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Performance Measures of Warm Asphalt Mixtures for Safe and Reliable Freight Transportation Phase II: Evaluation of Friction and Raveling Characteristics of Warm Mix Asphalt Mixtures with Anti-stripping Agents

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16. Abstract

The viscosity of asphalt decreased significantly when 0.5% of WMA additive was added, but it remained relatively steady as the dosage rate increased up to 3.0%. The reduction pattern in viscosity as the dosage rate increases was similar for both CECABASE RT® and LEADCAP at all test temperatures of 120°C,125°C, 130°C and 135 °C and a similar pattern was observed for both Sasobit® and Rediset. Based on the ABCD test device, the virgin asphalt binder PG 64-34 cracked at -51.0°C and the PG 64-28 cracked at -41.3°C. As the WMA additives were increased from 0.5% to 3.0%, the cracking temperatures increased slightly, but remained steady near the cracking temperature of the virgin asphalt binder. The ABCD test results confirmed that the cracking temperature of asphalt binder was not significantly affected by any of these four WMA additives.

The BPN value steadily decreased as the specimen surface was abraded by a rotating rubber although the MTD value did not change significantly. The most significant change in BPN has occurred between 30 and 45 minutes of abrasion whereas no significant change was observed between 45 and 65 minutes of abrasion.

The control WMA without additive exhibited the lowest Tensile Strength Ratio (TSR) value of 53.3%, which increased to 66.6% with lime and 83.5% with an Anti-stripping agent (ASA). WMA-Sasobit exhibited 73.7% but it slightly decreased to 72.7% with lime and 72.3% with ASA. WMA-LEADCAP exhibited 80.3% but it decreased to 78.5% with lime and increased to 81.4% with ASA. The control HMA exhibited 82.7% and it increased to 89.3% with lime and 92.6% with ASA. It can be concluded that TSR values of both WMA-Sasobit and WMA-LEADCAP were not affected by lime or ASA.

A more extensive study should be performed quantifying the temperature-viscosity relationship of asphalt mixed with varying amounts of WMA additives at different temperatures. An additional study should be performed on the effect of lime and anti-stripping agent on WMA mixtures with various additives. It is recommended that the skid test should be performed on WMA pavements in the field after several years of service.

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ABSTRACT

The viscosity of asphalt decreased significantly when 0.5% of WMA additive was added, but it remained relatively steady as the dosage rate increased up to 3.0%. The reduction pattern in viscosity as the dosage rate increases was similar for both CECABASE RT® and LEADCAP at all test temperatures of 120°C,125°C, 130°C and 135 °C, and a similar pattern was observed for both Sasobit® and Rediset. Based on the ABCD test device, the virgin asphalt binder PG 64-34 cracked at -51.0°C and the PG 64-28 cracked at -41.3°C. As the WMA additives were increased from 0.5% to 3.0%, the cracking temperatures increased slightly but remained steady near the cracking temperature of the virgin asphalt binder. The ABCD test results confirmed that the cracking temperature of asphalt binder was not significantly affected by any of these four WMA additives.

The BPN value steadily decreased as the specimen surface was abraded by a rotating rubber although the MTD value did not change significantly. The most significant change in BPN has occurred between 30 and 45 minutes of abrasion whereas no significant change was observed between 45 and 65 minutes of abrasion. The control WMA without additive exhibited the lowest Tensile Strength Ratio (TSR) value of 53.3%, which increased to 66.6% with lime and 83.5% with an Anti-stripping agent (ASA). WMA-Sasobit exhibited 73.7% but it slightly decreased to 72.7% with lime and 72.3% with ASA. WMA-LEADCAP exhibited 80.3% but it decreased to 78.5% with lime and increased to 81.4% with ASA. The control HMA exhibited 82.7% and it increased to 89.3% with lime and 92.6% with ASA. It can be concluded that TSR values of both WMA-Sasobit and WMA-LEADCAP were not affected by lime or ASA.

A more extensive study should be performed quantifying the temperature-viscosity relationship of asphalt mixed with varying amounts of WMA additives at different temperatures.

An additional study should be performed on the effect of lime and anti-stripping agents on WMA mixtures with various additives. It is recommended that the skid test should be performed on WMA pavements in the field after several years of service.

1. INTRODUCTION

The basic concept of warm mix asphalt (WMA) technologies is to reduce the asphalt binder viscosity, which allows the asphalt to attain a suitable viscosity to coat the aggregates and thus compact asphalt mixtures at lower temperatures. The WMA technology was introduced in the United States in 2002 for lowering emissions and improving the working environment. Crows (2008) and Newcomb (2009) reported that 45 states in the US have used warm mix asphalt technology in real construction or field trial projects. Moreover, Alabama, California, Florida, Illinois, New York, North Carolina, Ohio, Pennsylvania, Texas, Virginia, Washington and Wisconsin have allowed the use of WMA mixtures on many highway projects.

The WMA mixtures were mainly evaluated for rutting resistance and moisture sensitivity because a lower mixing temperature may cause the incomplete drying of the aggregate. As a result, it may affect the adhesion between asphalt and the aggregate increasing the rutting potential in asphalt pavement. However, from the recent construction projects, it was reported that the moisture sensitivity and rutting resistance between WMA and HMA were quite similar. For example, WMA pavements using Aspha-min, Sasobit and Evotherm were constructed at three separate sites in Missouri. After two years of service life, no rutting was found in either WMA or HMA pavements. The WMA pavements using Aspha-min, Sasobit and Evotherm were also constructed in Ohio. It was reported that rutting resistance and moisture damage of the

WMA pavements were identical to those of HMA pavements (NCAT 2010).

Phase 1 of the study was performed to evaluate strength, moisture sensitivity, stiffness, and rutting resistance of WMA mixtures with six WMA additives, which included Cecabase RT®, Sasobit®, Evotherm J1, Rediset™ WMX and LEADCAP, along with the control WMA mixture without additive and the control HMA mixture. Overall, Sasobit®, Evotherm J1 and Rediset™ WMX additives were effective in producing WMA mixtures in the laboratory that are comparable to HMA mixtures.

Based on the moisture susceptibility test results, no WMA mixtures satisfied the Superpave requirement. Therefore, during the phase 2 study anti-stripping agents were added to the WMA mixtures in order to improve the moisture susceptibility. To address a safety concern for WMA pavements under heavy truck traffic with a high tire pressure, the friction and raveling characteristics were evaluated in the laboratory.

One of main concerns for adding WMA additives to asphalt is that it might reduce the cracking resistance at a low temperature. To address this concern, this paper presents impacts of various amounts of WMA additives on the viscosity and low-temperature cracking of asphalt binder. In addition, the moisture sensitivity test was conducted to investigate the rutting resistance. For the moisture sensitivity test, both lime and an anti-stripping agent (LOF 65-00) were used to improve the moisture sensitivity resistance.

1.1 Objectives

To provide a safe and reliable highway for truck traffic, warm mix asphalt (WMA) pavement must meet requirements for moisture sensitivity, raveling and friction resistance. However, a major difficulty in evaluating WMA mixtures is that there is no national research evaluating these fundamental characteristics.

The objective of this research is (1) to evaluate impacts of various amounts of WMA additives on the viscosity and low-temperature cracking of asphalt binder; (2) to evaluate the skid resistance of WMA mixtures and (3) investigate the effectiveness of anti-stripping agents to improve moisture sensitivity of warm mix asphalt mixtures.

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 moisture sensitivity, raveling and fiction characteristics. This information would be very useful for pavement engineers who are interested in implementing the WMA technologies. Identified reliable WMA technologies from this research would contribute to the road safety by minimizing an accident risk caused by an unsafe road surface condition for increasing freight movements on the US surface transportation system.

1.3 Advantages

Warm mix asphalt (WMA) technologies are able to reduce the binder resistance to high shear forces, such as 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 mixing and placement
- Less worker exposure to fumes and smoke during the placement operation
- Lower compaction temperature in the field
- Longer construction season
- Increased pavement density
- Longer haul distances
- Ability to incorporate higher percentages of RAP
- Ability to place and compact thicker lifts
- Ability to open to traffic sooner

The WMA products/processes work differently and are categorized into three groups: organic additive, foaming additive and chemical additive. These WMA technologies are emerging rapidly in the United States (NAPA 2007; Brian 2007; Bonaquist 2008; Dukatx 2009; Hurley at el 2010).

2. LITERATURE REVIEW

The use of warm mix asphalt (WMA) is rapidly increasing for the construction of roads world-wide. To sustain this development, it is necessary to understand the behavior of asphalt binder when different amounts of WMA additives are used. One of the major impacts of these WMA additives on the asphalt binder is that they would reduce the asphalt viscosity at a lower temperature. The reduction in asphalt viscosity allows the asphalt to mix and compact at a lower temperature. This approach brings about significant savings because the requirement of heating the aggregates up to 170°C is no longer. This new discovery is currently revolutionizing the road construction industry.

Hurley and Prowell (2005, 2006) evaluated three different WMA technologies: Aspha-Min®, Sasobit® and Evotherm™, and concluded that all three technologies improved the compactibility of the asphalt mixture and resulted in lower air voids compared to HMA. That said, these technologies showed increasing tendencies to rutting and moisture susceptibility. This can be attributed to decreased aging of the binder, 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; 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 content may be lowered to increase the air void. Of course, lowering asphalt content could negatively affect the compactability 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 binder at a mid-range temperature of 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 because the reductions in the latter 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 compactability of asphalt mixture and resulted in acceptable density at a temperature below a normal compaction temperature by 68°F to 104°F. In addition, the mixtures modified with Sasobit® exhibited a greater resistance to densification under simulated traffic.

Hensley (1998) recommended that asphalt compaction occur on the field at a target viscosity of 0.28 + 0.02Pa.s and a corresponding temperature of 160°C. Bahia et al. (2006) recommended 3 Pa.s as a limiting low shear viscosity for estimating compaction temperature. Lu & Redelius (2006) studied the effect of asphalt that contains wax naturally. They concluded that when using waxy asphalt the asphalt mixtures showed a higher fracture temperature. With regards to moisture sensitivity, they found that adding wax to asphalt does not negatively affect the moisture sensitivity. The N-alkane rich crystallizing material in asphalt lowered the complex modulus at temperatures over approximately 40°C and exhibited a stiffening effect at a lower temperature below 40°C (Kvasnak et al. 2009). Asphalt containing natural waxes has a higher modulus and a lower phase angle compared to mixtures containing non-waxy asphalt. However, the significant hardening of some asphalt observed in binder testing by a Bending Beam Rheometer (BBR) was not observed in the moisture sensitivity test of asphalt mixtures (Gonzalez-Leon 2009). 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).

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 for the indirect tensile strength test, dynamic modulus test and dynamic creep test. They reported that WMA additives had improved the compactibility of CIR-foam mixtures resulting in a lower air void. The indirect tensile strength of CIR-foam mixtures with Sasobit® was the highest, and the dynamic module of CIR-foam mixture with WMA additives was higher than those without any additive. Flow number of CIR-foam mixtures with Sasobit® was the highest followed by ones with Aspha-min® and ones 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.

Prowell and Hurley (2008) evaluated the current WMA technologies that could significantly benefit the highway transportation system in the United States. NAPA (2008) published a WMA related document that included mix design and field trial data. As shown in Figure 2.1, Crews (2008) and Newcomb (2009) concluded that the number of states with WMA projects has increased significantly.

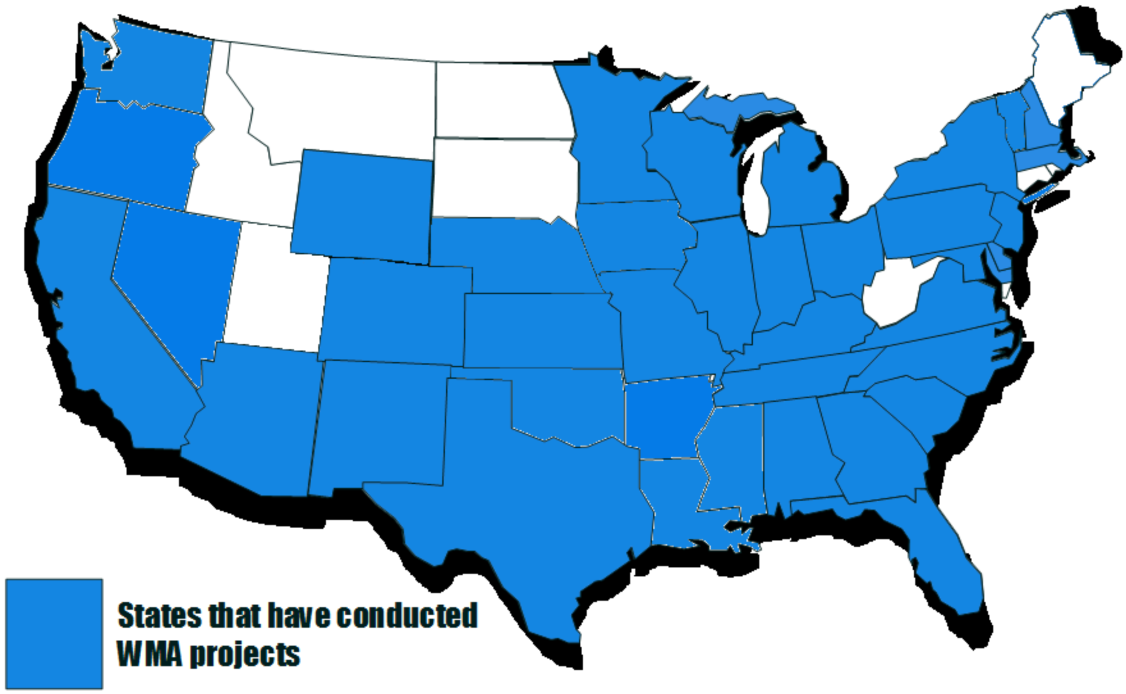


Figure 2.1 States where WMA projects were implemented

As summarized in Table 2.1, a number of WMA technologies have been developed and implemented in the US. These commercial WMA products/processes are available to produce asphalt mixtures at significantly lower temperatures than HMA.

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. However, the performance, durability and compatibility of WMA test sections should be researched further.

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 Additive	Ceca	No
	Asphaltan®	Unspecified Organic Additive	Romonta	No
	Ecoflex	Unspecified Organic Additive	Colas	No
	Sonneborn	Unspecified Organic Additive	Sonneborn	Yes
	LEADCAP	Unspecified Organic Additive	Kumho Pertochemical	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
	LT Asphalt	Absorbent filter	Nynas	No
	ECOMAC	Foaming	Screg	No
	LEA, EBE and EBT	Sequential coating using wet fine aggregate and unspecified additive	LEACO,Fairco and EiffageTP	Yes
	LEAB	Sequential coating using wet fine aggregate and unspecified additive	BAM	No
Chemical Additive	Evotherm ET	Emulsion with unspecified additive	MeadWestvaco Asphalt Innovations	Yes
	Evotherm DAT	Unspecified additive		Yes
	Evotherm J1	Unspecified additive		Yes
	Rediset™ WMA	Unspecified additive	Akzo Nobel Surfactants	Yes
	REVIX™	Unspecified additive	Mathy Technology and Engineering Services Inc. and Paragon Technical Services Inc.	No

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, Route 220 Virginia (2006) • 10% RAP, Missouri (2006); 14% RAP, Wisconsin (2006) • M-95, Michigan (2006) • SR 541, Ohio (2006) • I-70 Colorado (2007)
Foaming	WAM-Foam®	• First field trial in Norway (1999); RV120, Norway (2000); FV 82 Frogn, Norway (2001) • NCC road, Sweden (2002) • Ooms Abenhorn, Netherlands (2003) • Conglobit, Italy (2004)
	Double Barrel® Green	• Chattanooga, Tennessee (2007); 50% RAP, Chattanooga, Tennessee (2007) • Johnson County, North Carolina (2007) • Vancouver, British Columbia (2007) • S.R. 46 from US 431 to S.R. 96, Tennessee (2007) • York County, Sacramento (2007)
	Ultrafoam GX™ Process	• N/A
	Terex® Warm Mix Asphalt System	• Oklahoma City, Tennessee (2008)
	Low Energy Asphalt (LEA®)	• Cortland, New York (2006) • RT 11, 98B, Bomax Rd. RT 38, RT 13, RT 79, New York (2007)
	Aspha-Min®	• With PMA in Germany (2003) • Parking lot in Orlando, Florida (2004) • Charlotte, North Carolina (2004) • Montreal, Quebec, Canada (2004) • Columbus, Ohio (2005) • Hookest, New Hampshire (2005); Belmont, New Hampshire (2006) • OGFC in Orlando, Florida (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 (2007)
Chemical Additive	Rediset™ WMA	• Chico, California (2007)
	REVIX™	• CTR 11, Goodhue City, Minnesota (2007) • STH 33, La Crosse County, Wisconsin (2007) • State Ret. 53, Gainesboro, Tennessee (2007) • Highway 25, Smithville, Mississippi (2007) • CIR project, HWY 346, Iowa (2008)
Emulsion Additives	Evotherm™	• County Road 900, Indiana (2005) • County Road, New York (2005) • Binder layer, Canada (2005) • Eskimo road, San Antonio (2005) • NCAT test track, Alabama (2005) • Miller Paving, Canada (2005); Road #46, Canada (2005) • Route 143, Virginia (2006) • SR 541, Cambridge, Ohio (2006) • I-70 Colorado (2007)

As shown in Table 2.3, NCAT (2010) reported that several WMA projects were completed in 2010, and, as shown in Table 2.4, six existing pavements are being monitored for the short-term performance.

Table 2.3 New construction projects to be documented as part of NCHRP 9-47A

State	WMA Technology	Estimated Tonnage
Indiana	Evotherm DAT, Advera And Heritage wax	20,000
Michigan	Advera and Evotherm 3G	10,000
Virginia	Astec DBG	60,000
Montana	Evotherm 3G	20,000
Washington	AQUABlack	75,000
New York	Sonneborn, Hydrogreen And Cecabase	TBD
Pennsylvania	Aqua Foam	TBD
Florida	Terex WMA Foam	TBD

Table 2.4 Monitoring projects to be documented as part of NCHRP 9-47A

State	Construction Date	WMA Technology	Total tons placed
Missouri	2006. 09	Evotherm ET, Sasobit and Asphamin	6,600
New York	2007. 07	LEA	19,000
Colorado	2007. 08	Evotherm ET, Sasobit and Advera	3,000
Tennessee	2007. 10	Astec DBG, Advera, Evotherm DAT And Sasobit	3,500
Texas	2008. 06	Astec DBG	75,000
Washington	2008. 06	Sasobit	13,000

3. VISCOSITY AND LOW-TEMPERATURE CRACKING OF ASPHALT WITH WMA ADDITIVES

The concept of warm mix asphalt technologies is to reduce the asphalt binder viscosity. This reduction allows the asphalt to attain a suitable viscosity to coat the aggregates and enables the mixtures to compact at lower temperatures. Therefore, the viscosity level of the asphalt binder is very essential for the proper coating of asphalt on the aggregates. Many studies have addressed the benefits of warm mix asphalt, but limited research has been done as to a comparative study for the effect of viscosity on the asphalt binder with different WMA additives. It is very difficult to control the temperature in the field and it is often found that the aggregates are mixed at different temperatures at each construction site.

During this phase 2 study, the effect of temperature on the viscosity of the binder with WMA additives was investigated to determine the lowest temperature that can be used to mix asphalt with aggregates. In addition, the impacts of various amounts of WMA additives on low-temperature cracking of asphalt binder were identified. The viscosity and lowest cracking temperature of asphalt binder with four WMA additives were measured and compared with those of straight asphalt binder.

3.1 Viscosity and Low Temperature Cracking Tests

The viscosity is needed to ensure proper handling of the asphalt binder and for quality control and assurance. As shown in Figure 3.1, a chart of viscosity versus temperature was developed for determining the optimum mixing and compaction temperatures of asphalt mixture (ASTM 2493). The viscosity of the asphalt binder should be between 0.15 and 0.19 Pa.s for mixing and 0.25 and 0.31 Pa.s for compaction. The SuperPave specification requires the viscosity of asphalt binder to be below 3.0 Pa.s at 135°C in order to be pumped through the asphalt plant.

To characterize the low temperature property of the asphalt binder, as shown in Figure 3.2, the asphalt binders with WMA additives were tested using the Asphalt Binder Cracking Device (ABCD) in the environment chamber. The ABCD is a testing device to determine the low temperature cracking property of asphalt binder, and it was used to quantify the impact of WMA additives on the low temperature property of asphalt binder. The strain and temperature readings are recorded on 10-second intervals from strain gauge in a silicone mold shown in Figure 3.2.

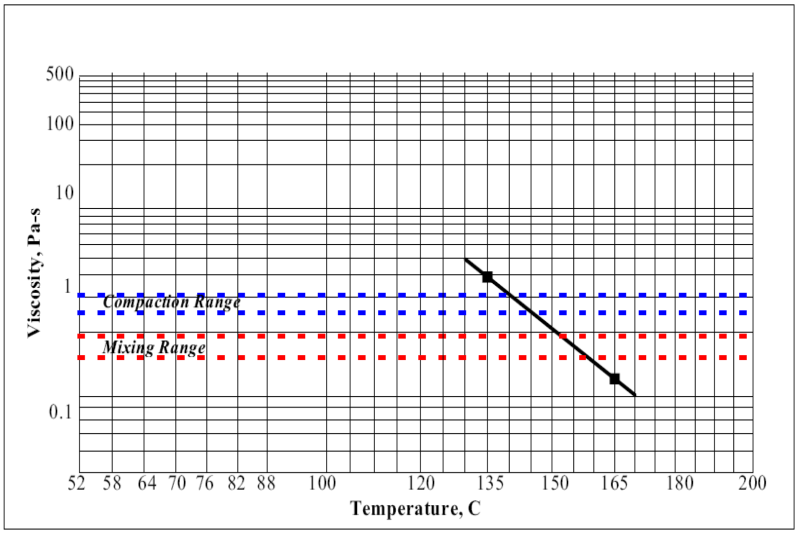


Figure 3.1 Mixing and compaction temperature (ASTM 2493)

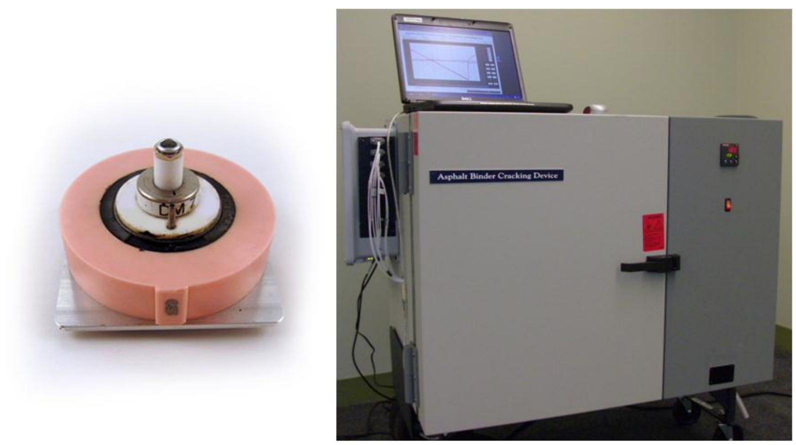


Figure 3.2 Asphalt Binder Cracking Device (ABCD) and environmental chamber

<u>3.2 Viscosity Testing Plan</u>

As summarized in Table 3.1, five different dosage rates (0.5%, 1.0%, 1.5%, 2.0% and 3.0% of asphalt weight) for each WMA additive were selected to measure the viscosity. The viscosity test was conducted from 120°C to 135°C with increments of 5°C, and three readings were recorded for each sample at an interval of 60 seconds.

Table 3.1 Dosage rate of WMA additives adopted for this study

WMA Additives	Dosage Rate (%)	Temperature (°C)	Dosage Rate recommended by manufacturer
CECABASE RT®	0.5% 1.0% 1.5% 2.0% 3.0%	120°C 125°C 130°C 135°C	0.4% of binder weight
Sasobit®			1.5% of binder weight
LEADCAP			3.0% of binder weight
Rediset™WMX			2.0% of binder weight

3.3 Viscosity Test Results

3.3.1 Straight Asphalt Binder (A)

The viscosity of the PG 64-28 virgin asphalt was measured at 120, 125, 130 and 135°C and the test results are summarized in Table 3.2. The highest viscosity value was 3.01 Pa.s measured at 120°C and lowest viscosity value was 1.25 Pa.s at 135°C. As Figure 3.9 demonstrates, and as expected, the viscosity has decreased significantly as the temperature increased from 120 to 135°C. It should be noted that the virgin asphalt would be too stiff to mix with aggregates at 120 °C.

Table 3.2 Viscosity test results of the straight asphalt binder

	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
Virgin Asphalt	1.25	2.37	2.85	3.01

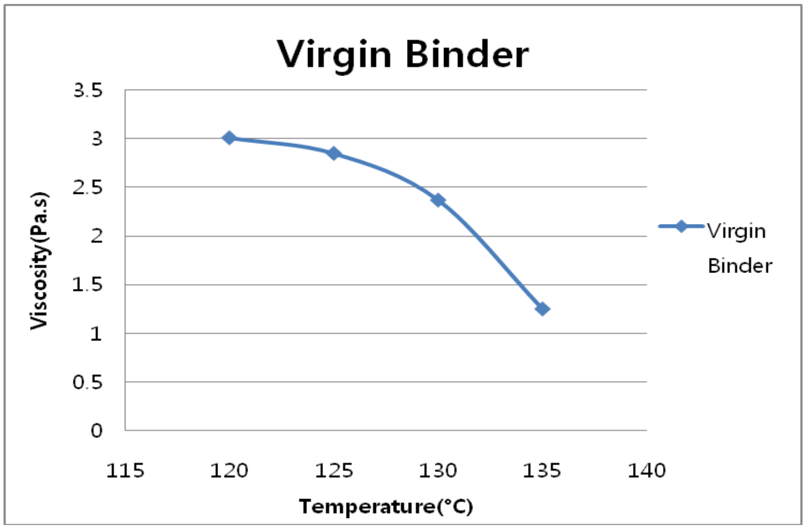


Figure 3.3 Plots of viscosity of straight asphalt binder against testing temperature

3.3.2 Evotherm J1 (B)

Evotherm J1 was developed without water so that it would reduce an internal friction between asphalt binder, aggregate, and among coated aggregate particles during mixing and compaction (Bonaquist 2008; Anderson et al. 2008). Evotherm J1 can be directly added to asphalt binder at a specified dosage rate by weight of asphalt. Table 3.3 summarizes the viscosity test results of asphalt binder using Evotherm J1. As shown in Figure 3.4, the viscosity decreased as the temperature and dosage rate increased. The viscosity decreased significantly when the small amount of 0.5% was added at temperatures between 120 and 130 °C. It should be noted that the increase of dosage rate from 0.5% up to 3.0% did not significantly lower the viscosity.

Table 3.3 Viscosity test results of asphalt binder using Evotherm J1

Dosage Rate	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.11	1.46	1.92	2.25
1.0%	1.07	1.33	1.79	2.10
1.5%	1.05	1.23	1.72	1.95
2.0%	0.95	1.16	1.65	2.04
3.0%	0.84	1.08	1.45	1.84

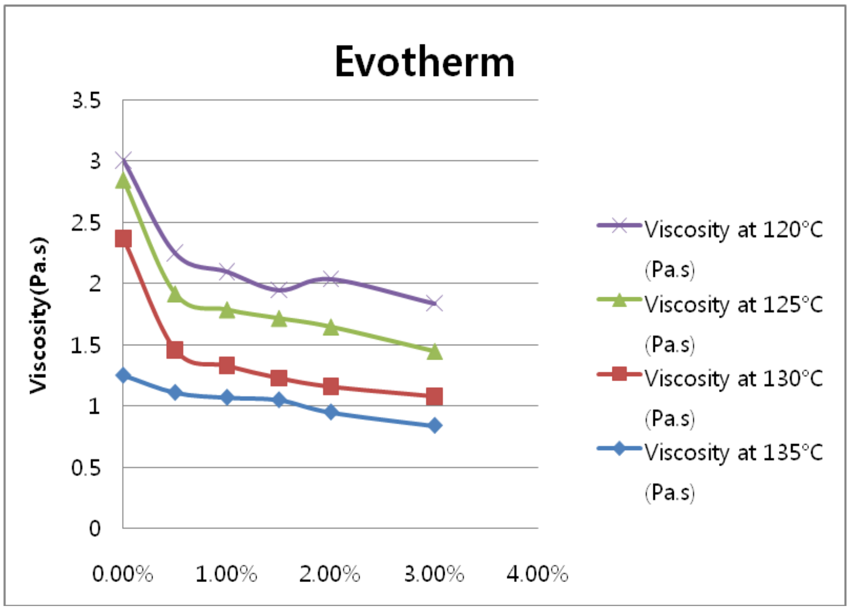


Figure 3.4 Plots of viscosity of asphalt binder using with Evotherm J1 against dosage rate

3.3.3 Rediset (C)

Rediset additive is a combination of organic additive and surfactants with the aim of enhancing the adhesion between asphalt and aggregates (Akzo Nobel 2009). It can be directly added to aggregates at a specified dosage rate by weight of asphalt. Table 3.4 summarizes the viscosity test results of asphalt binder using Rediset. As shown in Figure 3.5, the viscosity decreased as the temperature and dosage rate increased. The viscosity decreased significantly when the small amount of 0.5% was added at temperatures between 125 and 130 °C. However, for a temperature of 120 °C, the reduction in viscosity was not as significant, and the further reduction in viscosity was achieved by increasing the dosage rate from 0.5 to 1.0%.

Table 3.4 Viscosity test results of asphalt binder using Rediset

Dosage Rate	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.20	1.54	2.02	2.49
1.0%	1.13	1.44	1.93	2.14
1.5%	1.12	1.40	1.84	2.09
2.0%	1.11	1.39	1.86	1.99
3.0%	0.94	1.15	1.66	2.07

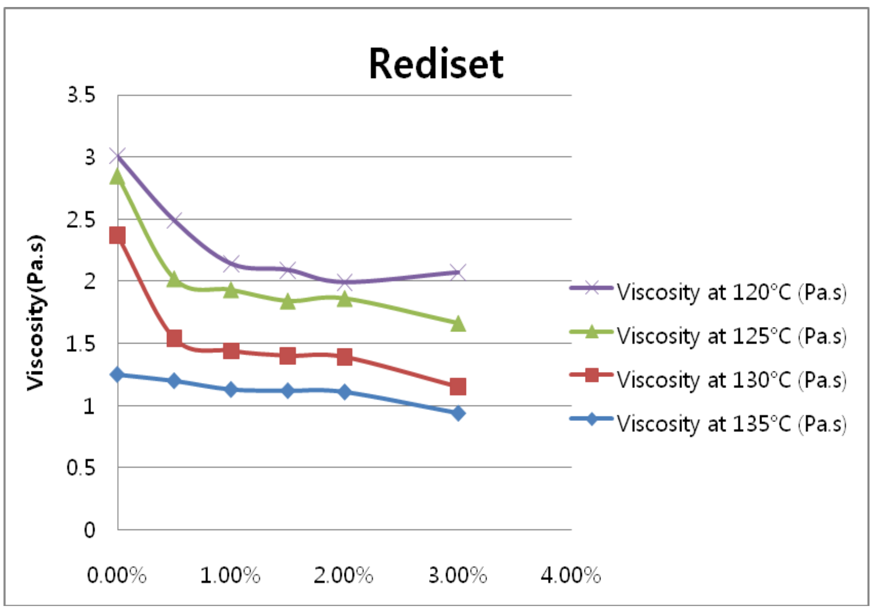


Figure 3.5 Plots of viscosity of asphalt binder using Rediset against dosage rate

3.3.4 Sasobit® (D)

Sasobit® is a Fischer-Tropsch wax produced from the coal gasification process and is typically added to the asphalt (wet process) or the asphalt mixture (dry process) at a specified dosage rate by weight of asphalt. Table 3.5 summarizes the viscosity test results of asphalt binder using Sasobit. As shown in Figure 3.6, the viscosity decreased as the temperature and dosage rate increased. The viscosity decreased significantly when the small amount of 0.5% was added at temperatures between 125 and 130 °C. Notwithstanding, for a temperature of 120 °C the reduction in viscosity was not as significant, and the further reduction in viscosity was achieved by increasing the dosage rate from 0.5 to 1.5%.

Table 3.5 Viscosity test results of asphalt binder using Sasobit

Dosage Rate	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.22	1.54	1.99	2.40
1.0%	1.22	1.46	1.94	2.32
1.5%	1.12	1.38	1.89	2.14
2.0%	0.96	1.32	1.72	2.06
3.0%	0.96	1.23	1.72	2.00

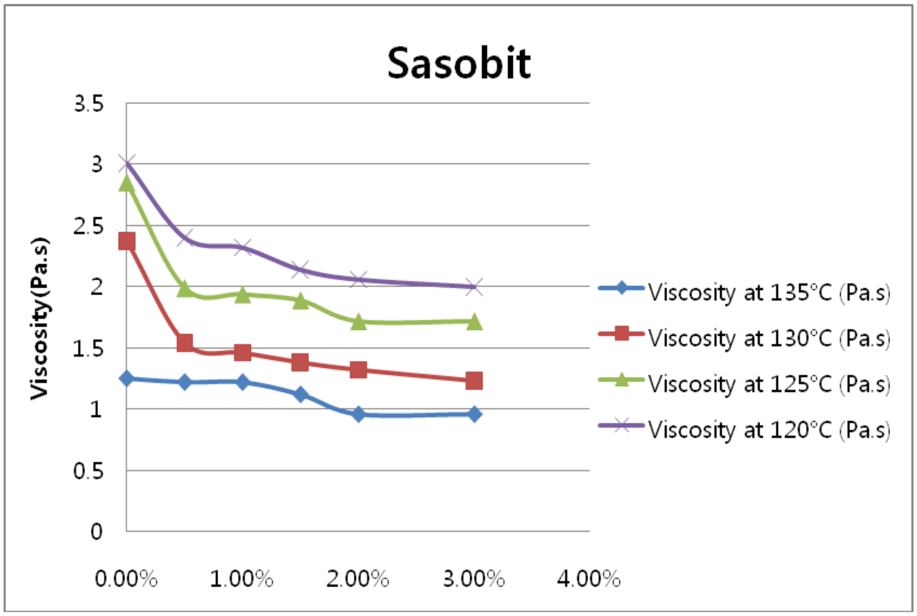


Figure 3.6 Plots of viscosity of asphalt binder using Sasobit

3.3.5 Cecabase RT (E)

Cecabase RT is room temperature liquid additive that can be mixed easily into the hot asphalt binder before the asphalt mix production. The liquid Cecabase RT additive can be added to asphalt at a specified dosage rate by weight of asphalt. Table 3.6 summarizes the viscosity test results of asphalt binder using Cecabase RT. As shown in Figure 3.7, the viscosity decreased as the temperature and dosage rate increased. The viscosity decreased significantly when the small amount of 0.5% was added at all temperatures. For a temperature of 120 °C, the reduction in viscosity was not as significant and the further reduction in viscosity was achieved by increasing the dosage rate from 0.5 to 1.0%. It should be noted that the reduction in viscosity was higher than any other WMA additives tested in this study.

Table 3.6 Viscosity test result of asphalt binder with Cecabase RT

Dosage Rate	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	0.95	1.16	1.44	1.96
1.0%	0.75	0.91	1.20	1.52
1.5%	0.73	0.86	1.11	1.45
2.0%	0.68	0.84	1.06	1.40
3.0%	0.65	0.78	0.99	1.28

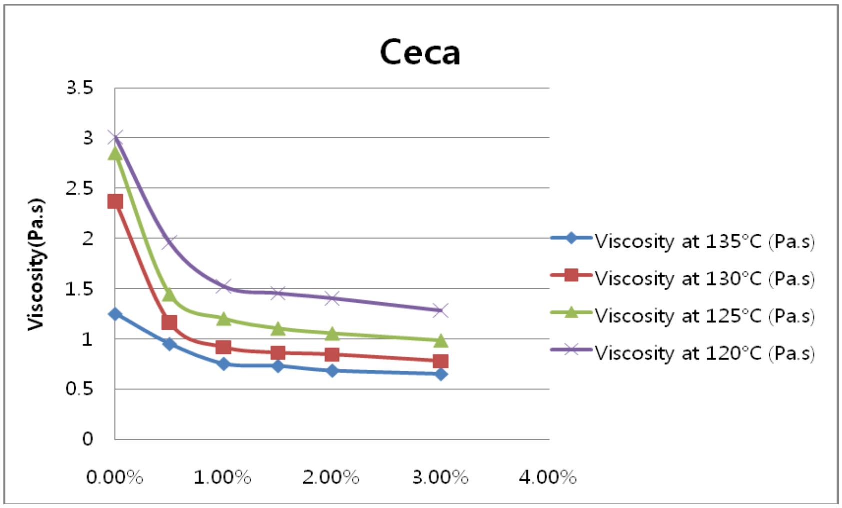


Figure 3.7 Plots of viscosity of asphalt binder using Cecabase RT

3.3.6 LEADCAP (F)

LEADCAP is an organic WMA additive, which is a wax-based composition including crystal controller and adhesion promoter. Crystal controller adjusts the wax crystallinity at the low temperature. LEADCAP additive can be added to asphalt at a specified dosage rate by the weight of asphalt. Table 3.7 summarizes the viscosity test results of asphalt binder using LEADCAP. As shown in Figure 3.8, the viscosity decreased as the temperature and dosage rate increased. The viscosity decreased significantly when the small amount of 0.5% was added at temperatures between 125 and 130 °C. However, for a temperature of 120 °C, the reduction in viscosity was not as significant and a further reduction was achieved by increasing the dosage rate from 0.5 to 1.0%. It should be noted that the reduction in viscosity was significantly higher than that of Sasobit particularly for temperatures between 120 and 125 °C.

Table 3.7 Viscosity test results of asphalt binder using LEADCAP

Dosage Rate	Viscosity at 135°C (Pa.s)	Viscosity at 130°C (Pa.s)	Viscosity at 125°C (Pa.s)	Viscosity at 120°C (Pa.s)
0.5%	1.12	1.08	1.28	1.81
1.0%	1.03	0.96	1.23	1.71
1.5%	0.89	0.91	1.20	2.08
2.0%	0.77	0.90	1.20	1.80
3.0%	0.76	0.92	1.18	3.18

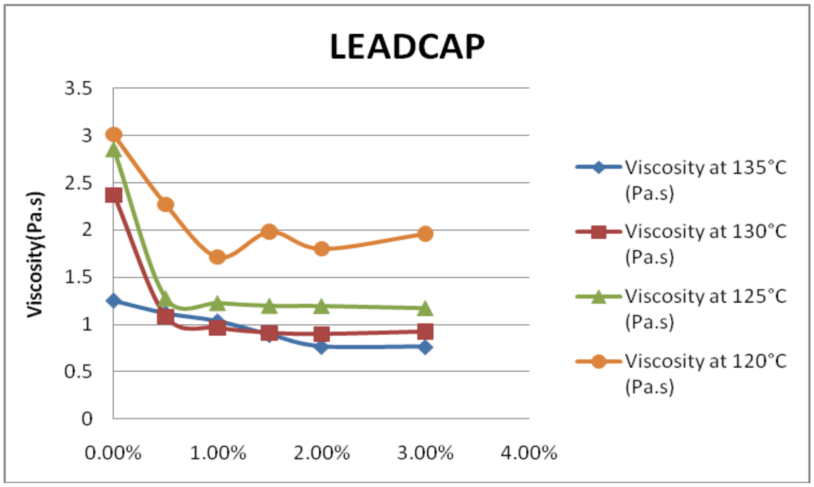
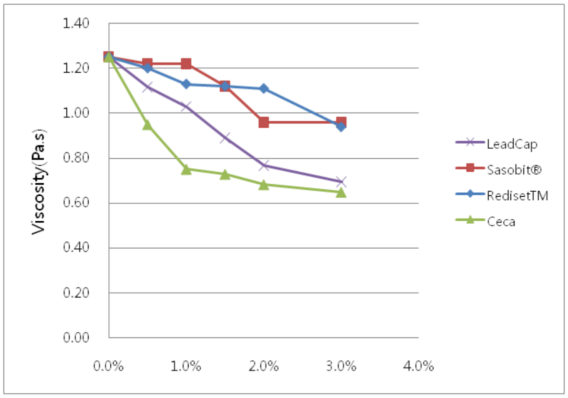


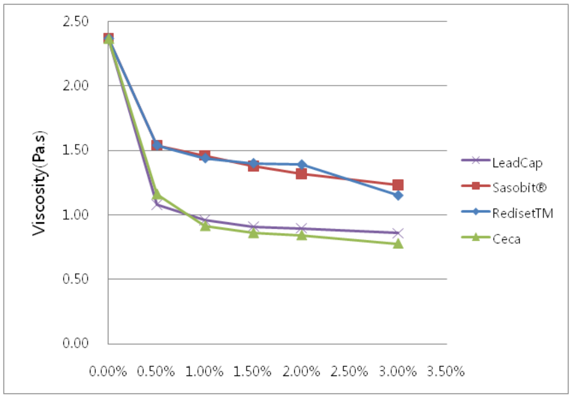
Figure 3.8 Plots of viscosity of asphalt binder using LEADCAP

3.4 Summary of Viscosity Test Results

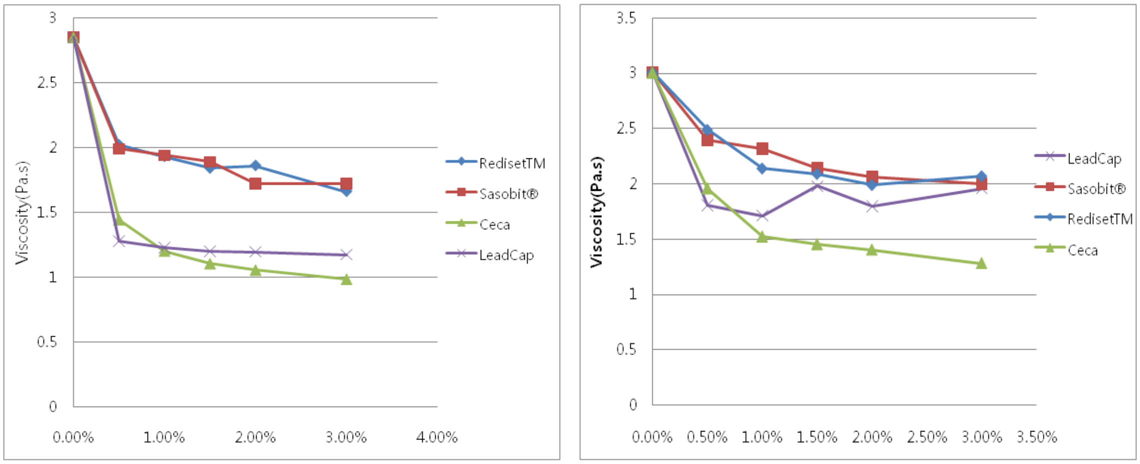
For each temperature from 135, 130, 125 to 120°C, the viscosity is plotted against the dosage rate in Figure 3.9 (a), (b), (c), and (d), respectively. As shown in Figure 3.9 (a), the test results show a steady decline in viscosity with increased dosage of additives. The viscosity of asphalt decreased significantly when 0.5% of CECABASE RT® was added, but the viscosity did not decrease when up to 1.0% of Sasobit® was added. Figure 3.9 (b) and (c) show a more drastic reduction in viscosity when 0.5% of WMA additive was added with the viscosity remaining relatively steady as the dosage rate increased up to 3.0%. The reduction pattern in viscosity as the dosage rate increases was similar for both CECABASE RT® and LEADCAP at all test temperatures and a similar pattern was observed for both Sasobit® and Rediset. Figure 3.9 (d) shows that the behavior of LEADCAP at 120°C became similar to Sasobit® and Rediset as the dosage rate increased from 1.0% to 3.0%.



(a) Temperature at 135°C



(b) Temperature 130°C



(c) Temperature 125°C (d) Temperature at 120°C

Figure 3.9 Plots of viscosity of asphalt binder at four different temperatures

3.5 Low Temperature Cracking Test Results

As shown in Figure 3.10, real-time plots of the strains developed in asphalt binders with varying amounts of LEADCAP were automatically generated as the test temperature was gradually lowered. The test ended when the sample was cracked, producing a sudden jump in strain. When the amount of LEADCAP increased from 0.5 to 3.0%, as can be seen from Figure 3.10, the cracking temperature of asphalt binder slightly decreased from -49.9°C to -48.6°C. This result indicates that the cracking temperature of asphalt binder would not be significantly affected by LEADCAP. However, it is interesting to note that when the amount of LEADCAP increased from 0.5% to 3.0%, the failure strain increased from 130.6 to 167.7 microstrains. This result supports that LEADCAP increases the ductility of asphalt binder.

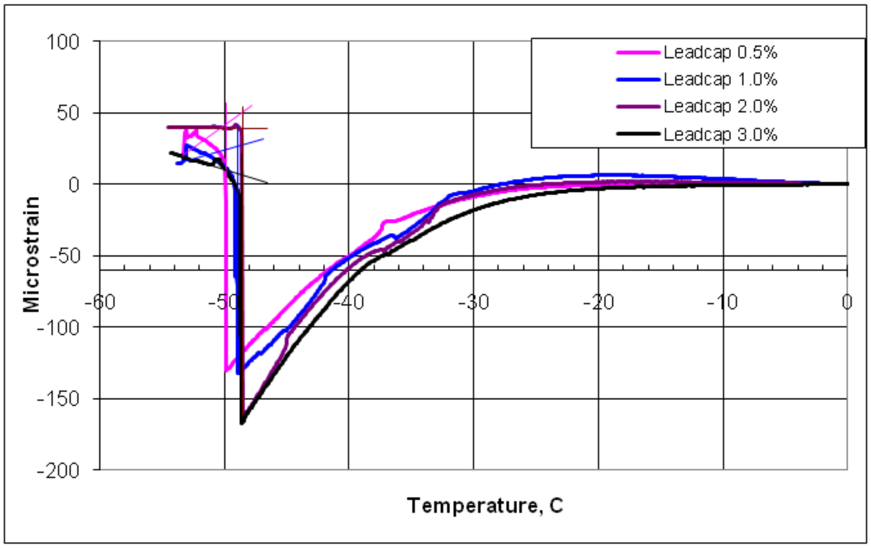


Figure 3.10 ABCD test results of the LEADCAP with varying amounts

Table 3.8 summarizes the cracking temperatures of asphalt binder with varying amounts of WMA additives at 0.5, 1.5, 2.5 and 3.0%. The cracking temperature was obtained directly from the temperature versus strain plot at the strain jump and plotted against the dosage rate in Figure 3.11. The virgin asphalt binder PG 64-34 cracked at -51.0°C and the PG 64-28 cracked at -41.3°C. As the WMA additives were increased from 0.5 to 3.0%, the cracking temperatures increased slightly, but remained steady near the cracking temperature of the virgin asphalt binder. The ABCD test results confirmed that the cracking temperature of asphalt binder was not significantly affected by any of these four WMA additives.

Table 3.8 Cracking Temperature of Binders with WMA Additives

Dosage	Sasobit (64-34)	Rediset (64-34)	Leadcap (64-34)	Leadcap (64-28)	Ceca (64-34)
0.50%	-48.3	-48.8	-49.8	-39.8	-48.43
1.50%	-49.77	-51.5	-48.9	-40.7	-49.5
2.50%	-49.29	-49.7	-48.6	-36.9	-48.85
3.00%	-48.1	-50.2	-48.6	-39.4	-51.67

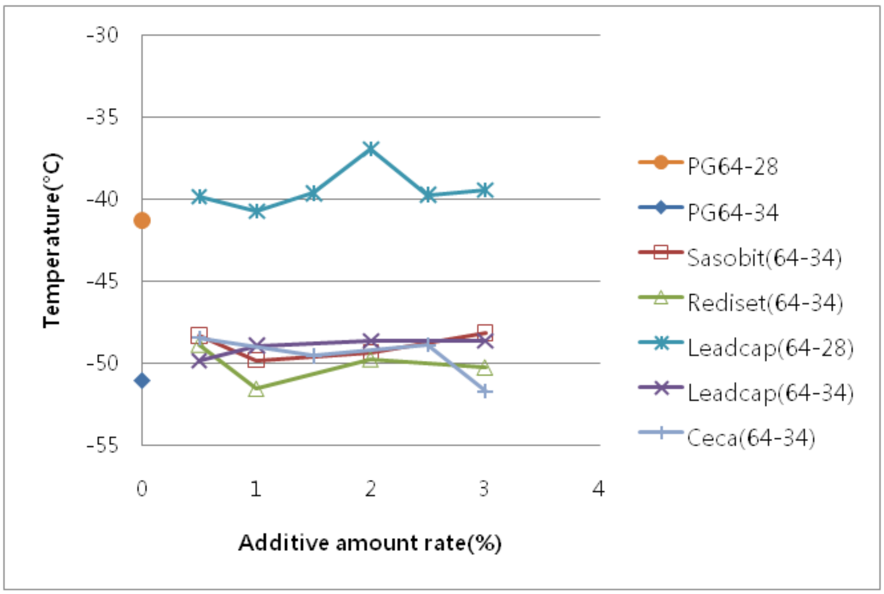


Figure 3.11 Temperature at which crack occurs by additive

4. EVALUATION OF FRICTION CHARACTERISTIC OF WMA PAVEMENT

The frictional characteristic of pavement is one of the primary factors needed to determine highway safety. Therefore, friction characteristics of WMA mixtures should be evaluated before they can be applied as a surface layer on highways. Galambos et al. (1977) reported that macrotexture is essential in providing escape channels to water in the tire-surface interaction, thus reducing hydroplaning. Jayawickrama et al. (1996) found that the magnitude of microtexture depends on initial roughness on the aggregate surface and the ability of the aggregate to retain this roughness against the polishing action of traffic. Chelliah (2002) reported that 25% of all traffic accidents occur when pavement surfaces are wet and 13.5 % of those traffic accidents caused by water film on pavement surfaces are critical. Over the years, the WMA research has been focused on the moisture susceptibility of the WMA mixtures and their rutting potential, and there is limited research done about friction characteristics of WMA pavements.

4.1 Skid Resistance of Pavements

The tire-pavement interactions are affected by road geometric design, paving materials, weather conditions and micro-topography (Ludema and Gujrati 1973). Over time, the skid resistance of the pavement surface decreases due to a polishing of pavement surface which is a result of shearing action from tires. Stephens and Geotz (1967) indicated that angularity of coarse aggregates contribute to tire-pavement friction by establishing point contacts that protrude from above the tire's water level. Geol (1995) reported that the coefficient of friction is significantly affected by the grading of aggregates used in the preparation of asphalt mixtures. As shown in Figure 4.1, the micro-texture would depend on surface aggregate properties in the material and is responsible mainly for pavement friction at low speeds. The macro-texture is the result of the size, shape, and arrangement of aggregate particles in the asphalt mixtures.

The locked wheel trailer can be used to measure the skid resistance of the pavement surface at any speed. The ribbed tire skid resistance values ranges from 27 at 96km/h to 57 at 64 km/h, while the smooth tire resistance values ranges from 11 at 96km/h to 53 at 64km/h on various types of pavement. Normally, the skid resistance value decreases as the speed increases. Hibbs (1996) measured the skid resistance on nine test sections at a speed of 56km/ h, 72km/ h, and 90km/ h. Skid resistance value ranged from 60 at 56km/h to 26 at 90km/h for ribbed and smooth tires on various pavement surfaces. The skid resistance value of smooth tires was generally lower than that of ribbed tire at high speed. The influence of macro and microtextures on the sliding friction coefficients are plotted against the speed (Hibbs 1996).

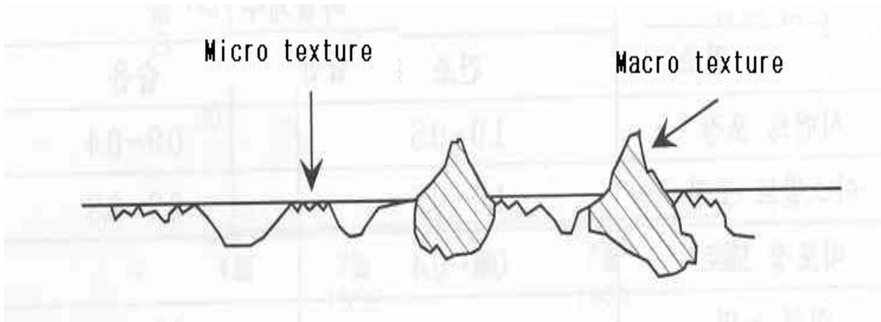


Figure 4.1 Type of the pavement surface texture

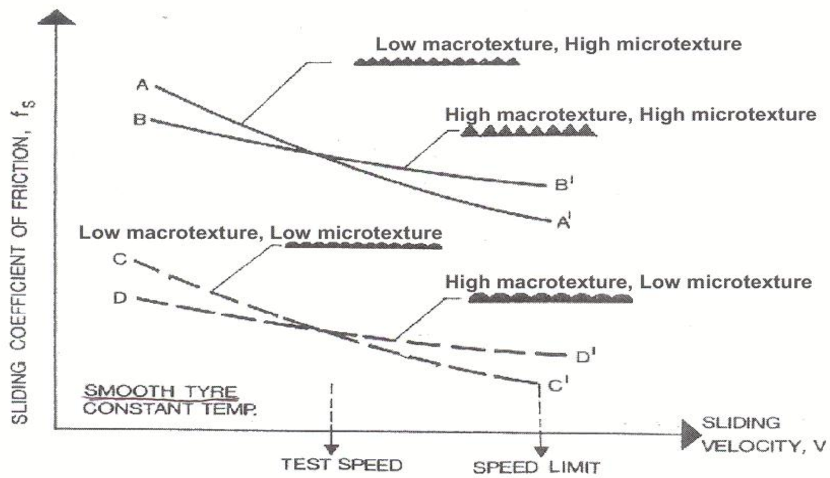


Figure 4.2 Decreasing skid resistance value as a function of speed (Hibbs 1996)

Road wear is caused by flaws in the pavement materials due to aggregate displacement and broken aggregates caused by tires. Further, the wear and abrasion of pavements can cause sliding accidents, particularly in rain. Poor drainage causes less contact between the road and tire surfaces resulting in a wet, slippery road surface—making traffic accidents likely. Figure 4.3 shows that, given the British Pendulum Number (BPN), the higher mean macro-texture depth will lower the accident rate (Alexandros 1997). Figure 4.4 illustrates that the Skid Number (SN) decreases as the water film thickness and speed increases (Alexandros 1997).

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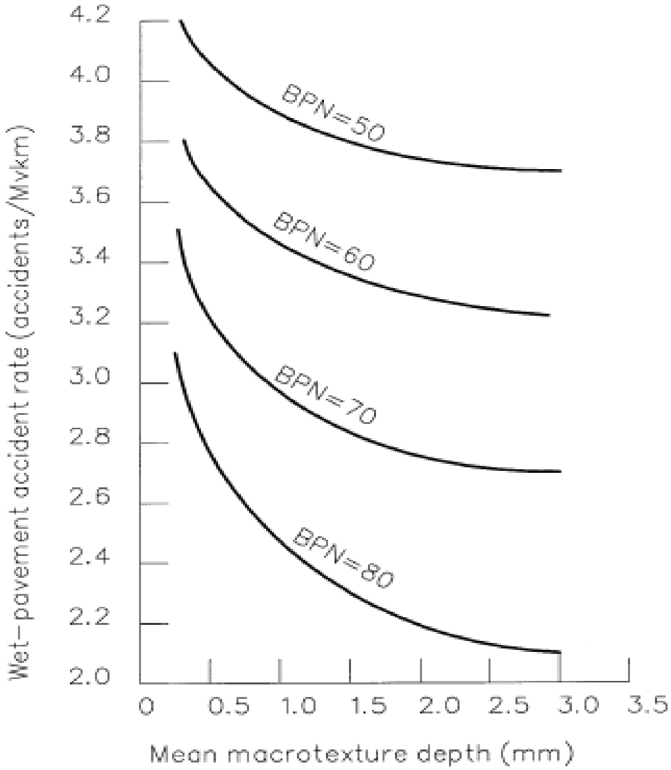

Figure 4.3 Relationship among accident rate, BPN and macrotexture (Alexandros 1997)

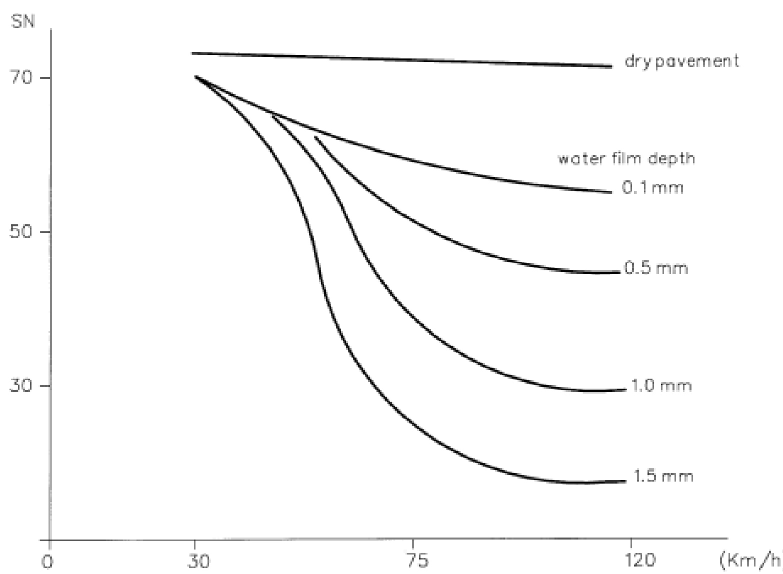

Figure 4.4 Relationship among SN, Water Film Depth and Speed (Alexandros 1997)

4.2 Laboratory Tests of Skid Resistance

A locked wheel skid trailer (ASTM E 274-97) is one of the more widely used devices to measure the skid resistance of pavements in the field. In this study, a British Pendulum Test (BPT), a regularly used mobile device, was used to evaluate the skid resistance of warm mix asphalt pavement and hot mix asphalt pavement in the laboratory.

4.2.1 Sand Patch Method

To evaluate the surface texture of WMA pavement, as shown in Figure 4.5, the surface texture depth was measured by the sand patch method following ASTM E965. The sand patch test procedure is described below.

1. Sweep the pavement surface with a soft hand brush.
2. Fill the cylinder with sand to the top and level with a straight edge.
3. Pour the measured sand on the test surface and, with the rubber disc spreading tool, sweeping it into a circular patch with the surface depressions filled to the level of the peaks.
4. Measure the diameter of the sand patch at four or more equally spaced locations and record to the nearest 1 mm (1/10 in.).
5. Calculate the surface texture depth by dividing the volume of sand by the circular surface area covered by sand.

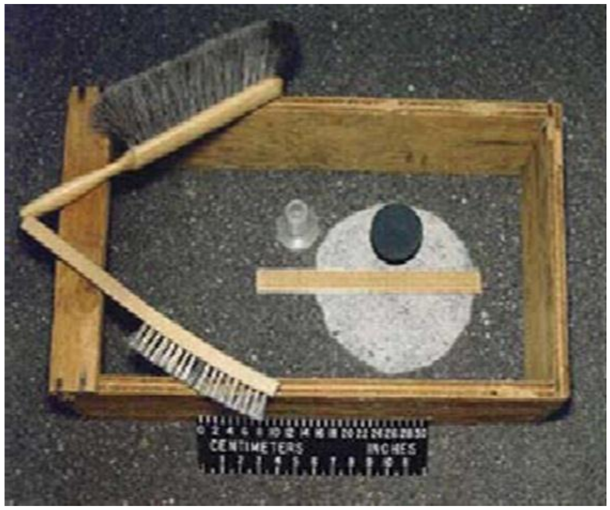

Figure 4.5 Tools to measure the surface texture of pavements

4.2.2 British Pendulum Test

To evaluate the friction characteristic of WMA mixtures, as shown in Figure 4.6, the friction coefficient was measured from the compacted specimens in the laboratory using the BPT device. The friction testing procedure using the BPT is summarized as follows:

1. Wet the test surface and slider using distilled water unless a dry test is being carried out.
2. Bring the pointer round to its stop. Release the pendulum arm by pressing the button C and catch it on its return swing before the slider strikes the road surface. Note the reading indicated by the pointer.
3. Return the arm and pointer to the release position, keeping the slider clear of the test surface by utilizing the lifting handle. Repeat swings, spreading the water over the contact area with a spray between each swing (unless dry testing). Record the readings as

required by the standard used.

4. Raise the head of the tester so that it swings clear of the surface again and check the free swing for zero error.

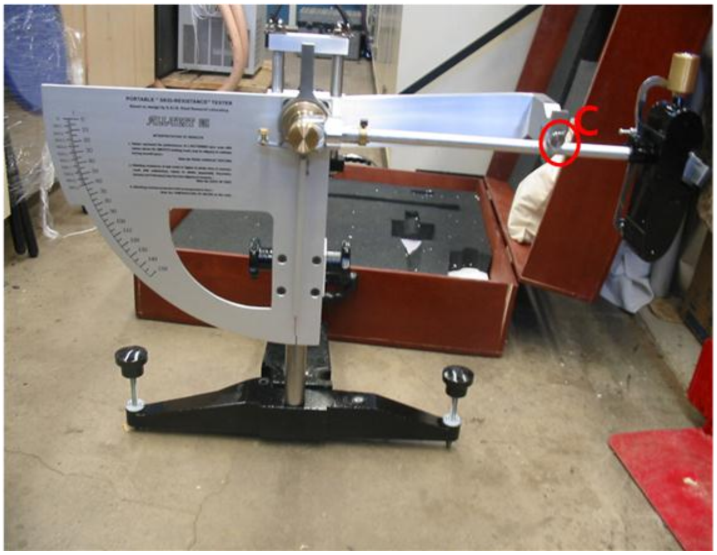

Figure 4.6 British Pendulum device to measure friction coefficient

As shown in Figure 4.7, the sliding length should be between 125 and 127 mm

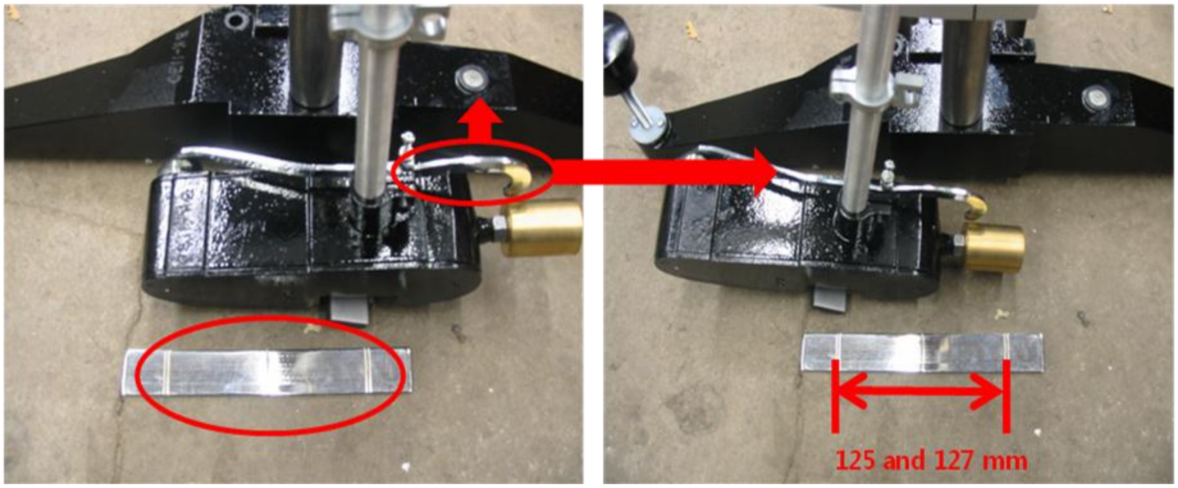

Figure 4.7 Sliding length needed for BPT

As expected, the friction coefficient was affected by the contact area of the BPT device on the asphalt specimen in the laboratory. When the bottom of the pendulum of the BPT device touches the center of the specimen, as shown in Figure 4.8, it will create a contact area in a rectangular shape. However, if the BPT device is not centered at the specimen, the contact area would be lessened.

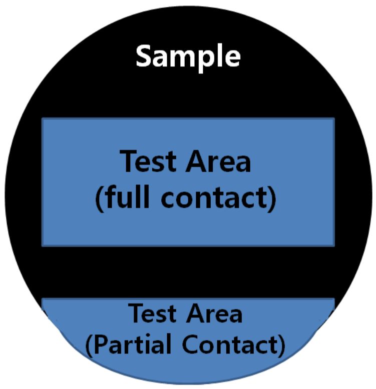

Figure 4.8 Contact area between sample and the bottom of the pendulum of BPT Device

Skid resistance values measured for three samples by different contact area are summarized in Table 4.1. Although there was no significant difference among three specimens, as shown in Figure 4.9, the difference in skid resistance values between full and partial contact areas was very significant, ranging between 15.3 and 16.8.

Table 4.1 Skid resistance measured from different contact area

Full	BPN	MTD	SN 40	Partial	BPN	MTD	SN 40
Sasobit	93.0	1.6	72.7	Sasobit	75.7	1.6	57.3
WMA 1	95.0	1.8	75.5	WMA 1	77.0	1.8	59.6
WMA 2	95.0	1.3	72.9	WMA 2	76.0	1.3	56.1

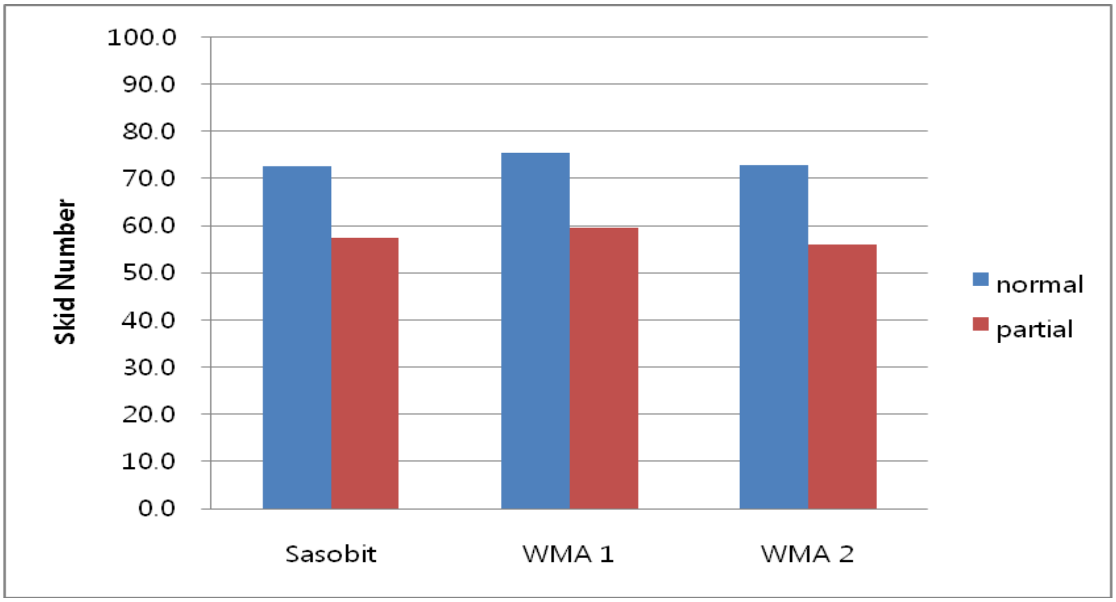

Figure 4.9 Skid number measured from different contact areas from different samples

4.2.3 Abrasion Test

The abrasion test was performed to evaluate the abrasion resistance of WMA mixtures using the polishing device, as shown in Figure 4.10. First, the WMA mixtures with Sasobit and LEADCAP were produced at temperatures between 117°C and 121°C whereas the control HMA mixtures were kept at 147°C. Second, the WMA mixtures were compacted at temperatures between 112°C and 123°C whereas the control HMA mixture remained between 126°C and 135°C. Two test specimens were prepared for each WMA additive and control HMA. The abrasion head was then rotated while touching on the surface at the speed of 78 rpm for 15 minutes.

Figure 4.10 Polishing testing device

Table 4.2 summarizes BPN, MTD and SN 40 values of WMA specimens with Sasobit, no additive and LEADCAP. It should be noted that the BPN value steadily decreased although the MTD value did not change significantly. For all three specimens, as shown in Figure 4.14, the most significant change in skid number has occurred between 30 and 45 minutes of abrasion whereas no significant change was observed between 45 and 65 minutes of abrasion. It can be postulated that the polishing effect on WMA is significant enough to necessitate a skid test on pavements in the field after several years of service. As shown in Figure 4.11, 4.12 and 4.13, it can be observed that the surface was worn by a rotating head for up to 60 minutes of abrasion.

Table 4.2 Skid resistant results of polishing test

	Sasobit			Control WMA			LEADCAP		
Time(min)	BPN	MTD	SN 40	BPN	MTD	SN 40	BPN	MTD	SN 40
0	92.0	1.6	71.7	89.3	1.2	67.5	102.0	1.1	78.2
15	93.0	1.6	72.6	89.3	1.1	67.0	95.0	1.1	72.0
30	89.3	1.5	69.1	82.7	1.1	61.1	94.3	1.1	71.4
45	73.3	1.2	53.0	75.7	1.1	54.8	70.3	0.9	49.0
60	73.7	1.2	53.8	76.7	1.1	55.9	70.3	0.9	49.1

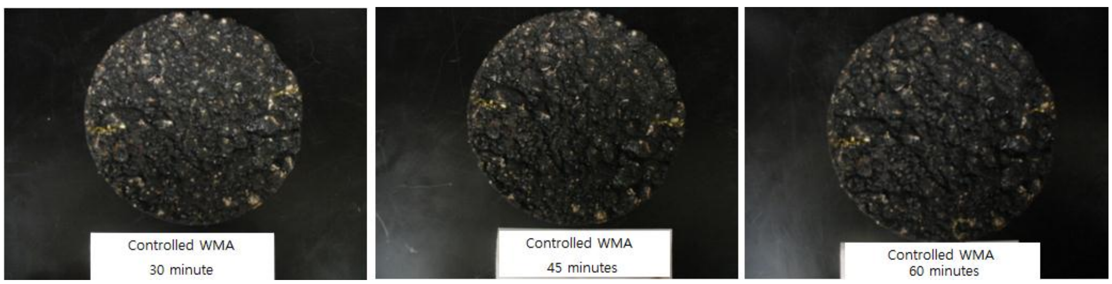

Figure 4.11 Control WMA mixture after abrasion for 30, 45, and 60 minutes

Figure 4.12 WMA-Sasobit mixture after abrasion for 30, 45, and 60 minutes

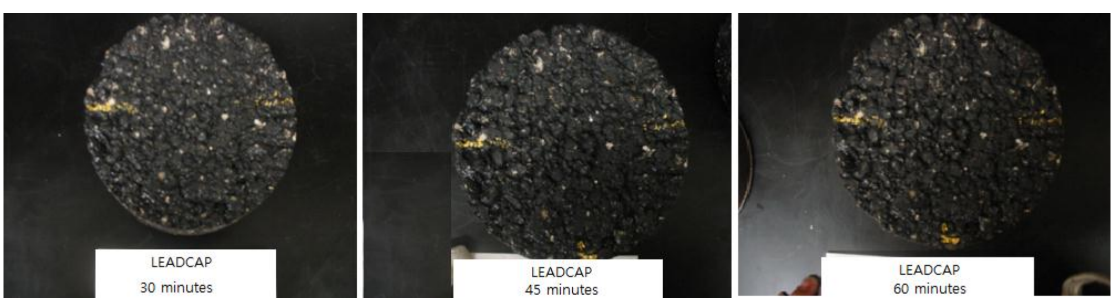

Figure 4.13 WMA-LEADCAP mixture after abrasion for 30, 45, and 60 minutes

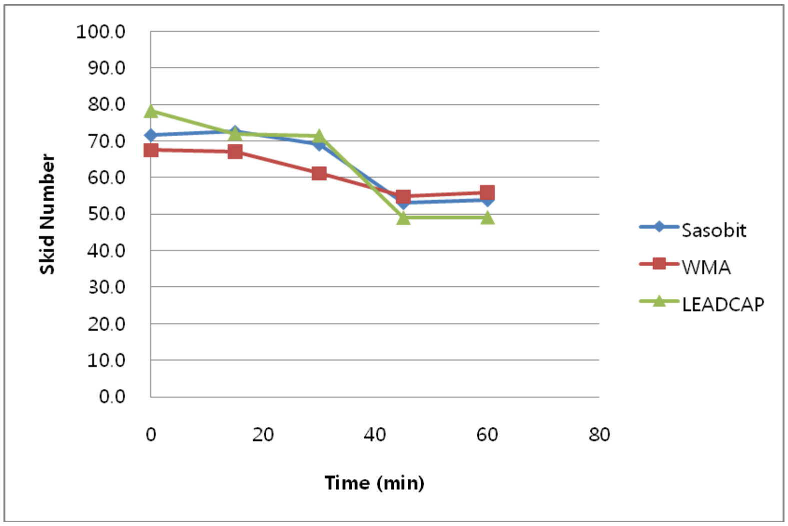

Figure 4.14 Skid number against polishing time for three different WMA mixtures

5. EVALUATION OF MOISTURE SENSITIVITY

It was suspected that WMA mixtures may be more susceptible to moisture damage than HMA mixtures. 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). Hurley and Prowell (2006) evaluated the moisture susceptibility of WMA mixtures containing Aspha-min®, Sasobit®, and Evotherm®. They reported that WMA mixtures with Aspha-min® exhibited the lower TSR value than HMA mixtures below the SuperPave TSR value 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. Gonzalez-Leon et al (2009) reported that WMA mixtures with Cecabase RT® additive achieved a minimum requirement of 0.75, which is a value derived from 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, the modified Lottman test was performed following AASHTO T 283 procedure. The experiment plan and the testing condition are summarized in Table 5.1.

Table 5.1 Condition of modified Lottman test

Classification	Specification
Condition	• Temperature: 25˚C • Dry & Wet Condition
WMA Additive	• LEADCAP • Sasobit
Sample Type	• HMA, HMA+Lime, HMA+Anti-stripping (LOF 65-00) • WMA, WMA+Lime, WMA+ Anti-stripping (LOF 65-00) • WMA (LEADCAP), WMA (LEADCAP)+Lime, WMA (LEADCAP)+ Anti-stripping (LOF 65-00) • WMA (Sasobit), WMA (Sasobit)+Lime, WMA (Sasobit)+ Anti-stripping (LOF 65-00)

5.1 Moisture Sensitivity Testing Procedure

To perform the modified Lottman test eight specimens, four for dry condition and four for wet condition, were prepared for each of the following: the control WMA mixture, WMA mixture with lime, WMA mixture with anti-stripping, the control HMA mixture, HMA mixture with lime, HMA mixture with anti-stripping and WMA mixtures with Sasobit additive. To prepare the test specimens with 7±0.5% air void, as summarized in Table 5.2, all specimens were compacted at between 11 and 40 gyrations. As shown in Figure 5.1, for dry conditioning, three specimens in a sealed pack were placed in the water bath at 25˚C for 2 hours, and 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 5.2 Number of gyrations applied to produce WMA and HMA specimens for moisture sensitivity test

Mix Type	Number of Gyrations							
	Dry Condition				Wet Condition			
	#1	#2	#3	#4	#1	#2	#3	#4
WMA	26	33	25	25	21	22	28	31
WMA_Lime	24	16	17	14	15	16	17	16
WMA_Anti-stripping (LOF 65 -00)	27	24	29	32	25	26	30	40
LEADCAP	31	26	27	27	26	24	30	34
LEADCAP_Lime	21	18	19	17	19	20	16	23
LEADCAP_Anti-stripping (LOF 65-00)	30	26	31	33	36	30	35	30
Sasobit	23	11	22	-	16	24	17	-
Sasobit_Lime	17	20	21	-	21	18	22	-
Sasobit_ Anti-stripping (LOF 65-00)	26	32	26	-	22	24	22	-
HMA	18	18	17	18	13	17	18	18
HMA_Lime	19	13	22	21	20	26	17	19
HMA_Anti-stripping(LOF 65 00)	16	12	20	11	17	17	11	12

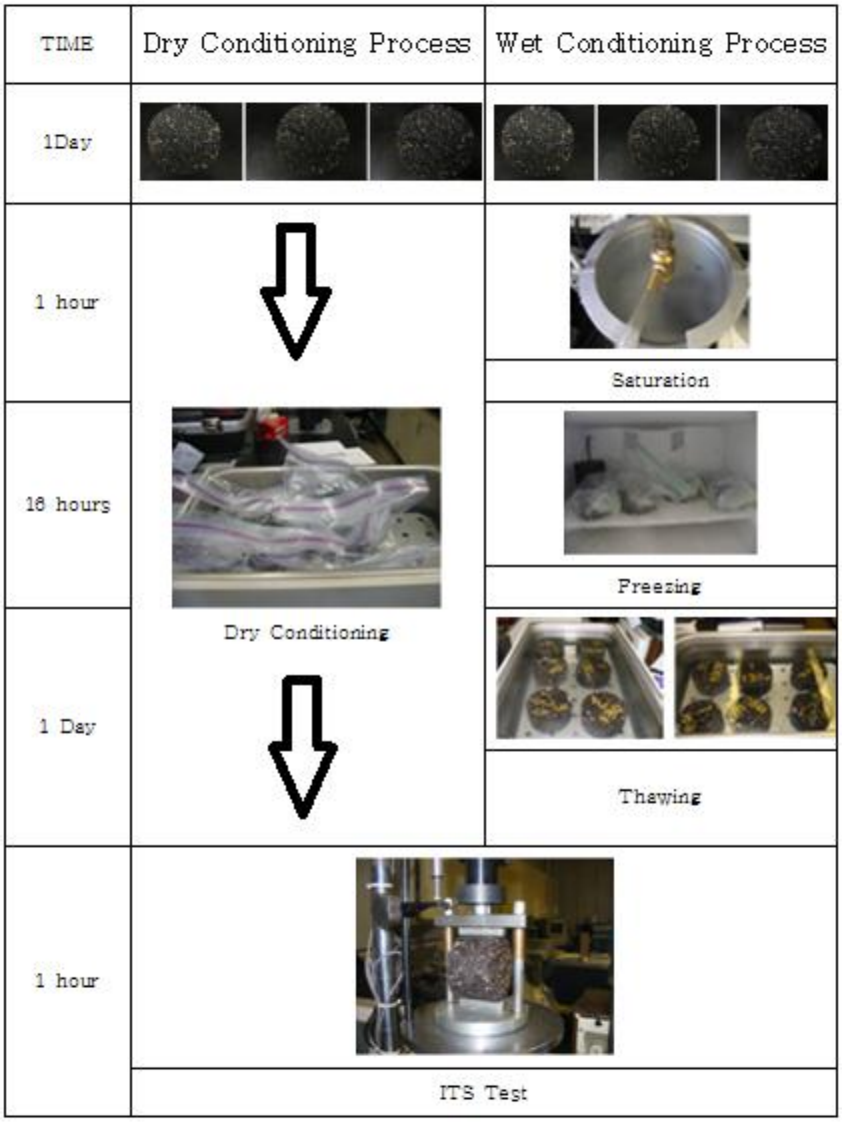

Figure 5.1 Flow chart of moisture sensitivity test for WMA and HMA specimens

5.2 Mixing and Compaction Temperatures

As shown in Table 5.3 and Table 5.4, 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 of around120°C whereas the control HMA mixture was kept around 135°C. WMA mixtures were compacted at temperatures between 105°C and 110°C with the control HMA mixture between 125°C and 130°C.

Table 5.3 Temperature data of producing WMA and HMA mixtures for moisture sensitivity tests

		Type of Mixture											
		Control WMA	Control WMA _Lime	Control WMA_ Anti-stripping	WMA_ LEADCAP	Wma_ LEADCAP _Lime	WMA_LEADCAP_ Anti-stripping	Sasobit	Sasobit _Lime	Sasobit _Anti-stripping	Control HMA	Control HMA _Lime	Control HMA_ Anti-stripping
Asphalt Binder		145	145	145	145	145	145	145	145	145	145	145	145
Aggregates		123	125	125	125	125	125	125	125	125	149	149	149
Mixing		119	120	120	119	121	119	120	120	119	137	134	135
Before Compaction	#1 (Dry)	113.6	111.8	117.7	107.9	104.6	112	108.5	101.4	105.9	127.4	126.9	128.9
After Compaction	#1 (Dry)	103.7	93.8	96.9	101.3	96.2	94.1	102.1	89.5	91.4	108.6	99.3	100.5
Before Compaction	#2 (Dry)	114.6	112.8	117.3	107.9	110	107.3	110.4	106.1	109.3	126.3	127.4	129.1
After Compaction	#2 (Dry)	106.8	91.5	97.4	90.5	89.3	95.4	99.6	86.3	87.1	104.3	101.3	103.4
Before Compaction	#3 (Dry)	115.5	110.1	116.7	104.6	109.1	108.5	96.3	107.4	104.2	125.6	125.6	126.4
After Compaction	#3 (Dry)	94.2	84.2	98.6	88.9	93.4	91.3	95.6	86.3	80.4	100.4	105.9	112.3
Before Compaction	#4 (Dry)	111.1	113.8	110.8	105.1	105.7	109.1	-	-	-	130.3	129.6	121.3
After Compaction	#4 (Dry)	91.4	87.8	89.4	91.1	84.9	88.9	-	-	-	104.6	106.1	100.6

Table 5.4 Temperature data of producing WMA and HMA mixtures for moisture sensitivity tests (continued)

		Type of Mixture											
		Control WMA	Control WMA _Lime	Control WMA_Antistripping	WMA_ LEADCAP	WMA_ LEADCAP _Lime	WMA_LEADCAP_ Anti-stripping	Sasobit	Sasobit _Lime	Sasobit _Anti-stripping	Control HMA	Control HMA _Lime	Control HMA_ Anti-stripping
Asphalt Binder		145	145	145	145	145	145	145	145	145	145	145	145
Aggregates		123	125	125	125	125	125	125	125	125	149	149	149
Mixing		119	120	120	119	121	119	120	120	119	135	135	136
Before Compaction	#1 (Wet)	109.4	108.3	112.3	105.1	104.3	107.9	106.9	107.1	106.9	131.3	125.3	133.8
After Compaction	#1 (Wet)	106.4	87.6	95.2	96.6	94	90.5	101.4	91.9	94.3	114.9	101.3	104.7
Before Compaction	#2 (Wet)	106.9	108.4	110.7	106.8	106.1	111.3	107.1	97.9	108.4	130.6	126.1	130.6
After Compaction	#2 (Wet)	105.5	91.1	87.4	99.6	89.3	91	94.9	88.3	87.9	109.9	103.6	102.4
Before Compaction	#3 (Wet)	107.0	107.3	111.5	105.7	105.9	111.6	109	106.9	104.3	n/a	125.6	127.6
After Compaction	#3 (Wet)	90.3	92.6	85.6	85.3	90.6	92.5	92.6	85.8	88.4	102.8	101.3	109.7
Before Compaction	#4 (Wet)	107.5	106.3	111.7	105.9	101.6	108.1	-	-	-	124.4	130.3	129.8
After Compaction	#4 (Wet)	85.4	83.6	87.3	89.3	89.5	89.9	-	-	-	105.9	101.9	111.9

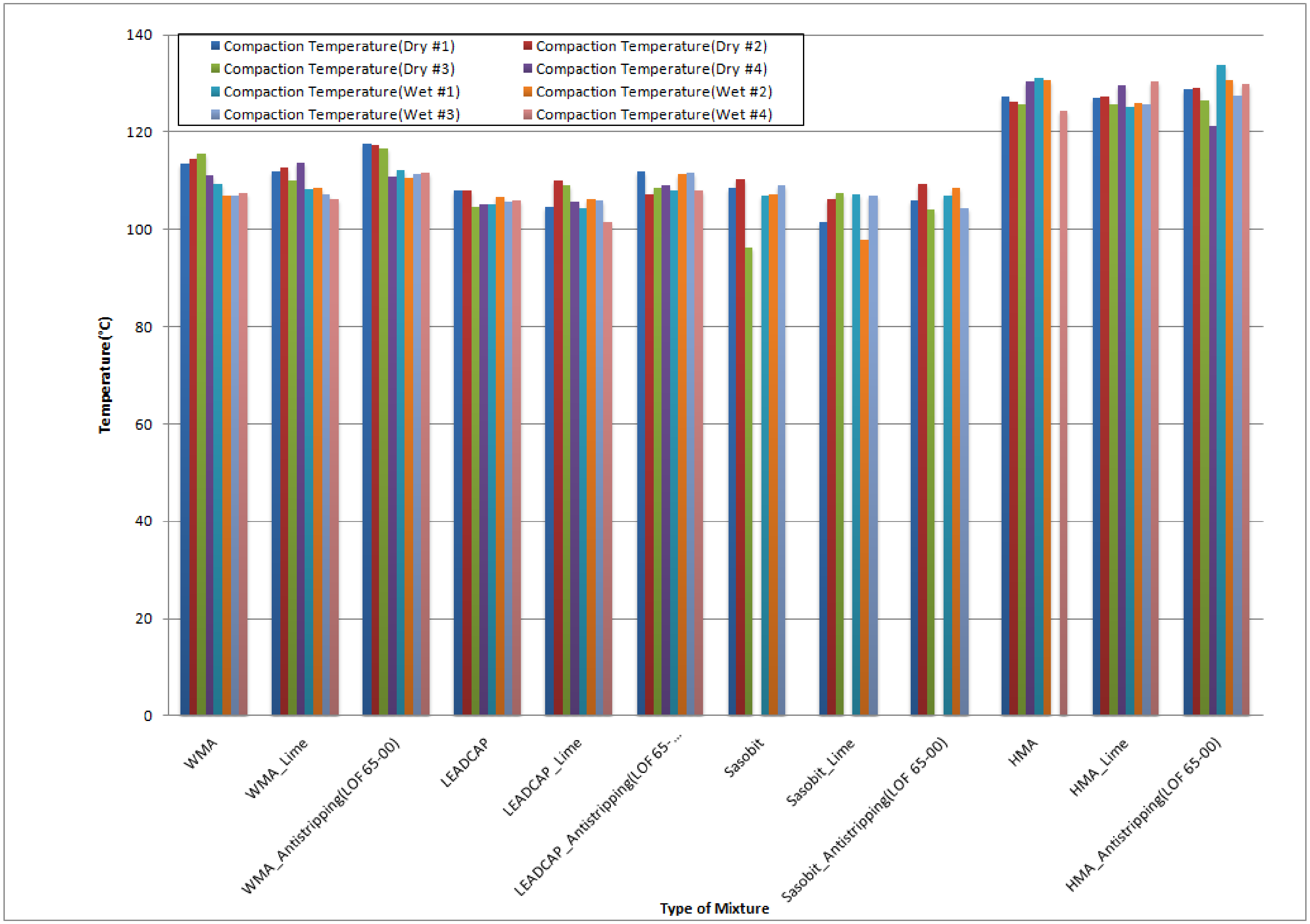

Figure 5.2 Mixing and compaction temperatures of WMA and HMA mixtures for moisture sensitivity test

5.3 Bulk Specific Gravities and Air Voids

The bulk specific gravities of each specimen were determined following AASHTO T 166 (AASHTO 2001). Table 5.5 and 5.6 summarize the bulk specific gravities and air voids of the WMA mixtures and the control HMA mixture and plotted in Figure 5.3 and 5.4, respectively. Air voids of all specimens ranged between 5.8% and 8.3%.

5.4 Results of Tensile Strength Ratio Test

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:

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

ITS_{Wet} = average indirect tensile strength at wet condition
ITS_{Dry} = average indirect tensile strength at dry condition

Table 5.7 summarizes indirect tensile strengths and TSR values of WMA, WMA-LEADCAP, WMA-Sasobit, and HMA with and without lime or Anti-Stripping Agent (ASA). The indirect tensile strengths of samples for each category were very consistent with a small standard deviation value, which indicates that indirect tensile strength tests were performed consistently. Figure 5.5 and 5.6 show plots of the average indirect tensile strengths and tensile strength ratio, respectively. The control WMA without additive exhibited the lowest TSR value of 53.3%, which increased to 66.6% with lime and 83.5% with ASA. WMA-Sasobit exhibited 73.7% but it slightly decreased to 72.7% with lime and 72.3% with ASA. WMA-LEADCAP exhibited 80.3% but it decreased to 78.5% with lime and increased to 81.4% with ASA. The control HMA exhibited 82.7% and it increased to 89.3% with lime and 92.6% with ASA. It can be concluded that TSR values of both WMA-Sasobit and WMA-LEADCAP were not affected by lime or ASA.

Table 5.5 Bulk specific gravities of WMA and HMA mixtures for moisture sensitivity tests

Condition		Control WMA	Control WMA_ Lime	Control WMA_Anti-stripping	WMA_ LEADCAP	WMA_ LEADCAP _Lime	WMA_ LEADCAP _Anti-stripping	Sasobit	Sasobit _Lime	Sasobit_ Anti-stripping	Control HMA	Control HMA _Lime	Control HMA_Anti-stripping
Dry	# 1	2.23	2.27	2.28	2.28	2.26	2.24	2.27	2.29	2.27	2.27	2.28	2.28
	# 2	2.22	2.27	2.22	2.27	2.26	2.26	2.27	2.24	2.28	2.28	2.28	2.26
	# 3	2.27	2.27	2.27	2.28	2.25	2.26	2.26	2.22	2.28	2.29	2.28	2.26
	# 4	2.23	2.24	2.25	2.27	2.27	2.27	2.27	2.26	2.27	2.28	2.28	2.26
	Ave.	2.24	2.26	2.26	2.28	2.26	2.26	2.27	2.25	2.28	2.28	2.28	2.26
	St. dev.	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.00	0.01
Wet	# 1	2.3	2.27	2.23	2.27	2.26	2.27	2.27	2.28	2.27	2.25	2.28	2.27
	# 2	2.23	2.24	2.24	2.26	2.25	2.24	2.27	2.25	2.27	2.27	2.27	2.27
	# 3	2.23	2.25	2.28	2.28	2.27	2.26	2.27	2.26	2.28	2.27	2.27	2.26
	# 4	2.22	2.23	2.22	2.27	2.26	2.26	2.27	2.29	2.28	2.25	2.28	2.25
	Ave.	2.25	2.25	2.24	2.27	2.26	2.26	2.27	2.27	2.28	2.26	2.28	2.26
	St. dev.	0.04	0.02	0.03	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.00	0.01

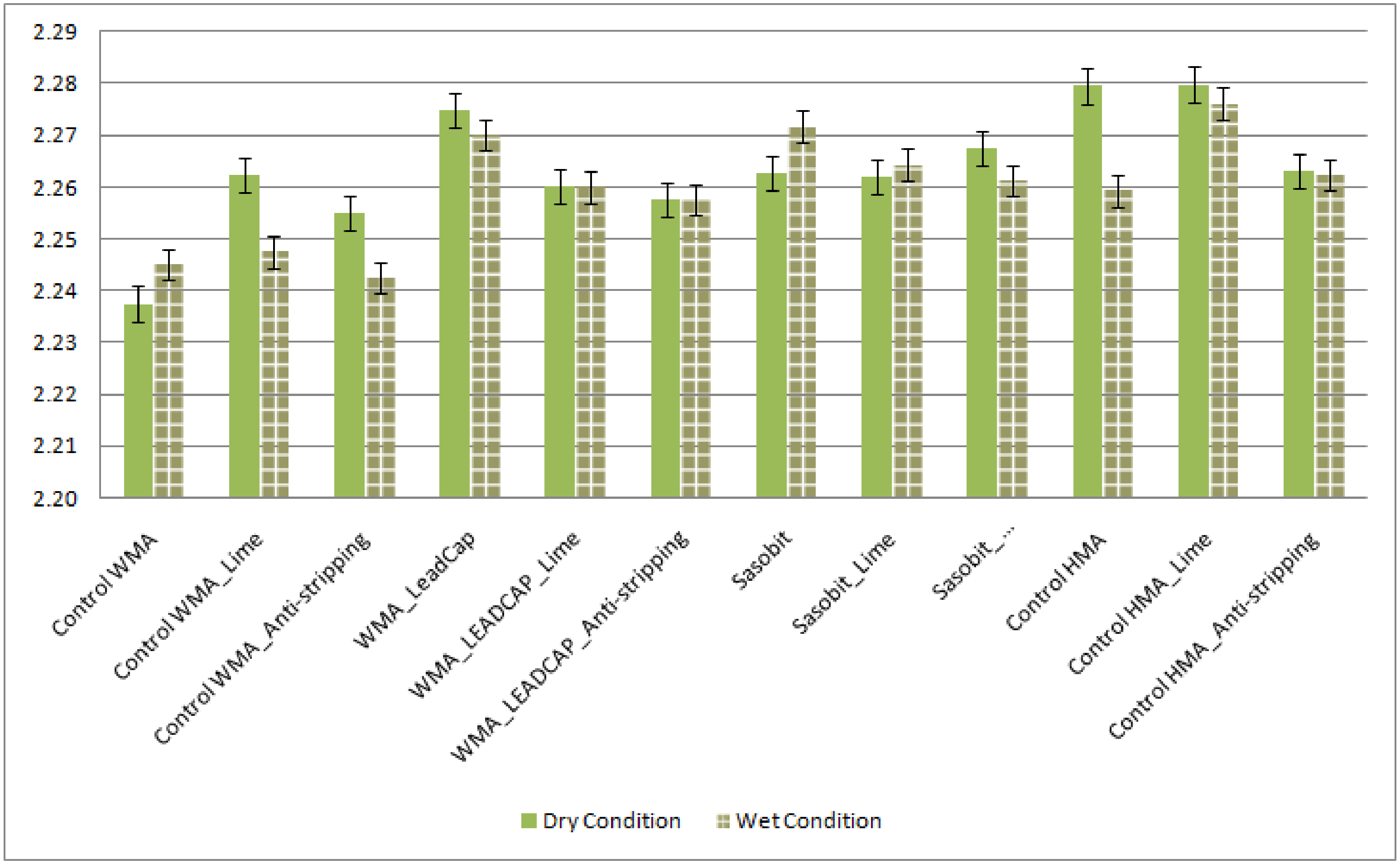

Figure 5.3 Average bulk specific gravities of WMA and HMA mixtures for moisture sensitivity test

Table 5.6 Air voids of WMA and HMA mixtures for moisture sensitivity tests

Condition		Control WMA	Control WMA_Lime	Control WMA_Anti-stripping	WMA_ LEADCAP	WMA_ LEADCAP _Lime	WMA_ LEADCAP _Anti-stripping	Sasobit	Sasobit _Lime	Sasobit_ Anti-stripping	Control HMA	Control HMA _Lime	Control HMA_Anti-stripping
Dry	# 1	8.6	5.9	6.6	6.9	6.4	8.2	6	6.6	6.8	6.1	5.3	6.6
	# 2	9	6	8.7	7.3	6.4	7.4	7.4	6.4	7.3	5.5	5.1	7.1
	# 3	7.2	5.9	6.9	7	6.8	7.7	6	5.6	7.9	5.3	5.4	7.3
	# 4	8.7	7.4	7.7	7.2	6	7.3	-	-	-	5.8	5.3	7.4
	Ave.	8.4	6.3	7.5	7.1	6.4	7.7	6.5	6.2	7.3	5.7	5.3	7.1
	Stdev	0.8	0.7	0.9	0.2	0.3	0.4	0.8	0.5	0.6	0.4	0.1	0.4
Wet	# 1	5.9	5.9	8.3	7.1	6.4	7.2	6.4	6.3	7.2	6.9	5.3	6.9
	# 2	8.7	7.4	8.1	7.5	6.8	8.2	6.2	6	8.3	6.2	5.6	6.9
	# 3	8.6	7	6.6	6.9	6	7.4	5.8	6.1	7.3	6.2	5.6	7.1
	# 4	9	7.6	8.7	7.3	6.3	7.7	-	-	-	6.7	5.3	7.6
	Ave.	8.1	7.0	7.9	7.2	6.4	7.6	6.1	6.1	7.6	6.5	5.4	7.1
	Stdev	1.4	0.8	0.9	0.3	0.3	0.4	0.3	0.2	0.6	0.3	0.1	0.3

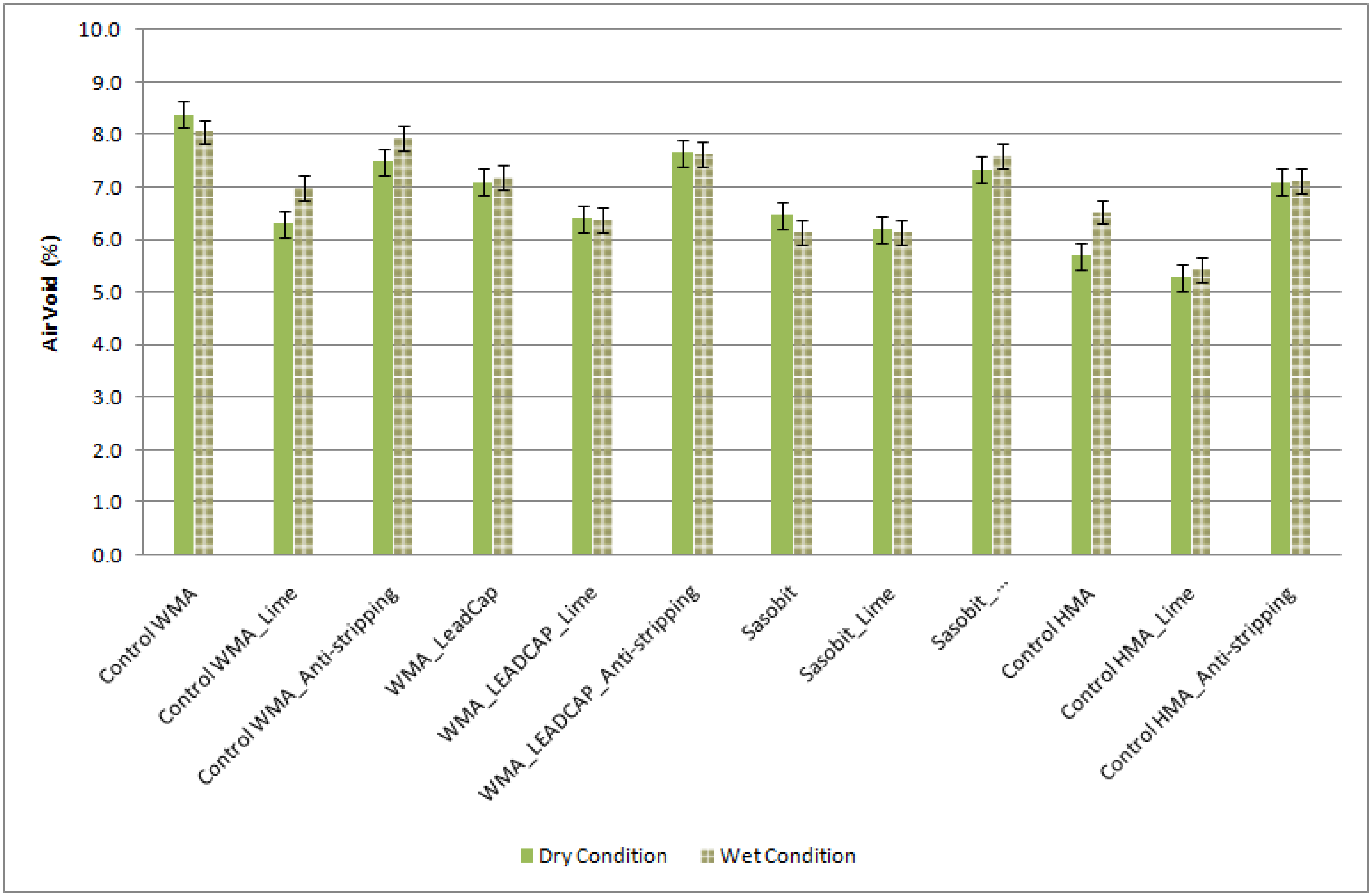

Figure 5.4 Average air voids of WMA and HMA mixtures for moisture sensitivity test

Table 5.7 Indirect tensile strengths at dry and wet conditions and tensile strength ratio of WMA and HMA mixtures

Condition		Control WMA	Control WMA _Lime	Control WMA_Anti-stripping	WMA_ LEADCAP	WMA_ LEADCAP _Lime	WMA_ LEADCAP_ Anti-stripping	Sasobit	Sasobit _Lime	Sasobit_ Anti-stripping	Control HMA	Control HMA_Lime	Control HMA_Anti-stripping
		Type of Mixture (ps)											
Dry Condition	# 1	103.2	123.7	131.9	n/a	124.7	116.0	137.1	147.8	148.9	105.9	125.5	134.9
	# 2	110.5	116.1	123.8	104.4	134.2	120.3	128.4	149.8	146.3	116.3	134.0	127.1
	# 3	n/a	111.1	127.9	111.3	134.7	116.5	135.3	154.3	146.8	117.8	141.4	135.4
	# 4	111.5	120.2	131.8	117.8	129.8	127.4	-	-	-	116.8	137.1	128.4
	Ave.	108.4	117.8	128.9	111.2	130.8	120.0	133.6	150.6	147.3	114.2	134.5	131.4
	St.dev.	4.5	5.4	3.8	6.7	4.7	5.2	4.6	3.3	1.4	5.6	6.8	4.3
Wet Condition	# 1	52.3	75.1	104.5	n/a	100.7	97.7	100.5	110.1	106.3	88.3	108.4	119.2
	# 2	55.0	76.1	102.3	87.4	101.9	96.7	100.0	108.1	109.4	94.2	126.2	118.9
	# 3	58.8	82.3	109.2	88.4	103.0	96.6	95.1	110.5	103.9	94.5	116.9	130.8
	# 4	64.9	80.4	114.7	92.2	105.1	100.0	-	-	-	100.8	129.0	117.9
	Ave.	57.8	78.5	107.7	89.3	102.7	97.7	98.5	109.5	106.5	94.5	120.1	121.7
	St.dev.	5.5	3.4	5.5	2.5	1.9	1.6	3.0	1.3	2.7	5.1	9.4	6.1
TSR (%)		53.3%	66.6%	83.5%	80.3%	78.5%	81.4%	73.7%	72.7%	72.3%	82.7%	89.3%	92.6%

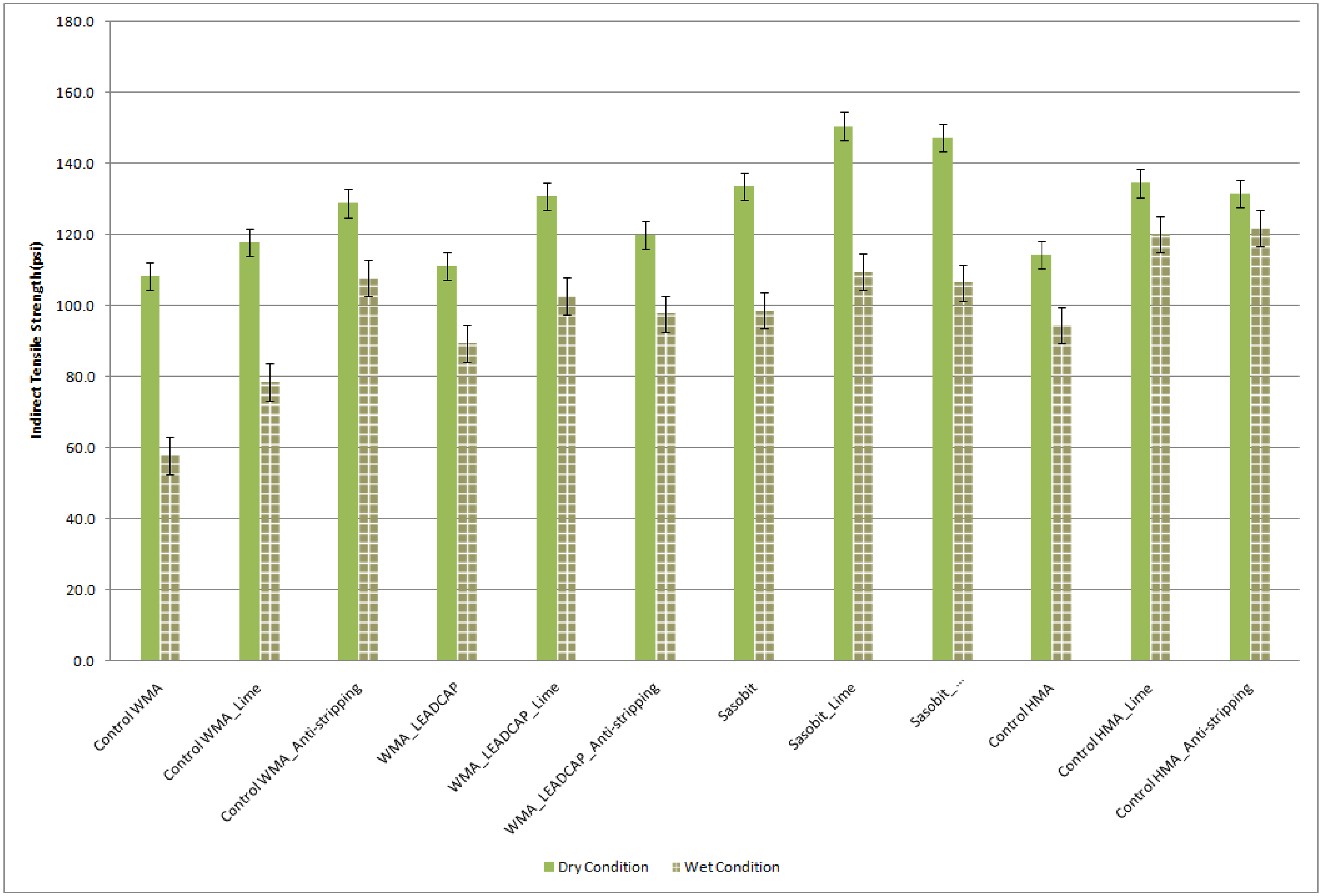

Figure 5.5 Average indirect tensile strength at dry and wet conditions

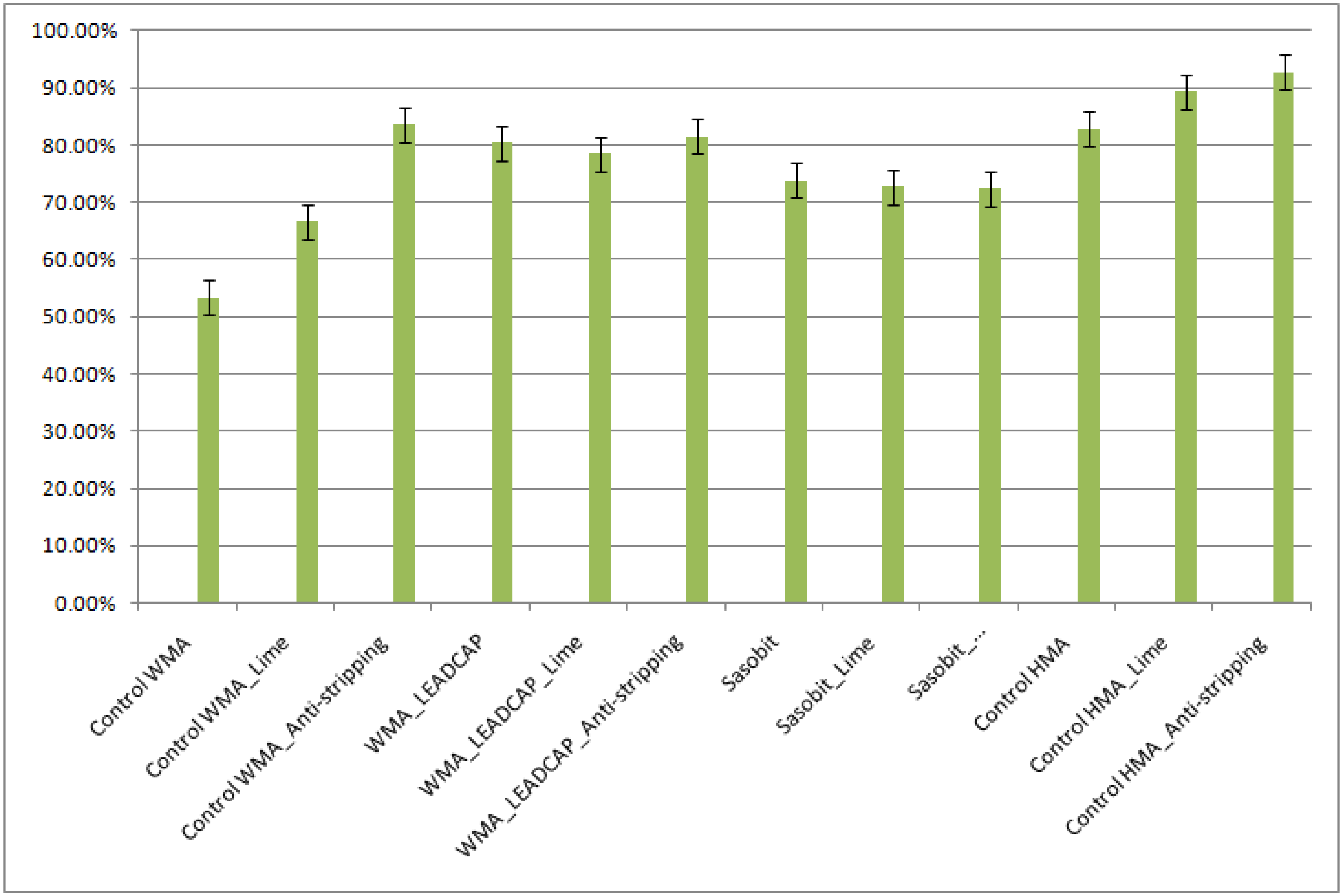

Figure 5.6 Tensile strength ratio of WMA and HMA mixtures

6. SUMMARY AND CONCLUSIONS

The implementation of Warm mix asphalt (WMA) is rapidly increasing. To provide a safe and reliable highway for heavier truck traffic with a high tire pressure the WMA mixtures should provide a sufficient skid resistance and a resistance to low-temperature cracking and moisture damage. In this study, we evaluated: (1) the temperature-viscosity relationship, (2) resistance to low-temperature cracking, (3) resistance to abrasion, and (4) the effectiveness of lime and anti-stripping agents in improving moisture sensitivity.

6.1 Conclusions

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

1. The viscosity of asphalt decreased significantly when 0.5% of WMA additive was added, but it remained relatively steady as the dosage rate increased up to 3.0%. The reduction pattern in viscosity as the dosage rate increases was similar for both CECABASE RT® and LEADCAP at all test temperatures of 120°C,125°C, 130°C and 135 °C. A similar pattern was observed for both Sasobit® and Rediset.
2. Based on the ABCD test device, the virgin asphalt binder PG 64-34 cracked at -51.0°C and the PG 64-28 cracked at -41.3°C. As the WMA additives were increased from 0.5 to 3.0%, the cracking temperatures increased slightly, but remained steady near the cracking temperature of the virgin asphalt binder. The ABCD test results confirmed that the

cracking temperature of the asphalt binder was not significantly affected by any of these four WMA additives.

3. The BPN value steadily decreased as the specimen surface was abraded by a rotating rubber although this did not change the MTD value significantly. The most significant change in BPN occurred between 30 and 45 minutes of abrasion, whereas no significant change was observed between 45 and 65 minutes of abrasion.
4. The control WMA without additive exhibited the lowest Tensile Strength Ratio (TSR) value of 53.3%, which increased to 66.6% with lime and 83.5% with an Anti-stripping agent (ASA). WMA-Sasobit exhibited 73.7% but it slightly decreased to 72.7% with lime and 72.3% with ASA. WMA-LEADCAP exhibited 80.3% but it decreased to 78.5% with lime and increased to 81.4% with ASA. The control HMA exhibited 82.7% and it increased to 89.3% with lime and 92.6% with ASA. It can be concluded that TSR values of both WMA-Sasobit and WMA-LEADCAP were not affected by lime or ASA.

6.2 Future Studies

A more extensive study should be performed quantifying the temperature-viscosity relationship of asphalt mixed with varying amounts of WMA additives at different temperatures. Additionally, a more extensive study should be performed on the effect of lime and anti-stripping agent on WMA mixtures with various additives. Finally, it is recommended that the skid test should be performed on WMA pavements in the field after several years of service.

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