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Performance Measures of Warm Asphalt Mixtures for Safe and Reliable Freight Transportation

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16. Abstract

Warm mix asphalt (WMA) is an emerging technology that can allow asphalt to flow at a lower temperature for mixing, placing and compaction. The advantages of WMA include reduced fuel consumption, less carbon dioxide emission, longer paving season, longer hauling distance, reduced oxidation of asphalt, early opening to traffic and a better working environment in the field. In the United States, WMA has become popular in recent years. However, to provide a safe and reliable highway for heavier truck traffic with a high tire pressure, WMA mixtures must meet requirements for strength, stiffness, rutting, and moisture resistance.

WMA mixtures with six commercially available WMA additives that include CECABASE RT®, Sasobit®, Asphalt-min®, Advera WMA, Evotherm J1, and Rediset^{TM} WMX, along with the control WMA mixture without any additive and the control HMA mixture, were evaluated for their air voids, indirect tensile strengths and moisture susceptibilities. To evaluate a long-term reliable performance over a wide range of traffic and climatic conditions, the dynamic modulus and the repeated load tests were conducted on these mixtures using the simple performance testing equipment. Based on the limited test results, Sasobit®, Evotherm J1 and Rediset^{TM} WMX were effective in producing WMA mixtures in the laboratory that is comparable to HMA mixtures.

17. Key Words
Warm mix asphalt (WMA), indirect tensile strength, moisture susceptibility, dynamic modulus, dynamic creep

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Chapter 1 Introduction

Warm mix asphalt (WMA) is an emerging technology that can allow asphalt to flow at a lower temperature for mixing, placing and compaction. The advantages of WMA include reduced fuel consumption, less carbon dioxide emission, longer paving season, longer hauling distance, reduced oxidation of asphalt, early opening to traffic and a better working environment in the field. However, it is difficult for pavement engineers to select a proper WMA product or equipment because there are a large number of technologies marketed without a guarantee of an equal or better performance compared to the hot mix asphalt (HMA). To provide a safe and reliable highway for truck traffic, WMA mixtures must meet requirements for wear and frictional characteristics and for rutting and moisture resistance.

Six commercially available WMA products were collected and evaluated in the laboratory: CECABASE RT®, Sasobit®, Asphalt-min®, Advera WMA, Evotherm J1, and Rediset™ WMX. These six WMA mixtures and two controls—a WMA mixture without any additive and a HMA mixture—were evaluated for their fundamental engineering properties by performing the indirect tensile strength test and the moisture sensitivity test. To evaluate a long-term reliable WMA mixture performance over a wide range of traffic and climatic conditions, the dynamic modulus and the repeated load tests were conducted using simple performance testing equipment.

1.1 Objectives

To provide a safe and reliable highway for truck traffic, warm mix asphalt (WMA) pavement must meet requirements for strength, moisture sensitivity, stiffness, rutting and skid resistance. However, a major difficulty in evaluating WMA mixtures is that there is no national research that evaluates a large number of WMA technologies using dynamic modulus and repeated load tests.

The main objective of this research is to (1) investigate the available technologies for producing WMA and (2) evaluate various WMA products with respect to their fundamental engineering properties and performance-related characteristics.

First, the available technologies for producing WMA mixtures were investigated and six WMA products that indicated the greatest potential for both economic and environmental benefits were selected. Second, experimental methods to produce WMA mixtures in the laboratory were identified based on a literature review of the past research. Third, various WMA mixtures were tested in the laboratory for their fundamental engineering properties and performance-related characteristics.

1.2 Benefits

The main product anticipated from this research is the evaluation results of various warm mix asphalt (WMA) materials with respect to their strength, moisture sensitivity and performance characteristics. This information would be very useful for pavement engineers who are interested in WMA technologies for implementation. Identified reliable WMA technologies from this research would contribute to road safety by minimizing the accident risk posed by unsafe road surface conditions. Such precautionary measures will be increasingly important with the continued growth in freight movement on the U.S. surface transportation system.

1.3 Advantages

Warm mix asphalt (WMA) technologies are intended to reduce the binder resistance to high shear forces like mixing and compaction, but maintain the resistance to normal stresses encountered by traffic loading. The advantages claimed for WMA include:

- less burner fuel required to heat the aggregates
- lower emissions at the asphalt plant
- less hardening of the asphalt binder in the mixing and placement
- less worker exposure to fumes and smoke during the placement operation
- an additional range to the compaction temperatures in the field
- longer construction season due to the ability to compact at lower temperatures

- improved pavement density due to the ease of compaction
- a possibility of longer haul distances
- the ability to incorporate higher percentages of RAP
- the ability to place and compact thicker lifts
- the capacity to open roads to traffic sooner

Organic additives, foaming, and chemical additives of these technologies are all being used to produce WMA and new technologies are emerging rapidly.

Chapter 2 Literature Review

At the Bitumen Forum of Germany in 1997, warm mix asphalt (WMA) technology was identified as one of ways to lower emissions. The WMA technology was introduced in the United States in 2002 when the National Asphalt Pavement Association, NAPA, sponsored an industry scanning tour to Europe for asphalt paving contractors. In 2004, the World of Asphalt convention featured a demonstration project of WMA, and since then WMA additive manufacturers have successfully performed many demonstration projects throughout the United States. Prowell and Hurley (2008) evaluated the current WMA technologies that could significantly benefit highway transportation systems in the United States. NAPA (2008) published a WMA related documentation that included mix design and field trial data. As shown in figure 2-1, Crews (2008) indicated that the number of states with WMA projects have increased significantly.

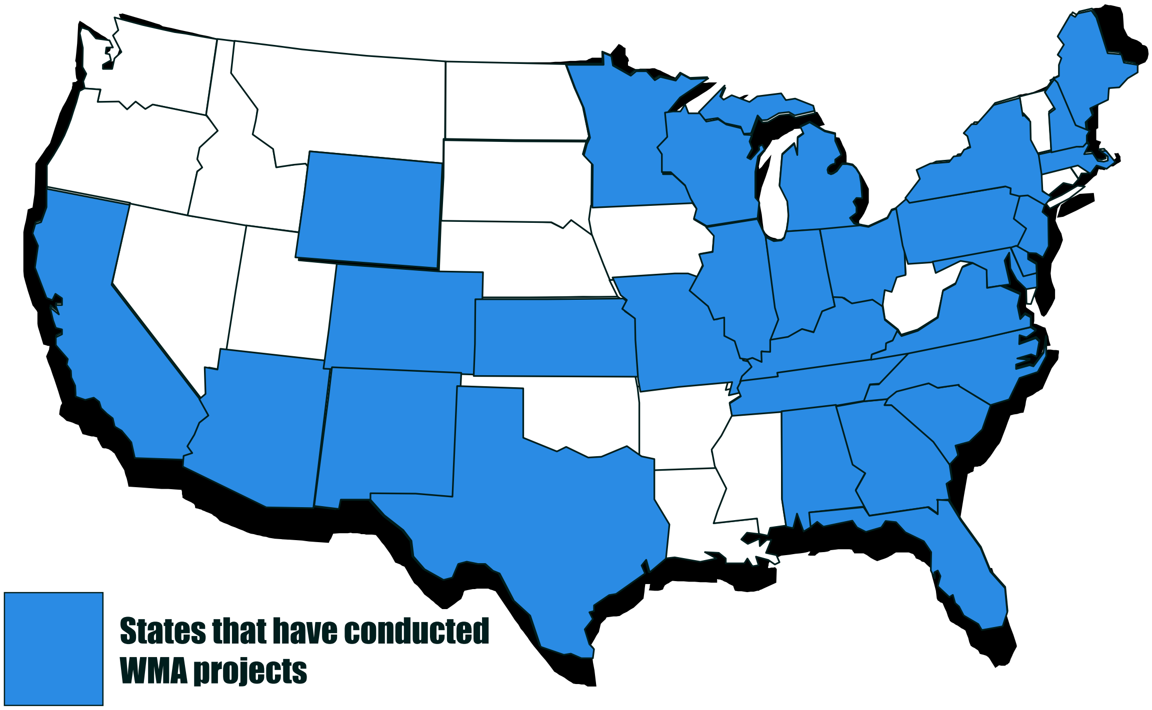

Fig. 2-1 States where WMA Projects were Conducted

As summarized in table 2-1, a number of WMA technologies have been developed and implemented in the United States. These commercial WMA products/processes are available to produce asphalt mixtures at significantly lower temperatures than HMA. The WMA products/processes work differently and are categorized into three groups: organic additive; foaming, and chemical additive (NAPA 2007; Bonaquist 2008).

Table 2-1 List of Warm Mix Asphalt Technologies in the World

Category	Name	Process/Additive	Company	US Project
Organic Additive	Sasobit	Fischer Tropsch Wax	Sasol Wax Americas, Inc.	Yes
	Asphaltan-B	Montan Wax	Romanta	No
	Licomont BS-100	Fatty Acid Amide	Clariant	No
	Cecabase RT	Unspecified Organic Addtive	Ceca	No
Foaming	Aspha-min	Zeolite	Eurovia	Yes
	Advera	Zeolite	PQ Corporation	Yes
	Double Barrel Green	Foaming Nozzle	Astec Industries, Inc.	Yes
	Ultrafoam GX	Foaming Nozzle	Gencor Industries	Yes
	Terex® Warm Mix Asphalt System	Foaming Nozzle	Terex Roadbuilding	Yes
	Aqua-Black	Foaming Nozzle	Maxam Equipment	Yes
	WMA Foam	Soft binder followed by hard binder	Kolo Veidekke, Shell Bitumen	No
	Low Energy Asphalt	Sequential coating using wet fine aggregate and unspecified additive	McConnaughay Technologies	Yes
Chemical Additive	Evotherm ET	Emulsion with unspecified additive	MeadWestvaco Asphalt Innovations	Yes
	Evotherm DAT	Unspecified additive		Yes
	Evotherm J1	Unspecified additive		Yes
	Rediset^{TM} WMA	Unspecified additive	Akzo Nobel Surfactants	Yes

Hurley and Prowell (2005; 2006) evaluated three different technologies, Aspha-Min®, Sasobit® and Evotherm™, and concluded that all three improved the compactibility of the asphalt mixture and resulted in lower air voids compared to HMA. However, they showed increasing tendencies to rutting and moisture susceptibility. This can be attributed to decreased aging of the binder, possible presence of moisture in the mixture, and incomplete drying of the aggregates due to a lower temperature. They reported that Sasobit® increased the PG grade of the binder, and, therefore, a lower grade binder should be used than the PG grade specified. They also reported that air void was less in the WMA mixture and the optimum asphalt binder content may be lowered to increase the air void. However, lowering of asphalt content could negatively affect the compactibility of the mixtures.

Gandhi and Amirkhanian (2007) demonstrated that two of the three binders maintained the same PG grade with the addition of Sasobit®. Biro et al. (2007) reported that Sasobit® changed the flow properties of certain binders from Newtonian flow to shear thinning flow and increased the viscosity of the binders at a mid-range temperature of 60°C (140°F). They also reported that Sasobit® significantly reduced a permanent deformation based on the repeated creep recovery test.

Kristjánsdóttir et al. (2007) reported that HMA producers are unlikely to adopt WMA technology purely for the benefits of lowered emissions and reduced fuel costs. This is because the reductions in fuel costs can be offset by the increased price for the WMA technologies. They also noted that the reduction in the viscosity makes the best business case for WMA because the reduced viscosity can alleviate compaction problems associated with cold weather paving while improving the workability with stiff mixtures.

Nazimuddin et al. (2007) reported that Sasobit® decreased the rut depth which justifies the increase in high temperature binder grading. Kunnawee et al. (2007) reported AC 60/70 binder modified with 3.0% Sasobit® improved the compactibility of asphalt mixture and resulted in acceptable density at a temperature below a normal compaction temperature by 20°C (68°F) to 40°C (104°F). In addition, the mixtures modified with Sasobit® exhibited a greater resistance to densification under simulated traffic.

To determine the effect of WMA additives on CIR-foam mixtures, Lee et al. (2007) prepared three types of CIR-foam specimens: (1) CIR-foam with 1.5% of Sasobit®, (2) CIR-foam with 0.3% Aspha-min®, and (3) CIR-foam without any additive. They were evaluated with the indirect tensile strength test, dynamic modulus test and dynamic creep test. They reported that WMA additives have improved the compactibility of CIR-foam mixtures, resulting in a lower air void. The indirect tensile strength was highest for CIR-foam mixtures with Sasobit® and the dynamic moduli of CIR-foam mixture with WMA additives were higher than those without any additive. Flow number was highest for CIR-foam mixtures with Sasobit®, followed by mixtures with Aspha-min® and those without any additive. Based on the limited test results, they concluded that WMA additives could improve characteristics of CIR-foam mixtures by increasing its resistance to both fatigue cracking and rutting.

Table 2-2 summarizes many field trials that have been performed using various WMA technologies (NAPA 2008). Overall, the WMA sections achieved a comparable density as the HMA sections at a significantly lower temperature. The energy savings and the air quality improvements by using WMA were observed but the performance, durability and compatibility of WMA test sections should be researched further.

Table 2-2 List of Field Trials using Warm Mix Asphalt Technologies

Category	Name	Field Trial
Organic Additive	Sasobit®	• I 95/I 495, Washington D.C. (2005) • Route 211, Virginia (August 2006) • Route 220, Virginia, (August 2006) • With 10% RAP, Missouri (May 2006) • With 14% RAP, Wisconsin (June 2006) • M-95, Michigan (September 2006) • SR 541, Ohio (September 2006) • I-70 Colorado (July 2007)
Foaming	WAM-Foam®	• First field trial in Norway (May 1999) • RV120, Norway, (September 2000) • FV 82 Frogn, Norway (April 2001) • NCC road, Sweden (2002) • Ooms Abenhorn, Netherlands (2003) • Conglobit, Italy (2004)
	Double Barrel® Green	• Chattanooga, Tennessee (June 2007) • 50% RAP, Chattanooga, Tennessee (June 2007) • Johnson County, North Carolina (Sep. 2007) • Vancouver, British Columbia (Sep. 2007) • S.R. 46 from US 431 to S.R. 96, Tennessee (Oct. 2007) • York County, Sacramento (Oct. 2007)
	Ultrafoam GX™ Process	• N/A
	Terex® Warm Mix Asphalt System	• Oklahoma City, Oklahoma (2008)
	Low Energy Asphalt (LEA®)	• Cortland, New York (September 2006) • RT 11, 98B, Bomax Rd. RT 38, RT 13, RT 79, New York (July-September 2007)
	Aspha-Min®	• With PMA in Germany (2003) • Parking lot in Orlando, Florida (February 2004) • Charlotte, North Carolina (September 2004) • Montreal, Quebec, Canada (2004) • Columbus, Ohio (October 2005) • Hookest, New Hampshire (December 2005) • Belmont, New Hampshire (March 2006) • OGFC in Orlando, Florida (February 2006) • SR 541 in Cambridge, Ohio (2006)

	Advera WMA	• Hillsboro Pike, Tennessee (2007) • City Street, Vermont (2007) • Miller Park, Wisconsin (2007) • Yellowstone NP Entrance Rd, Wyoming (2007) • I-70, Colorado (July 2007)
Chemical Additive	Rediset$^{\text{TM}}$ WMA	• Chico, California (November 2007)
	REVIX$^{\text{TM}}$	• CTR 11, Goodhue City, Minnesota (September 2007) • STH 33, La Crosse County, Wisconsin (September 2007) • State Ret. 53, Gainesboro, Tennessee (November 2007) • Highway 25, Smithville, Mississippi (November 2007) • CIR project, HWY 346, Iowa, (August 2008)
Emulsion Additives	Evotherm$^{\text{TM}}$	• County Road 900, Indiana (July 2005) • County road, New York (September 2005) • Binder layer, Canada (September 2005) • Eskimo road, San Antonio (November 2005) • NCAT test track, Alabama(November 2005) • Miller Paving, Canada (August 8, 2005) • Road #46, Canada (October 5, 2005) • Route 143, Virginia (October 2006) • SR 541, Cambridge, Ohio (September 2006) • I-70 Colorado (July 2007)

Chapter 3 Warm Mix Products Evaluated

To produce warm mix asphalt (WMA) mixtures in the laboratory, as shown in figure 3-1, six WMA additives were obtained: CECABASE RT®, Sasobit®, Asphalt-min®, Advera WMA, Evotherm J1, and Rediset^{TM} WMX. Table 3-1 summarizes supplier information about warm mix asphalt (WMA) additives evaluated for this study.

Fig. 3-1 Pictures of Six Warm Mix Asphalt Additives

Table 3-1 List of Warm Mix Asphalt Products Evaluated for this Research

Category	Name	WMA Supplier Information
Organic Additive	CECABASE RT®	Ceca Group Contact Person: Serge Roncen Phone: 33-1-4900-3800 E-mail: Serge.roncen@ceca.fr
	Sasobit®	Sasol Wax Americas, Inc. Contact Person: John M. Shaw Phone: (203) 925-4316 E-mail: john.Shaw@Sasolwax.us.com
Foaming	Asphalt-min®	The Hubbard Group Contact Person: Allen Hendricks Phone: (704) 375-8474 E-mail: AHendricks@BlytheConstruction.com
	Advera WMA	PQ Corporation Contact Person: Annette G. Smith Phone: (610) 651-4469 E-mail: annette.smith@pqcorp.com
Chemical Additive	Evotherm J1	MeadWestvaco Asphalt Innovations Contact Person: Jonathan Maclver Phone: (843) 746-8116 E-mail: evotherm@meadwestvaco.com
	Rediset™ WMA	Akzo Nobel Surfactants Contact Person: Dr. Sundaram Logaraj Phone: (312) 544-7046 E-mail:Sundaram.Logaraj@sc.akzonobel.com

3.1 Organic Additives

Organic additives that have melting points below a normal HMA production temperature can be added to asphalt to reduce its viscosity. With organic additives, the viscosity of asphalt is reduced at the temperature above the melting point in order to produce asphalt mixtures at lower temperatures. Below the melting point, organic additives tend to increase the stiffness of asphalt (Bonaquist 2008).

3.1.1 CECABASE RT®

As shown in figure 3-2, CecabaseRT® allows the production of an asphalt mixture at a temperature of 22°C (72°F) below a typical hot mix asphalt. This additive, which is liquid at room temperature, can be easily mixed into the hot asphalt binder before the asphalt mix production. The liquid CecabaseRT® additive should be added to asphalt at an application rate of 0.2% to 0.5% by weight of asphalt. The Cecabase RT® additive acts at the interface between mineral aggregate and asphalt, in a similar way that a surfactant acts at an interface between water and asphalt that does not significantly change the rheological properties of asphalt. Gonzalez-Leon et al. (2009) reported that WMA mixtures using the Cecabase RT® additive could be compacted in a similar fashion to a HMA, resulting in comparable air void contents with equivalent mechanical properties and water resistance. The effectiveness of the Cecabase RT® was demonstrated in a field test, where a production temperature was reduced by up to 27°C (81°F) yielding a WMA mixture comparable to a typical HMA mixture.

Fig. 3-2 Cecabase RT® Additive

3.1.2 Sasobit®

As shown in figure 3-3, Sasobit® has been used in three different sizes for WMA pavements in the United States. Sasobit® is a Fischer-Tropsch wax produced from the coal gasification process and is typically added at the rate of 1.5% by weight of asphalt. Sasobit® can be added to the asphalt (wet process) or the asphalt mixture (dry process). After stirring, Sasobit® forms a homogeneous solution with the base binder and lowers the viscosity of asphalt. The Sasobit® manufacturer claims that a mixing temperature can be lowered by up to 32°C (90°F) (Sasol Wax).

(a) 5mm diameter (b) 1mm diameter (c) powder

Fig. 3-3 Sasobit® Additive

3.2 Foaming Additives

Synthetic zeolites have been used to enhance the coating of aggregates by asphalt at a lower production temperature. Due to its porous composition, Zeolite includes approximately 20% water that is trapped in its structure. Upon heating to approximately 185°F the water is released and then foamed asphalt is produced (Bonaquist 2008).

3.2.1 Aspha-min®

As shown in figure 3-4, Aspha-min® is zeolite that is supplied in a powder or granular form and it is typically added to the asphalt mixture at a dosage of 0.3% by weight of the mix. By adding it to the mixture along with the asphalt, a very fine water spray is created as crystalline water is released. This expulsion causes a volume expansion in asphalt, thereby increasing the workability of the mixture at a lower temperature. The Aspha-min® manufacturer claims that a mixing temperature can be lowered by up to 10°C (50°F) (Eurovia Services).

(a) powder form (b) granular form

Fig. 3-4 Aspha-min® Additives

3.2.2 Advera WMA

As shown in figure 3-5, Advera WMA is another form of zeolite and has the same dosage rate as Aspha-min®. The Advera WMA manufacturer claims that a mixing temperature can be lowered by up to 21°C (70°F) (PQ Corporation).

Fig. 3-5 Advrea WMA Additive

3.3 Chemical Additives

Various chemical additives, such as surfactants, are emerging WMA additives that help asphalt coat the aggregates at lower temperatures. Most of them are proprietary and the manufacturers do not disclose detailed information about their chemical compositions (Bonaquist 2008; Anderson et al. 2008).

3.3.1 Evotherm J1

Initially, MeadWestvaco developed Evotherm™ which is composed of 70% asphalt and 30% water by weight along with a small amount of surfactant. Later, a new Evotherm® DAT, Dispersed Additive Technology, was developed with a lesser amount of water that can be directly injected as a solution to the asphalt line at the plant. Recently, Evotherm J1, also known as REVIX, was developed as a solution without water that would reduce an internal friction between binder and aggregate and between coated aggregate particles during mixing and compaction (Bonaquist 2008; Anderson et al. 2008). As shown in figure 3-6, the liquid Evotherm J1 can be added to asphalt at a dosage rate of 0.5% by weight of asphalt. The effectiveness of the Evotherm J1 was demonstrated in a field test, where a production temperature was reduced by up to 56°C, or 133°F (MeadWestvaco*)*.

Fig. 3-6 Evotherm J1 Additive

3.3.2 Rediset^{TM} WMX

As shown in figure 3-7, Rediset^{TM} WMX is a combination of organic additives and surfactants that is developed to enhance the adhesion between asphalt and aggregates (Akzo Nobel). It is supplied in a pellet form that can be added to the asphalt or the mixture at a dosage rate of 1.5% to 2.5% by weight of asphalt (Bonaquist 2008).

Fig. 3-7 Rediset^{TM} WMA Additive

Chapter 4 Laboratory Mix Design

The plan for this experiment is described in this section which includes aggregate gradation, optimum asphalt content, optimum WMA additive content and testing temperatures.

4.1 Aggregate Gradation and Asphalt Type Selection

Five stockpiles of aggregates (3/4" crushed, 3/8" chip, crushed limestone, manufactured sand, and natural sand) and PG 70-34 of asphalt binder were used to prepare laboratory specimens. As summarized in table 4-1, five stockpiles of aggregates were combined to produce the design gradation that would meet SuperPave requirements. The design gradation with a nominal maximum aggregate size of 19.0 mm (3/4 inch) was produced as shown in figure 4-1.

Table 4-1 Gradation of Five Stockpiles of Aggregates and Design Gradation

Sieve Size	Gradation (%)					
	3/4" Crushed	3/8" Chip	Crushed Limestone	Manufactured Sand	Natural Sand	Design
25mm	100.0	100.0	100.0	100.0	100.0	100.0
19mm	99.4	100.0	100.0	100.0	100.0	99.9
12.5mm	39.2	100.0	100.0	100.0	100.0	84.8
9.5mm	12.4	89.5	99.9	100.0	100.0	74.9
#4	3.6	21.6	97.5	99.7	97.6	51.4
#8	1.3	8.0	67.0	73.3	92.5	34.5
#16	0.7	5.8	37.8	35.8	81.8	21.0
#30	0.6	4.9	22.2	14.2	59.2	13.1
#50	0.5	4.2	13.7	3.3	14.9	7.1
#100	0.4	3.3	7.5	0.7	1.0	3.8
#200	0.3	2.4	3.9	0.3	0.3	2.2
Proportion	25%	30%	35%	5%	5%	100%

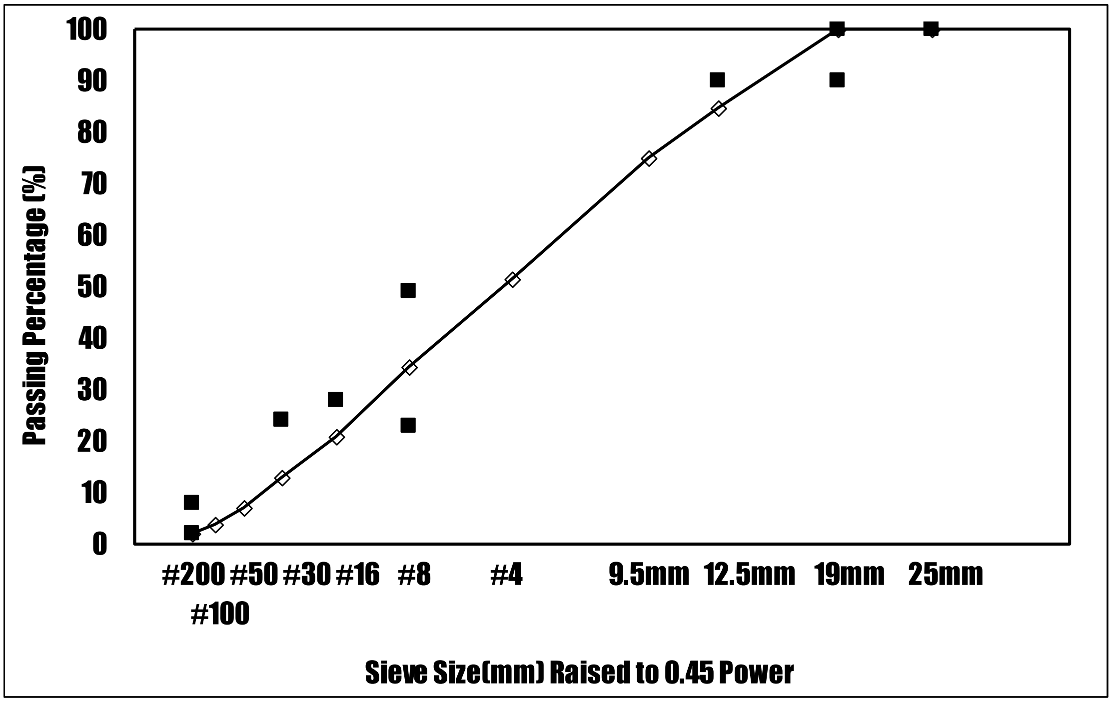

Fig. 4-1 Design Gradation for Laboratory Specimens

4.2 Design Number of Gyration and Optimum Asphalt Content

The mix design parameters for laboratory specimens were determined following the Iowa DOT specification I.M. 510 (Iowa DOT, 2005). As shown in table 4-2, 68 gyrations were selected for the surface mix under traffic of 3 Million ESAL. Based on table 4-3, the optimum asphalt content of 5.5% was selected for aggregates with a nominal maximum aggregate size of 19.0 mm (3/4 inch).

Table 4-2 Iowa DOT Specifications for the Number of Gyrations for HMA Mixtures

Mix Designation	No. of Gyrations		
	N_{ini}	N_{design}	N_{max}
HMA 3M S L-4	7	86	134
HMA 3M S L-3			
HMA 3M S			
HMA 3M I			

Table 4-3 Optimum Asphalt Content in Percent from I.M. 510

Mixture Type	Nominal Maximum Aggregate Size			
	1 inch	3/4 inch	1/2 inch	3/8 inch
Intermediate and Surface	4.75	5.5	6.00	6.00
Intermediate and Surface	5.25	5.75	6.00	6.25
Base	5.25	6.00	6.00	6.25

4.3 Dosage Rate of Warm Mix Asphalt Additives

Following the manufacturers' recommendations, as summarized in table 4-4, laboratory WMA specimens were produced. WMA specimens were prepared by the wet process for CECABASE RT®, Sasobit®, and Evotherm J1 and by the dry process for Sasobit®, Asphalt-min®, Advera WMA, and Rediset^{TM} WMX.

Table 4-4 Mixing Process Methods and Quantity of WMA Additives

Additive	Process	Quantity
CECABASE RT®	Wet Process	0.40% of binder weight
Sasobit®	Dry Process Wet Process	1.50% of binder weight
Asphalt-min®	Dry Process	0.30% of mixture weight
Advera WMA	Dry Process	0.25% of mixture weight
Evotherm J1	Wet Process	0.50% of binder weight
Rediset^{TM} WMX	Dry Process	2.00% of binder weight

4.4 Sample Preparation

Table 4-5 summarizes temperatures of asphalt, aggregate and mixtures during the mixing and compaction process. The aggregate was heated at temperature of 125°C (257°F) for 6 hours and the PG 70-34 asphalt was heated at 145°C (293°F) for 1.5 hours in the oven. To produce WMA mixtures by the dry process, the WMA additive was added to the heated aggregate and manually stirred in the bucket mixer and then asphalt was added. To produce WMA mixtures by the wet process, WMA additive was added to the heated asphalt and to the heated aggregate.

Aggregate, asphalt and WMA additive were mixed for 60 seconds and the WMA mixtures were then heated at 125°C for 20 minutes in the oven. The heated WMA mixtures at 125°C were placed in a preheated gyratory mold at 125°C and compacted for 86 gyrations.

To prepare a control HMA mixture the aggregate was heated at temperature of 165°C (329°F) for 6 hours and PG 70-34 asphalt was heated at 145°C for 1.5 hours in the oven. Next, the heated asphalt was added into the heated aggregate in the bucket mixer. Aggregate and asphalt were mixed for 60 seconds and the HMA mixtures were then heated at 135°C (275°F)for 20 minutes in the oven. The heated HMA mixtures at 135°C were added in a preheated gyratory mold at 135°C and compacted for 86 gyrations.

Table 4-5 Temperatures of Asphalt, Aggregate and Mixture

Temperature (°C)	WMA with additive	Control WMA without additive	Control HMA
Asphalt Temperature	145°C	145°C	145°C
Aggregate Temperature	125°C	125°C	165°C
Mixing Temperature	115°C-125°C	115°C-125°C	150°C
Compaction Temperature	115°C-120°C	115°C-120°C	130°C -135°C

4.5 Experimental Plan

As shown in figure 4-2, basic characteristics of laboratory specimens were measured that include mixing and compaction temperature, maximum specific gravity, bulk specific gravity, and air void. To evaluate fundamental engineering properties and performance-related characteristics of laboratory specimens, as summarized in table 4-6, four laboratory tests were conducted: indirect tensile strength test, moisture sensitivity test, dynamic modulus test, and repeated load test.

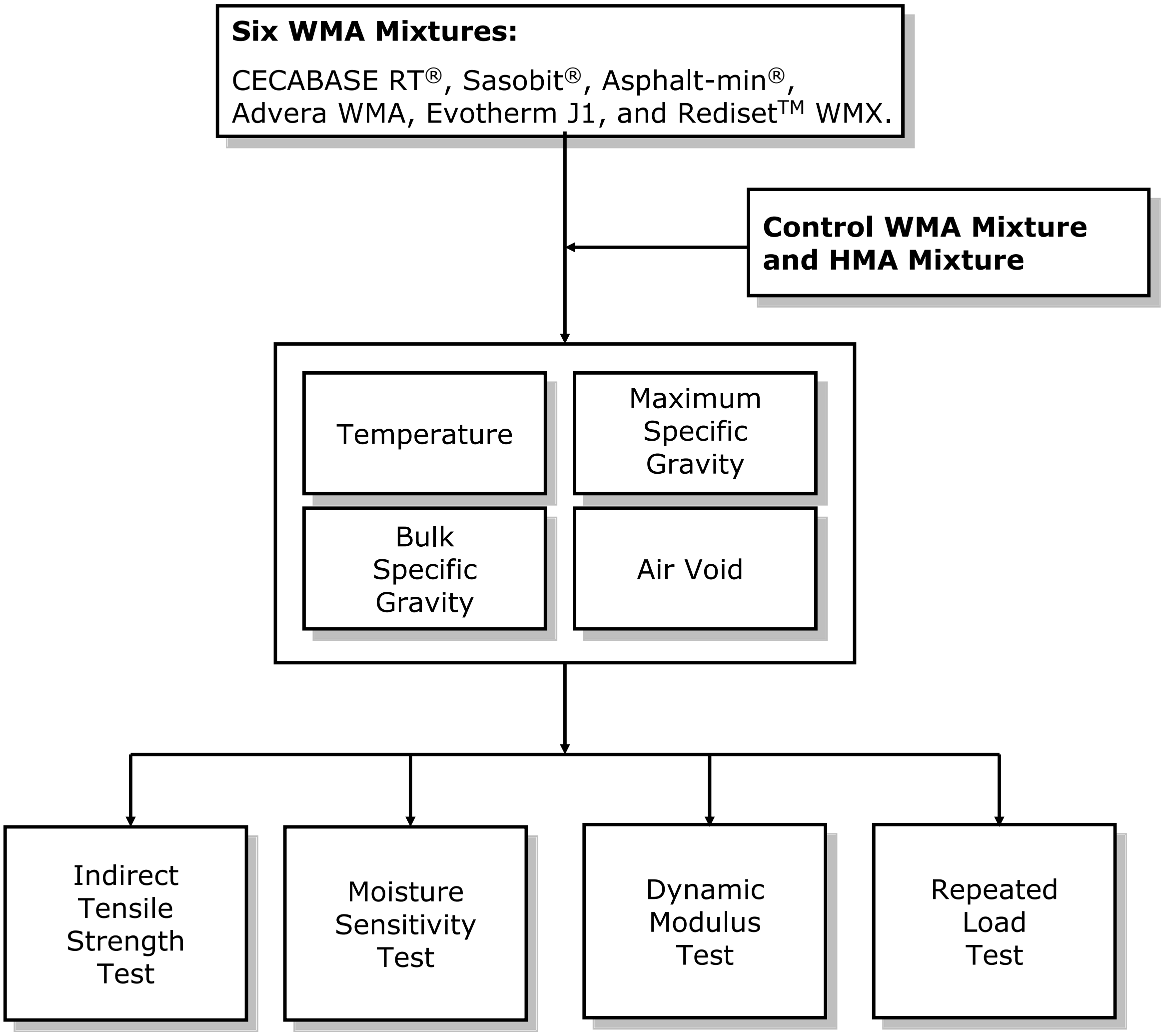

Fig. 4-2 Flow Chart of Experiment Plan

Table 4-6 Conditions of Four Laboratory Tests

Test	Testing Condition
Indirect Tensile Strength Test	• Testing Temperature: 25˚C • Dry specimens
Moisture Sensitivity Test	• Testing Temperature: 25˚C • Dry and wet conditioned specimens
Dynamic modulus Test	• Testing Temperature: 4.4˚C, 21.1˚C, and 37.8˚C • Loading Frequency: 25Hz, 10Hz, 5Hz, 1Hz, 05Hz, 0.1Hz
Dynamic Creep Test	• Testing Temperature: 45˚C • Loading Pressure: 600kPa • Applied Loading Cycle: 10,000 cycles

Chapter 5 Indirect Tensile Strength Test

The indirect tensile strength test has been used for characterizing the resistance to failure of asphalt mixtures caused by tensile stresses (Huang et al. 1995). Hurley and Prowell (2006) performed the indirect tensile strength test to evaluate the strength gain over different aging times.

5.1 Indirect Tensile Strength Testing Procedure

To determine the indirect tensile strength of different types of warm mix asphalt (WMA) mixtures, as summarized in table 5-1, eight WMA mixtures, a control WMA mixture and a control HMA mixture were produced in the laboratory. Three test specimens for each mixture were prepared by gyratory compactor at 86 gyrations. After curing for one-day at room temperature, the bulk specific gravity of the compacted specimens were measured. The next day, as shown in figure 5-1, the indirect tensile strength of specimens was measured after curing in the oven at 25˚C for 2 hours.

Table 5-1 List of WMA and HMA Mixtures for Indirect Tensile Strength Test

Mix Type	Mixing Process Method	Number of Specimen
CECABASE RT®	Wet Process	3 specimens
Sasobit®	Wet Process	3 specimens
Sasobit®	Dry Process	3 specimens
Aspha-min® (Powder)	Dry Process	3 specimens
Aspha-min® (Granular)	Dry Process	3 specimens
Advera WMA	Dry Process	3 specimens
Evotherm J1	Wet Process	3 specimens
Rediset^{TM} WMX	Dry Process	3 specimens
Control WMA	-	3 specimens
Control HMA	-	3 specimens

Fig. 5-1 Indirect Tensile Strength Equipment

5.2 Mixing and Compaction Temperatures of Indirect Tensile Strength Specimens

As shown in table 5-2, the temperatures of asphalt, aggregate, mixture, and compacted specimen were recorded throughout the sample preparation process and plotted in figure 5-2. WMA mixtures were produced at temperatures between 117˚C and 124˚C whereas this occurred for the control HMA mixture at around 150˚C. WMA mixtures were compacted at temperatures between 112˚C and 123˚C whereas the control HMA mixture was compacted around 133˚C.

5.3 Theoretical Maximum Specific Gravities

As shown in figure 5-3, the theoretical maximum specific gravity of mixtures was measured using a CoreLok device. Table 5-3 summarizes the theoretical maximum specific gravities of eight WMA mixtures and the control WMA and HMA mixtures that are plotted in figure 5-4. As can be seen from figure 5-4, the theoretical maximum specific gravity of the control WMA mixture showed the highest value whereas that of the WMA mixture with Sasobit® by dry process showed the lowest value. Overall, the theoretical maximum specific gravities of mixtures ranged between 2.420 and 2.449.

Table 5-2 Temperatures of Asphalt, Aggregate, Mixture and Compacted Specimen for Indirect Tensile Strength Test

Temperature (˚C)		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Asphalt Binder		145	145	145	145	145	145	145	145	145	145
Aggregates		122	125	120	121	125	122	120	125	125	160
Mixing		119	120	120	120	119	117	119	120	124	150
Before Compaction	#1	120	119	118	116	115	116	117	117	116	133
After Compaction		96	92	106	102	96	85	103	97	87	121
Before Compaction	#2	119	117	120	117	114	120	112	118	118	133
After Compaction		97	92	105	94	96	103	88	99	96	102
Before Compaction	#3	117	121	123	116	114	118	119	119	122	134
After Compaction		94	95	105	94	96	102	101	99	97	104

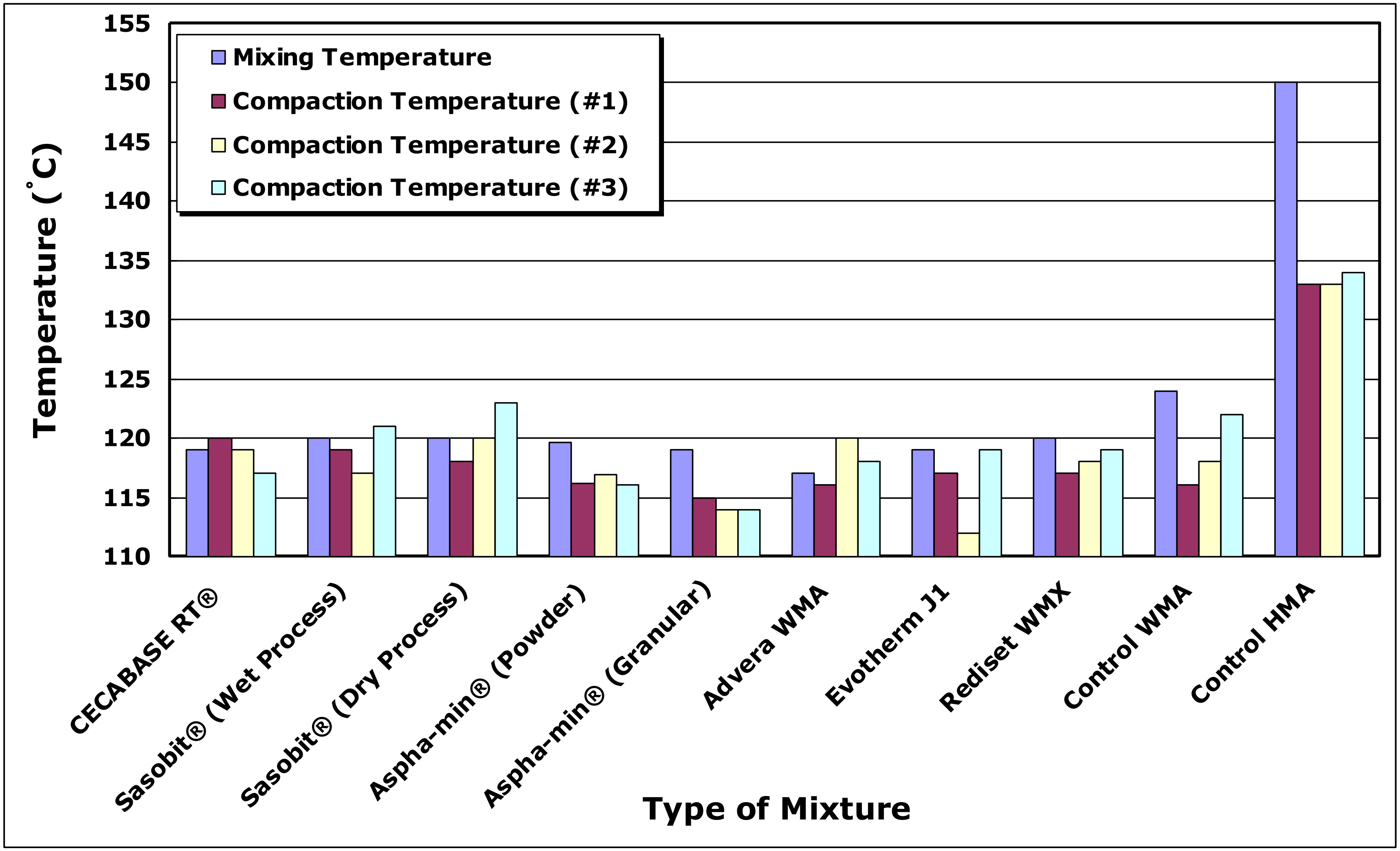

Fig. 5-2 Mixing and Compaction Temperatures of Indirect Tensile Strength Test Specimens

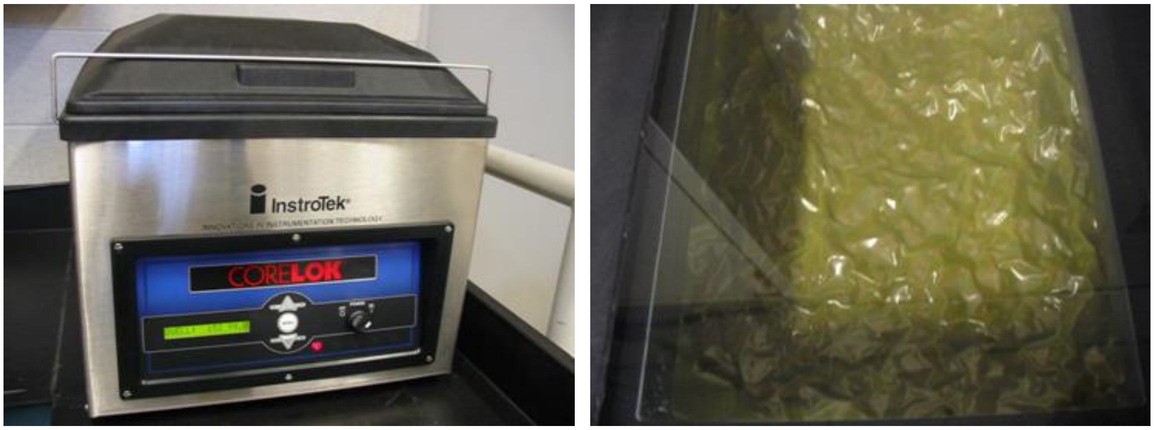

Fig. 5-3 CoreLok Device to Measure Theoretical Maximum Specific Gravity

Table 5-3 Theoretical Maximum Specific Gravities of WMA and HMA mixtures

Mix Type	Mixing Process	Theoretical maximum specific gravity		
		#1	#2	Average
CECABASE RT®	Wet Process	2.447	2.428	2.438
Sasobit®	Wet Process	2.414	2.426	2.420
Sasobit®	Dry Process	2.428	2.423	2.426
Aspha-min® (Powder)	Dry Process	2.430	2.438	2.434
Aspha-min® (Granular)	Dry Process	2.431	2.434	2.433
Advera WMA	Dry Process	2.443	2.448	2.446
Evotherm J1	Wet Process	2.453	2.441	2.430
Rediset™ WMX	Wet Process	2.453	2.441	2.447
Control WMA	-	2.449	2.448	2.449
Control HMA	-	2.426	2.437	2.432

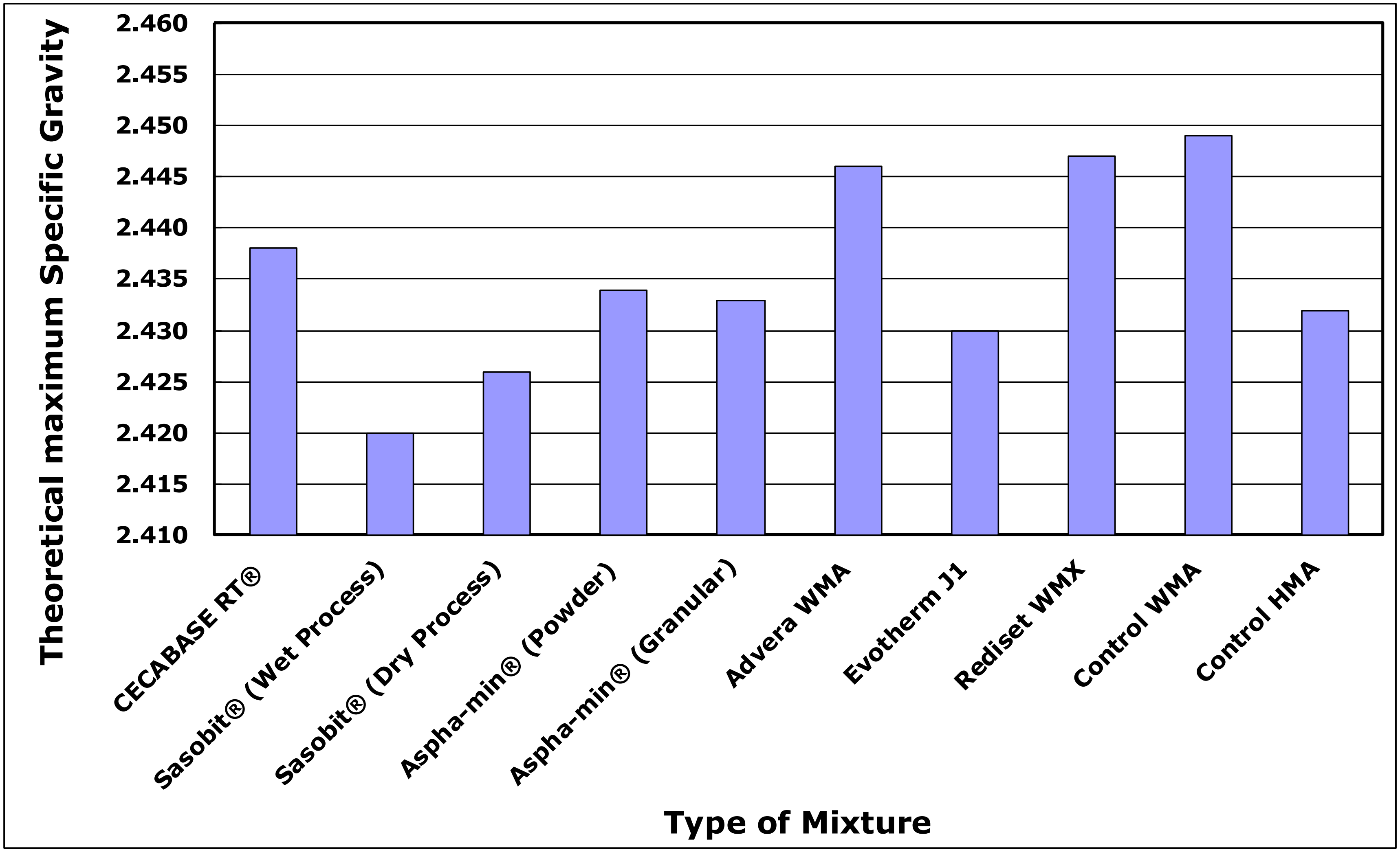

Fig. 5-4 Average Theoretical Maximum Specific Gravities of WMA and HMA Mixtures

5.4 Bulk Specific Gravities and Air Voids of Indirect Tensile Test Specimens

The bulk specific gravity of each specimen was determined following the AASHTO T 166 (AASHTO 2001). Table 5-4 summarizes the bulk specific gravities and air voids of the WMA mixtures and the control HMA mixture that were prepared for indirect tensile strength test. Given the same compaction level of 68 gyrations, the bulk specific gravities of WMA specimens ranged between 2.364 and 2.431 and the control HMA specimens ranged between 2.390 and 2.400. All specimens exhibited a small amount of air voids ranging between 0.7% (Rediset™ WMX) and 2.9% (Advera).

Figure 5-5 and figure 5-6 show plots of average bulk specific gravities and air voids of the specimens, respectively. As figure 5-6 demonstrates, it is interesting to note that the average air voids of WMA specimens with Aspha-min® (Granular), Evotherm J1, and Rediset™ WMX were lower than that of the control HMA specimens. This indicates these additives are effective in compacting an asphalt mixture at a lower temperature.

5.5 Indirect Tensile Strength Results

The indirect tensile strength test was performed and the indirect tensile strength of the specimens was calculated using the following formula:

$$\text{Indirect Tensile Strength (psi)} = \frac{2 \times P_{\max}}{\pi \times D \times t}$$

P_{max} = maximum load, lb;

D = specimen height before tensile test, in; and

T = specimen diameter, in

The indirect tensile strengths of eight WMA mixtures, the control WMA mixture and the control HMA mixture are summarized in table 5-5 and their average values are plotted in figure 5-7. The indirect tensile strengths of WMA specimens ranged between 54.5psi and 94.0psi whereas those of the HMA specimens ranged between 93.3psi and 104.7psi. Overall, the average indirect tensile strengths of WMA mixtures with chemical additives were higher than the control WMA mixture, followed by the WMA mixtures with organic and foaming additives. Particularly, the Rediset^{TM} WMX specimen exhibited the highest indirect tensile strength whereas Sasobit® specimen prepared by a dry process exhibited the lowest value.

Table 5-4 Bulk Specific Gravities and Air Voids of WMA and HMA Mixtures for Indirect Tensile Strength Test

No. of Specimen		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Asphamin® (Powder)	Asphamin® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Bulk Specific Gravity	# 1	2.395	2.393	2.404	2.382	2.406	2.364	2.413	2.431	2.391	2.390
	# 2	2.367	2.369	2.414	2.366	2.399	2.395	2.408	2.424	2.395	2.399
	# 3	2.385	2.376	2.404	2.389	2.403	2.388	2.400	2.428	2.384	2.400
	Ave.	2.382	2.380	2.407	2.379	2.403	2.382	2.407	2.428	2.390	2.397
	St. Dev	0.0142	0.0123	0.0058	0.0118	0.0035	0.0163	0.0066	0.0035	0.0056	0.0055
Air void (%)	# 1	1.8	1.1	1.8	2.2	1.1	3.3	0.7	0.7	2.3	1.6
	# 2	2.9	2.1	1.4	2.8	1.4	2.1	0.9	0.9	2.2	1.3
	# 3	2.2	1.8	1.8	1.8	1.2	2.4	1.2	0.8	2.6	1.2
	Ave.	2.3	1.7	1.7	2.3	1.2	2.6	1.0	0.8	2.4	1.4

	St. Dev	0.5568	0.5132	0.2309	0.5033	0.1528	0.6245	0.2517	0.1000	0.2082	0.2082

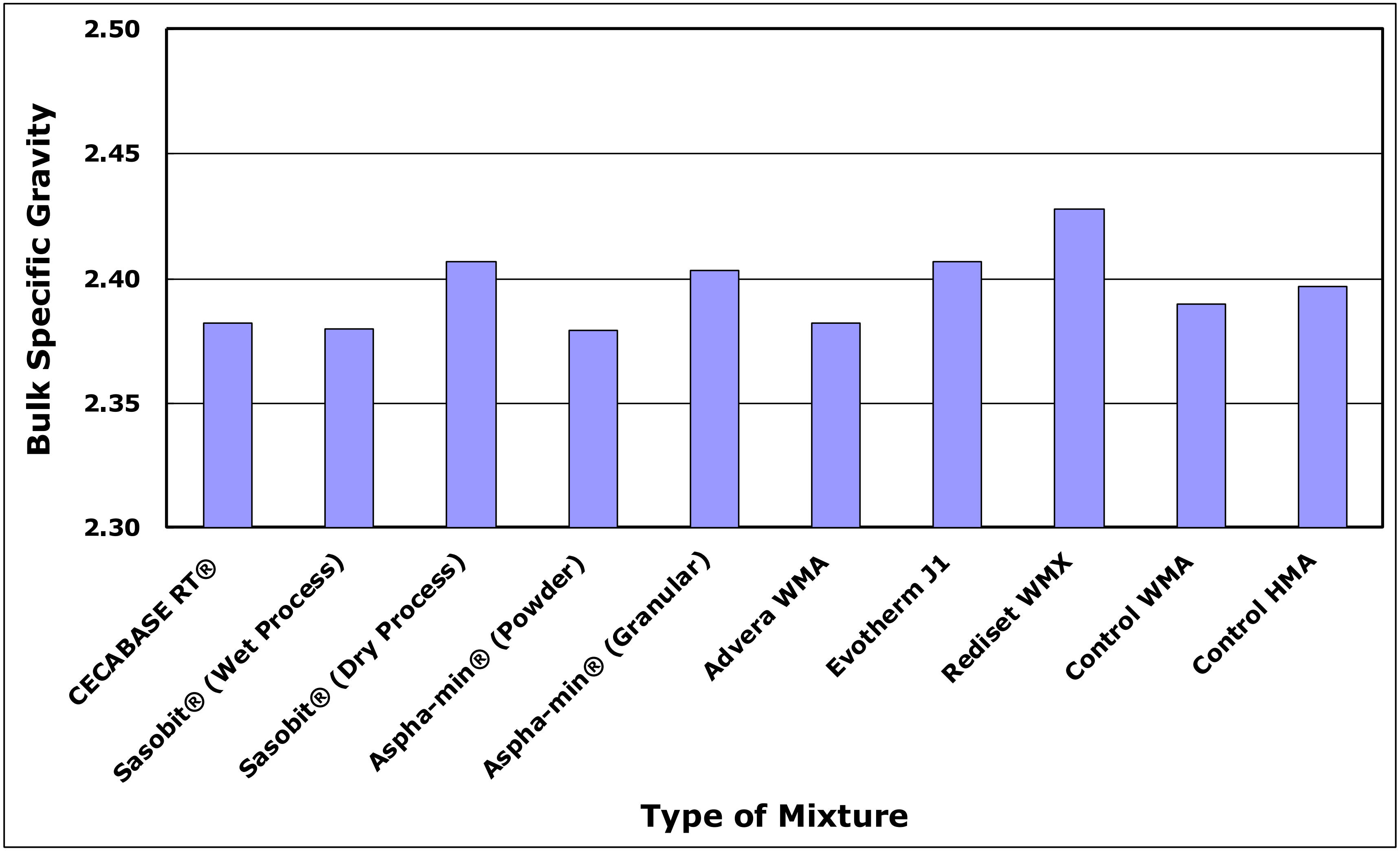

Fig. 5-5 Average Bulk Specific Gravities of WMA and HMA Mixtures Prepared for Indirect Tensile Strength Test

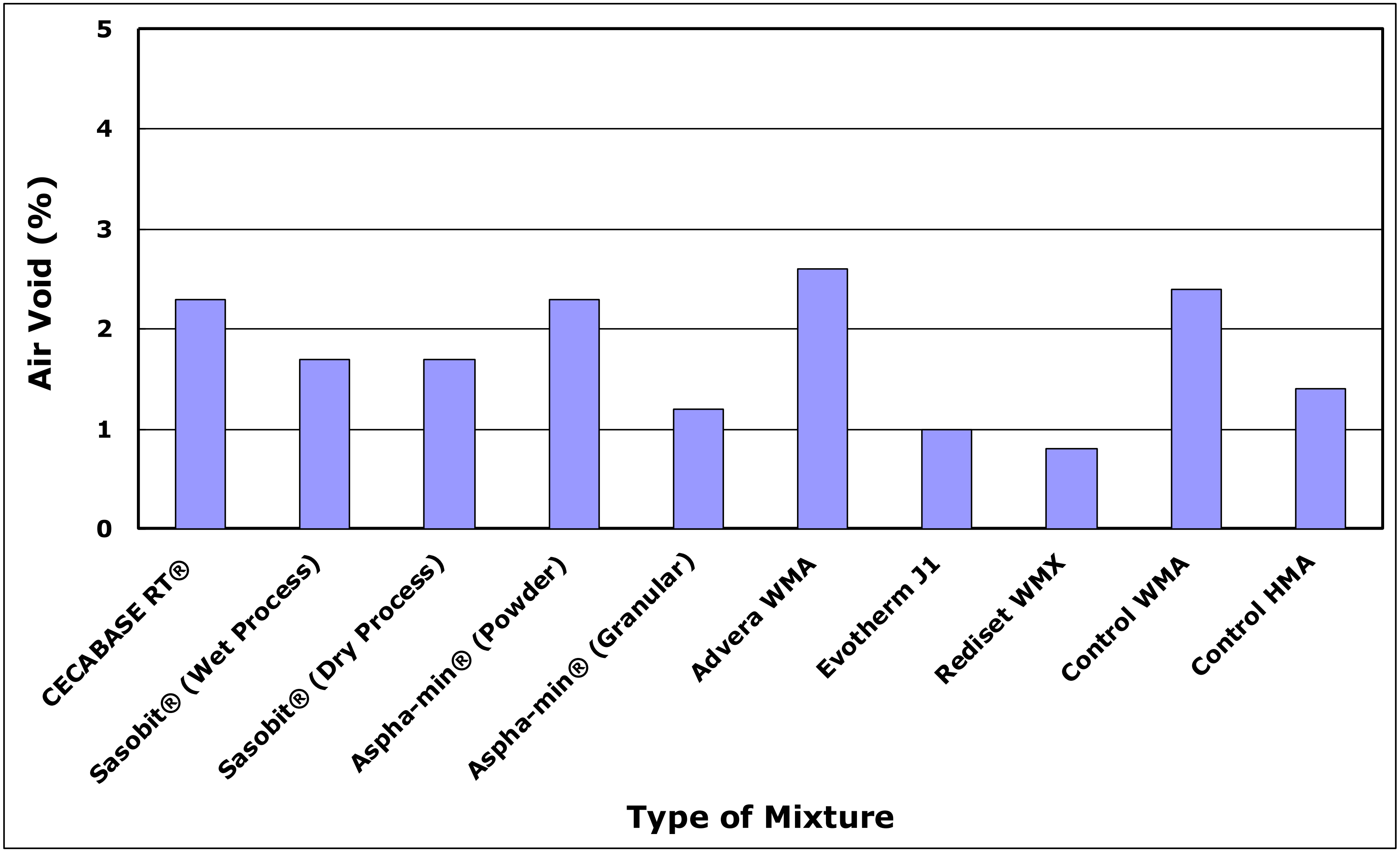

Fig. 5-6 Average Air Voids of WMA and HMA Mixtures Prepared for Indirect Tensile Strength Test

Table 5-5 Indirect Tensile Strengths of WMA and HMA Mixtures

No. of Specimen		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Indirect Tensile Strength (psi)	# 1	72.1	78.9	57.5	63.5	78.2	63.5	83.1	90.6	81.8	103.6
	# 2	64.1	84.0	54.5	60.2	77.5	74.9	88.7	94.0	73.7	93.3
	# 3	68.6	84.7	61.4	70.3	81.7	75.4	88.1	91.9	82.7	104.7
	Ave.	68.3	82.5	57.8	64.7	79.1	71.3	86.6	92.2	79.4	100.5
	St. Dev	4.0104	3.1660	3.4598	5.1501	2.2502	6.7308	3.0746	1.7156	4.9568	6.2883

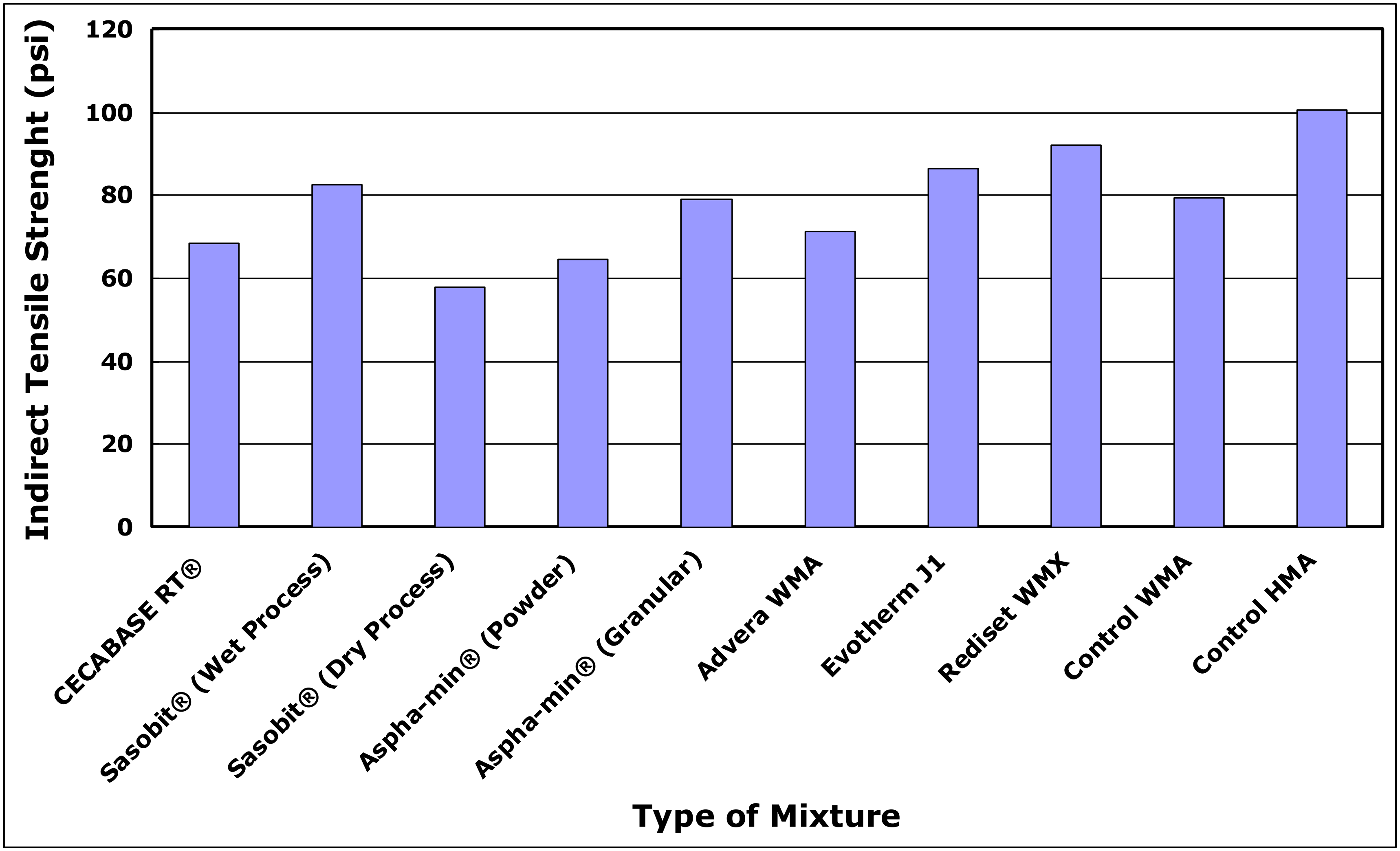

Fig. 5-7 Average Indirect Tensile Strengths of WMA and HMA Mixtures

To determine if there is a correlation between air voids and indirect tensile strengths, as illustrated by table 5-6, specimens were ranked in an increasing order of air voids and in a decreasing order of indirect tensile strength. Overall, HMA mixture and WMA mixtures with chemical additives such as Rediset^{TM} WMX, Evotherm J1 and Sasobit® (wet process) exhibited high indirect tensile strengths along with low air voids. Although Sasobit® mixtures prepared in both dry and wet processes resulted in the same amount of air void, the specimen prepared in the wet process exhibited a higher tensile strength. This result indicates that the indirect tensile strength may not be significantly affected by the air void.

Table 5-6 Ranking of Air Voids and Indirect Tensile Strengths from WMA and HMA Mixtures

Type of Mix	Ranking			
	Air Void (%)	Ranking of Air Void	Indirect Tensile Strength (psi)	Ranking of ITS
CECABASE RT®	2.3%	**7**	68.3psi	**8**
Sasobit® (Wet Process)	1.7%	**5**	82.5psi	**4**
Sasobit® (Dry Process)	1.7%	**5**	57.8psi	**10**
Aspha-min® (Powder)	2.3%	**7**	64.7psi	**9**
Aspha-min® (Granular)	1.2%	**3**	79.1psi	**6**
Advera WMA	2.6%	**10**	71.3psi	**7**
Evotherm J1	1.0%	**2**	86.6psi	**3**
Rediset^{TM} WMX	0.8%	**1**	92.2psi	**2**
Control WMA	2.4%	**9**	79.4psi	**5**
Control HMA	1.4%	**4**	100.5psi	**1**

Chapter 6 Moisture Sensitivity Test

The moisture damage in asphalt mixtures is defined as a loss of strength due to the presence of moisture in terms of a tensile strength ratio (TSR). It was suspected that WMA mixtures may be more susceptible to moisture damage than HMA mixtures. Hurley and Prowell (2006) evaluated the moisture susceptibility of WMA mixtures containing Aspha-min®, Sasobit®, and Evotherm® and reported that WMA mixtures with Aspha-min® exhibited the lower TSR value than HMA mixtures below the Superpave specification of 80%. Kvasnak et al. (2009) reported that the laboratory-produced WMA mixtures using Evotherm® DAT additive was more moisture susceptible than the plant-produced WMA mixtures. They also reported that the TSR values of WMA mixtures were higher than 80%. Gonzalez-Leon et al (2009) reported that WMA mixtures with Cecabase RT® additive achieved a minimum requirement of 0.75; that is, a ratio of the fracture force of the wet specimen over the dry specimen. Xiao et al. (2009) reported that TSR values of WMA mixtures with Sasobit® and Aspha-min® additives were lower than 85% but increased above 85% when 1.0% or 2.0% hydrated lime was added. To evaluate the moisture sensitivity of WMA mixtures in this study the modified Lottman test was performed following AASHTO T 283 procedure.

6.1 Moisture Sensitivity Testing Procedure

To perform the modified Lottman test, six specimens (three for dry conditions and three for wet conditions) for each of eight WMA mixtures, the control WMA mixture and the control HMA mixture were prepared. To prepare the test specimens with 7 ± 0.5% air void, as summarized in table 6-1, all specimens were compacted at between 6 and 20 gyrations. As shown in figure 6-1, for dry conditioning, three specimens in a sealed pack were placed in the water bath at 25˚C for 2 hours. For wet conditioning, three specimens saturated at between 70% and 80% were placed in a freezer at -18˚C for 16 hours and in water bath at 60˚C for 24 hours followed by conditioning in water bath at 25˚C for 2 hours.

Table 6-1 Number of Gyrations Applied to Produce WMA and HMA Specimens for Moisture Sensitivity Test

Mix Type	Mixing Process	Number of Gyration					
		Dry Condition			Wet Condition		
		#1	#2	#3	#1	#2	#3
CECABASE RT®	Wet Process	17	16	17	15	16	18
Sasobit®	Wet Process	10	9	11	15	9	11
Sasobit®	Dry Process	14	10	11	12	12	12
Aspha-min® (Powder)	Dry Process	21	19	20	18	16	16
Aspha-min® (Granular)	Dry Process	14	15	14	11	12	14
Advera WMA	Dry Process	16	18	17	20	17	16
Evotherm J1	Wet Process	10	11	10	10	6	9
Rediset™ WMX	Wet Process	8	9	11	11	9	12
Control WMA	-	15	18	10	14	16	10
Control HMA	-	14	16	14	15	17	12

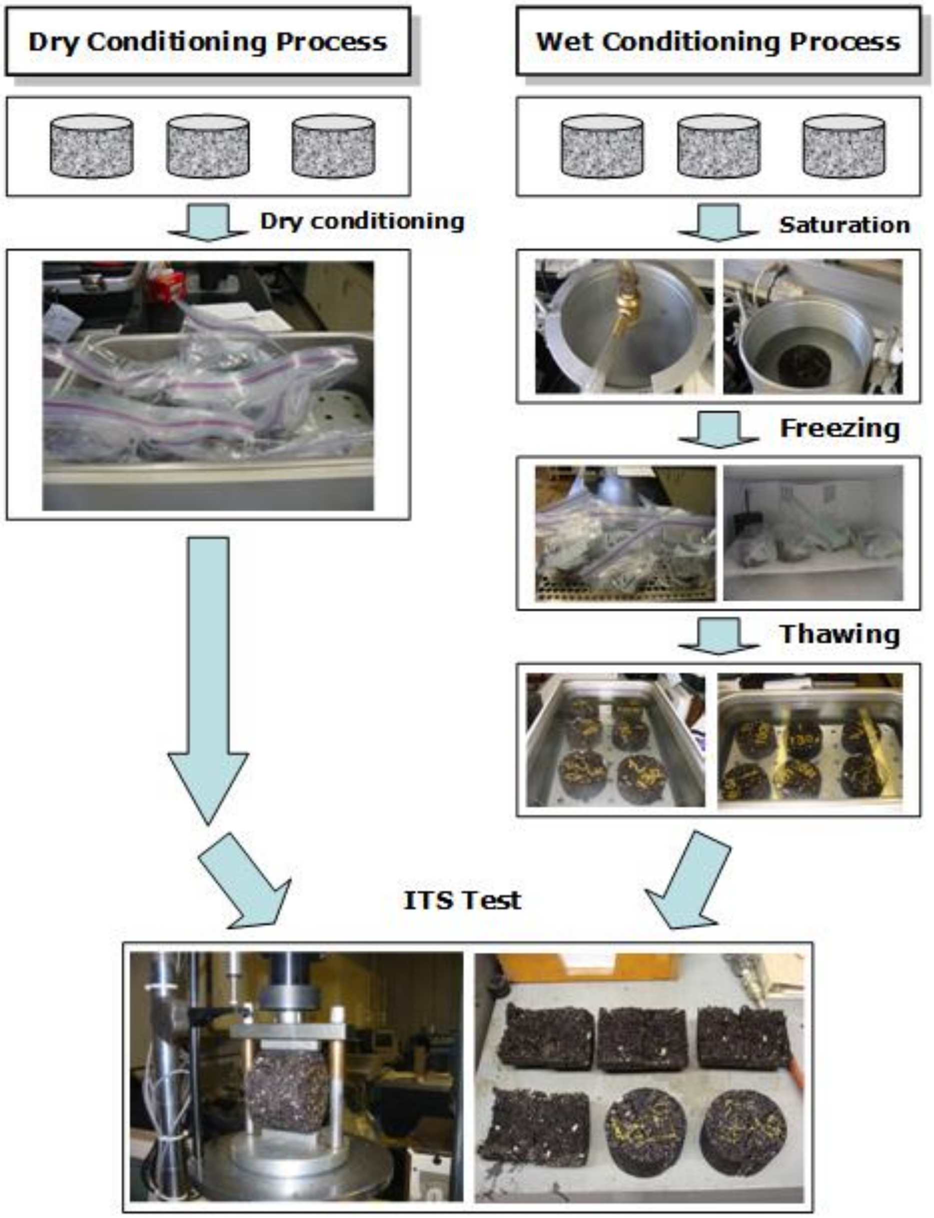

Fig. 6-1 Flow Chart of Moisture Sensitivity Test for WMA and HMA Specimens

6.2 Mixing and Compaction Temperatures

As shown in table 6-2, the temperatures of asphalt, aggregate, mixture, and compacted specimen were recorded throughout the sample preparation process and were plotted in figure 6-2. WMA mixtures were produced at temperatures between 117°C and 121°C whereas the control HMA mixture at 147°C. WMA mixtures were compacted at temperatures between 112˚C and 123°C whereas the control HMA mixture at around 126°C to 135°C.

Table 6-2 Temperature Data of Producing WMA and HMA Mixtures for Moisture Sensitivity Test

Temperature (˚C)		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Asphalt Binder		145	145	145	145	145	145	145	145	145	145
Aggregates		123	125	120	123	123	N/A	125	125	125	160
Mixing		119	121	117	119	120	N/A	119	121	119	147
Before Compaction	#1 (Dry)	114	120	117	113	112	113	116	121	121	131
After Compaction		99	114	99	97	96	99	111	109	116	110
Before Compaction	#2 (Dry)	115	123	119	114	116	117	118	121	121	126
After Compaction		100	109	100	99	100	99	109	105	108	95
Before Compaction	#3 (Dry)	115	120	117	113	113	117	117	121	120	133
After Compaction		97	109	99	97	98	101	104	106	107	108
Before Compaction	#1 (Wet)	115	122	119	114	117	117	114	121	121	135
After Compaction		95	112	107	100	105	100	110	115	115	100
Before Compaction	#2 (Wet)	115	120	118	115	116	114	116	121	123	132

After Compaction		99	107	104	99	102	98	101	116	115	107
Before Compaction	#3 (Wet)	114	122	117	115	117	114	114	121	121	135
After Compaction		96	110	106	99	101	98	101	108	109	115

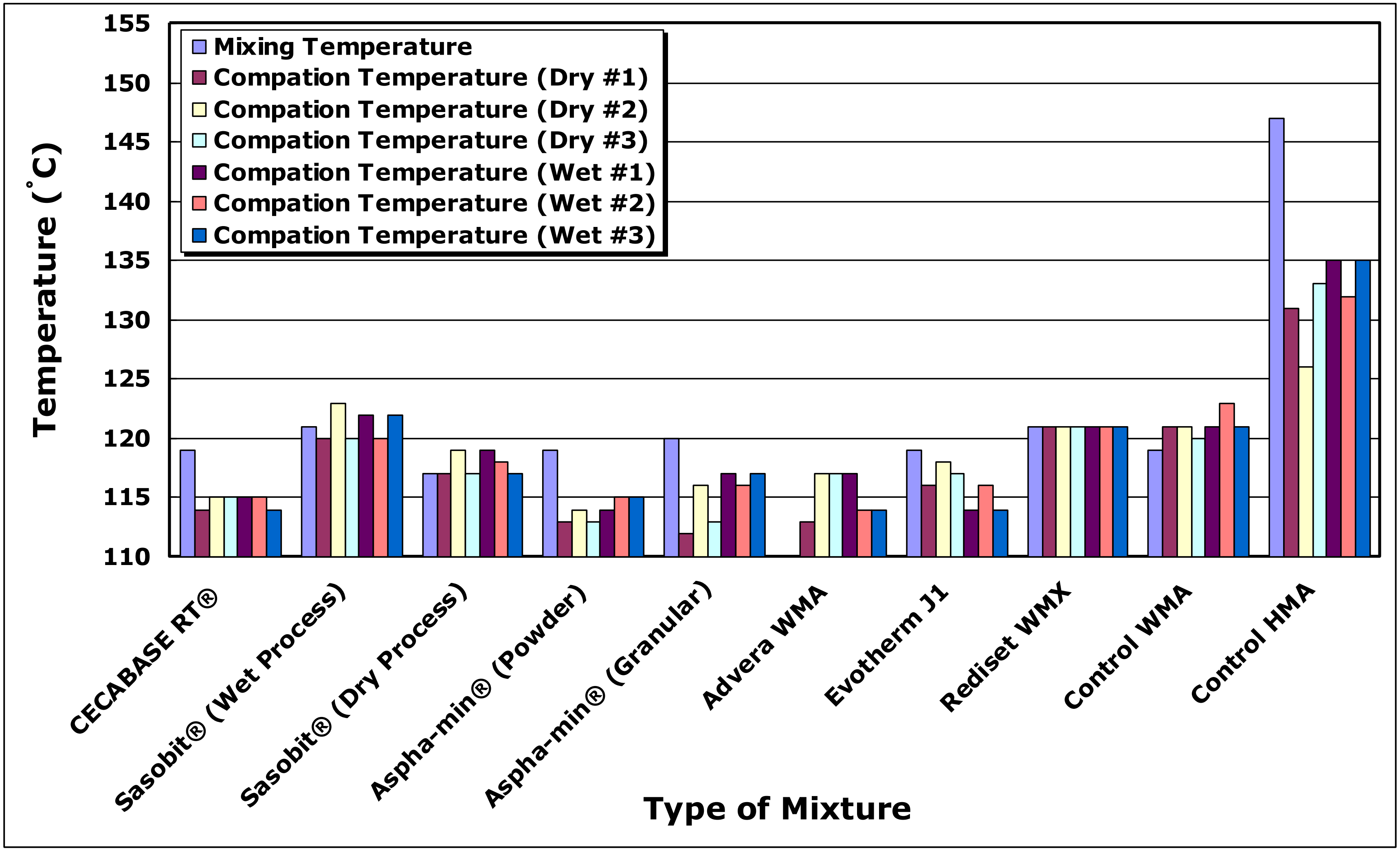

Fig. 6-2 Mixing and Compaction Temperatures of WMA and HMA Mixtures for Moisture Sensitivity Test

6.3 Bulk Specific Gravities and Air Voids of Tensile Strength Ratio Specimens

The bulk specific gravities of each specimen were determined following the AASHTO T 166 (AASHTO 2001). Table 6-3 and table 6-4 summarize the bulk specific gravities and air voids, respectively, of the WMA mixtures and the control HMA mixture that were prepared for indirect tensile strength test. All specimens exhibited air voids ranging between 6.5% and 7.5% (Advera WMA). Figure 6-3 and figure 6-4 show the plots of average bulk specific gravities and air voids of the specimens, respectively.

6.4 Results of Tensile Strength Ratio

The tensile strength ratio (TSR) is defined as a ratio of the indirect tensile strength of a wet specimen over that of a dry specimen as follows:

$$\text{Tensile strength ratio (TSR)} = \frac{ITS_{Wet}}{ITS_{Dry}} \times 100$$

$\mathrm{ITS}_{\mathrm{Wet}}$ = average indirect tensile strength at wet condition

$\mathrm{ITS}_{\mathrm{Dry}}$ = average indirect tensile strength at dry condition

Indirect tensile strengths and TSR values of eight WMA mixtures, the control WMA mixture and the control HMA mixture are summarized in table 6-5 and their average values are plotted in figure 6-5. As can be seen from table 6-5, the indirect tensile strengths of three specimens were very consistent, which indicates that all indirect tensile strength tests were performed accurately. The average TSR values of WMA specimens ranged between 31.9% and 61.5% whereas that of the HMA specimens was 68.0%—all below the Superpave specification of 80%.

As shown in table 6-6 specimens were ranked in a decreasing order of indirect tensile strength in dry condition, indirect tensile strength in wet condition and TSR value. Among WMA specimens, the Evotherm J1 specimen exhibited the highest TSR value whereas the Advera WMA specimen exhibited the lowest value. The TSR value was significantly affected by the tensile strength in a wet condition. For example, the indirect tensile strength of Aspha-min® (Powder) in dry condition was 80.9psi (Ranked #1) but that in wet condition was 28.7psi (Ranked #7), resulting in a TSR of 35.4% (Ranked # 9).

Table 6-3 Bulk Specific Gravities of WMA and HMA Mixtures for Moisture Sensitivity Test

Condition		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Dry	# 1	2.271	2.253	2.266	2.273	2.258	2.264	2.257	2.276	2.270	2.270
	# 2	2.265	2.247	2.269	2.272	2.276	2.281	2.265	2.289	2.273	2.262
	# 3	2.262	2.263	2.268	2.264	2.270	2.280	2.259	2.285	2.280	2.260
	Ave.	2.266	2.254	2.268	2.270	2.268	2.275	2.260	2.283	2.274	2.264
Wet	# 1	2.280	2.261	2.268	2.272	2.268	2.278	2.253	2.273	2.270	2.268
	# 2	2.260	2.248	2.267	2.274	2.274	2.275	2.261	2.279	2.276	2.265
	# 3	2.263	2.261	2.266	2.270	2.276	2.282	2.270	2.288	2.284	2.253
	Ave.	2.268	2.257	2.267	2.272	2.273	2.278	2.261	2.280	2.277	2.262

Table 6-4 Air Voids of WMA and HMA Mixtures for Moisture Sensitivity Test

Condition		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Dry	# 1	6.9%	6.9%	6.6%	6.6%	7.2%	7.5%	7.1%	7.0%	7.2%	6.7%
	# 2	7.1%	7.1%	6.6%	6.6%	6.5%	6.8%	6.8%	6.5%	7.1%	7.0%
	# 3	7.2%	6.5%	6.5%	7.0%	6.7%	6.8%	7.0%	6.6%	6.8%	7.1%
	Ave.	7.1%	6.8%	6.6%	6.7%	6.8%	7.0%	7.0%	6.7%	7.0%	6.9%
Wet	# 1	6.5%	6.6%	6.5%	6.7%	6.8%	6.9%	7.3%	7.1%	7.2%	6.7%
	# 2	7.3%	7.1%	6.6%	6.6%	6.5%	7.0%	7.0%	6.9%	7.0%	6.9%
	# 3	7.2%	6.6%	6.6%	6.7%	6.5%	6.7%	6.6%	6.5%	6.7%	7.4%
	Ave.	7.0%	6.8%	6.6%	6.7%	6.6%	6.9%	7.0%	6.8%	7.0%	7.0%

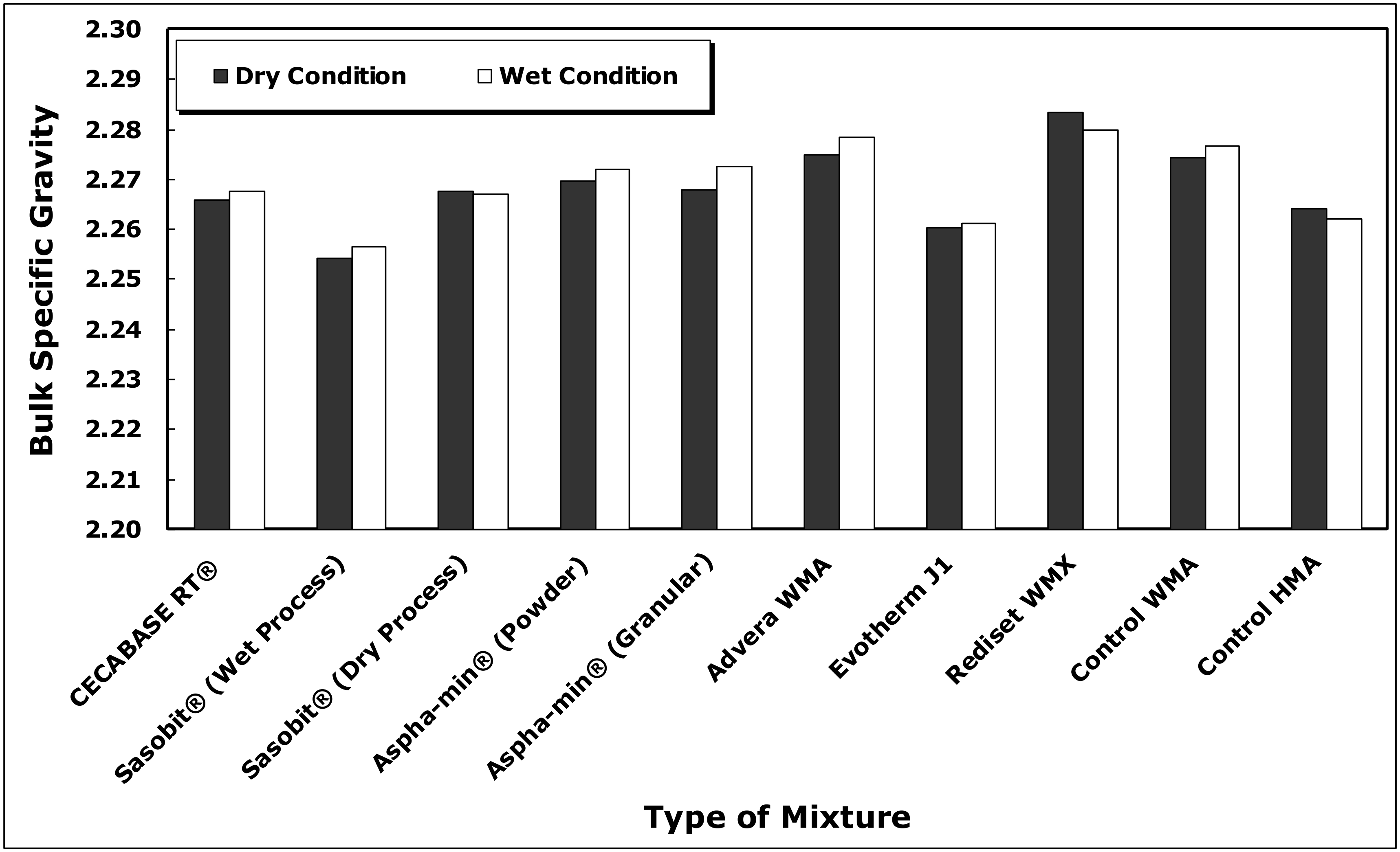

Fig. 6-3 Average Bulk Specific Gravities of WMA and HMA Mixtures for Moisture Sensitivity Test

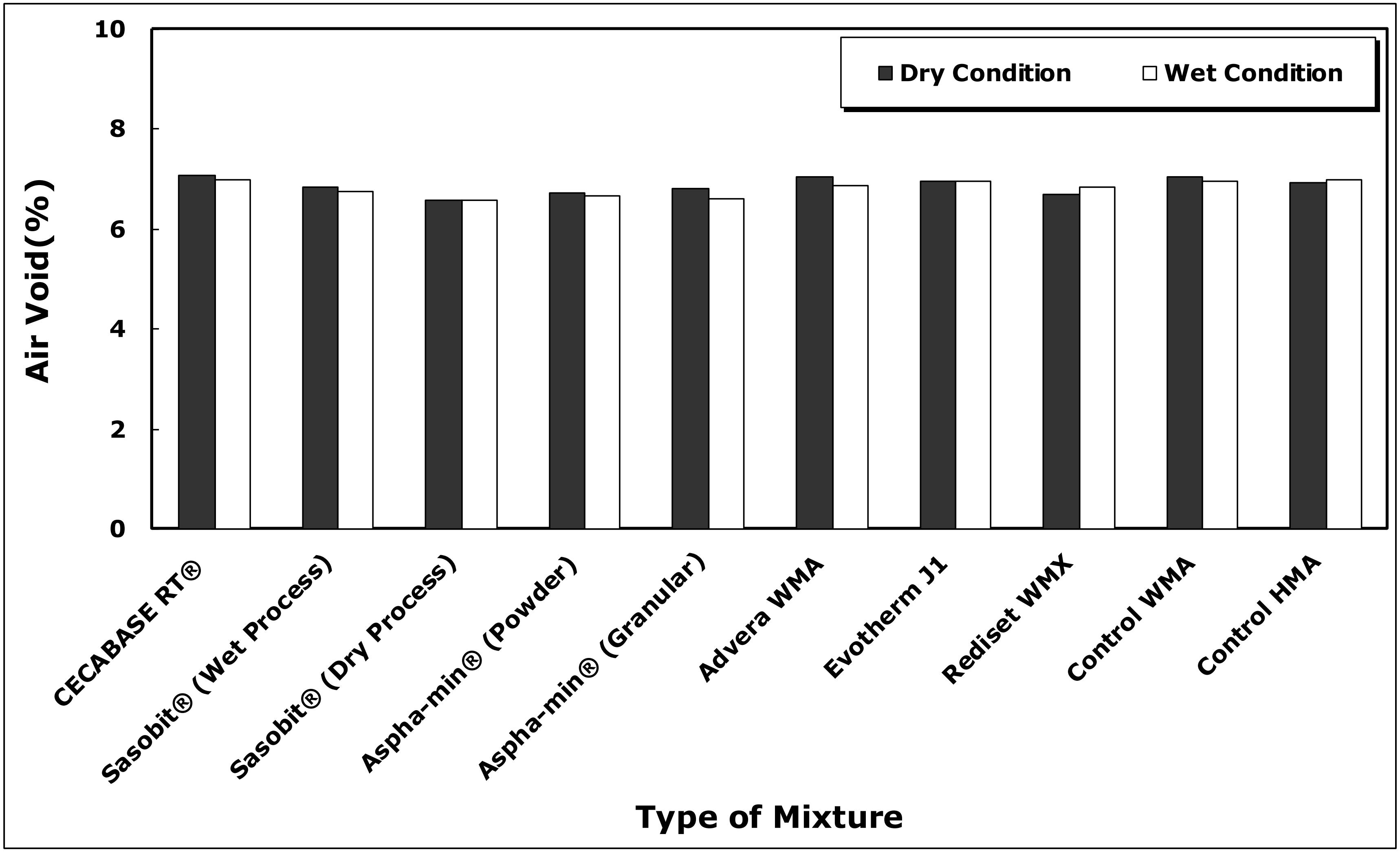

Fig. 6-4 Average Air Voids of WMA and HMA mixtures for Moisture Sensitivity Test

Table 6-5 Indirect Tensile Strengths at Dry and Wet Conditions and Tensile Strength Ratio of WMA and HMA Mixtures

Condition		Type of Mixture									
		CECABASE RT®	Sasobit® (Wet Process)	Sasobit® (Dry Process)	Aspha-min® (Powder)	Aspha-min® (Granular)	Advera WMA	Evotherm J1	Rediset™ WMX	Control WMA	Control HMA
Dry Condition	# 1	76.7psi	66.2psi	75.1psi	77.6psi	65.3psi	73.6psi	50.1psi	78.6psi	71.7psi	76.7psi
	# 2	70.7psi	59.2psi	76.6psi	84.4psi	62.5psi	79.4psi	52.7psi	74.0psi	81.3psi	78.9psi
	# 3	72.5psi	67.2psi	74.8psi	80.7psi	66.6psi	75.0psi	55.7psi	74.0psi	76.9psi	83.9psi
	Ave.	73.3psi	64.2psi	75.5psi	80.9psi	64.8psi	76.0psi	52.8psi	75.5psi	76.6psi	79.8psi
Wet Condition	# 1	35.5psi	26.4psi	37.6psi	28.0psi	19.8psi	23.4psi	32.1psi	43.6psi	27.9psi	50.4psi
	# 2	35.6psi	25.2psi	39.1psi	30.2psi	27.4psi	25.9psi	32.4psi	41.1psi	28.3psi	56.2psi
	# 3	35.7psi	28.1psi	37.6psi	27.8psi	26.2psi	23.4psi	32.9psi	45.9psi	31.6psi	56.2psi
	Ave.	35.6psi	26.6psi	38.1psi	28.7psi	24.5psi	24.2psi	32.5psi	43.5psi	29.3psi	54.3psi
Tensile Strength Ratio (%)		48.6%	41.4%	50.5%	35.4%	37.8%	31.9%	61.5%	57.6%	38.2%	68.0%

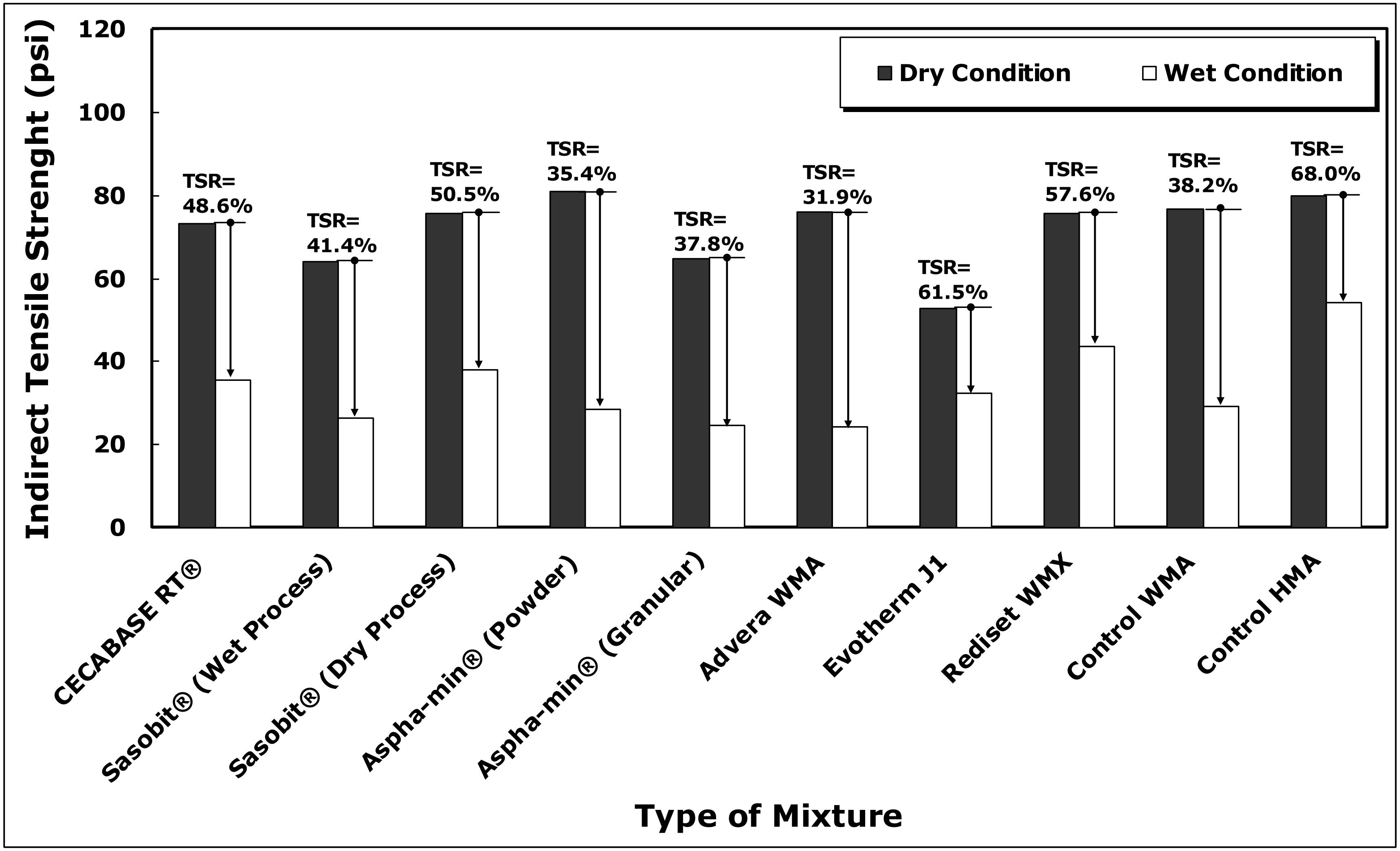

Fig. 6-5 Average Indirect Tensile Strength at Dry and Wet Conditions and Tensile Strength Ratio of WMA and HMA Mixtures

Table 6-6 Ranking of Average Indirect Tensile Strengths at Dry and Wet Conditions and TSR from Eight WMA Mixtures along with a Control WMA and HMA Mixture

Type of Mix	Ranking					
	ITS at Dry Condition	Ranking of ITS at Dry Condition	ITS at Wet Condition	Ranking of ITS at Dry Condition	Tensile Strength Ratio	Ranking of TSR
CECABASE RT®	73.3psi	**7**	35.6psi	**4**	48.6%	**5**
Sasobit® (Wet Process)	64.2psi	**9**	26.6psi	**8**	41.4%	**6**
Sasobit® (Dry Process)	75.5psi	**3**	38.1psi	**3**	50.5%	**4**
Aspha-min® (Powder)	80.9psi	**1**	28.7psi	**7**	35.4%	**9**
Aspha-min® (Granular)	64.8psi	**8**	24.5psi	**9**	37.8%	**8**
Advera WMA	76.0psi	**6**	24.2psi	**10**	31.9%	**10**
Evotherm J1	52.8psi	**10**	32.5psi	**5**	61.5%	**2**
Rediset^{TM} WMX	75.5psi	**3**	43.5psi	**2**	57.6%	**3**
Control WMA	76.6psi	**5**	29.3psi	**6**	38.2%	**7**
Control HMA	79.8psi	**2**	68.0psi	**1**	68.0%	**1**

Chapter 7 Dynamic Modulus Test

The dynamic modulus test has been used for characterizing the visco-elastic response of the HMA mixtures under different loading and temperature conditions. The dynamic modulus of HMA mixtures is altered by a combined effect of asphalt binder stiffness and aggregate size distribution (Clyne et al. 2003; Ekingen 2004; Brown et al. 2004; Birgisson et al. 2004; Lundy et al. 2005). In this study, dynamic modulus of WMA mixtures are measured and compared against HMA mixtures.

7.1 Theory

The fundamental concept behind the dynamic modulus test is a linear visco-elasticity of asphalt mixtures. The stress-to-strain relationship under a continuous sinusoidal loading for linear visco-elastic materials is defined by a dynamic modulus. The dynamic modulus is mathematically defined as the maximum dynamic stress (σ_0) divided by peak recoverable axial strain (ε_0) as follows:

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0}.$$

The measured dynamic modulus at different temperatures can be then shifted relative to the frequency so that several curves can be aligned to form a single master curve. In constructing the master curve, as shown in figure 7-1, the measured dynamic moduli at test temperatures higher than the reference temperature are horizontally shifted to lower frequencies and those measured at test temperatures lower than the reference temperature are shifted to the higher frequencies. A master curve can be constructed based on the time-temperature correspondence principle, which utilizes the equivalency between frequency and temperature. The master curve allows various asphalt mixtures to be compared over extended ranges of frequencies and temperature.

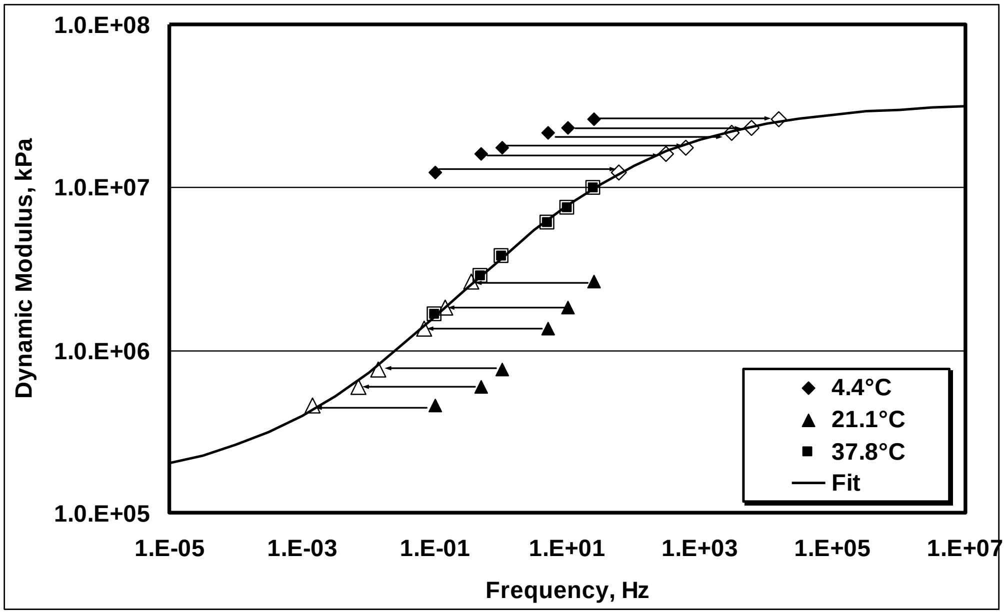

Fig. 7-1 Construction of Master Curve

<u>7.2 Dynamic Modulus Testing Procedure</u>

Witczak et al. (2002) and Bonaquist et al. (2003) described the Superpave simple performance test (SPT) equipment, which can perform dynamic modulus, static creep and repeated load tests at various loading and temperature conditions. As shown in figure 7-2, a test specimen can be accessed from all sides; a magnetic mounted extensometer can be installed on the test specimen with a minimum disruption to the environmental chamber which can provide a testing temperature between 4˚C and 60˚C.

To determine the dynamic modulus of different types of warm mix asphalt (WMA) mixtures, summarized in table 7-1, eight WMA mixtures, a control WMA mixture and a control HMA mixture were produced in the laboratory. Two test specimens with 100-mm diameter and 150-mm height for each were prepared by gyratory compactor at 86 gyrations. After curing one day at room temperature the bulk specific gravity of the compacted specimens were measured. The following day, the dynamic modulus test was performed at three temperatures—4.4°C, 21.1°C, and 37.8°C—and six frequencies: 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, and 0.1Hz (ASSHTO 2007). To minimize potential damage to the specimens, testing began at the lowest temperature and increased incrementally to a higher temperature. For a given temperature, the testing began with the highest frequency of loading and proceeded to a lower frequency.

Fig. 7-2 Simple Performance Testing (SPT) Equipment

Table 7-1 List of WMA and HMA Mixtures for Dynamic Modulus Test

Mix Type	Mixing Process Method	Number of Specimen
CECABASE RT®	Wet Process	2 specimens
Sasobit®	Wet Process	2 specimens
Sasobit®	Dry Process	2 specimens
Aspha-min® (Granular)	Dry Process	2 specimens
Advera WMA	Dry Process	2 specimens
Evotherm J1	Wet Process	2 specimens
Rediset$^{\mathrm{TM}}$ WMX	Dry Process	2 specimens
Control WMA	-	2 specimens
Control HMA	-	2 specimens

As shown in figure 7-3, two linear variable displacement transducers (LVDT's) were adjusted to the end of its linear range to allow a full range to be available for the accumulation of compressive permanent deformation. A minimum contact load equal to 5.0% of the dynamic load was applied to the specimen. A sinusoidal axial compressive load was applied to the testing specimen while maintaining the axial strain at 100 microstrain. The test results during the last ten cycles were recorded for each frequency.

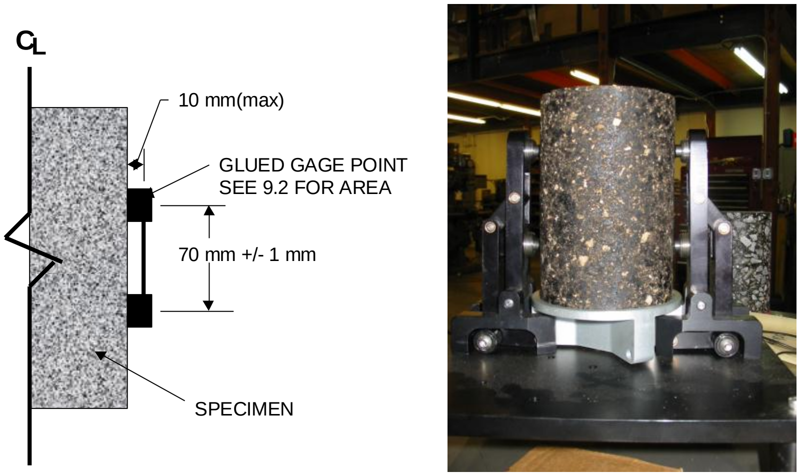

Fig. 7-3 Glued Magnetic Gauge Points Placed on Both Sides SPT Specimen

7.3 Bulk Specific Gravities and Air Voids of Dynamic Modulus Test Specimens

The bulk specific gravities of each specimen were determined following the AASHTO T 166 (AASHTO 2001). Table 7-2 summarizes the bulk specific gravities and air voids of seven WMA mixtures and the control HMA mixture that were prepared for the dynamic modulus test. Given the same compaction level of 68 gyrations, the bulk specific gravities of WMA specimens ranged between 2.361 and 2.401 and the control HMA specimens ranged between 2.384 and 2.490. All specimens exhibited a relatively small amount of air voids ranging between 0.9% (Sasobit®) and 3.5% (Aspha-min®-granular).

Figure 7-4 and figure 7-5 show plots of average bulk specific gravities and air voids of the specimens, respectively. As shown in figure 7-5, it should be noted that the average air voids of WMA specimens with any additive were lower than WMA without an additive. Furthermore, the air void of the WMA specimens with Sasobit® was even lower than that of the control HMA specimens. This result indicates all additives, and Sasobit® in particular, are effective in compacting an asphalt mixture at a lower temperature.

Table 7-2 Bulk Specific Gravities and Air Voids of Mixtures for Dynamic Modulus Test

Type of Mix	No. of Specimen	Bulk Specific Gravity		Air Void (%)	
		Individual	Average	Individual	Average
CECABASE RT®	# 1	2.394	2.386	1.6%	1.9%
	# 2	2.378		2.3%	
Sasobit® (Wet Process)	# 1	2.396	2.397	1.0%	1.0%
	# 2	2.398		0.9%	
Sasobit® (Dry Process)	# 1	2.392	2.390	1.4%	1.5%
	# 2	2.388		1.6%	
Aspha-min® (Granular)	# 1	2.361	2.362	3.0%	2.9%
	# 2	2.362		2.9%	
Advera WMA	# 1	2.377	2.386	3.0%	2.6%
	# 2	2.395		2.2%	
Evotherm J1	# 1	2.381	2.381	2.0%	2.0%
	# 2	2.382		2.0%	
Rediset^{TM} WMX	# 1	2.401	2.400	1.9%	1.9%
	# 2	2.400		1.9%	
Control WMA	# 1	2.362	2.369	3.5%	3.2%
	# 2	2.376		2.9%	
Control HMA	# 1	2.390	2.387	1.7%	1.8%
	# 2	2.384		1.9%	

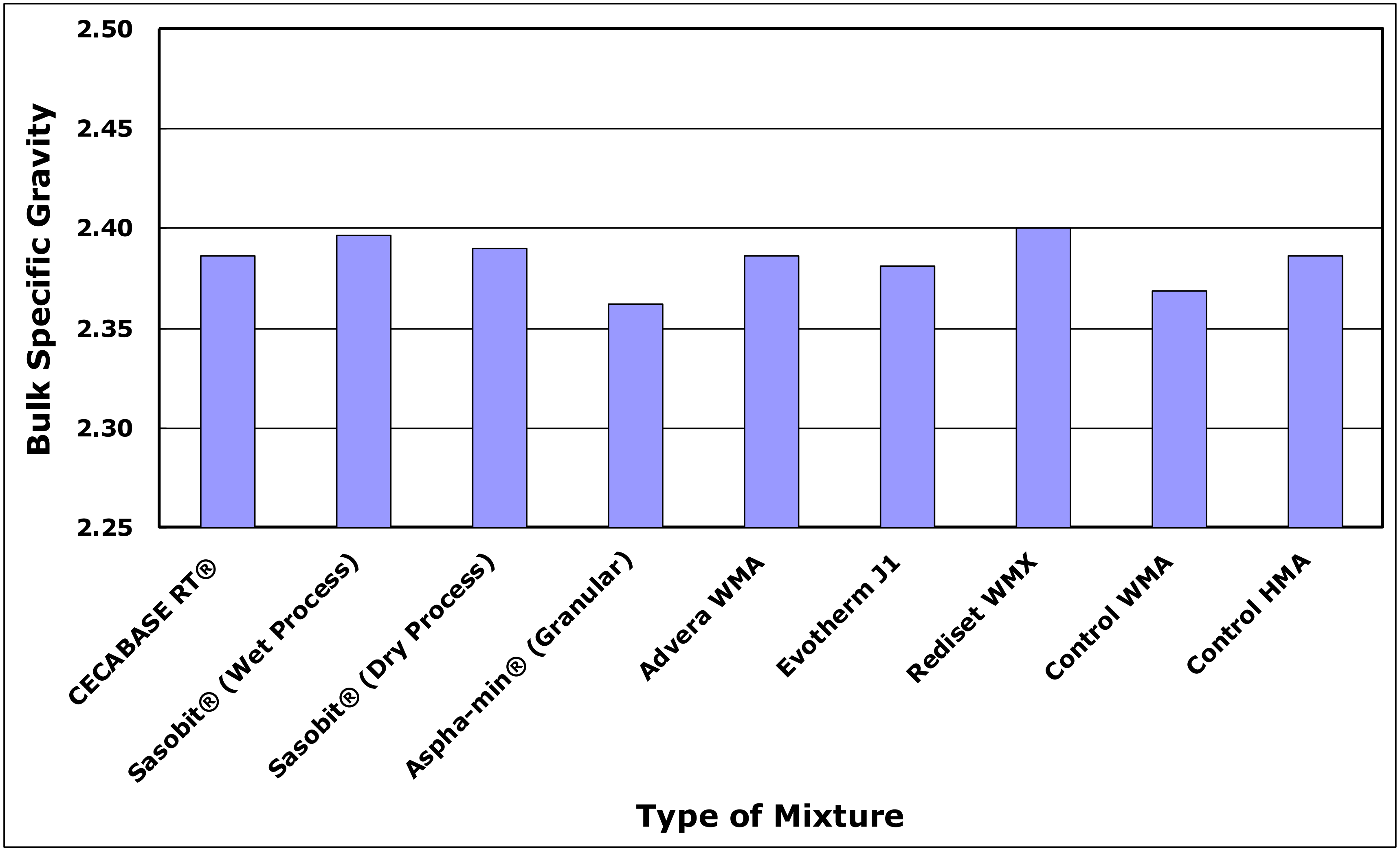

Fig. 7-4 Average Bulk Specific Gravities of WMA and HMA Mixtures for Dynamic Modulus Test

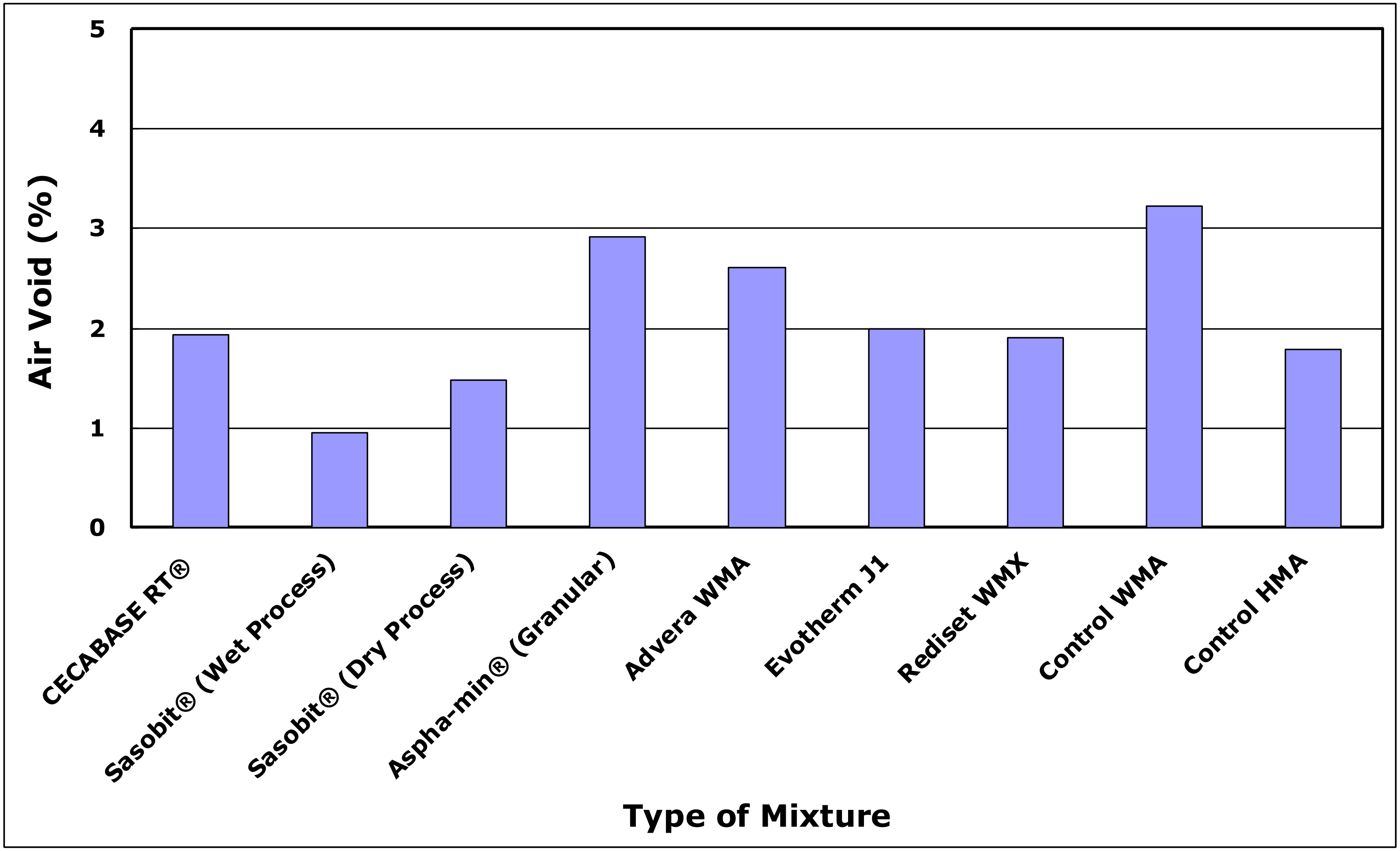

Fig. 7-5 Average Air Voids of WMA and HMA Mixtures for Dynamic Modulus Test

7.4 Dynamic Modulus Test Results

The dynamic modulus test was performed on each specimen twice and the test results are summarized in tables 7-3 to 7-11. The dynamic moduli are plotted against the loading frequency at 4.4°C, 21.1°C, and 37.8°C in figures 7-6, 7-7 and 7-8, respectively. For a given loading frequency, the dynamic modulus decreased as temperature increased. For a given testing temperature, the dynamic modulus increased as the loading frequency increased. As shown in figure 7-6, at 4.4˚C, dynamic moduli of all WMA mixtures were lower than those of the control HMA mixtures, except the WMA mixture with Sasobit® (wet process). As shown in figure 7-7, at 21.1˚C dynamic moduli of WMA mixtures with Sasobit®, Evotherm J1 and Rediset WMA additives were higher than those of the control HMA mixture. WMA mixture with Sosobit® exhibited the highest dynamic modulus whereas the control WMA mixture showed the lowest dynamic modulus. As shown in figure 7-8, at 37.8˚C dynamic moduli of WMA mixtures with Sasobit® and Rediset were higher than those of the control HMA mixture whereas the control WMA mixture exhibited the lowest dynamic modulus.

As shown in table 7-12, specimens were ranked in a decreasing order of dynamic modulus at three different temperatures. Overall, WMA mixtures with Sasobit® ranked the highest followed by the control HMA mixture. The control WMA mixture and WMA mixture with CECABASE RT® ranked the lowest. It is interesting to note that rankings of these specimens changed when the temperature increased from 4.4˚C to 37.8˚C. For example, the control HMA mixture ranked on the top at 4.4˚C but it ranked in the middle at 21.1˚C and 37.8˚C. This indicates that the control HMA mixture lost its modulus value more than WMA mixtures with Sasobit® or Rediset WMX.

Table 7-3 Summary of Dynamic Moduli for WMA Mixture with CECABASE RT®

Dynamic Modulus (kPa)									
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	13,163,000	11,744,390	12,453,695	4,561,584	5,483,318	5,022,451	1,419,569	2,080,682	1,750,125
10	11,433,060	10,018,548	10,725,804	3,089,922	4,012,752	3,551,337	1,108,792	1,707,013	1,407,902
5	9,957,143	8,627,845	9,292,494	2,372,867	3,181,358	2,777,113	846,761	1,378,869	1,112,815
1	6,695,958	5,585,455	6,140,706	1,197,508	1,726,182	1,461,845	456,214	773,136	614,675
0.5	5,443,361	4,482,912	4,963,136	929,387	1,380,091	1,154,739	395,377	654,264	524,820
0.1	3,434,647	2,828,505	3,131,576	614,368	956,285	785,327	306,754	517,719	412,237

Table 7-4 Summary of Dynamic Moduli for WMA Mixture with Sasobit® by Wet Process

Dynamic Modulus (kPa)									
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	14,610,195	16,082,360	15,346,278	6,614,129	7,508,094	7,061,112	3,102,539	3,002,977	3,052,758
10	13,141,375	14,123,755	13,632,565	4,942,118	5,412,885	5,177,501	2,187,093	2,124,360	2,155,726
5	11,655,825	12,549,205	12,102,515	3,964,157	4,324,049	4,144,103	1,805,960	1,743,200	1,774,580
1	8,327,230	9,003,714	8,665,472	2,261,203	2,478,344	2,369,773	901,049	910,222	905,636
0.5	7,019,287	7,636,090	7,327,689	1,797,126	1,970,822	1,883,974	762,675	769,320	765,998
0.1	4,747,255	5,210,037	4,978,646	1,174,539	1,281,263	1,227,901	600,159	612,614	606,386

Table 7-5 Summary of Dynamic Moduli for WMA Mixture with Sasobit® by Dry Process

	Dynamic Modulus (kPa)								
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	14,477,160	14,132,605	14,304,883	7,073,870	6,935,236	7,004,553	2,044,997	2,048,747	2,049,515
10	13,002,750	11,830,315	12,416,533	5,396,640	5,250,289	5,323,464	1,545,057	1,627,641	1,586,349
5	11,553,460	10,423,660	10,988,560	4,276,883	4,161,447	4,219,165	1,291,283	1,303,265	1,291,625
1	8,300,542	7,197,575	7,749,059	2,383,817	2,292,179	2,337,998	740,470	716,204	720,221
0.5	6,988,818	5,952,270	6,470,544	1,819,016	1,753,443	1,786,229	627,946	602,731	607,242
0.1	4,632,853	4,001,409	4,317,131	1,130,472	1,092,047	1,111,259	504,795	476,541	481,084

Table 7-6 Summary of Dynamic Moduli for WMA Mixture with Aspha-min® (Granular)

	Dynamic Modulus (kPa)								
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	13,083,975	13,203,355	13,143,665	5,440,649	4,683,005	5,061,827	1,824,996	1,759,201	1,792,098
10	11,652,475	11,464,505	11,558,490	3,914,309	3,369,312	3,641,810	1,420,746	1,357,569	1,389,157
5	10,172,980	9,954,390	10,063,685	3,067,077	2,629,732	2,848,404	1,035,363	996,424	1,015,893
1	6,893,706	6,599,009	6,746,358	1,575,343	1,356,324	1,465,833	564,679	550,532	557,606
0.5	5,604,924	5,341,708	5,473,316	1,234,497	1,079,800	1,157,149	475,731	468,407	472,069
0.1	3,521,043	3,325,664	3,423,353	823,606	730,072	776,839	371,624	368,185	369,905

Table 7-7 Summary of Dynamic Moduli for WMA Mixture with Advera WMA

Dynamic Modulus (kPa)									
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	12,370,385	15,570,245	13,970,315	5,774,014	5,192,464	5,483,239	2,366,577	2,637,570	2,502,073
10	10,813,250	13,493,710	12,153,480	5,087,001	3,693,949	4,390,475	1,721,216	1,405,944	1,563,580
5	9,414,733	11,766,320	10,590,526	3,078,398	2,886,432	2,982,415	1,204,595	1,301,923	1,253,259
1	6,256,735	7,984,769	7,120,752	1,572,178	1,505,980	1,539,079	531,285	578,541	554,913
0.5	5,068,058	6,486,495	5,777,276	1,216,022	1,185,435	1,200,729	465,174	389,602	427,388
0.1	3,183,080	4,010,710	3,596,895	792,172	808,289	800,231	265,314	266,158	265,736

Table 7-8 Summary of Dynamic Moduli for WMA Mixture with Evotherm J1

Dynamic Modulus (kPa)									
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	11,053,550	13,685,675	12,369,613	5,515,235	5,901,896	5,708,566	1,557,235	1,789,178	1,673,206
10	9,417,899	12,134,755	10,776,327	3,995,530	4,328,895	4,162,212	1,238,888	1,410,841	1,324,864
5	8,389,245	10,678,900	9,534,072	3,078,568	3,393,454	3,236,011	975,566	1,192,722	1,084,144
1	5,270,760	7,395,940	6,333,350	1,574,009	1,841,179	1,707,594	534,415	691,484	612,949
0.5	4,258,333	6,105,881	5,182,107	1,201,235	1,438,065	1,319,650	459,062	598,567	528,815
0.1	2,745,556	3,968,021	3,356,789	768,675	967,511	868,093	371,626	499,124	435,375

Table 7-9 Summary of Dynamic Moduli for WMA Mixture with Rediset^{TM} WMX

	Dynamic Modulus (kPa)								
Temp.	4.4°C			21.1°C			37.8°C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	15,155,685	13,759,225	14,457,455	6,620,303	6,005,401	6,312,852	2,285,236	2,330,710	2,307,973
10	13,340,645	12,246,470	12,793,558	4,729,714	4,325,040	4,527,377	1,565,510	1,563,246	1,564,378
5	11,795,760	10,749,280	11,272,520	3,686,099	3,353,459	3,519,779	1,275,022	1,288,979	1,282,000
1	8,317,499	7,532,321	7,924,910	1,961,845	1,779,389	1,870,617	718,173	622,728	670,451
0.5	6,952,018	6,252,777	6,602,398	1,535,768	1,331,898	1,433,833	613,433	532,347	572,890
0.1	4,540,099	4,071,565	4,305,832	971,678	857,667	914,672	501,619	438,737	470,178

Table 7-10 Summary of Dynamic Moduli for Control WMA mixture

	Dynamic Modulus (kPa)								
Temp.	4.4°C			21.1°C			37.8°C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	12,354,820	14,794,750	13,574,785	4,232,341	5,165,577	4,698,959	1,438,593	1,738,247	1,588,420
10	10,766,095	12,979,490	11,872,793	3,061,699	3,819,982	3,440,840	1,109,378	1,337,843	1,223,610
5	9,408,191	11,450,845	10,429,518	2,389,223	2,984,466	2,686,844	898,970	1,114,606	1,006,788
1	6,376,140	7,889,566	7,132,853	1,225,043	1,572,750	1,398,897	519,539	599,379	559,459
0.5	5,160,398	6,535,318	5,847,858	976,317	1,240,660	1,108,488	454,951	518,850	486,901
0.1	3,220,682	4,162,723	3,691,702	681,655	842,356	762,006	373,579	416,630	395,105

Table 7-11 Summary of Dynamic Moduli for Control HMA Mixture

	Dynamic Modulus (kPa)								
Temp.	4.4˚C			21.1˚C			37.8˚C		
Freq. (Hz)	# 1	# 2	Ave.	# 1	# 2	Ave.	# 1	# 2	Ave.
25	15,424,690	16,382,205	15,903,448	5,314,758	5,502,553	5,408,656	1,842,607	1,873,402	1,858,005
10	13,613,645	14,592,905	14,103,275	3,826,413	4,024,350	3,925,382	1,458,556	1,476,754	1,467,655
5	12,001,910	12,831,175	12,416,543	3,014,139	3,178,365	3,096,252	1,208,758	1,221,236	1,214,997
1	8,397,271	9,067,886	8,732,578	1,658,554	1,756,996	1,707,775	645,490	660,123	652,807
0.5	6,973,737	7,577,136	7,275,436	1,330,788	1,392,584	1,361,686	547,026	562,319	554,673
0.1	4,489,921	4,935,442	4,712,682	915,700	960,187	937,944	437,043	447,112	442,078

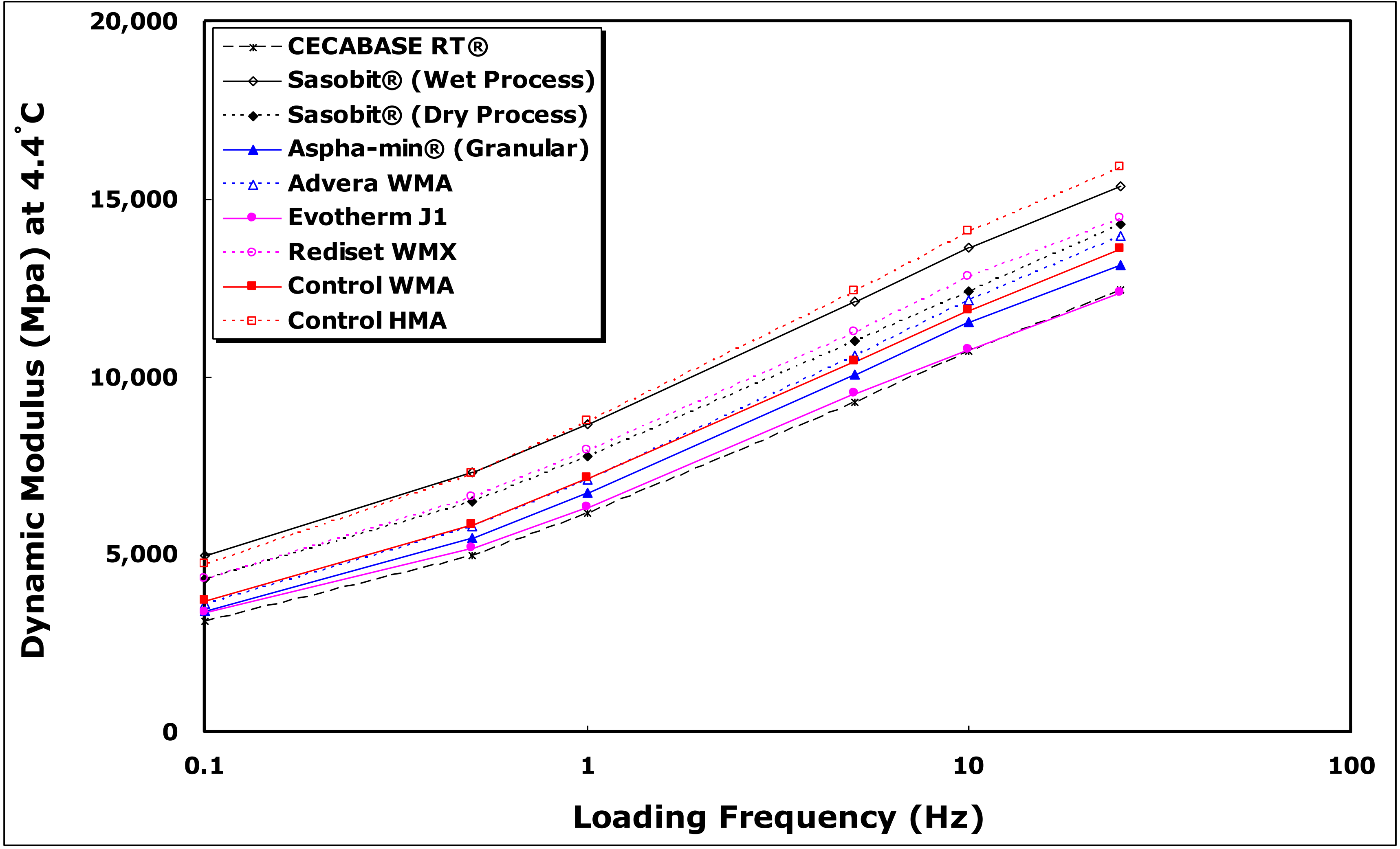

Fig. 7-6 Average Dynamic Moduli Measured at 4.4˚C against Loading Frequency for WMA and HMA Mixtures

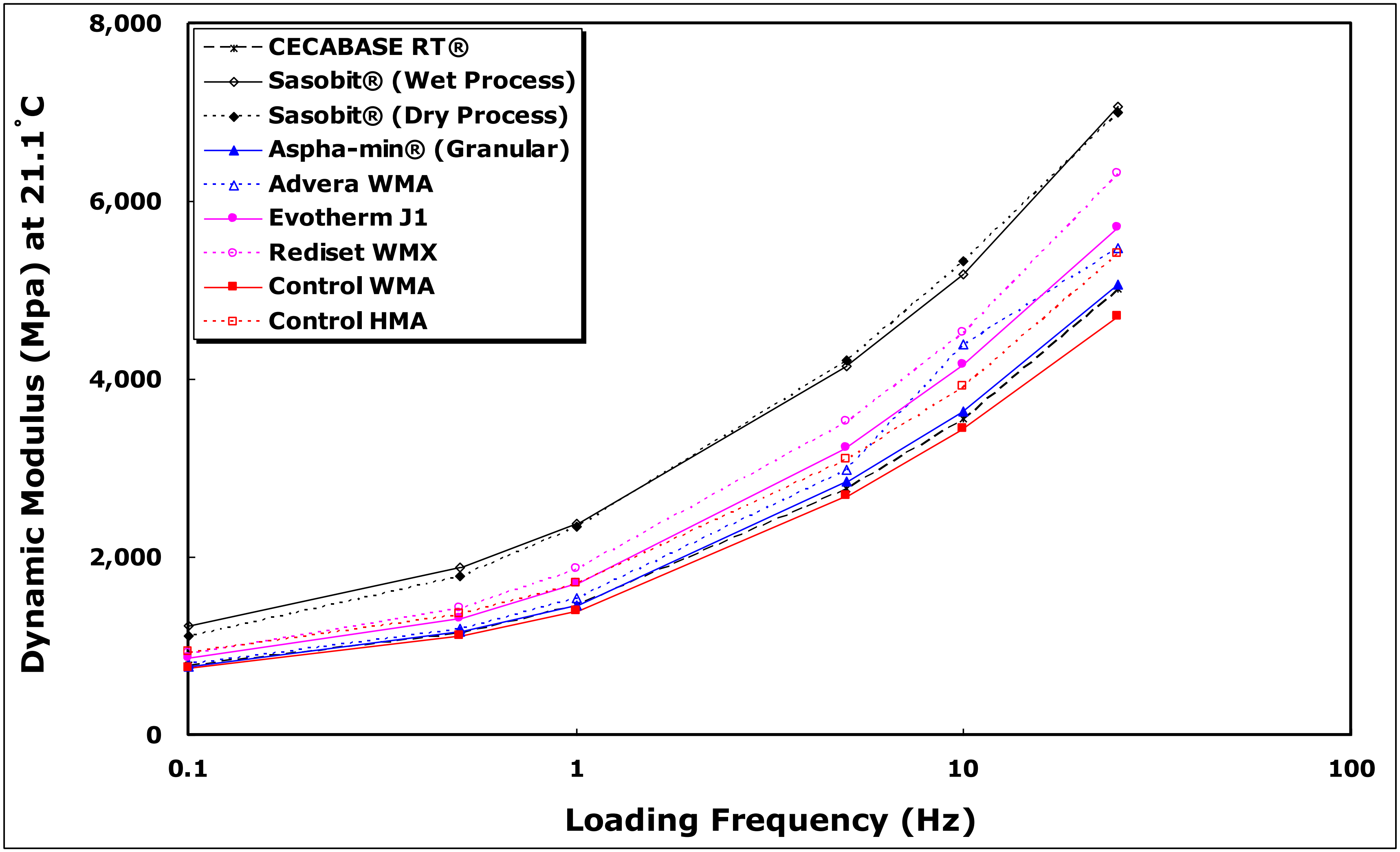

Fig. 7-7 Average Dynamic Moduli Measured at 21.1˚C against Loading Frequency for WMA and HMA Mixtures

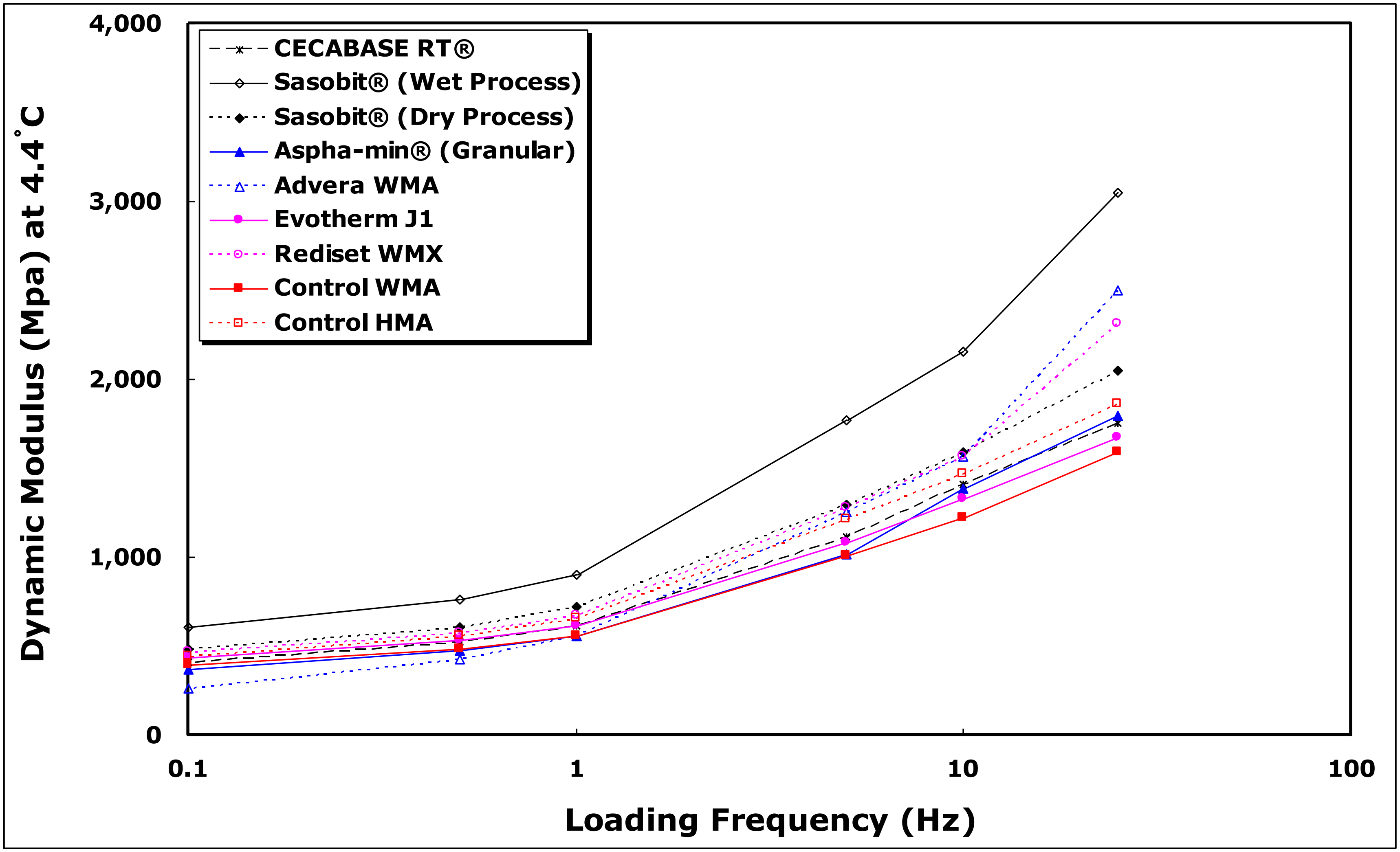

Fig. 7-8 Average Dynamic Moduli Measured at 37.8˚C against Loading Frequency for WMA and HMA Mixtures

Table 7-12 Rankings of Dynamic Modulus Three Different Testing Temperatures for WMA and HMA Mixtures

	Rankings of Dynamic Modulus																						
Temp.	4.4˚C							21.1˚C							37.8˚C							Total Ave.	Overall Rank.
Freq.	25	10	5	1	0.5	0.1	Rank	25	10	5	1	0.5	0.1	Rank	25	10	5	1	0.5	0.1	Rank		
CECABASE RT®	8	9	9	9	9	9	**9**	8	8	8	8	8	7	**8**	7	6	6	5	9	6	**6**	7.7	**9**
Sasobit® (Wet Process)	2	2	2	2	1	1	**2**	1	1	2	1	1	1	**1**	1	1	2	1	1	1	**1**	1.3	**1**
Sasobit® (Dry Process)	4	4	4	4	4	3	**4**	2	2	1	2	2	2	**2**	4	4	1	2	2	2	**3**	2.7	**2**
Aspha-min® (Granular)	7	7	7	7	7	7	**7**	7	7	7	7	7	8	**7**	6	7	8	8	8	7	**7**	7.1	**7**
Advera WMA	5	5	5	6	6	6	**5**	5	4	6	6	6	6	**6**	2	3	4	9	7	9	**4**	5.5	**5**
Evotherm J1	9	8	8	8	8	8	**8**	4	5	4	5	4	5	**4**	8	8	7	6	5	5	**8**	6.4	**6**

Rediset ™ WMX	3	3	3	3	3	4	**3**	3	3	3	3	3	4	**3**	3	2	3	3	3	3	**2**	3.1	**3**
Control WMA	6	6	6	5	5	5	**5**	9	9	9	9	9	9	**9**	9	9	9	7	6	8	**9**	7.5	**8**
Control HMA	1	1	1	1	2	2	**1**	6	6	5	4	5	3	**5**	5	5	5	4	4	4	**5**	3.6	**4**

7.5 Master Curve

By shifting dynamic modulus test results to a reference temperature of 21.1˚C a master curve was constructed for each of seven WMA mixtures, the control WMA mixture and the control HMA mixture. As shown in table 7-13, all model and empirical parameters of the WLF equation were obtained by minimizing the sum of the square of the error of the Sigmoidal model using the Excel's optimization solver function.

Figure 7-9 shows a master curves constructed for each of seven WMA mixtures, the control WMA mixture and the control HMA mixture. Master curves of all WMA mixtures, except the WMA mixture with Advera, are quite similar to the control HMA mixture, which confirms that their viscoelastic responses are similar to that of HMA mixture. Figure 7-10 shows plots of shift factors against temperatures at each of seven WMA mixtures, the control WMA mixture and the control HMA mixture.

Table 7-13 Model Parameters of Constructed Master Curves

Type of Mix	Parameter			
	α	β	δ	γ
CECABASE RT®	1.941	0.301	5.363	0.754
Sasobit® (Wet Proess)	1.888	0.003	5.446	0.742
Sasobit® (Dry Process)	1.971	-0.106	5.343	0.739
Aspha-min® (Granular)	2.049	0.206	5.272	0.737
Advera WMA	2.744	-0.278	4.672	0.605
Evotherm J1	1.811	0.216	5.442	0.817
Rediset^{TM} WMX	1.842	0.161	5.437	0.843
Control WMA	1.954	0.354	5.363	0.751
Control HMA	2.112	0.217	5.312	0.654

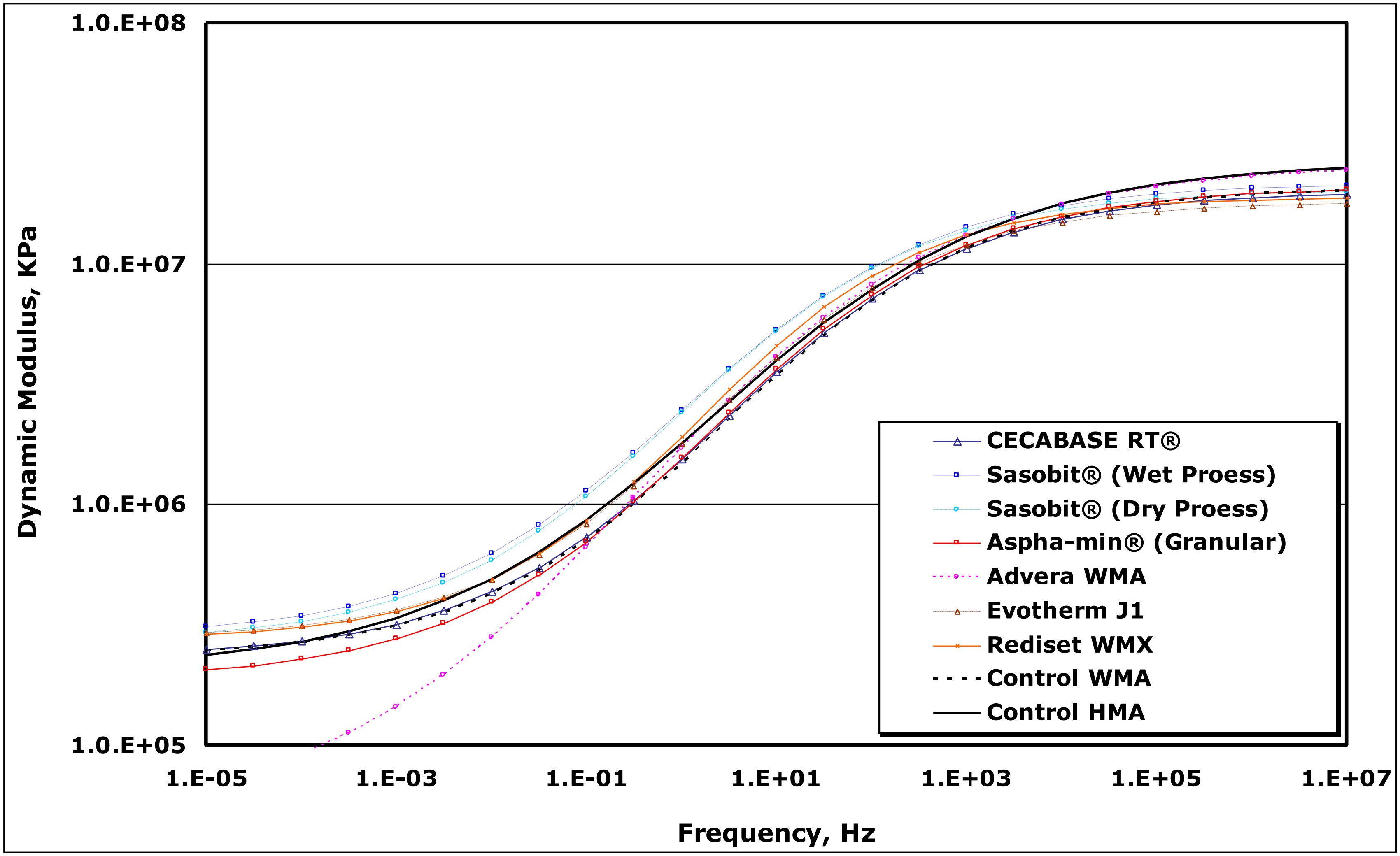

Fig. 7-9 Master Curves of WMA and HMA Mixtures

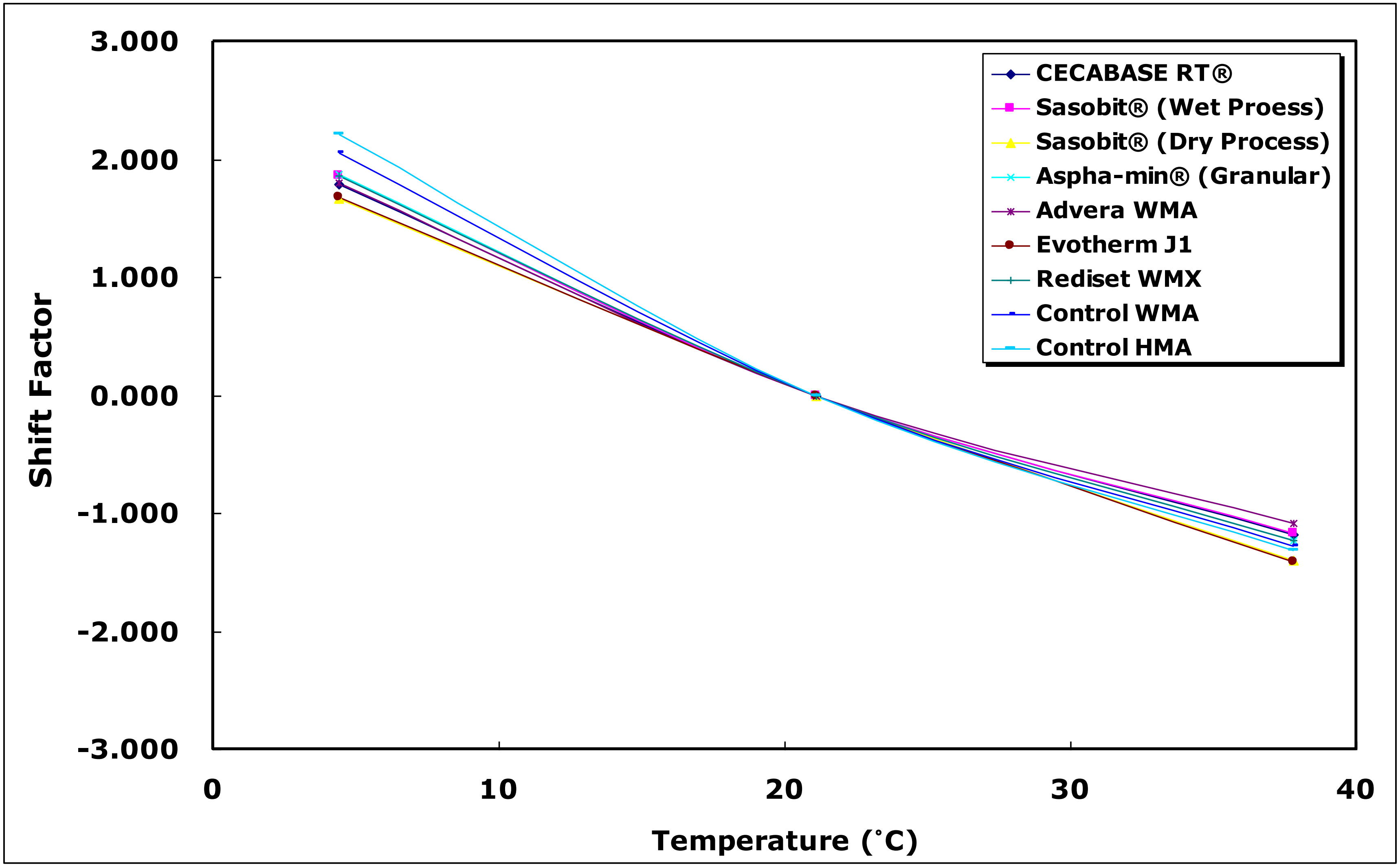

Fig. 7-10 Shift Factors against Three Temperatures

Chapter 8 Repeated Load Test

With increasing truck traffic loading and tire pressure, rutting is one of the most critical distress types occurring in asphalt pavements. Therefore, it is important to perform repeated load test in order to identify a problematic mix before it is utilized in roadways. Numerous studies have been conducted in the past to correlate the result from repeated load tests with the rutting of HMA mixtures in the field (Witczak et al. 2002; Kaloush et al. 2002; Pan et al. 2006; Mohammand et al. 2006).

To determine the rutting potential of WMA mixtures, Hurley and Prowell (2006) conducted a Hamburg wheel-tracking test and reported that the addition of Sasobit®, Aspha-min®, or Evotherm™ does not increase the rutting potential. Prowell et al. (2007) evaluated the rutting potential of WMA mixtures with Evotherm™ under accelerated loading at the test track. They found that in-place densities of the WMA surface layers were equal to or better than the HMA surface layers when the compaction temperature was reduced by 8˚C to 42˚C. They also reported that WMA test sections showed excellent field performance in terms of rutting after the application of traffic level of 515,333 ESALs in 43 days. Gonzalez-Leon et al. (2009) conducted a wheel tracking testing and reported that the deformation of WMA mixtures were very similar to that of HMA mixtures under 30,000 cycles, well below the requirement of 5%. In this study, the repeated load test was performed on WMA mixtures, the control WMA mixture and the control HMA mixture following the NCHRP Report 465 procedure (Witczak et al. 2002).

8.1 Theory

The repeated load test was developed to identify the permanent deformation characteristics of HMA mixtures by applying a haversine load and recording the cumulative deformation as a function of the number of load cycles. The load is applied for 0.1 second with a rest period of 0.9 second in one cycle and repeated up to 10,000 loading cycles. Figure 8-1 shows that results from the repeated load test are normally presented in terms of the cumulative permanent deformation strain (ε_p) versus the number of loading cycles. The cumulative permanent deformation strain curve is generally defined by three stages: a primary, secondary, and tertiary stage (EI-Basyoung et al. 2005). The permanent deformation increases rapidly in the primary stage and the incremental deformation decreases in the secondary stage. In the tertiary stage, the permanent deformations increase rapidly and the flow number (FN) is defined as the number of loading cycles applied until the beginning of tertiary stage.

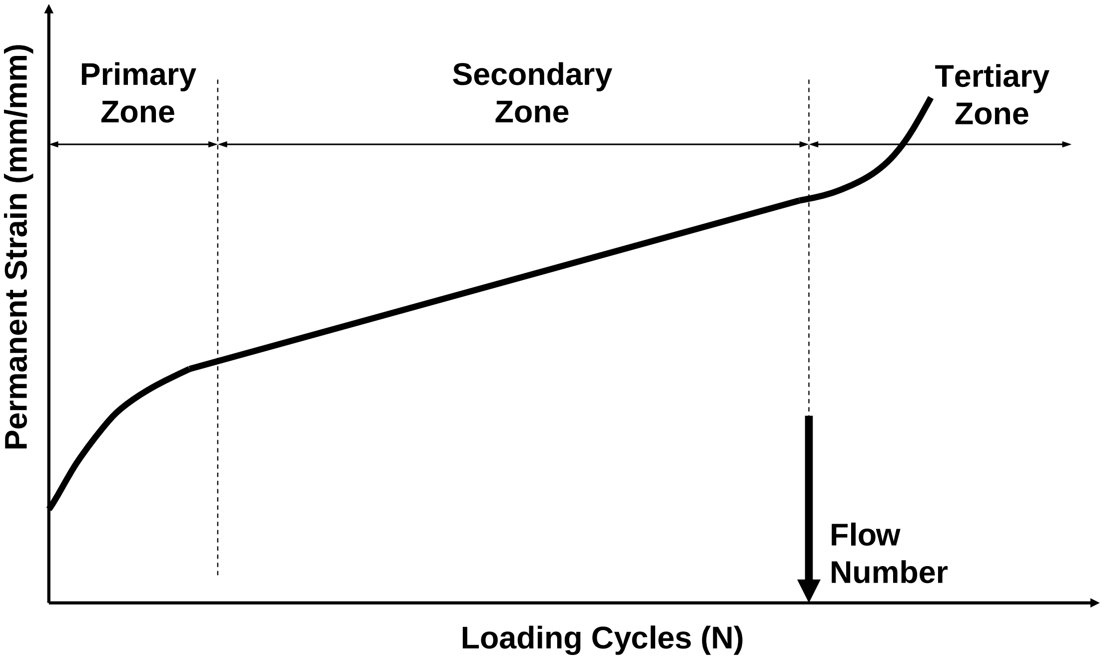

Fig. 8-1 Permanent Deformation Behavior against Loading Cycles

8.2 Repeated Load Testing Procedure

To determine the flow number of different types of warm mix asphalt (WMA) mixtures, as summarized in table 8-1, seven WMA mixtures, the control WMA mixture and the control HMA mixture were produced in the laboratory. Two specimens, both with a 100-mm diameter and a 150-mm height, were prepared by gyratory compactor at 86 gyrations. After curing for one day at room temperature, the bulk specific gravity of the compacted specimens were measured.

The uniaxial compression load without confinement was applied to obtain a loading stress level of 600kPa at 45˚C. The loading stress was applied in the form of a haversine curve with a loading time of 0.1 second with a rest period of 0.9 second in one cycle. The test was conducted up to 10,000 cycles or until achieving 5.0% of cumulative permanent deformation stain.

Table 8-1 List of WMA and HMA Mixtures for Repeated Load Test

Mix Type	Mixing Process Method	Number of Specimen
CECABASE RT®	Wet Process	2 specimens
Sasobit®	Wet Process	2 specimens
Sasobit®	Dry Process	2 specimens
Aspha-min® (Granular)	Dry Process	2 specimens
Advera WMA	Dry Process	2 specimens
Evotherm J1	Wet Process	2 specimens
Rediset^{TM} WMX	Dry Process	2 specimens
Control WMA	-	2 specimens
Control HMA	-	2 specimens

8.3 Bulk Specific Gravities and Air Voids of Repeated Load Test Specimens

The bulk specific gravity of each specimen was determined following the AASHTO T 166 (AASHTO 2001). Table 8-2 summarizes the bulk specific gravities and air voids of the WMA mixtures and the control HMA mixture that were prepared for the repeated load test. Given the same compaction level of 68 gyrations, the bulk specific gravities of WMA specimens ranged between 2.377 to 2.408 and the control HMA specimens ranged between 2.364 to 2.408. All specimens exhibited a small amount of air voids ranging between 0.8% (Sasobit®- wet process) and 2.7% (Advera WMA).

Figures 8-2 and 8-3 contain plots of the average bulk specific gravities and air voids of the specimens, respectively. As shown in figure 8-3, the average air voids of WMA mixtures with CECABASE RT®, Sasobit®, Aspha-min® (Granular), Evotherm J1, and Rediset™ WMX additives were lower than that of the control HMA specimens. This finding indicates these additives are effective in compacting an asphalt mixture at a lower temperature.

Table 8-2 Bulk Specific Gravities and Air Voids of WMA and HMA Mixtures for Repeated Load Test

Type of Mix	No. of Specimen	Bulk Specific Gravity		Air Void (%)	
		Individual	Average	Individual	Average
CECABASE RT®	# 1	2.394	2.386	1.8%	2.1%
	# 2	2.377		2.5%	
Sasobit® (Wet Process)	# 1	2.401	2.405	0.8%	0.6%
	# 2	2.408		0.5%	
Sasobit® (Dry Process)	# 1	2.399	2.395	1.1%	1.3%
	# 2	2.392		1.4%	
Aspha-min® (Granular)	# 1	2.381	2.387	2.2%	1.9%
	# 2	2.394		1.6%	
Advera WMA	# 1	2.384	2.383	2.5%	2.6%
	# 2	2.382		2.6%	
Evotherm J1	# 1	2.392	2.395	1.6%	1.4%
	# 2	2.398		1.3%	
Rediset^{TM} WMX	# 1	2.399	2.397	2.0%	2.0%
	# 2	2.395		2.1%	
Control WMA	# 1	2.397	2.399	2.1%	2.0%
	# 2	2.401		2.0%	
Control HMA	# 1	2.364	2.372	2.7%	2.4%
	# 2	2.380		2.1%	

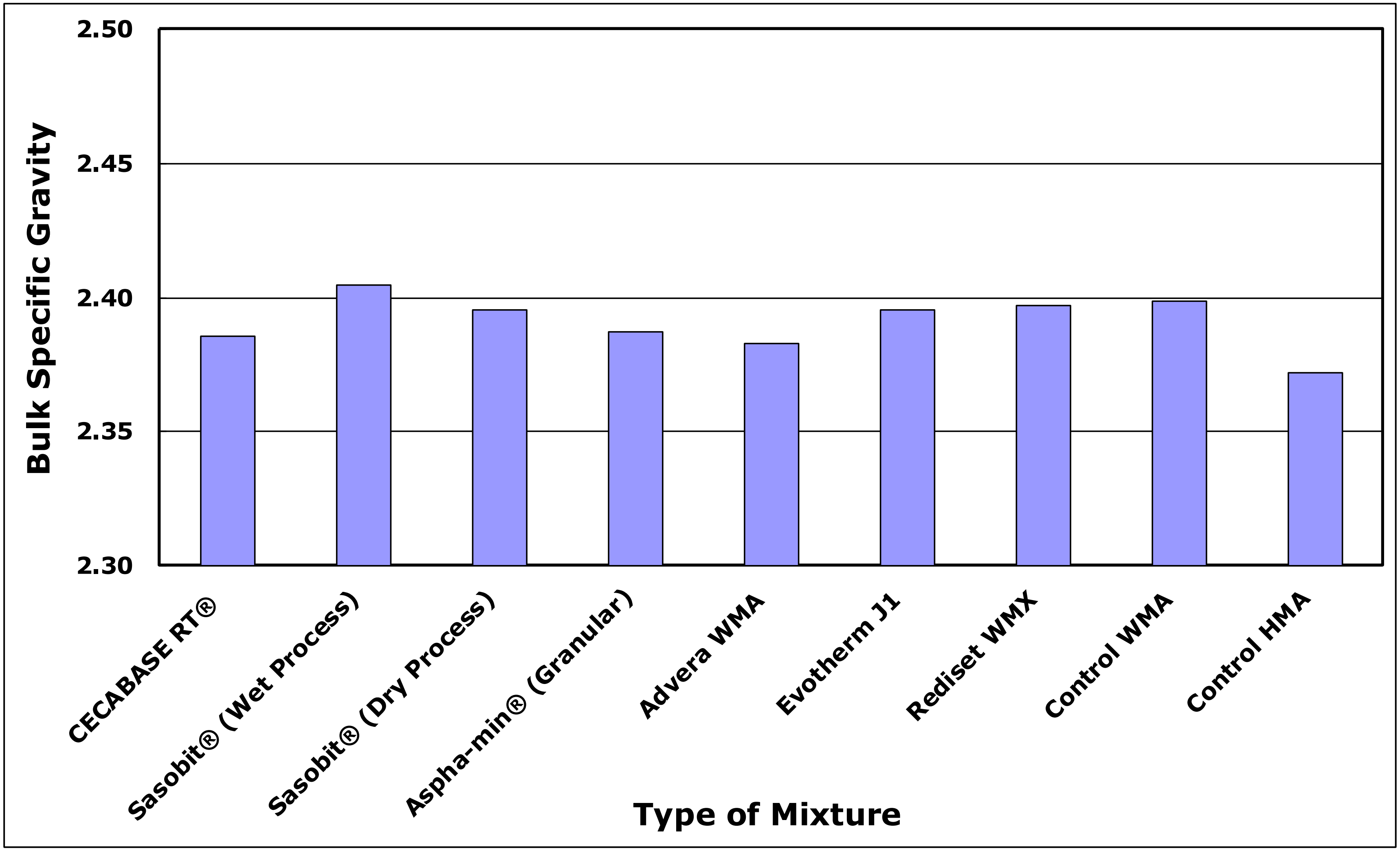

Fig. 8-2 Average Bulk Specific Gravities of WMA and HMA Mixtures for Repeated Load Test

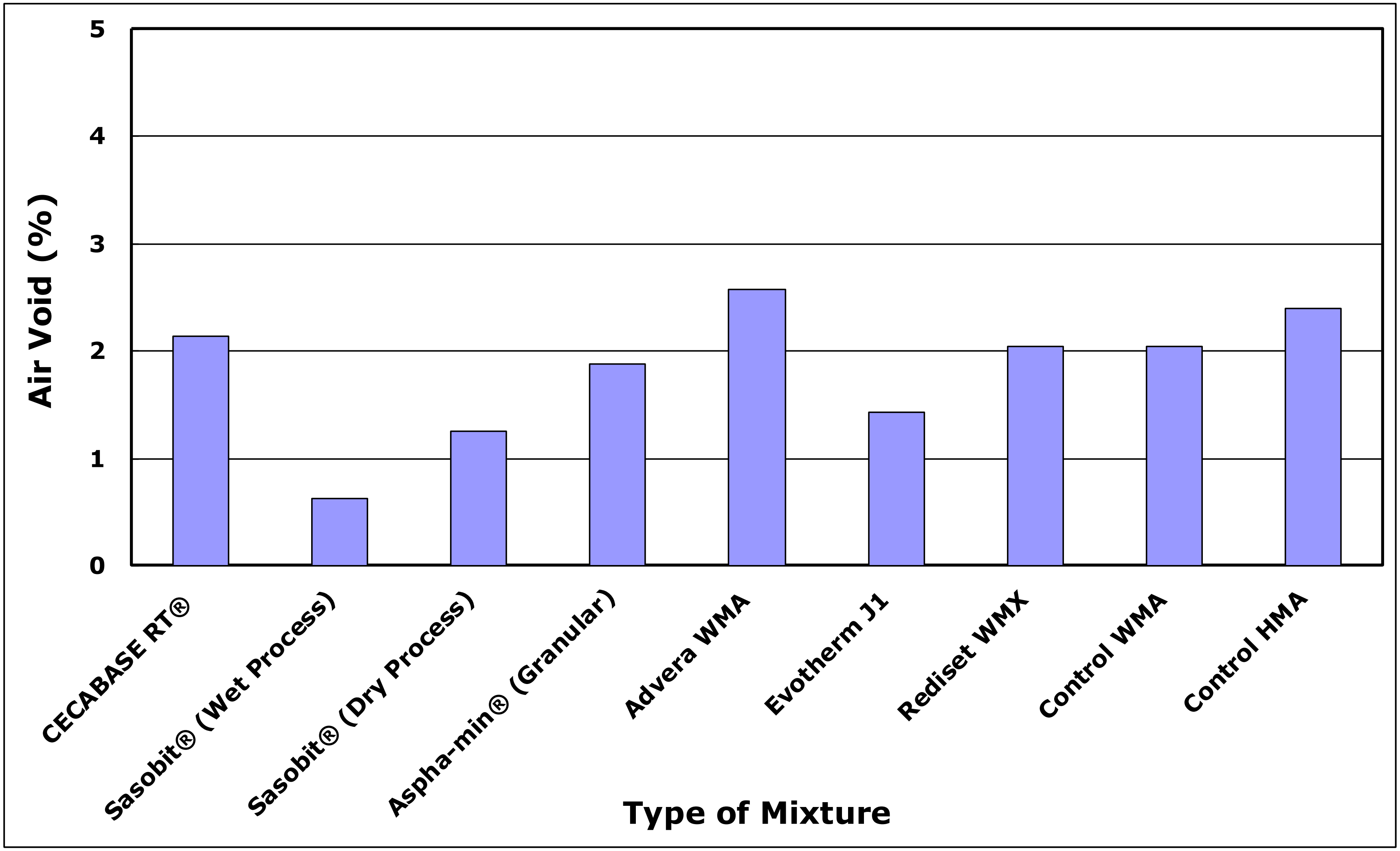

Fig. 8-3 Average Bulk Specific Gravities of WMA and HMA Mixtures for Repeated Load Test

8.4 Repeated Load Test Results

Flow numbers of seven WMA mixtures, the control WMA mixture and the control HMA mixture (two specimens for each) are summarized in table 8-3 and the cumulative permanent strains are plotted against the number of loading cycles in figure 8-4. It should be noted that the control WMA specimen, the control HMA specimen and all WMA specimens, except CECABASE RT® and Advera WMA, passed the requirement of 10000 cycles.

To determine if there is a correlation between air voids and flow number, as shown in table 8-4, specimens were ranked in an increasing order of air voids and a cumulative permanent strain. Overall, WMA mixtures with Sasobit® (both wet and dry processes) exhibited the lowest permanent deformation followed by the control HMA mixture. Conversely, WMA mixtures with Advera WMA were the highest followed by CECABASE RT®. With the exception of the control HMA mixture that exhibited the low permanent deformation with a relatively high air void, overall the specimens with higher air voids exhibited the higher permanent deformation. It is interesting to note that the WMA mixture with Sasobit® also exhibited the highest dynamic modulus.

Table 8-3 Flow Number and Permanent Deformation of WMA and HMA Mixtures

Type of Mix	No. of Specimen	Flow Number		Cumulative Permanent Deformation
		Individual	Average	
CECABASE RT®	# 1	5081	7541	5.00%
	# 2	10000		4.26%
Sasobit® (Wet Process)	# 1	10000	10000	2.23%
	# 2	10000		1.76%
Sasobit® (Dry Process)	# 1	10000	10000	1.98%
	# 2	10000		1.85%
Aspha-min® (Granular)	# 1	10000	10000	3.28%
	# 2	10000		3.10%
Advera WMA	# 1	4181	2466	5.00%
	# 2	7541		5.00%
Evotherm J1	# 1	10000	10000	3.23%
	# 2	10000		2.57%
Rediset^{TM} WMX	# 1	10000	10000	2.23%
	# 2	10000		2.45%
Control WMA	# 1	10000	10000	2.19%
	# 2	10000		2.16%
Control HMA	# 1	10000	10000	2.17%
	# 2	10000		1.99%

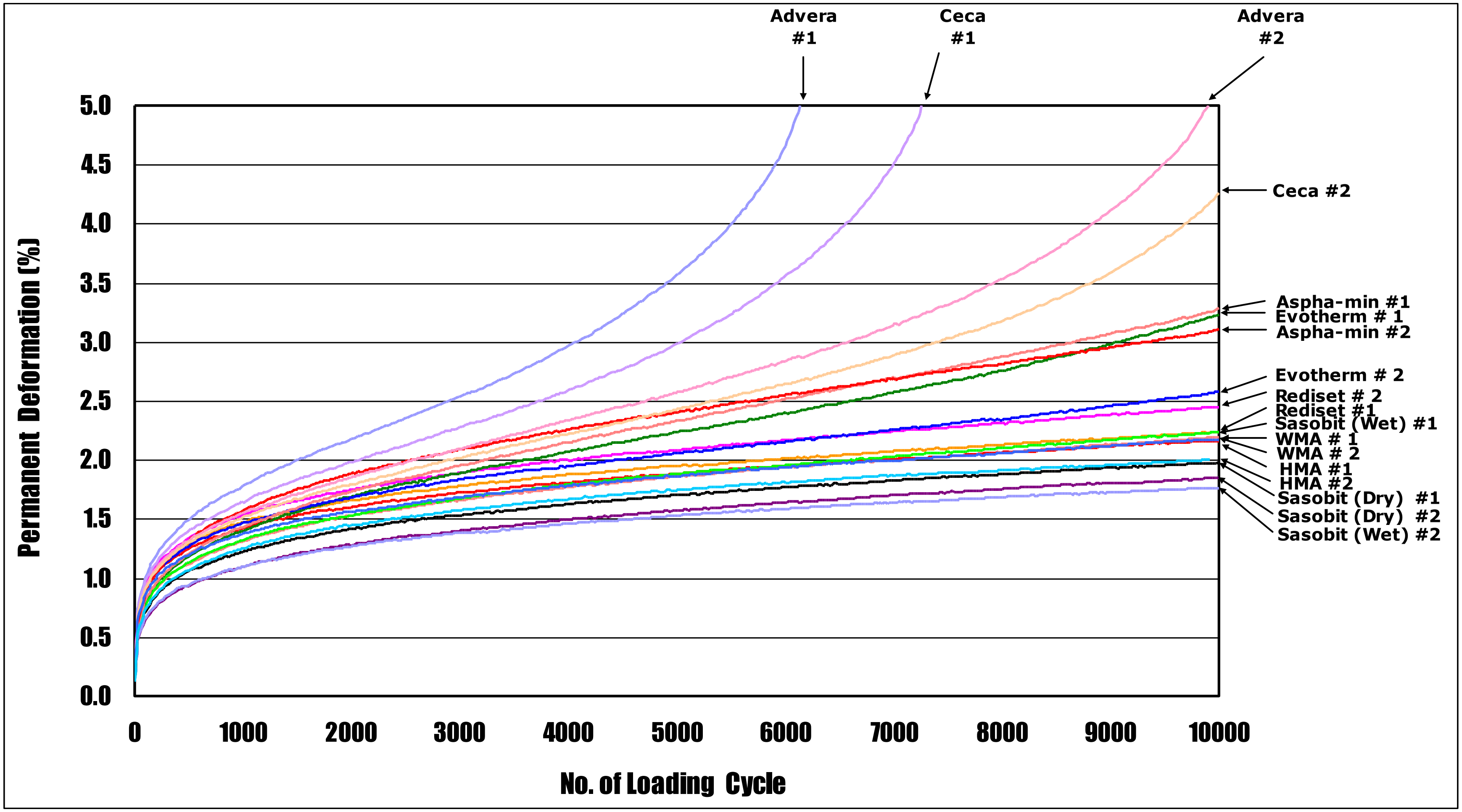

Fig. 8-4 Plots of Permanent Deformation against Loading Cycle of WMA and HMA Mixtures

Table 8-4 Ranking of Permanent Deformation from Seven WMA Mixtures and Control WMA and HMA Mixtures

Type of Mix	No. of Specimen	Air Void		Ranking of Air Void	Permanent Deformation		Ranking of Permanent Strain
		Individual	Average		Individual	Average	
CECABASE RT®	# 1	1.8%	2.1%	**7**	5.00%	4.63%	**8**
	# 2	2.5%			4.26%		
Sasobit® (Wet Process)	# 1	0.8%	0.6%	**1**	2.23%	2.00%	**2**
	# 2	0.5%			1.76%		
Sasobit® (Dry Process)	# 1	1.1%	1.3%	**2**	1.98%	1.92%	**1**
	# 2	1.4%			1.85%		
Aspha-min® (Granular)	# 1	2.2%	1.9%	**4**	3.28%	3.19%	**7**
	# 2	1.6%			3.10%		
Advera WMA	# 1	2.5%	2.6%	**9**	5.00%	5.00%	**9**
	# 2	2.6%			5.00%		
Evotherm J1	# 1	1.6%	1.4%	**3**	3.23%	2.90%	**6**
	# 2	1.3%			2.57%		
Rediset$^{\text{TM}}$ WMX	# 1	2.0%	2.0%	**5**	2.23%	2.34%	**5**
	# 2	2.1%			2.45%		
Control WMA	# 1	2.1%	2.0%	**5**	2.19%	2.18%	**4**
	# 2	2.0%			2.16%		
Control HMA	# 1	2.7%	2.4%	**8**	2.17%	2.08%	**3**
	# 2	2.1%			1.99%		

Chapter 9 Summary and Conclusions

Warm mix asphalt (WMA) is an emerging technology that can allow asphalt to flow at a lower temperature for mixing, placing and compaction. The advantages of warm mix asphalt (WMA) include reduced fuel consumption, less carbon dioxide emission, a longer paving season, longer hauling distances, reduced oxidation of asphalt, early opening to traffic and a better working environment in the field. In the United States, warm mix asphalt (WMA) has become popular in recent years. However, to provide a safe and reliable highway for heavier truck traffic with a high tire pressure, warm mix asphalt (WMA) mixtures must meet requirements for strength, stiffness, rutting, and moisture resistance.

Warm mix asphalt (WMA) mixtures with six commercially available WMA additives—CECABASE RT®, Sasobit®, Asphalt-min®, Advera WMA, Evotherm J1, and Rediset™ WMX—along with the control WMA mixture without any additive and the control HMA mixture, were evaluated for their air voids, indirect tensile strengths and moisture susceptibilities. To evaluate a long-term reliable performance over a wide range of traffic and climatic conditions, the dynamic modulus and the repeated load tests were conducted on these mixtures using the simple performance testing equipment.

To compare these WMA additives, as shown in table 9-1, they are ranked in terms of indirect tensile strength, tensile strength ratio, dynamic modulus and permanent deformation. Based on the limited test results, Sasobit®, Evotherm J1 and Rediset^{TM} WMX were effective in producing WMA mixtures in the laboratory that are comparable to HMA mixtures.

Table 9-1 Ranking of ITS, TSR, Dynamic Modulus, and Permanent Deformation for Eight WMA Mixtures and Control WMA and HMA Mixtures

Type of Mix	Ranking				Total Average	Overall Ranking
	Indirect Tensile Strength	Tensile Strength Ratio	Dynamic Modulus	Permanent Deformation		
CECABASE RT®	**8**	**5**	**9**	**8**	**7.50**	**8**
Sasobit® (Wet Process)	**4**	**6**	**1**	**2**	**3.25**	**2**
Sasobit® (Dry Process)	**10**	**4**	**2**	**1**	**4.25**	**4**
Aspha-min® (Powder)	**9**	**9**	**-**	**-**	**9.00**	**10**
Aspha-min® (Granular)	**6**	**8**	**7**	**7**	**7.00**	**7**
Advera WMA	**7**	**10**	**5**	**9**	**7.75**	**9**
Evotherm J1	**3**	**2**	**6**	**6**	**4.25**	**4**
Rediset^{TM} WMX	**2**	**3**	**3**	**5**	**3.25**	**2**
Control WMA	**5**	**7**	**8**	**4**	**6.00**	**6**
Control HMA	**1**	**1**	**4**	**3**	**2.25**	**1**

9.1 Conclusions

Based on the limited laboratory experiment, the following conclusions are derived:

1. Warm mix asphalt (WMA) mixtures with various additives were mixed and compacted well in the laboratory at the temperatures between 113˚C to 126˚C.
2. Warm mix asphalt (WMA) mixtures provided comparable densities and air voids to the hot mix asphalt (HMA) mixture at a lower temperature which indicates that WMA additives are effective in compacting asphalt mixtures at a lower temperature.
3. The hot mix asphalt (HMA) mixture exhibited the highest indirect tensile strength followed by WMA mixtures with Evotherm J1 and Rediset™ WMX.
4. The tensile strength ratio (TSR) values of WMA mixtures ranged between 31.9% and 61.5% whereas that of the HMA mixture was 68.0%, all of which are below the Superpave specification of 80%. The Evotherm J1 specimen exhibited the highest TSR value whereas the Advera WMA specimen exhibited the lowest value.
5. Warm mix asphalt (WMA) mixtures with Sasobit® exhibited the highest dynamic modulus followed by the control HMA mixture. The hot mix asphalt (HMA) mixture lost its dynamic modulus value more often than WMA mixtures with

Sasobit® or Rediset^{TM} WMX when a test temperature was increased from 4.4˚C to 37.8˚C.

6. Warm mix asphalt (WMA) mixtures with Sasobit® exhibited the lowest permanent deformation followed by the control HMA mixture.

9.2 Future Studies

Given the limited laboratory test results performed for this study, it is recommended that the use of anti-stripping agents and friction characteristic should be evaluated against several WMA mixtures with a controlled WMA mixture and a controlled HMA mixture.

1. Based on the moisture susceptibility test, no WMA mixtures satisfied the Superpave requirement of 80%. Therefore, further research should be performed to improve the moisture susceptibility of the WMA mixtures.
2. For the safety issue of heavy truck traffic with a higher tire pressure, the friction characteristics of WMA mixtures should be evaluated in the laboratory and the field. Friction characteristics should be measured from the existing WMA sections in service.
3. To determine the durability of WMA mixtures, a raveling test should be performed.
4. To address a concern for traffic safety associated with rain, the water draining

characteristics of the WMA mixtures should be evaluated.

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