Development of a RTFO-Aging Test Protocol for WMA Binders and Its PG Grading

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16. ABSTRACT

Warm mix asphalt (WMA) is one of the Every Day Counts (EDC) technology announced by the Federal Highway Administration (FHWA) and it is becoming increasingly popular in every state. Despite several benefits, the use of WMA is still not indisputable because of its possible rutting susceptibility. Although several laboratory rutting tests are currently in use in different states, very few of the tests use full scale loading conditions. Therefore, current test methods are good to evaluate the effects of different mix parameters, but often do not correlate well with field rutting distresses. The objective of this study is to evaluate a full-scale laboratory wheel load tester by correlating the rut depths with rut depth obtained from testing in Asphalt Pavement Analyzer (APA). A full-scale wheel load testing will eliminate the need of rigorous field evaluation. Laboratory made Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) have been used in dry and submerged condition for evaluation of this tester. After 1200 wheel passes the rut depth for WMA was always greater than the rut depth of HMA either in dry or submerged testing. This trend also corroborates with the APA test results. Binder was extracted and recovered from WMA and HMA specimens, and it was hypothesized that increased rutting and moisture susceptibility of WMA specimen is the result of reduced short-term aging of the WMA than that of HMA.

Asphalt mix consist of different aggregate sizes. A study was conducted to investigate how total binder content in the mix is distributed among different aggregate size. The effect of aggregate size on aging of the mix, and consequently on its rutting performance was also studied. It was found that asphalt content associated with fine aggregate group is the highest among the three groups: coarse, medium and fine. In a mix, binder associated with fine aggregate is aged more than the binder associated with other aggregate and aging of a mix is mostly contributed by the aging of the fine portion of mix.

To simulate the reduced aging of WMA binders in the laboratory, series of RTFO tests were conducted on two binder types at three different temperatures for four aging periods. STOA was performed for same time duration on laboratory mix produced at the temperatures like those three RTFO aging temperatures. A RTFO aging model was developed correlating the rheological properties of STOA mix with RTFO aged binder to simulate the aging for WMA as well as for HMA. Investigation of rheological properties of RTFO and STOA binder depicts that change in aging index of binder follows a linear relationship with aging time and the rate of change of aging index also changes linearly with temperature. This study affirms that STOA exhibits more sensitivity to temperature than that of RTFO aging.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Final Report
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EXECUTIVE SUMMARY

Warm mix asphalt (WMA) is one of the Every Day Counts (EDC) technology announced by the Federal Highway Administration (FHWA) and it is becoming increasingly popular in every state. Despite several benefits, the use of WMA is still not indisputable because of its possible rutting susceptibility. Although several laboratory rutting tests are currently in use in different states, very few of the tests use full scale loading conditions. Therefore, current test methods are good to evaluate the effects of different mix parameters, but often do not correlate well with field rutting distresses. The objective of this study is to evaluate a full-scale laboratory wheel load tester by correlating the rut depths with rut depth obtained from testing in Asphalt Pavement Analyzer (APA). A full-scale wheel load testing will eliminate the need of rigorous field evaluation. Laboratory made Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) have been used in dry and submerged condition for evaluation of this tester. After 1200 wheel passes the rut depth for WMA was always greater than the rut depth of HMA either in dry or submerged testing. This trend also corroborates with the APA test results. Binder was extracted and recovered from WMA and HMA specimens, and it was hypothesized that increased rutting and moisture susceptibility of WMA specimen is the result of reduced short-term aging of the WMA than that of HMA.

Asphalt mix consist of different aggregate sizes. A study was conducted to investigate how total binder content in the mix is distributed among different aggregate size. The effect of aggregate size on aging of the mix, and consequently on its rutting performance was also studied. It was found that asphalt content associated with fine aggregate group is the highest among the three groups: coarse, medium and fine. In a mix, binder associated with fine aggregate is aged more than the binder associated with other aggregate and aging of a mix is mostly contributed by the aging of the fine portion of mix.

To simulate the reduced aging of WMA binders in the laboratory, series of RTFO tests were conducted on two binder types at three different temperatures for four aging

periods. Short term oven aging (STOA) was performed for same time duration on laboratory mix produced at the temperatures like those three RTFO aging temperatures. A RTFO aging model was developed correlating the rheological properties of STOA mix with RTFO aged binder to simulate the aging for WMA as well as for HMA. Investigation of rheological properties of RTFO and STOA binder depicts that change in aging index of binder follows a linear relationship with aging time and the rate of change of aging index also changes linearly with temperature. This study affirms that STOA exhibits more sensitivity to temperature than that of RTFO aging.

CHAPTER 1
INTRODUCTION

Hardening of asphalt binder in the mix happens over time because of volatilization of light asphalt component and oxidation during service life. This process is referred to as aging *[1]*. During the mixing and compaction process, binders undergo aging at higher temperatures and consequently a higher oxidation rate occurs which is known as short term aging. As WMA is produced at a lower temperature than HMA, there is a probability for WMA that the binder in the mix does not attain sufficient stiffness *[2, 3]*. It can be hypothesized that lower aging of WMA allows densification of compacted pavement that may lead the compacted mix subjected to more rutting in comparison with traditional HMA.

In PG tests, asphalt binder samples for low temperature cracking test (using a bending beam rheometer), fatigue cracking test (G*sinδ using a dynamic shear rheometer) and rutting susceptibility test (G/sinδ using a dynamic shear rheometer) are all prepared following the rolling thing film oven (RTFO) aging procedure *[4].* Rolling thin film oven (RTFO) aging that represents aging during production, is performed at 163°C at which hot mix asphalt is prepared. Warm mix asphalt is prepared at lower temperatures and therefore, there is a need for developing a revised RTFO aging test procedure for WMA binders for accurate performance grading and for determining if grade bumping is necessary.

Short Term Oven Aging (STOA) is a widely practiced method to simulate the short-term aging in the laboratory for mix. AASHTO R 30 recommends conditioning the loose HMA for 2 hours at compaction temperature for volumetric design, and 4 hours at 135^0C for preparing specimens for performance testing *[5].* In a recent study conducted by Epps Martin et al. (2014), 2 hours of STOA at 135^0C for HMA and 116^0C for WMA was recommended to simulate the short-term aging *[6]*. AASHTO T 240 recommends performing RTFO test at 163^0C for 85 minutes. It is expected that RTFO is capable of producing the field short term aging effect for the HMA in the laboratory by measuring the effect of heat and hot air on a thin film of moving asphalt binder. In reality because of wide mixing temperature range, and variation in storage and paving time, field aging differs significantly from that of RTFO aging for HMA let alone for the WMA as there does not exist any established method to predict the binder aging in laboratory *[7]*. A revised RTFO protocol is needed to be developed to successfully predict the WMA binder aging in the laboratory.

1.1 LITERATURE REVIEW

Despite several benefits like, lower fuel consumption, extend paving season, increased haul distance and possibility to incorporate more RAP, use of WMA is still not indisputable because it is expected that WMA will not compromise with the strength of the pavement. Potential source of inferior performance of WMA are compactibility, moisture sensitivity and rutting resistance. Though HMA mix design results can be applied to WMA the samples should be tested for compactibility, moisture sensitivity and rutting because these properties can be different in case of WMA than that of HMA *[8]*.

Number of studies were conducted to evaluate the rutting resistance of WMA. The National Cooperative Highway Research Program (NCHRP) Report 691 evaluated rutting resistance of different field mixes by flow number test. It was found that all the WMA process except sasobit showed less rutting resistance than the control HMA. The rutting resistance decreased approximately 6 percent for every 5.5°C reduction in compaction temperature. Flow number was used by Copeland et al. (2010) to predict the rutting resistance of WMA and similar trend like NCHRP project stated above, was obtained *[9]*. WMA showed lower flow number that means lower rut resistance in comparison to HMA regardless to addition of RAP with WMA.

Hasan et al. (2013) carried out an investigation on HMA and foamed WMA prepared by both water injection and additive advera *[10]*. Asphalt pavement analyzer was used to determine the rutting susceptibility of the mixes; for HMA rutting depth was 2.5 mm and for WMA this value was as high as 6 mm. It was reported that the rutting potential of the mixture would increase because of lower production temperature. It can be mentioned that the DSR test was performed on the conditioned binder not on the binder extracted from the mix.

Abbas et al. (2016) compared the aging characteristics of foamed WMA and traditional HMA using two binders and one aggregate *[2]*. From DSR test on extracted binder from laboratory mixes it was concluded that laboratory prepared foamed WMA mixes experience lower level of aging compared to HMA mixes. This test result was confirmed by FTIR and GPC test results. Carbonyl and sulfoxide indices from FTIR indicates higher level of aging in HMA and percentage of large molecular size in GPC supports this finding.

Ayman et al. (2012) evaluated the performance of foamed WMA and compared it to traditional HMA on the basis of indirect tensile strength, dynamic modulus, modified Lottman and asphalt pavement analyzer tests *[3]*. Two binders and two aggregates were used for this study. WMA made of limestone aggregate with PG 70-22M binder exhibits rutting depth of 5 mm (0.2 in) while in case of gravel mix with 64-22 binder rutting depth was found 15 mm (0.6 in) In case of HMA these values are 2.5 mm (0.1 in) and 8.7 mm (0.35 in) respectively, One of the findings of this study is that, WMA is more susceptible to rutting than that of HMA because binders might not be stiff enough as they undergo less aging and mix can easily be densified even after proper compaction.

In a research study conducted by Malladi et at. (2014) WMA prepared by three different technologies (Advera, foamer and Sasobit) were evaluated for their moisture susceptibility by TSR test and permanent deformation by utilizing the APA *[11]*. For HMA and WMA rut depth was 5 mm and 6 mm respectively which was an indication of good performance of the mix according to NCDOT. In this study correlation between rutting potential and binder stiffness was not established for WMA or HMA.

A study based on the laboratory mix and tests was conducted by Xiao et al. (2013) to demonstrate the effect of compaction temperature on moisture susceptibility and rutting resistance of WMA containing moist aggregate using a foaming technology *[12]*. It was observed that with the increase of compaction temperature compaction effort to achieve the same density decreases and also rut depth for the mixes decrease slightly regardless to the aggregate type of foaming water content.

Field cores of WMA and HMA obtained from different field sites in Washington were tested to evaluate the resistance to fatigue and thermal cracking as well as susceptibility to rutting and moisture damage by Brower et al. (2012) *[13]*. Different WMA technologies were applied in separate projects among those water injection mixes proved to be susceptible to rutting in laboratory test but none of the road section produced significant rutting.

Field performance of WMA in Norway, Germany and France was studied by a team of 13 material experts during 2007 (D'Angelo et al., 2008) *[14]*. Based on the 3 years of field performance it was reported that WMA could perform equally or better than HMA to resist the pavement rutting regardless to the WMA technologies used.

Wielinksi et al. (2009) reported some performance results of two WMA paving projects where WMA was produced by a foaming technology developed by Granite Construction, Inc known as double barrel green system *[15]*. For one project APA rutting was found 5.0 and 7.2 mm for HMA and WMA respectively while in another project these values are 7.8 and 9.4 mm. This indicates that laboratory test shows significant difference in rutting susceptibility of WMA though no measurable rutting was observed within 5 months of construction in either sites.

Based on the literature discussed above rutting performance of WMA is not consistent in all the cases. Most of the laboratory rutting tests prove that WMA is more susceptible to rutting whereas, field performance of WMA is not as poor as it shows in laboratory test. So, there is a need to evaluate the actual rutting performance of WMA and to investigate the factor which is responsible for rutting.

To evaluate the rutting performance of the compacted mix numbers of simulative tests are being performed. Asphalt Pavement Analyzer, Hamburg Wheel-Tracking Device, Laboratory Wheel-Tracking Device in Purdue University, Dry Wheel-Tracker, Rotary Loaded Wheel Tester and Model Mobile Load Simulator are some of the machines *[16]*. All those machines have some advantages and limitations too. The purpose of this study is not to conduct any comparative study. In this study a full-scale wheel was utilized to find the rutting potential of laboratory compacted mixes. This machine is named as Full-Scale Wheel Load Tester. This machine is more realistic in comparison to other laboratory tests in a way that it uses the real wheel load when passes through the specimens.

Hardening and embrittlement of asphalt binder in the mix over time because of volatilization of light asphalt component, oxidation during service life or steric hardening is referred to as aging *[17]*. During the mixing through compaction process binders undergo through aging at higher temperature and consequently higher oxidation rate which is known as short term aging. Long term aging is characterized by continuing oxidation and exposure to climatic condition during its service life relatively at lower temperature which results to a slower oxidation rate.

During WMA mixing process lower temperature is used for mixing and the mix is subjected to lower short-term aging at reduced temperature. So, there is a probability that the binder in the mix do not attain sufficient stiffness that may lead the compacted mix subjected to more rutting in comparison with traditional HMA. To determine the binder short term aging RTFO is widely used as a laboratory simulation technique. AASHTO T 240 describes the procedure to simulate the short time aging of the HMA in the lab but it is disputable if it can successfully simulate it or not. But for WMA there does not exist any established method to predict the binder aging in laboratory. This study is focused on to evaluate the rutting susceptibility of WMA as well as to establish a model to simulate a RTFO aging model which can successfully predict the-short term aging of both HMA and WMA.

To simulate the short-term aging of the mix the standard practice is to condition the loose mix in the oven prior to compaction. AASHTO R 30 recommends of conditioning the loose mixes for 2 hours at compaction temperature for volumetric design and 4 hours at 1350C for preparing specimens for performance testing. This protocol was established for HMA only but there is no laboratory STOA protocol was mentioned for WMA in that standard. In other study Martin et al (2014) recommended 2 hours of STOA for HMA at 135^0C and for WMA at 116^0C *[6]*. In spite of previous research efforts still there is a need for comprehensive study to establish an STOA method that would incorporate the WMA technology, wide variety of mixing temperature and other effect such as, aggregate type, binder source, inclusion of RAP and plant type. Different researchers followed different time and temperature combination to simulate short term oven aging (STOA). This study was aimed to develop a correlation between STOA and RTFO aging of binder so that the RTFO aging time and temperature can be determined using this model for whatever time-temperature combination is selected for STOA.

Asphalt binder type, binder source, aggregate absorption, aggregate source, moisture content of aggregate pile, plant type, production temperature, storage time in silo, hauling distance are the factor primarily responsible for short term aging characteristics of asphalt mixtures. Although establishing any relation between short term field aging and RTFO aging method is difficult because of wide variety of factors, there should exist a correlation between RTFO and STOA as it is performed at controlled environment. Lee et al. (2008) predicted the required RTFO aging time to get the same effect of STOA on the basis of increased large molecular size (LMS) ratio obtained by GPC method. Aging of WMA was not considered in that study. It might be a good approach to alter the RTFO aging time and temperature from the standard protocol to match with the specific field condition *[19]*. RTFO, conducted at 163^0C for 85 minutes might be an approach to characterize the binder but it is not capable of representing the short-term aging of the binder in the field as well as in laboratory *[20].*

1.2 OBJECTIVE

Primary objective of this study is to investigate the reduced short-term aging of WMA and its consequence on mix performance especially in rutting. To fulfil this objective a full=scale wheel load tester was developed and was utilize along with APA for determining the rutting potential of laboratory compacted mix.

Asphalt concrete mix consists of different aggregate sizes. Asphalt content associated with each aggregate varies with size. Another objective of this study is to determine the asphalt content associated to each aggregate size and to find the contribution of aggregate aging in rutting susceptibility of asphalt mix.

Furthermore, to investigate the effect of STOA and RTFO aging temperature and time on the rutting parameter ($G^*/\sin\delta$) of binder subjected to wide variety of short term aging time at different temperature. Based on the results, this study aims to develop a RTFO aging model by correlating the rheological properties of STOA mixes to predict the STOA effect by testing the binder in RTFO.

1.3 SCOPE

This study considers only the PG 58 and PG 64 binder. No polymer modified binder was tested. WMA was mixed as low as at 135^0C and RTFO was performed as low as at 120^0C. The RTFO model proposed here might not be valid below this temperature. Performance of WMA is evaluated in term of rutting only.

CHAPTER 2
METHODOOGY

Initially HAM and WMA prepared in laboratory and in the plant were tested in APA for determining the rutting susceptibility. Although APA is a widely used rutting tests it does not use full scale loading conditions. Therefore, a full-scale wheel load tester was developed and was utilized to evaluate rutting susceptibility that would not need rigorous field evaluation. It is hypothesized that lower aging during the production phase of WMA is responsible for increased rutting of compacted WMA. Asphalt concrete consists of combination of different aggregate size. Which aggregate size has higher contributes to the aging was determined by aggregate size analysis of the mix. The mix was subjected to STOA and then aggregate were separated into three size groups. Asphalt content associated to each aggregate size was determined as well as the aging properties of different size groups. The last portion of the study dealt with revised RTFO model. Series of RTFO and STOA were performed at different time-temperature combination to get the similar aging effect for both the STOA of mix and RTFO aging of binder. Figure 1 shows the overall experimental plan for this study.

2.1 SELECTION OF MATERIALS

HMA and WMA used for this study were produced in laboratory as well as in the plant. Laboratory mix was a ½ inch NMS mix with 4.8% asphalt content. Advera was used as a WMA additive. Two types of binders were used: PG 64 and PG 58, and the aggregate was crushed granite and manufactured sand. HMA was mixed and aged at 163^0C and 150^0C respectively while mixing and aging temperature of WMA was 135^0C and 120^0C respectively.

The same mix was used throughout the study for all the investigation. To simulate the short-term aging in oven, same mix was used with additional one mixing and aging temperature of 148^0C and 135^0C respectively.

HMA and foamed WMA plant mix was collected from Madden Contracting Co Inc. The nominal maximum size of the mix was ½ inch and aggregate was lime stone. PG 64-22 asphalt binder was used for the mix with 5.0% asphalt content.

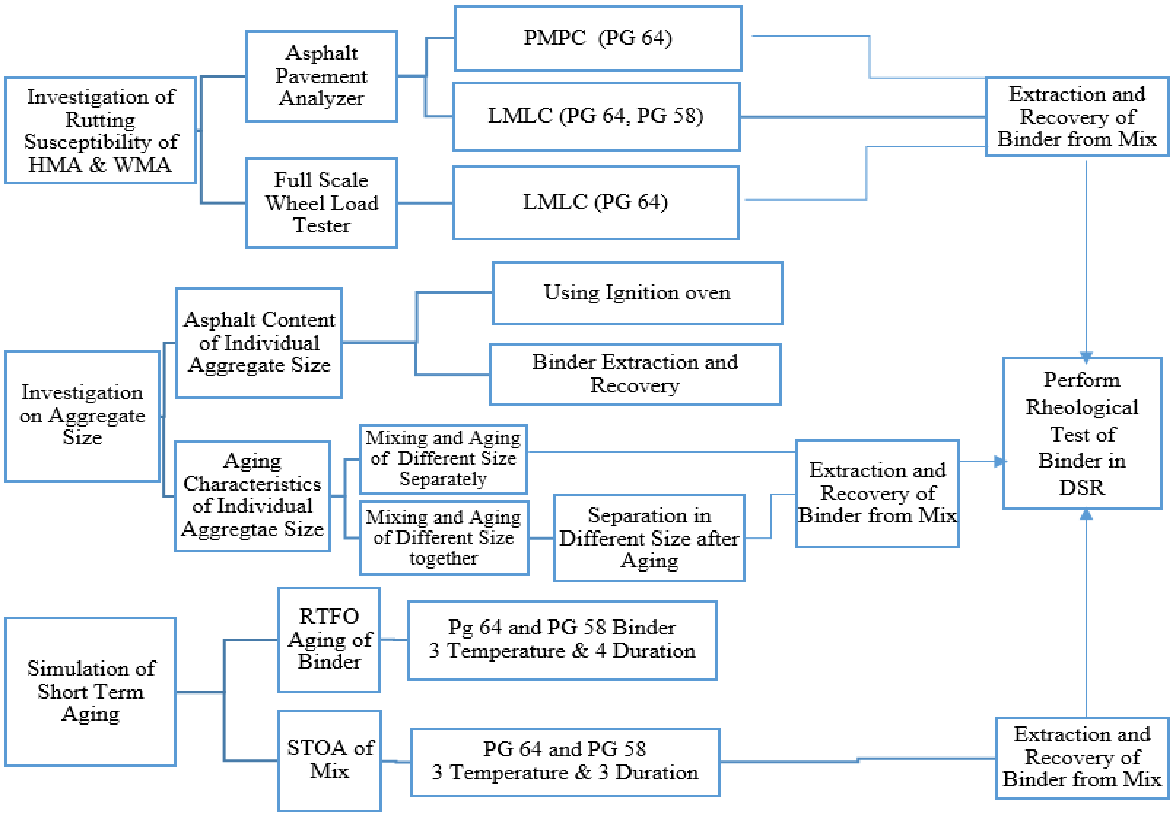


Figure 1. Flow Chart for detailed experimental plan

2.2 EXPERIMENTAL PLAN

2.2.1 Evaluation of Rutting Susceptibility

The whole study was conducted in three steps. At the first step, rutting potential of laboratory and plant HMA & WMA was evaluated using Asphalt Pavement Analyzer (APA). A full-scale wheel load tester was designed and built in the Louisiana Tech University laboratory to investigate and to compare the rut resistance of HMA and WMA. Table 1 describes the experimental plan for evaluation of rutting susceptibility.

Table 1. Experimental plan for evaluation of rutting susceptibility

Tests	Binder Type	Mixing/ Compaction Temperature	Remark
APA (PMPC)	PG 64	170^{0}C and 140^{0}C	Without reheating
APA (LMLC)	PG 64, PG 58	163^{0}/150^{0}C and 135^{0}/120^{0}C	Tested two different sets
Full Scale Wheel Load Tester (LMLC)	PG 64	163^{0}/150^{0}C and 135^{0}/120^{0}C	Dry and submerged testing

2.2.2 Investigation of Aggregate Size

Asphalt mix consists of different aggregate sizes. Not all the aggregate coated with asphalt by the same amount. Asphalt associated with aggregate varies with the aggregate size. A study was conducted to find the asphalt content associated with different aggregate size. When the asphalt content was determined, different aggregate were mix with known asphalt content and aged in the oven. On the other hand, whole mix was oven aged and different size were separated after aging. Complex modulus of the extracted binder was determined to investigate the aging characteristics. Table 2 describes the experimental plan for this section.

Table 2. Work plan for aggregate size investigation

<table>
<tr><th>Working Plan</th><th>Mixing/Aging Temperature</th><th>Aging Duration</th><th colspan="2">Method Used</th></tr>
<tr><td>Asphalt Content Determination</td><td>163^{0}C/150^{0}C</td><td>2 hours</td><td colspan="2">AC determined by Ignition Oven and by Extraction</td></tr>
<tr><td>Mixing and Aging of Different Size Aggregate Separately</td><td>163^{0}C/150^{0}C</td><td>2 hours</td><td>Extraction of Binder after Aging</td><td rowspan="2">Complex modulus was determined on extracted binder</td></tr>
<tr><td>Mixing and Aging of Different Size Aggregate Together</td><td>163^{0}C/150^{0}C</td><td>4 hours</td><td>After Aging Mix were sieved to three different sizes and then extracted</td></tr>
</table>

2.2.3 Simulation of Short Term Aging

A series of RTFO tests were conducted on two binder types at three different temperatures and for four aging periods. Short term oven aging (STOA) was performed for same time duration on laboratory mix produced at same three RTFO aging temperatures. Table 3 describes the detailed test matrix for short term aging simulation.

Table 3. Experimental plan for simulating the short term aging

Aging Type	Conditioning	Binder Type	Temperature	Duration	Extraction	Rheology
Short Term Aging of Binder	RTFO Aging of Binder	PG 64, PG 58	163^0C, 148^0C, 135^0C	60, 85, 120, 240 minutes	No extraction required	Dynamic Shear Modulus at 64^0C (for PG 64 binder) and 58^0C (PG 58 binder) with 25 mm plate, 12 rad/sec angular frequency, 10% strain rate
Short Term Aging of Mix	Oven Aging of Laboratory Mix	PG 64, PG 58	150^0C, 135^0C, 120^0C	0, 60, 120, 240 minutes	One batch from each temperature and duration. Total 24 extractions	
	Plant Produced Mix (without reheating)	PG 64	170^0C, 140^0C	Immediately after mixing; From wrapped box at 2, 4, 8 hour duration for HMA and WMA. For HMA additional specimens were collected from Site and from silo after 14 hours of mixing	6 extractions for HMA and 4 extractions for WMA	

2.3 EXPERIMENTAL PROCEDURES

2.3.1 Development of HMA and WMA Mix Design in Laboratory

The asphalt concrete used in this study was designed according to AASHTO PP 28 “standard practice for Superpave volumetric design for hot mix asphalt (HMA). Optimum asphalt content was determined according to the table 502-5 of section 502 of the 2006 Louisiana Standard Specifications for Roads and Bridges. Mix was produced at 163^0C and aged 150^0C for 2 hours in an oven. At design gyration of 100, the air void was found 3.89%.

Crushed granite and industrial sand were used as the aggregate conforming the gradation requirement of table 502-4 of the standard specification. The gradation of aggregate used for this mix is shown in figure 2. Aggregate were tested for coarse aggregate angularity, fine aggregate angularity, flat and elongated particles and sand equivalency.

To get an optimum WMA mix design, the gradation of aggregate and asphalt content were not altered. Advera was added to the binder as a WMA additive. The challenge was to figure out the optimum amount of Advera that could produce WMA at lower mixing and aging temperature with the same density as that of HMA. After numbers of trials, two advera contents at two mixing temperatures were selected for preparing WMA in the laboratory for further testing. 0.3% advera was used for WMA with a mixing and aging temperature of 148^{0}C and 135^{0}C respectively, and 0.5% advera was used for WMA where mixing and aging temperature was 135 and 120^{0}C respectively. For both the cases, mixes were aged for 2 hours in the oven to simulate the short-term aging. In this asphalt mix design, it was assumed that oven aging temperature would be 13 to 15^{0}C lower than the mixing temperature.

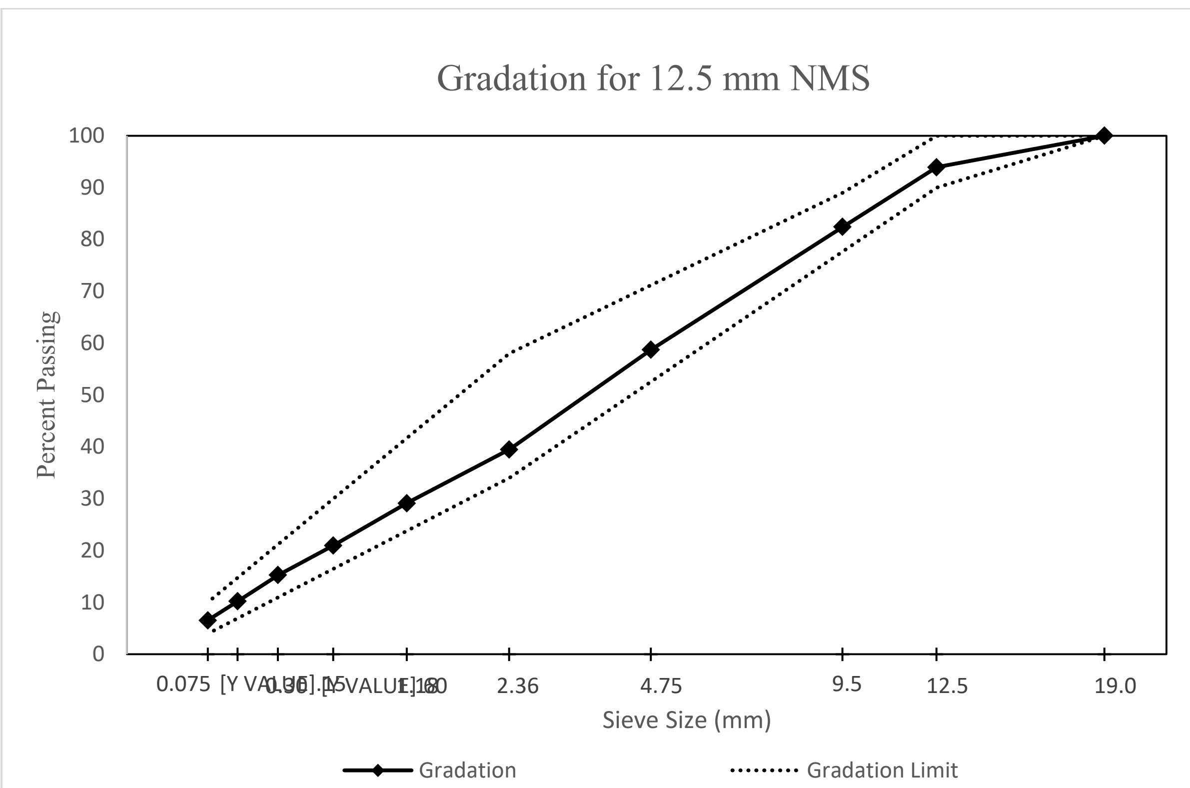


Figure 2. Aggregate gradation for SUPERPAVE mix design

2.3.2 Preparation of Rutting Specimens

Two types of specimens were tested for determination of rutting susceptibility. Cylindrical specimens were used in APA and brick specimens were used in full scale wheel load tester.

2.3.2.1 Gyratory Specimen Preparation

Rutting tests were performed on laboratory mix laboratory compacted (LMLC) and plant mix plant compacted (PMPC) gyratory compacted specimens. In the case of LMLC specimens the HMA and WMA were targeted to compact at 7% air void. For PG 64 binder 38 gyrations were required to achieve 7% air voids while for PG 58 binder the required number of gyration was 37. PMPC specimens were compacted just after the mix was collected from the truck but without being reheated. It was compacted by fixing the height at 3 inches. The weight of each specimen was 3066.8 gram. One important observation was, WMA required a lesser number of gyration (average gyration 62) to produce the compacted mix of the same height than that for HMA (average gyration 68). Perhaps because of the presence of water foam in the mix, it helped to get compacted more easily at a less compaction effort.

2.3.2.2 AVC Specimen Preparation

Brick specimens for testing is full scale wheel tester was prepared in Asphalt Vibratory Compactor (AVC). According to compactor's manual, it can compact the asphalt mix to 3 inch height. The compactor runs for 25 seconds then the mold was rotated horizontally for uniform compaction throughout the length of the specimen and continued for 25 more second. Dimension of the specimen is 12 inch x 5 inch x 3 inch. Weight of the asphalt mix required to make the specimen of desired air void was calculated and poured into the mold for compaction.

2.3.3 APA Test Set up

Asphalt pavement analyzer (APA) was used to determine the rut resistance of the LMLC and PMPC mixes. Testing temperature was fixed at the same temperature of the binder grade. The testing was conducted at 100 psi hose pressure and 100 pounds vertical wheel load. Rutting was measured manually after 8000 cycle wheel-passes.

2.3.4 Full Scale Wheel Load Tester

2.3.4.1 Description and Working Principle of the Machine

In this study, a newly developed portable full-scale wheel load testing machine was used inside the lab to determine the rutting of brick specimens compacted in AVC. This full-scale wheel load tester was hand built at the Louisiana Tech University by welding together a frame that could support a load of up to 6000 lbs. The tester primarily uses a piston and a single wheel in a steel frame. Five steel plates with dimension of 1”x2’x4’ have been welded together to apply 1500 pounds of load on testing wheel. Several batches of five steel plates can be loaded to provide sufficient loading for a test. There is a series of hydraulic hoses connected to a solenoid that is attached to a hydraulic pump. A hydraulic pump of 23 horse power was utilized to run this machine (Figure 4a). There are two magnets attached on the frame that moves with the wheel. There are two sensors on the frame at fixed position. By adjusting the distance between two magnets it is possible to control the span of the wheel (Figure 4b). The solenoid which regulates the inflow and outflow of hydraulic oil in the piston is controlled by a programmable Arduino. This program alternately turns on and off the solenoid and consequently the fluid flow to the piston so that the direction of the wheel movement reverses when it reaches to one end of its span. The speed of the wheel is controlled by regulating the flow of the hydraulic oil. The speed was chosen in such a way that average time for a single wheel pass is around 11 to 15 seconds.

2.3.4.2 Preparation of Mold for Specimen Testing

Any kind of rutting specimens need to be strongly supported by all sides to resist deformation or bulging. Initially A wooden mold was prepared to accommodate 6 specimens. Two 4"x4"x46" wooden posts and two 4"x4"x 9" wooden posts were used in the long direction and in the short direction, respectively. The short direction posts had an adjustable gap. Perpendicular to the long direction, at the edge, two 3/4-inch threaded bars with nuts were used to adjust the side supports. Specimens were placed on the mold side by side and after that, the nuts on the threaded bar was tightened to ensure the support. Once the nuts were tightened enough, the bolts on the short end were screwed into the wood to fully secure the specimens with the mold. Although there was no support from the bottom, but the side supports were strong to lift the specimens in air. First set of tests were performed using this mold. 6 specimens were placed inside the wooden mold for one test (figure 3a). Two specimens at two ends are named as dummy, because they act as support and help the wheel to pass the four test specimens completely. Afterward the testing, the specimens were taken out from the mold and the rut depth were measured manually by placing the specimen in a APA rut mold (figure 3b). Second set of tests were performed using steel mold which is much more improved and could perform the submerged test also.

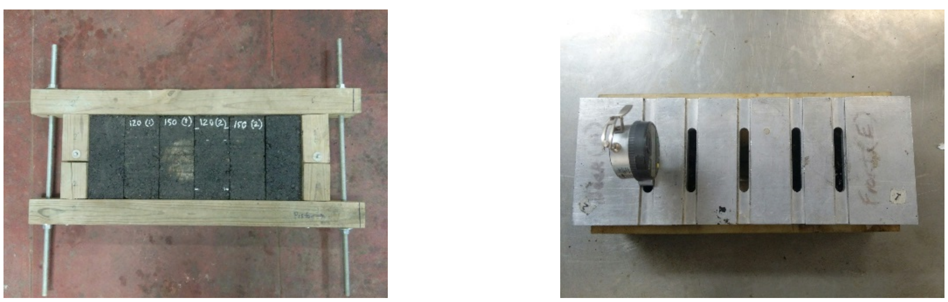


Figure 3. (a) Wooden mold for full scale wheel load testing, (b) Measuring the rut depth manually for first set of testing

A quarter inch steel plate was bent and welded to desired shape of 18 inch wide and 40 inch long with 4 inch depth. At the middle of mold, 30 inch x 10 inch space was separated by 3 inch deep steel plates welded to the bottom of the mold to secure the specimens for testing. One 10 inch side has an adjustable plate to hold the specimens tightly during testing. The 30 in sides are fixed and there is 0.04 inch gap to put the specimen into the mold (Figure 4c).

Figure 4. (a) Full view of full scale wheel load tester, (b) Sensors and magnets to control the span of wheel, (c) Specimen mold for testing, (d) Testing in dry condition is going on, (e) Submerged testing is going on, (f) Specimens in the mold after the testing is over, (g) After the testing rut depth is measured manually for individual specimen, (h) HMA specimen after rutting, (i) WMA specimen after rutting

Remaining space of the mold is utilized to hold the water to facilitate the submerged testing. On the one end of the mold a hole was created to fix a 1500 watt immersion heater to maintain the high temperature during the submerged testing. A submersible pump was set at the bottom of the mold near the heater to circulate the hot water throughout the mold. The mold can hold 6 brick specimens side by side. Three brick specimens can be tested at a time in this mold. Two specimens near the piston and one specimen at the far end are placed to provide the necessary space for the wheel to completely pass over the target specimens.

2.3.4.3 Temperature Control

During the first set of testing temperature could not be controlled. To ensure the same testing temperature for both the HMA and WMA specimens, 2 of each specimen type were tested at the same time. Temperature controlling system was then incorporated for the second set of testing.

During the dry test (figure 4d) temperature was maintained by two 1500 watt infrared heaters. Those were placed at certain distance and height from the specimen top. The heaters were controlled by two controllers which were triggered by temperature sensors attached to specimens. If the temperature of the specimen is below the set point the heater turns on and when it goes above the set point it turns off automatically. The specimens were preheated for 6 hours in a forced draft oven before testing. The heaters were used to maintain the temperature during the test. In case of submersible test (figure 4e), water is heated to certain temperature by an immersion heater. This heater is also controlled by the same controller that is used for heaters.

Both the dry and submerged test were performed at 40^0C (104^0F). In figure 5 the variation of the specimen temperature during the test is plotted with time along with the environmental temperature. From the figure it is noticeable that the infrared heaters can successfully maintain the desired temperature during the test although little fluctuation is observed. In case of submerged testing temperature is maintained by hot water so the temperature is steadier.

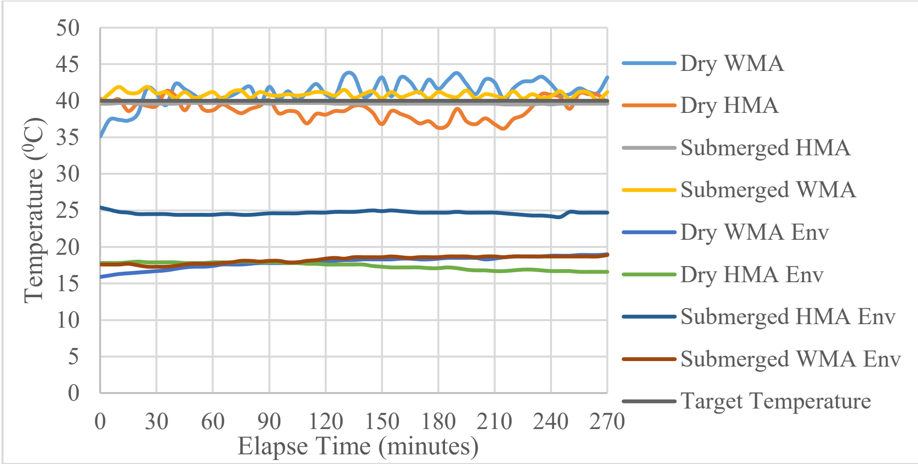


Figure 5. Variation of temperature with time during the test

2.3.4.4 Calculation of Rut Depth

The wheel of the machine passes perpendicular to the long side (10 inch) of the specimens. 9 locations on the top surface of the specimens are selected to measure the rutting depth manually using a strain gauge (figure 6). Point 'a' in the figure 6 represents the average of rutting depth at location 1, 2, and 3 which is denoted as along the left edge of wheel in the table. Point 'b' is the average of rutting depth at location 4, 5 and 6, while 'c' is the average of rutting depth at location 7, 8 and 9. The maximum value among these three points was reported as the rutting depth of the specimen. Table 4 is an example of recording data for determining the rut depth of the specimen after the testing. This table is prepared for dry rutting test of WMA specimens. For the first set of testing, the specimen was placed in a different mold afterward the test to read the depth using a strain gauge. In the second set of testing the rut depth was calculated keeping the specimen in the test mold.

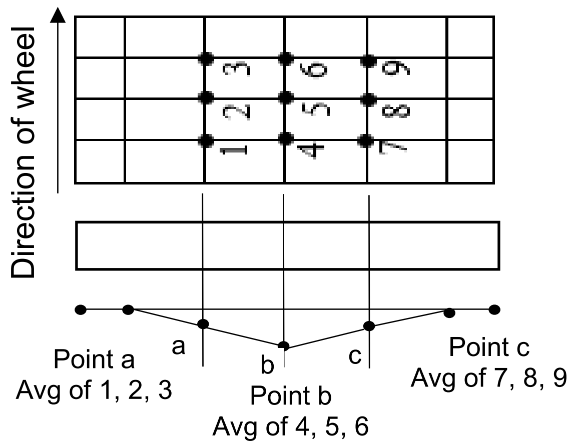


Figure 6. 9 different points on the brick specimen where rut depth was measured and qualitative representation of rut depth

Table 4. Sample data collection table for recording the rut depth: WMA specimen rut depth for dry testing

Location	Location No.	Specimen 1		Specimen 2		Specimen 3		Avg of 3 specimen (StDev)
		Rut Depth (mm)	Avg of 3 points (StDev)	Rut Depth (mm)	Avg of 3 points (StDev)	Rut Depth (mm)	Avg of 3 points (StDev)	
Along right edge of wheel	1	2.286	2.794 (0.508)	4.318	4.318 (0.203)	5.080	4.318 (0.914)	3.180 (0.914)
	2	3.302		4.572		4.572		
	3	2.794		4.318		3.302		
Along the center of wheel	4	1.778	2.032 (0.432)	2.032	2.032 (0.203)	2.286	2.286 (0.152)	2.286 (0.178)
	5	2.540		2.286		2.286		
	6	1.778		2.286		2.540		
Along left edge of wheel	7	1.778	1.778 (0.610)	1.270	1.524 (0.152)	2.032	2.032 (0.127)	1.778 (0.152)
	8	2.540		1.778		1.778		
	9	1.270		1.778		2.032		

2.3.4.5 Test Methods

During the first set of testing, two HMA and two WMA specimens were placed into the mold and tested at the same time. As the temperature was not controlled during the test, to ensure the same testing temperature both the specimens were tested at the same environmental temperature. Number of wheel pass was selected as 2000 for the test. Prior to the testing the specimens were heated at 40^0C for 6 hours and then those were placed into the wooden mold.

While testing was performed in the improved system in controlled temperature, three target specimens were preheated at 40^0C for 6 hours before testing. The test was performed at 40^0C though the binder was PG 64. Because of slower speed of the wheel at 64^0C it might cause severe damage that would not be the practical case. The specimens were placed in the mold with three more supporting specimens and the side was tightened properly. In case of submerged testing the specimens were being saturated at testing temperature of 40^0C for 12 hours. The machine was loaded with 3000 pounds of load before the test started. The speed of the wheel pass was selected as 13 second per cycle which is the maximum feasible speed achievable by the machine. Initial reading of the specimens was recorded before the test began. The machine ran for 1200 cycles which took 4 and a half hours to complete. After the testing was over the final rut depths was measured manually.

2.3.5 Documentation of Plant Mixing

The mixing plant, Madden Contracting Co Inc., Natchitoches, LA was visited for documentation of whole mixing process. The plant can produce both HMA and foamed WMA. Fresh mixes were collected from the silo and was then compacted in the plant laboratory without reheating. Loose HMA and WMA specimen were collected immediately after mixing and stored in a completely wrapped card board box. After 2, 4 and 8 hours, a small portion of mix was separated for further extraction. In the case of HMA, a specimen was collected from construction site which was at a 55 minutes hauling distance. Another HMA loose mix was collected from the silo after 14 hours of storage at 163^0C.

2.3.6 Investigation of Aggregate Size Influence in a Mix

Mix used for the analysis was designed earlier. It is a ½ in nominal size mix with total asphalt content of 4.8%. For further calculations, asphalt content is expressed as a percentage of total aggregate. In this mix asphalt content is 5.01% of total aggregate. Initially mix was sieved in five different sizes and asphalt content associated to each size was determined using an ignition oven. From the observed data it was decided to separate the mix into three size categories. Another mix was prepared and after 2 hours of aging it was separated into the predetermined three sizes. The detailed procedure of determining the asphalt content is described in the result section.

Whenever the asphalt content associated with each aggregate size is known, three mixes were prepared with the known asphalt content. The gradation of the mix was chosen in such a way that only desired size of aggregate is available in the mix. It was then aged and extracted for investigation for oxidative aging.

Another mix was prepared and aged in the oven for four hours. After the aging the mix was divided into three sized and extracted for investigation for oxidative aging.

2.3.7 Testing of Rheological Properties of Recovered Binder

The binder from the compacted WMA and HMA were extracted using a centrifuge (ASTM D 2172) and then was recovered using rotary evaporator (ASTM D 5404) using n-Propyl Bromide *[22, 23]*. Rheological properties of the recovered binder and RTFO aged binder were tested using a DSR (AASHTO T 315) *[24]*. DSR was used to find the rutting parameter $G^*/\sin\delta$ and aging index (AI), which is defined as the ratio of rutting parameter of aged and unaged binder. This term AI is used throughout the study to quantify the oxidative aging of the binder.

2.4 METHODOLOGY BASED ON THE TASK

Task 1. Literature Review: A through literature review was performed to acquire the updated knowledge regarding the relationships between aging and rutting of WMA as well as the short-term aging characteristics of HMA and WMA.

Task 2. Selection of Materials: One laboratory mix and one plant mix were selected for the whole study. Advera was used as a WMA additive in the laboratory mix and water foaming technology was used for plant WMA.

Task 3. Extraction of Binders from Short-Term Oven-Aged Lab Mix: Different duration times and temperatures of oven conditioning of HMA and WMA mixes were selected and binder was extracted recovered for investigation of aging characteristics.

Task 4. Perform Rheological Tests to Investigate Reduction in Aging. G/sinδ of the extracted and recovered binders in Task 3 was performed using a DSR and aging index was determined to prove the reduction in aging due to temperature reduction in WMA using lab mix.

Task 5. Perform RTFO and Compare with Short –Term Oven Aging: RTFO was performed on original binders for different durations and different temperatures. Rheological tests were performed on RTFO aged binders. A correlation was established between RTFO aging and short-term aging with respect to G*/sinδ and aging index.

Task 6. Revision of RTFO Aging Procedure: In this section a revised RTFO aging procedure is proposed correlating the rheological properties of STOA mixes to predict the STOA effect by testing the binder in RTFO.

Task 7. Documentation of Drum Mixing Processes: Madden Contracting Co Inc., Natchitoches, LA was visited to document the mixing and storage process of HMA and WMA. Temperature and duration at every step was monitored.

Task 8. Extraction and Investigation of Short-Term Aging of Field Mix and Revision of RTFO Aging Procedure: Short term aged plant mix was extracted and tested to determine the aging index. Because of limitation of plant mix and high variability in short term aging parameters RTFO aging procedure could not be revised based on field data.

Task 9. Evaluation of Low Temperature Performance Grading of Extracted Asphalt Binder from WMA and HMA (Lab and Field Mixes) due to Reduced Short-Term Aging in Warm Mix Asphalt:

Task 10. Investigation of Increase in Aging due to Foaming Process using Lab Mix: Effect of foaming agent on the aging of binder was investigated. Binder was extracted just after the mixing of HMA and WMA. The extracted binder was tested to find the effect in term of aging index.

Task 11. Evaluation of Increase in Rutting (if any) Susceptibility Due to Reduced Aging in WMA: Rutting susceptibility of WMA was investigated by testing the compacted mix in APA as well as in a full-scale wheel load tester. Both the laboratory and plant mix were tested.

CHAPTER 3
DISCUSSION OF RESULTS

3.1 RUTTING SUSCEPTIBILITY OF WMA

3.1.1 APA Test Results

Average rut depth of WMA and HMA specimens are shown in the figure 7. LMLC mix made of PG 58 binder showed 8.3% increase in rutting for WMA in comparison to HMA while mix made of PG 64 produced 55.3% more rutting. HMA made of PG 58 itself is more susceptible to rutting because of the soft binder when compared to PG 64. So lower aging of the softer binder did not increase the percentage of change though it rutted more than the PG 64. Rutting results from PMPC specimen exhibits similar result. In this case WMA specimen showed 10.6% more rutting susceptibility than that of HMA.

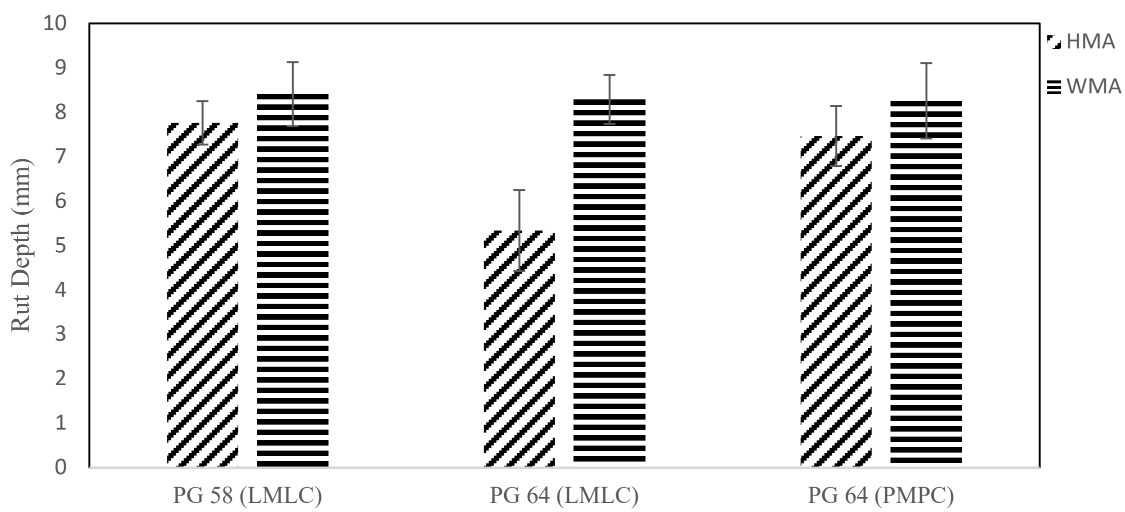


Figure 7. Rut depth of HMA and WMA tested in APA

3.1.2 Full Scale Wheel Load Test Result

After the test is done, rutting depths were measure when the specimens were in the mold (figure 4f, 4g). Figure 8 displays the average maximum rut depth of the specimens along the rolling direction of the wheel. It is noticeable that WMA specimens rutted higher than the HMA specimens in both the dry and submerged conditions. The average increase in rutting depth for WMA specimen is 34% compared to the HMA specimens. This increase in rutting may not be statistically significant as sample size small but this trend is true for all the specimens.

Physical observation of specimens after the submerged testing exhibits that moisture causes a significant damage to both the HMA and WMA. Increase in rutting depth for HMA after submerged testing is 20% whereas, for WMA this change is 57%. This is a clear indication of moisture induced damage of the asphalt mix and WMA is more susceptible to this damage than that of HMA.

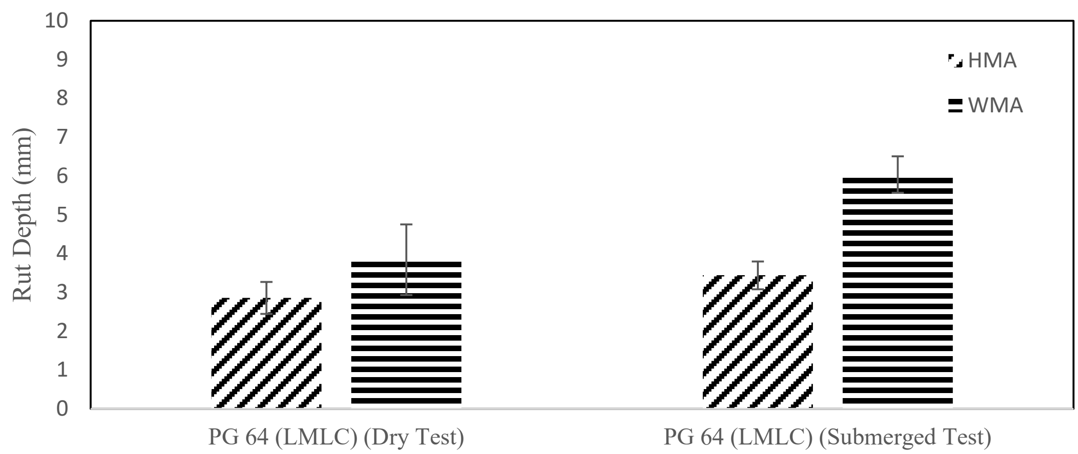
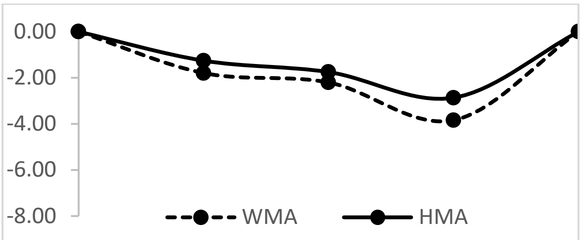
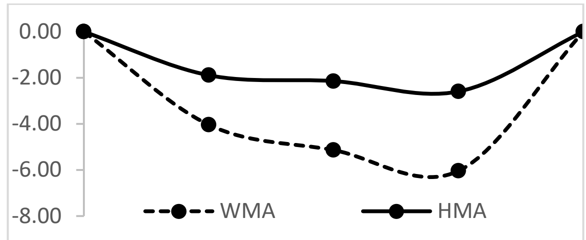


Figure 8. Rut depth of HMA and WMA tested in full scale wheel load tester

It was expected that the line at the middle of the wheel path would give the most rutting depth, but after testing, the line along the right side of the wheel was found to experience maximum rutting. It is because the wheel exerted more pressure along the right line as it was little tilted to the right after the machine was loaded. Figure 9 shows the quantitative comparison of rut depth of HMA and WMA for both the dry and submerged test. This rutting depth cannot be directly compared with the APA results as the scale of loading and other parameters are not similar. It can be concluded that the full-scale wheel loading tester is capable of testing the rutting susceptibility of asphalt mix and it can also differentiate the rutting potential of HMA and WMA.



(a)



(b)

Figure 9. (a) Average rut depth (mm) of WMA and HMA specimen after dry testing, (b) Average rut depth (mm) of WMA and HMA specimen after submerged testing.

3.1.3 Rutting Susceptibility from First Set of Testing

The second set of tests were performed in a controlled temperature and used a better mold for holding the specimens compare to first set of tests. Yet, the result from fist set of tests corroborates with the APA test results as well as full scale wheel load tester result in second trial. HMA specimen exhibits 3.41 mm of rut whereas, WMA experienced 6.60 mm in dry condition (figure 10). That test set up was not capable of performing the test in submerged condition. The rut depth in first set of tests is much higher than the send set of test result. The number of cycle was selected as 2000 for first trial whereas, in second trial the number of cycle was set as 1200.

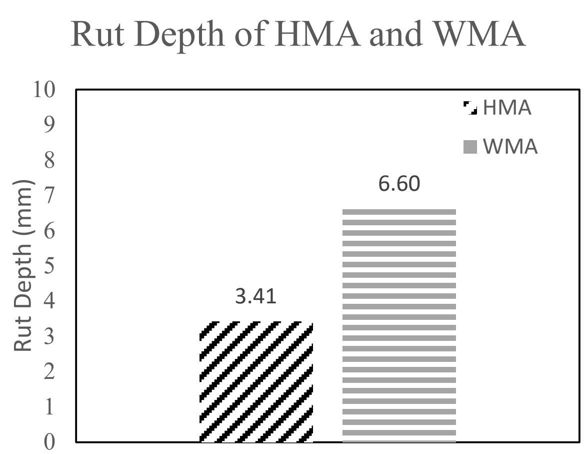


Figure 10. Full scale wheel load tester result from first set of tests

3.2 INVESTIGATION ON PLANT PRODUCED MIX

3.2.1 Preparation and Collection of Plant Mix

The mixing plant, Madden Contracting Co Inc., can produce both HMA and foamed WMA. At every step of mixing, storage and transportation, the temperature as well as the duration were monitored. Aggregates were heated for 12 to 15 minutes at 175^{0}C then got mixed with heated binder. The mixing process continued for 2 to 4 minutes. After mixing it was stored in a silo at an elevated temperature. Boxes of mix were collected from the truck. At the time of collection, temperature of HMA was between 144 to 155^{0}C and for WMA this value varied from 121 and 126^{0}C. Foamed WMA mix was prepared with 2% water content at 140^{0}C, but the temperature of binder was not lowered. Figure 11 (a-i) describes the different stages of plan mix production and observed temperatures are reported in the figure.

Both the HMA and WMA were compacted in the plant laboratory without reheating the mix. Those specimens were used to investigate the rutting susceptibility of mixes using APA. After testing in the APA, binder was extracted and recovered to find the rutting parameter for both the HMA and WMA.

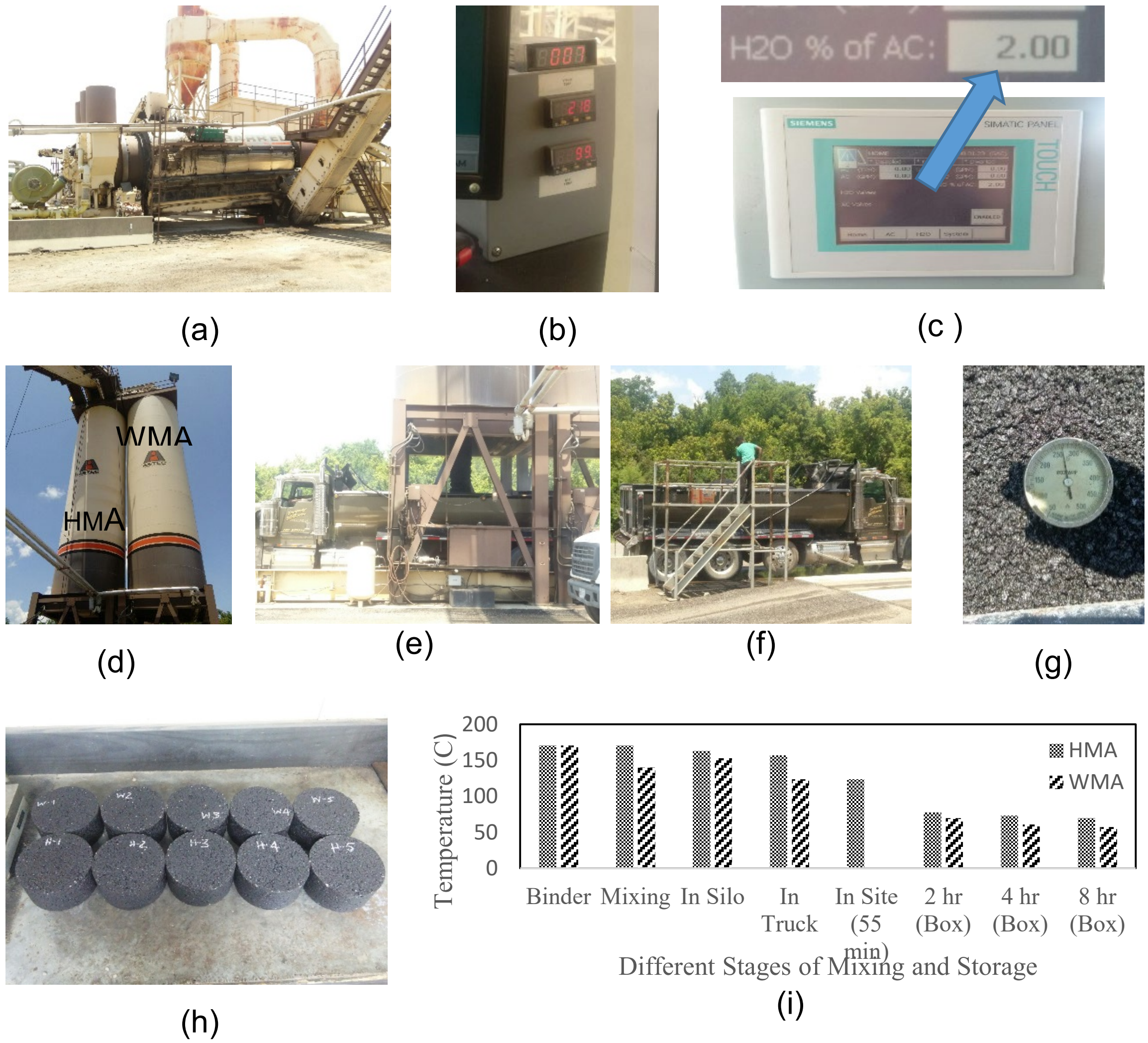


Figure 11. Collection of mix from the plant. (a) Mixing drum in plant, (b) Temperature is monitored from the plant control room, (c) Foaming water content regulator, (d) Mix is stored in silo at elevated temperature before delivering to truck, (e) Mix is being delivered in to the truck, (f) Loose mix is being collected in a card board box for later extraction, (g) Temperature of the mix in the truck is monitored using thermometers, (h) Gyratory compacted HMA and WMA specimens prepared in the plant without reheating the mix, (i) Temperature at different stages of mixing and storage for HMA and WMA

3.2.2 Investigation on Aging Index of Plant Produced Mix

After the mixing process is done mix is stored in a silo at an elevated temperature. Shortest time the mix was store in the silo was around 30 minutes. Mix was then delivered to the truck and transported to the construction site. Mix was collected in a card board box for extraction and recovery in future. The longest time the mix was kept in the silo was overnight, to be precise it was 14 hours. One box of mix was collected from the truck which was carrying that mix. Figure 12 shows the aging index of HMA and WMA at different duration of time after mixing. The AI is calculated based on the $G^*/\sin\delta$ value of unaged binder: 1.408 kPa. AI of unaged binder is assumed to be 1. It was observed that aging index of HMA when the first truck is being loaded was 1.989.

The mix collected from the construction site, 55 minutes after being loaded onto the truck, exhibited the aging index of 2.115. It indicates that carrying the mix to the construction site has very little effect on increasing the stiffness of the binder. Specimens were taken out after 2, 4, and 8 hours from separate storage boxes made of card board to check the change in aging index with time. Those boxes were kept under the sun light and fully wrapped by tape so that the mix does not come into direct contact of outside air. It was expected that the mix would be sufficiently aged inside the card board box, but because of quick heat dissipation the mix was not aged as expected. Figure 12 shows change in aging index with time. The maximum AI of plant mix was observed in the mix which was stored in the silo for 14 hours and the AI value was 6.833. It was expected that, although mixes are stored at elevated temperatures in the silo it might not get aged because it did not come into contact of air. This assumption was not completely true. The significant part of the short-term aging was happening in the silo. If mix is stored in silo for a longer period, the field AI will supersede the STOA. Because of a wide variety of factors, one specific protocol is not capable to determine the plant AI.

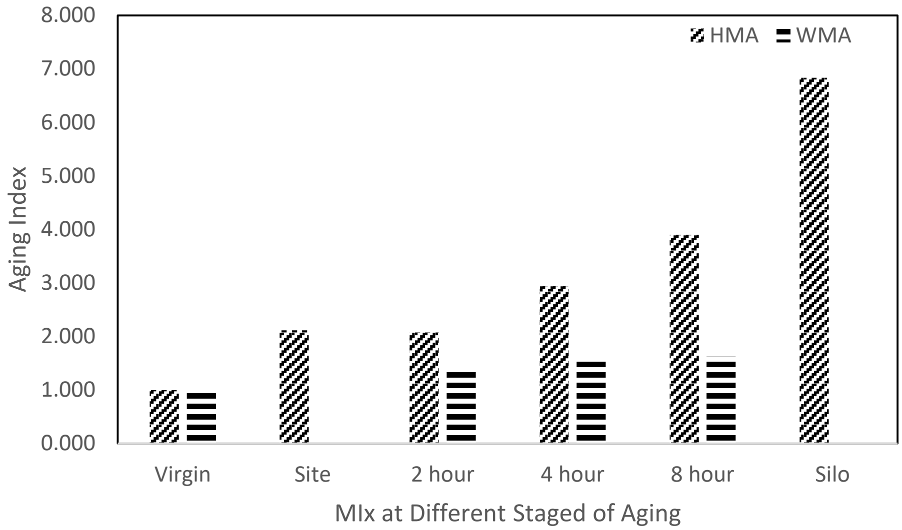


Figure 12. Aging Index of plat mix at different stage of short term aging

3.2.3 Effect of Mixing Temperature on Short Term Aging

How mixing temperature affects the aging of the binder in the mix was investigated in this study. HMA and WMA specimens were collected right after the mixing process where mixes were not allowed for further aging in the oven. HMA was mixed at 163^0C and WMA was mixed at 135^0C. Binder was extracted and recovered from the mix and the rutting parameter (G*/sinδ) was determined in DSR. The result is reported in figure 10 as aging index (AI) which is the ratio of the G*/sinδ of binder after and before aging. From the figure 10 it is observed that AI of the PG 64 binder changes 5.7% for HMA and 9.7% for WMA. In the case of PG 58 binder, the values are 16.9% and 33.6%. On the other hand WMA and HMA are collected from plant mix as soon as possible after the mixing. HMA was collected after 40 minutes of mixing while WMA was collected after 30 minutes of mixing from the silo. The aging index between them is noticeable. Aging index for HMA increases 50.6% and for WMA this increase is 25.9%.

The results imply that a portion of short term aging of the binder occurs during the mixing process. During the heating and mixing process, binder loses its volatile parts and some oxidative reactions may take place. This aging process is more pronounced in cases of plant mixing because the mixing process is done in the drum at a higher ambient temperature of 170^{0}C. Laboratory mix is produced at lower ambient temperature than that of plant mix.

Though laboratory WMA is mixed at lower temperatures, it shows an increase of AI higher than the HMA, but the plant mix WMA exhibits a lower increase in AI than HMA. In the laboratory, Advera was used as a WMA additive and the fine particles of the additive can act as a filler material which results into an increase in the complex modulus *[15]*. With aging time, the effect of granular particles of the additive was superseded by the aging effect of binder, which is clear from the figure 13. In the plant mix, as water was used as a foaming agent, the percent increase in AI of WMA was lower than that of HMA. There is also a possibility that during the storage period, some part of aging occurred at different storage temperatures for WMA and HMA which eventually distinguished the two mixes in terms of AI. So, it can be concluded that the laboratory mixing and aging process cannot completely simulate aging during the mixing process that is happening in the plant.

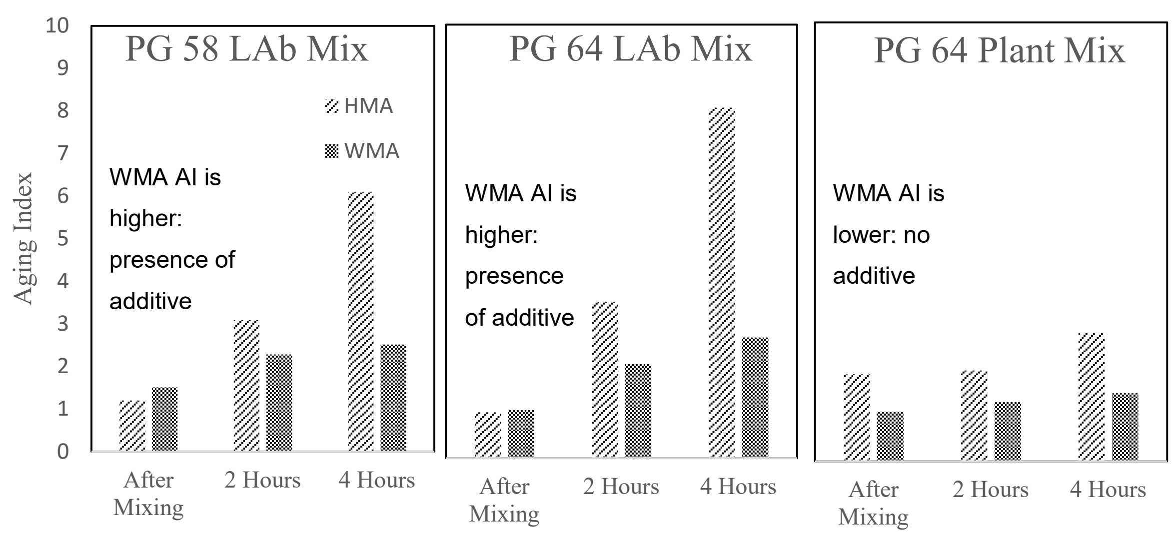


Figure 13. Effect of mixing temperature on binder aging during mixing process

3.2.4 Effect of Compaction effort on WMA

Plant produced foamed WMA and HMA were collected from the silo within one hour of mixing and was compacted in the plant without reheating. 3066 grams of mix was poured into gyratory compactor mold and was compacted to fixed height of 75.0 mm. Number of gyration required to make 75 mm specimen for WMA and HMA was recorded.

3.2.4.1 Number of Gyration to Get Same Height

Five WMA and five HMA specimens were compacted in the plant. Number of gyration required to compact the mix are tabulated in table 5. Average number of gyration required for WMA was 62 whereas, for HMA this number was 68. Presence of water foam in the binder probably made the mix easily compactible. The water foam in the mix was not distributed in a controlled way. This might be the cause of variation in gyration number for different WMA specimens. Compaction effort required for HMA was more consistent which makes the standard deviation smaller.

Table 5. Plant Mix Plant Compacted (PMPC) Specimen Compaction Data

Mix Type	Gyration	Average (StDev)	Negative coefficient 'a'	Average (StDev)	R^2 value
WMA 1	68	62.20 (8.79)	2.598	2.6796 (0.0733)	0.9971
WMA 2	50		2.795		0.9975
WMA 3	60		2.696		0.9968
WMA 4	73		2.657		0.9936
WMA 5	60		2.652		0.9969
HMA 1	67	68.00 (21.24)	2.514	2.5244 (0.0420)	0.9969
HMA 2	72		2.468		0.9951
HMA 3	67		2.584		0.9961
HMA 4	67		2.538		0.9962
HMA 5	67		2.518		0.9960

3.2.4.2 Ease of Compaction of WMA

In figure 14, height of the specimen with number of gyration is plotted for one WMA and one HMA mix as an example. When number of gyration is plotted in log scale a straight line was obtained which follow the equation: y = -a*ln(x) + C with high R^2 value provided in table 5. Negative coefficient 'a' is the measure of change in slope of the line. As 'a' gets larger the height of the specimen changes rapidly with number of gyration which is an indication of ease of compaction. Five different values of 'a' are obtained for WMA and five for HMA are provided in table 5. Average value of 'a' for WMA is 2.6796 and for HMA this value is 2.5244. A two sample T-test was conducted and it was found that at 95% confidence interval there exists a significant difference between these two means with p value of 0.006. So, it can be concluded that WMA is more easily compactible than HMA.

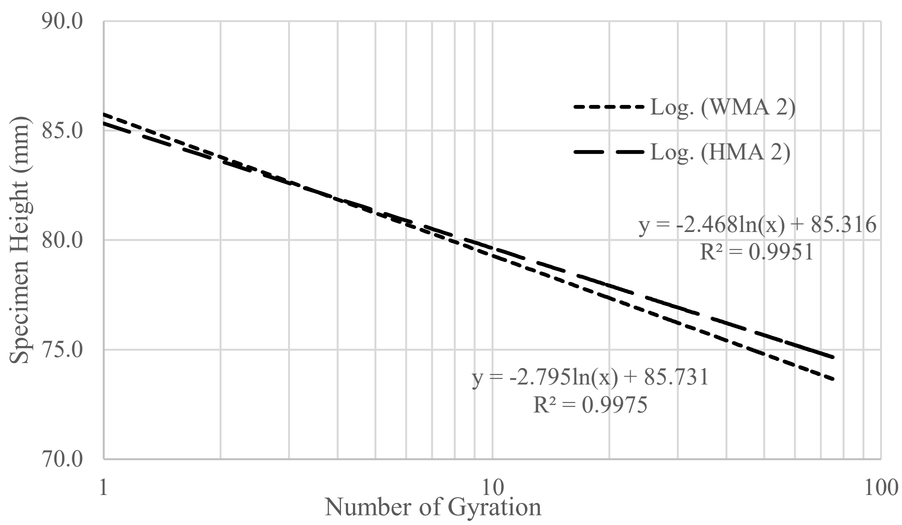


Figure 14. Change of specimen height with gyration

Different field test demonstrates that WMA does not show inferior rut resistance than HMA although laboratory WMA does. Above discussion clarifies that WMA requires less compaction effort than HMA to get the same density. So, if WMA and HMA are compacted with same effort WMA will be compacted more than HMA. In the field slightly over compacted WMA may perform similar or even better to resist rutting. Lower stiffness of binder which causes the rut is compensated by the higher density of mix. In the laboratory as both WMA and HMA are compacted to same density WMA shows more susceptibility to rutting than HMA.

3.3 INVESTIGATION OF AGGREGATE SIZE ON MIX AGING

3.3.1 Determination of Asphalt Content of Each Aggregate Size

In the following section the step by step procedure is explained, how the asphalt content of different size of aggregate is calculated in a mix. The mix was made of 4.8% (of total mix) asphalt content. 4600 grams of aggregate were used for this mix. So, asphalt content by the weight of aggregate is 5.04%

1. The mixing process was done at 163^{0}C and the mix was aged at 150^{0}C temperature for 4 hours in a laboratory forced draft oven. After short term aging the loose mix was cooled down by continuous stirring. Proper caution was taken to keep the mix as loose as possible. The cooled down mix was then sieved using the following sieves shown in the table 6.
2. An ignition oven was then used to find the asphalt content of each size of the mix. AASTHO T308 was followed to determine the asphalt contents. When the aggregate was taken out of the oven after burning, some smaller size of aggregates was found in certain size mix.

Table 6. Preliminary determination of asphalt content of different size of aggregate in the mix

Mix Retain on	Mix Passing Through	Weight of Mix before Burning	Weight of Agg. after Burning	Amount of Asphalt	Percent of Asphalt	Comment
3/8 in	-	1088.6	1065.3	23.3	2.19	Coarse Agg. Group
#4	3/8 in	1091.0	1053.9	29.9	2.81	
#8	#4	1109.9	1050.9	51.8	4.89	Medium Agg Group
#16	#8	824.3	752.7	66.5	8.77	Fine Aggregate Group
#30	#16	587.9	528.1	56.2	10.57	
#40	#30	31.8	28.8	2.8	9.65	

3. From the asphalt content corresponding to different aggregate size, it was decided to divide the mix into three different size groups. Because there was a noticeable change in asphalt content when the aggregate size group changes. For further calculation the mix will be divided into three sizes: Coarse (retained

on #4 sieve), Medium (passing through #4 and retained on #8) and fine (passing through #8).

4. Another mix was prepared and aged at 163^{0}C and 150^{0}C respectively. The mix was divided into two parts for asphalt content determination in two different ways: using ignition oven (AASHTO T308) and by extracting binder using centrifuge (ASTM D2172).
5. The mix was separated into three different sizes: coarse, medium and fine. Each mix was burned in the ignition oven and asphalt content was determined. The mixes contained some smaller or finer particle than the designated mix size. The aggregate was sieved after burning and sieve analysis was performed. Asphalt content and sieve analysis are given in table 7 and 8 respectively.

Table 7. Asphalt content determination for three different aggregate sizes

Mix Size	Weight of Mix before Burning	Weight of Agg. after Burning	Amount of Asphalt
Ret. on #4	999.0	968.4	30.6
Ret. on #8	803.5	753.4	50.1
Passing #8	592.7	533.6	59.1
Total	2395.2	2255.4	139.8

6. Aggregate was taken out of ignition oven after being burnt and was then sieved. Sieve analysis is given in table 8. From the table 8 it is clearly noticeable that the coarse aggregate obtained from coarse mix is 83.7% while the medium aggregate obtained from medium mix is 61.4%. To find the asphalt content corresponds to specific aggregate size the following calculations are performed. It can be mentioned that the definition of coarse, medium and fine aggregate is similar to the definition of mix size.

Table 8. Sieve analysis of aggregate after burning in ignition oven

Mix retain on #4		**Mix retain on #8**		**Mix passing #8**	
Sieve	**% Retain**	**Sieve**	**% Retain**	**Sieve**	**% Retain**
3/8	40.4	3/8	-	3/8	-
# 4	43.3	# 4	-	# 4	-
# 8	5.6	# 8	61.4	# 8	
# 16	0.5	#16	13.7	#16	32.5
# 40	1.6	# 40	3.7	# 40	35.0
# 100	3.3	# 100	8.3	# 100	15.1
# 200	1.7	# 200	4.3	# 200	5.5
Pan	3.6	Pan	8.7	Pan	11.8

7. In the above table 7 corresponding binder content column shows that the total asphalt content is 139.8 gm whereas initially the asphalt was taken 112.97 gm. (5.04% of 2255.4 gram of aggregate). This excess amount of asphalt was contributed by the loss of aggregate during handling and burning which was considered as asphalt. So the excess amount of 26.83 gm asphalt should be deducted from the individual asphalt content of aggregate. To deduct the asphalt content from individual aggregate, the ratio at which asphalt is divided into different aggregate size was used. In table 9 amount of asphalt is calculated after the adjustment of excess asphalt.

Actual Asphalt in the Mix	2255.4*5.04/100 =	112.97
Excess Asphalt Obtain from Calculation	139.8 – 112.97 =	26.83
Deduct AC from Agg. Ret. on #4	26.83*30.6/139.8 =	5.87
Deduct AC from Agg. Ret. on #8	26.83*50.1/139.8 =	9.61
Deduct AC from Agg. Pass #8	26.83*59.1/139.8 =	11.34

Table 9. Calculation of asphalt after balancing the error

Mix or Aggregate Size	Corresponding Binder	Deduction of AC to Balance the Error	Corrected Binder
	gram	gram	gram
Ret. on #4	30.6	5.87	24.73
Ret. on #8	50.1	9.61	40.48
Passing #8	59.1	11.34	47.76
Total	139.8		112.96

8. Using the corrected asphalt content, the actual asphalt content of different size of aggregate was calculated. It can be mentioned that a specific aggregate size contains aggregate less than its size group because it cannot be separate the smaller size completely as they stay as a cluster. So necessary corrections are made and shown here. Table 10 shows contribution of smaller aggregate size in a larger aggregate group.

Table 10. Contribution of smaller aggregate size in a larger aggregate group

Mix Size	Weight After burning (gm)	Weight After Sieving (gm)		
		Ret. on #4	Ret. on #8	Pass. #8
Ret. on #4	968.4	810.5	54.2	103.5
Ret. on #8	753.4	-	461.6	290.2
Passing #8	533.6	-	-	530.2
Combined AC		24.73	40.48	47.76

% Asphalt of Fine aggregate from Fine mix = (47.76/530.2)*100 = 9.01%. Using this percentage, asphalt associated to Fine aggregate from Medium mix can be calculated as, (9.01/100)*290.2 = 26.14 grams. Which implies that asphalt associated to Medium aggregate in medium mix = 40.48 – 26.14 = 14.34 grams. So, % asphalt of Medium aggregate from Medium mix is determined as (14.34/461.6)*100 = 3.11%

In the similar way asphalt content of coarse aggregate can be calculated. Asphalt associated to Fine aggregate from Course mix = (9.01/100)*103.5 = 9.32 gram. Asphalt associated to Medium aggregate from Coarse mix = (3.11/100)*52.4 = 1.63 gram. Total Asphalt associated to Fine and Medium aggregate in Coarse mix = 9.32 + 1.63 = 10.95 gram. So, asphalt associated to Coarse aggregate in Coarse mix = 24.73 – 10.95 =

13.78 gram. % Asphalt of Coarse aggregate in Coarse mix is (13.78/810.5)*100 = 1.70%

Similar analysis was performed for the remaining portion of the mix where asphalt content was determined by extraction of binder from the mix. The asphalt contents were found 1.60, 3.73 and 9.63% for coarse, medium and fine aggregate respectively. Average of the percent asphalt content obtained from two methods are 1.65, 3.42, and 9.32% respectively and are considered as actual asphalt content of aggregate. Table 11 shows the actual asphalt content obtained in two methods for different aggregate size.

Table 11. Calculated actual asphalt content of aggregate

Aggregate Size Group	**Ignition Oven Method**	**Extraction Method**	**Average**
Coarse Aggregate	1.70%	1.60%	1.65%
Medium Aggregate	3.11%	3.73%	3.42%
Fine Aggregate	9.01%	9.63%	9.32%

From the above table 11 it is observed that asphalt content obtained from ignition oven method yields little lower than the actual asphalt whereas, extraction method gives an over estimate. So, average of asphalt content obtained from two methods can be considered as actual asphalt content. For preparing this mix 4600 grams of aggregate was taken where coarse, medium and fine aggregate are 1899.4, 883.4 and 1817.2 grams respectively. 230.4 gram asphalt was added to it according to the mix design. Total calculated asphalt using the average percentage obtained in this study gives: (1899.4*1.65 + 883.4*3.42 + 1817.2*9.3)/100 = 230.9 grams. So, this method can estimate the actual asphalt content associated to each aggregate size successfully.

3.3.2 Mixing and Aging of Different Aggregate Size Separately

Aggregate-binder mix was prepared at 163^{0}C and aged for 4 hours at 150^{0}C. Three different size of aggregates were used to make the mix. Asphalt content of each mix was determined from the previous analysis in table 11. Binder content is express as a percentage of the aggregate. After oven aging, the binder was extracted from the mix following ASTM D5404. The extracted binder was then tested for stiffness. Figure 12 shows the aging index of the binders after extraction of binder from short term oven aged mix at 150^{0}C for four hours. The stiffness was determined at 64^{0}C. It can be mentioned that the stiffness of the virgin binder after extraction was found 1.944 at 64^{0}C.

Table 12. Aggregate size and binder content for mixing

	Aggregate Size and Quantity		
	Coarse (gm)	**Medium (gm)**	**Fine (gm)**
	Retain on 1/2 in sieve: 177	Retain on #8 sieve: 600	Retain on #40 sieve: 216
	Retain on 3/8 in sieve: 333		Retain on #100 sieve: 80
	Retain on #4 sieve: 690		Retain on #200 sieve: 37
			Pan material: 67
Total Aggregate	1200 gm	600 gm	400 gm
% Asphalt	1.65%	3.42%	9.32%
Total Asphalt	19.8 gm	20.5 gm	37.3 gm

The proportion of the aggregate was chosen in such a way that the proportion of each kind of aggregate in the individual mix remained the same as that in the original mix. Total aggregate amount was selected in such a way that the asphalt content was at least 20 gm. Otherwise it would be difficult to get the extracted binder out of the conical flask of rotavapor.

3.3.3 Mixing and Aging of Different Aggregate Size Together

To investigate the effect of aggregate size on mix aging, mix was prepared at 163^{0}C and aged at 150^{0}C for four hours. After short term aging in oven the mix was separated into three sizes and then binder was extracted from three size groups. Aging index was determined and plotted in figure 15 with the aging index of separately aged mix.

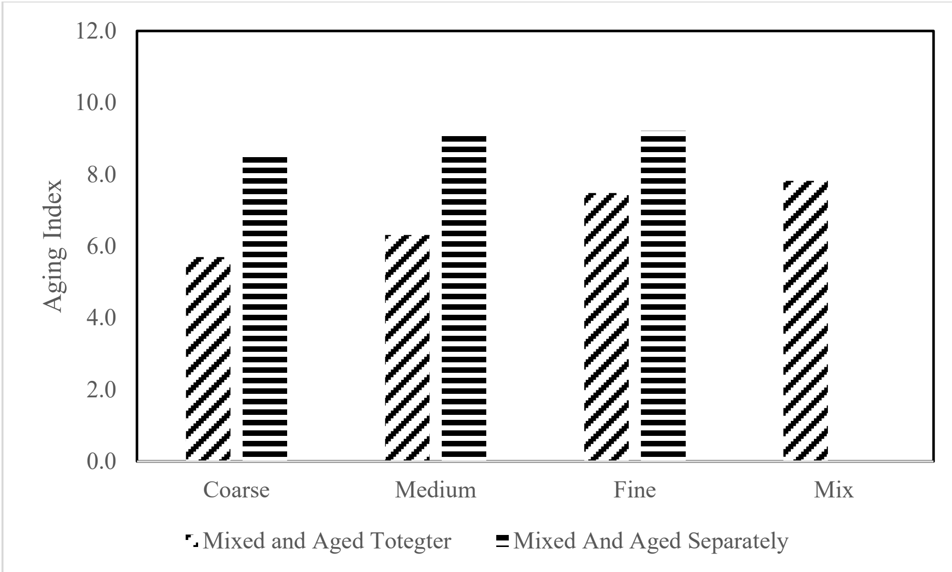


Figure 15. Aging index of extracted binder from different size mix

3.3.4 Effect of Aggregate Size on Mix Aging

From figure 15 it is observed that when mix is prepared and aged separately, all the aggregate size gets aged uniformly and the aging index is much higher than the actual mix. On the other hand, when the mix is aged as a whole, and binder is extracted from different size group it is observed that fine aggregates are aged much more than the coarse one. In a mix coarse and medium aggregate are covered with fine aggregate that let the larger aggregate to age less. As a substantial asphalt content is associated with fine aggregate the mix aging shows a close agreement with the aging index of fine aggregate. Rutting is a consequence of densification of asphalt concrete under repeated wheel loading. Densification of asphalt concrete occurs mainly because of the compaction of asphalt mastic. So, the rutting potential of a mix depends on the extent of aging that the fine aggregate experiences.

3.4 SIMULATION OF SHORT TERM AGING

3.4.1 Effect of Time and Temperature on Aging Index of RTFO Aged Binder

Both the PG 64 and PG 58 binders were aged in RTFO at 120, 148 and 163^{0}C for 60, 85, 120 and 240 minutes. The specimen collected after RTFO aging were tested in DSR to find the rutting parameter G*/sinδ and aging index (AI), which is defined as the ratio of rutting parameter of aged and unaged binder, was calculated for each specimen. Aging index of RTFO aged binders were plotted in the Figure 16 against time. As binders get exposed for longer time in heat and air flow they get more aged. It is clearly observed that the change in aging index with time follows a linear relationship for both the PG 64 and PG 58 binders irrespective of the aging temperature. The coefficient of correlation varies from 0.90 to 0.99 which is an indication of good linear relationship. If the aging temperature is raised, still it follows the linear relationship but with a higher slope because higher RTFO aging temperature expedites the short-term aging mechanism of the binder.

The slope of the Aging Index-Time line for PG 58 binder is slightly higher for specific temperature than that for PG 64 binder except at 148^{0}C. In general, the difference between the values of slope for both the binders are close enough. It is easy to comprehend from the figure 8 that the slopes are very close at specific temperature for both the binders. The change in slope with temperature was used later to develop a RTFO aging model which is discussed in later sections. It can be said that RTFO aging does not differentiate between binder grades when they are subjected to short term aging.

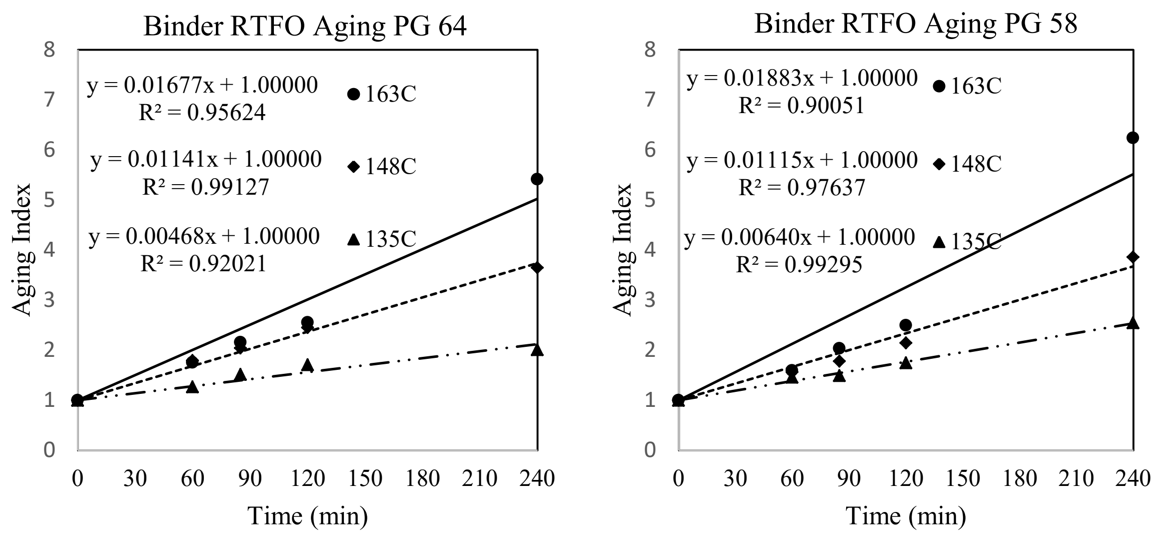


Figure 16. RTFO aging with temperature

3.4.2 Effect of Time and Temperature on Aging Index of Oven Aged Mix

Laboratory compacted mixes were aged in the oven for 1, 2 and 4 hours. HMA was mixed and aged at 163 and 150^{0}C respectively. Two WMA mixes were prepared in the laboratory where advera was added as a WMA additive. One WMA was mixed and aged at 148 and 135^{0}C respectively while for the other mix the temperatures were 135 and 120^{0}C respectively. When the mix was sufficiently aged in the oven it was taken out and cooled in room temperature. Binder was extracted and recovered on the next day for testing the stiffness in DSR. The aging index of recovered binder from the oven aged mix is plotted in the figure14 where a linear relationship is observed. From figure 19 and 17 it is noticeable that both the RTFO aging of binder and oven aging of mixes age the binder linearly with time.

Short term aging simulated in RTFO does not differentiate much between binders grades, both the binders get aged to similar extent. In case of oven aged mix this assumption is not true, two binders get aged at different rate.

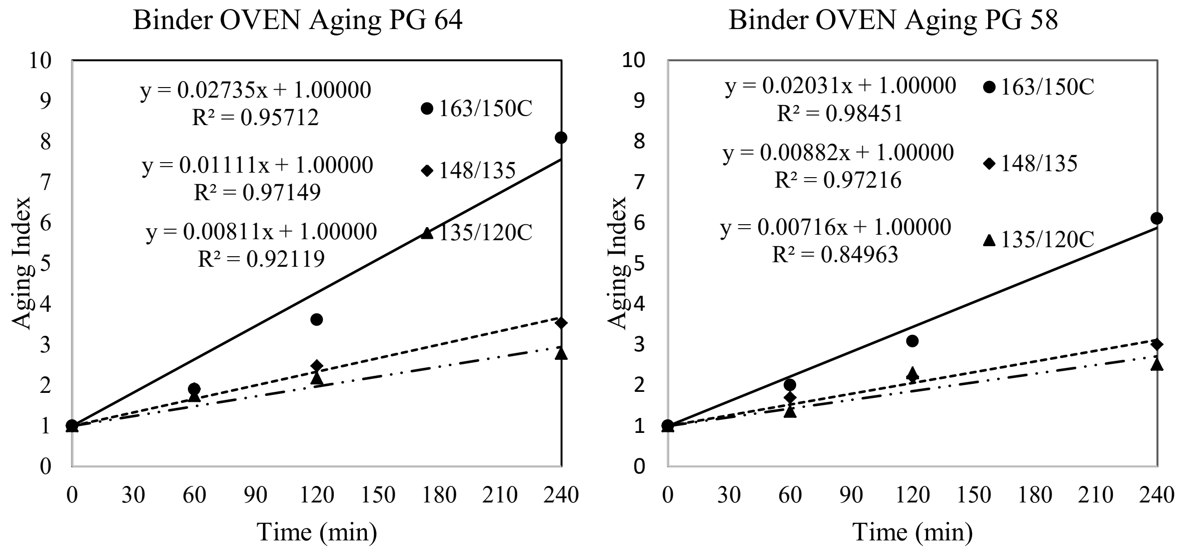


Figure 17. Oven aging with temperature

3.4.3 Rate of Change of Aging Index with Temperature

From figure 19 and 17 it is obvious that at higher aging temperature, for both the RTFO and oven aging, the rate of change in aging index is higher. It is expected that there might exist a relation between the rate of change in aging index and the aging temperature. Figure 18 is the plot of the slope of aging index-time line obtain from figure 19 and 17. PG 64 and PG 58 binders extracted from oven aged mix have different slope but they both follow the linear relation with temperature. In case of RTFO aged binders the points are so closely located that considering one trend line can represent both the binders. It is noticeable from the figure that oven aging accelerates the aging process faster than that of RTFO aging as slope of the rate of change of AI is higher for the oven aged mix in comparison to RTFO aged binder.

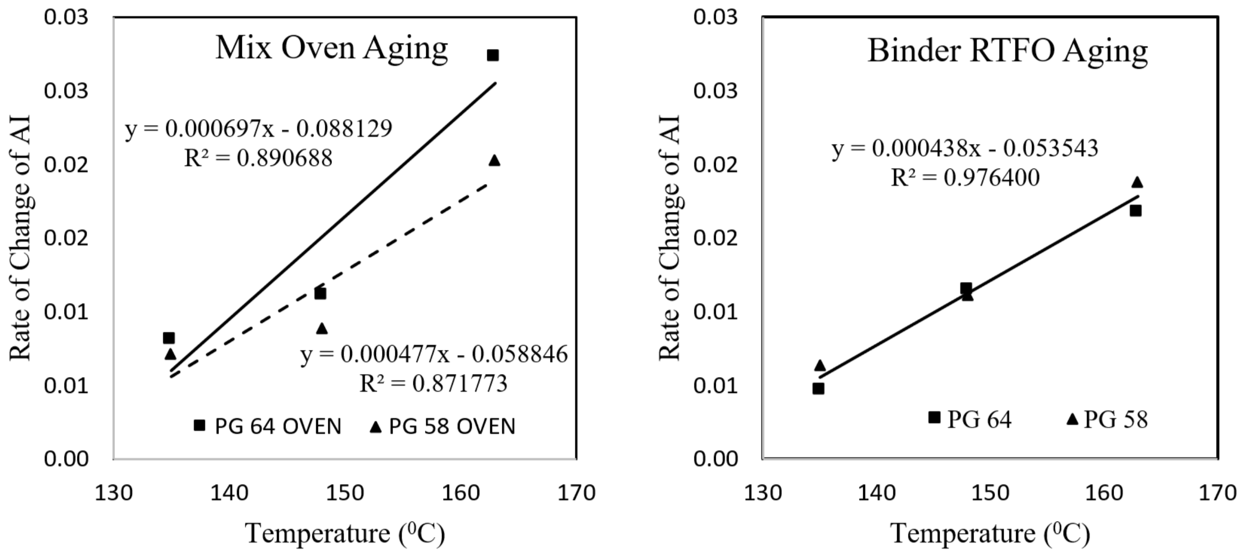


Figure 18. Rate of change of Aging Index with temperature

3.4.4 Development of an Aging Model

Figure 18 along with the idea developed in figure 19 and 17 can be utilized to develop an aging model for RTFO aged binder and oven aged mix. Short term aging of binder or the mix is dependent of both the aging temperature and the aging time. So, the model should consider two input parameters: temperature and time. Figure 19 and 17 provide the relation between aging index and time at three different temperatures. Slope of the aging index-time line for oven aged PG 64 mix at 135, 148 and 163^{0}C are 0.0081, 0.0111 and 0.0273 respectively. When these values of slope of AI-Time is plotted against aging temperature in Figure 10 they show a linear relation with the regression equation y = 0.000697x – 0.088129, where *y* is the slope of AI-Time line at given temperature *x*. This equation can be used to predict the slope of AI-Time line at any temperature. Whenever the slope at any temperature is obtained, aging index with time can be calculated as they follow a linear relationship.

AI = Sr*Time + 1

= (m*Temp + Intercept)*Time + 1

= m*Temp*Time + Intercept*Time + 1

= $m*x_1*x_2 + C*x_2 + 1$

Sr is calculated slope of AI-Time plot, changes with temperature m is slope of Rate of change of AT-Temp plot, obtained from regression equation

Following this approach three aging equations are developed. Where X_1 and X_2 are oven aging temperature and time respectively. For RTFO aging this variables are chosen as Y_1 and Y_2 intentionally to distinguish between oven and RTFO aging.

PG 64 Oven Aging: $AI = 0.000697*X_1*X_2 – 0.088129*X_2 + 1$ **Eq. 1**

PG 58 Oven Aging: $AI = 0.000477*X_1*X_2 – 0.058850*X_2 + 1$ **Eq. 2**

RTFO Aging for PG 64 and PG 58: $AI = 0.000440*Y_1*Y_2 – 0.05354*Y_2 + 1$ **Eq. 3**

Observed aging indices were plotted against the predicted AI calculated from the developed model. If the points are below the 1:1 line it means the model over predicts the AI and vice versa. To develop this prediction model binder was aged in RTFO from 135 to 163^0C and mixing temperature of the mix was between 135 and 163^0C. Figure 16 shows that at higher temperature the uncertainty of the data point to follow a linear regression increases. So beyond this temperature range which was used to develop the model may not predict the actual aging of the RTFO aged binder as well as the oven aged mix.

The equation (1), (2) were used to predict the mix oven aging for PG 64 and PG 58 binder respectively while equation (3) was used for predicting the aging index of RTFO aged both the binders. Aging temperature and duration are the independent variables used in those equations. The plots indicated that AI were in a good agreement as shown in Figure 16, which clearly shows that the developed equations give a good prediction of the AI for oven aged mix or RTFO aged binder.

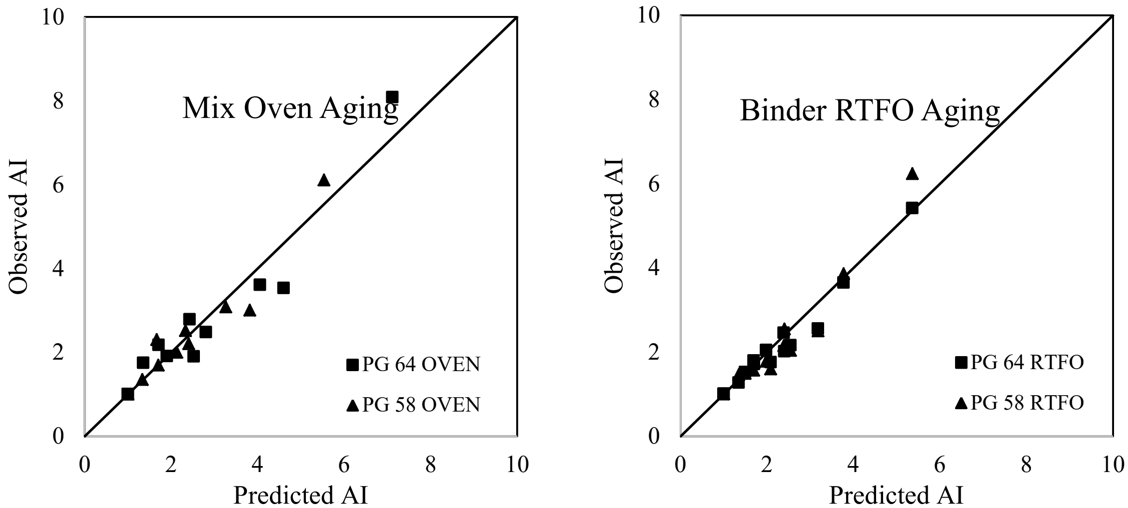


Figure 19. Predicted and observed AI value

3.4.5 Application of the model to determine RTFO temperature and time to simulate oven aging

Two aging equations are developed for one bin der: binder RTFO aging and mix oven aging. This model can be utilized to select the suitable RTFO aging temperature and time so that it can successfully predict the oven aging of the mix. Aging equation for oven aged PG 64 mix is:

$$\text{AI (OVEN)} = 0.000697*(X_1)*(X_2) - 0.088129*(X_2) + 1$$

And for RTFO aged binder the equation is:

$$\text{AI (RTFO)} = 0.00044*(Y_1)*(Y_2) - 0.05354*(Y_2) + 1$$

The equation for oven aging can be rearranged as follows:

$$\begin{aligned}\text{AI (OVEN-64)} &= 0.000697*(X1)*(X2) - 0.088129*((X2) + 1\\ &= 0.00044*(0.94X1)*(1.64X2) - 0.05354*(1.64X2) + 1\\ &= 0.00044*(Y1)*(Y2) - 0.05354*(Y2) + 1\\ &= \text{AI (RTFO)}\end{aligned}$$

In above equations X_1 and X_2 are oven mixing temperature and time while Y_1 and Y_2 are RTFO aging temperature and time. AI (OVEN-64) equation implies that RTFO aging should be conducted at $0.94*X_1$ and the duration will be $1.64*X_2$ to get the same aging effect on the binder when the mixed is aged in the oven for X_2 minutes and the mixing temperature was $X_1{}^0$C. In the case of PG 58 binder the factors are 0.99 and 1.09 for temperature and time respectively. It indicates that RTFO aging can simulate the mix oven aging more closely for PG 58 than that for PG 64 binder. For example, a WMA is produced at 140^0C and it is aged in the oven for 2 hours. To get the same aging effect in RTFO, the test should be conducted at 0.94*148 or 139^0C and duration should be selected as 1.64*120 or 196 minutes.

3.4.6 RTFO aging model for Plant mix

In this study a good correlation was found between binders RTFO aging and mix oven aging. RTFO causes less aging than that caused by the oven aging. In field it is difficult to predict the short-term aging because numbers of variables are involved. Short term aging occurred during mixing can be predicted but storage and hauling time will vary. So, it is not possible to develop a model that can predict the short-term mix aging in the field with the collected data. Mixing time, temperature, storage time, hauling distance and time those factors can be considered while predicting the short-term plant aging but it will be site specific. It might be a good approach to alter the RTFO aging time and temperature from the standard protocol to match with the specific field condition.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

This study aimed to prove the hypothesis that reduced aging of binder during the mixing process at lower temperature increases the rutting potential of WMA. Based on the results presented in the study the following conclusions can be made.

- WMA is more susceptible to rutting than that of HMA. Irrespective of the binder, mix type and testing method WMA shows 8% to 57% of increase in rutting.
- Full scale wheel load tester can successfully determine the rutting potential of asphalt mix. It can be used to simulate the rutting of compacted specimen in the laboratory.
- WMA requires less compaction effort than HMA to get the same density. So, in the field slightly over compacted WMA may perform similar or even better to resist rutting. Lower stiffness of binder which causes the rut is compensated by the higher density of mix. In the laboratory as both WMA and HMA are compacted to same density WMA shows more susceptibility to rutting than HMA.
- Asphalt content associated to fine aggregate group is the highest among the three groups: coarse, medium and, fine; they hold 1.65, 3.42 and 9.32% of asphalt when the asphalt content of the mix is 4.8% though this percentages is subjected to change with aggregate gradation.
- In a mix binder associated with fine aggregate is aged more than the binder with other aggregate. Aging of a mix is mostly contributed by the aging of the fine portion of mix.
- Change in stiffness for RTFO aged binder and oven aged mix follow a linear relationship with aging time. The rate of change of AI also changes linearly with temperature. STOA exhibits more sensitivity to temperature than that of RTFO aged binder.

- There exists a correlation between RTFO aged binder and oven aged mix. Following the aging model developed in this study aging temperature and duration can be selected for RTFO testing to simulate aging effect that a binder experiences in oven aging of the mix. To get the similar stiffness of oven aged mix prepared using PG 64 binder at $X_1{}^0C$ and being aged in the oven for X_2 minutes the binder should be aged in RTFO for $1.64*X_2$ minutes at $0\ .94*X_1{}^0C$.
- Main portion of short term aging in the field occur during the storage of the mix in the silo. Very small portion of aging occurs during mixing and transportation phase.
- Because of wide variety of factors, RTFO aging cannot be directly correlated with plant aging. RTFO aging protocol need to be adjusted depending on the actual field condition.

IMPLEMENTATION/ TECHNOLOGY TRANSFER

Peer-Reviewed Conference Papers

1. Arafat, S. and Wasiuddin, N. M. (2018). “Evaluation of a Full Scale Wheel Load Tester to Determine the Rutting and Moisture Susceptibility of Asphalt Mix in Laboratory”. Accepted for presentation as a poster and inclusion in the proceedings in ASCE International Conference on Transportation & Development 2018, Pittsburgh, Pennsylvania. July 15-18, 2018.

2. Arafat, S. and Wasiuddin, N. M. (2019). “Evaluation of RTFO Aging Procedure for Warm Mix Asphalt”. Abstract submitted to International Airfield and Highway Pavements Conference, Chicago, Illinois. July 21-24, 2019. Final paper is due by February 27, 2019.

Other Presentations

1. Arafat, S. and Wasiuddin, N. M. (2017). "Investigation of Rutting Susceptibility of Warm Mix Asphalt due to Reduced Short Term Aging: Laboratory and Field Study". Presented at the SPTC Summer Symposium, Oklahoma City on August 15, 2017.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
APA	Asphalt Pavement Analyzer
AI	Aging Index
FHWA	Federal Highway Administration
LADOTD	Louisiana Department of Transportation and Development
LMLC	Laboratory Mix Laboratory Compacted
LTOA	Long Term Oven Aging
LTRC	Louisiana Transportation Research Center
PG	Performance Grading
PMPC	Plant Mix Plant Compacted
RTFO	Rolling Thin Film Oven
STOA	Short Term Oven Aging

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