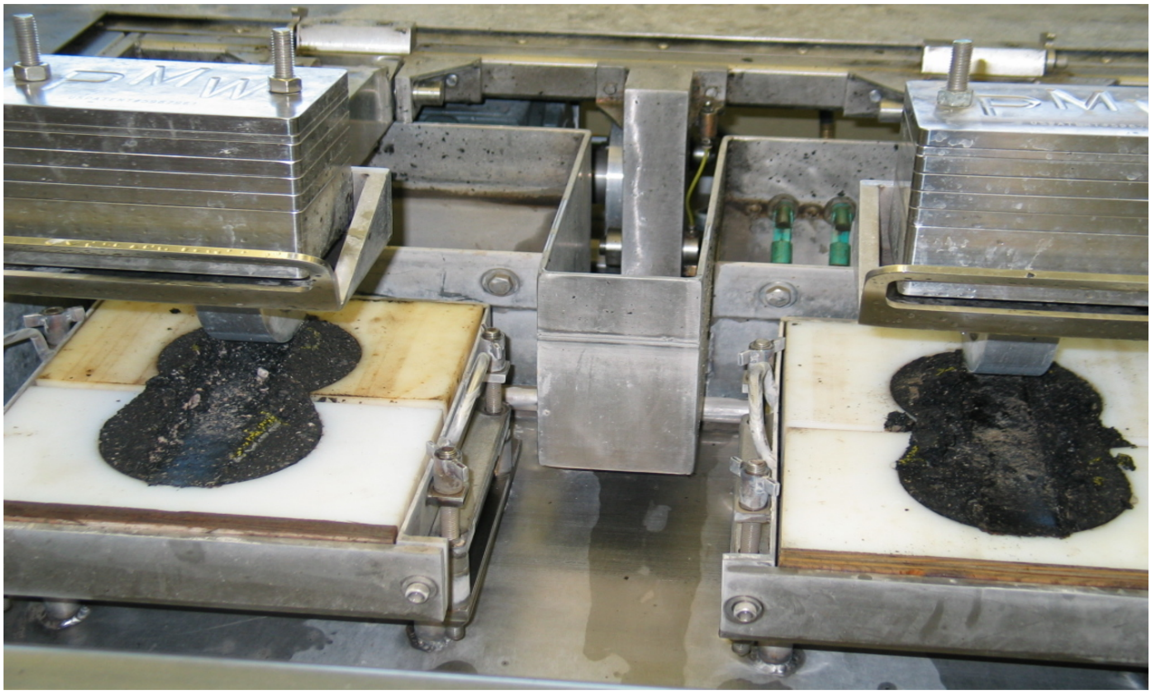
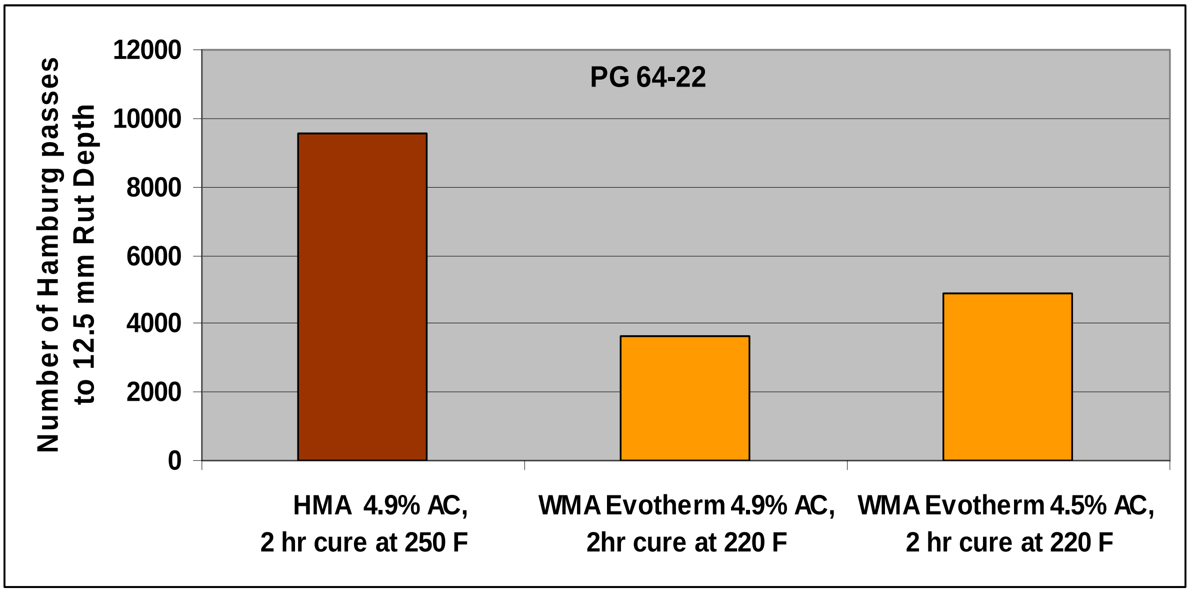


Figure 2.13. Hamburg Wheel Tracking Test (HWTT) Set-Up.

Based on the TGC mixture designs presented previously, optimum asphalt content for the Evotherm mix was determined to be 4.5 percent. HWTT results for WMA Evotherm at the actual optimum asphalt content (4.5 percent) and at the HMA optimum of 4.9 percent are shown in Figure 2.14. A significant reduction in number of passes to 12.5 mm rut depth was exhibited in the WMA specimens. Reducing the WMA asphalt content to 4.5 percent improved the HWTT results somewhat.

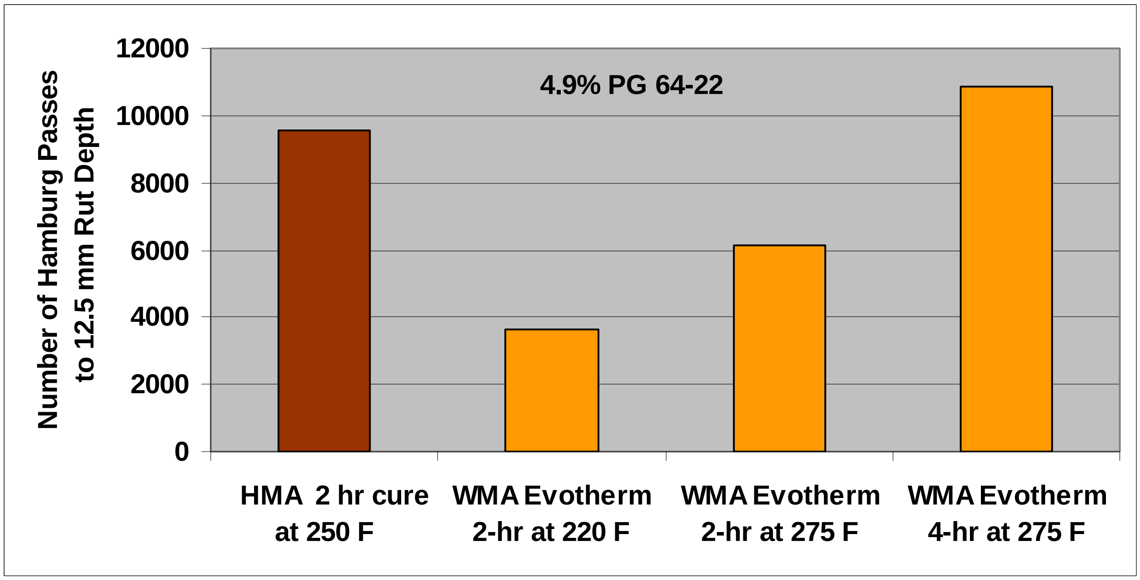


Mix/Cure/Compact 255/220/220ºF

Mix/Cure/Compact 255/220/220ºF

Figure 2.14. Effect of Asphalt Content on WMA Hamburg Wheel Tracking Test (HWTT) Results.

Figure 2.15 presents the Hamburg results for WMA Evotherm mixtures oven cured (loose mix) at three different conditions: 2 hours at the compaction temperature (220ºF), 2 hours at 275ºF, and 4 hours at 275ºF. The 4-hour cure at 275ºF is the only WMA curing condition that produced a mixture similar to the Hamburg results for the HMA.



Mix/Cure/Compact 255/220/220ºF (2 hours)

Mix/Cure/Compact 290/275/220ºF (2 hours)

Mix/Cure/Compact 290/275/220ºF (4 hours)

Figure 2.15. Effect of Curing Time and Temperature on WMA Hamburg Wheel Tracking Test (HWTT) Results.

Figure 2.16 shows the HWTT results for all three WMA processes and the HMA mix cured according to two different conditions: 2 hours at the compaction temperature (220ºF) and 4 hours at 275ºF. The increase in curing time and temperature had only a slight impact on HWTT results for the HMA mixture but had a significant impact on all WMA mixtures. This significant change with curing time and temperature for the WMA mixtures is not understood at this time. The mixtures produced in the laboratory were produced with oven-dried aggregate. The Advera and Evotherm processes introduce moisture into the mix which could explain the improvement in HWTT results as oven curing time and temperature is increased. However, the Sasobit process does not introduce any moisture into the mix, yet a significant stiffening of this mix appeared to occur with increased curing time and temperature.

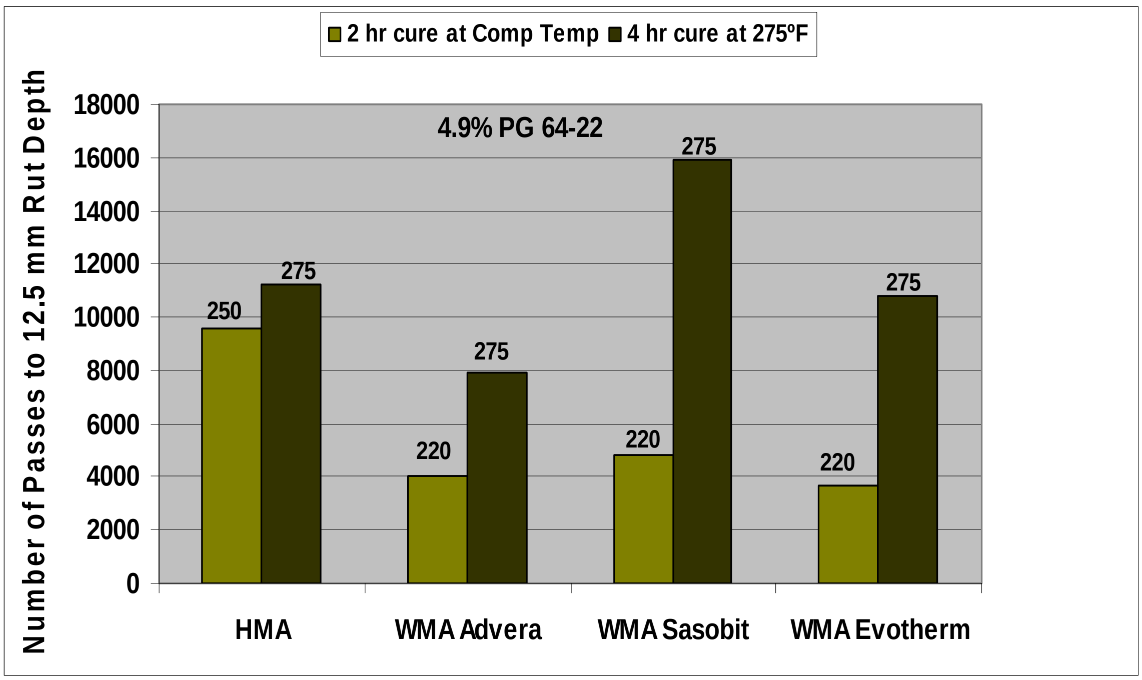


Figure 2.16. Effect of Curing Time and Temperature on Hamburg Wheel Tracking Test (HWTT) Results for Different Types of WMA.

Figure 2.17 shows the HWTT results of all three WMA mixtures designed using different aggregate types, as discussed previously. Asphalt content for the Brownwood limestone mixtures (LS) was 4.9 percent for the HMA and all three WMA mixtures. The asphalt content for the Delta sandstone (SS) mixtures was 4.5 percent for the HMA and all three WMA mixtures. No lime or liquid anti-stripping agent was used for any of the mixtures. All mixtures were cured for 2 hours at the compaction temperature (250ºF for the HMA and 220ºF). All of the warm mixes exhibited a reduction in number of passes to failure indicating a propensity for rutting and/or moisture sensitivity, and results were only marginally affected by aggregate type.

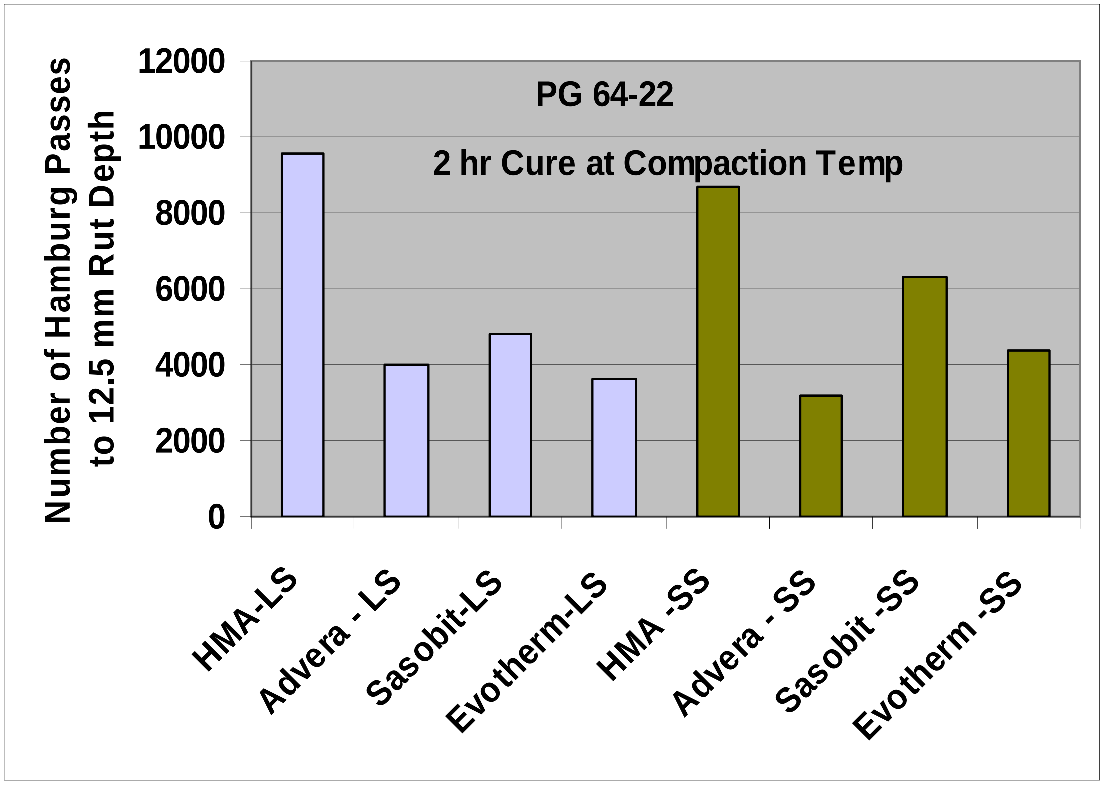


Figure 2.17. Effect of Aggregate Type on Hamburg Wheel Tracking Test (HWTT) Results for Different Types of WMA.

SUMMARY

- Dense-graded WMA mixtures that are designed according to Tex-206-F, Part I using the Texas Gyratory Compactor (TGC) will have a significantly lower optimum asphalt content than the corresponding HMA mixture without the WMA additive. This is true for all three WMA processes investigated herein, which include Sasobit, Evotherm, and Advera. Even when the mixing and compaction temperature for the warm mixtures was reduced to 60ºF below that used for HMA, compaction was enhanced sufficiently to cause a reduction in density and, thus optimum asphalt content.
- At the time of this testing, TxDOT procedures required a laboratory oven-curing procedure prior to molding specimens. This procedure consisted of a two-hour cure of the mixture at the recommended compaction temperature. WMA mixtures that are cured at their respective compaction temperature exhibit HWTT results as much as half that achieved for the corresponding HMA.
- Increasing the oven curing time from two hours to four hours and increasing the oven curing temperature to 275ºF resulted in significant increase in WMA-HWTT results that were comparable to the corresponding HMA. Increasing the oven curing time for HMA from two hours to four hours and to 275ºF did not result in a significant increase in HWTT results.

- The significant increase in HWTT results for WMA as a result of increased curing time and temperature is not well understood. While moisture in the mix is a likely culprit, the Sasobit WMA mixture (designed in the laboratory) contained no added source of moisture; so it appears that asphalt aging or absorption occurs during the curing process, which is affecting the performance properties.

CHAPTER 3

COMPACTION/WORKABILITY CHARACTERISTICS OF WARM MIX ASPHALT

COMPACTABILITY ASSESSED USING SUPERPAVE GYRATORY COMPACTOR

Plant Mixed Laboratory Compacted Mixtures

WMA technologies provide the advantage of being able to produce and compact asphalt mixtures at temperatures below that of conventional HMA. The information presented in this chapter is intended to characterize the improvement (if any) in workability/compactability expected from WMA compared to HMA and to provide a better understanding of the different WMA technologies.

To evaluate the compactability of different types of WMA, the compactive effort required to achieve a target density in the SGC was measured. Two different compaction parameters from the SGC were measured:

(1) number of gyrations required to achieve a target density;
(2) slope of the compaction curve, as shown in the example in Figure 3.1.

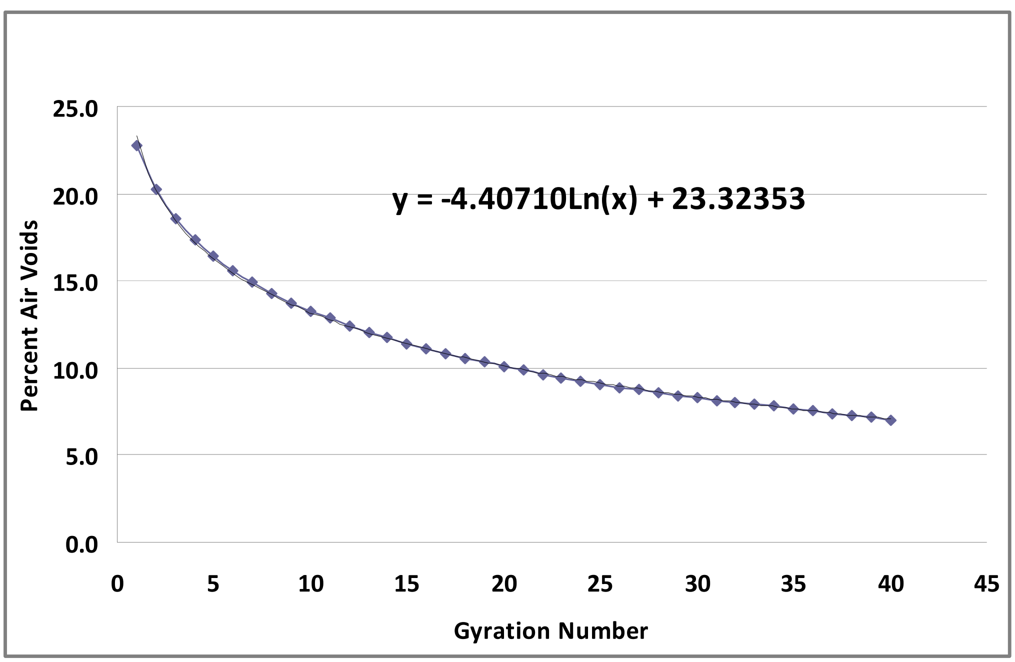


Figure 3.1. A Typical SGC Compaction Curve for WMA.

WMA and HMA mixtures produced during the Lufkin field trials were sampled at the plant, sealed, and stored in five-gallon buckets. These mixtures were reheated and compacted approximately two months later in TTI's laboratory. No additional oven-curing was performed prior to compaction. The samples were heated to the compaction temperature and immediately compacted. Compaction temperatures which were selected are as follows:

- 175ºF – considered the cessation temperature for field compaction of HMA;
- 200ºF – a potential WMA field compaction temperature;
- 220ºF – a potential WMA field compaction temperature;
- 250ºF – TxDOT standard laboratory compaction temperature for PG 64-22 HMA mixes.

Table 3.1 shows the experiment layout for evaluating the compaction characteristics of the Lufkin plant mix. In addition, TTI technicians compacted plant mix on-site at the contractor's field lab (East Texas Asphalt) to produce samples for HWTT testing. The compaction characteristics of the samples that were compacted at the field lab are shown here and compared to the mixtures that were reheated and compacted later. The samples which were compacted on-site at the field lab were oven-cured for two hours at their respective compaction temperatures:

- 2 hours at 250ºF for HMA;
- 2 hours at 220ºF for all WMA mixture types.

Table 3.1. Experiment Design to Evaluate the Compaction Characteristics of Lufkin Plant Produced HMA and WMA.

SGC Compaction Characteristics to Achieve Target Density										
SGC Compaction Temperature	**PG 64-22 HMA**		**PG 64-22 WMA Sasobit**		**PG 64-22 WMA Evotherm**		**PG 64-22 WMA Advera**		**PG 64-22 WMA Rediset**	
Target Density										
	93%	96%	93%	96%	93%	96%	93%	96%	93%	96%
175ºF	xxx		xxx		xxx		xxx		xxx	
200ºF	xxx		xxx		xxx		xxx		xxx	
220ºF	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
250ºF	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx

The compaction data that were produced as a result of the experiment shown in Table 3.1 are shown in Tables 3.2 through 3.6.

Table 3. 2. SGC Compaction Characteristics of Lufkin Plant–Produced HMA (Reheated and Compacted at TTI Two Months after Production).

Laboratory Compaction Temperature	Target Air Voids, %	Sample Height (mm)	Number of Gyrations to Achieve Target Density	Absolute Value of Slope of Compaction Curve	Average Number of Gyrations to Achieve Target Density	Average Slope of Compaction Curve
175ºF	7	63.21	64	4.534	63	4.561
		63.27	60	4.555		
		63.23	65	4.594		
200ºF	7	63.27	64	4.494	60	4.480
		63.21	55	4.481		
		63.18	60	4.464		
220ºF	7	63.03	50	4.264	51	4.308
		63.03	53	4.318		
		63.37	50	4.342		
250ºF	7	63.47	51	4.232	48	4.243
		63.37	47	4.232		
		63.29	45	4.264		
220ºF	4	116.23	86	4.588	88	4.583
		116.32	90	4.578		
250ºF	4	116.55	86	4.563	85	4.539
		116.45	83	4.515		

Table 3. 3. SGC Compaction Characteristics of Lufkin Plant–Produced Sasobit WMA (Reheated and Compacted at TTI Two Months after Production).

Laboratory Compaction Temperature	Target Air Voids, %	Sample Height (mm)	Number of Gyrations to Achieve Target Density	Absolute Value of Slope of Compaction Curve	Average Number of Gyrations to Achieve Target Density	Average Slope of Compaction Curve
175ºF	7	63.34	62	4.569	63	4.612
		63.49	64	4.607		
		63.53	63	4.661		
200ºF	7	63.38	55	4.381	55	4.457
		63.46	54	4.502		
		63.44	56	4.489		
220ºF	7	63.47	52	4.401	51	4.461
		63.48	49	4.463		
		63.40	52	4.518		
250ºF	7	63.39	50	4.223	49	4.325
		63.36	48	4.363		
		63.27	49	4.389		
220ºF	4	116.65	95	4.720	96	4.708
		116.69	96	4.695		
250ºF	4	116.69	86	4.662	83	4.692
		116.80	80	4.721		

Table 3.4. SGC Compaction Characteristics of Lufkin Plant–Produced Evotherm WMA (Reheated and Compacted at TTI Two Months after Production).

Laboratory Compaction Temperature	Target Air Voids, %	Sample Height (mm)	Number of Gyrations to Achieve Target Density	Absolute Value of Slope of Compaction Curve	Average Number of Gyrations to Achieve Target Density	Average Slope of Compaction Curve
175ºF	7	63.27	66	4.556	67	4.552
		63.15	69	4.527		
		63.25	67	4.574		
200ºF	7	63.29	57	4.418	58	4.465
		63.18	60	4.48		
		63.17	56	4.497		
220ºF	7	63.19	53	4.285	54	4.338
		63.21	55	4.352		
		63.15	54	4.378		
250ºF	7	63.26	45	4.352	44	4.344
		63.23	44	4.316		
		63.19	43	4.363		
220ºF	4	116.33	101	4.491	100	4.515
		116.32	99	4.538		
250ºF	4	116.47	82	4.524	82	4.535
		116.33	82	4.546		

Table 3. 5. **SGC Compaction Characteristics of Lufkin Plant–Produced Advera WMA (Reheated and Compacted at TTI Two Months after Production).**

Laboratory Compaction Temperature	Target Air Voids, %	Sample Height (mm)	Number of Gyrations to Achieve Target Density	Absolute Value of Slope of Comp. Curve	Average Number of Gyrations to Achieve Target Density	Average Slope of Compaction Curve
175ºF	7	63.44	48	4.834	46	4.845
		63.42	46	4.822		
		63.32	45	4.878		
200ºF	7	63.36	40	4.567	39	4.650
		63.43	37	4.669		
		63.31	40	4.715		
220ºF	7	63.44	39	4.378	37	4.463
		63.43	37	4.450		
		63.47	35	4.562		
250ºF	7	63.37	33	4.309	33	4.386
		63.41	31	4.385		
		63.28	34	4.465		
220ºF	4	116.37	66	4.741	67	4.772
		116.43	68	4.803		
250ºF	4	116.54	55	4.826	56	4.807
		116.42	56	4.788		

Table 3. 6. SGC Compaction Characteristics of Lufkin Plant–Produced Akzo Nobel Rediset WMA (Reheated and Compacted at TTI Two Months after Production).

Compaction Temperature	Target Air Voids, %	Sample Height (mm)	Number of Gyrations to Achieve Target Density	Absolute Value of Slope of Comp. Curve	Avg. Number of Gyrations	Avg. Slope of Compaction Curve
175ºF	7	63.21	54	4.600	58	4.606
		63.21	61	4.581		
		62.87	60	4.638		
200ºF	7	63.19	50	4.298	48	4.346
		63.28	47	4.370		
		63.21	46	4.371		
220ºF	7	63.27	40	4.407	41	4.408
		63.33	40	4.409		
		63.32	42	4.409		
250ºF	7	63.27	41	4.156	40	4.273
		63.29	39	4.352		
		63.43	39	4.312		
220ºF	4	116.33	89	4.441	84	4.511
		116.34	78	4.580		
250ºF	4	116.69	72	4.509	74	4.526
		116.45	75	4.542		

TTI obtained samples of the HMA and four different WMA mixtures produced at East Texas Asphalt in Lufkin. Hamburg-size specimens were compacted by a TTI technician using the laboratory facilities and equipment of East Texas Asphalt. Upon sampling the mixes from the plant, the mixtures were cured for two hours at the compaction temperature (250ºF for the HMA, and 220ºF for the WMAs). The number of gyrations required to achieve 93 percent density is shown in Figure 3.2. These data are compared to the compaction data for the mixtures, which were returned to TTI's laboratory, reheated, and compacted two months later (Figure 3.3).

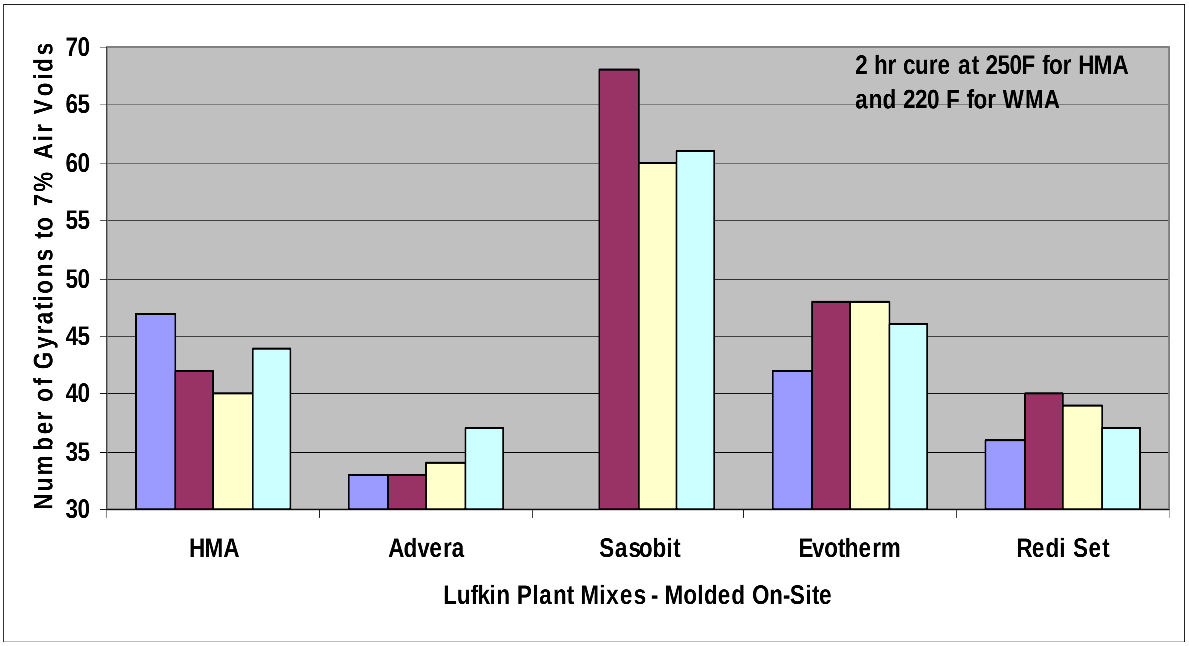


Figure 3.2. Number of Gyrations to 7 Percent Air Voids for Lufkin Plant Mixes Compacted On-Site.

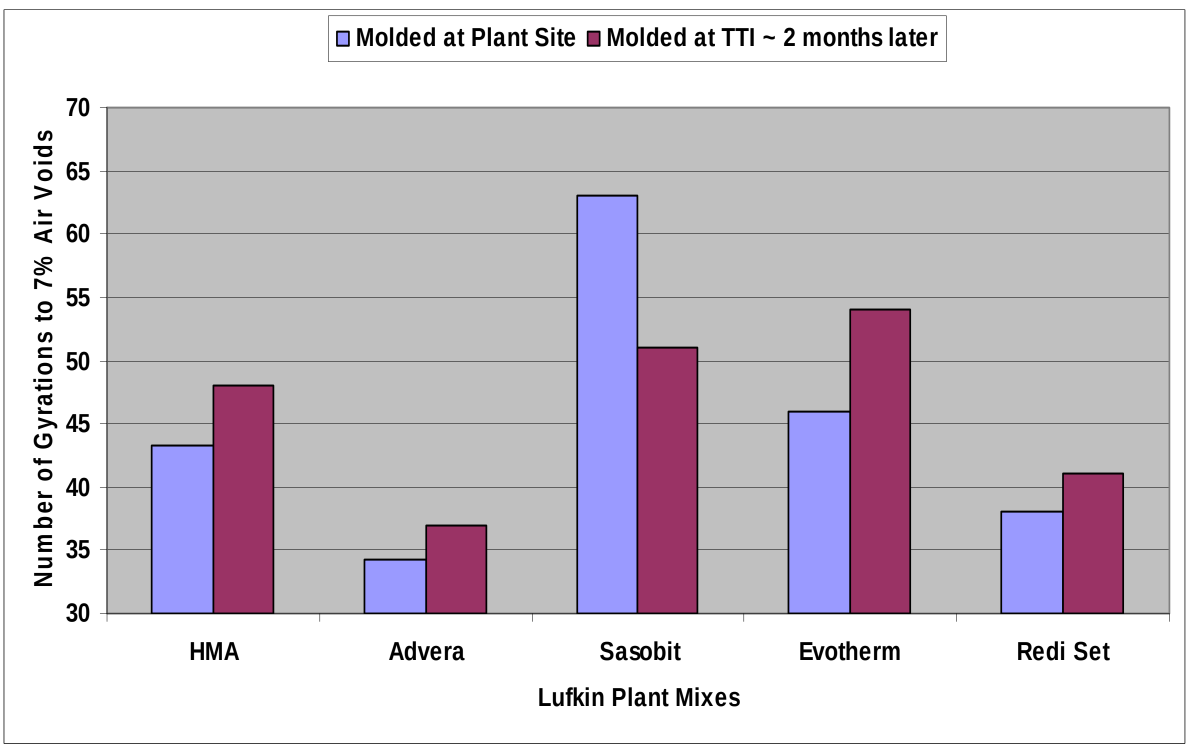


Figure 3.3. Average Number of Gyrations to 7 Percent Air Voids for Lufkin Plant Mixes Compacted On-Site Compared to Mixes Compacted Two Months Later.

The data for the Sasobit mixtures appear suspect since the compaction requirement was significantly greater than for the other mixtures and since the field compaction of this mixture was comparable to the other WMA mixtures. Further evidence of this is that the Sasobit mixture, which was reheated and compacted later, was significantly easier to compact two months later, as shown in Figure 3.3. Except for this mix, the compactability of the WMA mixtures compacted at the plant (30ºF below the HMA) were comparable or better than the HMA.

It is interesting to note that, even for the mixtures stored in buckets for 2 months and then reheated and compacted, the Advera and Rediset mixtures were still significantly easier to compact than the HMA. The researchers found this to be particularly interesting for the Advera, since this product releases moisture in the hot mix plant causing a foaming action to aid in compaction. These data indicate that not all of the moisture in the Advera additive was released/expelled in the drum mix plant, since it was still easier to compact than the HMA.

Except for the Sasobit mix, all of the mixtures including the HMA required a slightly greater compaction effort after two months of storage but the Advera and Rediset mixtures were still significantly easier to compact than the HMA. The compaction benefits achieved by the Evotherm technology were not as evident after long-term storage of the mix in the laboratory.

Compaction results (number of gyrations to 93 percent density) for all of the mixtures that were reheated and compacted after storage in the laboratory for two months are presented in Figure 3.4. The Sasobit and Evotherm mixtures had similar compaction requirements to the HMA mixture. The Rediset and Advera mixtures were significantly easier to compact than the HMA even at temperatures as low as 175ºF.

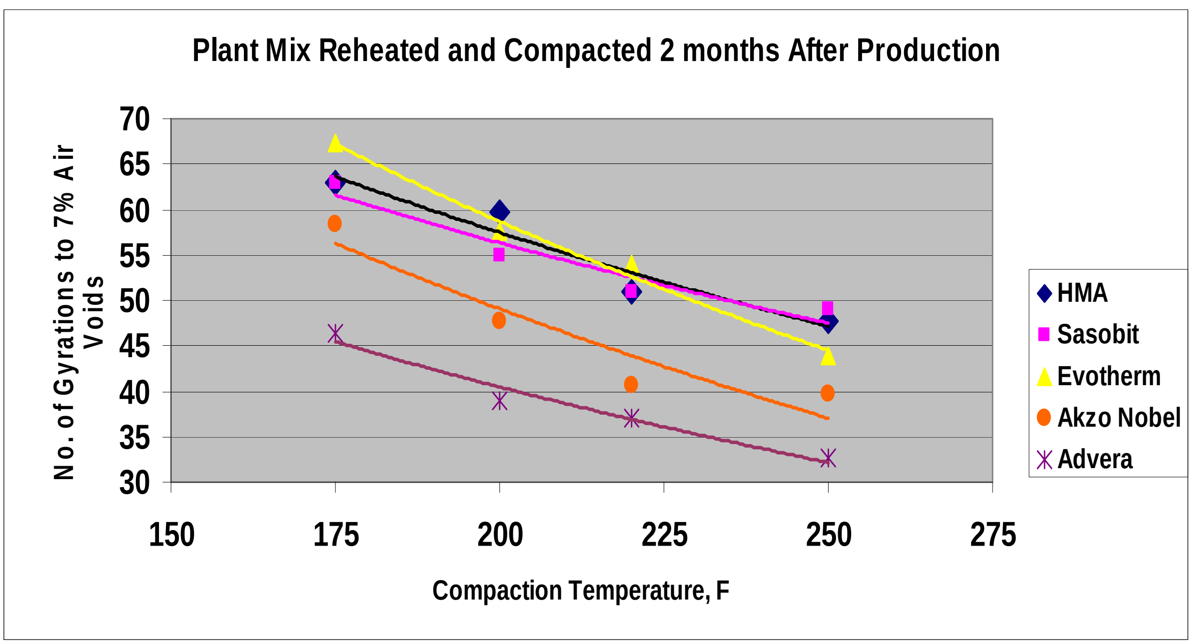


Figure 3.4. Average Number of Gyrations to 7 Percent Air Voids for Lufkin Plant Mixes Compacted After Two Months of Laboratory Storage.

The same mixtures were also compacted to 96 percent density for two temperatures: 250ºF (which is the compaction temperature for PG 64-22) and 220ºF, which was the compaction temperature used in Lufkin for all of the WMA mixtures. These laboratory-stored Advera and Rediset mixtures were easier to compact than the HMA mixture.

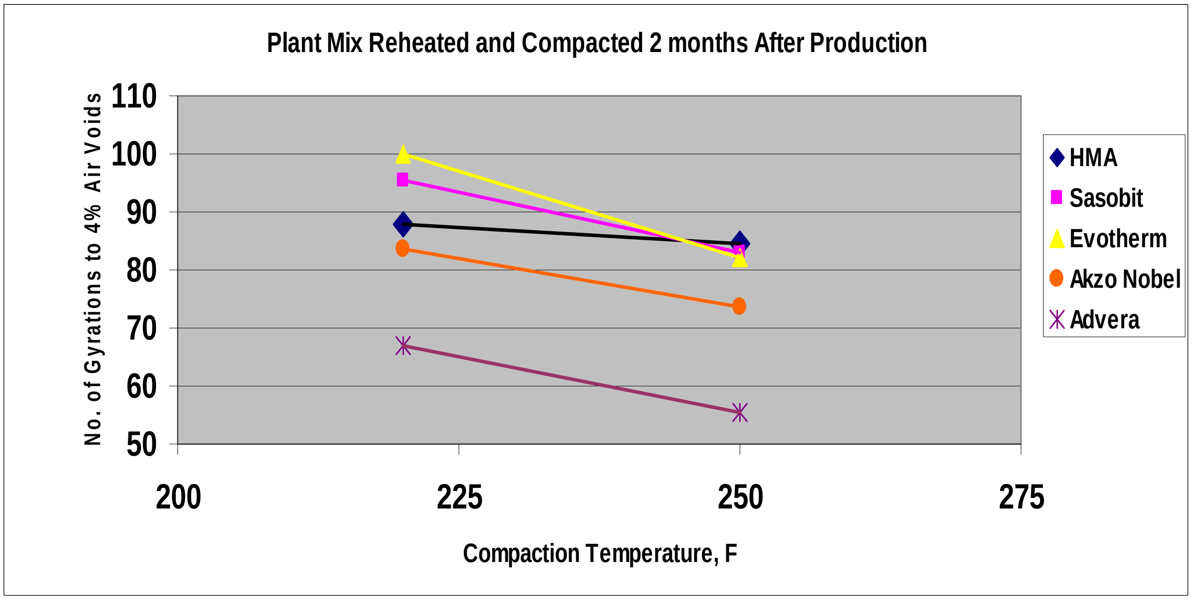


Figure 3.5. Average Number of Gyrations to 4 Percent Air Voids for Lufkin Plant Mixes Compacted After Two Months of Laboratory Storage.

The slope of the SGC compaction curve is believed to be a better indication of the "compactability" of a mix than just counting the number of gyrations to achieve a target density. The absolute value of the slope of the compaction curve for all of the Lufkin mixtures compacted at different temperatures is shown in Figure 3.6.

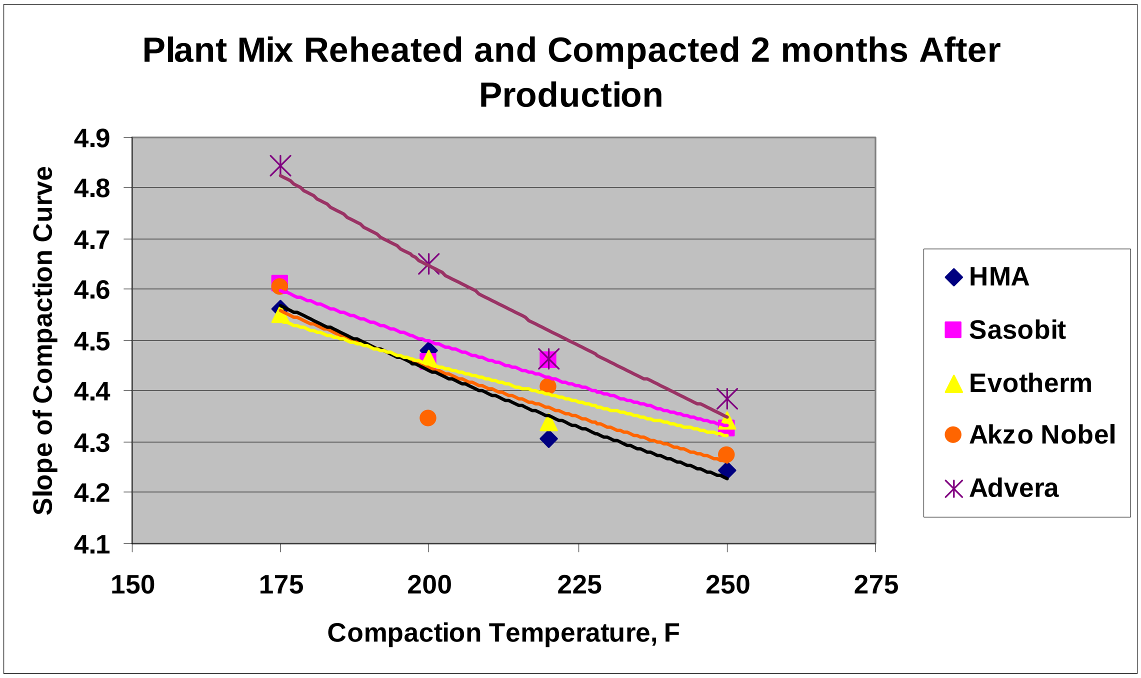


Figure 3.6. Average Absolute Value of the Slope of the SGC Compaction Curve for Lufkin Plant Mixes Compacted After 2 Months of Laboratory Storage.

A similar compaction experiment was conducted on plant produced SMA mixtures from Beaumont where the Rediset technology was used. This mixture was produced with a PG 76-22 asphalt, and both the HMA and WMA mixtures were sampled at the plant and returned to TTI's laboratory where the mixtures were reheated and compacted approximately 1 week after they were sampled. These results are presented in Figure 3.7.

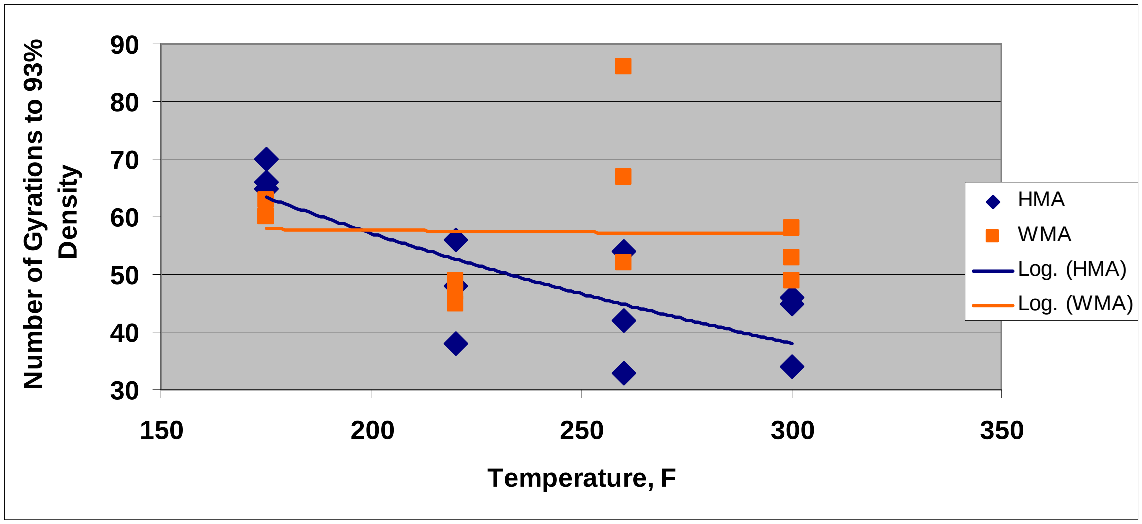


Figure 3.7. SGC Compaction Characteristics of Plant Produced HMA and Rediset WMA for Stone Mastic Asphalt Mixture from Beaumont

Compactability of Lab Mixed/Lab Compacted Mixtures

HMA and WMA mixtures were fabricated in the laboratory and evaluated for their compactability. Various cure times and temperatures were investigated, and these data are presented in Table 3.7.

In Figure 3.8, laboratory mixed/laboratory compacted specimens of HMA are compared to Evotherm WMA. When the HMA and WMA asphalt contents are the same (4.9 percent), the Evotherm WMA is significantly easier to compact at a temperature 30ºF lower than the HMA. If the Evotherm mix is designed using the TGC, the asphalt content is reduced to 0.4 percentage points lower than the HMA (from 4.9 percent to 4.5 percent). This reduction in asphalt content causes a significant increase in the required compaction effort to achieve 93 percent density.

Table 3.7. Compactability of Laboratory Mixed/Laboratory Compacted WMA and HMA Mixtures.

Sample ID	Asphalt %	Mix/Cure/Comp Temps, ºF	Oven Cure Time, hrs	Air Voids 1	2	3	4	Avg AV	No. SGC Gyrations 1	2	3	4	Avg Gyr
PG 64-22 HMA Control	4.9	290-250-250	2	7.0	6.9	6.8	7.0	**6.9**	25	26	25	24	**25**
PG 64-22 Asphamin	4.9	255-220-220	2	6.8	7.0	7.0	6.8	**6.9**	27	28	26	31	**28**
PG 64-22 Sasobit	4.9	255-220-220	2	6.7	6.8	6.7	6.9	**6.8**	25	27	27	27	**27**
PG 64-22 Evotherm	4.9	255-220-220	2	7.0	7.1	6.9	6.9	**7.0**	14	16	14	15	**15**
PG 64-22 Evotherm	4.9	290-275-220	2	6.7	6.8	6.8	6.7	**6.8**	29	25	28	25	**27**
PG 64-22 Evotherm	4.9	290-275-220	4	6.9	6.7	6.8	6.8	**6.8**	22	23	24	21	**23**
PG 64-22 Evotherm	4.5	255-220-220	2	6.8	7.2	6.8	7.1	**7.0**	34	47	41	31	**38**
PG 76-22 HMA Control	4.9	325-300-300	2	7.3	7.5	7.6	7.6	**7.5**	27	28	26	28	**27**

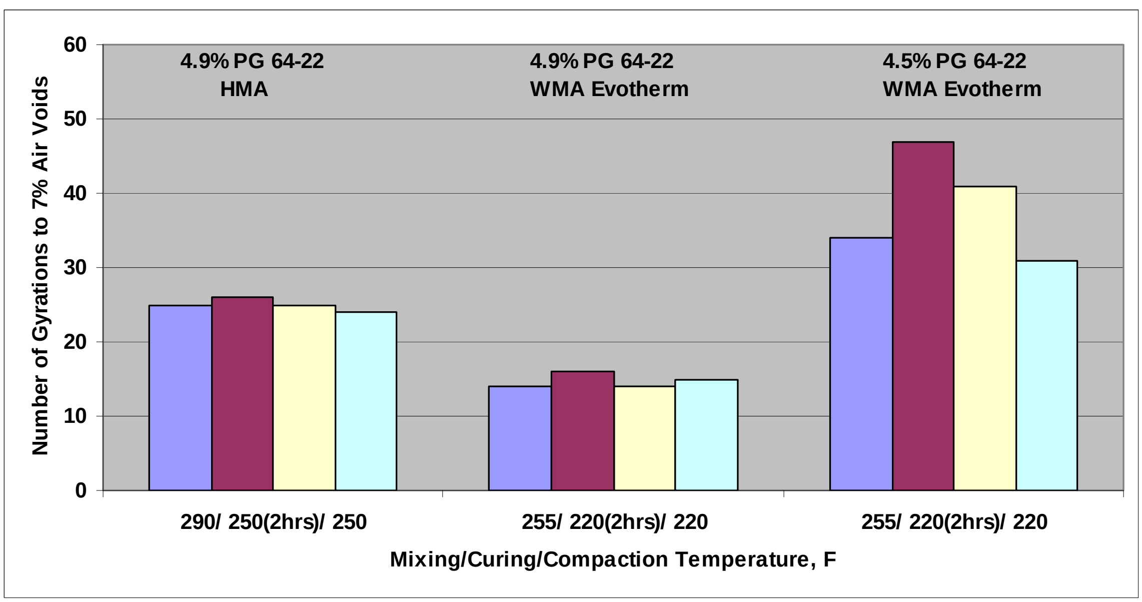


Figure 3.8. Compaction Effort of Lab Mixed/Lab Compacted HMA Mixtures Compared to WMA Evotherm Mixtures.

Figure 3.9 shows the effects of laboratory curing time and temperature on the compactability of lab mixed/lab compacted WMA Evotherm mixtures. The WMA mixtures that were cured for two hours at the compaction temperature of 220ºF were significantly easier to compact than the HMA mixtures that were cured for two hours at 250ºF. Increasing the WMA curing temperature to 275 ºF for both two hours and four hours resulted in a significant loss of compactability making the mix comparable to the HMA.

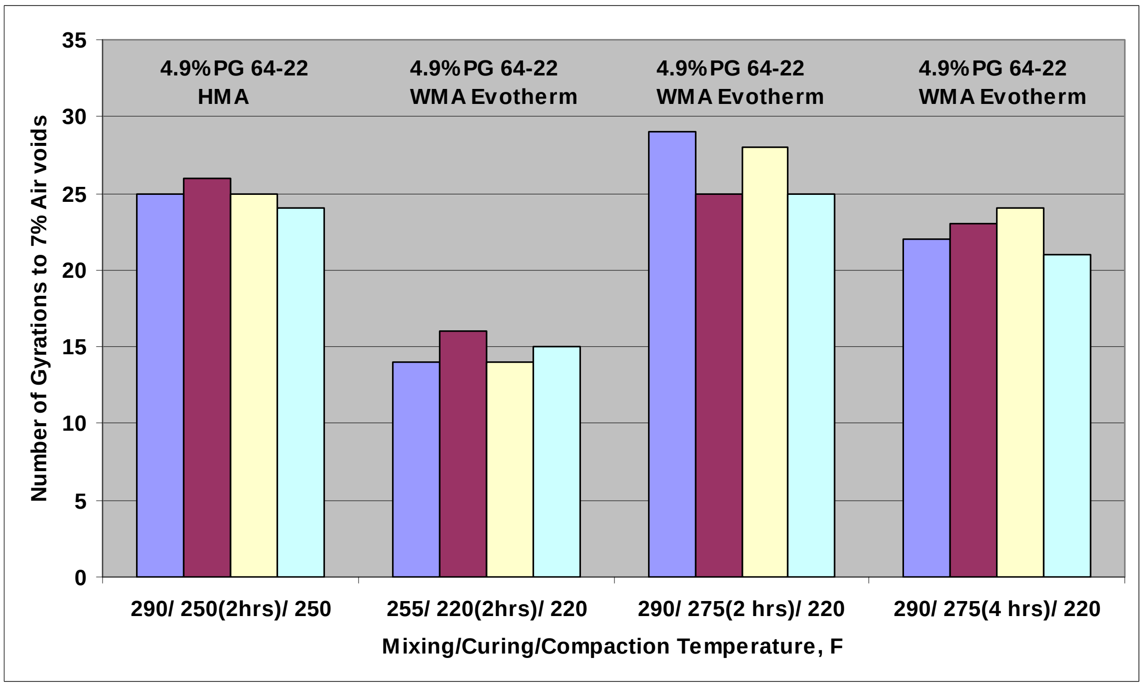


Figure 3.9. Compaction Effort of Lab Mixed/Lab Compacted HMA Mixtures Compared to WMA Evotherm Mixtures Cured at Different Times and Temperatures.

Lab mixed/lab compacted samples of HMA are compared to three different types of WMA mixtures in Figure 3.10. All of these mixtures were cured for two hours at the compaction temperature (250ºF for HMA and 220ºF for WMA). The WMA Advera and Sasobit mixtures compacted at a temperature 30ºF less than the HMA, had similar compaction requirements to the HMA. The Evotherm WMA mixture was significantly easier to compact than the other WMA mixtures and the HMA.

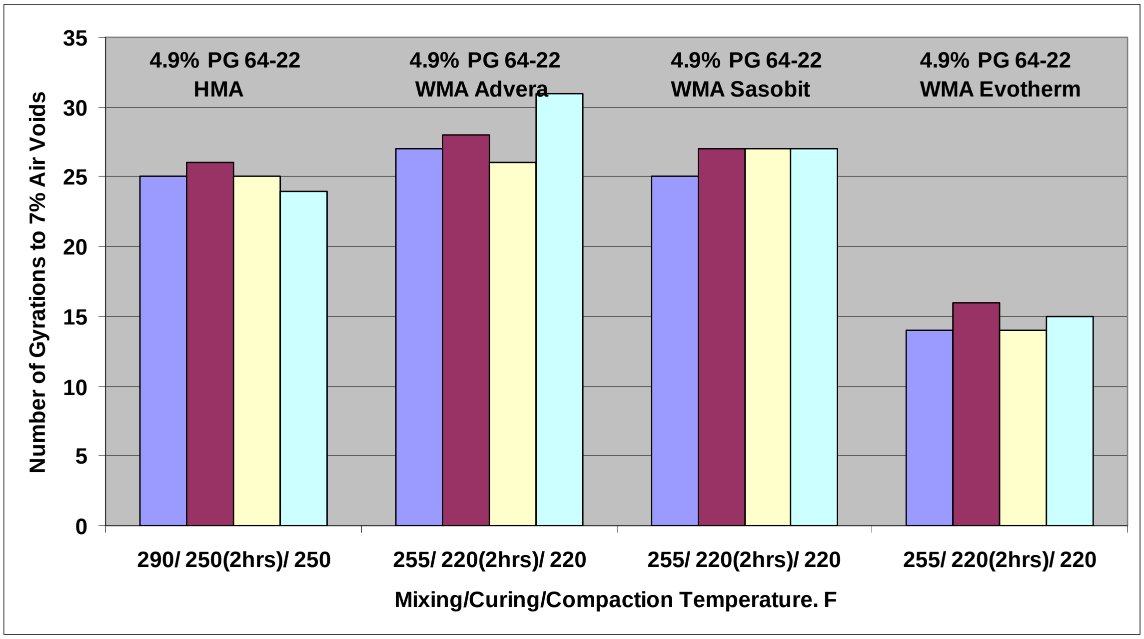


Figure 3.10. Compaction Effort of Lab Mixed/Lab Compacted HMA Mixtures Compared to Different Types of WMA Mixtures.

BROOKFIELD ROTATIONAL VISCOSITY MEASUREMENTS

To better understand the role of different WMA additives, asphalt binders were blended with the WMA additives and tested for viscosity at different temperatures using a Brookfield rotational viscometer. A PG 64-22 from Martin Asphalt (which was used in the Lufkin field trial) and a PG 64-22 from Valero (used for the laboratory study) were modified with Sasobit, Advera, Evotherm, and Rediset. These data are presented in Table 3.8. A Valero PG 76-22 was compared to an Advera-modified PG 76-22.

Some WMA technologies are not binder additives and do not claim to modify the viscosity of the binder but enhance the workability and compaction of the mix through the use of a foaming action and/or surfactants. The data shown here indicate which additives actually reduce the viscosity of the binder.

At test temperatures of 290ºF (Figure 3.11), 250ºF (Figure 3.12), and 220ºF (Figure 3.13), the Sasobit and Rediset modified binders exhibited a significantly lower viscosity than the unmodified binder. The Advera- and Evotherm-modified binders had a higher viscosity at these temperatures, which does not compare to the improved SGC compactability seen with these additives in mixtures. This further indicates that these additives improve the compaction characteristics of the mix but not by reducing the viscosity of the binder.

Table 3.8. Brookfield Viscosity Data at Different Temperatures for Binders Modified with WMA Additives.

Sample ID	Test Temperature						
	175ºF	200ºF	220ºF	250ºF	290ºF	300ºF	325ºF
	Brookfield Rotational Viscosity, cp						
PG 64-22 Valero	34972	9396	3757	1224	371	-	-
PG 64-22 Valero With Sasobit	57042	11823	3408	1038	325	-	-
PG 64-22 Valero With Advera	37458	9948	4017	1296	392	-	-
PG 64-22 Valero With Evotherm	37125	9500	3763	1190	322	-	-
64-22 Valero With Rediset	32583	8000	3098	956	310	-	-
PG 64-22 Martin *	29417	7854	3171	1052	325	-	-
PG 64-22 Martin With Sasobit	73333	13028	2950	865	276	-	-
PG 64-22 Martin With Asphamin	31542	8183	3338	1100	341	-	-
PG 64-22 Martin With Evotherm	29500	7756	3188	1033	344	-	-
PG 64-22 Martin With Rediset	43458	7792	2696	844	272	-	-
PG 76-22 Valero	178333	37889	12625	3670	1057	769	444
76-22 Valero With Advera	220667	43625	14375	4100	1088	839	472

* The PG 64-22 Martin Asphalt is that used for the Lufkin Field Test Sections.

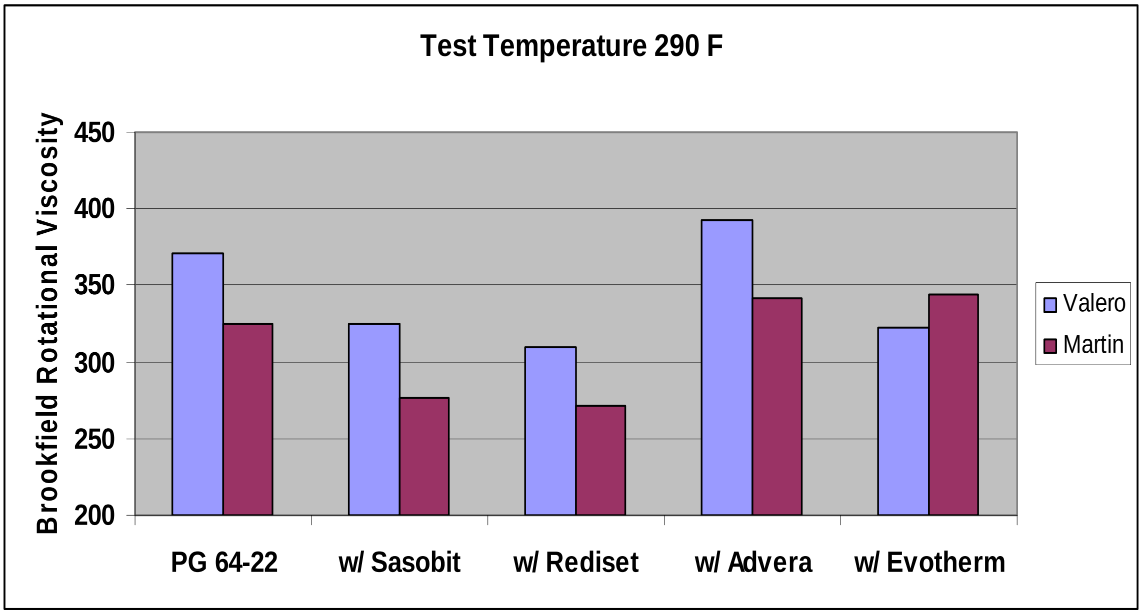


Figure 3.11. Brookfield Rotational Viscosity at 290°F for Binders Modified with WMA Additives.

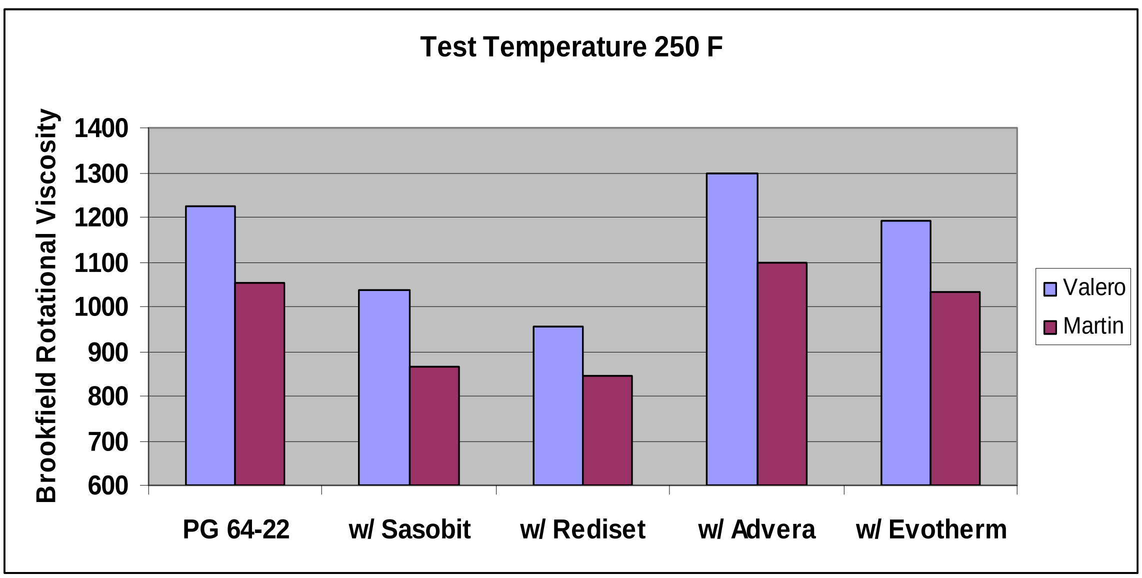


Figure 3.12. Brookfield Rotational Viscosity at 250°F for Binders Modified with WMA Additives.

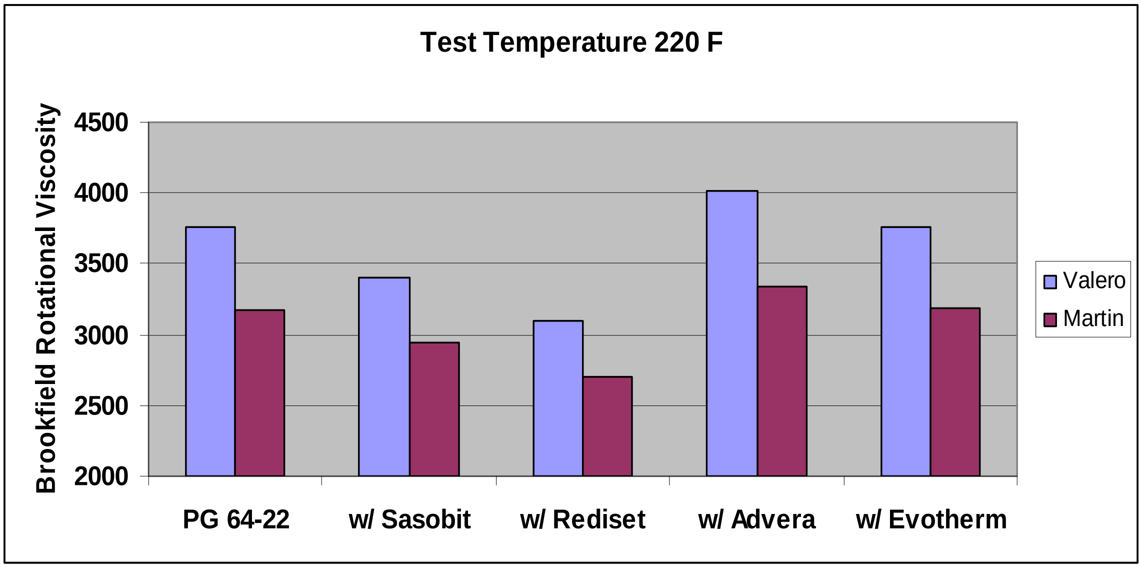


Figure 3.13. Brookfield Rotational Viscosity at 220ºF for Binders Modified with WMA Additives.

At temperatures of 200ºF and lower (Figures 3.14 and 3.15), the Sasobit-modified binders show a significant increase in viscosity. This is consistent with the product literature, which states that the product is a wax that decreases the viscosity of the binder at temperatures above the melting point of the wax (210ºF).

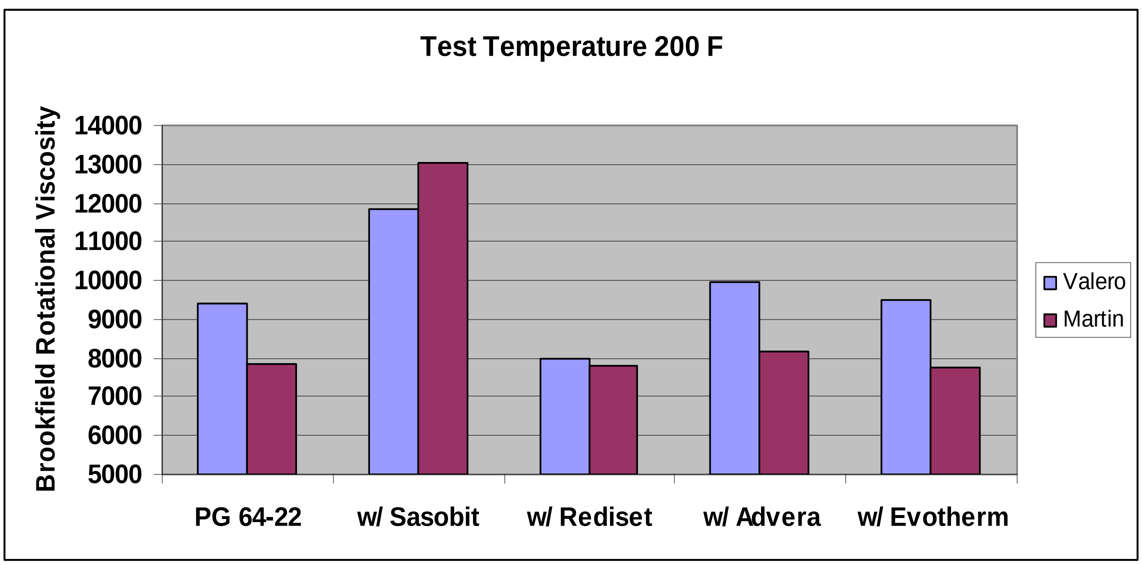


Figure 3.14. Brookfield Rotational Viscosity at 200ºF for Binders Modified with WMA Additives.

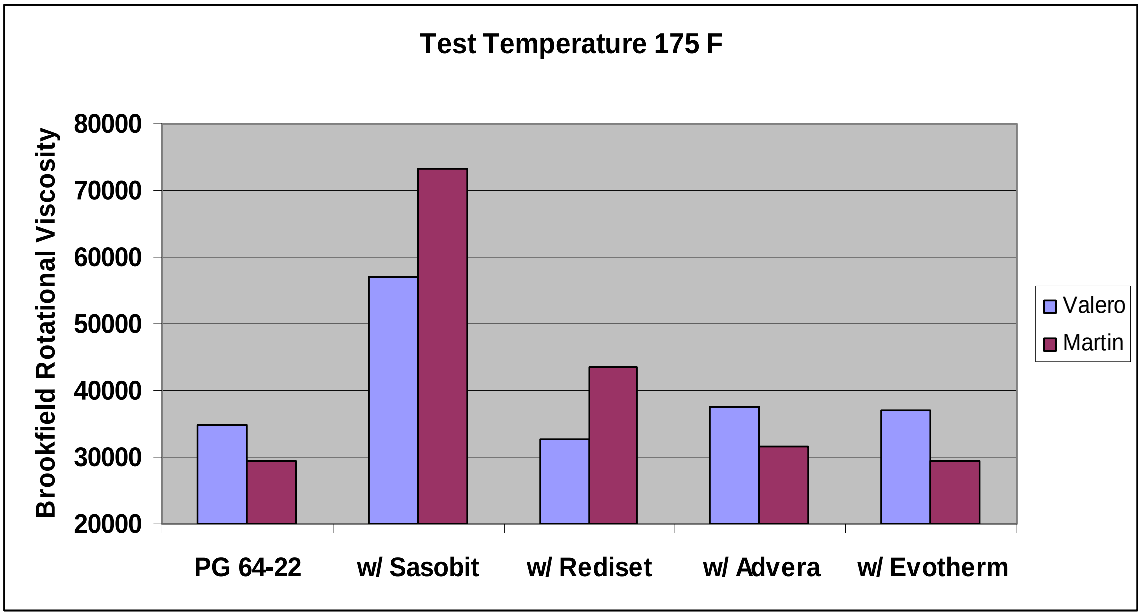


Figure 3.15. Brookfield Rotational Viscosity at 175ºF for Binders Modified with WMA Additives.

SUMMARY

- The SGC is an effective tool for evaluating the compaction characteristics of WMA when compared to the corresponding HMA without any additive.
- WMA plant mixes which were sampled, stored for two months, reheated and compacted were still significantly easier to compact in the SGC than the HMA. For some of the WMA mixes, this is true even at temperatures as low as 175ºF.
- Lab mixed, lab compacted WMA exhibited similar compaction characteristics to HMA when compacted at 30ºF below the HMA.
- Not all warm mix additives are the same and can have different effects on the compactability of a mix.
- Brookfield rotational viscosity is an effective tool for evaluating the workability/compaction characteristics for assessing WMA additives that are marketed as modifiers to the binder.
- At test temperatures of 290ºF, 250ºF, and 220ºF, the Sasobit- and Rediset-modified binders exhibited a significantly lower viscosity than the unmodified binder.

CHAPTER 4

MOISTURE SUSCEPTIBILITY AND CRACKING RESISTANCE OF LABORATORY FABRICATED WARM MIX ASPHALT MIXTURES

This chapter describes the results of a laboratory investigation to measure the cracking resistance and moisture sensitivity of different types of WMA compared to HMA. Rutting and moisture susceptibility tests were performed using the HWTT as described in Chapters 2 and 5. The parameters investigated and tests performed, as described in this chapter, are listed in Table 4.1.

Table 4.1. Laboratory Tests to Indicate Material Properties of WMA.

Material Property	Laboratory Test
Reflection Cracking Resistance	Overlay Test
Fatigue Cracking Resistance	Dynamic Mechanical Analysis (DMA)
Moisture Susceptibility	Surface Energy Measurements DMA

OVERLAY TEST RESULTS

The overlay tester was developed to judge a mixture's resistance to thermally induced reflection cracking. However, mixes that perform well in this test should have good fatigue resistance. It is generally considered that dense-graded mixtures should last a minimum of 300 cycles for acceptable field performance. Most TxDOT mixtures designed in the TGC will not currently meet this criterion.

The overlay tester is shown in Figure 4.1, and the test loading parameters were as follows:

- Loading: cyclic triangular displacement-controlled waveform,
- Loading rate: 10 seconds per cycle,
- Test temperature: 25 °C (77 °F), and
- Specimen size: 6 inch total length by 3 inch width by 1.5 inch.

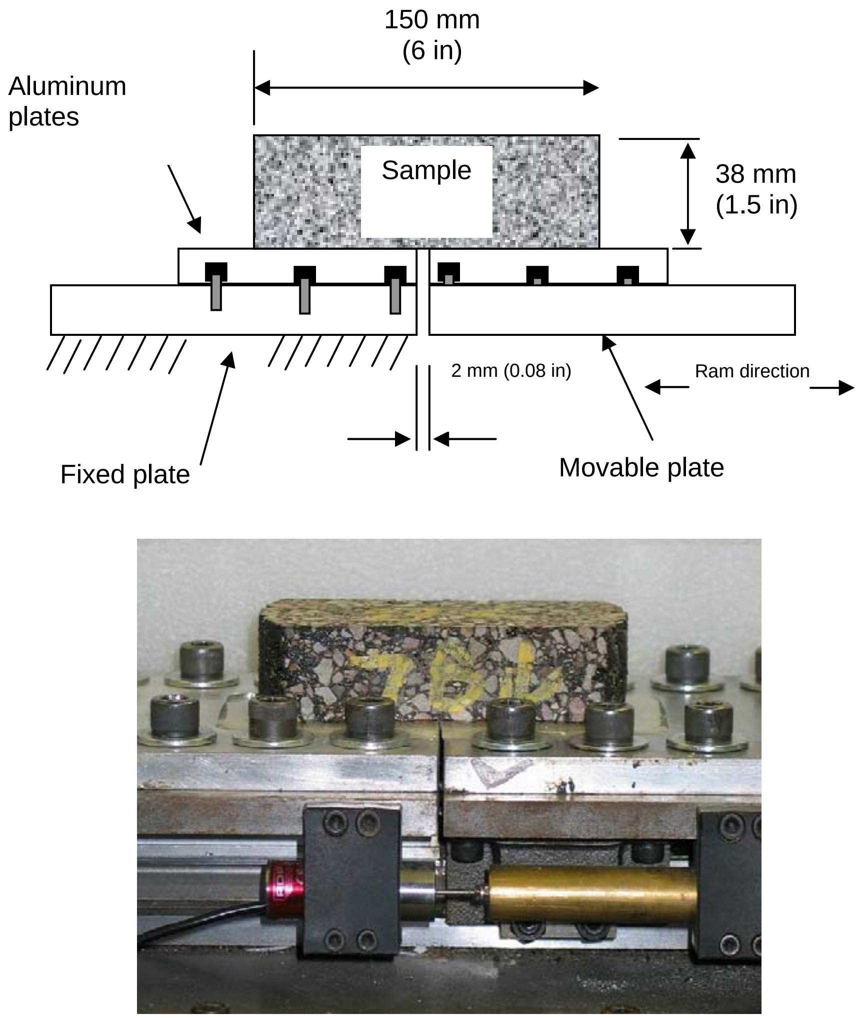


Figure 4.1. Schematic and Photograph of Overlay Test.

The test was performed on mixtures that were designed and fabricated in TTI's laboratory using the materials previously described in Chapter 2:

- Vulcan Brownwood limestone (mix design in Appendix A).
- Delta Sandstone/Hanson limestone blend (mix design in Appendix A).

Oven curing times for the mixtures were as follows:

- PG 64-22 HMA (2 hours at 250ºF);
- PG 76-22 HMA (2 hours at 290ºF); and
- All WMA mixtures (2 hours at 220ºF).

Results of this testing are presented in Figure 4.2. The Advera and Evotherm WMA mixtures exhibited a significant improvement in cracking resistance to that of the control HMA for both the limestone (LS) and sandstone (SS) mixture designs. However, it should be noted that this level of improvement may be significantly reduced with the implementation of a longer oven curing time and/or temperature.

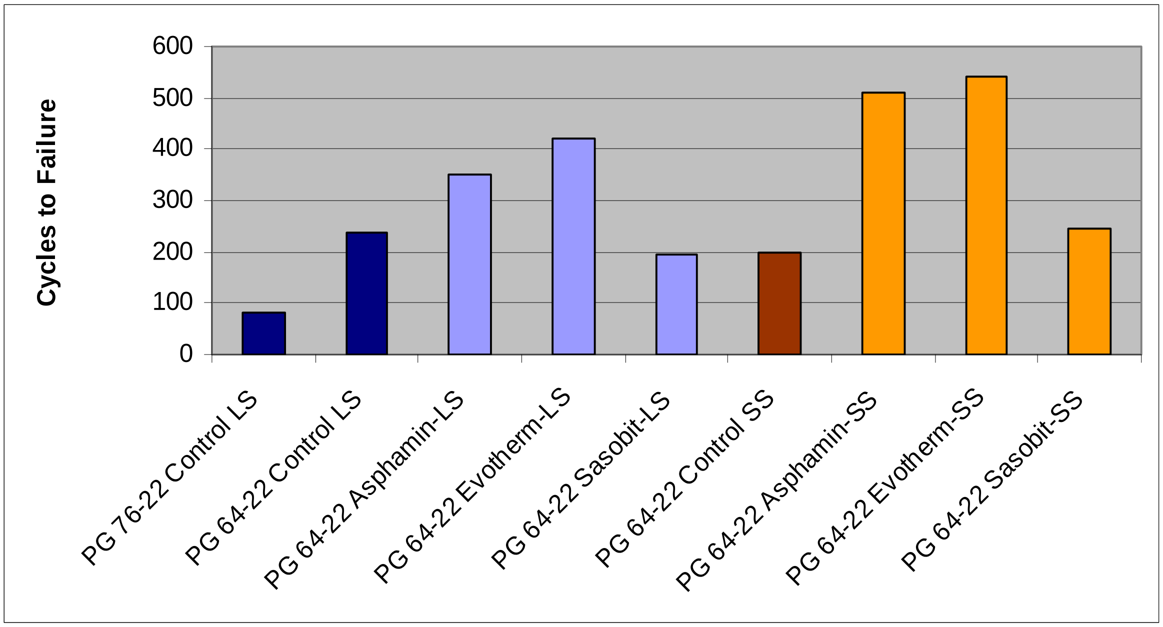


Figure 4.2. Overlay Test Results for Laboratory Produced HMA and WMA Mixtures.

PREDICTED FATIGUE LIFE (DRY AND WET) USING DYNAMIC MECHANICAL ANALYSIS (DMA)

The DMA was used to evaluate each mixture's fatigue life. The DMA applies cyclic, torsional strain-controlled loading to cylindrical asphalt mastics until failure. For each mixture, a minimum of 5 samples were tested in both wet and dry conditions.

Cylindrical asphalt mastic specimens made of a mixture of the aggregate portion smaller than 1.18 mm and the asphalt binder were tested using the DMA (Lytton et al., 2005). The asphalt mastic consisted of a Valero PG 64-22 and a blend of field sand and Brownwood Vulcan limestone screenings corresponding to the mix design shown in Appendix A.

The DMA specimens were prepared by mixing the asphalt binder with the portion of aggregates previously defined using a mechanical mixer. After short-term oven aging for 2 hours at the compaction temperature (250ºF for the HMA and 220ºF for the WMAs), the SGC was used to compact the asphalt mastic specimens to 152 mm in diameter and 85 mm in height. Afterwards, the sides of the specimens were trimmed to a height of 50 mm, and several specimens of 12 mm in diameter were cored, as shown in Figure 4.3.

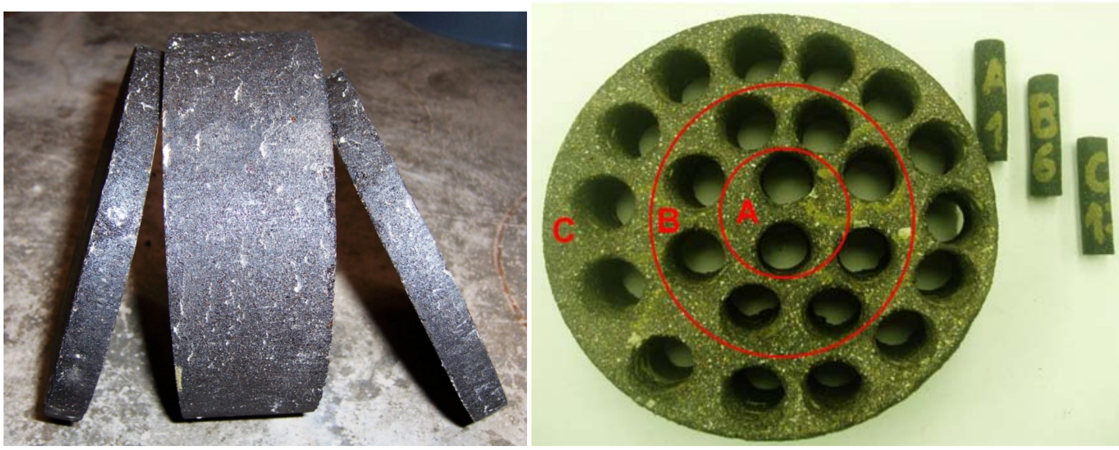


Figure 4.3. SGC Compacted Asphalt Mastic Sample After DMA Specimens Extracted.

Some of the asphalt mastic specimens were moisture conditioned following a method established by Kim et al. (2004), where the specimens are placed in distilled water under vacuum for 1 hour. The saturation level of the specimens measured was between 60 and 80 percent as shown in Table 4.2. The dry and wet asphalt mastic specimens were then subjected to a sinusoidal shear strain in the DMA (Figure 4.4) in order to evaluate the accumulation of damage.

Fatigue life (N_f) for each sample is determined as shown in Figure 4.5.

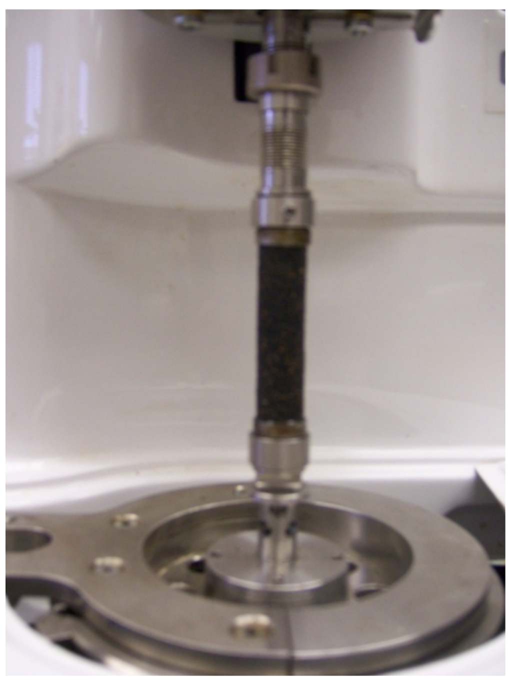


Figure 4.4. Asphalt Mastic Specimen in DMA Testing Apparatus.

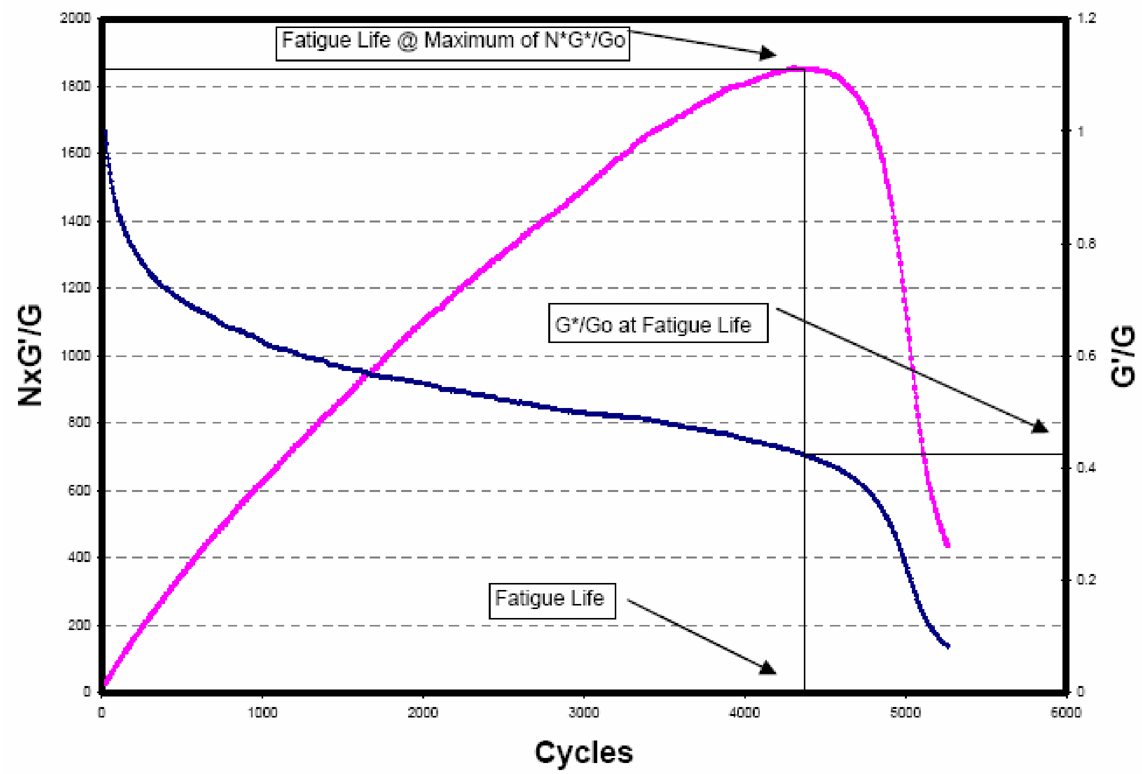


Figure 4.5. Typical DMA Plot to Determine Sample Fatigue Life.

Fatigue life results from the DMA tests are shown in Table 4.2 with the averages shown in Figure 4.6. All of the WMA mixture types exhibited a significant improvement in fatigue for the dry tests. The average wet fatigue life for the WMA mixtures was greater than the HMA; however, the decrease in fatigue life (from dry to wet) was greater for the WMA mixtures, indicating a propensity for moisture susceptibility.

These data support the overlay test data, which indicates better cracking resistance with the WMA mixtures. But as mentioned previously, longer curing times and/or greater curing temperatures can have a negative effect on the laboratory cracking test results.

Table 4.2. Fatigue Life Results from DMA.

Mixture Type	Dry				Wet				
	ID	Air Voids, %	Cycles to Failure, N	Average Cycles to Failure	ID	Air Voids, %	Sat. %	Cycles To Failure, N	Average Cycles to Failure
PG 64-22 HMA	A1 A3 B5 B7 B9	7.9 8.1 7.9 7.8 7.1	42,528 36,231 21,539 43,748 51,814	39,172	A2 B1 B4 B6 B8	8.0 7.7 8.2 7.7 8.1	64 72 72 65 67	2,943 32,353 8,059 19,140 19,440	16,387
Advera WMA	C1 C2 C3 C5 C11	8.7 8.2 8.7 7.9 8.6	144,827 100,749 176,911 175,112 108,245	141,169	C4 C8 C10 C12 13	8.7 8.0 9.0 8.2 8.5	73 72 78 75 78	17,661 32,363 17,051 58,740 25,447	30,252
Evotherm WMA	4 5 9 12 13	6.7 7.1 8.1 7.5 6.5	Err 117,541 143,028 131,934 Err	130,834	3 10 15 17 18	7.5 7.2 6.9 6.7 8.2	71 68 69 78 81	135,832 11,054 42,538 100,449 91,104	76,195
Sasobit WMA	1 2 7 16 18	8.1 8.3 8.0 8.5 8.2	162,218 180,209 159,520 135,832 110,644	149,685	4 8 9 10 19	8.1 8.5 8.0 8.3 8.5	62 65 64 62 62	48,525 41,349 50,344 15,242 31,444	37,381

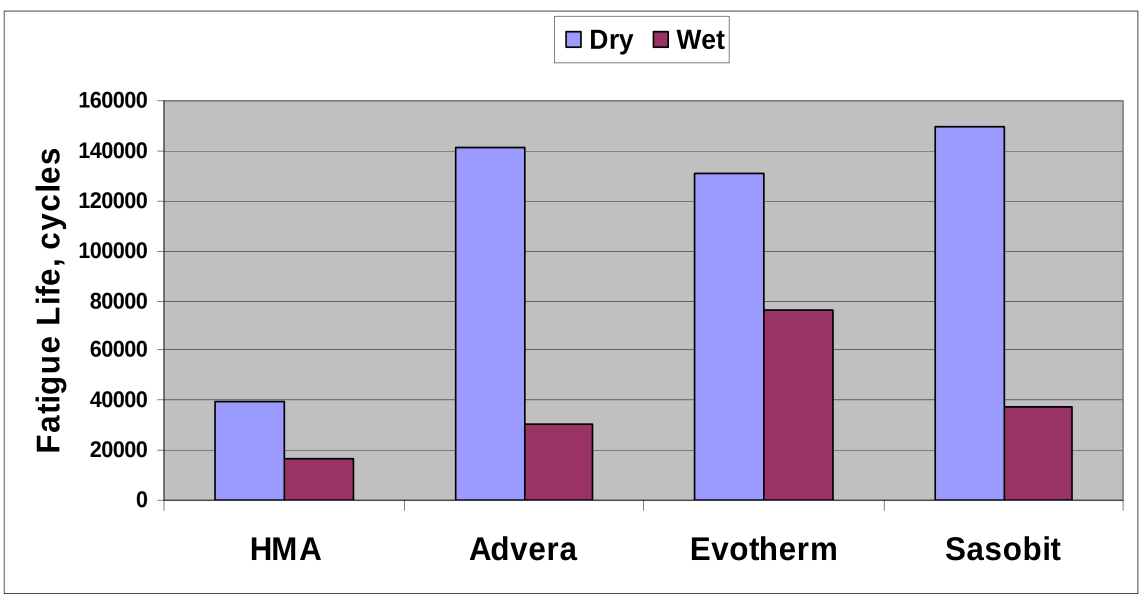


Figure 4.6. Average Fatigue Life (Wet and Dry) for HMA and WMA.

DETERMINATION OF SURFACE FREE ENERGY AND WORK OF ADHESION

This section describes the determination of surface free energy (SFE) and work of adhesion to further characterize the potential effect of WMA additives on the performance of WMA.

From the thermodynamic point of view, the SFE of a material is the amount of work (energy) required to create a unit area of new surface of that material in vacuum. According to the Good-Van Oss-Chaudhury (2) theory, based on the source of intermolecular forces, the SFE can decompose into three separate components. These components correspond to: monopolar acidic, Γ^{+}; monopolar basic, Γ^{-} (these two terms define the polar component Γ^{AB}), and Lifshitz-van der Waals or nonpolar component, Γ^{LW}. The SFE, Γ, of a given material is computed according to Equation 1, which was applied in this study to calculate the SFE of both asphalt and aggregate surfaces.

$$\Gamma = \Gamma^{LW} + 2\sqrt{\Gamma^{+}\Gamma^{-}} = \Gamma^{LW} + \Gamma^{AB} \tag{1}$$

SFE components for asphalts and aggregates were determined using the Wilhelmy Plate (WP) method and the Universal Sorption Device (USD), respectively. The WP method allows computing of the contact angle of a probe liquid on the asphalt surface. Thin glass plates (50 mm by 24 mm by 0.15 mm thick), coated with a thin asphalt film, are immersed and withdrawn from a probe liquid at very slow and constant speed while suspended from an accurate balance that registers the loading force for the immersion and receding processes. Using the forces measured during the advancing and receding processes, advancing and receding contact angles are calculated, respectively. The advancing (or wetting) and receding (or dewetting) contact angle determinations are used to compute two separate sets of SFE components. Equation 2, derived from the analysis of forces for the measurement setup of the WP method, is used to calculate the contact angle (θ):

$$\cos\theta = \frac{\Delta F + V_{im}\left(\rho_L - \rho_{air}\right)g}{P_t \Gamma_L} \tag{2}$$

where, ΔF is the force measured with the balance, V_{im} is the volume of the immersed plate, ρ_L is the density of the probe liquid, ρ_{air} is the density of the air, g is the local acceleration of gravity, P_t is the perimeter of the asphalt coated plate, and Γ_L is the total SFE of the probe liquid.

By using the equation proposed by Good, van Oss and Chaudhury (1988) (Equation 3), the contact angle of a probe liquid, L, in contact with a solid, S, is related to the SFE components (Γ^{LW}, Γ^{+}, and Γ^{-}) of the liquid and the solid as follows:

$$W_{LS}^{a} = \Gamma_L\left(1 + \cos\theta\right) = 2\sqrt{\Gamma_S^{LW}\Gamma_L^{LW}} + 2\sqrt{\Gamma_S^{+}\Gamma_L^{-}} + 2\sqrt{\Gamma_S^{-}\Gamma_L^{+}} \tag{3}$$

where W_{LS}^{a} represents the work of adhesion. Determination of the contact angles of a particular asphalt with at least three known probe liquids allows one to obtain a system of linear simultaneous equations based on Equation 3. The solution of this system of unknowns will render the magnitudes of the SFE components of the asphalt (represented in this case by Γ_S^{LW}, Γ_S^+, and Γ_S^-). The five liquids used in this study provide excellent calculation reliability. Table 4.3 presents the SFE characteristics of these probe liquids (Van Oss, et al, 1988). The SFE measurements were performed according to the procedure described in detail by Hefer et al. (2006), and the liquids included in the final calculation of asphalt SFE were screened as suggested by Hefer et al. (2006) using a plot of $\Gamma_L(\cos\theta)$ versus Γ_L.

Table 4.3. Surface Free Energy Characteristics of Probe Liquids at 20°C (ergs/cm^2).

Probe Liquid	Γ_L	Standard Deviation	Γ_L^{LW}	Γ_L^+	Γ_L^-
Water	72.8	0.2	21.8	25.5	25.5
Glycerol	64.0	0.3	34.0	3.92	57.4
Formamide	**58.0**	0.2	39.0	2.28	39.6
Ethylene glycol	48.0	0.2	29.0	1.92	47.0
Methylene fodide[1]	50.8	0.1	50.8	0.0	0.0

[1]Also known as diiodomethane.

The SFE of the aggregates was indirectly determined using the USD based on the gas adsorption characteristics of three probe vapors. The work of adhesion (W_a) of the probe vapor (V) on a solid (aggregate) (S) and their SFE components are related, as indicated by Equation 4.

$$W_a = 2\sqrt{\Gamma_S^{LW}\Gamma_V^{LW}} + 2\sqrt{\Gamma_S^+\Gamma_V^-} + 2\sqrt{\Gamma_S^-\Gamma_V^+} \qquad (4)$$

where the SFE components (Γ_i^j) are defined as previously indicated. In addition, this work of adhesion can be quantified in terms of the equilibrium spreading pressure of the probe vapor on the solid surface (π_e) and the SFE of the probe vapor (Γ_V) as:

$$W_a = \pi_e + 2\Gamma_V \qquad (5)$$

Equations (4) and (5) lead to:

$$\pi_e + 2\Gamma_V = 2\sqrt{\Gamma_S^{LW}\Gamma_V^{LW}} + 2\sqrt{\Gamma_S^+\Gamma_V^-} + 2\sqrt{\Gamma_S^-\Gamma_V^+} \qquad (6)$$

Computation of the spreading pressure is conducted by applying Equation 7 and using the adsorption isotherm of the amount of solvent adsorbed versus relative pressure at constant temperature. It is determined using the USD.

$$\pi_e = \frac{RT}{A}\int_0^{p_0}\frac{n}{P}dP \qquad (7)$$

where, R is the universal gas constant, T is absolute temperature, A is the specific surface area of the aggregate, n is the mass of the adsorbed vapor on the aggregate surface, and P is the vapor pressure of the probe vapor. The specific surface area of the aggregate is calculated using the USD through the application of the Brunauer, Emmett, and Teller (BET) equation.

Therefore, the SFE of aggregates can be computed by solving a system of three linear equations in the form of Equation 6. For this purpose, the aggregate must be tested using three different known probe vapors in the USD. Table 4.4 presents the characteristics of the probe vapors used to measure the SFE of the aggregates included in this study.

Table 4.4. Surface Free Energy Characteristics of Probe Vapors (ergs/cm^2).

Vapor	Γ_v	Γ_v^{LW}	Γ_v^{+}	Γ_v^{-}
Distilled water	72.60	21.60	25.50	25.50
n-Hexane	18.40	18.40	0.00	19.60
Methyl Propyl Ketone	24.70	24.70	0.00	0.00

Once the SFE components of both asphalt (A) and aggregate (S) are quantified, the work of adhesion between these two materials (in the absence of water at the interface) is computed as:

$$W_{AS}^{dry} = 2\sqrt{\Gamma_A^{LW}\Gamma_S^{LW}} + 2\sqrt{\Gamma_A^{+}\Gamma_S^{-}} + 2\sqrt{\Gamma_A^{-}\Gamma_S^{+}} \qquad (8)$$

The work of adhesion between asphalt and aggregate in the presence of water (W) is computed by applying Equation 9.

$$W_{ASW}^{wet} = 2\begin{bmatrix} -\sqrt{\Gamma_A^{LW}\Gamma_W^{LW}} - \sqrt{\Gamma_S^{LW}\Gamma_W^{LW}} + \sqrt{\Gamma_A^{LW}\Gamma_S^{LW}} + \Gamma_W^{LW} \\ -\sqrt{\Gamma_W^{+}}\left(\sqrt{\Gamma_A^{-}} + \sqrt{\Gamma_S^{-}} - \sqrt{\Gamma_W^{-}}\right) \\ -\sqrt{\Gamma_W^{-}}\left(\sqrt{\Gamma_A^{+}} + \sqrt{\Gamma_S^{+}} - \sqrt{\Gamma_W^{+}}\right) + \sqrt{\Gamma_A^{+}\Gamma_S^{-}} + \sqrt{\Gamma_A^{-}\Gamma_S^{+}} \end{bmatrix} \qquad (9)$$

In addition, the work of cohesion of the asphalt binder (asphalt-asphalt interface) in the absence and in the presence of water at the interface is calculated according to Equations 10 and 11, respectively.

$$W_{AA}^{dry} = 2\left(\Gamma_A{}^{LW} + 2\sqrt{\Gamma_A{}^{+}\Gamma_A{}^{-}}\right) \tag{10}$$

$$W_{AA}^{wet} = 2\begin{bmatrix} -2\sqrt{\Gamma_A{}^{LW}\Gamma_W{}^{LW}} + \Gamma_A{}^{LW} + \Gamma_W{}^{LW} \\ -\sqrt{\Gamma_W{}^{+}}\left(2\sqrt{\Gamma_A{}^{-}} - \sqrt{\Gamma_W{}^{-}}\right) \\ -\sqrt{\Gamma_W{}^{-}}\left(2\sqrt{\Gamma_A{}^{+}} - \sqrt{\Gamma_W{}^{+}}\right) + 2\sqrt{\Gamma_A{}^{+}\Gamma_A{}^{-}} \end{bmatrix} \tag{11}$$

The wetting and dewetting SFE components are used to compute corresponding works of adhesion. According to Kim (2009), the dewetting work of adhesion can be used to predict fracture, and the wetting work of adhesion can be used to predict healing ability in asphalt concrete mixtures. Further, the nonpolar component of the wetting (healing) work of adhesion, W^{LW}, is inversely related to the short-term healing rate, while the polar component, W^{AB}, is directly related to the long-term healing rate. Furthermore, the total amount of healing directly relates to the ratio of the polar to the nonpolar component of the wetting work of adhesion, W^{AB}/W^{LW}.

The magnitude of the work of adhesion is positive in the absence of water on the interface and typically negative when water is present at the interface. While the positive values indicate resistance to fracture and capacity to heal, the negative magnitudes show that water will promote debonding along the interface, since it will adhere more strongly than asphalt to the aggregate surface.

The energy ratio (ER) presented in Equation 12 can be used to identify material combinations with smaller susceptibility to moisture damage, which are associated with higher values of ER (Bhasin et al., 2007). In fact, higher ER values are obtained from: (*i*) high magnitudes of work of adhesion in dry condition (W_{AS}^{dry}), which indicate that more work is required to separate the asphalt from its interface with the aggregate, and (*ii*) smaller magnitudes of work of adhesion in wet condition (W_{ASW}^{wet}) that indicate less thermodynamic potential for water to cause debonding at the asphalt-aggregate interface.

$$ER = \frac{W_{AS}^{dry}}{W_{ASW}^{wet}} \tag{12}$$

Experimental Design

SFE determinations were evaluated for two asphalt sources, two aggregate sources, and four WMA additives as follows:

- Asphalt
    - Lufkin PG 64-22 (from field trials);
    - Valero PG 64-22 (from lab study);

  - Valero PG 76-22 (limited testing performed).
- Aggregate
  - Gravel (Fordyce);
  - Limestone (Hanson).
- WMA Additives
  - Advera;
  - Sasobit;
  - Evotherm;
  - Rediset.

The procedures used for specimen fabrication, laboratory conditioning, and testing using the Wilhemy Plate (WP) method and the USD correspond to those described Lytton et al. (2005). The application of the WP method requires the use of thin uniform films of the binder to be tested. The asphalt binders were combined with the different WMA additives. The Rediset and Sasobit additives are considered binder additives. However, the Advera and Evotherm additive are added into to the mix and are effective at least, in part, due to a foaming action which occurs when mixed with hot aggregate.

Results of Surface Free Energy (SFE) and Work of Adhesion and Cohesion

Table 4.5 presents values of the components and total SFE of the aggregates. Table 4.6 and 4.7 show the same parameters for asphalts computed using both receding and advancing contact angles, respectively. The SFE determinations of these aggregates of different origin showed important differences in their components related basically to discrepancies in the monopolar basic component (Γ^-).

Table 4.5. Components and Total Surface Free Energy of Aggregates (ergs/cm^2).

Aggregate	Γ(ergs/cm^2	Γ^{LW}	Γ^{AB}	Γ^+	Γ^-
River Gravel	111.26	44.37	66.90	1.63	687.89
Limestone	95.53	45.17	50.36	1.33	474.99

Note: Γ = total surface free energy, Γ^{LW} = Lifshitz-van der Waals component or nonpolar component, Γ^{AB} =acid-base component or polar component, Γ^+ = acid component, Γ^- = base component.

SFE results for the asphalts showed that the addition of the WMA additives modified both the individual components as well as the total SFE related to both fracture and healing. These modifications will induce effects on the corresponding work of adhesion for the asphalt-aggregate system in both wet and dry conditions. Some additional differences may emerge as aging progresses further modifies, in different proportions, the SFE components of each asphalt-additive combination.

Table 4.6. Components and Total Surface Free Energy of Asphalts Based on Receding Contact Angles (Dewetting-Fracture).

Asphalt	Γ(ergs/cm^2	Γ^{LW}	Γ^{AB}	Γ^{+}	Γ^{-}
PG 64-22 Lufkin control, 1	41.20	21.67	19.53	5.62	16.96
PG 64-22 Lufkin+Advera, 2	40.66	31.22	9.43	0.88	25.31
PG 64-22 Lufkin+Sasobit, 3	42.83	41.13	1.71	0.05	15.77
PG 64-22 Lufkin+Evotherm, 4	52.10	47.58	4.52	0.33	15.46
PG 64-22 Lufkin+Rediset, 5	41.43	41.43	0.00	0.00	19.38
PG 64-22 Valero control, 6	31.99	20.05	11.94	1.99	17.94
PG 64-22 Valero+Advera, 7	38.56	38.24	0.31	0.00	16.72
PG 64-22 Valero+Sasobit, 8	45.02	42.72	2.30	0.15	8.95
PG 64-22 Valero+Evotherm, 9	47.01	44.35	2.65	0.12	14.81
PG 64-22 Valero+Advera, 10	37.22	37.22	0.00	0.00	23.25
PG 76-22 Valero control, 11	32.82	17.84	14.98	3.97	14.14
PG 76-22 Valero_Advera, 12	45.62	43.17	2.45	0.11	14.02

Table 4.7. Components and Total Surface Free Energy of Asphalts Based on Advancing Contact Angles (Wetting-Healing).

Asphalt	Γ(ergs/cm^2	Γ^{LW}	Γ^{AB}	Γ^{+}	Γ^{-}
PG 64-22 Lufkin control, 1	12.84	8.71	4.13	1.77	2.41
PG 64-22 Lufkin+Advera, 2	12.70	7.04	5.66	2.99	2.69
PG 64-22 Lufkin+Sasobit, 3	14.00	9.95	4.06	1.59	2.59
PG 64-22 Lufkin+Evotherm, 4	22.39	18.32	4.07	0.74	5.56
PG 64-22 Lufkin+Akzonobel, 5	30.28	30.28	0.00	0.00	0.00
PG 64-22 Valero control, 6	17.90	17.38	0.52	0.03	1.93
PG 64-22 Valero+Advera, 7	12.22	7.79	4.44	1.85	2.66
PG 64-22 Valero+Sasobit, 8	19.83	19.83	0.00	0.00	2.67
PG 64-22 Valero+Evotherm, 9	17.21	15.32	1.89	0.97	.93
PG 64-22 Valero+Akzonobel, 10	18.73	18.73	0.00	0.70	0.00
PG 76-22 Valero control, 11	11.41	6.60	4.81	2.73	2.12
PG 76-22 Valero_Asphamin, 12	17.71	16.19	1.52	0.29	2.03

The values of work of cohesion are presented in Figures 4.7 and 4.8. These results illustrate the positive effect of some of the additives on cohesive fracture (at the asphalt-asphalt interface) in the absence of water, since more work should be applied to propagate a crack into the asphalt-additive combinations than in the base asphalt. As discussed by Lytton (2004), cohesive fracture can be typically associated with thick asphalt films on the aggregate, while adhesive fracture is usually associated with thin asphalt films. At intermediate thicknesses, failure may be partly adhesive and partly cohesive.

In the presence of water, the values of work of cohesion decreased as compared to those calculated in the dry condition. The positive values (Figures 4.7 and 4.8) indicate that the presence of water will not induce a cohesive fracture process. A positive effect of some of the additives is similarly observed in this second set of data, since the work of cohesion values were higher as compared to the values computed for the base asphalt alone. In addition, the results indicate that the Valero with Rediset and the Lufkin with Advera are more prone to cohesive fracture in the presence of water than they would be without the additives.

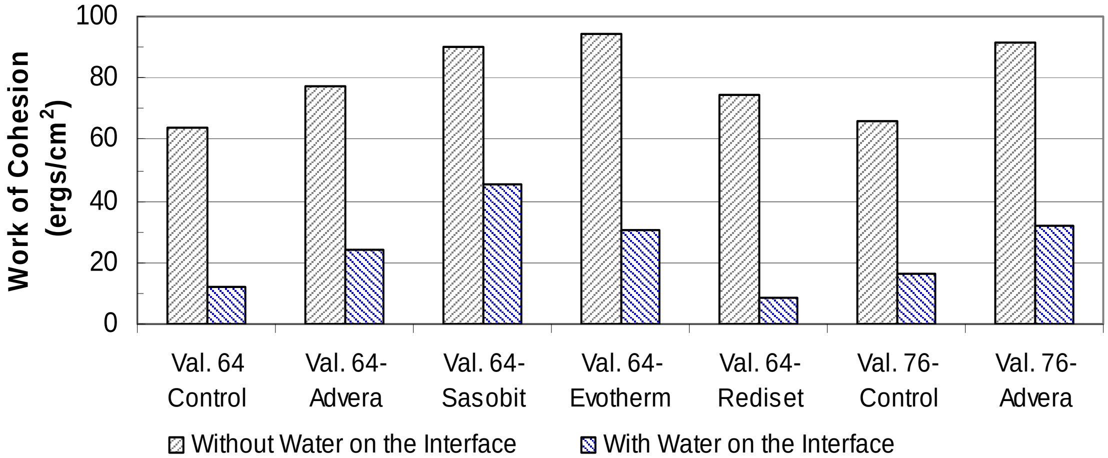


Figure 4.7. Work of Cohesion for Both Dry and Wet Conditions Using Valero Base Asphalt.

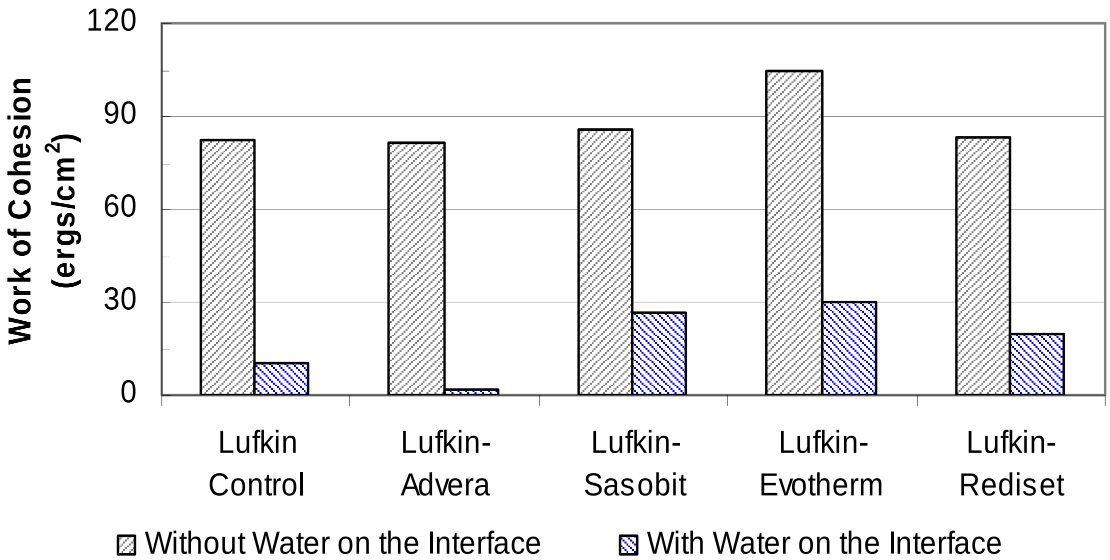


Figure 4.8. Work of Cohesion for Both Dry and Wet Conditions Using Lufkin Martin Base Asphalt.

Figures 4.9 and 4.10 show the values of work of adhesion for each aggregate and asphalt combination in the dry condition. In all cases, the work of adhesion decreased with the addition of each WMA additive. These results may suggest that there is no improvement in the resistance to adhesive fracture (at the asphalt-aggregate interface) with the addition of WMA additives for either aggregate or base asphalt.

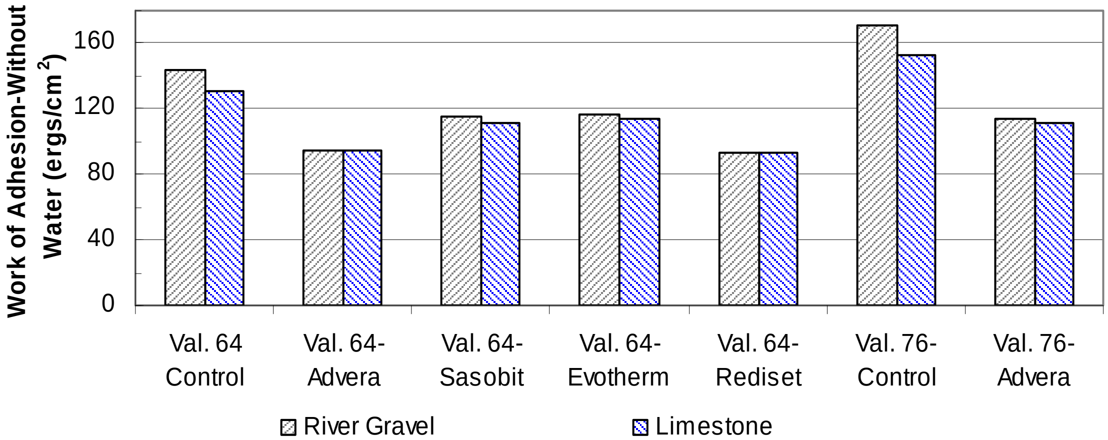


Figure 4.9. Work of Adhesion in Dry Condition for Valero Base Asphalt.

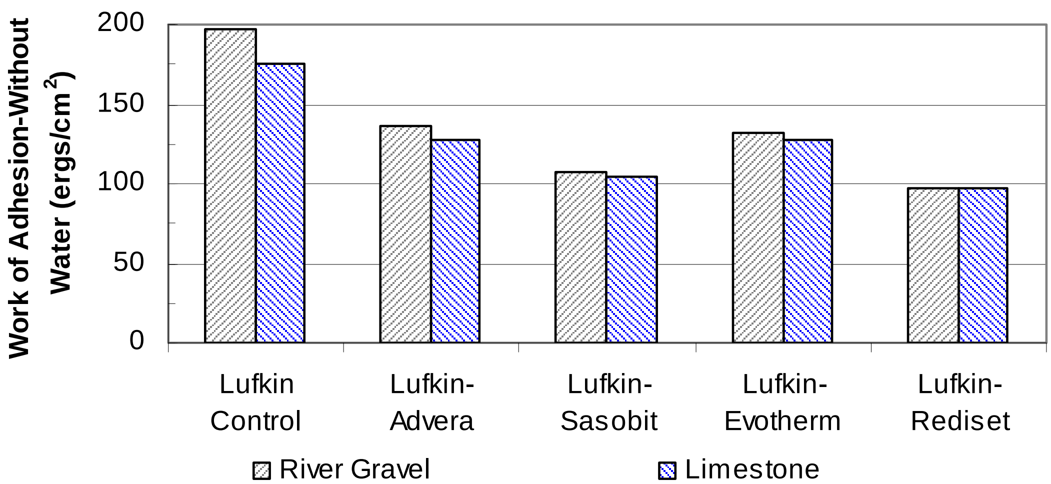


Figure 4.10. Work of Adhesion in Dry Condition for Martin Base Asphalt.

Results of work of adhesion for each aggregate and asphalt combination in the presence of water at the aggregate-asphalt interface are shown in Figures 4.11 and 4.12. The negative magnitudes indicate that water will cause debonding along the interface. Higher magnitudes are indicative of a higher energy potential for disrupting the asphalt-aggregate bonding in the presence of water. Consequently, the results shown in Figures 4.11 and 4.12 suggest that moisture damage susceptibility is not reduced after incorporating the WMA additives. Smaller work of adhesion values were reported for the limestone-asphalt combinations indicating less susceptibility to moisture damage for this system as compared to the river gravel-asphalt combinations. This conclusion agrees with practical observations, reporting that, in general, asphalt mixes fabricated using calcareous (limestone) aggregates are less prone to exhibit moisture damage when compared to those fabricated employing siliceous (gravel) aggregates.

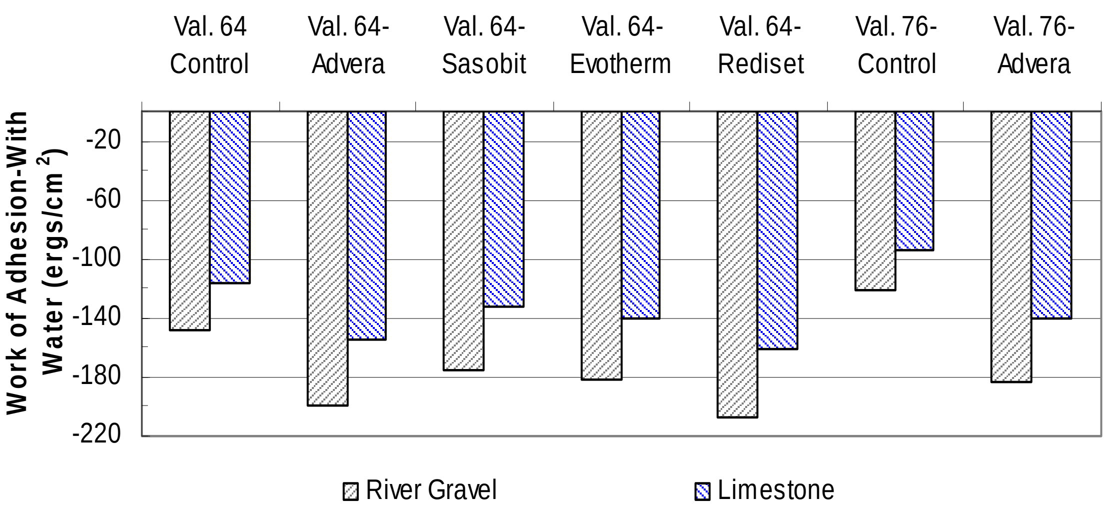


Figure 4.11. Work of Adhesion in Wet Condition for Valero Base Asphalt.

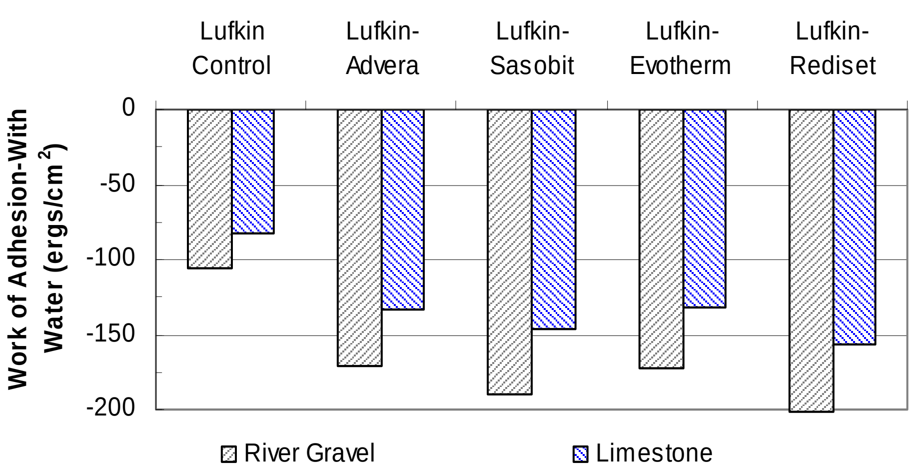


Figure 4.12. Work of Adhesion in Wet Condition for Martin Base Asphalt.

The values of ER shown in Figures 4.13 and 4.14, computed based on the values of work of adhesion, suggest that susceptibility to moisture damage did not decrease upon addition of the WMA additives.

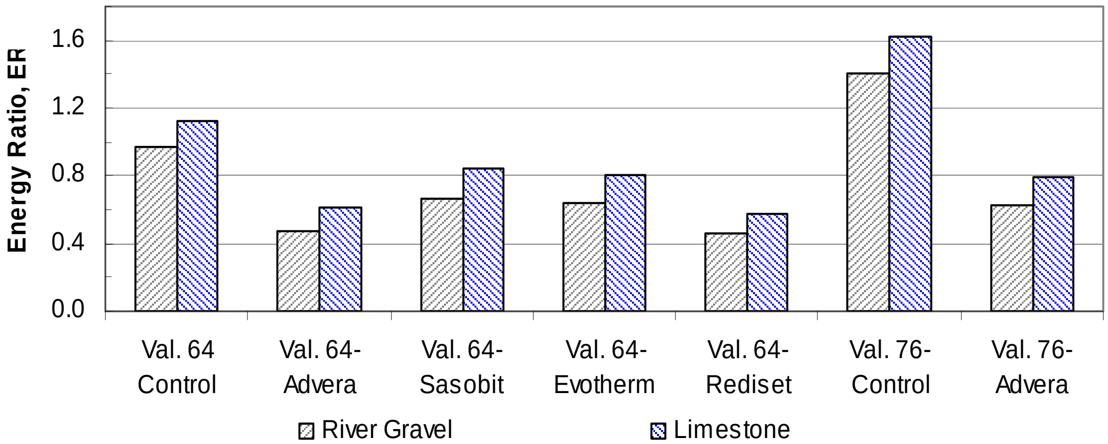


Figure 4.13. Comparison of Energy Ratios (Fracture) for Valero Base Asphalt.

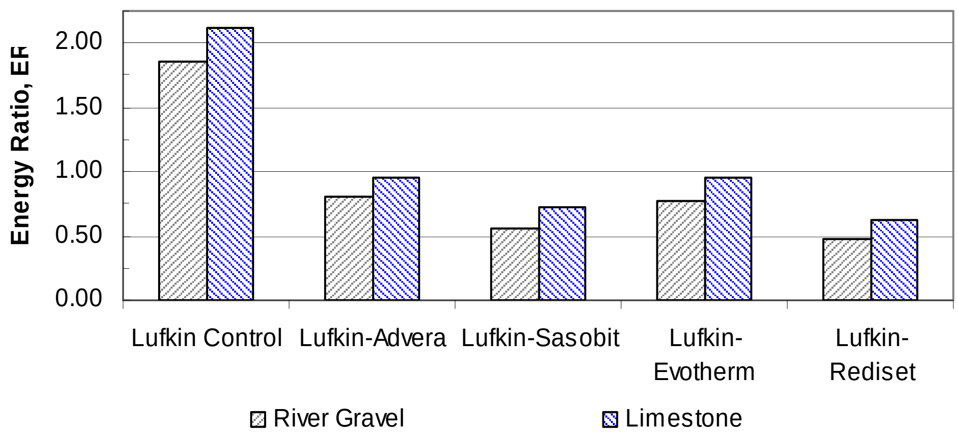


Figure 4.14. Comparison of Energy Ratios (Fracture) for Martin Base Asphalt.

Summary and Conclusions for Surface Free Energy (SFE) Study

SFE testing for the PG 64-22 asphalt and the aggregates employed in the mixtures used to conduct the performance evaluation were conducted as part of this study. In addition, SFE for different asphalt-WMA additive combinations (fabricated using the PG 64-22 asphalt) were determined. Based on these SFE values, values of work of cohesion and adhesion were computed for both dry and wet (presence of water at the aggregate-asphalt interface) conditions. Corresponding results suggested a positive effect of the WMA additives combined with the asphalts tested here to prevent cohesive fracture (at the asphalt-asphalt interface) in both dry and wet conditions. However, improvement in the resistance to adhesive fracture (at the asphalt-aggregate interface) was not revealed in either dry or wet conditions.

The aforementioned conclusions are only related to the responses of the particular asphalt-aggregate combinations used in this study. Different responses may be expected for other material combinations. A different asphalt may exhibit total SFE values of similar order of magnitude to those reported in this study, but their SFE components can differ as a function of their particular chemical compositions, which can also imply different responses after the addition of WMA additives. Further, aggregates with varied origins can exhibit a large range of values of total SFE and SFE components with direct consequences on their interaction with asphalt in terms of work of adhesion.

In summary, characterization of materials using SFE and corresponding computations of work of cohesion and adhesion constitute a fundamental tool to optimize the selection of material combinations and to understand the effect of their modification in terms of fundamental material properties that can be linked to performance models to better engineer asphalt mixtures.

SUMMARY

- Overlay test data from lab mixed, lab compacted samples indicate a significant improvement in fatigue resistance for the Advera and Evotherm WMA mixtures. This was with a 2-hour cure at the compaction temperature, and this level of improvement may be significantly reduced with the implementation of a longer oven curing time and/or higher temperature.
- Fatigue life results from the DMA tests indicated that all of the WMA mixture types had a significant improvement in fatigue for the dry tests. The average wet fatigue life for the WMA mixtures was also greater than the HMA; however, the decrease in fatigue life (from dry to wet) was greater for the WMA mixtures indicating a propensity for moisture susceptibility. But, as mentioned previously, these results could be affected negatively with an increase in oven curing time and/or temperature.
- Surface Free Energy results indicate that the resistance to adhesive fracture (at the asphalt-aggregate interface) was reduced, in both wet and dry conditions, for all WMA additives/binder/aggregate combinations investigated in this study.

CHAPTER 5
FIELD EVALUATION OF WARM MIX ASPHALT TECHNOLOGIES

Several WMA field projects were evaluated throughout the course of this research study. These projects are described in the following.

SAN ANTONIO LOOP 368

Project Description

This project represents the first WMA trial placed by TxDOT. Evotherm was used to fabricate the WMA. Evotherm, developed by MeadWestvaco Asphalt Innovations, used a technology that is based on a chemical package that included emulsification agents; additives to improve aggregate coating, mixture workability, and compaction; as well as adhesion promoters (anti-stripping agents). Evotherm utilized a high residue emulsion (about 70 percent binder) that improves adhesion of the asphalt to the aggregate. Table 5.1 presents the San Antonio Loop 368 project details. This project is further described in Button et al. (2007), which was Research Report 0-5597-1 associated with this study.

Table 5.1. San Antonio Loop 368 WMA Field Project Details.

Project Location	Loop 368 (Old Austin Highway) See Figure 5.1
Construction Dates	August-September 2006
WMA Tonnage	~ 2000 tons
Mix Design Information	• Item 341, Type C Dense Graded • Valero PG 76-22 • Aggregate: 88% Vulcan Helotes LS (SAC B) 12% Field Sand • Anti-strip: 0.75% liquid for HMA, none for WMA • AC Content: 4.6% (Both HMA and WMA)
WMA Technology	Evotherm Emulsion Based Technology
Mixture Production	Temperature at Load Out: HMA 320 ºF WMA 220 ºF
Placement and Compaction	Mat Thickness: 2 inches Average In-Place Density: HMA 94.2% WMA 93.4%

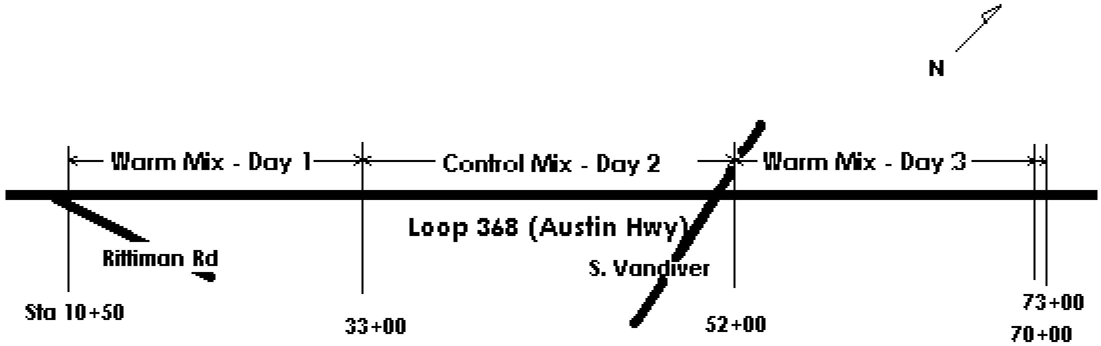


Figure 5.1. San Antonio Loop 368 Evotherm Field Trial Location and Layout.

Mixture Properties of Plant Produced Lab Compacted Samples

Samples of the loose WMA and HMA were sent to TxDOT's Construction Division Laboratory in Austin. These WMA samples were reheated and compacted to 93 percent density using the SGC at two different temperatures: 240°F and 300°F. The control samples were compacted to 93 percent density in the SGC at 300°F. These samples were subjected to HWTT and Overlay Testing, and the results are shown in Tables 5.2 and 5.3.

Generally, the WMA samples compacted at 300°F performed better in the HWTT than those compacted at 240°F. All of the WMA samples failed the HWTT with the exception of the samples compacted at 300°F from the second night of WMA production.

The overlay test results shown in Table 5.3 for both the WMA and the control HMA are typical of many current TxDOT dense graded mixes.

Table 5.2. Loop 368 HWTT Results of Plant Produced Lab Molded Samples.

Plant Mix Description	Sample	Molding Temp	Rut at 5K, mm	Rut at 10K, mm	Rut at 15K, mm	Rut at 20K, mm	Passes
Day 1 WMA Sampled at 750 Tons, Lot 1, Sublot 2	1, 2	240	7.8				7400
	3, 4	240	6.4				9700
	1, 2	300	5.9	12.2			10500
	3, 4	300	9.1				8700
Day 1 WMA Sampled at 250 Tons, Lot 1 Sublot 1	1, 3	240	9.6				6500
	2, 4	240	9.7				6600
	1, 2	300	4.2	10.7			11300
	3, 4	300	4.3	8.1			14700
Day 2 Control Mix	2, 3	300	2.3	3.6	5.1	7.0	20000
	4, 5	300	3.3	5.5	7.8	10.3	20000
Day 3 WMA Sampled at 250 Tons, Lot 2	1, 2	240	3.7	9.2			13001
	3, 7	240	5.2	10.7			10701
	6, 7	300	2.6	3.2	4.2	5.6	20000
	4, 5	300	1.5	2.8	4.1	5.2	20000

Table 5.3. Loop 368 Overlay Test Results of Plant Produced Lab Molded Samples.

Overlay Results						
Mix Description	**Sample**	**Molding Temp**	**Max load (lbs)***	**Final** Load (lbs)**	**% Decline**	**Cycles**
Day 1 WMA Sampled at 750 Tons, Lot 1 Sublot 2	**1**	**240**	582.9	39.8	93.2	12
	2		577.2	30.9	94.6	21
	1	**300**	646.4	34.6	94.6	3
	2		600.9	38.8	93.5	7
Day 1 WMA Sampled at 250 Tons, Lot 1 Sublot 1	**1**	**240**	575	38.1	93.4	21
	2		631.3	43.5	93.1	21
	1	**300**	838.2	58.4	93	77
	2		795.7	54.8	93.1	7
Day 2 Control Mix	**1**	**300**	877.1	59.7	93.2	8
	2		851.6	57.4	93.3	12
Day 3 WMA Sampled at 250 Tons, Lot 2	**1**	**240**	627.7	43.5	93.1	11
	2		646.2	44.6	93.1	36
	1	**300**	650.9	44.1	93.2	6
	2		661.6	41.4	93.7	2
	3		628.4	42.4	93.3	6

*Max Load is the load associated with the initial test cycle.
** Final Load is the load associated with the last test cycle.

Short-Term Field Performance

Evaluation of One-Month Road Cores

District personnel obtained cores one month after the warm and control mixes were placed and were sent to TxDOT's construction division in Austin for testing. Results of these tests are tabulated in Table 5.4.

The G_a in Table 5.4 represents the bulk specific gravity of the mix and the G_r represents the maximum specific gravity. The maximum specific gravity values shown in Table 5.4 are based on averages values associated with the respective production lot shown.

Core samples taken for the indirect tensile strength tests included 3 samples taken from the wheel path and 3 samples taken from between the wheel paths for each lot. Averages of the densities of these cores are summarized in Figure 5.2. Any mix tenderness, binder softening, or insufficient curing that one may expect to be associated with the WMA could be reflected with increased densities in the wheel path after one month of trafficking. However, the densities in the wheel path are *less* than the densities between the wheel paths for both the WMA and the control mix. Note in Table 5.4 (Indirect Tensile Strength Cores) that the cores taken in the wheel paths are generally thicker than the cores taken between the wheel path. This may be an indication that the wheel paths may have been rutted prior to overlaying, although the surface had been cold milled months before. This variation in material thickness will lead to a differential compaction effort resulting in the roller applying more effort on the higher points of the pavement, or in this case, between the wheel paths.

Table 5.4. Test Results from One-Month Roadway Cores.

Hamburg Results

Core	Description	Rut at 5K, mm	Rut at 10K, mm	Rut at 15K, mm	Rut at 20K, mm	Total Passes	Ga	Gr	Density, %
1a	Warm Mix, Lot 1 sublot 1, 1st night (15+00 CL 6'offset CL)	8.2				6401	2.307		94.3
1b							2.313	2.446	94.6
2a	Warm Mix, Lot 1 sublot 2 (15+60 OL 7' Offset South Bond)	7.3				7901	2.236		92.1
2b							2.272	2.428	93.6
1a1	Control Mix	6.8	9.1			14601	2.306		93.5
1a2							2.275		92.3
1b1	Control Mix	4.5	5.7	7.5	10.7	20000	2.265		91.8
1b2							2.287	2.466	92.7

Overlay Results

Core	Description	Max load (lbs)	Final Load (lbs)	% Decline	Cycles	Ga Original	Ga Trimmed	Gr	Density, %
2c	Warm Mix, Lot 1 sublot 2 (15+60 OL) (7'Offset South Bond)	626.4	43.6	93.0	638	2.252	2.243		92.4
2d		554.8	38.8	93.0	224	2.242	2.240	2.428	92.3
1c	Warm Mix, Lot 1 sublot 1 , 1st night	696.0	47.9	93.1	41	2.317	2.317		94.7
1d		783.0	52.6	93.3	118	2.312	2.313	2.446	94.6

Indirect Tensile Strength

Core	Description	Diam (in)	Ht (in)	Load (lbs)	Strength (psi)	Ga	Gr	Density, %
1a	Day 1 Warm Mix	5.9	1.9	2254	128.1	2.248	2.437	92.2
1b		5.9	1.8	2269	136.1	2.248		92.2
1c		6.0	1.8	2085	123.0	2.255		92.5
1a(wp)		6.0	2.0	2285	121.3	2.240		91.9
1b(wp)		5.9	2.0	2247	122.5	2.247		92.2
1c(wp)		5.9	2.0	2260	122.6	2.234		91.7
2a1d	Day 3 Warm Mix	5.9	2.0	2842	153.4	2.331	2.440	95.5
2b1e		5.9	2.0	3293	177.8	2.320		95.1
2c1f		6.0	2.0	2874	152.5	2.331		95.5
2a(wp)		6.0	2.4	3422	151.4	2.287		93.7
2b(wp)		5.9	2.4	3433	154.4	2.284		93.6
2c(wp)		5.9	2.5	3607	155.8	2.279		93.4
3a	Day 2 Control Mix	5.9	1.7	2266	143.9	2.258	2.466	91.6
3b		5.9	1.7	2420	153.7	2.273		92.2
3c		5.9	1.7	2552	162.1	2.255		91.4
3a(wp)		5.9	1.7	3079	195.5	2.322		94.2
3b(wp)		5.9	1.8	3178	190.6	2.310		93.7
3c(wp)		5.9	1.8	3031	181.8	2.319		94.0

Indirect Tensile Strength Test Results for Road Cores

Results from the indirect tensile strength tests are shown in Table 5.4. Comparing the tensile strength of the cores in the wheel paths to those between the wheel paths indicate no significant difference as shown in Figure 5.3. Average tensile strengths for each lot are shown in Figure 5.4 and are compared to the tensile strength of the lab molded sample tested during the mix design process. The tensile strengths of the WMA cores taken at one month show a significant improvement over the tensile strength of the WMA tested during the mix design process (which was 60 psi for the WMA and 170 psi for the HMA).

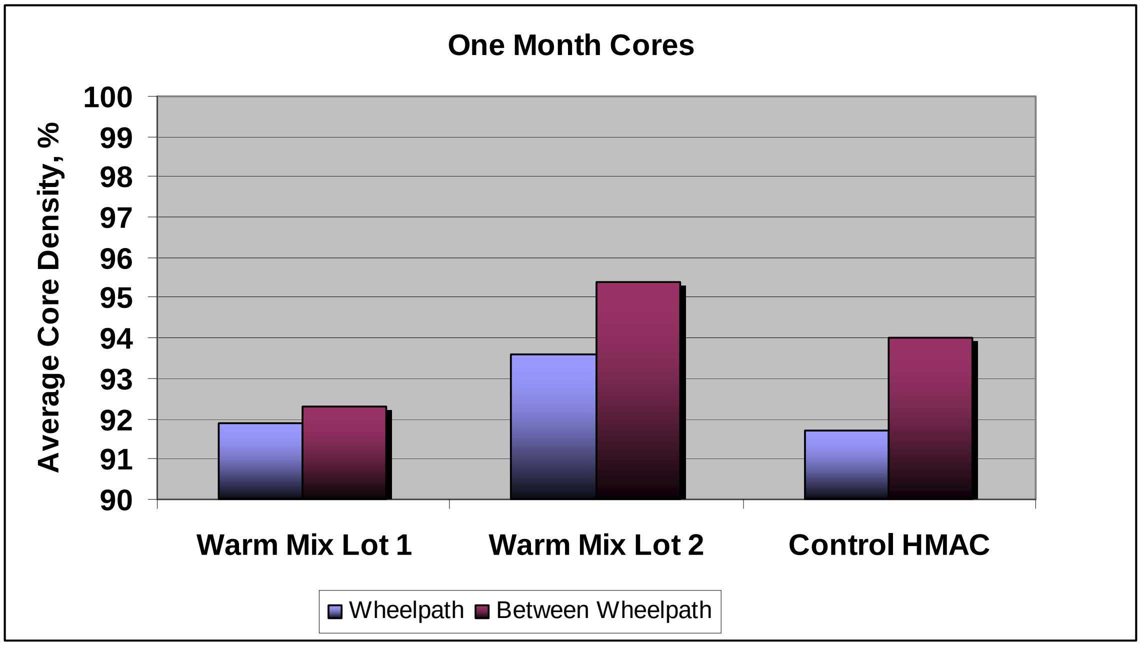


Figure 5.2. Average Core Densities in the Wheel Paths and Between the Wheel Paths for WMA and Control Mixes.

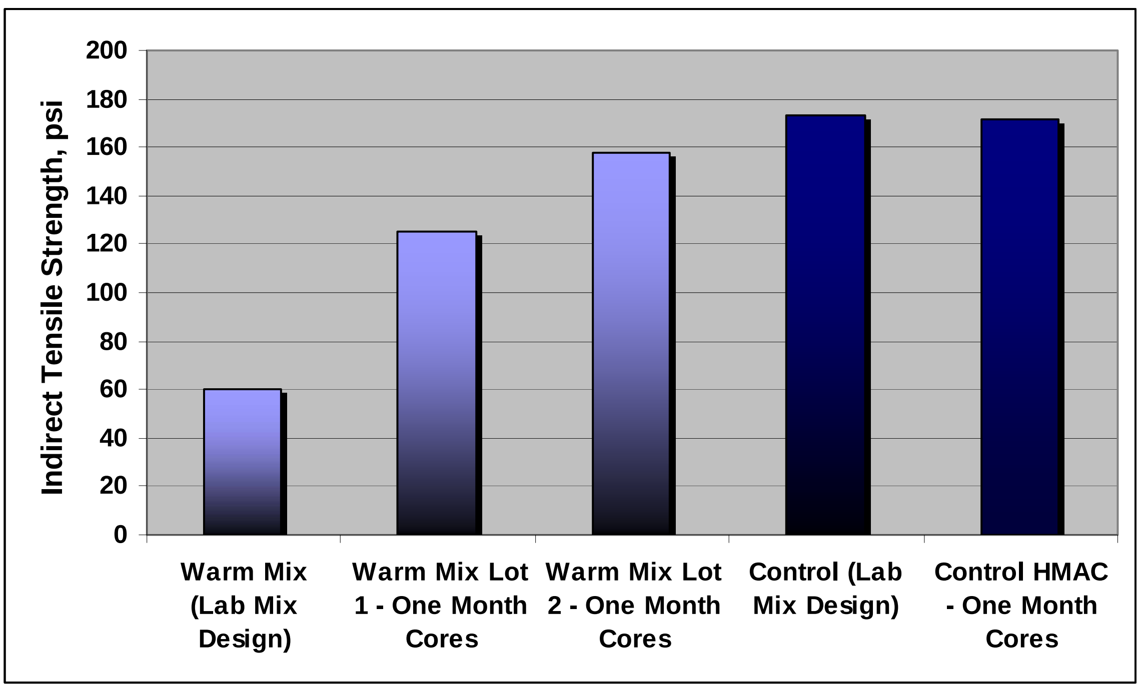


Figure 5.3. Indirect Tensile Strength of Road Cores for WMA and Control Mix Compared to Values Obtained from the Mixture Design.

Hamburg Wheel Tracking Test (HWTT) Results for Road Cores

HWTT results for the one-month roadway cores are compared to the lab molded plant mix samples in Figure 5.4. The data in Figure 5.4 show the number of passes to achieve ½ inch rut depth. As mentioned previously, some improvement is observed in the WMA samples compacted at 300°F versus those compacted at 240°F. However, the WMA cores taken at one month did not indicate that the mix improved with time (in terms of rut or moisture susceptibility resistance) compared to the lab molded samples.

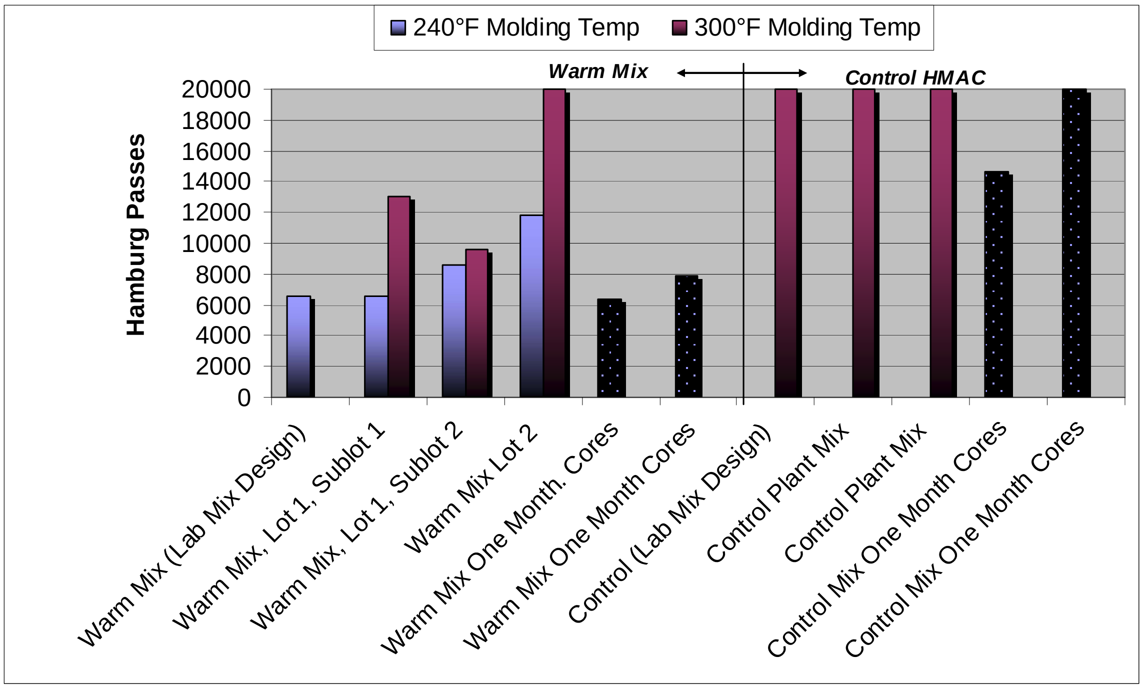


Figure 5.4. Hamburg Wheel Tracking Test Results for Lab Molded WMA and Control Mixes Compared to One-Month Roadway Cores.

Overlay Test Results for One-Month Road Cores

Overlay test results for the roadway cores are compared to the lab molded plant mix samples in Figure 5.5. All lab molded WMA and control HMA specimens performed poorly in the overlay test. However, there was a significant improvement in some of the cores taken at one month from the WMA sections. There may be a difference in density associated with the cores as compared with the lab compacted specimens. The lab specimens were compacted to 93 percent density, and the WMA road cores ranged from 92.3 to 94.6 percent density. This difference in density would not account for the improvement seen in the overlay test road cores. This indicates there is a "curing" effect that is occurring with time providing for improved cracking resistance.

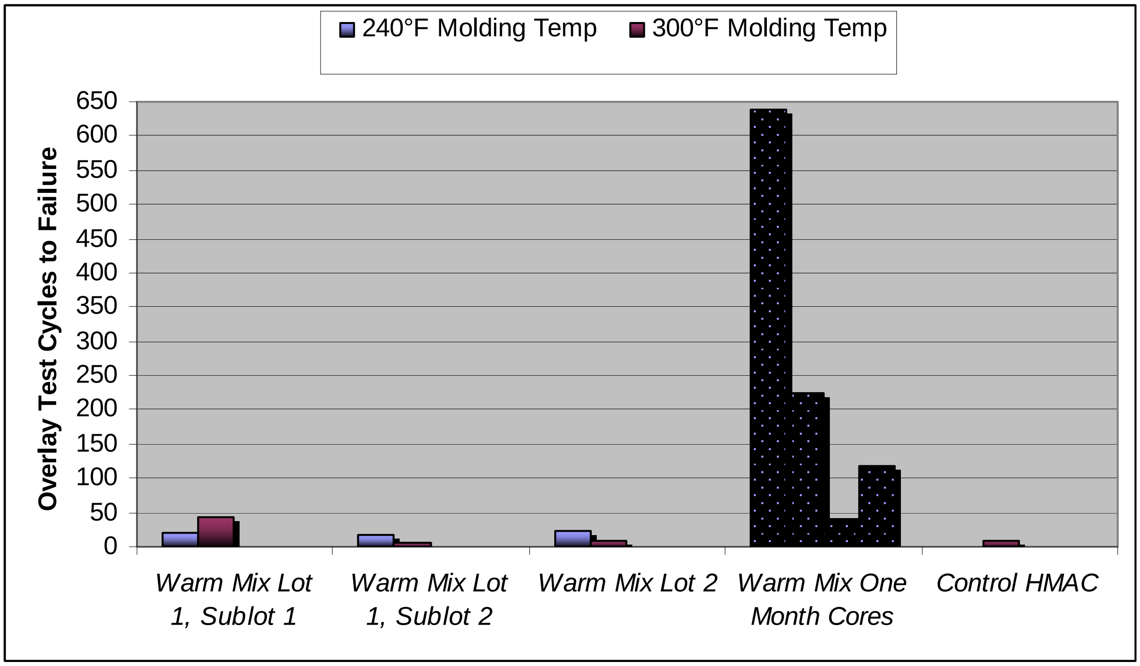


Figure 5.5. Overlay Test Results for Lab Molded WMA and Control Mixes Compared to One-Month Roadway Cores.

X-Ray CT Image Analysis of One-Month Cores

X-ray CT images were scanned and analyzed to determine the air void distribution of the field cores. The X-ray CT system at Texas A&M University acquired digital images using the mini-focus system, which works with an X-ray source of 350 kV. Figure 5.6 shows the X-ray system setup that includes, as basic components, the X-ray source and the detector with the test specimen placed in between. After the source transmits X-ray radiation with a certain initial intensity, the attenuated intensity of the X-ray, after penetrating through the specimen, is registered by the detector. Two dimensional images at each specific vertical position of the specimen are created by rotating the specimen 360° with respect to its center. In this study, images with a vertical gap of 1 mm were obtained for the specimens. In addition, the pixel size was approximately 0.17 mm. Additional details on the principle of operation of the X-ray CT system and image capturing process can be found in Masad et al., 2004.

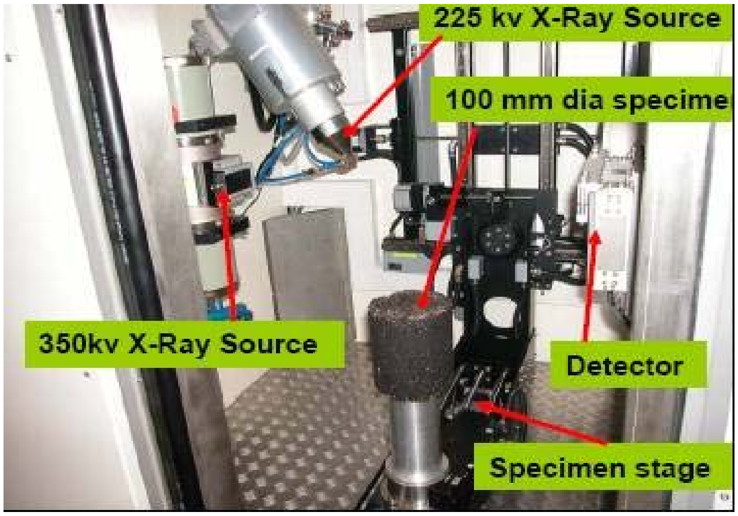


Figure 5.6. Texas A&M University X-Ray CT Image Analysis Equipment.

X-Ray CT image analyses of cores taken from the WMA and HMA sections of the San Antonio project are shown in Figures 5.7.

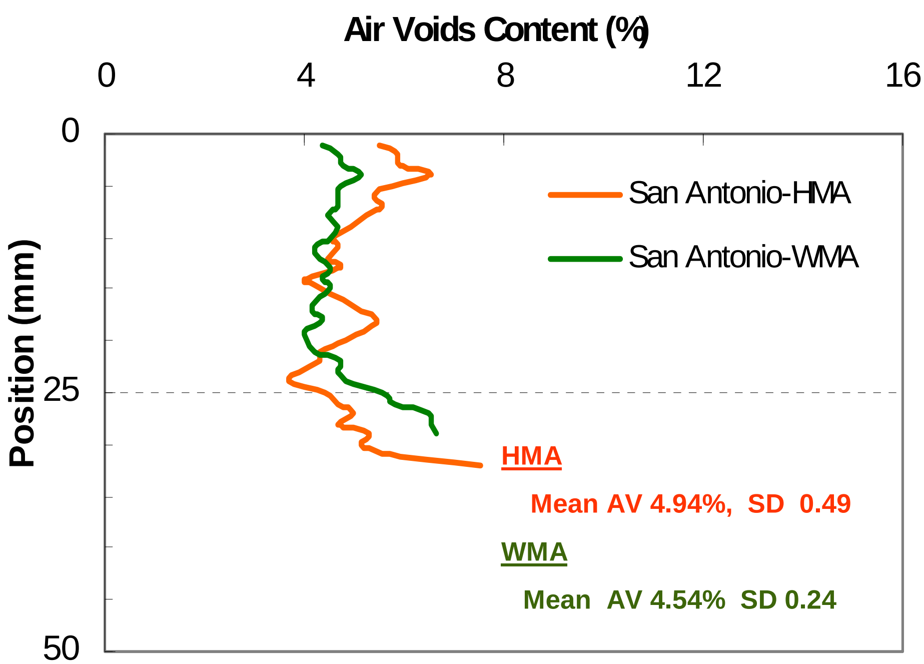


Figure 5.7. X-Ray CT Analysis of Air Void Distribution with Depth (Position) for San Antonio Cores.

The y-axis represents the position of the image on the core. Position "0" is at the top of the core. The mean air void content for the HMA was 4.95 percent with a standard deviation of 0.49. The mean air void content for the WMA core was 4.54 percent with a standard deviation of 0.24. In this analysis, the air voids in the WMA core are more uniformly distributed than the air voids in the HMA core.

Long-Term Field Performance

Field cores were taken after one year of service and are shown in Figure 5.8. It was observed in the cores from the HMA pavement that the asphalt absorption into the aggregate was visibly evident; whereas, in the WMA cores, no asphalt absorption could be observed. This reduced absorption in the WMA is likely due to the reduced production temperature. In addition, the water which was present in the aggregates (due to a recent rain) did not get completely dried out (due to the reduced production temperature) and prevented asphalt from penetrating the aggregate surface.

Resilient moduli tests were performed on the cores taken after one year of service and these data are presented in Figure 5.9. The WMA cores even after one year are not as stiff as the HMA cores.

Cores were also taken after 30 months of service. HWTT and overlay test results for the 12-month and 30-month cores are shown in Figures 5.10 and 5.11, respectively. After 12 months of service the HMA and WMA sections exhibit similar properties.

Figure 5.12 shows the Loop 368 project after 3 years of service. Some cracking is beginning to appear in both the WMA and HMA sections as shown in Figure 5.13. However, there is no evidence of any rutting in either WMA or HMA sections and both of the sections are performing equivalently.

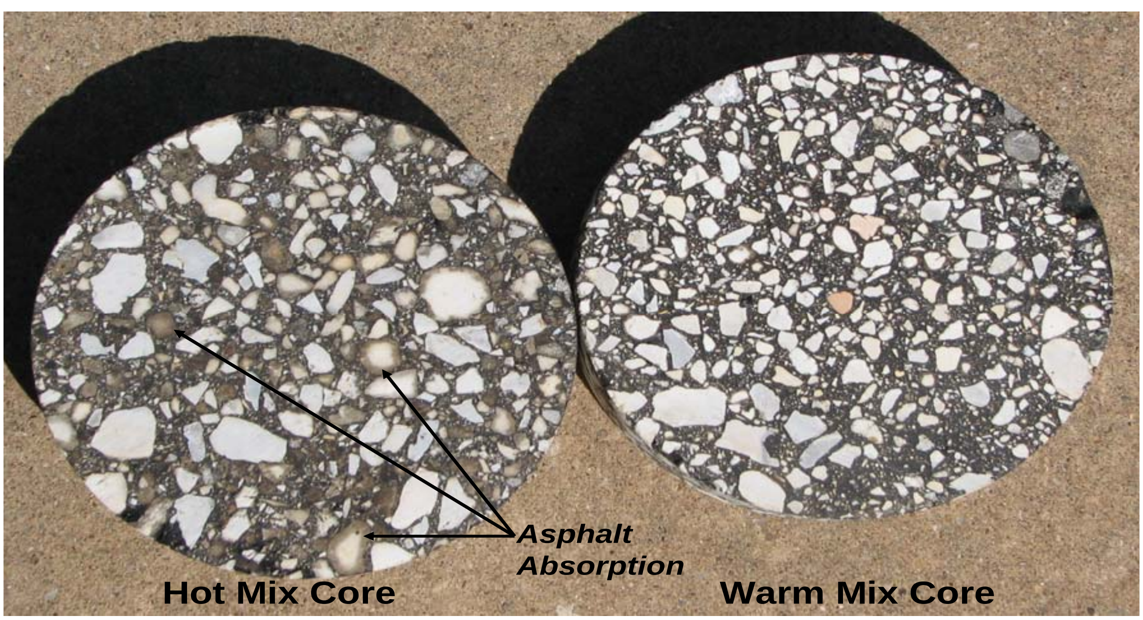


Figure 5.8. Photos of Loop 368 One-Year Cores.

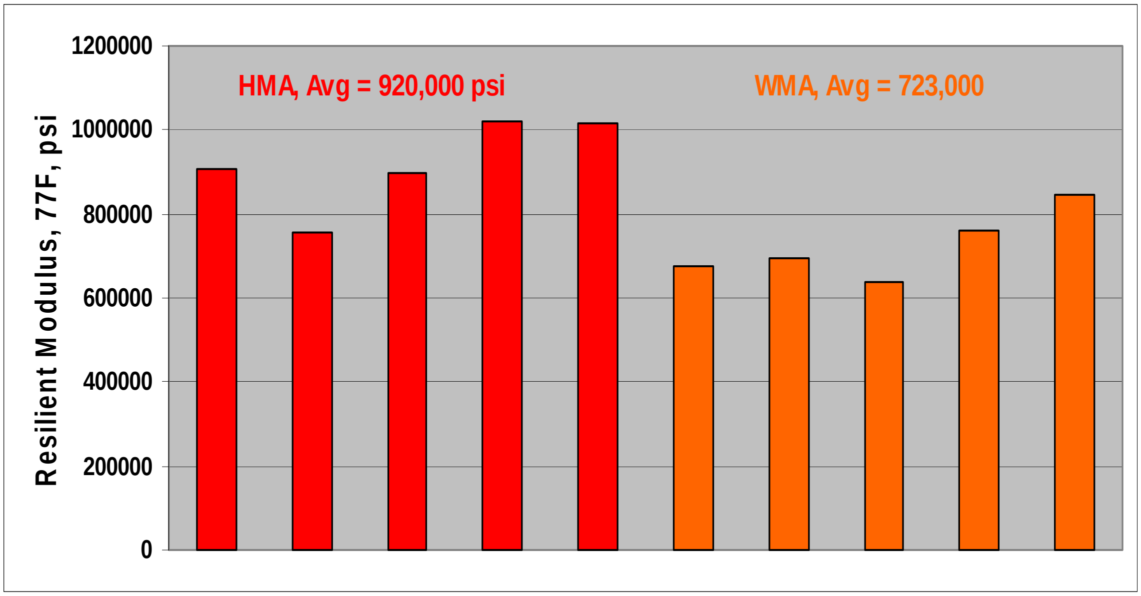


Figure 5.9. Resilient Moduli of Loop 368 One-Year Cores.

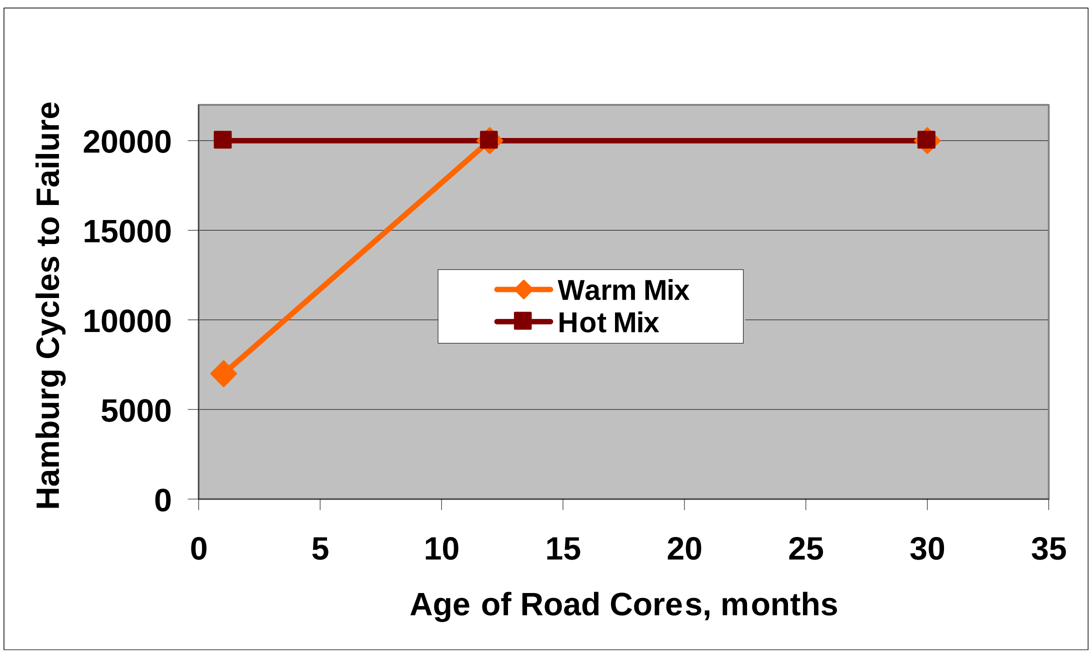


Figure 5.10. Hamburg Wheel Tracking Tests on Loop 368 Road Cores.

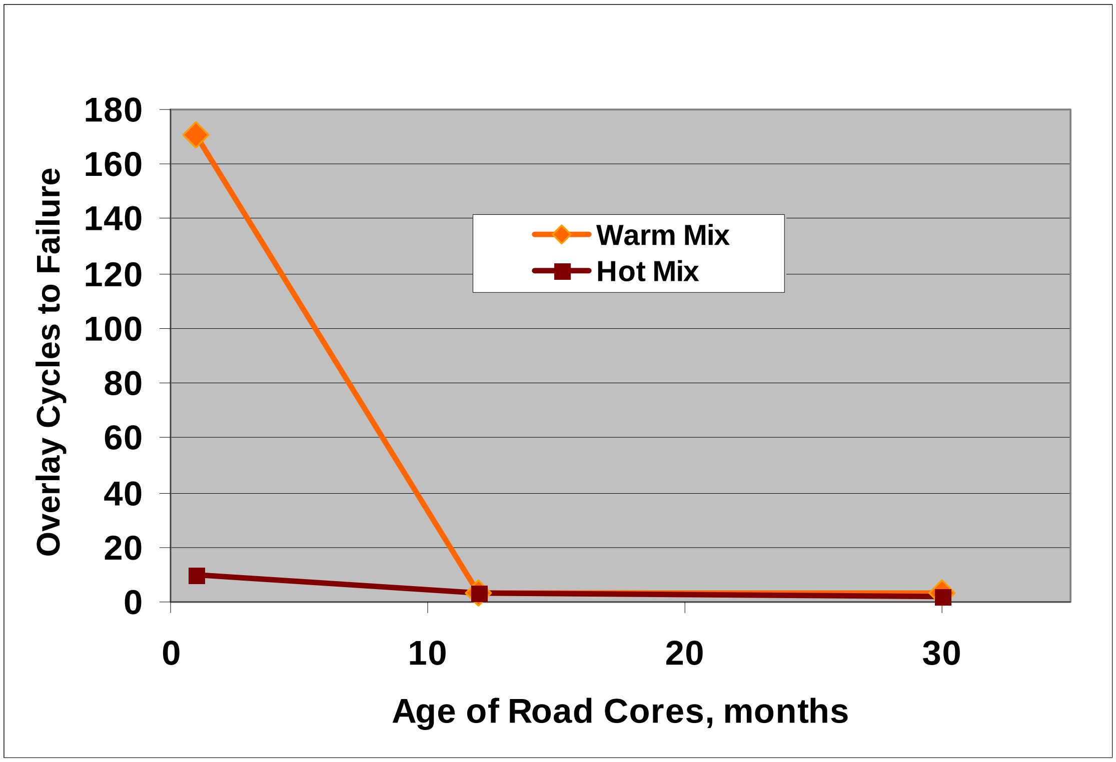


Figure 5.11. Overlay Test Results on Loop 368 Road Cores.

Figure 5.12. San Antonio WMA Section after 3 Years of Service.

Figure 5.13. Evidence of Cracking Appearing in Both WMA and HMA Sections.

AUSTIN SH 71

The first WMA project placed by the Austin District was on SH 71 in the summer of 2008. The project limits are from 0.6 miles west of Riverside Drive to Presidential Boulevard (Figure 5.14). Details regarding the project are shown in Table 5.5.

Table 5.5. Austin SH 71 WMA Field Project Details.

Project Location	SH 71
Construction Dates	June 2008
WMA Tonnage	8000 tons
Mix Design Information	• Item 341, Type C Dense Graded • PG 76-22 • Aggregate: 91% Hanson New Braunfels LS 9 % Field Sand • Anti-strip: 0.8% liquid for HMA and WMA • AC Content: 4.8% (Both HMA and WMA)
WMA Technology	Evotherm DAT
Mixture Production	Temperature at Load Out: HMA 330 ºF WMA 240 ºF
Placement and Compaction	Mat Thickness: 2 inches In-Place Density: HMA 94.2% WMA 93.4%
Cost	HMA: $62/ton WMA: $65.75/ton

Figure 5.14. WMA Project on SH 71 in Austin.

Mixture Production Properties

The mixture was produced by Industrial Asphalt and a summary of the production data from the project is as follows:

HWTT Rut Depth at 20,000 Cycles
- HMA 2.3 mm
- WMA 12.2 mm

Lab Molded Density
- HMA 96.9 %
- WMA 96.3 %

In-Place Density
- HMA 93.4 %
- WMA 92.9 %

AC Content
- HMA 4.8 %
- WMA 4.9 %

During production of the trial batch, samples of the WMA were compacted at two different curing/compaction temperatures (225 and 250ºF) in both the TGC and the SGC. The average of these results is shown in Figure 5.15. The SGC produced a higher density and only a very slight decrease in the lab molded density was observed when reducing the temperature from 250 to 225ºF. The TGC at 250ºF was used for the control of the job.

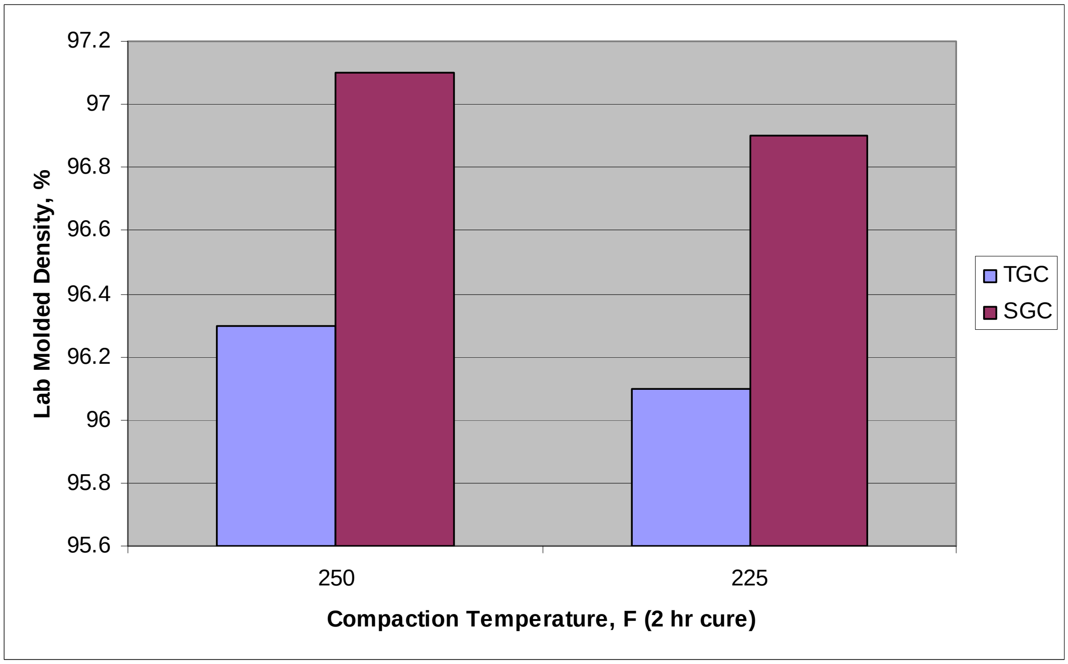


Figure 5.15. TGC and SGC Lab Molded Density of Trial Batch WMA at Different Curing and Compaction Temperatures.

Cores taken soon after construction were tested by TTI with the following results:

HWTT Rut Depth		*Cycles*
• HMA	4.5 mm	20,000
• WMA	12.5 mm	18,500

Indirect Tensile Strength

- HMA 159 psi
- WMA 104 psi

Evaluation of the In-Place Density of the WMA Using Ground Penetrating Radar (GPR)

TxDOT's GPR equipment is shown in Appendix C where the background on the use of GPR from measuring the in-place surface density of asphalt surfaces is described. The surface dielectric, automatically measured by GPR, is a direct indication of the in-place density of a new asphalt surface layer. The GPR signals can also be used to measure layer thickness and the uniformity of compaction with depth.

In July 2008, GPR data was collected in all four lanes of the WMA project on SH 71 in Austin. The two EB lanes contain the Type C WMA, and the westbound lanes have the same mix made with traditional hot binder. GPR data as processed using TTI COLORMAP system is shown in Figure 5.16. The depth scale is on the left. The total thickness of the HMA varies from 8 to 24 inches. The top 3 inches is the new WMA overlay.

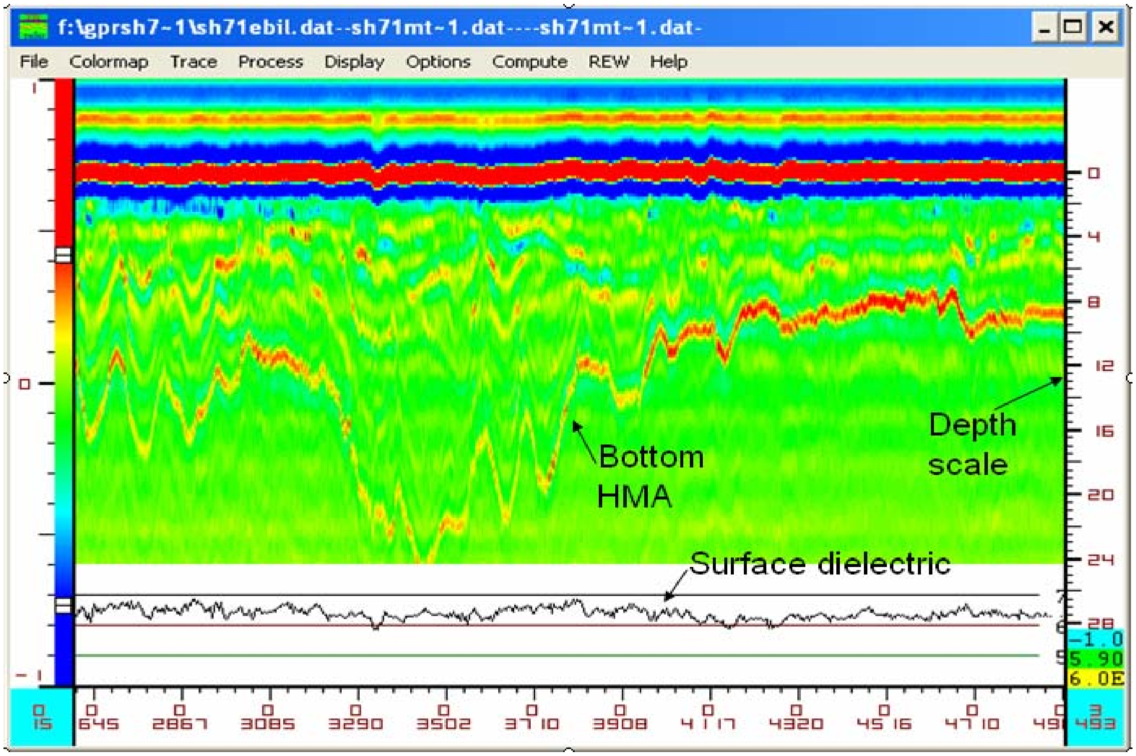


Figure 5.16. Typical GPR Data from the WMA Section on SH 71.

To assess the compaction and uniformity of the WMA layer the most significant feature of this figure is the surface dielectric plot at the bottom of the figure. Each line on this plot represents 1 unit on the dielectric scale. Significant periodic decreases would indicate construction problems. The average dielectric and its variation is a good indicator of asphalt density and uniformity. Figures 5.17 and 5.18 show the distribution of surface dielectrics for both the WMA and traditional HMA. These were taken from areas on this project with similar lower pavement thickness and no bridge decks. In both cases, the significant decrease in the middle of the plot was a cold joint at the end of a day's production.

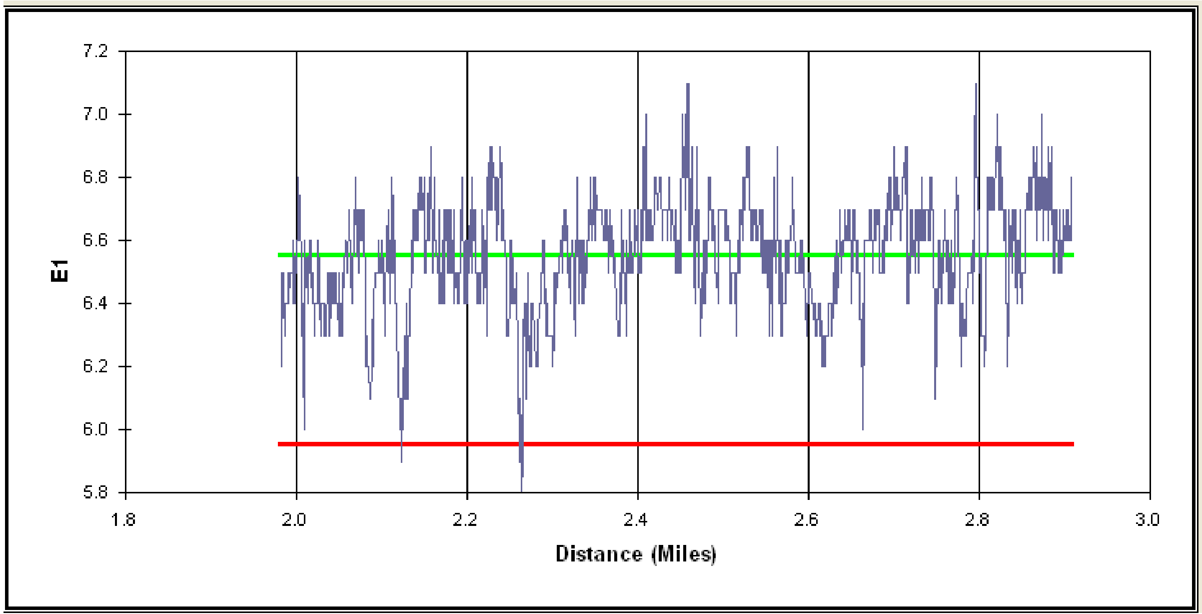


Figure 5.17. Dielectric (Density) Plot for the SH 71 HMA Section.

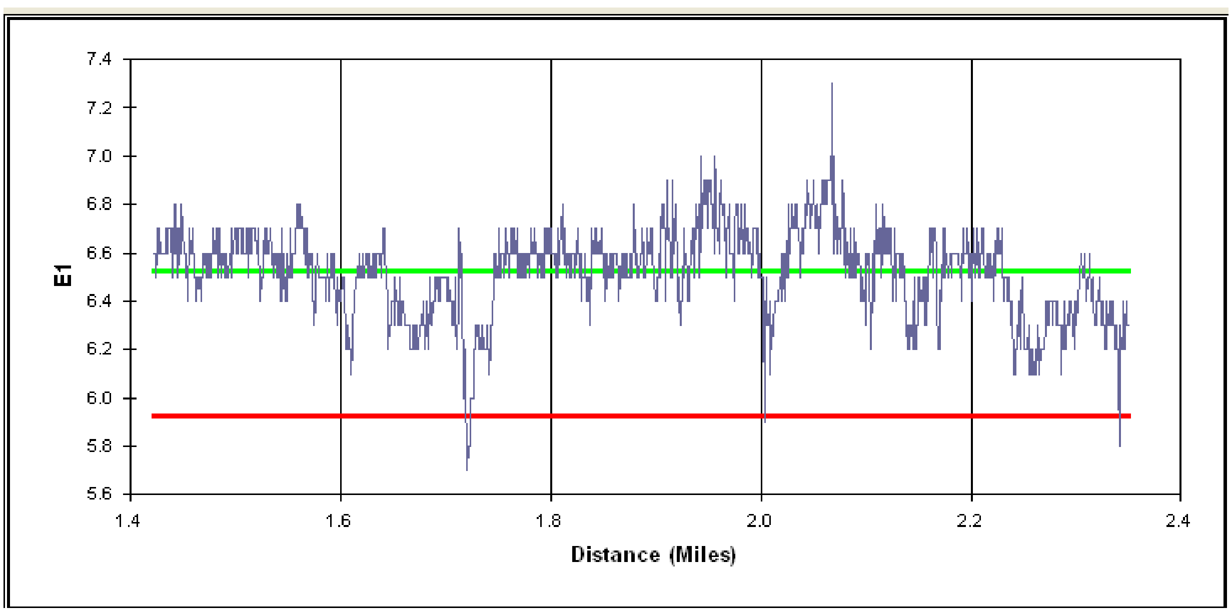


Figure 5.18. Dielectric (Density) Plot for the SH 71 WMA Section.

The average values for each are shown below

HMA Mean Dielectric value = 6.55, Standard deviation 0.17
WMA Mean Dielectric value = 6.52, Standard deviation 0.18

For practical purposes, the GPR did not pick up any significant differences between the two surface types. The similar dielectrics will mean that these materials will have very similar density profiles. Therefore, it is concluded that for this project the WMA was compacted to the same density and as uniformly as the traditional HMA layer.

In addition to the uniform density, no large reflections were found at the interface between either the WMA or the HMA overlay and the underlying existing HMA layer. This implies that both mixes compacted well with depth, and there are no bonding problems to the existing HMA layer.

Long-Term Field Performance

Evaluation of the pavement after one year of service indicated that there were no signs of distress in either the HMA or the WMA pavement sections. Cores were taken of each and results of the laboratory tests are presented in Table 5.6.

Table 5.6. Laboratory Test Results on SH 71 Field Cores (After 1-yr Service).

Sample ID	Air Voids %	Indirect Tensile Strength, psi	Overlay Test Results		Hamburg Wheel Tracking Test Results, Rut Depth at 20,000 Cycles, mm
			Max Load, lbs	Cycles	
Hot Mix Cores					
H1	6.9	145.2	-	-	-
H2	6.2	155.5	-	-	-
H3	5.8	158.7	-	-	-
H4	6.0	-	805	18	-
H5	6.5	-	893	2	-
H6	5.7	-	822	3	-
H7	6.1	-	-	-	1.7
H8	6.2	-	-	-	
H9	6.4	-	-	-	1.6
H10	5.9	-	-	-	
Average	**6.2**	**153.1**	**840**	**8**	**1.7**
Warm Mix Cores					
W1	6.5	130.5	-	-	-
W2	7.2	131.0	-	-	-
W3	7.7	134.9	-	-	-
W4	6.6	-	793	3	-
W5	6.3	-	695	61	-
W6	6.4	-	682	5	-
W7	6.7	-	-	-	3.4
W8	6.6	-	-	-	
W9	7.7	-	-	-	3.0
W10	7.4	-	-	-	
Average	**6.9**	**132.1**	**723**	**23**	**3.2**

After one year of service, the WMA tensile strength increased from 104 psi to an average of 132 psi, which is still less than the HMA. The strength for the HMA did not change. The overlay test data for the WMA and HMA cores were similar except that the maximum load at failure for the WMA was lower than the HMA indicating a lower stiffness. The HWTT results for the WMA improved from 18, 500 cycles to failure after construction to 20,000 at one year.

Throughout the first year of service, the WMA section exhibited an increase in stiffness while the HMA stayed about the same. At one year, both the field and laboratory performance characteristics for the WMA and HMA are similar with the WMA behaving slightly less stiff than the HMA.

LUFKIN FM 324

In February and March of 2008, the Lufkin district placed four different WMA technology field trials (Figure 5.19). A description of the project details is shown in Table 5.7.

Figure 5.19. Construction of Lufkin WMA Field Trials.

Table 5.7. Lufkin WMA Field Trial Project Details.

Project Location	FM 324, Lufkin
Construction Dates	February/March 2008
WMA Tonnage	~ 4000 tons (~1000 tons/WMA technology)
Mix Design Information	• Item 341, Type D Dense Graded • PG 64-22 • Aggregate: 91% Hanson Chico LS 9 % Field Sand • Anti-strip: 1% lime for HMA and all WMA • AC Content: 4.6% (Both HMA and WMA)
WMA Technology	Sasobit, Evotherm DAT, Akzo Nobel Rediset, Advera
Mixture Production	Temperature at Load Out: HMA 270 ºF WMA 240 ºF
Placement and Compaction	Mat Thickness: 1.5 inches

Mixture Production Properties

The mixture was produced by East Texas Asphalt, and a summary of the production data from the project is presented in Table 5.8.

Table 5.8. Project Production Data for Lufkin Field Trials.

Mixture Type	AC Content, %	Lab Molded Density, %	In-Place Air Voids, %
PG 64-22 HMA	4.1	95.7	10.1
WMA Rediset	4.2	97.4	NA
WMA Advera	4.5	97.5	11.7
WMA Evotherm	4.3	97.3	10.6
WMA Sasobit	4.3	97.4	11.5

TTI's Pave-IR System was used to evaluate the thermal characteristics of the WMA and HMA materials. The Pave-IR was installed on the back of the paving machine (Figure 5.20) and provides full coverage of the material displaying the thermal profile to the paver operator in real-time. It consists of transverse bars with ten infrared sensors and the Pave-IR software package which collects and displays the thermal profile as the paving train progresses.

Figure 5.20. Pave-IR Installed on Paving Machine.

A thermal image profile of a segment of the HMA and the WMA from the Lufkin field trials is shown in Figures 5.21 and 5.22, respectively. The HMA material appeared to have greater temperature differentials when compared to the WMA, which was more uniform in temperature distribution. This may not be surprising, since the WMA is closer to ambient temperatures during construction, therefore, the temperature differential is less. Frequency histograms for the thermal profiles are shown in Figures 5.23 and 5.24 for the HMA and WMA, respectively. These data support what Figures 5.21 and 5.22 show that the HMA exhibits a wider range in temperature distribution. Each bar in the figure represents the number of occurrences for that temperature.

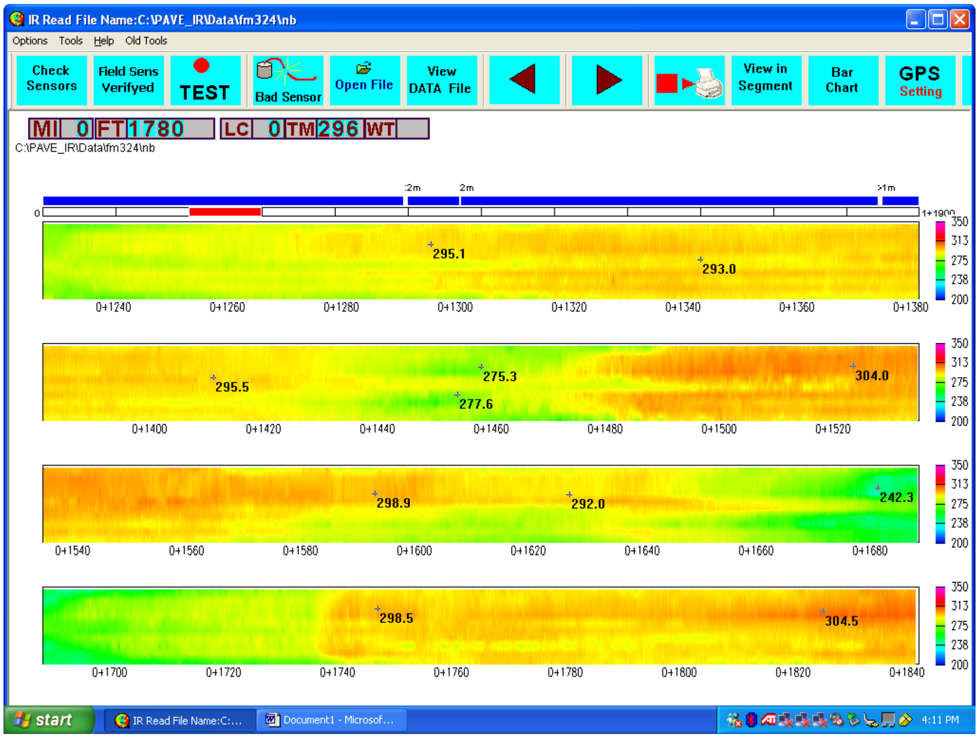


Figure 5.21. Pave-IR Thermal Image of HMA Material from Lufkin.

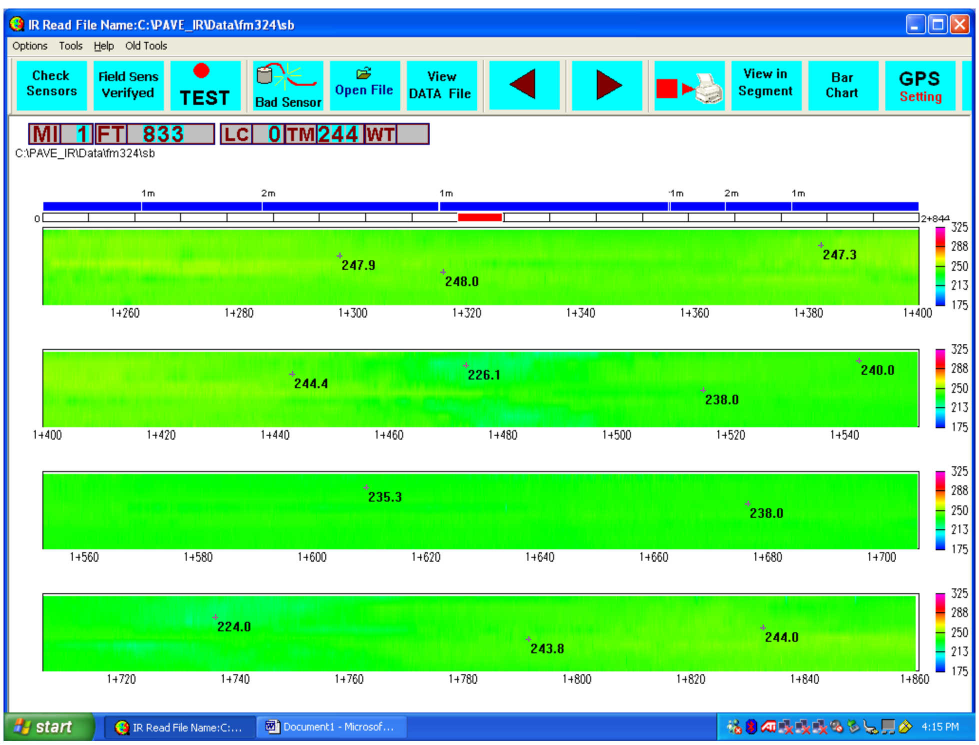


Figure 5.22. Pave-IR Thermal Image of WMA Material from Lufkin.

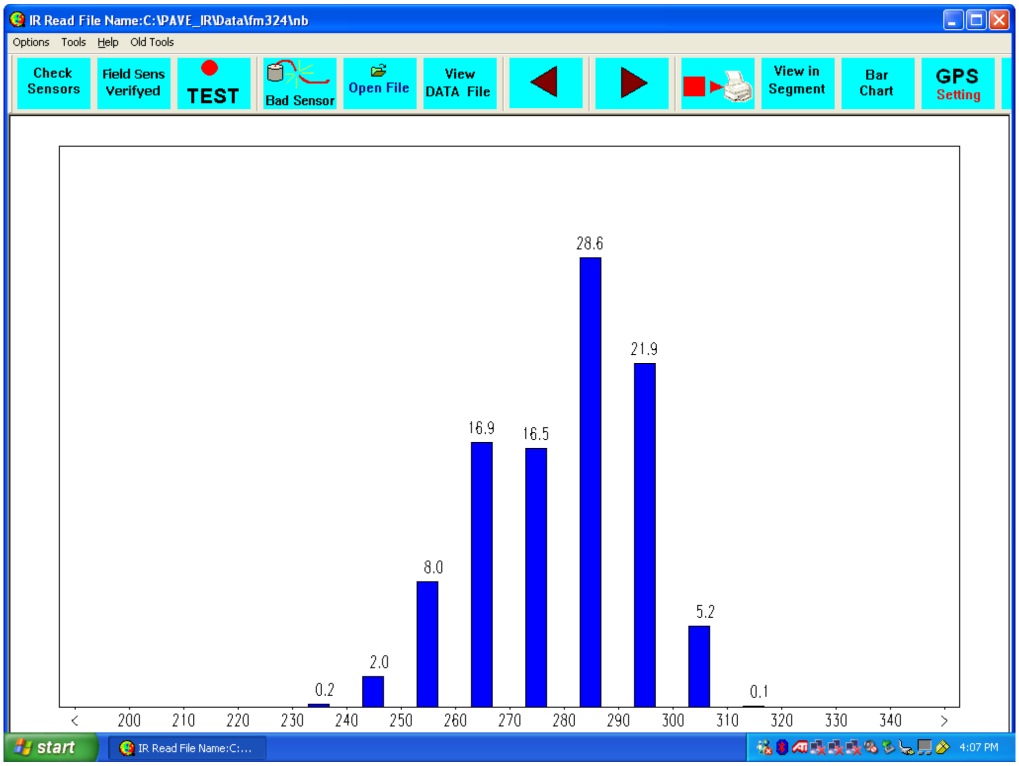


Figure 5.23. Pave-IR Frequency Histogram for HMA Material Temperature Profile.

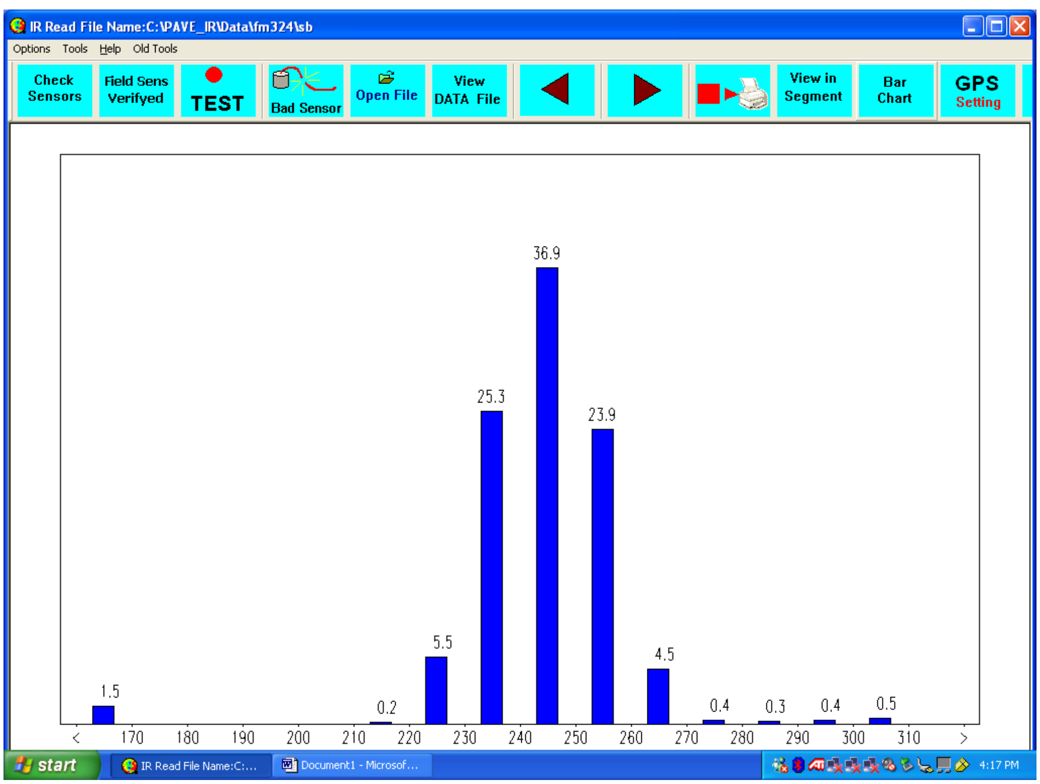


Figure 5.24. Pave-IR Frequency Histogram for WMA Material Temperature Profile.

Tests on Field Produced Lab Compacted Samples

TTI technicians were onsite to sample and mold samples for later testing. Prior to molding, the plant mixes were cured for 2 hours at 250ºF for the HMA and 220ºF for all of the WMA technologies. The samples were brought back to TTI's laboratory for testing.

Results of the HWTT are presented in Table 5.9 and Figure 5.25. For a PG 64-22, the specification limits the rut depth to no more than ½ inch at 10,000 cycles, but this district does not enforce a HWTT requirement, since their mixes will often not meet the minimum though they have historically performed well. The Sasobit and HMA mix were the only samples that passed the HWTT criteria with this 2-hour oven curing time.

Results from overlay tests on the lab compacted plant mixes are shown in Tables 5.10 and in Figure 5.26. The Advera and Evotherm mixes exhibited dramatic improvements in cracking resistance compared with the HMA.

Table 5.9. Hamburg Wheel Tracking Test Results from Plant Mixed, Lab Compacted Specimens.

Mixture Type	Rut Depth (mm)	Failure Cycle
Control	12.75	15,000
Control	12.72	13,400
Sasobit	12.62	10,900
Sasobit	12.63	11,000
Evotherm	12.70	7,900
Evotherm	12.56	7,700
Asphamin	12.75	6,900
Asphamin	12.80	8,000
Akzo Nobel	12.79	8,900
Akzo Nobel	12.74	8,400

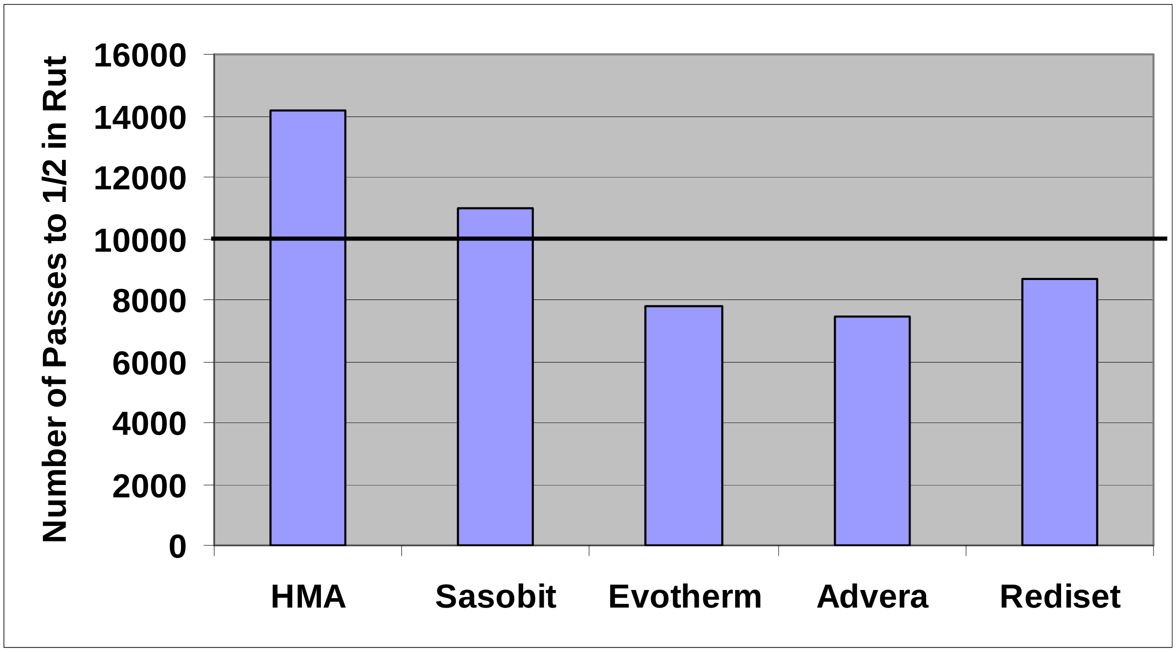


Figure 5.25. Average HWTT Results for Plant Produced, Lab Compacted Mixes.

Table 5.10. Overlay Test Results from Plant Mixed, Lab Compacted Specimens.

Mixture Type	Sample	Overlay Test Results		Air Voids After Cutting, %
		Max Load, lbs	No. of Cycles to Failure (defined as 7% of max load)	
Control	1	713.4	46	6.1
	2	677.5	211	6.0
Sasobit	1	674.3	22	6.2
	2	723.0	69	6.0
Asphamin P/Q	1	562.3	553	5.7
	2	620.9	142	5.9
Evotherm	1	576.0	650	6.3
	2	525.7	403	6.4
Akzo Nobel	1	650.2	113	5.8
	2	656.8	176	6.3

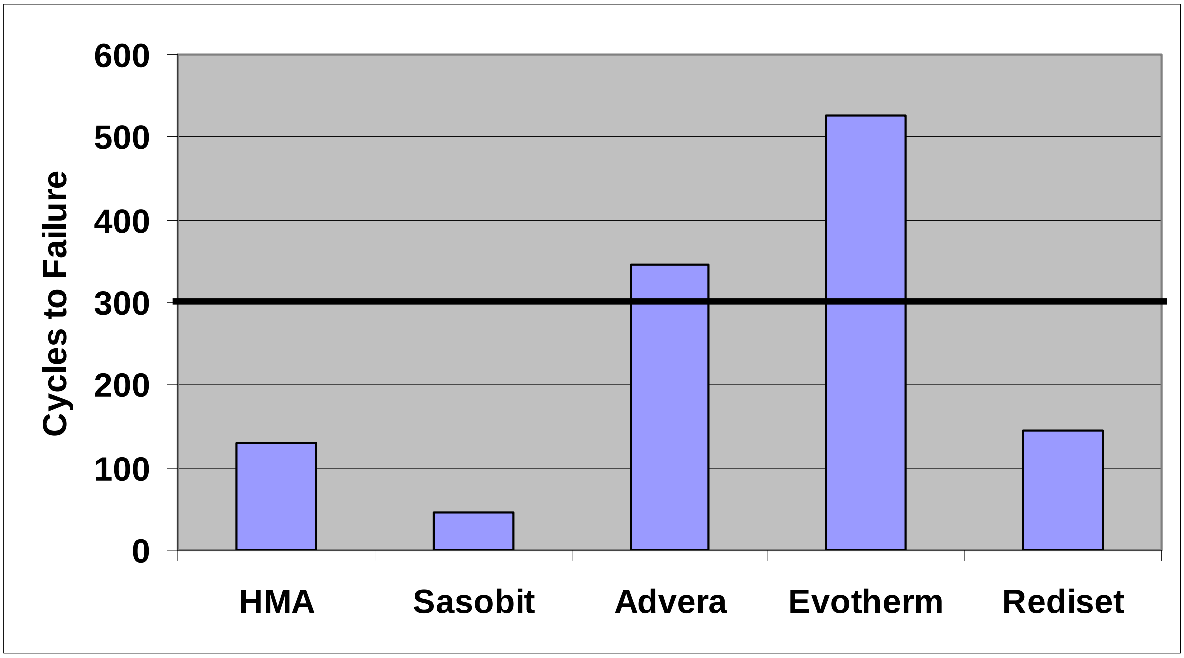


Figure 5.26. Average Overlay Test Results for Plant Produced, Lab Compacted Mixes.

Field Performance

Field performance of all four of the WMA technologies test sections as well as the HMA sections have performed well in the first year of service. No evidence of rutting or cracking has been observed.

Results of laboratory tests conducted on the field cores are shown in Table 5.11.

Table 5.11. Laboratory Test Results on FM 324 Field Cores (after 1-yr Service).

Sample ID	Air Voids in Wheel Path %	Air Voids Between Wheel Paths, %	Indirect Tensile Strength, psi	Overlay Test Results		Hamburg Wheel Tracking Test Results, Rut Depth at 20,000 Cycles, mm
				Max Load, lbs	Cycles	
Hot Mix Asphalt						
H1	5.7	-	-	-		7.3
H2	5.1	-	-	-		
H3	4.9	-	-	1069	156	-
H4	6.1	-	186.8	-		-
H5	6.8	-	-	1040	271	-
H6	6.1	-	151.7	-		-
H7	6.9	-	-	-		-
H8	6.3	-	189.4	-		-
H9	-	7.1	-	-		-
H10	-	7.6	-	-		-
Average	**6.0**	**7.3**	**176.0**	**1055**	**214**	**7.3**
Sasobit Warm Mix Asphalt						
S1	6.9	-	-	-		7.9
S2	6.8	-	-	-		
S3	6.4	-	210.3	-		-
S4	6.9	-	-	1240	2	-
S5	7.2	-	-	-		-
S6	6.2	-	207.5	-		-
S7	7.1	-	-	1207	5	-
S8	6.2	-	185.2	-		-
S9	-	8.2	-	-		-
S10	-	8.8	-	-		-
Average	**6.7**	**8.4**	**201.0**	**1224**	**4**	**7.9**
Evotherm Warm Mix Asphalt						
E1	7.0	-	-	-		5.6
E2	7.5	-	-	-		
E3	7.3	-	151.1	-		-
E4	7.0	-	176.6	-		-
E5	7.1	-	149.5	-		-
E6	7.5	-	-	965	92	-
E7	8.1	-	-	-		-
E8	7.9	-	-	816	148	-
E9	-	9.3	-	-		-
E10	-	9.6	-	-		-
Average	**7.4**	**9.5**	**159.1**	**891**	**120**	**5.6**
Advera Warm Mix Asphalt						
Ad1	5.7	-	-	-		6.6
Ad2	7.2	-	-	-		
Ad3	5.9	-		-		-
Ad4	6.1	-	146.9	1310	2	-
Ad5	5.6	-	-	-		-
Ad6	6.1	-	168.7	-		-
Ad7	5.7	-	-	926	32	-
Ad8	6.2	-	160.1	-		-
Ad9	-	8.4	-	-		-
Ad10	-	7.1	-	-		-
Average	**6.1**	**7.8**	**158.6**	**1118**	**17**	**6.6**
Akzo Nobel Rediset Warm Mix Asphalt						
AN1	8.4	-	-	-		3.0
AN2	7.5	-	-	-		
AN3	6.9	-	-	1346	2	-
AN4	6.3	-	223.7	-		-
AN5	6.6	-	-	1374	2	-
AN6	6.3	-	239.5	-		-
AN7	6.5	-	221.6	-		-
AN8	6.7	-	-	-		-
AN9	-	13.1	-	-		-
AN10	-	10.7	-	-		-
Average	**6.9**	**11.9**	**228.3**	**1360**	**2**	**3.0**

FORT WORTH BU 287 PROJECT

In the summer of 2008, the Fort Worth district constructed its first WMA project on BU 287 north of Saginaw. The project limits were from 200 feet south of RR Bridge to 400 feet north of Bailey Boswell Road for a total length of 4.8 miles. Average daily traffic was 24,100 vehicles per day. For the first approximately 3 miles of the project, the roadway is four-lane divided with 10 foot shoulders. The remainder is a two-lane, undivided, with 10 foot shoulders. The pavement structure varies throughout the project. Much of the cross-section consists of several inches asphalt concrete pavement over 8 inches of crushed stone flexible base. A portion of the project is CRCP with an existing 3 ½-inch overlay, which was milled and replaced; and another portion consists of jointed concrete pavement (Figure 5.27), which was to be overlayed with 3½ inches of Type D-WMA. The overall construction consisted of shoulder rehabilitation, which included placement of 10 inches of Item 341 dense-graded Type B-WMA (Figure 5.28), and the entire project was then surfaced with 3.5 inches of Item 341 dense-graded Type D-WMA.

The area engineer, Ralph Browne, P.E., required the use of WMA on this project to address two issues as described below.

1) Past district experience with overlaying jointed concrete pavement had resulted in construction problems at the joints. When the high-temperature hot mix was placed over the joints, expansion of the sealant (or possibly water in the joints) caused a heaving and rupture in the HMA surface. The lower placement temperature of the WMA was specified to reduce this occurrence.
2) Due to the construction sequencing, all traffic was diverted onto the shoulders, constructed of 10 inches of Type B base). This would need to occur at the end of the day to allow placement of the Type B. Specifications require that the compacted material be allowed to cool to a temperature of 160ºF before allowing traffic. This is difficult to achieve by 5:00 pm for a thick asphalt material constructed in the heat of a Texas summer. The WMA was placed at a significantly lower temperature to address this issue.

The district specified the use of WMA with a temperature requirement for the mix as follows:

> *Unless otherwise recommended by the warm mix additive supplier and approved by the Engineer, the target discharge temperature for mixtures containing PG 64 shall be 250°F and for PG 76 shall be 260°F. Target temperatures may vary between 215°F-275°F, as accepted by the Engineer. Notify the Engineer of the target discharge temperature, and produce the mixture within 15°F of the target. Monitor the temperature of the material in the truck before shipping to ensure that it does not exceed the target temperature by more than 15°F. The Department will not pay for or allow placement of any mixture that exceeds the target temperature by more than 15°F, unless approved by the Engineer. However, the load will be allowed to cool on site to target temperature +15°F for full payment.*

Figure 5.27. BU 287 Jointed Concrete Pavement Prior to Type D WMA Overlay.

Figure 5.28. BU 287 Shoulder Rehab and Asphalt Pavement Prior to Overlay

This district does not typically have a HWTT requirement for HMA but requires that a mix exhibit 0 percent stripping when subjected to the Boil Test (Tex-530-C). Information regarding the project is listed in Tables 5.12 and 5.13.

Table 5.12. Fort Worth BU 287 Type B WMA Project Details.

Project Location	BU 287 North of Saginaw
Construction Dates	Summer 2008
WMA Tonnage	20,000 tons
Mix Design Information	• Item 341, Type B Dense Graded • PG 64-22 • Aggregate: 75% Hanson Perch Hill LS 20% RAP 5 % Field Sand • Anti-strip: 1% liquid anti-strip • AC Content: 4.3%
WMA Technology	Evotherm DAT
Mixture Production	Temperature at Load Out: 240 ºF
Laydown and Compaction	Mat Thickness: 10 inches (shoulder rehab)
Cost	$52/ ton

Table 5.13. Fort Worth BU 287 Type D WMA Project Details.

Project Location	BU 287 North of Saginaw
Construction Dates	Summer 2008
WMA Tonnage	32,000 tons
Mix Design Information	• Item 341, Type B Dense Graded • PG 76-22 • Aggregate: 90% Hanson Perch Hill LS 0% RAP 10 % Field Sand • Anti-strip: 1% liquid anti-strip • AC Content: 5.0%
WMA Technology	Evotherm DAT
Mixture Production	Temperature at Load Out: 275 ºF
Laydown and Compaction	Mat Thickness: 3 1/2 inches
Cost	$63/ ton

Evotherm technical representatives provided onsite technical support and adjusted the Evotherm DAT concentrate and flow rate into the plant to optimize workability, coating, and production air voids.

Haul distance from the plant to the job site was 50 miles. The plant operator noted that, due to the long haul distance, the plant could not operate continuously. Starting and stopping the operation of the plant affected the fuel-efficiency of the plant. Still, the operator noted that production of the WMA resulted in a reduction of about 0.8 gallons of fuel used for each ton of mix produced.

For quality control of the mixture production, the Type B mix was molded at 230ºF and the Type D mix was molded at 270ºF (after 2 hour cure). Target lab density for both the Type B and Type D mixtures was 96.5 percent. The production data are summarized in Table 5.14.

For comparison purposes, TxDOT performed lab-molded densities for the Type B mix using both the SGC (75 gyrations) and TGC. The two compactors produced approximately the same laboratory molded density: 96.5 percent for the TGC and 96.7 percent for the SGC (Figure 5.29).

Table 5.14. Fort Worth BU 287 Project WMA Production Data.

Mixture Type	HWTT Results (from Trial Batches), mm rut depth/number of cycles*	Indirect Tensile Strength (from Trial Batches), psi	Project Average AC Content, %	Project Average Lab Molded Density, %	Project Average In-Place Air Voids, %
Type B PG 64-22	12.5 mm 11,000 cycles	142	4.4	96.4	6.6
Type D PG 64-22	12.5 mm 11,150 cycles	159	4.6	96.6	7.3

*2 hour cure at 230ºF for Type B and 270ºF for Type D.

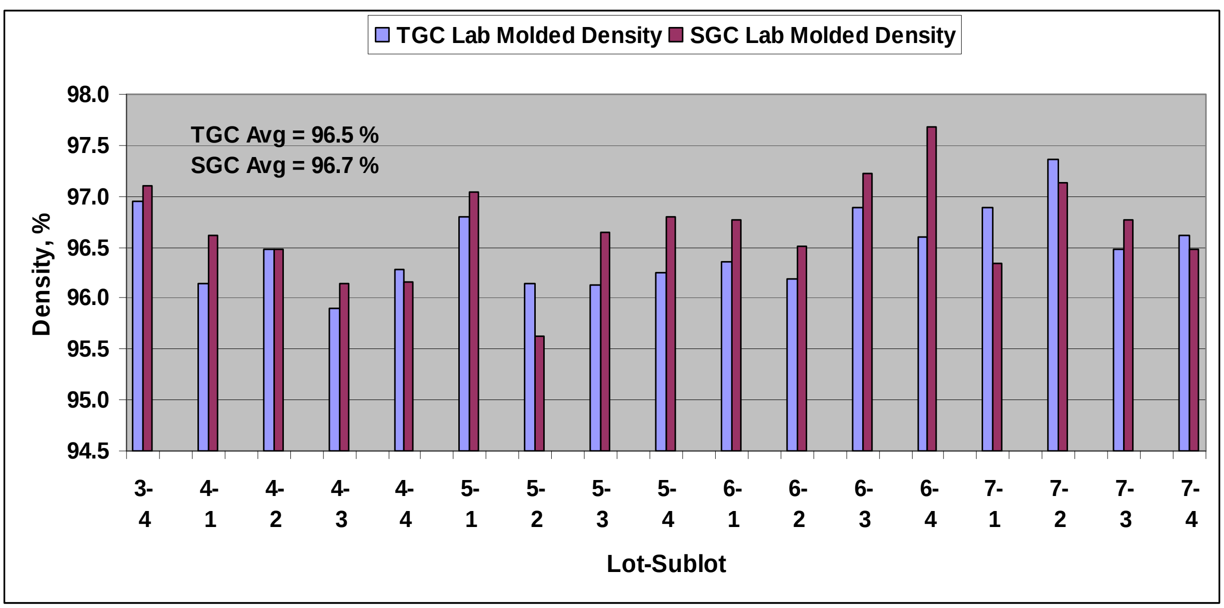


Figure 5.29. SGC and TGC Lab Molded Density for Type B Mix.

Field Performance Evaluation

Most of the WMA projects that have been placed in Texas are relatively thin overlays. However, the Type B shoulder, which was placed in this BU 287 project, was 10 inches thick allowing for a structural evaluation. GPR data were collected on the shoulder to assess the uniformity of the mixture with depth. Figure 5.30 shows an example of how GPR can be used to identify density problems in a thick layer of a perpetual pavement where compaction deficiencies were experienced at the bottom of each pavement lift. This is compared with the thick WMA layer on BU 287 in Figure 5.31. The GPR data revealed that the almost 14 inch thick WMA shoulder on BU 287 shows the entire pavement layer to be uniformly compacted with depth and no signs of any defects. (See Appendix B for further explanation on the use of GPR to identify density problems.)

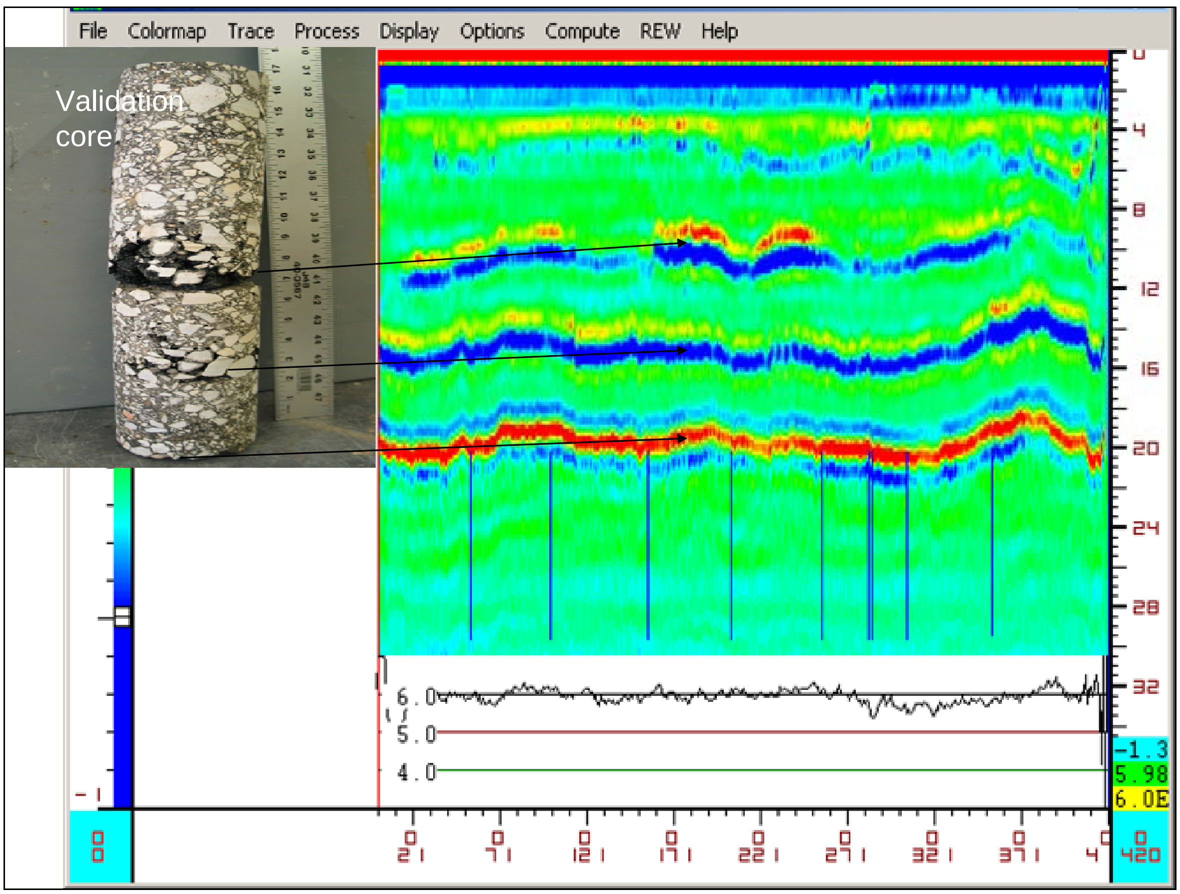


Figure 5.30. Example on the Use of GPR to Identify Compaction Problems or Segregation in Thick Pavement Layers.

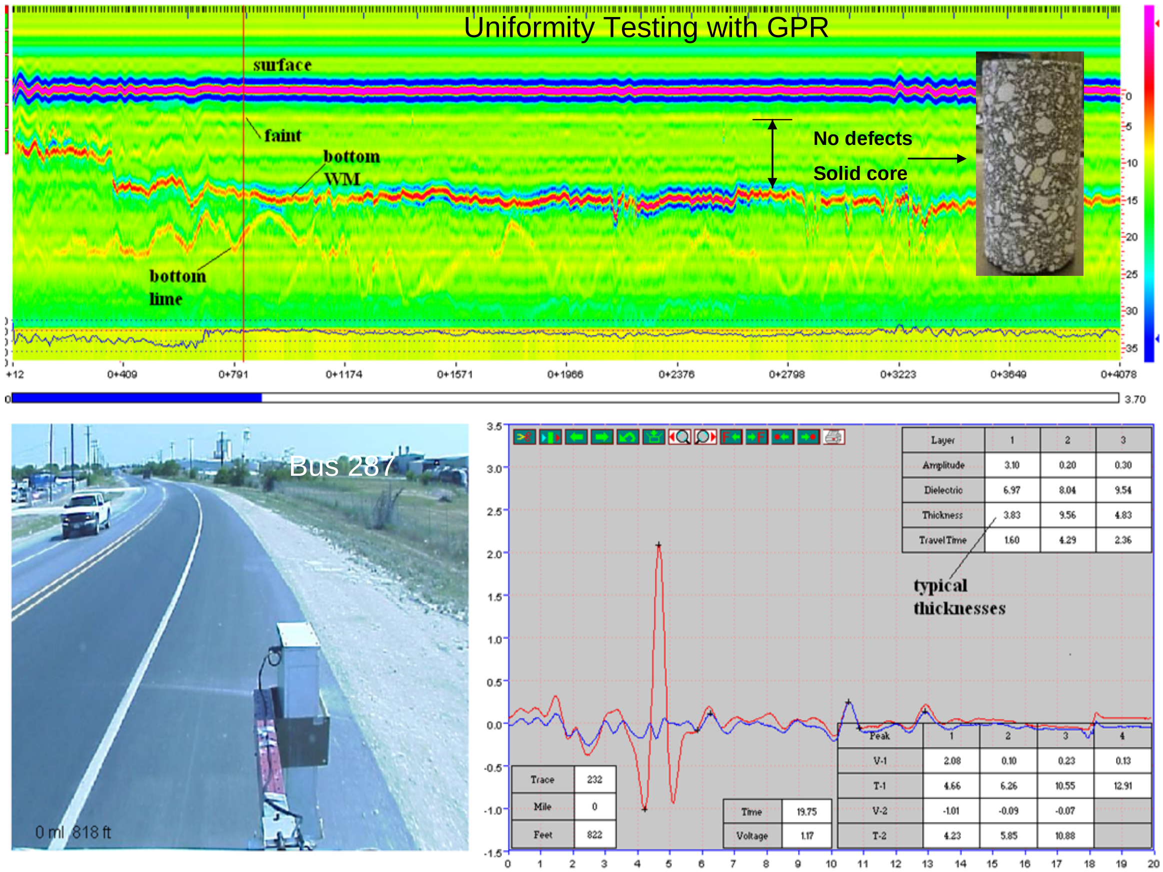


Figure 5.31. GPR Data from BU 287 Showing WMA Layer Uniformity with Depth.

Two months after construction, falling weight deflectometer (FWD) (Figure 5.32) tests were performed on the 14-inch thick WMA shoulder of BU 287. Since this project did not have a HMA section to serve as a control, a similar pavement was used for comparison.

Figure 5.32. TxDOT's Falling Weight Deflectometer (FWD) Testing Equipment.

SH 114 in the Fort Worth district had a similar pavement structure to the WMA shoulder construction of BU 287. It consisted of a Type B base material with an almost identical mix design from the same aggregate source and plant. The MODULUS program was used to backcalculate the moduli values for the pavement sections. A summary of the overall average of the FWD results from the two pavements are as shown below:

SH 114 HMA Pavement	**BU 287 WMA Shoulder**
- Item 341 Type B HMA	- Item 341 Type B WMA
- Bridgeport Limestone	- Bridgeport Limestone
- AC Content 4.5% PG 64-22	- AC Content 4.3% PG 64-22
- FWD Modulus at 106ºF = 580 ksi	- FWD Modulus at 93ºF = 739 ksi
- *FWD Modulus at 77ºF = 1392 ksi*	- *FWD Modulus at 77ºF = 1256 ksi*

Based on these data, there is no significant difference in structural strength characteristics of the two different pavements.

Cores were taken at the time of construction and then after one year of service. These data are summarized below:

Type B Mix:

Cores Taken During Construction	**Cores Taken After One-Year of Service**
- HWTT: 12.5-mm rut at 13700 cycles	- HWTT 12.5-mm rut at 17,800 cycles
- Overlay Test: 1032 lb, 7 cycles	- Overlay Test: 1232 lb, 3 cycles
- IDT: 154 psi	- IDT: 162 psi

Type D Mix:

Cores Taken During Construction
- HWTT: 12.5-mm rut at 16500 cycles
- Overlay Test: 1032 lb, 7 cycles
- IDT: 137 psi

Cores Taken After One-Year of Service
- HWTT: 6.7-mm rut at 20,000 cycles
- Overlay Test: 1232 lb, 3 cycles
- IDT: 166 psi

Field performance during the first year of service has been good with no evidence of rutting or cracking distress (Figure 5.33).

Figure 5.33. Fort Worth BU 287 WMA Project after One Year of Service.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

During the first year and a half of this research study, TxDOT had only placed 1000 tons of WMA as a demonstration. By the end of the third year of the study, TxDOT had placed more than 1,000,000 tons of WMA and allowed the use of WMA in all dense-graded mixtures through the implementation of Special Provision 341---020, described in Appendix C. This research was focused on learning as much as possible during this span of time regarding the effects of WMA technologies on mixture design, lab performance characteristics, and field performance. An ongoing implementation study is underway to continue to monitor performance of WMA field sections. A summary of the findings from this study are presented below.

Mixture Design

- Dense-graded WMA mixtures, which are designed according to Tex-206-F, Part I, using the TGC will have a significantly lower optimum asphalt content than the corresponding HMA mixture without the WMA additive. This is true for all three WMA processes investigated herein which includes Sasobit, Evotherm, and Advera. Even when the mixing and compaction temperature for the warm mixtures was reduced to 60ºF below that used for HMA, compaction was enhanced sufficiently to cause a reduction in density and, thus, optimum asphalt content.
- At the time of this testing, TxDOT procedures required a laboratory oven-curing procedure prior to molding specimens. This procedure consisted of a two-hour cure of the mixture at the recommended compaction temperature. WMA mixtures, which are cured at their respective compaction temperature, exhibit HWTT results as low as half that achieved for the corresponding HMA.
- Increasing the oven curing time from two hours to four hours and increasing the oven curing temperature to 275ºF resulted in a significant increase in WMA HWTT results that were comparable to the corresponding HMA. Increasing the oven curing time for HMA from two hours to four hours and to 275ºF did not result in a significant increase in HWTT results.
- The significant increase in HWTT results for WMA, as a result of increased curing time and temperature, is not well understood. While moisture in the mix is a likely culprit, the Sasobit WMA mixture (designed in the laboratory) contained no added source of moisture, so it appears that asphalt aging and/or absorption occurs during the curing process, which is affecting the performance properties.

Compaction/Workability Characteristics

- The SGC is an effective tool for evaluating the compaction characteristics of WMA when compared to the corresponding HMA without any additive.
- WMA plant mixes, which were sampled, stored for two months, reheated, and compacted were still significantly easier to compact in the SGC than the HMA. For some of the WMA mixes, this is true even at temperatures as low as 175ºF.

- Lab mixed, lab compacted WMA exhibited similar compaction characteristics to HMA when compacted at 30ºF below the HMA.
- Not all WMA additives perform equivalently and can have different effects on the compactability of a mix.
- Brookfield rotational viscosity is an effective tool for evaluating the workability/compaction characteristics for assessing WMA additives which are marketed as modifiers to the binder.
- At test temperatures of 290ºF, 250ºF, and 220ºF, the Sasobit and Rediset modified binders exhibited a significantly lower viscosity than the unmodified binder.

Cracking and Moisture Susceptibility of WMA

- Overlay test data from lab mixed, lab compacted samples indicate a significant improvement for the Advera and Evotherm WMA mixtures. This is with a two-hour cure at the compaction temperature, and this level of improvement may be significantly reduced with the implementation of a longer oven curing time and/or temperature.
- Fatigue life results from the DMA tests indicated that all of the WMA mixture types exhibited a significant improvement in fatigue for the dry tests. The average wet fatigue life for the WMA mixtures was also greater than the HMA; however, the decrease in fatigue life (from dry to wet) was greater for the WMA mixtures indicating a propensity for moisture susceptibility. But, as mentioned previously, these results could be reduced with an increase in oven curing time and/or temperature.
- Surface Free Energy results indicate that the resistance to adhesive fracture (at the asphalt-aggregate interface) was reduced in both wet and dry conditions for all WMA additives/binder/aggregate combinations investigated in this study.

Field Performance

- Field performance of the WMA projects evaluated in this study have been equivalent to comparable HMA projects. The oldest WMA pavement in Texas is 3 years old and is performing similarly to the HMA control section.
- Cores from field projects taken one year after construction indicate a significant "stiffening" of the WMA mixes as measured by HWTT, Overlay test, and Indirect Tensile Strength.
- Some of the WMA technologies exhibited significant improvement in overlay test results. Even after one year of service, overlay tests on cores from some of the test sections indicated improved cracking resistance.
- GPR of WMA projects indicate that they are as uniformly constructed (in terms of density) as corresponding control HMA sections.
- X-ray CT data indicate that the density or air void distribution with depth in the material may be even more uniform than HMA.
- FWD data indicate the structural strength characteristics of the Evotherm Type B base layer in the Fort Worth project are equivalent to a similar HMA project.

RECOMMENDATIONS

Results of this research indicate that the compaction characteristics of an asphalt mixture are significantly enhanced by WMA technologies. This increased compactability results in an increase in laboratory molded density, which could result in a lower optimum asphalt content when the additives are incorporated during design. This research has shown that even reducing the mixture design and compaction temperature for TGC designs will still produce lower optimum asphalt contents than a mix design performed without the additive. This reduction in asphalt content can improve HWTT results and reduce the cost of the mix; however, this could have a negative impact on the durability of TxDOT dense-graded mixtures since TGC mixes already tend to be "dry" in terms of asphalt content.

The current special provision (SP 341-020) allows the option to include the additive or not during the design. It is recommended that the additive not be included during the design if doing so results in reducing the optimum asphalt content.

The most common WMA technology used within TxDOT today is the foaming technology. At the present time, the laboratory technology of incorporating moisture, or foam into the mix is not readily available. As a result, the mix must be designed without foam which is incorporated during the trial batch and when establishing the job mix formula. This transition from the laboratory mix design without the foam to the trial batch production with the foam will likely result in a reduction in asphalt content due to the increased lab molded density afforded by the foam. To prevent a lower asphalt content resulting from the trial batch, one or both of the following may be employed, which are allowed in the current special provision:

- Increase the target density from 96 percent to 97.5 percent.
- Lower the laboratory mixing and compaction temperature to produce the target lab-molded density at the optimum asphalt content as designed.

Prior to TxDOT's implementation of WMA technologies, mixtures were cured for two hours at the compaction temperature (as specified for a particular PG binder grade). This research has shown that curing WMA in the laboratory for two hours at their compaction temperature, which is lower than conventional HMA, results in mixtures with low HWTT performance results. HWTT results for plant produced WMA mixtures are also sometimes below TxDOT requirements when low curing and compaction temperatures are used. However, HWTT results from field cores shows a significant improvement in rutting resistance produced during the first year of service. To standardize the curing procedure for all types of WMA technologies and to better reflect results from field core testing, at this time, it is recommended that WMA mixtures be cured for four hours at 275ºF for performance testing. This recommendation has been implemented in current procedures as described in Appendix C.

For job control of lab-molded density, it is recommended that the WMA mixtures be cured for two hours at the compaction temperature, as determined appropriate during trial batch production, such that asphalt content for the job mix formula is as close to the design as possible, as mentioned previously. There is still much to be learned about the compactability improvements offered by different WMA technologies and what should be the appropriate compaction temperature for a given technology and mix.

Recommendations for Additional Research

Because rapidly escalating scarcity and cost of highway construction materials, particularly, asphalt and aggregate, contractors and even DOTs have shown increased interest in the use of recycled asphalt pavement (RAP) and shingles (RAS), particularly, tear-off shingles. More recently, WMA has risen to prominence in the asphalt construction industry. Blending of these recycled products, containing age-hardened binders, into asphalt mixtures at temperatures significantly lower than those historically utilized raises major questions. The main one being, will the hardened binders be activated and become a part of the asphalt pavement binder system? If so, how much will be activated? What amount of activated aged binder is acceptable? How can this be accurately and practically measured during mixture design? How can it be monitored during mixture production? Research is vitally needed to answer these questions before many lane-miles of such mixtures are placed which may lead to premature distress or even failure.

Many, if not most, of the WMA processes involve the use of water (both steam and/or liquid water) to temporarily extend and soften the asphalt binder to achieve mixing and compaction at lower-than-conventional HMA temperatures. Many paving agencies and asphalt researchers are concerned that this water may remain in a mixture for a significant period after compaction, both in laboratory specimens and in a pavement layer. If testing is performed on specimens (laboratory compacted or pavement cores) temporarily containing water, will the properties be significantly affected? Will these specimens accurately predict field performance. Evidence in Texas has shown that, occasionally, a freshly made specimen will not pass the HWTT, but, after a certain period, the specimen will pass the HWTT. A curing procedure is needed to ensure that specimens are tested that more accurately represent the pavement layer in the field.

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APPENDIX A
MIX DESIGNS REFABRICATED FOR LAB STUDY

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

File Version: 06/09/03 10:53:11

SAMPLE ID:	A-15-05-891	SAMPLE DATE:	07/19/05
LOT NUMBER:	Design Verification	LETTING DATE:	
STATUS:		CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	1993
SAMPLED BY:		SPEC ITEM:	
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL:		MIX TYPE:	Type_C
PRODUCER:	Dean Word FM 2252		Valero PG 76-22
AREA ENGINEER:		PROJECT MANAGER:	
COURSE\LIFT:		STATION:	DIST. FROM CL:

		BIN FRACTIONS																				
		Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7								
Aggregate Source:		Delta		Hanson		Hanson		Hanson		GEM												
Aggregate Number:		Ty C Rock		3/8"-#4		1/4"-#10		Red Screenings		Silica												
Sample ID:		Sandstone		Limestone		Limestone		Limestone		Sand						Combined Gradation						
Rap:(Yes/No), % Asphalt:																Total Bin						
Individual Bin (%):		25.0	Percent	15.0	Percent	17.0	Percent	29.0	Percent	14.0	Percent		Percent		Percent	100.0%		Lower & Upper Type_C Specification Limits		Individual % Retained	Cumulative % Retained	Sieve Size
Sieve Size:	Sieve Size: (mm)	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Within Spec's					
7/8"	22.400	100.0	25.0	100.0	15.0	100.0	17.0	100.0	29.0	100.0	14.0		0.0		0.0	100.0	Yes	98.0	100.0	0.0	0.0	7/8"
5/8"	16.000	95.3	23.8	100.0	15.0	100.0	17.0	100.0	29.0	100.0	14.0		0.0		0.0	98.8	Yes	95.0	100.0	1.2	1.2	5/8"
3/8"	9.500	7.5	1.9	86.7	13.0	100.0	17.0	100.0	29.0	100.0	14.0		0.0		0.0	74.9	Yes	70.0	85.0	23.9	25.1	3/8"
No. 4	4.750	2.7	0.7	18.2	2.7	59.0	10.0	97.2	28.2	100.0	14.0		0.0		0.0	55.6	Yes	43.0	63.0	19.3	44.4	No. 4
No. 10	2.000	2.0	0.5	3.5	0.5	5.4	0.9	71.5	20.7	99.8	14.0		0.0		0.0	36.6	Yes	30.0	40.0	19.0	63.4	No. 10
No. 40	0.425	1.8	0.5	1.4	0.2	1.5	0.3	26.3	7.6	85.7	12.0		0.0		0.0	20.6	Yes	10.0	25.0	16.0	79.4	No. 40
No. 80	0.180	1.7	0.4	1.3	0.2	1.3	0.2	10.5	3.0	23.4	3.3		0.0		0.0	7.1	Yes	3.0	13.0	13.5	92.9	No. 80
No. 200	0.075	1.5	0.4	1.2	0.2	1.2	0.2	4.7	1.4	6.3	0.9		0.0		0.0	3.1	Yes	1.0	6.0	4.0	96.9	No. 200

\# Not within specifications # Not cumulative

Asphalt Source & Grade:	Valero PG 76-22	Binder Percent, (%):	4.5	Specific Gravity of Asphalt:	1.032

Remarks:

Test Method:	Tested By:	Tested Date:
Tx207		
Tx208		
Tx210		
Tx227		
Tx228		
Tx229		
Tx231		
Tx236		

Reviewed By:	Completed Date:

TEXAS DEPARTMENT OF TRANSPORTATION
BROWNWOOD DISTRICT LABORATORY

HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

File Version: 10/23/06 16:46:13

SAMPLE ID:	H0C23025010301	SAMPLE DATE:	06/13/2003
LOT NUMBER:	001	LETTING DATE:	
STATUS:	COMP	CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	1993
SAMPLED BY:	NED ALLEN JENNINGS	SPEC ITEM:	
SAMPLE LOCATION:	03-006C VULCAN BWDDES	SPECIAL PROVISION:	
MATERIAL:	QCQA1CMC00	MIX TYPE:	Type_C
PRODUCER:	VULCAN MATLS BROWNWOOD , TX		
AREA ENGINEER:		PROJECT MANAGER:	
COURSE\LIFT:		STATION:	

DIST. FROM CL:

BIN FRACTIONS

	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7
Aggregate Source:	Vulcan Brownwood	Vulcan Brownwood	Vulcan Brownwood	Vulcan Brownwood			
Aggregate Number:	C Rock	DF Rock	M-Sand	Field Sand			
Sample ID:							
Rap:(Yes/No), % Asphalt:							

Sieve Size:	Sieve Size: (mm)	Bin No.1 Cum.% Passing	Bin No.1 Wtd Cum. %	Bin No.2 Cum.% Passing	Bin No.2 Wtd Cum. %	Bin No.3 Cum.% Passing	Bin No.3 Wtd Cum. %	Bin No.4 Cum.% Passing	Bin No.4 Wtd Cum. %	Bin No.5 Cum.% Passing	Bin No.5 Wtd Cum. %	Bin No.6 Cum.% Passing	Bin No.6 Wtd Cum. %	Bin No.7 Cum.% Passing	Bin No.7 Wtd Cum. %	Combined Gradation Cum. % Passing	Within Spec's	Lower & Upper Type_C Specification Limits (Lower)	(Upper)	Individual % Retained	Cumulative % Retained	Sieve Size
Individual Bin (%):		26.0	Percent	32.0	Percent	32.0	Percent	10.0	Percent		Percent		Percent		Percent	Total Bin 100.0%						
7/8"	22.400	100.0	26.0	100.0	32.0	100.0	32.0	100.0	10.0		0.0		0.0		0.0	100.0	Yes	98.0	100.0	0.0	0.0	7/8"
5/8"	16.000	95.0	24.7	100.0	32.0	100.0	32.0	100.0	10.0		0.0		0.0		0.0	98.7	Yes	95.0	100.0	1.3	1.3	5/8"
3/8"	9.500	15.5	4.0	98.5	31.5	100.0	32.0	100.0	10.0		0.0		0.0		0.0	77.5	Yes	70.0	85.0	21.2	22.5	3/8"
No. 4	4.750	0.8	0.2	40.0	12.8	99.0	31.7	100.0	10.0		0.0		0.0		0.0	54.7	Yes	43.0	63.0	22.8	45.3	No. 4
No. 10	2.000	0.4	0.1	5.0	1.6	79.5	25.4	100.0	10.0		0.0		0.0		0.0	37.1	Yes	30.0	40.0	17.6	62.9	No. 10
No. 40	0.425	0.3	0.1	0.8	0.3	23.2	7.4	96.0	9.6		0.0		0.0		0.0	17.4	Yes	10.0	25.0	19.7	82.6	No. 40
No. 80	0.180	0.3	0.1	0.4	0.1	6.6	2.1	35.0	3.5		0.0		0.0		0.0	5.8	Yes	3.0	13.0	11.6	94.2	No. 80
No. 200	0.075	0.1	0.0	0.3	0.1	1.8	0.6	8.8	0.9		0.0		0.0		0.0	1.6	Yes	1.0	6.0	4.2	98.4	No. 200

\# Not within specifications \# Not cumulative

Asphalt Source & Grade:	Koch Pav Solutions 76-22	Binder Percent, (%):	5.2	Specific Gravity of Asphalt:	1.039

Remarks:

Design performed by Ned Jennings Vulcan Materials

Test Method:	Tested By:	Tested Date:
TX207	NED ALLEN JENNINGS	06/16/03
TX208	MICHAEL SORLEY	06/16/03
TX210		
TX227	NED ALLEN JENNINGS	06/16/03
TX228		
TX229		
TX231		
TX236	NED ALLEN JENNINGS	06/16/03

Reviewed By: Completed Date:

APPENDIX B

BASICS OF GPR

The Texas DOT's 1 gigahertz (1 GHz) air-coupled Ground Penetrating Radar unit is shown in Figure B1. The radar antenna is attached to a fiber glass boom and suspended about 5 feet from the vehicle and 14 inches above the pavement. This particular GPR unit transmits and receives 50 pulses per second, and can effectively penetrate to a depth of around 24 inches. This system sends discrete pulses of radar energy into the pavement and captures the reflections from each layer interface within the structure. At each interface within a pavement structure, a part of the incident energy will be reflected and a part will be transmitted. A typical plot of captured reflected energy versus time for one pulse is shown in Figure B1, as a graph of volts versus arrival time in nanoseconds. To understand GPR signals, it is important to understand the significance of this plot.

The reflection A_0 is known as the end reflection; it is internally generated system noise that will be present in all captured GPR waves. The more important peaks are those that occur after A_0. The reflection A_1 is the energy reflected from the surface of the pavement, and A_2 and A_3 are reflections from the top of the base and subgrade, respectively. These are all classified as positive reflections, which indicate an interface with a transition from a low to a high dielectric material. These amplitudes of reflection and the time delays between reflections are used to calculate both layer dielectrics and thickness. The dielectric constant of a material is an electrical property which is most influenced by moisture content and density. An increase in moisture will cause an increase in layer dielectric; in contrast, an increase in air void content will cause a decrease in layer dielectric.

The concept of using layer dielectric to measure mat density is now widely recognized by industry. In fact, the new generation of asphalt density gauges (such as the PQI) all measure surface dielectric and correlate it to surface density.

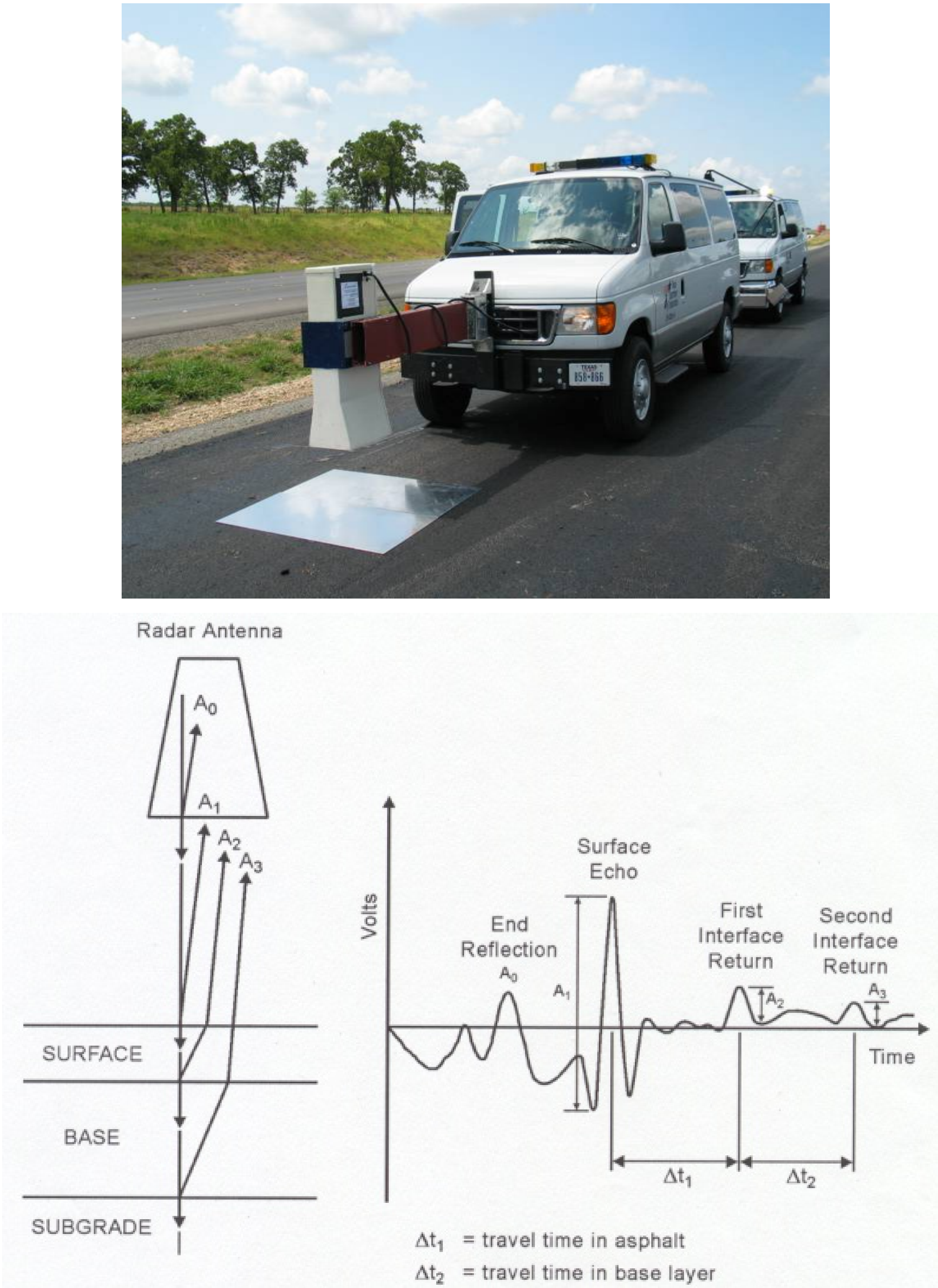

Figure B1. GPR Equipment and Principles of Operation.

To assess the in-place density of any asphalt surface, the reflection (A_1) is used to calculate the dielectric of the surface layer. Numerous studies in Texas and Finland have related the surface dielectric to density of the top layer of asphalt (Saarenketo, 1998; Sebesta, 2002). To do this, it is necessary to take calibration cores in areas where large variations in computed dielectric are observed. These cores are taken back to the laboratory for density measurements. A typical set of data is shown in Figure B2.

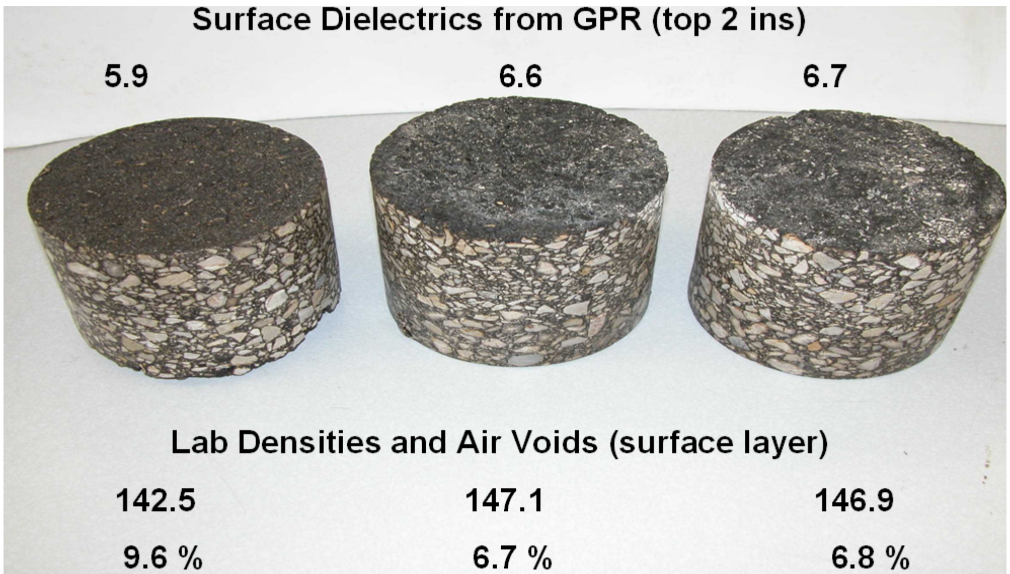

Figure B2. Calibration Cores Relating Dielectric and Density.

As the measured surface dielectric goes down, the density in that layer also decreases. GPR has been used to check for the uniformity of compaction. Periodic decreases in surface dielectric are known to be related to "truck-end segregation" in new surface layers. A well compacted HMA will have a uniform surface dielectric. Sebesta (2002) reported that variations (decreases) in surface dielectric of more than 0.6 units are indications that the new mat will not be within density tolerances.

GPR is widely used in Texas to measure the condition of flexible pavements. During a typical GPR run, the surface dielectric is automatically calculated and displayed along the bottom of the GPR plot. A typical set of data from both a well compacted and a badly segregated mat are shown in Figure B3.

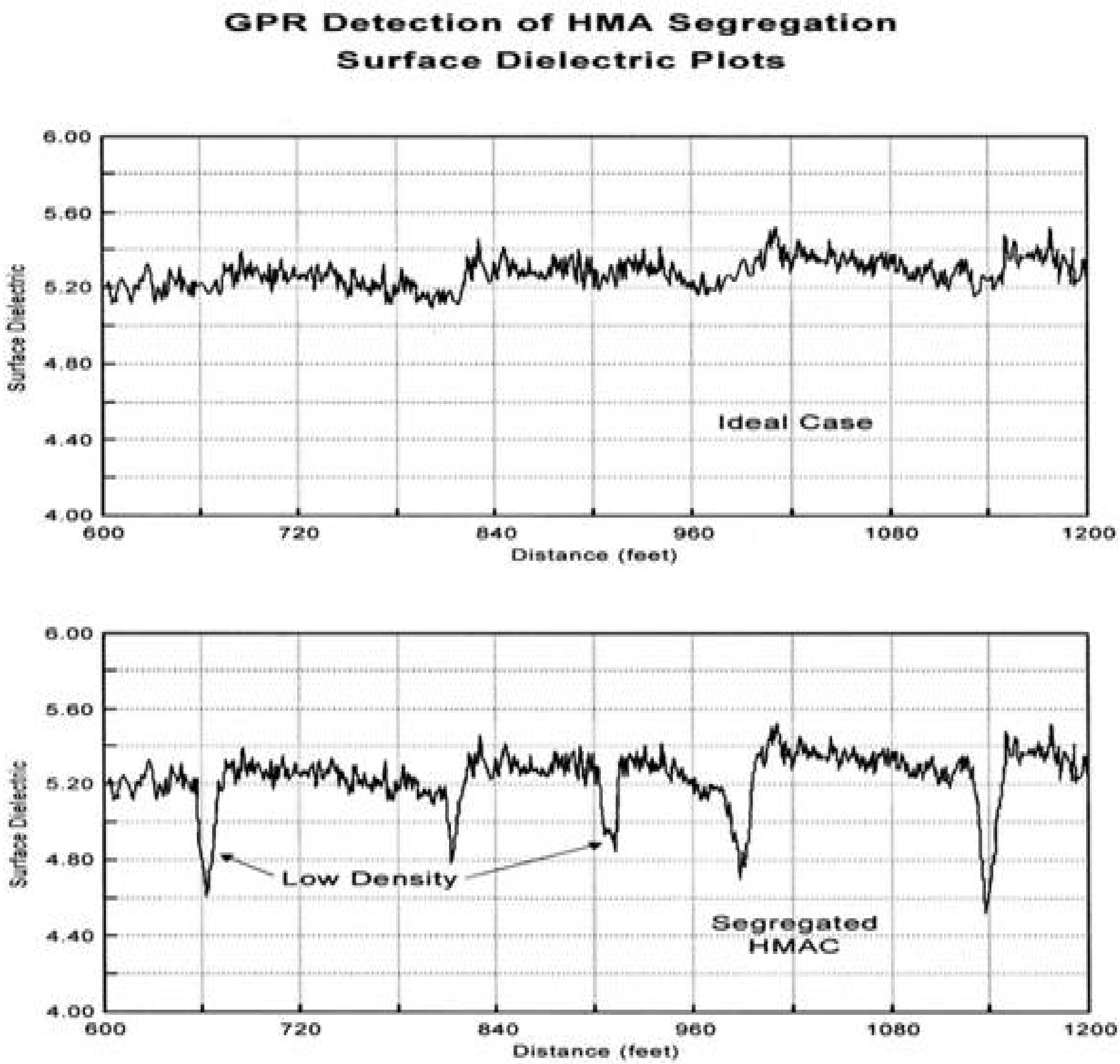

Figure B3. Surface Dielectric Profiles from a Well Compacted and Badly Segregated Pavement Section.

APPENDIX C
GUIDELINES ON THE CONSTRUCTION OF WARM MIX ASPHALT

GUIDELINES AND CRITERIA FOR WMA MIXTURE DESIGN

During the course of this research study, the Department implemented the use of WMA on a wide scale. To facilitate this, test procedures were modified, in part, based on the results of this research, with respect to warm mix.

Optimum Asphalt Content

Results of this research indicate that the compaction characteristics of an asphalt mixture are significantly enhanced by warm mix asphalt technologies. This increased compactability results in an increase in laboratory molded density, which could result in a lower optimum asphalt content when the additives are incorporated during design. This research has shown that even reducing the mixture design and compaction temperature for TGC designs will still produce a lower optimum asphalt content than a mix design performed without the additive. This reduction in asphalt content can improve Hamburg wheel tracking test results and reduce the cost of the mix; however, this could have a negative impact on the durability of TxDOT dense-graded mixtures, since TGC mixes already tend to be "dry" in terms of asphalt content.

The current special provision (SP 341-020), described later, allows the option to include the additive or not during the design. It is recommended that the additive not be included during the design if doing so results in reducing optimum asphalt content.

The most common WMA technology used within TxDOT today is the foaming technology. At the present time, the laboratory technology of incorporating moisture, or foam into the mix is not readily available. As a result, the mix must be designed without foam which is incorporated during the trial batch and when establishing the job mix formula. This transition from the laboratory mix design without the foam to the trial batch production with the foam will likely result in a reduction in asphalt content due to the increased lab molded density afforded by the foam. To prevent deficient asphalt content, resulting from the trial batch, one or both of the following may be employed, which are allowed in the current special provision:

- Increase the target density from 96 percent to 97.5 percent.
- Lower the laboratory mixing and compaction temperature to produce the target lab-molded density at the optimum asphalt content as designed.

Mixture Curing

Prior to TxDOT's implementation of the use of WMA, mixtures were cured for two hours at the compaction temperature (as specified for a particular PG binder grade). This research has shown that curing warm mixtures in the laboratory for two hours at their compaction temperature, which is lower than conventional hot mix, results in mixtures with poor Hamburg performance. Hamburg test results for plant produced warm mixtures are also sometimes below TxDOT requirements when low curing and compaction temperatures are used. However, Hamburg results from field cores shows a significant improvement in rutting resistance is produced during the first year of service. To standardize the curing procedure for all types of warm mix technologies and to better reflect results from field core testing, at this time, it is recommended that WMA mixtures be cured for four hours at 275ºF for performance testing. This recommendation has been implemented in current procedures discussed below.

For job control of lab-molded density, it is recommended that the WMA mixtures be cured for two hours at the compaction temperature, as determined appropriate during trial batch production, such that asphalt content for the job mix formula is as close to the design as possible, as mentioned previously. There is still much to be learned about the compactability offered by different WMA technologies and what should be the appropriate compaction temperature for a given technology and mix.

Laboratory Mixing

Test Method Tex-205-F, "Laboratory Method of Mixing Bituminous Mixtures," has been modified by TxDOT as of June 2009 to accommodate WMA as follows:

> 4.8 Place the calculated quantity of asphalt and any required liquid additives into a small can to facilitate handling. Heat this material in an oven slowly to the temperature shown in Table 1.
>
> > **Note 7**—Do not allow the asphalt to heat to a temperature above the maximum temperature allowed for storage in the Department's *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges,* Item 300, or the recommended temperature obtained from the Construction Division's Materials and Pavements Section (CST/M&P), Flexible Pavements Branch.
> > **Note 8**—Incorporate and mix WMA additives into the laboratory mixture according to the WMA supplier's recommendations, when applicable.
>
> 4.15 Mix the aggregate and asphalt material continuously until the materials are coated thoroughly.
>
> > **Note 11**—Adjusting the mixing time or temperature may be necessary for some mixtures to coat the aggregate particles thoroughly. Carefully consider and calculate the speed and time of mixing and the clearance between the mixing device and the bowl to prevent abnormal degradation of the aggregate, when using a mechanical mixer.

Table 1 of this test method provides the asphaltic material mixing temperatures by grade and type. The table has been amended with the following notes:

> **Note 12**—When WMA additives are allowed and mixed in the laboratory, select the mixing temperatures according to the asphalt binder used in the mixture design, unless otherwise recommended by the WMA material supplier and allowed by the Engineer.
> **Note 13**—When WMA additives are required and mixed in the laboratory, select the mixing temperatures between 215°F and 275°F (102°C and 135°C), as recommended by the WMA material supplier.

Specimen Fabrication

Test Method Tex-206-F, "Compacting Specimens Using the Texas Gyratory Compactor (TGC)," was amended in September 2009 to accommodate WMA, as described below.

4.4 *WMA Laboratory or WMA Plant-Produced Mixtures:*

4.4.1 Prepare the laboratory bituminous mixture in accordance with Tex-205-F, or sample the plant-produced mixture in accordance with Tex-222-F.

4.4.2 Select a compaction temperature.

4.4.2.1 When WMA additives or processes are allowed, select the compaction temperature from Table 1 based on the asphalt binder used in the mixture design, unless otherwise recommended by the WMA material supplier and allowed by the Engineer.

Note 2—The compaction temperature may be reduced to the anticipated production temperature when allowed by the Engineer.

4.4.2.2 When WMA additives or processes are required, select a compaction temperature between 215°F and 275°F, as recommended by the WMA material supplier.

4.4.2.3 When compacting WMA mixtures for mechanical property testing, compact the specimens at 275ºF ±5ºF.

Note 3—Mechanical property testing includes the Indirect Tensile Strength Test (Tex-226-F) as well as any other laboratory test used to measure and predict performance.

4.4.3 Oven-cure the WMA mixture at the temperature selected in Section 4.4.2.1 or 4.4.2.2 for 2 hours, except when molding specimens for mechanical property testing.

4.4.3.1 Oven-cure the WMA mixture intended for preparing specimens for mechanical property testing at 275ºF ±5ºF for 4 hours prior to molding.

Test Method Tex-241-F, "Superpave Gyratory Compacting of Test Specimens of Bituminous Mixtures," was amended in July 2009 to accommodate WMA, as described below.

5.4 *WMA Laboratory or WMA Plant-Produced Mixtures:*

5.4.1 Prepare the laboratory bituminous mixture in accordance with Tex-205-F, or sample the plant-produced mixture in accordance with Tex-222-F.

5.4.2 Select a compaction temperature.

5.4.2.1 When WMA additives or processes are allowed, select the compaction temperature from Table 2 based on the asphalt binder used in the mixture design, unless otherwise recommended by the WMA material supplier and allowed by the Engineer.

Note 6—The compaction temperature may be reduced to the anticipated production temperature when allowed by the Engineer.

5.4.2.2 When WMA additives or processes are required, select the compaction temperature between 215°F and 275°F, as recommended by the WMA material supplier.

5.4.2.3 When compacting WMA mixtures for mechanical property testing, compact the specimens at 275 ±5ºF.

Note 7—Mechanical property testing may include the Hamburg Wheel-Tracking Test (Tex-242-F), Overlay Test (Tex-248-F), and Indirect Tensile Strength Test (Tex-226-F), as well as any other laboratory test used to measure and predict performance.

5.4.3 Oven-cure the WMA mixture at the selected compaction temperature for 2 hours except when molding specimens for mechanical property testing.

5.4.3.1 Oven-cure the WMA mixture intended for preparing specimens for mechanical property testing at 275 ±5ºF for 4 hours prior to molding.

5.4.4 Proceed to Section 5.5.

5.5 Select a mixture weight based on the ultimate disposition of the test specimens.

5.5.1 If a target air void level is desired, as would be the case for Superpave performance specimens, adjust the material weight to create a given density in a known volume.

5.5.2 If using the specimens to determine volumetric properties, adjust the material weight to result in a compacted specimen having dimensions of 150 mm (6 in.) in diameter and115 ±5 mm (4.5 ±0.2 in.) in height at the design number of gyrations.

Note 8 —It may be necessary to produce a trial specimen to achieve this height requirement. Generally, 4500–4700 g of aggregate are required to achieve this height for aggregates with combined bulk specific gravities of 2.55–2.70, respectively.

CONSTRUCTION SPECIFICATION ITEM 341-020 DENSE-GRADED HOT-MIX ASPHALT (QC/QA)

During the course of this research study, the Department implemented the use of WMA on a wide scale. To facilitate this, a special provision (SP 341-020) was developed, in part, based on the results of this research, which amends the standard specification of Item 341 with respect to warm mix, as cited below.

Article 341.2. Materials, Section F. Additives is supplemented by the following:

WMA is defined as additives or processes that allow a reduction in the temperature at which asphalt mixtures are produced and placed. WMA is allowed for use at the Contractor's option unless otherwise shown on the plans. The use of WMA is required when shown on plans. When WMA is required by the plans, produce an asphalt mixture within the temperature range of 215ºF and 275ºF. When WMA is not required as shown on plans, produce an asphalt mixture within the temperature range of 215ºF and 350ºF. Unless otherwise directed, use only WMA additives or processes listed on the Department's approved list maintained by the Construction Division.

Article 341.4. Construction, Section D. Mixture Design. The first paragraph and Table 7 are voided and replaced by the following:

The Contractor may elect to design the mixture using a TGC or a SGC, unless otherwise shown on the plans. Use the typical weight design example given in Tex-204-F, Part I when using a TGC or the Superpave mixture design procedure given in Tex-204-F, Part IV when using a SGC. Design the mixture to meet the requirements listed in Tables 1, 2, 3, 6, 7, and 8. When using the TGC, design the mixture at a 96.0% target laboratory-molded density or as noted in Table 7. When using the SGC, design the mixture at 75 gyrations (Ndesign). Use only a target laboratory-molded density of 96.0% when using the SGC to design the mixture; however, adjustments can be made to the Ndes value, as noted in Table 7.

Use an approved laboratory to perform the Hamburg Wheel test, and provide results with the mixture design, or provide the laboratory mixture and request that the Department perform the Hamburg Wheel test. The Construction Division maintains a list of approved laboratories. The Engineer will be allowed 10 working days to provide the Contractor with Hamburg Wheel test results on the laboratory mixture design

Table 7. Laboratory Mixture Design Properties.

Mixture Property	Test Method	Requirement
Target laboratory-molded density, %	Tex-207-F	96.0[1]
Design SGC gyrations (Ndesign)	Tex-241-F	75 gyrations[2]
Tensile strength (dry), psi	Tex-226-F	85-200[3]
Boil test[4]	Tex-530-C	-

1. May be adjusted within a range of 96.0–97.5% when shown on the plans or allowed by the Engineer when using the TGC (Tex-204-F, Part I).
2. May be adjusted within a range of 50–100 gyrations when shown on the plans or allowed by the Engineer when using the SGC (Tex-204-F, Part IV).
3. May exceed 200 psi when approved and may be waived when approved.
4. Used to establish baseline for comparison to production results. May be waived when approved.

Article 341.4. Construction, Section D. Mixture Design, Section 2. Job-Mix Formula Approval. The first paragraph is voided and replaced by the following:

2. Job-Mix Formula Approval. The job-mix formula (JMF) is the combined aggregate gradation and target asphalt percentage used to establish target values for hot mix production. JMF1 is the original laboratory mixture design used to produce the trial batch. When WMA is used, JMF1 may be designed and submitted to the Engineer without including the WMA additive. When WMA is used, document the additive or process used and recommend rate on the JMF1 submittal. The Engineer and the Contractor will verify JMF1 based on plant-produced mixture from the trial batch, unless otherwise approved. The Engineer may accept an existing mixture design previously used on a Department project and may waive the trial batch to verify JMF1.

Article 341.4. Construction, Section D. Mixture Design, Section 2. Job-Mix Formula Approval, Section a. Contractor's Responsibilities, Section (8) Trial Batch Approval is voided and replaced by the following:

(8) Trial Batch Approval. Upon receiving conditional approval of JMF1 from the Engineer, provide a plant-produced trial batch including the WMA additive or process, if applicable for verification testing of JMF1 and development of JMF2.

Article 341.4. Construction, Section D. Mixture Design, Section 2. Job-Mix Formula Approval, Section a. Contractor's Responsibilities, Table 9 is voided and replaced by the following:

Table 9. Operational Tolerances.

Description	Test Method	Allowable Difference from Current JMF Target	Allowable Difference between Contractor and Engineer[1]
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	±5.0[2]	±5.0
Individual % retained for sieves smaller than #8 and larger than #200		±3.0[2]	±3.0
% passing the #200 sieve		±2.0[2]	±1.6
Asphalt content, %	Tex-236-F	±0.3[3]	±0.3
Laboratory-molded density, %	Tex-207-F	±1.0	±1.0
In-place air voids, %		N/A	±1.0
Laboratory-molded bulk specific gravity		N/A	±0.020
VMA, %, min		Note 4	N/A
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	±0.020

1. Contractor may request referee testing only when values exceed these tolerances.
2. When within these tolerances, mixture production gradations may fall outside the master grading limits; however, the percent passing the #200 will be considered out of tolerance when outside the master grading limits.
3. Tolerance between trial batch test results and JMF1 is not allowed to exceed 0.5 percent, unless otherwise directed. Tolerance between JMF1 and JMF2 is allowed to exceed ± 0.3 percent.
4. Test and verify that Table 6 requirements are met.

Article 341.4. Construction, Section D. Mixture Design, Section 2, Job-Mix Formula Approval, Section b. Engineer's Responsibilities, Section (1) Gyratory Compactor is voided and replaced by the following:

(1) Gyratory Compactor. For mixtures designed in accordance with Tex-204-F, Part I, the Engineer will use a Department TGC, calibrated in accordance with Tex-914-K, to mold samples for trial batch and production testing. The Engineer will make the Department TGC and the Department field laboratory available to the Contractor for molding verification samples, if requested by the Contractor.

For mixtures designed in accordance with Tex-204-F, Part IV, the Engineer will use a Department SGC, calibrated in accordance with Tex-241-F, to mold samples for laboratory mixture design verification. For molding trial batch and production specimens, the Engineer will use the Contractor-provided SGC at the field laboratory or provide and use a Department SGC at an alternate location. The Engineer will make the Contractor-provided SGC in the Department field laboratory available to the Contractor for molding verification samples.

Article 341.4. Construction, Section E. Production Operations, Section 2. Mixing and Discharge of Materials is supplemented with the following:

When WMA is specified on the plans, produce the mixture and monitor the temperature of the material in the truck before shipping to ensure that it does not exceed 275ºF or is less than 215ºF. When WMA is specified, the Department will not pay for or allow placement of any WMA produced at more than 275ºF or less than 215ºF, unless otherwise directed.

Article 341.4. Construction, Section G. Placement Operations is voided and replaced by the following:

G. Placement Operations. Collect haul tickets from each load of mixture delivered to the project and provide the Department's copy to the Engineer approximately every hour, or as directed by the Engineer. Measure and record the temperature of the mixture as discharged from the truck or material transfer device prior to entering the paver and an approximate station number on each ticket. Unless otherwise directed, calculate the daily and cumulative yield for the specified lift and provide to the Engineer at the end of paving operations for each day. The Engineer may suspend production if the Contractor fails to produce haul tickets and yield calculations by the end of paving operations for each day.

Prepare the surface by removing raised pavement markers and objectionable material such as moisture, dirt, sand, leaves, and other loose impediments from the surface before placing mixture. Remove vegetation from pavement edges. Place the mixture to meet the typical section requirements and produce a smooth, finished surface with a uniform appearance and texture. Offset longitudinal joints of successive courses of hot mix by at least 6 in. Place mixture so longitudinal joints on the surface course coincide with lane lines, or as directed. Ensure that all finished surfaces will drain properly. Place mixture within the compacted lift thickness shown in Table 10, unless otherwise shown on the plans or allowed.

Article 341.4. Construction, Section G. Placement Operations, Section 1. Weather Conditions is voided and replaced with the following:

1. Weather Conditions. Place mixture when the roadway surface temperature is equal to or higher than the temperatures listed in Table 10A, unless otherwise approved or as shown on the plans. Measure the roadway surface temperature with a handheld infrared thermometer. The Engineer may allow mixture placement to begin prior to the roadway surface reaching the required temperature requirements if conditions are such that the roadway surface will reach the required temperature within 2 hrs. of beginning placement operations. Unless otherwise shown on the plans, place mixtures only when weather conditions and moisture conditions of the roadway surface are suitable in the opinion of the Engineer.

Article 341.4. Construction, Section G. Placement Operations, Section 1. Weather Conditions is supplemented by the following:

Table 10A. Minimum Pavement Surface Temperatures.

	Minimum Pavement Surface Temperatures in Degrees Fahrenheit	
High Temperature Binder Grade	**Subsurface Layers or Night Paving Operations**	**Surface Layers Placed in Daylight Operations**
PG 64 or lower	45	50
PG 70	55[1]	60[1]
PG 76 or higher	60[1]	60[1]

1. Contractors may pave at temperatures 10°F lower than the values shown in Table 10A when utilizing a paving process including WMA or equipment that eliminates thermal segregation. In such cases, the contractor must use either an infrared bar attached to the paver, a hand held thermal camera, or a hand held infrared thermometer operated in accordance with Tex-244-F to demonstrate to the satisfaction of the Engineer that the uncompacted mat has no more than 10°F of thermal segregation.

Article 341.4. Construction, Section G. Placement Operations, Section 3. Lay-Down Operations. The first paragraph is voided and not replaced.

Article 341.4. Construction, Section G. Placement Operations, Section 3. Lay-Down Operations. Table 11 is voided and not replaced.

Article 341.4. Construction, Section I. Acceptance Plan, Section 1. Referee Testing. The second paragraph is voided and replaced with the following:

The Construction Division will determine the laboratory-molded density based on the molded specific gravity and the maximum theoretical specific gravity of the referee sample. The in-place air voids will be determined based on the bulk specific gravity of the cores, as determined by the referee laboratory, and the Engineer's average maximum theoretical specific gravity for the lot. With the exception of "remove and replace" conditions, referee test results are final and will establish pay adjustment factors for the sublot in question. The Contractor may decline referee testing and accept the Engineer's test results when the placement pay adjustment factor for any sublot results in a "remove and replace" condition. Sublots subject to be removed and replaced will be further evaluated in accordance with Article 341.6, "Payment."

Article 341.4. Construction, Section I. Acceptance Plan, Section 2. Production Acceptance, Section c. Production Testing. The first paragraph is voided and replaced with the following:

The Contractor and Engineer must perform production tests in accordance with Table 12. The Contractor has the option to verify the Engineer's test results on split samples provided by the Engineer. The Engineer may use asphalt content results from quality control testing performed by the Contractor to determine VMA. Determine compliance with operational tolerances listed in Table 9 for all sublots.

Article 341.4. Construction, Section I. Acceptance Plan, Section 3. Placement Acceptance, Section a. Placement Lot, Section (2) Incomplete Placement Lots is voided and replaced by the following:

(2) Incomplete Placement Lots. An incomplete placement lot consists of the area placed, as described in Section 341.4.I.2.a(2), "Incomplete Production Lot," excluding miscellaneous areas as defined in Section 341.4.I.3.a(4), "Miscellaneous Areas." Placement sampling is required if the random sample plan for production resulted in a sample being obtained from an incomplete production sublot.

Article 341.4. Construction, Section I. Acceptance Plan, Section 3. Placement Acceptance, Section b. Placement Sampling. The third and fifth paragraphs are voided and replaced by the following:

Unless otherwise determined, the Engineer will witness the coring operation and measurement of the core thickness. Unless otherwise approved, obtain the cores within 1 working day of the time the placement sublot is completed. Obtain two 6-in. diameter cores side by side from within 1 ft. of the random location provided for the placement sublot. Mark the cores for identification, measure and record the untrimmed core height, and provide the information to the Engineer. Visually inspect each core and verify that the current paving layer is bonded to the underlying layer. If an adequate bond does not exist between the current and underlying layer, take corrective action to ensure that an adequate bond will be achieved during subsequent placement operations. For Type D and Type F mixtures, 4-in. diameter cores are allowed.

If the core heights exceed the minimum untrimmed values listed in Table 10, trim and deliver the cores to the Engineer within 1 working day following placement operations, unless otherwise approved. Trim the bottom or top of the core only when necessary to remove any foreign matter and to provide a level and smooth surface for testing. Foreign matter is another paving layer, such as hot mix, surface treatment, subgrade, or base material. Trim no more than 1/2 in. of material. Do not trim the core if the surface is level and there is not foreign matter bonded to the surface of the core.

Article 341.4. Construction, Section I. Acceptance Plan, Section 3. Placement Acceptance, Section c. Placement Testing is voided and replaced by the following:

c. Placement Testing. Perform placement tests in accordance with Table 12. After the Engineer returns the cores, the Contractor has the option to test the cores to verify the Engineer's test results for in-place air voids. The allowable differences between the Contractor's and Engineer's test results are listed in Table 9.

Article 341.6. Payment. The first paragraph is voided and replaced by the following:

The work performed and materials furnished in accordance with this Item and measured as provided under Article 341.5, "Measurement," will be paid for at the unit price bid for "Dense-Graded Hot-Mix Asphalt (QC/QA)" of the type, surface aggregate classification, and binder specified. When shown on the plans, "level up" may be specified. Pay adjustments for bonuses and penalties will be applied as determined in this Item except for level ups, where a pay adjustment factor of 1.000 will be assigned for all production and placement sublots. These prices are full compensation for surface preparation, materials including tack coat, placement, equipment, labor, tools, and incidentals.

Article 341.6. Payment, Section A. Production Pay Adjustment Factors is supplemented by the following:

When WMA is specified on the plans, at the Contractor's request the Engineer has the option to assign all sublots a production pay adjustment factor of 1.000. When the Engineer elects to assign all sublots a production pay adjustment factor of 1.000, control mixture production to yield a laboratory-molded density with an absolute deviation no greater than 1.0 percent from the target laboratory-molded density, as defined in Table 7 or as shown on plans, as tested by the Engineer. The Engineer may suspend production and shipment of mixture if the laboratory-molded density deviates more than 1.0 percent from the target laboratory-molded density for two consecutive sublots.