January 2015

Rut Performance Of In-Situ Warm Mix Asphalt Overlays In North Dakota

Mohammad Mahdi Rezapour Mashhadi

RUT PERFORMANCE OF IN-SITU WARM MIX ASPHALT OVERLAYS IN NORTH DAKOTA

by

Mohammad Mahdi Rezpour Mashhadi
Bachelor of Science, Islamic Azad University of Mashhad, 2007

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in Partial fulfillment of the Requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May 2015

This thesis, submitted by Mohammad Mahdi Rezapour Mashhadi in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

5/5/2015

Nabil Suleiman

Daba Gedafa 5/5/2015

Daba Gedafa

5/5/15

Iraj H.P. Mamaghani

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Wayne Swisher

Dean of the School of Graduate Studies

May 7, 2015

Date

Permission

Title Rut Performance of In-Situ Warm Mix Asphalt Overlays in North Dakota

Department Civil Engineering

Degree Master of Science

Signature: Mohammad Mahdi Rezapour Mashhadi

Date: 5/14/2015

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENTS

I would like to express my sincere appreciation and gratitude to my thesis committee chair, Dr. Nabil Suleiman, for his insight and continuous help throughout this research study. My sincere thanks are also extended to my committee members, Dr. Daba Gedafa and Dr. Iraj H.P. Mamaghani, for their valuable support and advice to complete this thesis.

ABSTRACT

With the concept of sustainable pavement materials and construction gaining acceptance in recent years, Warm Mix Asphalt (WMA) technology has been seen as a valid tool in realizing such sustainability. The low energy requirements and low emissions of WMA production and placement compared to Hot Mix Asphalts (HMA), synthesizes the sustainability appeal. As WMA pavements afford compaction at temperatures several dozen degrees lower than HMA, the rate of cooling drops dramatically allowing paving to continue into colder weather. North Dakota Department of Transportation (NDDOT) has used WMA technology in pavement construction in recent years hoping to extend the relatively short construction season.

Due to the lower mixing and compaction temperatures, the binders in warm mixes tend to exhibit less aging (stiffening) than the binders in hot mixes. In a previous study by a graduate student in civil engineering three years ago, the rut resistance of newly constructed WMA overlay near Valley City, WMA was found to be less rut resistant than their HMA specimen counterparts. For this study, field samples from the Valley City project were collected after being in service (aged) for three years. The research aims at comparing aged WMA rutting resistance to that when the specimens were newly constructed. The Asphalt Pavement Analyzer (APA) is used to compare the rutting resistances of WMA and the control HMA. Addressing the issue of binder aging and its effects on the overall rut performance of pavements gives further insight into the utility of WMA overlays in North Dakota.

The results show that there was a significant improvement in rutting resistance for aged WMA over un-aged WMA mixes. Even-though, the aged WMA specimens were less rut resistant than the aged HMA control sections, the rut resistance of WMA mixes under wet conditions show promising potential for durable WMA mixes.

CHAPTER 1

INTRODUCTION

1.1 Background

Warm mix asphalt (WMA) is a technology that allows the manufacturers of asphalt to lower the production and compaction temperature of asphalt mixtures by up to 100°F. Recently, stringent environmental regulations and rising prices of energy have resulted in an interest in using WMA technologies. Reducing mixing and compaction temperatures induce reduction in fuel cost and emission (Hurley & Prowell, 2005). Apart from those benefits, WMA can facilitate longer haul distances and cool weather pavement (D'Angelo et al., 2008).

Depending on the type of binder used, North American Hot Mix Asphalts (HMA) are generally heated to 300°F (Hurley & Prowell, 2005). WMA technologies give the processes and production the capability of reducing temperature without compromising the performance of the pavement (Hurley & Prowell, 2008).

A lower compaction temperature results in lower rutting resistance of asphalt mixes (Xiao et al., 2012). Traffic loading may cause lateral movement of pavement materials which results in a type of deformation or rutting distress. Consequently, vehicles can be pulled due to the rut depth (Xiao et al., 2010).

1.2 Objectives

The main objectives of this study are:

- To evaluate and compare the Asphalt Pavement Analyzer (APA) rut values of aged and un-aged WMA specimens for dry and wet conditions.
- To evaluate and compare the APA rut values of aged WMA and HMA specimens for dry and wet conditions.
- To assess the effects of in-place air voids on the rut resistances of WMA and HMA for aged and un-aged overlay mixes.

1.3 Organization of Thesis

Chapter 1 defines WMA and some of its advantages and disadvantages. A literature review of recent works on rutting resistance of WMA, especially with Evotherm, and some research on aged WMA rutting is presented in chapter 2. Chapter 3 presents specimen collection, preparation and rut testing. Chapter 4 displays and discusses the APA rut results under dry and wet conditions. Chapter 5 presents conclusions drawn from this study. Figure 1 illustrates the general flow chart for the experimental design of this study.

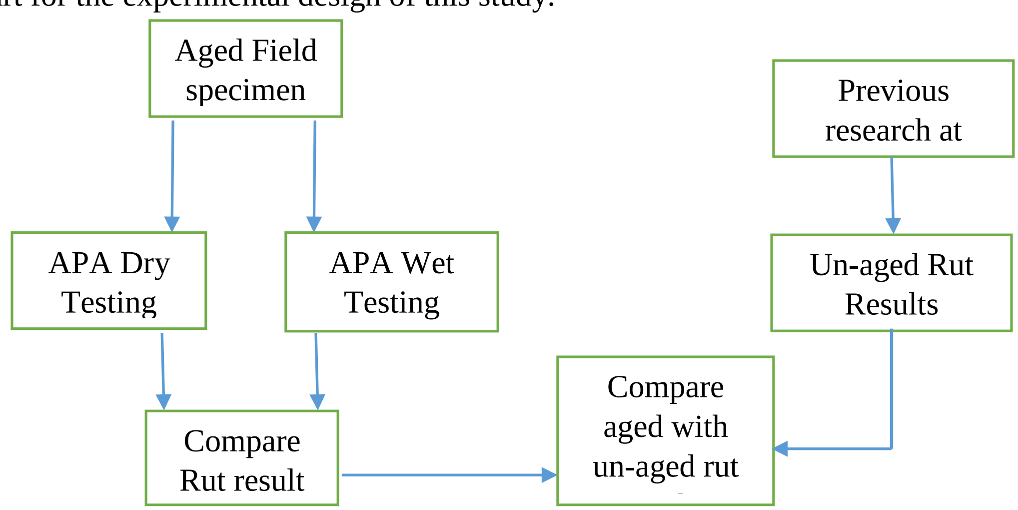

Figure 1: Flow chart for testing and analysis of the

CHAPTER 2

LITERATURE REVIEW

2.1 Different Types of Warm Mix Asphalt:

A number of WMA technologies have been identified and gained acceptance from the asphalt industry. In this technology, using a lower temperature during production and laying of WMA gives a big advantage. Some of these technologies are presented in Table1.

Table 1: Different WMA technologies (Prowell et al., 2007)

WMA Technology	Process Type
WAM-Foam	Foaming
Synthetic Zeolite	Foaming
Sasobit	Organic Additive
REVIX	Chemical Additive
Rediset WMX	Chemical Additive
(LEA)Low Energy Asphalt	Foaming
Evotherm	Chemical Additive
Double Barrel Green	Foaming

2.2 Rutting Evaluation of WMA

Evotherm was developed in the US. In the original type, the emulsion of Evotherm was produced using a chemical package designed to enhance adhesion, coating and workability. Most of the water flashes off as steam when the additive is mixed with the aggregate (Prowell, 2007).

Evotherm third Generation, 3G, is a water-free WMA which is easy and ready-to-use formula that allows application of asphalt at a lower temperature of 60 to 90°F lower than the traditional HMA.

However, moisture damage and rutting distress have been identified as the major concerns in WMA by many researchers (Doyle & Howard, 2013b; Kavussi & Hashemian, 2012).

A considerable number of articles has been published on WMA rutting with Evotherm.

A number of studies have reported decreased rutting of WMA with Evotherm. Hurley and Prowell (2008) measured rutting resistance of WMA with Evotherm by using the APA. They found out that the addition of Evotherm does not significantly affect the rutting resistance of asphalt.

Ghabchi et al. (2015) compared rutting resistance of WMA with Evotherm and HMA using Hamburg wheel tracking (HWT) test. The results reveal that the performance of WMA depends on the technology and the type of additive used, and WMA showed lower and, in some cases, equal rutting resistance compared to HMA.

The effects of three types of WMA additives were investigated by Du and Li (2012). The test results indicate that Evotherm Dispersed Asphalt Technology (DAT) improve rutting resistance of WMA.

Du and Liu (2012) evaluated the effects of WMA additives on the performance of SBS modified asphalt mixture by laboratory tests. The results indicate that Evotherm DAT reduced the mixing and compaction temperature by 40°C and it improved rutting resistance of the mixture.

Prowell et al. (2007) investigated field performance of WMA at National Centre for Asphalt Technology test track by incorporating Evotherm and PG 67-22 into the samples. The rutting resistance carried out by the APA indicated that WMA has similar rutting resistance as compare to HMA. A comparison was made between field and laboratory compacted asphalt concrete by Doyle and Howard (2013a) using WHT, they found no meaningful difference between two types of samples.

Leng et al. (2013) evaluated the mechanical properties of WMA made with two chemical additives which includes 0.5% Evotherm 3G and 0.5% Rediset LQ-1106. The results indicated that the rutting resistance of WMA was similar to that of the control HMA. Porter (2011) examined the effects of WMA additives on asphalt sensitivity to changes in temperature. The results indicate that the production of WMA with Evotherm is similar to HMA as long as the compaction temperature is not reduced more than 60 to 80°F. Shivaprasad et al. (2011) evaluated rutting susceptibility of HMA and WMA containing recycled materials and moist aggregates. Three WMA additives were used: Aspha-Min, Sasobit, and Evotherm. WMA showed similar rut resistance to HMA. They also found that aggregate source has a significant effect on rutting.

Never the less, there is some research indicating that mixtures with WMA have higher rutting resistance than HMA. Research carried out by Zhao et al. (2012) indicated that lowered compaction and mixing temperature will decrease the rutting resistance of WMA due to reduced binder aging.

Sargand et al. (2008) reported rutting of four lanes of asphalt pavement constructed in the Ohio Accelerated Pavement Loading Facility. Four lanes lateral profiles were recorded for rutting comparison under repeated application of 9,000 lb. All types of WMA, with Evotherm, Sasobit, and Aspha-Min, had more rutting under rolling wheel loads than traditional HMA, with Evotherm having the highest rutting.

Suleiman and Mandal (2010) assessed in situ performance of WMA with Evotherm 3G with APA in North Dakota. The results showed that WMA rut depth is 29% and 13% higher than those of HMA under wet and dry conditions, respectively. Reduced oxidation of the WMA binder is one of the reasons for reduced rutting resistance of WMA (West et al. 2014).

2.3 Aged WMA Rutting Resistance

Due to the fact that WMA is a relatively new product, there have not been enough old WMA pavements to investigate the effects of ageing behavior of aged WMA. Gandhi et al. (2010) conducted a laboratory study to evaluate the aging characteristics of WMA. They used an oven to artificially age the mixtures in order to simulate long-term aging and compare the results with un-aged samples. Although the results indicated that WMA with Sasobit improved the moisture susceptibility and rutting resistance of the samples, the additive did not have any effect on the rutting resistance of the samples after they were aged.

One of the objectives of the study carried out by Yina et al. (2015) was to investigate the performance of HMA and WMA with field and laboratory aging. They used Hamburg wheel tracking test, HWTT, to measure moisture susceptibility of the samples. They realized that laboratory and field aging significantly improve the moisture resistance of the mixtures, and better performance can be achieved by WMA versus HMA. Clements et al. (2012) investigated the effects of lowering mixing, compaction and aging temperatures using WMA with Evotherm 3G, 09 chemical additive. They found that rutting resistance was affected significantly by lowering the temperature of production. Behl et al. (2013) evaluated field performance of WMA pavement in India. Despite the fact that WMA sections were placed at a significantly lower temperature compared to HMA, WMA had a higher resilient modulus which can be an indication of better resistance to deformation and rutting resistance; and due to reduced oxidation and higher densities, the performance of WMA seemed to be improved over time. A field rutting evaluation of WMA after 64- month period indicated that rutting resistance of WMA is lower than HMA, 2.4 compare to 1.9, respectively (West et al. 2014).

So far, however, there has been little discussion about field performance of aged WMA by using the aggregate type and binder type of PG 58-28 used in ND, and as noted by Hurley and Prowell (2009) aggregate type and binder type make a difference on rutting resistance of a mixture. The experimental design used by Xiao et al. (2017) includes two lime contents, two aggregate moisture contents, three WMA including Evotherm and three aggregate sources. The results indicated that aggregate types significantly affected the rutting resistance of WMA. In response to a recent call for research to investigate the effects of aging on WMA and HMA with the aggregate and binder type used in ND, this study was undertaken to investigate and compare rutting resistance of aged WMA with that of HMA, a case study in ND.

CHAPTER 3

SPECIMEN COLLECTION, PREPARATION, AND TESTING

3.1 Sample Collection

The study test samples were collected from NDDOT overlay paving project near Valley City, North. About 5 miles of this experimental section project was paved with WMA using Evotherm 3G as an additive, while another 5 mile overlay section was considered the HMA control section. Both section. A PG 58-28 binder was used for both sections. The location of the WMA part is from reference point (RP) 56.480 to RF 61.233 and the control HMA part is from RP 51.000 to RP 56.000 (NDDOT, 2010).

Three years after construction, thirty two samples were collected for this study. Twenty four samples were used while the remaining eight samples were kept as spares. Those samples were taken from close proximity of an earlier study locations (Suleiman and Mandal, 2011) so proper comparisons can be made between the two studies based on sample aging.

3.2 Specimen Location

The samples used in this research for rutting comparison between WMA and HMA were provided by NDDOT. WMA and HMA have undergone the same traffic and environmental conditions. Similar binders and aggregates were used in the project where the samples were collected. The locations of the core specimen are presented in Table 2.

Table 2: Field core specimen identification

Core Locations	Core Number	Quantity - EB	Quantity - WB	Type
54.500	1-4	2	2	HMA
55.000	5-8	2	2	HMA
55.500	9-12	2	2	HMA
56.000	13-16	2	2	HMA
57.329	17-20	2	2	WMA
58.939	21-24	2	2	WMA
59.548	25-28	2	2	WMA
60.170	29-32	2	2	WMA

3.3 Specimen Preparation

Twenty four specimens were chosen for APA rut testing, twelve of them for dry and the other twelve for wet testing. Twelve HMA specimens were chosen in a similar manner to the WMA. A concrete saw was used to cut and prepare the specimens to a depth of three inches from the top, which is the required depth for APA rut testing. The top surface is kept undisturbed. Figure 3 illustrates the procedure. Different volumetric properties, bulk specific gravity and percent of air void of specimens were determined for possible correlation between rutting resistance and air voids.

Figure 2: The concrete saw used in sizing the specimens to APA height requirements.

3.4 Specimen Placement

For each APA run, 4 specimens, 2 HMA and 2 WMA, were used. Figure 3 demonstrates specimen placement in the molds. Two HMA specimens and 2 WMA specimens were tested as one run in the APA.

Figure 3: Placing specimens in the molds for running in APA

3.5 Samples Conditioning

For dry conditioning, prior to running the APA test, the specimens were heated for 6 hours to 58°C, matching the high temperature of the PG grade 58-28 used in the project by NDDOT. The 6 hour conditioning is done to ensure temperature uniformity throughout the specimen. This temperature would be maintained during the actual APA dry test as well. For wet conditioning, the specimens would be placed in a 58°C water bath for 24 hours prior to the test. The same test preparation procedure was maintained for both HMA and WMA cases.

3.6 Rut Testing

Asphalt Pavement Analyzer was used to compare the rutting resistance of WMA with correspondent HMA. Testing time for rutting is about 2 hours which consists of 8000 cycles. The wheel load applied in the APA is 100 psi which is uniformly applied on the specimens (Pirabarooban et al. 2003).

The utilization of the APA has been cost-effective, fast and practical to use. Evaluation of mix asphalt performance with respect to rutting was carried out using APA according to AASHTO TP 63-03, the standard method of test for determining rutting susceptibility of Asphalt paving mixture using APA. A 3/8 inch (9.0 mm) rutting depth was considered the criterion for failure. Figure 4 shows the rut results on four specimens after 8,000 APA loading cycles. In this figure, the two specimens on the left were HMA, and the two on the right are WMA specimens.

Figure 4: Rut depth by using APA: HMA, left, and WMA on the right

3.7 Mixing and Compaction Temperature of Specimens

According to the research carried out by Jongchul Song (2012) for NDDOT, WMA with Evotherm was laid down approximately 25 to 30°F lower than HMA on the respective job. The temperatures of pavement at windrow, behind the paver, and behind different rollers in North Dakota are presented in Table 3 for both HMA and WMA conditions. For comparison, the temperatures behind the roller would be used as compaction temperatures for WMA and HMA.

Table 3: Average WMA and HMA temperature during different pavement process operations in ND (Evert, 2013)

Average WMA and HMA Temperature (^oF)	Windrow	Behind Paver	Behind Roller	Behind 2nd Roller	Behind 3rd Roller
SS-3-020(072)069 WMA	249	234	228	161	162
SNH-3-281(093)128 HMA	283	273	250	224	165

3.8 Explaining Keywords

Throughout this paper the terms AWWMA, UWWMA, ADHMA, and UWHMA will be used to refer to aged wet WMA, un-aged wet WMA, aged dry HMA and un-aged wet HMA, respectively.

CHAPTER 4

RESULTS

4.1 Comparison between ADWMA and ADHMA rutting resistance

Rut resistance of asphalt under dry condition was investigated. The findings suggest that the difference between the average rutting depth of WMA and HMA is significant. The mean of WMA rut depth is 7.034 mm while the HMA has a mean rut depth of 4.45 mm. Which means that the rut resistance for WMA is 58 percent less than HMA under dry testing condition. The results are shown in Tables 4 and 5. As suggested by Brown et al. (2001), the Confidence level was set at 0.05 so if significance of 2-tailed test is less than 0.05, it means that we can reject the null hypothesis, H_o, or the difference is significant. Significance level of 0.05 was used for the comparisons in this thesis. Statistical Package for the Social Sciences (SPSS) was used as a means to analyze the data.

Table 4: Mean and standard deviation of ADWMA and ADHMA rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
ADWMA	6	7.0344	2.22042
ADHMA	6	4.4472	1.04842

Table 5: Statistical results of t-test between ADWMA and ADHMA, Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	4.017	0.065	2.98	10	0.01	2.58713
	Equal Variance not Assumed			2.98	9.973	0.014	2.58713

4.2 Comparison between AWWMA and AWHMA rutting resistance

An independent t-test was carried out to determine whether the differences between the two independent mean scores is significant. As can be seen from table 6, the rut depth of WMA is higher than HMA, 6.327 compared to 5.124, respectively. Rutting in WMA is 23 percent more than rutting in HMA. The result of the t-test from Table 7 indicates that the difference between rutting resistances of AWWMA and AWHMA is significant.

Table 6 Mean and standard deviation of AWWMA and AWHMA rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
AWWMA	6	6.3272	0.61741
AWHMA	6	5.1244	0.69498

Table 7: Statistical results of t-test between AWWMA and AWHMA, Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	0.005	0.944	3.66	10	0.003	1.20279
	Equal Variance not Assumed			3.66	13.808	0.003	1.20279

4.3 Comparison between UDWMA and UDHMA rutting resistance

The data from Suleiman and Mandal (2011) was statistically analyzed to investigate the significance of the difference between WMA and HMA rutting resistance under different conditions. The results of the analysis shown in Tables 8 and 9 indicate that un-aged WMA, under dry condition, has a lower rutting resistance compared to HMA. The Rutting depth of WMA is 8.9 mm compared to 7.922 mm for HMA. A 12 percent increase

Table 8: Mean and standard deviation of UDWMA and UDHMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
UDWMA	6	8.8983	0.46816
UDWMA	6	7.9217	0.74888

Table 9: Statistical results of t-test between UDWMA and UDHMA, Independent Samples Test

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Levene's Test for Equality of Variances</td><td colspan="4">t-test for Equality of Means</td></tr>
<tr><td>F</td><td>Sig</td><td>t</td><td>df</td><td>Sig (2-tailed)</td><td>Mean Difference</td></tr>
<tr><td rowspan="2">Rutting Depth</td><td>Equal Variances Assumed</td><td>.598</td><td>.457</td><td>2.709</td><td>10</td><td>.022</td><td>.97667</td></tr>
<tr><td>Equal Variance not Assumed</td><td></td><td></td><td>2.709</td><td>8.390</td><td>.026</td><td>.97667</td></tr>
</table>

4.4 Comparison between ADWMA and UDWMA rutting resistance

The results from Table 11 suggest that the difference between aged WMA and Un-aged WMA during a 3-year period is significant. Also the results from Table 10 indicate that WMA rutting resistance has improved during the period by 21 percent.

Table 10: Mean and standard deviation of ADWMA and UDWMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
ADWMA	6	7.0344	2.22042
UDWMA	6	8.8983	0.46816

Table 11: Statistical results of t-test between ADWMA and UDWMA, Independent Samples Test

		Levene's Test for Equality of Variances			
		F	Sig	Sig. (2-tailed)	Mean Difference
R	Equal Variances Assumed	8.418	0.013	0.068	-1.86396
	Equal Variances not Assumed			0.51	-1.86396

4.5 Comparison between UWWMA and UWHMA rutting resistance

The statistical analysis of the previous research being done by Suleiman and Mandal (2011) which is shown in Tables 12 and 13, revealed that un-aged WMA under wet condition had lower rutting resistance compared to HMA. A rut depth of 8.174 mm was observed for WMA and 6.622 mm for HMA. This means that WMA rutting resistance is better than the HMA rutting resistance by 19 percent when tested under wet condition. Tables 12 and 13 present the results.

Table 12: Mean and standard deviation of UWWMA and UWHMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
UWWMA	6	8.5717	0.80755
UWHMA	6	6.621	1.13572

Table 13: Statistical results of t-test between UWWMA and UWHMA, Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	1.028	0.335	3.428	10	0.006	1.95000
	Equal Variance not Assumed			3.428	9	0.008	1.95000

4.6 Comparison between AWWMA and UWWMA rutting resistance

As can be seen from Table 15, the rutting depth difference, under wet condition, between AWWMA and UWWMA is significant. The results shown in Table 14 indicate WMA rutting depth has decreased from 8.572 mm to 6.327 mm; an improvement of 26 percent.

Table 14: Mean and standard deviation of AWWMA and UWWMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
AWWMA	6	6.3272	.61741
UWWMA	6	8.5717	.80755

Table 15: Statistical results of t-test between AWWMA and UWWMA

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	.261	.619	-5.913	10	.000	-2.24450
	Equal Variance not Assumed			-5.677	9.096	.000	-2.24450

4.7 Comparison between ADHMA and UDHMA rutting resistance

Comparison was made between aged and un-aged HMA under dry condition. The results from Table 17 indicate that aged HMA under dry condition has higher rutting resistance as compared to un-aged HMA. An improvement of 44 percent. The results are presented in Table 16 and 17.

Table 16: Mean and standard deviation of ADHMA and UDHMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
ADHMA	6	4.4472	1.04842
UDHMA	6	7.9217	.74888

Table 17: Statistical results of t-test between AWWMA and UWWMA

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	1.935	.189	-6.878	10	.000	-3.47443
	Equal Variance not Assumed			-7.231	12	.000	-3.47443

4.8 Comparison between AWHMA and UWHMA rutting resistance

As can be seen from Table 19, the difference between AWHMA and UWHMA is significant. The results from Table 18 indicate that aged HMA, under wet condition, has higher rutting resistance compared to un-aged HMA, 5.1244 and 6.6217 respectively. Aging improves the wet HMA performance by 23 percent.

Table 18: Mean and standard deviation of AWHMA and UWHMA Rut depth

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
AWHMA	6	5.1244	.69498
UWHMA	6	6.6217	1.13572

Table 19: Statistical results of t-test between AWHMA and UWHMA

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Rutting Depth	Equal Variances Assumed	2.340	.152	-3.063	10	.010	-1.49729
	Equal Variance not Assumed			-2.853	7.765	.022	-1.49729

4.9 Comparison between un-aged WMA and un-aged HMA air voids

Statistical analysis was conducted to compare the significance of the difference between the air voids of un-aged WMA and HMA. The results of Table 21 show that the difference is significant. As can be seen from Table 20, air voids in un-aged WMA are lower than un-aged HMA by 15 percent, which is in accordance with the previous research by Prowell et al. (2007) indicating inclusion of WMA with Evotherm reduces air void of the mixtures compared to control mixes.

Table 20: Mean and standard deviation of un-aged WMA and HMA air voids

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
WMA	15	3.7740	.60633
HMA	15	4.4633	.96719

Table 21: Statistical results of t-test between un-aged HMA and WMA air void

		Levene's Test for Equality of Variances		t-test for Equality of Means			
		F	Sig	t	df	Sig (2-tailed)	Mean Difference
Aged air void	Equal variances assumed	4.315	.047	-2.339	28	.027	-.68933
	Equal variances not assumed			-2.339	23.532	.028	-.68933

4.10 Comparison between the air voids of aged WMA/ HMA mixes and un-aged WMA and HMA mixes

A paired samples t-test statistic is carried out to determine whether the difference between un-aged air voids and aged air voids mixtures is significant. Table 22 shows that the difference is significant and Table 23 indicates that air voids are reduced from 10.16 to 4.0119 percent. Which means aging reduced the air voids by 61 percent. Air voids difference is also significant between aged WMA and aged HMA as shown in Table 24. The in-place air voids of aged WMA were less than the aged HMA by18 percent.

Table 22: Mean and standard deviation of un-aged and aged mixtures air void

	Paired Differences		Paired Differences	t	Sig. (2-tailed)
	Mean	Std. Deviation			
Pair 1	Un-aged air mixtures air voids	-6.04433	8.15805	-4.058	.000
	Aged mixtures air voids				

Table 23: Statistical results of t-test between aged and un-aged mixtures air void

	Mean (mm)		Number of Samples	Std. Deviation	Std. Error Mean
Pair 1	Aged air mixtures air voids	4.1187	24	.86716	.15832
	Un-aged mixtures air voids	10.1630	24	8.35785	1.52593

Table 24: Air void between aged WMA and aged HMA

Type of Samples	Number of Samples Used	Mean (mm)	Std. Deviation
AHMA	16	4.3456	1.04631
AWMA	13	3.5531	.41570

4.11 General comparison between aged and un-aged WMA and HMA rutting

Figure 5 demonstrates the comparison between aged and un-aged WMA and HMA mixtures under dry and wet conditions.

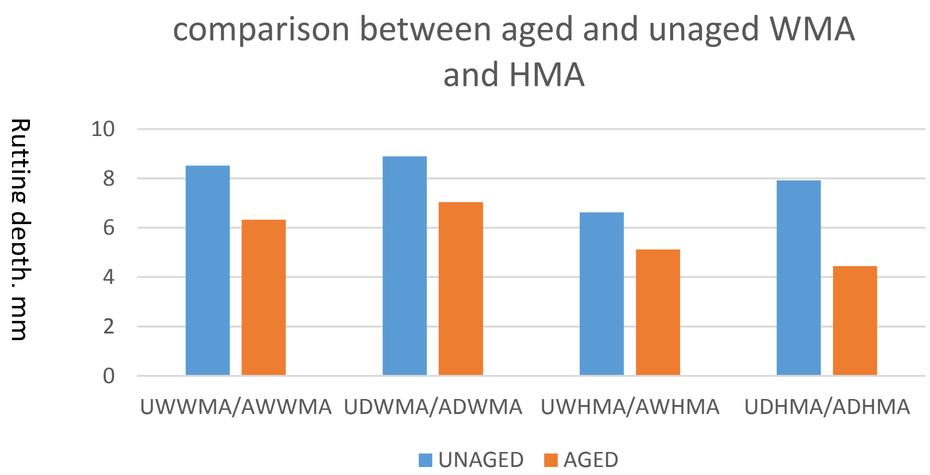

Figure 5: Comparison between Wet/Dry and aged/un-aged WMA and HMA rut depth

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The rut results data of the twenty four aged samples tested using the APA were analyzed statistically using the SPSS software. The analysis included comparisons between rut values of the aged WMA with the control HMA for both dry and wet testing conditions. The un-aged rut data from a previous study of the same paving project, Suleiman and Mandal (2011), were also statically analyzed and compared with the aged rut results of this study.

In general, the rut results obtained from the APA indicated that aged specimen were more rut resistant than un-aged specimen for both WMA and HMA mixes under dry and wet conditions. It was observed that the specimens tested three years after construction (aged) were more rut resistant than those tested immediately after construction (un-aged) by 21 percent and 26 percent under dry and wet testing conditions, respectively. On the other hand, aged HMA was more rut resistant than un-aged HMA by 44 percent and 23 percent for dry and wet testing conditions, respectively. Even-though the rate of rut resistance improvement was higher for HMA compared to WMA under dry condition, WMA rate of rut resistance improvement was higher than HMA under wet testing condition. This can be considered an indication that warm mixes can perform well under wet conditions. In other words, WMA can exhibit similar or even better durability than HMA.

The rut depth comparisons between aged WMA and aged HMA under dry and wet conditions reveal that WMA rut resistance is inferior to HMA by 58 percent and 23 percent, respectively. Again, the rate of rut resistance improvement for WMA is much better under wet testing compared to dry testing condition. For the un-aged rut resistance data, the analysis show that WMA specimens were 21 percent and 19 percent less rut resistant to the HMA specimens under dry and wet conditions, respectively.

Also, statistical analysis were performed on the in-place air voids for WMA and HMA for both aged and un-aged conditions. For the un-aged specimens, the in-place air voids for WMA were 15 percent lower than those of the HMA specimens. As for the aged specimens, the in-place air voids for WMA specimens were 18 percent lower than those of the HMA specimens.

Finally, the above rut resistance analysis demonstrated that WMA mixes can gain additional rut resistance with time (aging). The rate of rut resistance is higher under wet conditions when compared to dry conditions, indicating a favorable potential for durability. None of the aged specimens rut values, either WMA or HMA, has exceeded the rut failure criterion specified at 9 mm for this study.

5.2 Recommendations

Aging is a major factor in stiffening WMA mixes. A research that compares rutting resistances at different ages after construction is helpful in understanding the nature of aging in WMA mixes. The author recommends establishing such research in North Dakota using Evotherm WMA technology in combination with control HMA mixes. The author also recommends a research to study the rut resistance of aging WMA mixes constructed with different WMA technologies and determine the best suited alternative for North Dakota.

REFERENCES

Behl, A., Kumar, G., Sharma, G., & Jain, P. (2013). Evaluation of field performance of warm-mix asphalt pavements in india. *Procedia-Social and Behavioral Sciences, 104*, 158-167.

Clements, T. M., Blankenship, P. B., & Mahboub, K. C. (2012). The effect of loose mix aging on the performance of warm mix asphalt. *Journal of the Association of Asphalt Paving Technologists,* (81)

D'Angelo, J. A., Harm, E. E., Bartoszek, J. C., Baumgardner, G. L., Corrigan, M. R., Cowsert, J. E., Newcomb, D. E. (2008). *Warm-Mix Asphalt: European Practice,*

Doyle, J. D., & Howard, I. L. (2013a). Rutting and moisture damage resistance of high reclaimed asphalt pavement warm mixed asphalt: Loaded wheel tracking vs. conventional methods. *Road Materials and Pavement Design, 14*(sup2), 148-172.

Doyle, J. D., & Howard, I. L. (2013b). Rutting and moisture damage resistance of high reclaimed asphalt pavement warm mixed asphalt: Loaded wheel tracking vs. conventional methods. *Road Materials and Pavement Design, 14*(sup2), 148-172.

Du, S. W., & Li, S. S. (2012). The effect of different warm additives on performance properties of HMA. *Applied Mechanics and Materials, 178*, 1369-1372.

DU, S., & LIU, C. (2012). Effect of warm asphalt additives on performance properties of SBS modified asphalt mixture. *Highway, 10*, 035.

Evert, K. (2013). *Warm mix aspahlt.* (No. ND 2010-02).NDDOT.

Gandhi, T., Rogers, W., & Amirkhanian, S. (2010). Laboratory evaluation of warm mix asphalt ageing characteristics. *International Journal of Pavement Engineering, 11*(2), 133-142.

Ghabchi, R., Singh, D., & Zaman, M. (2015). Laboratory evaluation of stiffness, low-temperature cracking, rutting, moisture damage, and fatigue performance of WMA mixes. *Road Materials and Pavement Design,* (ahead-of-print), 1-24.

Hurley, G. C., & Prowell, B. D. (2008). Evaluation of evotherm for use in warm mix asphalt. *NCAT Report, 2*, 15-35.

Hurley, G. C., & Prowell, B. D. (2009). Evaluation of evotherm for use in warm mix asphalt. *NCAT Report, 2*, 15-35.

Kavussi, A., & Hashemian, L. (2012). Laboratory evaluation of moisture damage and rutting potential of WMA foam mixes. *International Journal of Pavement Engineering, 13*(5), 415-423.

Leng, Z., Gamez, A., & Al-Qadi, I. L. (2013). Mechanical property characterization of warm-mix asphalt prepared with chemical additives. *Journal of Materials in Civil Engineering, 26*(2), 304-311.

Pavement Technology, I. Retrieved from http://www.pavementtechnology.com/products/pavementanalyzer.asp. Accessed on February 15, 2015

Pirabarooban, S., Zaman, M., & Tarefder, R. (2003). Evaluation of rutting potential in asphalt mixes using finite element modeling. Paper presented at the *The Transportation Factor 2003. Annual Conference and Exhibition of the Transportation Association of Canada.* (*Congres Et Exposition Annuels De L'Association Des Transport Du Canada*)

Porter, A. (2011). *Sensitivity of warm mix asphalt to temperature, binder content, and laboratory stripping performance* University of Arkansas.

Prowell, B. (2007). Warm mix asphalt, the international technology scanning program summary report. *American Trade Initiatives, US,*

Prowell, B. D., Hurley, G. C., & Crews, E. (2007). Field performance of warm-mix asphalt at national center for asphalt technology test track. *Transportation Research Record: Journal of the Transportation Research Board, 1998*(1), 96-102.

Prowell, B. D., Hurley, G. C., & Frank, B. (2007). Warm-mix asphalt: Best practices.

Sargand, S. M., Edwards, W. F., & Bendana, J. (2008). Testing of perpetual pavement with warm asphalt concrete surface mixes in the ohio APLF Paper presented at the *APT'08. Third International Conference,*

Shivaprasad, P. V., Xiao, F., & Amirkhanian, S. N. (2011). Performance of warm-mix asphalt mixtures containing recycled coal ash and roofing shingles with moist aggregates for low-volume roads. *Transportation Research Record: Journal of the Transportation Research Board, 2205*(1), 48-57.

Suleiman, N., & Mandal, S. (2011). Evaluation of the rut resistance performance of warm mix asphalts in north dakota. *Sponsored by the North Dakota Department of Transportation, Report no.UND, 1*

West, R., Willis, J. R., Rodezno, C., Julian, G., & Prowell, B. (2014). Engineering properties and field performance of warm mix asphalt technologies.

Xiao, F., Amirkhanian, S. N., & Putman, B. J. (2010). Evaluation of rutting resistance in warm-mix asphalts containing moist aggregate. *Transportation Research Record: Journal of the Transportation Research Board, 2180*(1), 75-84.

Xiao, F., Punith, V., & Putman, B. J. (2012). Effect of compaction temperature on rutting and moisture resistance of foamed warm-mix-asphalt mixtures. *Journal of Materials in Civil Engineering*, *25*(9), 1344-1352.

Yina, F., Cucalona, L. G., Martina, A. E., Arambulab, E., & Parkb, E. S. (2015). Performance evolution of hot-mix and warm-mix asphalt with field and laboratory aging. *Asphalt Paving Technology 2014: Volume 83, Journal of the Association of Asphalt Paving Technologists*, , 109.