Field Aging and Oil Modification Study

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16. Abstract

The objectives of this research project included: 1. Develop laboratory short- and long-term aging protocols that will simulate field aging effects measured on plant-produced mixtures from field strip by comparing mixture and extracted binder properties to those of laboratory-produced mixtures, and 2. Verify the effects of softening oils and polymers used to adjust binder grades on results of short- and long-term aging protocols developed in this study. In addition to these objectives, to develop the laboratory short- and long-term aging protocols, a study on the effect of reheating and aging procedures was conducted at the beginning of the project. The analysis of the study results led to the following findings:

- Based on the oven comparison and pre-heating effects results call for the standardization of mixture handling and aging procedures to minimize possible influence of variation in mixture temperature. Size of containers used for sampling, condition of container (open versus closed), and checking distribution of temperatures within the oven are important items that should be included in standard sampling, handling, and aging of field produced mixtures.
- Mixtures produced in laboratory had comparable volumetric properties to plant-produced mixtures. However, it is noted that methods used for measuring Gmm could be variable and highly operator dependent. A careful look at details for measuring Gmm, and developing a more consistent protocol, is highly recommended.
- Properties at high temperatures (MSCR) and intermediate temperatures (LAS) of binders extracted and recovered from plant-produced mixtures are significantly different than properties of binders recovered from lab-produced mixtures. The same properties are also different than original binders collected from site. These differences could be due to solvent used in extraction as well as interaction with aggregates. This is particularly important for new MSCR parameters. It is highly recommended that this issue of solvent used in extraction and recovery be addressed to avoid disputes between suppliers and agency.
- In general, correlations between HWT and SCB-IFIT tests results of lab- and plant-produced mixtures are acceptable. It is therefore not recommended to change number of aging hours or oven temperature in the laboratory short-term aging to simulate plant short-term aging.
- The Flexibility Index (FI) parameter is highly sensitive to mixture aging and magnitude of FI is controlled by post-peak slope during test. However, change in P200 content, AC% or Dust to Binder Ratio values in plant-produced mixes does not appear to affect resulting FI for either binder grade.
- The eight blends prepared with different oils and additives to target PG58-34 resulted in binders with different properties and characteristics (%R and Jnr) which could affect performance of mixtures prepared with these blends. SCB-IFIT results showed that mixtures with REOB oil have the lowest FI values at all aging levels, but also the lowest aging rates when compared to the mixture with no oils or with bio-oils. The use of bio-oil significantly improved FI values at different aging levels, but also increased aging rate of FI. The mixtures with no oils showed similar FI results and aging rates to mixtures with bio-oils.
- The collective results from the field samples and oil modification of this study confirm that long-term oven aging of 14 hours (LTOA-14) is too severe for asphalt mixtures and not suitable to distinguish between mixtures. The use of 6 hours is therefore recommended as the standard long-term aging procedure for asphalt mixtures.

17. Key Words Asphalt Mixture Aging, Oil Modification, Mixture Design, Field Aging, Flexibility Index, HWT, Rutting, Cracking, Binder Grades	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

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2. Introduction and Research Objectives

Asphalt pavements exhibit changes in physical and mechanical properties over time due to aging of asphalt binders in mixtures. The rate of aging is affected by asphalt binders' composition and interactions with mix design components (e.g., aggregates gradation, surface area, and voids content or connectivity). Literature also suggests that changes in performance-based properties of asphalt mixtures are dependent on climatic conditions and aggregates source or mineralogy (Moraes, 2014). Binder changes are due primarily to two phases of aging: loss of volatile components and oxidation during high temperature production and construction stage, called short-term aging (STA); and progressive, in-place oxidation at ambient pavement temperatures, called long-term aging (LTA) (Bell, et al., 1994). In addition, recent research has shown that interactive effects between aggregate (particularly the P200 material) and asphalt binder significantly changes the rate of asphalt aging (Moraes, 2014). It is generally accepted that aging process of asphalt binder results in performance improvements to pavement within high temperature service range, while aging detrimentally affects pavement performance at intermediate and low temperature service ranges. As such, particularly in cold climates like Wisconsin, the accurate estimation of aging effects on performance is critical to achieving cost-effective pavements.

Laboratory protocols for estimating effects of rate and extent of aging on performance of asphalt mixtures in field is an ongoing research topic on a national scale. The recently completed NCHRP 09-52 (NCHRP Report 815, 2015) project "Short-Term Laboratory Conditioning of Asphalt Mixtures" identified predictive methods to simulate short-term aging of asphalt mixtures, whereas the objective of recently completed NCHRP 09-54 project "Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction" identified methods to better predict long-term aging of asphalt mixtures.

The original objectives of this research project are first to perform a comprehensive review of laboratory aging protocols and select the method that best represents short-term aging of mixtures produced in the field, and second to define testing requirements for Hamburg Wheel Tracking (HWT) test as they pertain to estimating performance of mixtures in Wisconsin. However, based on a meeting with the Project Oversight Committee (POC) in February 2017, the second objective was changed and defined as "to verify the effect of low temperature additives on aging of mixtures." The following specific objectives are defined based on the original project request for proposal, and changes authorized in February 2017 POC meeting:

1. Plan and oversee construction of a field test strip which will be used to supply plant produced mixtures for measuring field aging effects (short- and long-term) on changes in performance related properties of mixtures and extracted binders.
2. Determine the effects of changing binder grade, binder content, filler content, and mixture traffic designation on mixture aging as measured by rutting and cracking resistance, as well as on moisture resistance potential.
3. Develop laboratory short- and long-term aging protocols that will simulate field aging effects measured on plant-produced mixtures from field strip by comparing mixture and extracted binder properties to those of laboratory-produced mixtures.
4. Verify the effects of softening oils and polymers used to adjust binder grades on results of short- and long-term aging protocols developed in this study. This specific objective is to

replace the original objective focused on optimum testing requirements for HWT test, as approved by the POC.

To develop the laboratory short- and long-term aging protocols, a comprehensive study on the effect of reheating and aging procedures was conducted at the beginning of this project. The details and results of this study are discussed in Chapter 3 of this report.

3. Research Approach

This research project is divided into two main phases. The first phase involved monitoring and sampling of the construction of eight field test strips and replication of the plant-produced mixtures in laboratory. The second phase involved replicating one of the plant-produced mixtures in laboratory using eight different asphalt binder formulations each targeting same continuous performance grade (true grade). This chapter presents the research approach for each of the phases.

3.1 Field and Laboratory Aging Study

Following the extensive literature review completed in January 2017 (Bahia, et al., 2017) for this project, a partial factorial design of experiment was selected to balance practicality with identifying important factors related to aging. A fractional factorial design can be utilized to reduce the required number of test sections in half from 16 sections to eight sections in this instance.

The fractional factorial design is constructed by aliasing factors that are considered unimportant or less significant than the main factors of the study which include: mix traffic level, asphalt binder content, modification level and filler (P200) level. Table 1 shows aforementioned factors in common (+, -) notation used for multi factor experimental designs.

Table 1. Summary of Experimental Factors at Two Levels (High and Low) to be Included in Experimental Design/Test Section.

Factor, #	High (+)	Low (-)
Mix Traffic Level, 1	Low Traffic (LT)	Medium Traffic (MT)
Modification, 2	Standard (S)	Heavy (H)
Asphalt Binder Content, 3	Design	Design +%
Filler (P200) Level, 4	Design	Design +%

In this study, it is desirable to select combinations of factors in each section such that main effects can be clearly detected in the statistical analysis portion of the study. This objective can be achieved using a fractional 2^{4-1} design through aliasing of interactive factors. Aliased factors are those that are undisguisable in an experimental design. This logic assumes that interactive factors are less significant than main factors; such as those listed in Table 1. In literature, method for producing a fractional factorial design can be done using design generators as shown in Table 2, which was taken from Wu and Hamada (2009). This procedure is also used in ruggedness design of experiments summarized in ASTM standard E1169 (2014).

Table 2. Design Generators Taken from Literature to Create Fraction Factorial Designs (Wu, et al., 2009). The Generator Framed in Red is Used to Design the Experiment for This Study.

Number of Factors k	Fraction and Resolution	Design Generators	Clear Effects
4[a]	2_{IV}^{4-1}	4 = 123	1, 2, 3, 4
5[b]	2_{III}^{5-2}	4= 12, 5 = 13	None
6	2_{III}^{6-3}	4 = 12, 5 = 13, 6 = 23	None
7	2_{III}^{7-4}	4 = 12, 5 = 13, 6 = 23, 7 = 123	None

[a] The aliases are 1 = 234, 2 = 134, 3 = 124, 4 = 123, 12 = 34, 13 = 24, 14 = 23.

[b] The aliases are 1 = 24 = 35 = 12345, 2 = 14 = 345 = 1235, 3 = 15 = 245 = 1234, 4 = 12 =235 = 1345, 5 = 13 = 234 = 1245, 23 = 45 = 125 = 134, 25 = 34 = 123 = 145.

Based on this experimental design approach, the eight test sections shown in Table 3 were generated. Note that actual mix design data provided from contractor producing field sections is included in this table. The actual mix designs details submitted and approved by WisDOT are available in Appendix A.

Table 3. Field Test Sections Design Factors.

Section No.	Test Sections Factors			
	Mix Traffic Level	Filler % (P200)	AC%	Modification
1 (Control)	LT (+)	5.2% (+)	5.8% (+)	PG58S-28 (+)
2	LT (+)	5.2% (+)	5.5% (-)	PG58H-28 (-)
3	LT (+)	6.2% (-)	5.8% (+)	PG58H-28 (-)
4	LT (+)	6.2% (-)	5.5% (-)	PG58S-28 (+)
5 (Control)	MT (-)	5.7% (+)	5.7% (+)	PG58H-28 (-)
6	MT (-)	5.7% (+)	5.4% (-)	PG58S-28 (+)
7	MT (-)	6.7% (-)	5.7% (+)	PG58S-28 (+)
8	MT (-)	6.7% (-)	5.4% (-)	PG58H-28 (-)

Paving of the eight test sections was completed early July 2017, and mixtures from each section were sampled in accordance with WisDOT standard practice by members of the research team. In addition to production samples, raw aggregate and asphalt binders were also sampled during production to replicate field mixtures in laboratory. Appendix B shows the station locations of the eight test sections, as provided by project.

The aging protocols selected for the study are summarized in Table 4 and are based on literature review, discussions with the POC, and findings of the oven comparison study conducted as part of this research (detailed later in this report). All samples were aged at the same temperature and in same condition (loose mix, approximately two-inch thick layer) for both Short-Term Oven Aged (STOA) and Long-Term Oven Aged (LTOA) conditions; however, the STOA samples were stirred at the one-hour mark whereas LTOA samples were not stirred during conditioning phase. Aging times of 6 and 14 hours were selected to (1) provide two significantly different aging times (i.e. change in mixture property would be expected to be significant) to capture LTOA rate, (2) provide a practical means to age many specimens within a week’s time, and (3) bracket the 12-hours aging period used by WisDOT and researchers in previous studies.

Table 4. Summary of Aging Protocols Selected for Aging Study.

Aging Duration	Loose or Compacted Mix	Duration	Temperature, °F	Remark
Short-Term Oven Aging (STOA)	Loose	2 hours	275	Sample in pan at thickness between 1-2 inches (per R30); Stir sample at 1 hr.
Long-Term Oven Aging (LTOA)	Loose	6 hours and 14 hours	275	Sample in pan at thickness between 1-2 inches (per R30); Do not stir sample

Several types of specimens were produced and tested during the field study portion of this project, so a common naming designation has been created that will be referred to during that section of this report, and as summarized in Table 5. For low-temperature and polymer modification portion of this project, all samples were lab-produced, aged, and compacted.

Table 5. Designations of Samples Produced and Tested During Field Aging Study.

Sample Designation	Sample Type	Sampling Location	Aging/Compaction Location
STOA	Lab Mixed, Lab Compacted (LMLC)	Lab	Lab
PSTA	Plant Mixed, Lab Compacted (PMLC)	Plant	Lab
LTOA-6	Plant Mixed, Lab Compacted (PMLC)	Plant	Lab
LTOA-14	Plant Mixed, Lab Compacted (PMLC)	Plant	Lab

Table 6 summarizes testing methods selected for the first phase of the study (i.e. Field Study). The mixtures prepared in the lab were tested at STOA condition only to be compared to PSTA (Plant Short-Term Aged) field mixture.

Table 6. Summary of Test Methods Selected for Field Aging Study.

Test Method	Testing Temperature	General Aging Condition
Extraction, Recovery, and Testing of Binder [MSCR for all, BBR & LAS for control mixes] (AASHTO T164 + ASTM D5404)	MSCR & BBR: PG Temps LAS: 25°C	PSTA, LTOA-6 & LTOA-14
Hamburgh Wheel-Tracking (HWT) Test (AASHTO T324)	46°C	PSTA
Illinois Semi-Circular Bending (SCB-IFIT) Test (AASHTO TP124)	25°C	PSTA, LTOA-6 & LTOA-14
Disk-shaped Compact Tension (DCT) Test (ASTM D7313)	LT PG + 10°C (-18°C)	LTOA-6 & LTOA-14

It should be noted that during this study type of solvent and residue recovery procedure used were shown to affect recovered binder properties, particularly for polymer modified binder ('H' designation binder) at high temperature with Multiple Stress Creep Recovery (MSCR) test; low-temperature Bending Beam Rheometer (BBR) properties were not shown to be as influenced by solvent and/or procedure used. In this study one solvent and recovery procedure was used for all testing and relative trends between sections are the response, so any biasing effect is accounted for; however, unless such a bias is known and accounted for, recovered binder results should be interpreted with care, particularly in comparing results from multiple labs that may use different solvents/procedures.

3.2 Asphalt Binder Modification Study

For the second phase of this study, the effects of softening oil and polymer modification used to adjust binder grades on the results of the short- and long-term aging were investigated. Eight combinations of softening oils and polymers were used to prepare a PG58-34 binder; for the purposes of this study, binders were formulated to have approximately the same AASHTO M320 (2017) continuous grade. The polymer and chemical modification levels were not formulated to meet AASHTO M332 (2014) or Combined States Binder Group designations for polymer modified binder, but rather to achieve a similar AASHTO M320 continuous grade. Included in the eight blends is a commercially viable control sourced from a local contractor (Blend 8). Table 7 shows composition and M320 grading parameters for the eight blends. For the purposes of this phase of the study, a single mix design was chosen. The field project 4-LT at regressed air void level (5.8% total AC) was chosen for analysis.

Table 7. Compositions of the Eight Blends to Prepare PG58-34 Binder.

Mix Design	**Project "4-LT at design AV (3%) and design dust"**							
Target Binder	**PG58-34**							
Base Binder	**PG58S-28**						**PG52S-34**	
Oil Type	**Bio-Oil (Vegetable)**			**Re-Refined Oil (REOB)**			**-**	
Composition	**Blend 1**	**Blend 2**	**Blend 3**	**Blend 4**	**Blend 5**	**Blend 6**	**Blend 7**	**Blend 8**
PG58S-28 Base Binder	**94.5%**	**95.8%**	**96.5%**	**91.0%**	**90.8%**	**93.5%**		**Contractor Supplied PG58-34**
PG52S-34 Base Binder							**96.85%**	
SBS (Kraton D243)	**2.0%**			**2.0%**				
Elvaloy (4170)		**1.0%**			**1.0%**			
PPA (115)		**0.2%**	**0.5%**		**0.2%**	**0.5%**		
SBS (Kraton D1101)							**3.0%**	
Sulfur							**0.15%**	
Bio-Oil	**3.5%**	**4.0%**	**3.0%**					
REOB				**7.0%**	**8.0%**	**6.0%**		
OB C.G.	61.3	65.8	60.5	63.5	61.9	61.5	66.4	61.2
RTFO C.G.	62.4	66.3	60.7	64.8	63.1	61.8	67.8	62.2
LT S(60)	-26.8	-26.2	-25.4	-29.0	-27.1	-27.5	-25.9	-26.5
LT m(60)	-25.6	-28.5	-25.7	-25.1	-25.5	-25.1	-25.8	-28.3
Continuous M320 PG	**61.3-35.6**	**65.8-36.2**	**60.5-35.4**	**63.5-35.1**	**61.9-35.5**	**61.3-35.1**	**66.4-35.8**	**61.2-36.5**

SBS is Styrene-Butadiene-Styrene Elastomeric Polymer

PPA is Poly-Phosphoric Acid high temperature modifier.
REOB is Recycled (Refined) Engine Oil Bottoms
Elvaloy is the trade name for an elastomeric terpolymer system trademarked by DuPont
O.B. is Original (unaged) Binder
RTFO is Rolling Thin-Film Oven Residue
C.G. is Continuous (true) Binder Grade
L.T. is Low Temperature
OB and RTFO C.G. are Original Binder and RTFO Binder Continuous (True) Grade, respectively

After preparing all the eight blends, eight mixtures were prepared at same binder content (5.8%) and same combined aggregate gradation. The only difference in these eight mixtures is composition or the polymers/oils used to prepare the PG58-34 binder. These mixtures were tested for volumetric properties and resistance to fatigue damage using the Illinois Flexibility Index Test (SCB-IFIT) at different aging levels; short-term oven aged (STOA), long-term oven aged for 6 hours (LTOA-6) & 14 hours (LTOA-14) as summarized in Table 8.

Table 8. Summary of Test Methods Selected for Binder Modification Study.

Test Method	Testing Temperature	General Aging Condition
Extraction, Recovery, and Testing of Binder [LAS] (AASHTO T164 + ASTM D5404)	MSCR: PG Temps LAS: 25°C	STOA, LTOA-6 & LTOA-14
Mixture Volumetrics	NA	STOA, LTOA-6 & LTOA-14
Illinois Semi-Circular Bending (SCB-IFIT) Test (AASHTO TP124)	25°C	STOA, LTOA-6 & LTOA-14

4. Development of Laboratory Preheating and Aging Protocol

Reheating and oven aging procedures of plant produced asphalt mixtures in laboratory are important topics to consider as performance testing of asphalt mixtures becomes more widely used by agencies. Differences between laboratory equipment and procedures could significantly affect aging which affects performance properties. The purpose of this part of the study is to investigate influence of sample size, oven type, and variation in reheating/aging temperatures on results of two performance tests on plant produced mixtures. A single mixture selected from the 2017 WisDOT Round Robin was tested for volumetric properties and performance using Hamburg Wheel-Tracking (HWT) Test and Semi-circular bending following Illinois Flexibility Index Test (SCB-IFIT).

Current guidance on Short-Term Oven Aging (STOA) of asphalt mixtures for use in mechanical property testing from AASHTO R30 is conditioning of uncovered, loose mixture specimens for four hours at 275°F, stirring every hour. Long-Term Oven Aging (LTOA), per the same AASHTO specification, is conducted on compacted specimens for 120 hours at 185°F with a cooling period of about 16 hours after aging.

Several research studies have concluded that the AASHTO recommended STOA protocol may be longer than what is needed to simulate plant production of mixtures, and a more reasonable duration is two hours of loose mix aging at 275°F, stirring after one hour (Hanz, et al., 2016, NCHRP Report 815, 2015). There appears to be consensus in literature that loose mix aging best simulates short-term aging during plant production.

There is no consensus, however, regarding aging conditions for LTOA. Experience in Wisconsin on pilot projects has shown the practical difficulty in following AASHTO guidelines when performance testing of mixtures is needed for acceptance in the field. This leads to the implementation of loose mixture aging at 275°F for 12 hours for these projects. Findings for Wisconsin mixtures suggest that this protocol “produced comparable asphalt binder properties to compacted mix aging under the current AASHTO R30 protocol”, although no claim as to the representation of this procedure to field mixtures was made (Hanz, et al., 2016). Recent work by Elwardany, et al. (2016) was conducted in support of NCHRP 09-54 and has found that loose mix aging above 212°F may “alter oxidation mechanisms”, however.

For the purposes of this study, all mixture conditioning and aging is conducted on loose mix samples, and no claim is made as to the representation of these methods of field production conditions. The testing program is intended to identify factors in laboratory (and between laboratories) that can affect mixture aging process in an effort to standardize mixture handling procedures.

Loose asphalt mixture was distributed to three separate laboratories. Each laboratory uses a different type of oven. These mixtures were preheated and aged, respectfully, and all mixtures were then transported to Modified Asphalt Research Center at the University of Wisconsin-Madison (UW-MARC) laboratory where one operator carried out all testing to limit testing bias. The preheating and aging procedure described later in Section 3 was used at each laboratory. Figure 1 shows the methodology of how results of the oven type study were obtained.

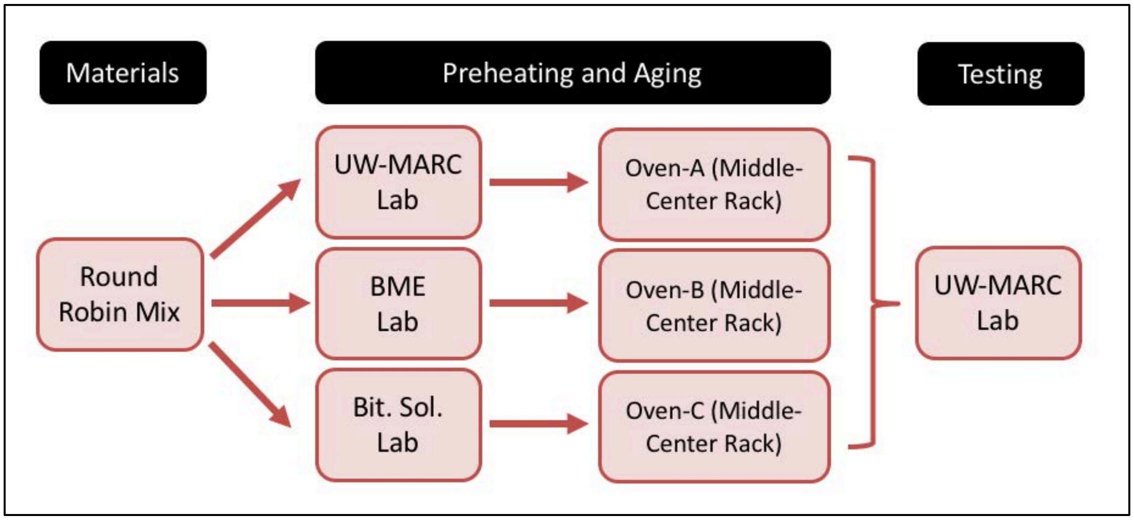


Figure 1. Methodology of Preheating and Aging Mixture Through Testing Phase.

4.1 Materials

In this study, one plant-produced asphalt mixture was used for all aging and testing activities. The mixture is a Wisconsin Standard Specification "E-3" mixture, which is a mix design designated for roads with a 20-year design ESAL range of 1 to 3 million. The mixture utilized PG58S-28 asphalt binder and Table 9 shows aggregate stockpile gradations and their respective properties. Table 10 shows volumetric data for three total asphalt contents of the mixture.

Table 9. Aggregate Gradation from Stockpiles and Properties.

Aggregate Gradation										
Aggregate Type (% Blend)		5/8 × 1/2 Chip (9%)	1/2 × 1/4 Chip (9%)	MFG'D Sand (29%)	Natural Sand (24%)	DEG Sand (1%)	FRAP (28%)	JMF	Specification	
									Min	Max
2	50.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1 ½	37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
1	25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
¾	19.0 mm	100.0	100.0	100.0	100.0	100.0	99.6	99.9	100	100
½	12.5 mm	65.3	100.0	100.0	100.0	100.0	95.2	95.5		100
3/8	9.5 mm	5.4	90.5	100.0	100.0	100.0	86.7	86.9		90
#4	4.75 mm	1.9	9.7	97.8	98.9	100.0	63.6	72.0		
#8	2.36 mm	1.8	1.9	67.5	89.8	100.0	45.6	55.2	28	58
#16	1.18 mm	1.8	1.8	39.4	77.2	100.0	33.3	40.6		
#30	0.6 mm	1.7	1.7	23.1	58.2	100.0	25.1	29.0		
#50	0.3 mm	1.7	1.7	11.1	17.6	100.0	17.0	13.5		
#100	0.15 mm	1.6	1.6	2.6	2.9	100.0	11.2	5.9		
#200	0.075 mm	1.4	1.4	1.2	1.0	100.0	7.9	4.0	2.0	10.0
	FAA	-	-	46.0%	39.4%	-	-	43%	43%	-
	Gsb	2.739	2.727	2.733	2.668	-	2.739	2.719	-	-

Chip is single sized clean aggregates
MFG'D Sand is manufactured (screenings from aggregate crushing) sand
DEG Sand is plant degradation (Big House Dust)

FRAP is fractionated recycled asphalt pavement
FAA is Fine Aggregate Angularity
Gsb is Specific Gravity of Aggregates
JMF is Job Mix Formula

Table 10. Volumetric Data of Three Separate Mixtures.

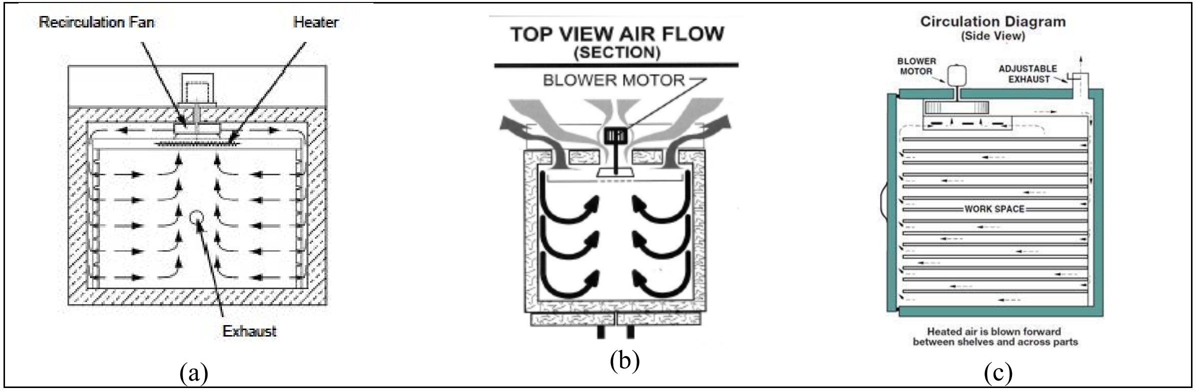
Volumetric Data											
Point	**Added Pb, %**	**Total Pb, %**	**Gmm**	**Gmb**	**Va, %**	**VMA, %**	**VFB, %**	**Unit Weight**	**% Gmm Ni**	**% Gmm Nm**	**TSR, %**
A	3.6	5.0	2.556	2.414	5.6	15.7	64.3	2407			
B	4.1	5.5	2.536	2.443	3.7	15.1	75.5	2436			
C	4.6	6.0	2.517	2.453	2.5	15.2	83.6	2446			
JMF	**4.0**	**5.4**	**2.540**	**2.438**	**4.0**	**15.2**	**73.7**	**2431**	**89.7**	**96.9**	**82.2**
										TSR N =	20
Specification						>14.5	70-76		<89.0	<98.0	

Pb is Percentage of Binder
Gmm is Theoretical Maximum Specific Gravity
Gmb is Bulk Specific Gravity
Va is Air Voids Percentage
VMA is Voids in Mineral Aggregates
VFB is Voids Filled with Binder
TSR is Tensile Strength Ratio

4.2 Oven Types

In this study, three separate ovens (in three different laboratories) were used for reheating and aging of loose mix samples: Oven-A, Oven-B and Oven-C. Oven-A uses a high-volume fan to convect heat through stainless steel ducts that are on each side of the oven. The intake of fresh air is fixed, as well as exhaust rate as it is regulated by a damper located on the back of the unit.

Oven-B operates in a similar fashion to Oven-A as the heating element is on the top and the hot air flows from the sides of the oven. The hot air originates in the back and moves forward as it circulates. The sides of interior are made up of an aluminized steel. Finally, Oven-C utilizes a stainless-steel interior and circulates hot air from back to front and across the shelves. Figure 2 shows hot air circulation inside the three ovens used in this study.



(a) (b) (c)

Figure 2. Air Flow of: (a) Oven-A, (b) Oven-B, and (c) Oven-C.

4.3 Development of Reheating & Aging Procedure

Before assessing effect of oven type or size on aging and/or performance of mixtures, a standardized preheating and aging procedure should be developed in order to limit the variability that HMA sample output might have. Table 11 is a roadmap of how the standardized procedure used later in this study for reheating and aging was developed. The results of each individual step-study were carried through where applicable, meaning when a finding was concluded it was used to achieve the result of the next step-study. The following sub-sections summarize results of the step-studies and their significant findings.

Table 11. Step-Studies Followed to Develop the Standardized Reheating and Aging Procedure.

Step-Study #	Step-Study Description
1	Reheating Boxed vs. Unboxed Block Samples in Oven
2	Reheating Covered vs. Uncovered Samples in Oven
3	Temperature Distribution inside Ovens & Effect of Location of Samples in Oven on Reheating
4	Effect of Number of Samples in Oven on Reheating
5	Effect of Opening the Oven to Stir Samples on Aging
6	Effect of Oven Temperature Accuracy on Aging Samples and Performance

4.3.1 Duration to Reheat Boxed versus Unboxed Mixtures

In Wisconsin, it is standard procedure to sample plant-produced mixtures in cardboard boxes to aid in transport and storage for Round Robin type testing; for this study, the boxes contained approximately 17 kg of loose mixture. After delivery of the boxed mixture to laboratory for testing, the box is reheated to be remixed and representatively split for further testing. This initial step, namely the reheat temperature and duration has yet to be standardized in Wisconsin. Therefore, it was important to evaluate time required to reheat boxed and unboxed mixtures.

One boxed sample and one unboxed sample (a boxed sample that had cardboard removed and placed in a metal pan) were reheated in a 275°F (135°C) oven to determine the duration it took for HMA block to reach a temperature at which it could be split and mixed representatively, as shown in Figure 3.

Figure 3. Reheating Boxed versus Unboxed HMA Blocks.

After two hours of heating, a temperature probe cast within the unboxed sample block reached 215°F (102°C) whereas the boxed sample only reached 135°F (57°C). Ultimately, the higher temperature of 215°F after two hours produced a mixture that could be broken apart and split representatively. This finding confirmed that there is a significant effect of unboxing the sample block on the time required for reheating. It should be noted that this ignores any effect of exposure to moving air within oven on aging of mixture.

4.3.2 Duration to Reheat Covered versus Uncovered Mixtures

Upon finding that the unboxed mixture reached splitting temperature faster, the study progressed to investigate after splitting the sample into pans, whether covered or uncovered mixtures reach target aging temperature quicker.

The reheated HMA block was remixed and placed into two stainless-steel pans (16”×11”×2.5”) with a thickness of 1.25 inch. One pan was covered with aluminum foil and the other was left uncovered in the middle rack of the oven preheated to the desired aging temperature of 275°F (135°C). Figure 4 shows that the uncovered sample took approximately 25% less time to reach the desired temperature (i.e. 275°F) relative to the covered sample. Again, effect of covering the sample during reheating and/or aging can slow down reheat process significantly.

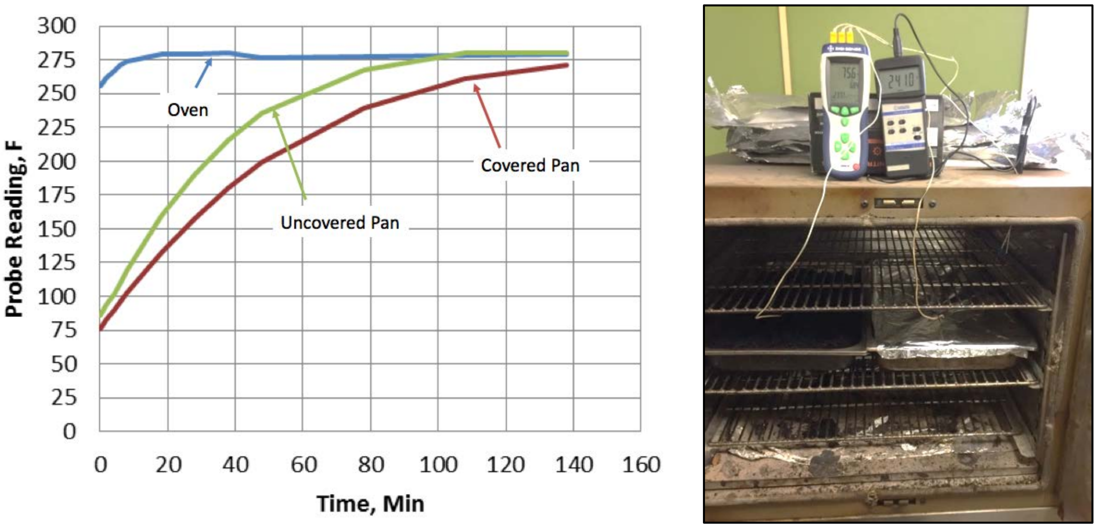


Figure 4. Monitoring Temperature of Covered versus Uncovered Samples.

4.3.3 Location of HMA Sample in Oven

Location of mixture inside the oven during reheating process may seem trivial but oven set point may not represent the temperature at all locations within the oven. Locations within oven may be warmer or cooler than others, therefore calibration may be needed for all ovens before use. To check temperature uniformity within an oven in this study oven, four probes were placed in different locations in an empty 275°F oven. Recorded temperatures showed that temperature distribution is not uniform in all locations of this oven as shown in Figure 5. Probe 4 in the bottom left corner of the oven was the hottest location with an average difference of about 15°F compared to Probe 3, the coolest location. The difference in probe readings for this oven varied by as much as approximately 10°F (AASHTO R30 has a tolerance window of 10.8°F for conditioning).

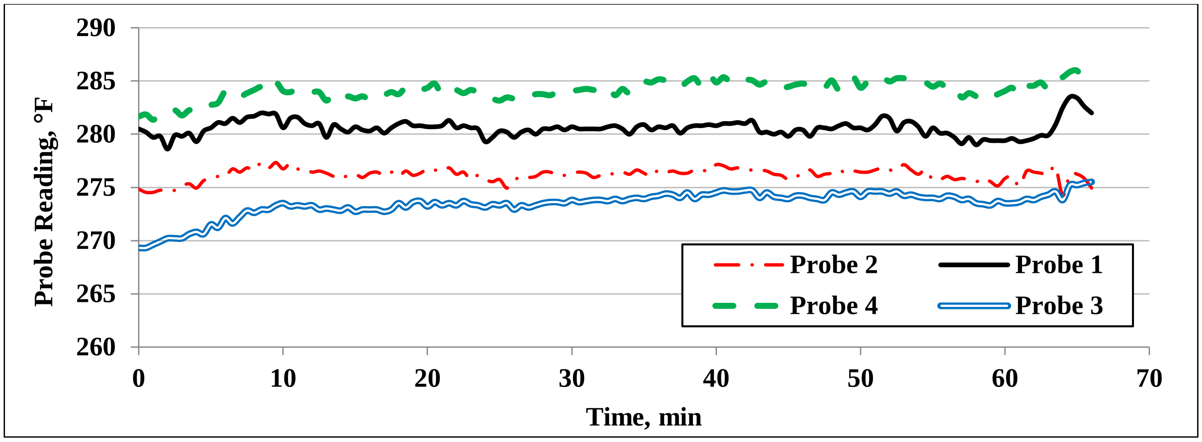
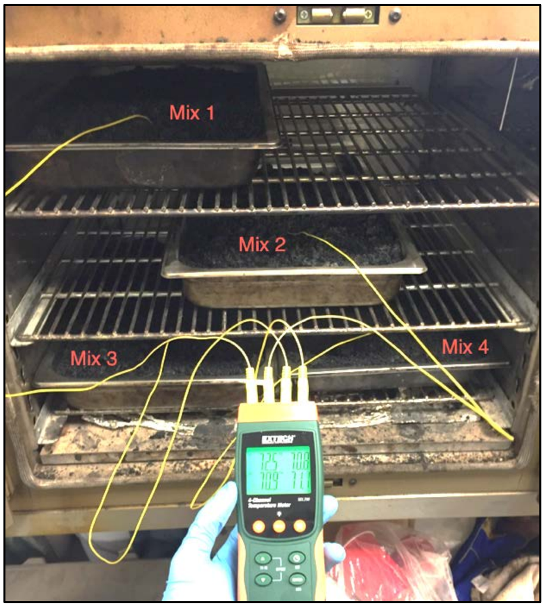


Figure 5. Temperature of Probes at Specified Locations in the Oven.

Besides, although the thermostat was reading correctly when measured against a traceable reference thermometer with a probe in same location, at least one area of the oven was outside of current AASHTO R30 (2010) limits; this finding suggests that although the oven set point (and thermostat accuracy) can be checked, the actual mixture temperatures at the sample location should be monitored. These results constituted further data to be collected using Oven-A. Temperature distribution in Oven-A appeared to be more uniform. It was found that individual ovens, even from the same model, should be calibrated and temperature distribution can be affected by oven type.

To investigate the effect of location inside the oven on mixture reheating, four uncovered HMA samples in pans (1.25-inch mixture thickness) were placed in the 275°F (135°C) Oven-B at different locations as shown in Figure 6.



Mix-Location #	Sample Location	Time to AASHTO Lower Limit (269.9°F), min	COV %
Mix-1	Left of top rack	193	23.0
Mix-2	Middle of center rack	135	
Mix-3	Left of bottom rack	115	
Mix-4	Right of bottom rack	139	

Figure 6. Temperature of Four Locations of Uncovered Mixtures in Oven-B.

All samples were at room temperature at start of the test and probes were cast one inch deep into center of the pan. The table in Figure 6 outlines duration it took each mixture, according to its location in the oven, to reach AASHTO R30 lower limit of oven aging temperature (269.9°F). As per results shown, sample position in the oven is demonstrated to affect reheat time significantly. In addition, temperature distribution is not necessarily uniform in the oven, particularly when it is fully loaded. This will be expanded upon in the next section.

4.3.4 Oven Loading

The effect of oven loading on temperature distribution and reheat duration was also investigated in this study. Two mixture samples were placed in the upper-center and the lower-center of the Oven-B. These samples were left undisturbed and temperature was monitored for more than 18 hours as recorded in Figure 7. The results show that mixes reached AASHTO R30 lower limits after 3 hours and 3.6 hours for top and bottom locations, respectively. Therefore, when oven is not fully loaded temperature distribution appears to be better compared to the previous section when oven was fully loaded, with a slight difference in reheating time, with respect to location in the oven.

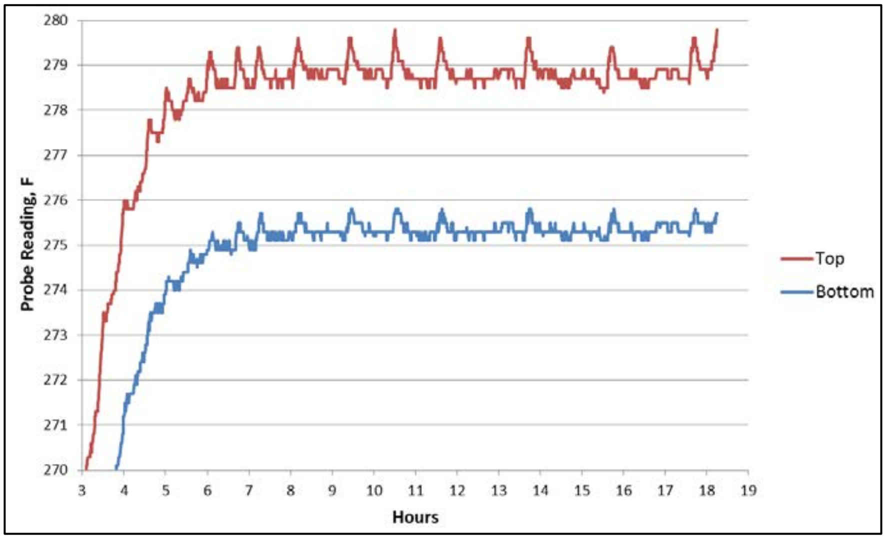


Figure 7. Temperature of Two HMA Samples Undisturbed for 18 Hours.

4.3.5 Opening Oven to Stir Samples

Simulating short-term aging of mixture samples requires stirring of sample one hour after reaching initial target temperature. In this part of the study, the effect of opening the oven door to stir samples on mixture temperature was investigated.

Two HMA sample pans were uncovered and placed in upper-center and lower-center locations of the Oven-B. These samples were stirred one hour after reaching the AASHTO R30 lower limit. Stirring loose mixture in each pan was completed in less than one minute. Figure 8 shows temperature of mixtures monitored before and after stirring.

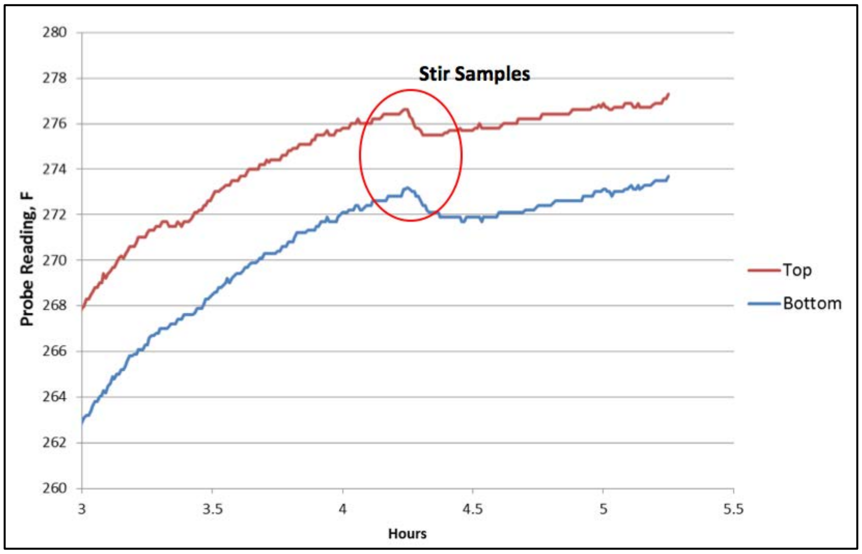


Figure 8. HMA Samples' Temperature at Top and Bottom Rack of the Oven Before and After Stirring.

As shown in the figure, top mixture returned to pre-stir temperature in about 38 minutes whereas bottom mixture took 51 minutes. However, neither mixture fell outside of AASHTO limits during stirring process. From this study, it is concluded that although opening the oven to stir mixture specimen will cause a reduction in mixture temperature, if duration of stirring is kept to a minimum, the decrease in temperature may not be significant (using AASHTO R30 temperature ranges as a benchmark). Furthermore, time required for mixture to return to pre-mixing temperature can vary significantly, which in turn may be an issue if the oven is opened repeatedly during aging process.

4.3.6 Effect of Temperature Accuracy of Oven on Performance of Aged Mixes

Although initial testing showed clear effects of sample covering and location in oven, it was important to determine if some variations in mixture temperatures can affect results of volumetric properties and performance in terms of rutting or permanent deformation.

A total of six mixture samples were prepared in pans for reheating and aging at two temperatures; 270°F and 285°F. Each aging temperature had three samples, one for determining the theoretical maximum specific gravity (Gmm) value and two for HWT test. The Gmm sample pan for each aging temperature was reheated and aged as the only sample in the oven on the middle-center rack. The two HWT pans for each temperature were placed in the oven at the same time, side by side on the middle-center rack. All six samples were STOA and followed the same reheating and aging procedure. The samples were uncovered during reheating and aging sequence. The Gmm, bulk specific gravity (Gmb), and HWT test procedures were tested as per ASTM D6857 (2011), AASHTO T331 (2010), and AASHTO T324 (2014), respectively.

Temperatures of mixtures were monitored throughout reheating and aging procedure using Oven-A. Among the samples conditioned at the same temperature, there was no statistical significance between samples, re-affirming the results obtained from Oven-B. Figure 9 to Figure 11 outline these results.

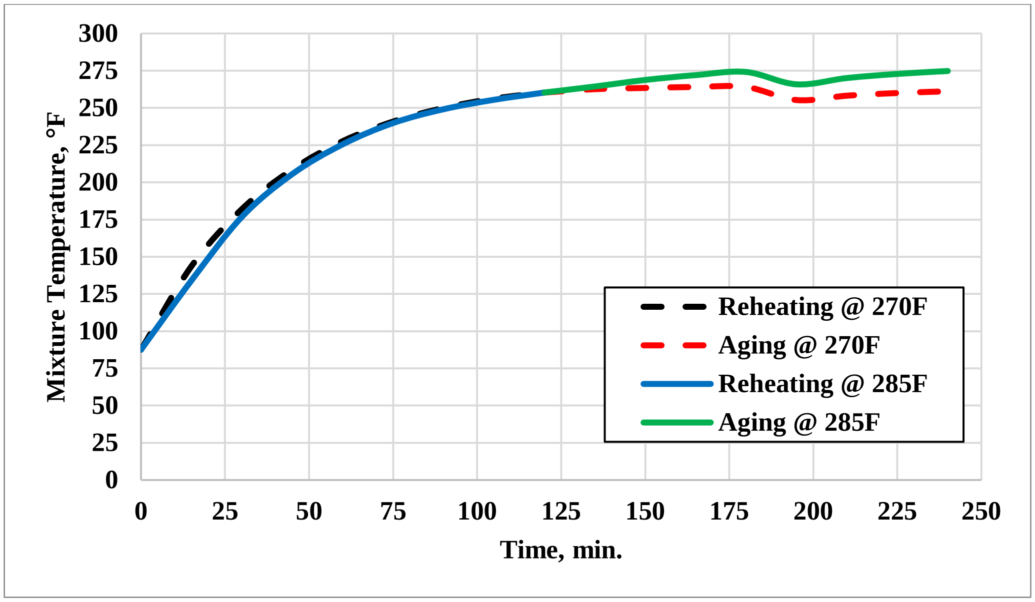


Figure 9. Mixture Temperature of Gmm Samples During Reheating and Aging Sequences.

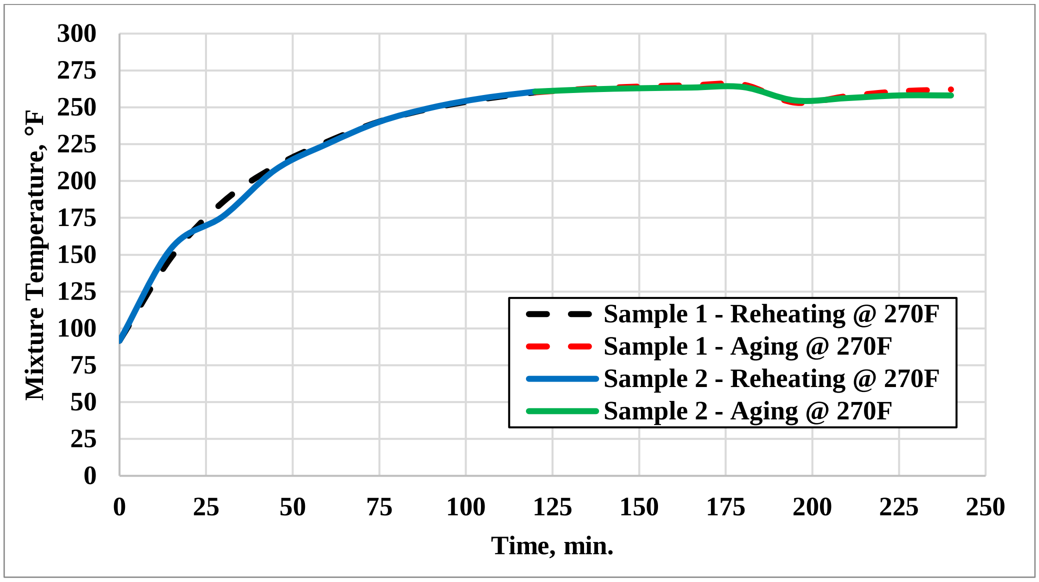


Figure 10. Mixture Temperature of HWT Samples During 270°F Reheating and Aging Sequences.

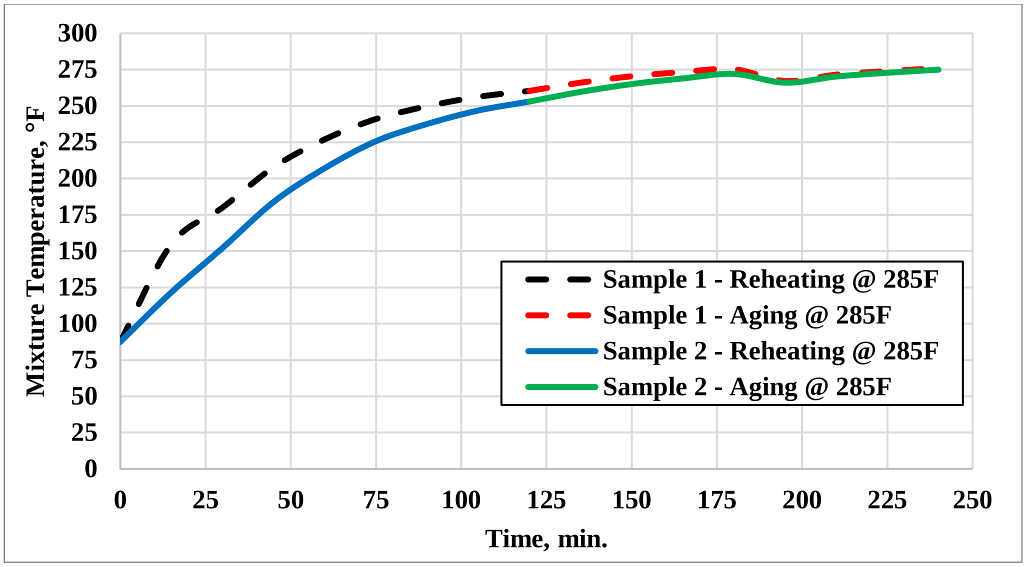


Figure 11. Mixture Temperature of HWT Samples During 285°F Reheating and Aging Sequences.

Sample reheating and aging does not have an effect on number of gyrations needed to compact the loose mixture to a specified height in the Superpave Gyratory Compactor (SGC). Each reheated and aged pan was used to compact 2 HWT samples (a and b). Samples 2a and 2b at 270°F shown in Figure 12 were completed by a separate operator from the other six samples between the two temperatures. The decreased amount of gyrations to reach a compaction height of 62.5 mm for these two specimens were attributed to operator error in the preparation of the SGC mold. Figure 12 and Figure 13 outline insignificant difference among number of gyrations required to reach compaction height.

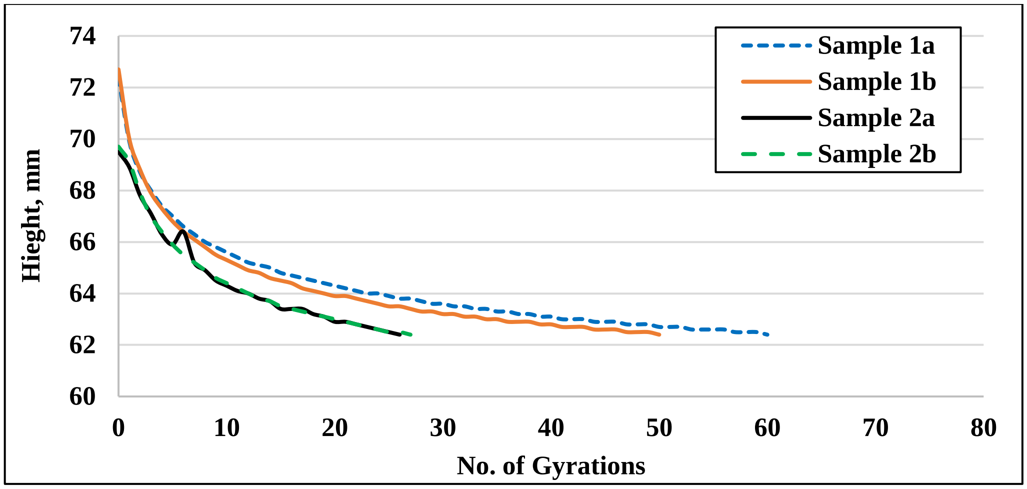


Figure 12. Recorded Height and Gyrations of Four 270°F Replicates for HWT Test.

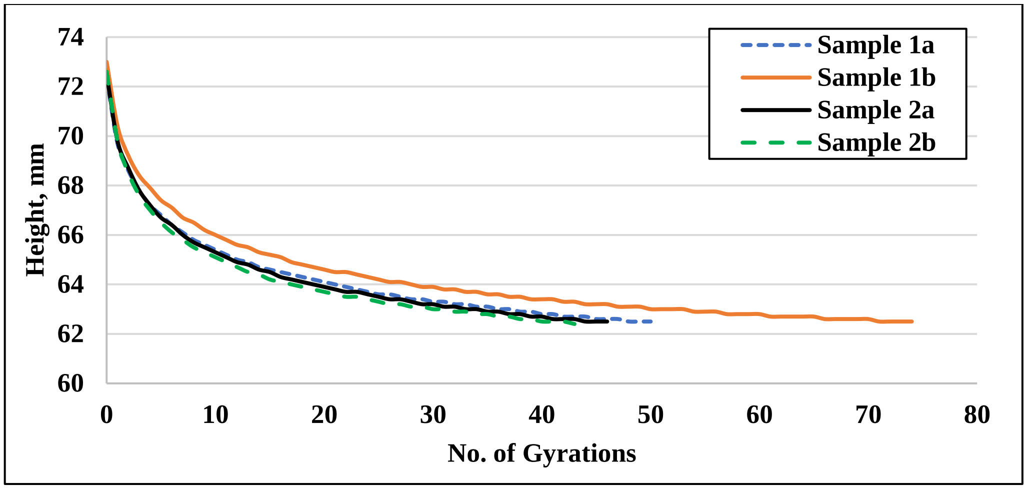


Figure 13. Recorded Height and Gyrations of Four 285°F Replicates for HWT Test.

The samples prepared for Gmm and HWT test were tested, and Table 12 shows variance among air voids, Gmm, and HWT test results between the two aging temperatures. Mainly Creep Slope (CS), which is the slope of rut depth versus number of passes curve before stripping, and rut depth at 20,000 passes were reported for these samples.

Table 12. Average Air Voids, Gmm, Rut Depth of the Samples Aged at 270°F and 285°F.

Parameters	Replicates per Aging Temp.	Samples Aged at 270°F	Samples Aged at 285°F
Average (Range) Air Voids, %	4	6.9% (6.4% - 7.2%)	6.4% (6.1% - 6.7%)
Average (Range) Gmm	2	2.526 (2.523 - 2.529)	2.528 (2.523 - 2.534)
Average Creep Slope, mm/1000 passes	2	0.43 (0.43 - 0.43)	0.48 (0.49 - 0.47)
Average Rut Depth at 20,000 passes, mm	2	3.9 (3.6 - 4.1)	4.1 (4.0 - 4.1)

The results clearly show that accuracy of oven temperature affected only air void content (however, air voids were still within the tolerance for the test), while Gmm and HWT results showed no effect of temperature change. Therefore, it can be concluded that accuracy of oven temperature during reheating and/or aging, even when slightly affecting percentage of air voids, does not affect the performance of this mixture tested using HWT test significantly.

4.4 Oven Type Comparison Study

The oven comparison study utilized the same three ovens previously mentioned and began with two Round Robin mixture blocks. Based on all previous step-studies and their findings, the following standardized preheating and aging procedure in addition to sample preparation and testing procedure shown in Table 13 were followed by each laboratory.

Table 13. Standardized Preheating and Aging Procedure.

Day	Seq.	Duration (hrs)	Action
1	A	2	Remove the sample block from the 2 cardboard boxes completely and place them in deep metal pans to be reheated in a 300°F oven for 2 hrs. *Do not stir or open the oven*.
	B	1	The 2 reheated sample blocks are then remixed and quartered to 3700 g/pan for testing (total 7 pans).
2	C	2	Preheating: the 2 Gmm pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	D	2	Aging: the 2 preheated Gmm pans will stay in the oven for STOA (2 hrs) at 275°F. Stir sample after the first hour. One pan will be removed after the 2 hrs.
		16	Aging: the other preheated Gmm pan will stay 16 hrs in the oven for LTOA (18 hrs) at 275°F.
3	E	2	Preheating: the 3 HWT pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	F	2	Aging: the 3 preheated HWT pans will stay in the oven for STOA (2 hrs) at 275°F. Stir sample after the first hour.
	G	2	Preheating: the 2 SCB-iFIT pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	H	18	Aging: the 2 preheated SCB-iFIT pans will stay 18 hrs in the oven for LTOA (18 hrs) at 275°F. Stir sample after the first hour.
4	A	2	Preheating: the 2 Gmm pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	B	3.5	Testing: the 2 preheated Gmm pans will be spread and Gmm test will be conducted (2 STOA + 2 LTOA-18).
	C	2	Preheating: the 3 HWT pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	D	3	Preparation: the preheated 3 HWT pans will be mixed and compacted to prepare 4 STOA replicates for HWT test.
5	E	18	Testing: the 4 HWT replicates will be tested.
	F	2	Preheating: the 2 SCB-iFIT pans (uncovered) are placed on the middle-center rack of a 275°F oven for 2 hrs. *Do not stir or open the oven.*
	G	3	Preparation: the preheated 2 SCB-iFIT pans will be compacted to prepare 4 LTOA replicates for SCB-iFIT test.
	H	1	Testing: the 4 SCB replicates will be tested.

The actions presented in aging phase (Days 1, 2, and 3) were followed in each laboratory/oven type. Then, the aged samples in pans were sent to UW-MARC laboratory for sample preparation and testing phase (Days 4 and 5).

The 18-hour LTOA was chosen to represent an extreme example for this study, and not necessarily to correlate to field aging. Each type of oven aged a group of seven pans that were then tested in one laboratory to determine the Gmm for STOA and LTOA samples, rutting resistance for STOA samples using HWT test, and cracking resistance for LTOA samples using a Semi-Circular Bending (SCB-IFIT) test (AASHTO TP124, 2016). Figure 14 shows pans used in this study (16”×11”×2.5”).

Figure 14. Typical Pan Used to Preheat/Age Loose Mixture for This Study.

4.4.1 Theoretical Maximum Specific Gravity Results

Table 14 shows Gmm results of STOA and LTOA samples of the three ovens (Oven-A, Oven-C and Oven-B). One of the STOA replicates of Oven-A was damaged during testing and data point was removed from analysis. The results indicate no significant effect of the oven type regardless of duration of aging. In addition, variation of results for all ovens is within the precision and bias criteria of ASTM D6857 (2011) specification. It is worth mentioning that LTOA protocol increased Gmm values which is logical and confirms the effect of more absorption during long-term aging of mixtures.

Table 14. Gmm Results for Each Sample per Oven Type.

Aging Term	Oven-Sample #	Gmm	Average		Difference Between Two Results (d2s)		Standard Deviation (1s)
STOA	Oven-A-1	Damaged	2.481	2.484	-	0.003	0.003
	Oven-A-2	2.481					
	Oven-C-1	2.485	2.487		0.003		
	Oven-C-2	2.488					
	Oven-B-1	2.482	2.483		0.001		
	Oven-B-2	2.483					
LTOA-18	Oven-A-1	2.515	2.499	2.497	0.033	0.013	0.013
	Oven-A-2	2.482					
	Oven-C-1	2.501	2.498		0.007		
	Oven-C-2	2.494					
	Oven-B-1	2.483	2.494		0.022		
	Oven-B-2	2.505					

4.4.2 Hamburg Wheel-Tracking Testing Results

Compacted asphalt mixtures that undergo HWT test can help predict failure susceptibility to permanent deformation (rutting) and moisture damage. In this study, samples were conditioned in a 46ºC water bath for 30 minutes before running the test for 20,000 passes (52 passes/min), per standard WisDOT procedure. The rut depth data is recorded during the test by Linear Variable

Differential Transformers (LVDTs) at the side of the steel wheel. As shown in Table 15, coefficient of variations for the average rut depth and creep slope results between different ovens are less than 7%. The minor variability among samples is to be expected and a similar variability was noted in a previous study of Wisconsin mixtures (Bahia, et al., 2016). The coefficient of variance values for each oven are within 1% of one another.

Table 15. HWT Results for STOA Samples per Oven Type.

Oven Type	Rut Depth at 20,000 Passes, mm			Creep Slope, mm/pass		
	Sample	Average	COV%	Sample	Average	COV%
Oven-A	5.43	5.41	4.2	0.45	0.41	6.6
	5.40			0.37		
Oven-C	5.39	4.97		0.44	0.38	
	4.56			0.32		
Oven-B	5.62	5.22		0.37	0.36	
	4.81			0.34		

4.4.3 SCB-IFIT Testing Results

In SCB-IFIT test, a semi-circular specimen with a 15-mm notch depth is subjected to a constant load in a three-point bending load configuration until fracture occurs (test setup is shown in Figure 15). Strain energy is computed at the notch of the specimen by recording load and deformation. The computed strain energy is used to compare cracking resistance of asphalt mixtures to meet volumetric requirements of differing traffic levels tested at intermediate temperatures. In this study, four replicate samples from each oven were prepared and tested under a loading rate of 50 mm/min after two hours conditioning at 25ºC.

Figure 15. General Test Setup of an SCB Sample.

The volumetric properties measured for each replicate are included in Table 16a. As shown, sample air voids, height, and thickness varied in a narrow range. The raw data was analyzed using SCB-IFIT software to determine slope (m), fracture energy (G_f) and flexibility index (FI) for each sample. Table 16b shows results of SCB-IFIT tests conducted for samples from each oven.

Table 16. Volumetric Properties & SCB-IFIT Results of LTOA-18 Samples per Oven Type.

(a) Volumetric Properties

Sample	Width, mm	Thickness, mm	Height, mm	Notch, mm	Gmb	Gmm	Air Void, %
Oven-A-1	149	50	76	15.5	2.314	2.499	7.5
Oven-A-2	150	50	78	15.5	2.318		7.3
Oven-A-3	149	49	68	15.5	2.313		7.5
Oven-A-4	150	51	70	15.5	2.323		7.1
Oven-C-1	150	49	73	15.5	2.324	2.498	7.0
Oven-C-2	150	51	72	15.5	2.310		7.6
Oven-C-3	150	49	75	15.5	2.312		7.5
Oven-C-4	150	49	71	15.5	2.307		7.7
Oven-B-1	150	51	75	15.5	2.326	2.494	7.7
Oven-B-2	150	51	71	15.5	2.306		7.6
Oven-B-3	151	51	75	15.5	2.288		8.3
Oven-B-4	150	51	72	15.5	2.310		7.4

(b) SCB-IFIT Slope, Fracture Energy, and FI Results

Oven-Sample #	Slope	Avg.	COV%		Fracture Energy, Joules/ m^2	Avg.	COV%		FI	Avg.	COV%	
Oven-A-1	-19.34	-10.1	7.6	10.8	1440.3	1229.4	26.9	17.5	0.7	1.2	33.8	24.3
Oven-A-2	-9.68				1607.6				1.7			
Oven-A-3	-10.99				998.6				0.9			
Oven-A-4	-9.65				1081.9				1.1			
Oven-C-1	-26.51	-11.2	8.9		1043.6	1131.7	10.0		0.4	1.0	14.8	
Oven-C-2	-12.36				1048.1				0.9			
Oven-C-3	-10.68				1259.8				1.2			
Oven-C-4	-10.59				1087.1				1.0			
Oven-B-1	-11.94	-10.5	19.4		1082.7	1055.3	3.7		0.9	1.0	14.1	
Oven-B-2	-9.06				1027.9				1.1			
Oven-B-3	Damaged				-				-			
Oven-B-4	-5.71				1156.4				2.0			

The raw values reported indicate significant replicate variability that have an effect on FI value. The testing procedure followed (IFIT-405, 2015) states that when four individual IFIT specimens are tested, FI value that is farthest from the average of four may be discarded as an outlier to lower variability of the average FI value that is reported. With regard to results reported in Table 16b, one sample from each oven was discarded, in this case sample 1 from Oven-A and Oven-C and sample 4 from Oven-B (highlighted in red font).

In order to check the statistical difference of FI results between oven types, one-way (or single-factor) analysis of variance (ANOVA) was conducted. The analysis was performed using a statistical significance level of 5% ($\alpha = 5\%$). Table 17 shows summary and results of ANOVA on FI results for LTOA-18 samples.

Table 17. ANOVA Results for Flexibility Index Values for LTOA-18 Samples of Each Oven Type.

Groups	Count	Sum	Average	Variance		
Oven-A	3	3.69	1.23	0.1497		
Oven-C	3	3.06	1.02	0.0273		
Oven-B	2	2.04	1.02	0.0242		
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.082	2	0.041	0.546	0.609	5.786
Within Groups	0.378	5	0.075			
Total	0.460	7				

Based on ANOVA results, the p-value is higher than 0.05 therefore there is no significant statistical difference between results of different ovens. In addition, Flexibility Index results for all mixture SCB samples were found to be at or below 2.0. The low flexibility index values can most likely be attributed to aging condition SCB-IFIT samples were subjected to. Figure 16 shows results from a recent study in Illinois (Al-Qadi, et al., 2015) in which many projects reported values of FI value at or below two; samples in Figure 16 were subjected to 12 hours of aging as opposed to 18 hours.

Although a relatively high variability was noted for samples tested in this study, the values obtained for Flexibility Index are on the same order as those reported in other studies. The 18-hour aging duration used in the present study may be considered too harsh to obtain reasonable differentiation between mixtures; previous work by Al-Qadi, et al. (2015) using 12 hours of aging appears to show more differentiation between mixtures. Nevertheless, current results indicate that oven type did not significantly affect results of SCB.

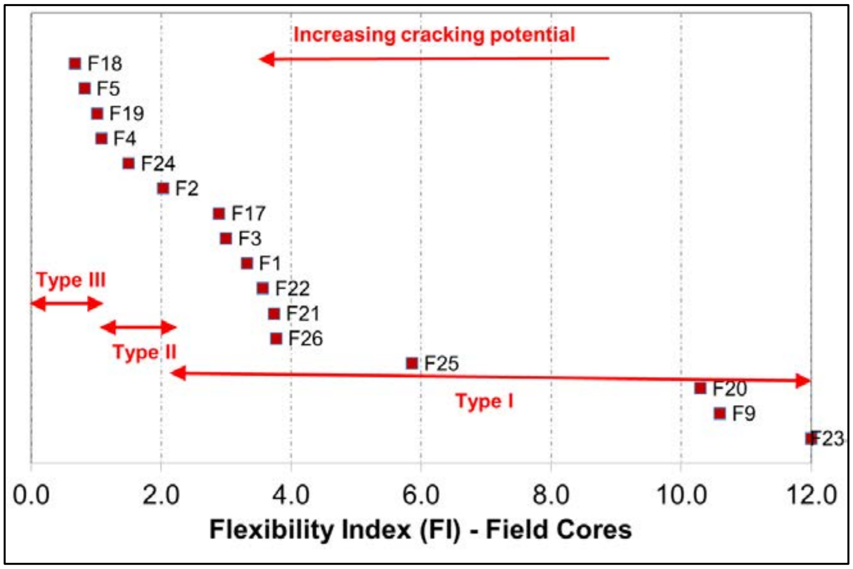


Figure 16. Flexibility Index Values for Field Cores from Al-Qadi, et al. (2015).

Consequently, it was decided to age new samples from same mixture for 14 hours instead of 18 hours in order to check if SCB testing results will be affected. Two pans per oven type were prepared to be long-term oven aged for 14 hours and to prepare four SCB replicates/oven type for testing. The SCB test procedure and parameters are similar to the previous set of samples (i.e. LTOA-18 samples).

The volumetric properties measured for each replicate are included in Table 18a. As shown, sample air voids, height, and thickness varied in a wider range than the previous samples. The raw data was analyzed using SCB-IFIT software to determine slope (m), fracture energy (G_f) and flexibility index (FI) for each sample. Table 18b shows results of SCB-IFIT tests conducted for samples from each oven.

Table 18. Volumetric Properties & SCB-IFIT Results of LTOA-14 Samples per Oven Type.

(a) Volumetric Properties

Sample	Width, mm	Thickness, mm	Height, mm	Notch, mm	Gmb	Gmm	Air Void, %
Oven-A-1	150	49	73	15	2.324	2.474	6.1
Oven-A-2	150	51	70	15	2.335		5.6
Oven-A-3	150	50	74	15	2.345		5.2
Oven-A-4	150	50	74	15	2.291		7.4
Oven-C-1	151	51	76	15	2.239	2.490	10.1
Oven-C-2	151	51	71	15	2.317		6.9
Oven-C-3	150	51	72	15	2.299		7.7
Oven-C-4	150	50	74	15	2.343		5.9
Oven-B-1	150	50	76	15	2.320	2.536	8.5
Oven-B-2	150	50	71	15	2.326		8.3
Oven-B-3	150	50	72	15	2.336		7.9
Oven-B-4	150	50	73	15	2.340		7.7

(b) SCB-IFIT Slope, Fracture Energy, and FI Results

Oven-Sample #	Slope	Avg.	COV%		Fracture Energy, Joules/ m^2	Avg.	COV%		FI	Avg.	COV%	
Oven-A-1	-8.91	-9.8	-12.6	-12.3	948.1	1023.5	10.4	15.9	1.06	1.1	2.0	28.1
Oven-A-2	-18.47				1383.3				0.75			
Oven-A-3	-10.65				1098.9				1.03			
Oven-A-4	Damaged				-				-			
Oven-C-1	-8.59	-9.8	-17.1		1339.3	1271.5	8.3		1.56	1.3	18.6	
Oven-C-2	-8.28				1255.6				1.52			
Oven-C-3	-10.47				1129.4				1.08			
Oven-C-4	-11.84				1361.8				1.15			
Oven-B-1	-7.76	-7.8	-18.3		1402.6	1412.2	12.0		1.81	1.8	6.3	
Oven-B-2	-6.44				1247.6				1.94			
Oven-B-3	-9.3				1586.3				1.71			
Oven-B-4	Damaged				-				-			

Similar to previous testing results, values reported indicate significant replicate variability that have an effect on FI value. The testing procedure followed (IFIT-405, 2015) indicates that when four individual SCB-IFIT specimens are tested, FI value that is farthest from the average of the four may be discarded as an outlier to lower the variability of average FI value that is reported.

With regard to results in Table 18b, only one sample from Oven-A was discarded (highlighted in red font).

To confirm the significance of differences, ANOVA analysis was used for FI results of this set of samples, and the p-value was calculated as shown in Table 19. It is shown that p-values between ovens is lower than 0.05. Therefore, there is a significant statistical difference between results of the different oven types when samples aged for 14 hours are used. However, since FI values for all mixture SCB-IFIT samples are found to be below 2.0, these statistically significant differences cannot be considered of any importance.

Table 19. ANOVA Results for Flexibility Index Values for LTOA-14 Samples of Each Oven Type.

Groups	Count	Sum	Average	Variance
Oven-A	2	2.09	1.05	0.0005
Oven-C	4	5.31	1.33	0.06129
Oven-B	3	5.46	1.82	0.0133

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.794	2	0.397	11.304	0.009	5.143
Within Groups	0.210	6	0.035			
Total	1.006	8				

Comparing results of the 18 hours aging with the 14 hours aging, it is observed that FI values remains within 1.0 – 2.0 values. There is, however, some improvement in variability for each of the ovens/labs.

In summary, based on testing the 18 hours aged samples and the 14 hours aged samples, it is concluded that oven type did not significantly affect results of SCB testing in this part of the study. The results, however, raise a concern that 14 hours aging could result in low FI values that cannot be used successfully to differentiate between mixtures with various compositions.

4.5 Summary of Findings from Oven Comparison Study

In this part of the study, influence of HMA sample size, oven type/brand, and variation in reheating/aging temperatures on results of performance tests for a selected mixture was investigated. The samples were tested for rutting and cracking resistance using HWT and SCB-IFIT tests, respectively. The following conclusions can be made based on the findings of this part of the study:

- Mixtures reach target aging temperatures quicker when mixture container is open in the oven to allow exposure of the mixture to moving air.
- The extent of oven loading can significantly affect the time it takes mixtures to reach the target aging temperature and can also affect the mixture temperature distribution within the oven.

- Briefly opening the oven to stir the sample during aging causes a reduction in mixture temperature, but in this study, it did not result in mixture temperature falling below the specification guidelines used.
- The accuracy of oven, as simulated by manually adjusting aging temperature between lower and upper limits of the specification used, did not show a significant effect on mixture volumetrics and performance for samples and test procedures used in this part of the study.
- Oven type did not affect Gmm results significantly. However, long-term aging changed Gmm values and confirmed there is effect of aging on mixtures' volumetric properties.
- No substantial influence of oven type was found on rut depth results obtained from HWT test.
- Resistance to fatigue cracking, as measured by FI value, indicates that the 14-hours aging results in similar values as the 18-hours, and that both aging periods result in low values ranging between 1.0 and 2.0. Although the 14-hours aging showed some minor differences between FI values, all FI values are small and differences between oven types cannot be considered important.
- Reducing long-term aging time to 14 hours did not affect results significantly as compared to the 18 hours of LTOA, although it has reduced variability between samples of each oven.

The results of this part of the study represent efforts to standardize mixture handling and aging procedures within Wisconsin, but it is envisioned that such efforts are needed on a national scale as well. In Appendix C a proposed standardized mixture handling, sampling and aging procedures are presented. This procedure was used in all mixture conditioned and tested in this study.

5. Comparison Between Plant-Produced Mixtures and Laboratory-Produced Short-Term Aged Mixtures

After collecting plant-produced field mixtures during construction of field sections in July 2017, binder extraction and recovery was conducted for mixtures from each test section to compare actual dust percentage (P200) and asphalt content to planned factors' levels. Extraction followed AASHTO T164 (2014), Method A with secondary high-speed centrifuge for fines recovery; the used solvent was n-Propyl Bromide (nPB) sold under the trade name Ensolv. Binder recovery followed ASTM D5404 (2012) and in all cases was completed within eight hours of the corresponding extraction. Two replicates were run for each section and results averaged; all replicates for a given section were found to be within AASHTO acceptable d2s limit for T164 asphalt content.

The results are summarized in Table 20 below and show that planned experimental factors (i.e. ±1.0% P200 and ±0.3% AC) were not achieved during production, and there are major differences between planned levels of P200 and asphalt binder contents and the measured results from extraction of plant-produced mixtures. In addition, Job Mix Formula (JMF) percentages for each mix design were changed prior to or during production, with actual percentages run during production shown in Table 21.

Table 20. Measured versus Planned Testing Factors.

Section No.	Test Sections Factors								
	Mix Traffic Level	Filler % (P200)			AC%			Modification	Change
		Planned	Measured	Diff.	Planned	Measured	Diff.		
1 (Control)	LT	5.2	5.6	+0.4	5.8	5.9	+0.1	PG58**S**-28	Control
2	LT	5.2	4.9	-0.3	5.5	5.6	+0.1	PG58**H**-28	Reduce AC Change PG
3	LT	6.2	5.5	-0.7	5.8	6.1	+0.3	PG58**H**-28	Increase P200 Change PG
4	LT	6.2	6.2	0.0	5.5	5.9	+0.4	PG58**S**-28	Increase P200 Reduce AC
5 (Control)	MT	5.7	4.4	-1.3	5.7	5.9	+0.2	PG58**H**-28	Control
6	MT	5.7	4.9	-0.8	5.4	5.5	+0.1	PG58**S**-28	Reduce AC Change PG
7	MT	6.7	5.5	-1.2	5.7	5.8	+0.1	PG58**S**-28	Increase P200 Change PG
8	MT	6.7	4.6	-1.1	5.4	5.4	0.0	PG58**H**-28	Increase P200 Reduce AC

Table 21. Actual versus Planned Aggregate Sources and Percentages.

Mix Design	Planned		Actual	
	Aggregate Type	% of Total Aggregates	Aggregate Type	% of Total Aggregates
LT	5/8 × 3/8 Bit Gravel	10	5/8 × 3/8 Bit Gravel	11
	3/8 Bit Aggregate	10	3/8 Bit Aggregate	8
	5/8 Screened Sand	55	5/8 Screened Sand	57
	Millings (5.2% AC)	25	Millings (5.2% AC)	24
MT	1/2 Bit Gravel	23	1/2 Bit Gravel	19
	3/8 Washed Gravel Man Sand	8	3/8 Washed Gravel Man Sand	10
	5/8 Screened Sand	49	5/8 Screened Sand	56
	RAP (5.5% AC)	20	Millings (5.2% AC)	15

As discussed earlier, LT and MT mix design levels were chosen for experimental plan of this study. Since coarse aggregate used for each mix design level in this study was similar in terms of fracture count and elongation (both crushed natural gravel), the principle difference between the mix design levels is Fine Aggregate Angularity (FAA), with the LT minimum limit of 40% and the MT minimum limit of 43%. However, due to changes realized during production and summarized above, both mix designs resulted in a similar combined gradation and Fine Aggregate Angularity, as shown in Table 22.

The difference in RAP percentage (24% for LT and 15% for MT, by percentage JMF) also affects Percent Binder Replacement (PBR or ABR). Although RAP percentage is not a direct factor studied in this project, the effect of PBR on mixture properties will be discussed in later sections. It is worth mentioning that both mixes used the same RAP source as shown earlier in Table 21.

Table 22. Comparison Between LT and MT Mix Designs' Parameters from Extraction and Recovery of Plant-Produced Mixes.

Mix Design Parameter	Sieve	LT	MT
		Avg. Combined Aggregate Gradation, %	
Avg. Combined Aggregate Gradation	¾	99.8	100.0
	½	97.3	94.4
	3/8	88.7	87.0
	#4	68.1	68.4
	#8	53.2	52.0
	#16	40.0	38.0
	#30	26.7	24.8
	#50	13.6	12.6
	#100	7.7	6.9
	#200	5.5	4.9
Fine Aggregate Angularity (FAA) LT: 40% min and MT: 43% min	-	42.6%	42.4%

These findings regarding production of mixtures raised an issue regarding statistical analysis of results, and regarding duplicating field sections in the laboratory. The statistical analysis of the partial factorial design is not possible due to differences between planned and measured values of controlled variables. In October 2017, research team presented detailed results of extraction and recovery of the field mixtures to the POC and introduced two possible options to move forward with the study. The POC decided to duplicate the field sections "as-produced" in laboratory and follow the proposed testing plan in order to:

1. Verify the ability of laboratory aging protocols to simulate plant aging of asphalt mixtures at all binder and filler contents meeting spec tolerances. (Objective 1 of the research study)
2. Conduct *general sensitivity* of aging and performance of the mixtures for differences in modification, AC% and P200. (Objective 2 of the research study - limited)

5.1 Mix Design Verification

In order to verify the mix design of the lab-produced mixture compared to the plant-produced mixtures, the bulk specific gravity (Gmb) and theoretical maximum specific gravity (Gmm) of laboratory-produced mixtures were compared to those of plant-produced mixtures as shown in Table 23.

Table 23. Results of Gmm and Gmb of Plant-Produced Mixtures Compared to Lab-Produced Mixtures.

Gmm Procedure/Location	**Mix Type**	**LT**				**MT**			
		1 (C)	**2**	**3**	**4**	**5 (C)**	**6**	**7**	**8**
AASHTO T209/QC	PMLC	2.481	2.491	2.472	2.494	2.485	2.497	2.483	2.492
ASTM D2041/Lab	PMLC	2.487	2.499	2.483	2.490	2.481	2.503	2.490	2.492
ASTM D6857/Lab	LMLC	2.471	2.487	2.481	2.475	2.462	2.488	2.441	2.495
ASTM D2041 Standard Deviation (1s) Multi-laboratory Precision (max 0.016)		0.008	0.006	0.006	0.010	0.012	0.008	0.027	0.002

Gmb Procedure/Location	**Mix Type**	**LT**				**MT**			
		1 (C)	**2**	**3**	**4**	**5 (C)**	**6**	**7**	**8**
AASHTO T166/QC	PMLC	2.399	2.408	2.427	2.422	2.418	2.410	2.421	2.428
AASHTO T166/Lab	PMLC	2.407	2.410	2.426	2.426	2.435	2.419	2.435	2.425
AASHTO T166/Lab	LMLC	2.419	-	-	-	2.424	-	-	-
AASHTO T166 Standard Deviation (1s) Multi-laboratory Precision (max 0.006) or [max d2s = 0.017]		0.010	[0.002]	[0.001]	[0.004]	0.009	[0.009]	[0.014]	[0.003]
Air Voids % using Gmm (D6857) and Gmb results obtained by research team (N_{design} target = 3.0%)		2.6	3.1	2.2	2.0	1.1	2.8	0.2	2.8
VMA % using Gmb results obtained by research team, Gsb of the Mix Design and measured Pb for each mix (LT min = 14.5 & MT min = 14.0)		17.0	16.6	16.5	16.3	16.1	16.3	16.0	16.0

The lab-produced Gmm samples were tested using the Automatic Vacuum Sealing procedure (Corelok) following ASTM D6857 (2011) and Gmb samples following AASHTO T166 (2016), while the plant-produced Gmm and Gmb samples (PMLC) were tested using the saturated surface dry method following AASHTO T209 (2016) and T166 (2016), respectively. Despite differences in procedure used between both mixture types, results are comparable and within the acceptable range between two results (d2s) and the standard deviation (1s) of multi-laboratory precision for Gmm and Gmb as shown in Table 23. Only the standard deviation of Gmm results for test section

MT 7 exceeded the maximum 0.016 limit and the standard deviation of Gmb results for LT 1 and MT 5 sections exceeded the maximum 0.006 limit. For future testing and analysis in this study, Gmm (ASTM D6857) and Gmb (AASHTO T166, 2016) results obtained by the research team are used.

In addition, air void (AV%) and VMA values for each test section were calculated using Gmm and Gmb results obtained by the research team. As shown in Table 23, air voids of all test sections except LT 2 were below the target air voids of mix design (i.e. 3.0%). The AV% of MT 7 is extremely low with 0.2% and this is due to low Gmm value (2.441) determined in the lab. It is also noticed that MT 5 and LT 4 mixtures have AV% below 2.0%. On the other hand, all VMA results are above the minimum limit provided by both mix designs (see Appendix A).

5.2 Extracted and Recovered Binders Testing Results for Plant- and Lab-Produced Mixtures

The Rolling Thin-Film Oven (RTFO) residue of binders extracted and recovered from the control plant-produced and lab-produced mixtures (LT 1 and MT 5) were tested using MSCR, while the PAV residue was tested using BBR and LAS tests. The objective was to check if properties of the recovered binders from the lab-produced mixtures are similar to those of the plant-produced mixtures. To evaluate whether exposure to the selected solvent produces a systematic bias in the results, a sample of each control binder was fully dissolved into the solvent and recovered and tested. Table 24 shows results of this comparison for the control binders (binder collected from the production site and tested in laboratory), the control binder dissolved into solvent and recovered before testing, and the recovered binders from the LT 1 and MT 5 test sections.

Table 24. Binder Testing Results of the Extracted and Recovered Binders from the Control Plant- and Lab-Produced Mixtures for (a) PG58S-28 and (b) PG58H-28.

MSCR on RTFO Residue	Temp. °C	PG58S-28 (Control)	PG58S-28 (Dissolved into solvent & recovered)	PSTA LT 1 PG58S-28	STOA LT 1 PG58S-28
Average % Recovery (3.2 kPa)	58	0.39	0.92	2.58	12.04
Average Jnr (3.2 kPa)	58	2.866	2.659	1.068	0.450
Percent Difference (3.2 kPa & 0.1 kPa)	58	12.91	13.18	10.81	7.61
BBR on PAV Residue	**Temp. °C**	**PG58S-28 (Control)**	**PG58S-28 (Dissolved into solvent & recovered)**	**PSTA LT 1 PG58S-28**	**STOA LT 1 PG58S-28**
Stiffness	-18	213	218	230	238
m-value	-18	0.326	0.327	0.337	0.344

(a)

MSCR on RTFO Residue	Temp. °C	PG58H-28 (Control)	PG58H-28 (Dissolved into solvent & recovered)	PSTA MT 5 PG58H-28	STOA MT 5 PG58H-28
Average % Recovery (3.2 kPa)	58	55.87	45.82	21.75	49.64
Average Jnr (3.2 kPa)	58	0.388	0.399	0.770	0.200
Percent Difference (3.2 kPa & 0.1 kPa)	58	23.09	26.58	24.38	16.91
BBR on PAV Residue	**Temp. °C**	**PG58H-28 (Control)**	**PG58H-28 (Dissolved into solvent & recovered)**	**PSTA MT 5 PG58H-28**	**STOA MT 5 PG58H-28**
Stiffness	**-18**	238	232	191	215
m-value	**-18**	0.336	0.338	0.349	0.352

(b)

For PG58S-28 control binder, exposure to solvent does not appear to have a lasting effect on binder properties measured, with only a slightly smaller Jnr value perhaps due to aging during the recovery process and nearly equal low temperature BBR properties. Binders recovered from mixtures differed significantly from control binders, however. The mixture binder was substantially stiffer than the control at high temperature, likely due to the effects of RAP binder in the mixture. Interestingly, low temperature properties showed slightly higher stiffness and m-value. This could be due to aggregate interactive effects and RAP binder effects. The differences between the two mixture binders (lab- vs. plant-produced) may be due to differences in aging history between lab and field.

Results for PG58H-28 show that solvent appears to be affecting polymer modification in the binder, resulting in an approximately 10% reduction in % Recovery with a minimal change to Jnr value. This could be a damaging effect of solvent to polymer network. The low temperature binder properties do not appear to be as affected by solvent. Similar to the S binder, there is significant differences noted between the control and mixture binder samples, likely due to not only solvent effects, but also aggregate interaction and differences between lab and field aging.

Based on the data presented in Table 24, it can be concluded that choice of solvent and/or recovery procedure can have a residual effect on recovered binder properties, particularly for polymer modified binders, and it is therefore imperative that when reporting and comparing such results the type of solvent and recovery procedure be listed or data generated that identifies solvent-polymer biasing effects, if any. This is an area of recommended research if WisDOT plans to use recovered binders for quality control, acceptance, or troubleshooting.

In addition, it cannot be assumed that virgin binder properties are representative of mixture binder properties, even after short term aging for mixtures within current WisDOT specification for recycled materials. The effects of mixture binder properties on performance are explored in later sections.

To further understand differences in mixture performance, extracted and recovered binder from the control mixtures (LT 1 and MT 5) were tested at intermediate temperatures for Linear Amplitude Sweep (LAS) test as per AASHTO TP101 (2016) to compare binders' performance. The LAS test results (Parameter B and N_f) are shown in Table 25 and it shows significant difference in fatigue life results (N_f) between the binder recovered from the plant-produced mixture and the one recovered from the lab-produced mixture. This also confirms that the extracted binders are not the same in the plant and the lab mixtures.

The Parameter B is calculated as follows:
$B = -2\alpha$; where α is calculated using the slope of $\log(w)$ $-\log G'(\omega)$ plot,
where $G'(\omega)=|G^*|\cdot\cos\delta(\omega)$. The parameter $\alpha = 1 + 1 / m$, where m is slope of the $\log(w)$-$\log G'(\omega)$ plot.

Table 25. LAS Results of Extracted and Recovered Binders from Control Plant- and Lab-Produced Mixtures.

LAS on RTFO Residue	Temp., °C	PSTA LT 1 PG58S-28		STOA LT 1 PG58S-28		PSTA MT 5 PG58H-28		STOA MT 5 PG58H-28	
		Rep. 1	Rep. 2	Rep. 1	Rep. 2	Rep. 1	Rep. 2	Rep. 1	Rep. 2
Parameter B	25	2.88	2.87	3.06	3.09	3.11	3.14	3.08	3.07
N_f @ 2.5%, Cycles	25	46,974	47,699	41,642	33,643	111,222	142,916	65,875	70,901
N_f @ 5%, Cycles	25	6,402	6,534	5,002	3,952	12,907	16,274	7,809	8,421

5.3 HWT Testing Results for the Plant- and Lab-Produced Mixtures

In order to compare rutting performance of the plant-produced mixtures to the STOA laboratory-produced mixtures, loose mixtures from both sources were pre-heated at 275°F for two hours before compaction to 60 ± 1 mm and 7 ± 1% air voids. All HWT testing was conducted at 46°C. Two tests were conducted for each plant- and lab-produced mixture and average passes to 12.5 mm rut depth were determined and compared as shown in Figure 17.

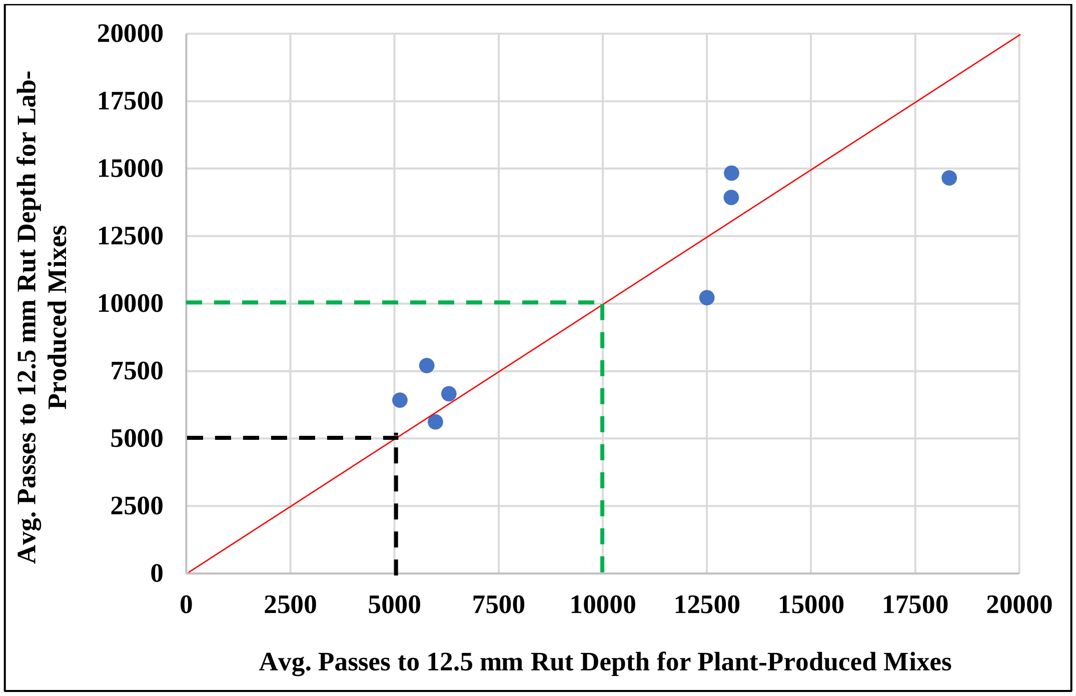


Figure 17. Average Passes to 12.5 mm Rut Depth for Plant- versus Lab-Produced Mixes.

The comparison shown in Figure 17 shows that there are two groups of data; one for the S-grade binder and one for the H-grade binder. The plant- and lab-produced mixtures with S binders are much lower in passes to 12.5 mm rut depth than those with H binder. However, both mixture types passed the WisDOT strawman criteria of a minimum of 5,000 passes for mixes with PG58S grade binder and 10,000 passes for mixes with PG58H grade binders. In addition, agreement between results of plant- and lab-produced mixtures is high with an average absolute difference in Passes to 12.5 mm rut depth of around 15% which can be attributed to the difference in binders' properties discussed earlier.

From HWT test data, Stripping Slope (SS) to Creep Slope (CS) ratio was equal or higher than 2.75 for some cases and both types of mixtures. Therefore, Stripping Inflection Point (SIP) results of both mixture types are compared in Figure 18. The SIP agreement is high, and this again shows the ability of lab-produced mixtures to replicate the performance of plant-produced mixtures against rutting.

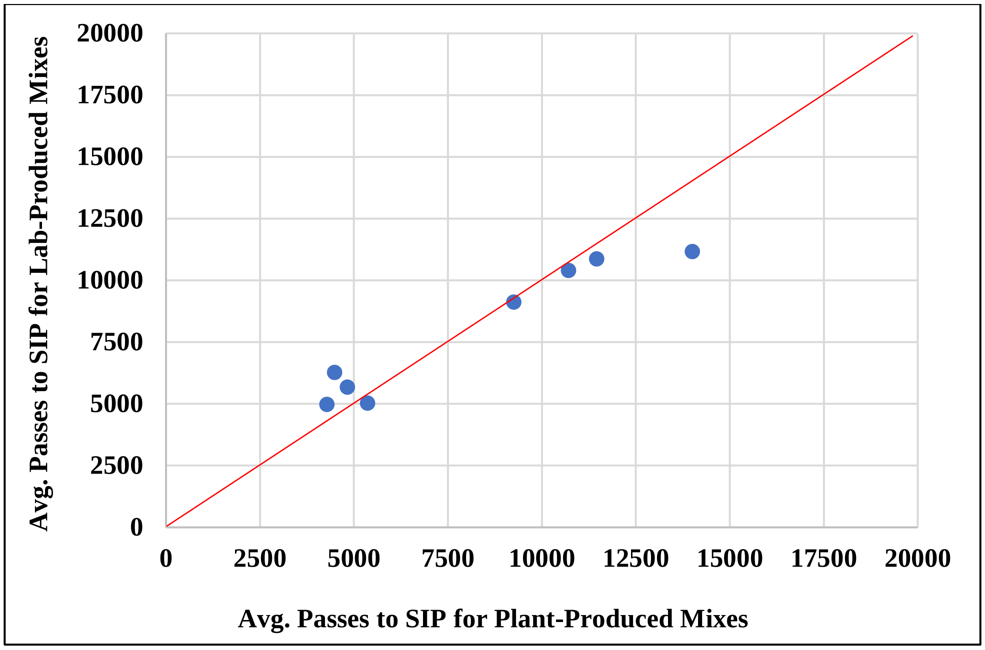


Figure 18. Average Passes to SIP for Plant- versus Lab-Produced Mixes.

5.4 SCB-IFIT Testing Results for the Plant- and Lab-Produced Mixtures

For SCB-IFIT testing, samples of the plant-produced (PSTA) mixtures and the STOA lab-produced mixtures were cooled to room temperature and then pre-heated at 275°F for two hours before compaction. Two 50 mm-thick slices were cut from the center of each compacted sample to achieve 7 ± 0.5% air voids as per Illinois Test Procedure 405 (AASHTO TP124, 2016). A minimum of four semi-circular samples were tested for each mixture, and average Flexibility Index (FI) and Post-Peak Slope (PPS) values of plant and lab mixtures were compared as shown in Figure 19 and Figure 20. The agreement between SCB-IFIT results of the lab-produced mixtures and the plant-produced mixtures is fair and for five out of eight mixtures the values fall on the equality line. The three outliers from the equality line belongs to sections LT 4, MT 5, and MT 7. The mixture from these sections showed the lowest AV% at N_{design}, as listed in Table 23. It is unclear if there is a specific factor resulting in the differences in density and performance of these mixtures. The only apparent distinction is Gmm of the plant-produced mixtures are significantly higher than the lab-produced mixture Gmm; it is the lab produced mixture Gmm that is used to produce samples for SCB-IFIT testing and thus could result in difference in air voids calculated. In addition, LAS results presented earlier in Table 25 showed that there is a significant difference between the recovered binders against fatigue cracking and this can explain the fair agreement in FI between the plant-produced (PSTA) mixtures and the STOA lab-produced mixtures.

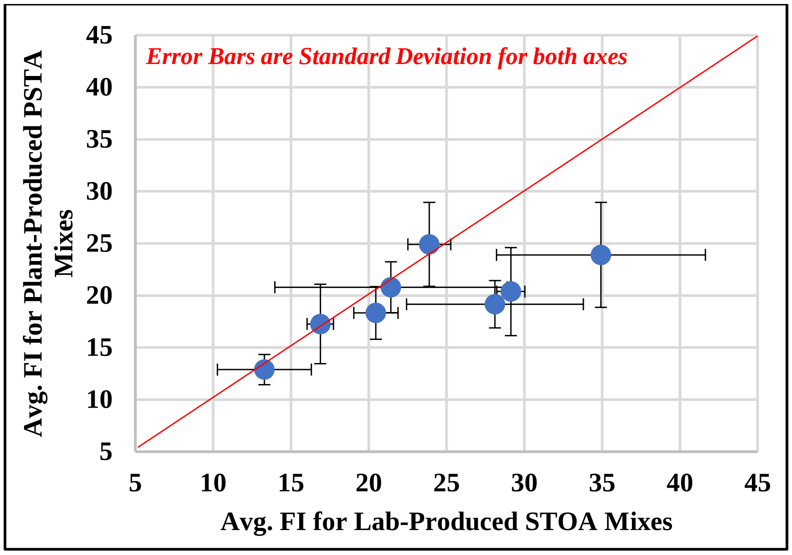


Figure 19. Average FI Results for Plant- versus Lab-Produced Mixtures.

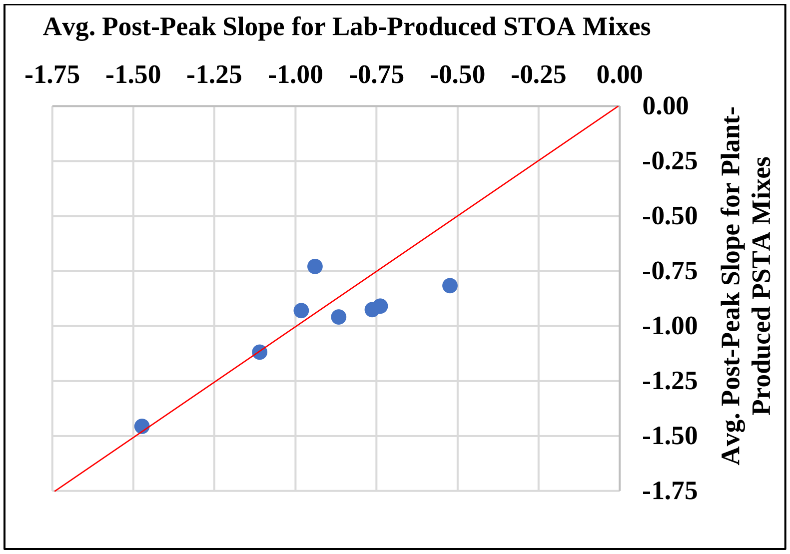


Figure 20. Average Post-Peak Slope Results for Plant- versus Lab-Produced Mixtures.

5.5 Summary of Findings for Plant- versus Lab-Produced Mixtures Study

Based on data and analysis results presented in this section of the report, the following findings can be stated:

- Measured binder and filler contents of the plant-produced mixtures did not match the targeted values defined in experimental design. Therefore, statistical analysis of the partial factorial design could not be carried out. However, there was sufficient variation in asphalt content and filler content to evaluate if general trends in aging rates can be defined as a function of binder content or filler content.
- The eight mixtures produced in laboratory had comparable volumetric properties to the plant-produced mixtures. Some notable variation in Gmm values for a few sections are recorded.
- Properties at high temperatures (MSCR) and intermediate temperatures (LAS) of binders extracted and recovered from the plant-produced mixtures are significantly different than properties of binders recovered from the lab-produced mixtures. The same properties are also considerably different than the original binders collected from site. These differences could be due to solvent used in extraction as well as interaction with aggregates or RAP.
- However, there are minor differences in low temperature properties (BBR: S and m) of extracted and recovered binders from lab- and plant-produced mixtures.
- The agreement between HWT results of the lab- and the plant-produced mixtures is high. This shows that performance of these mixture against permanent deformation is less sensitive to difference in binder properties between lab and plant than grade of the binder.
- The agreement between SCB-IFIT results of the lab-produced mixtures and the plant-produced mixtures is fair and five out of eight mixtures show equal values of FI. The three outliers from the equality line belongs to sections LT 4, MT 5, and MT 7. It is unclear if there is a specific factor resulting in differences in these mixtures. The only apparent distinction is Gmm of the plant-produced mixtures are significantly higher than the lab-produced mixtures Gmm.
- The cumulative results show acceptable level of equality between the Plant-produced and Lab-produced and aged samples. ***Therefore, laboratory short-term oven aging protocol followed in this study is sufficient to simulate the plant short-term aging***. However, differences in properties of the recovered binders between lab and plant mixtures need to be studied further to define reasons for these differences.

6. Effect of Mix Design Factors on Aging and Performance of Plant-Produced Mixtures

The effect of four pre-selected mix design factors on aging rate/extent and mixtures performance against rutting and fatigue cracking was evaluated during this phase of the study. In this study, effect of mix design level (LT & MT), asphalt binder modification; Standard Traffic (S) and High Traffic (H) as defined in AASHTO M332, filler or dust percentage (P200) and asphalt binder content (AC%) on mixture performance and aging rate is examined. However, due to differences between the planned and measured factors presented earlier in Chapter 3, a general sensitivity analysis for aging and performance of mixtures was conducted and it was decided to eliminate mix design level factor (LT & MT) and focus on the other factors (i.e. Binder Modification, Filler % and AC%). The following subsections present results and findings for each design factor.

6.1 Effect of Binder Modification

The effect of asphalt binder modification, as controlled by binder grade (S vs. H) in this study, on performance of the eight plant-produced mixtures against rutting and cracking, and on aging rate is discussed in this section of the report based on results of three performance tests: HWT, SCB-IFIT and Disk-shaped Compact Tension (DCT) test.

6.1.1 HWT Testing Results for the Plant-Produced Mixtures

All mixtures collected from field during production and construction were pre-heated at 275°F for two hours before compaction to 60 ± 1 mm and 7 ± 1% air voids. All testing was conducted at 46°C. Two tests were conducted for each field section and the average passes to 12.5 mm rut depth was determined as shown in Figure 21. It is clear that mixtures with S binder are much lower in passes to 12.5 mm rut depth than those with H binder. However, both mixture types passed the WisDOT strawman criteria of a minimum of 5,000 passes for mixes with PG58S grade binder and 10,000 passes for mixes with PG58H grade binders.

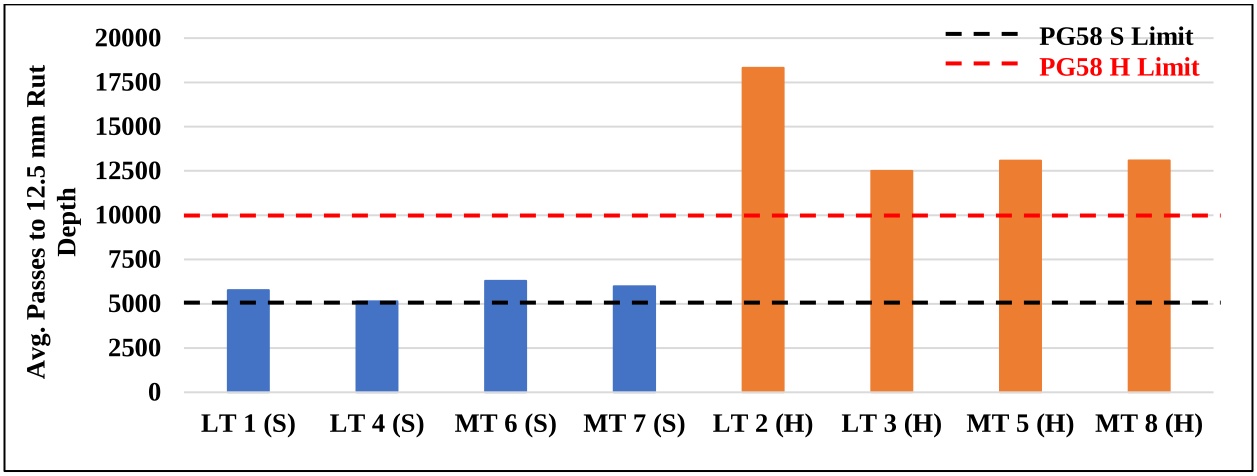


Figure 21. Average Passes to 12.5 mm Rut Depth for each Test Section.

From HWT test data, Stripping Slope (SS) to Creep Slope (CS) ratio was equal or higher than 2.75 for some test sections. Therefore, average Stripping Inflection Point (SIP) results of the mixtures are compared in Figure 22. The figure shows that three S Binder mixtures (LT 1, LT 4, and MT 6) and one H Binder mixture (LT 3) are not passing the WisDOT SIP strawman criteria, but all are passing the WisDOT modified Tensile Strength Ratio (TSR) test conducted as part of mix design procedure to measure moisture damage sensitivity.

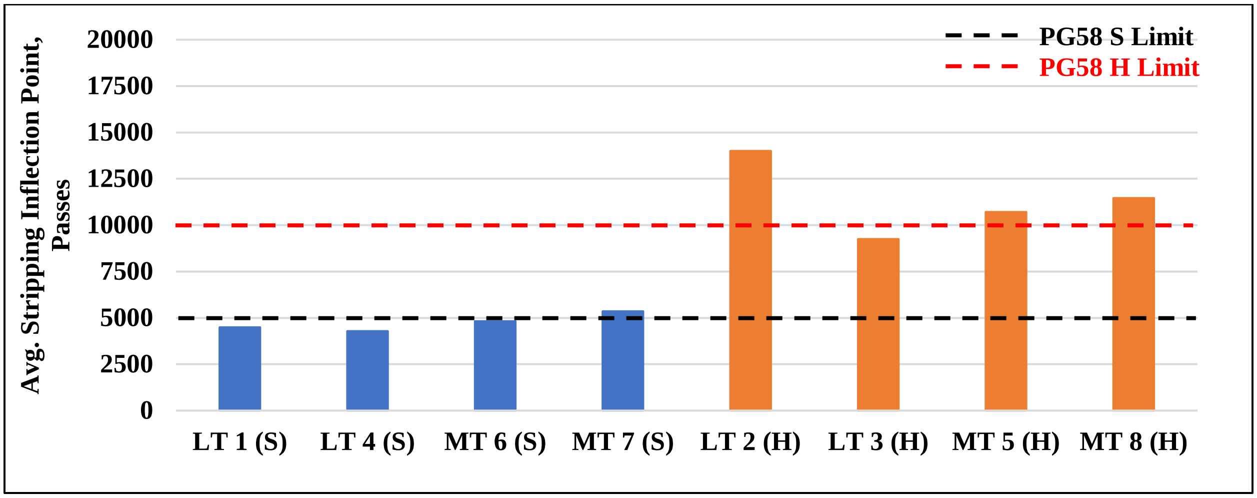
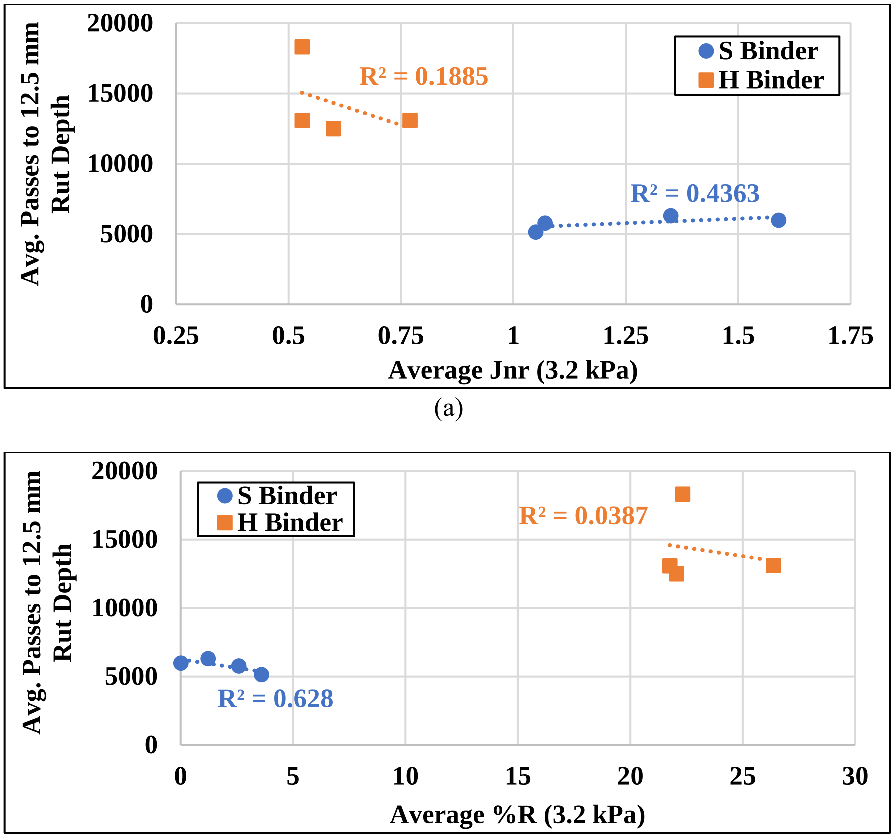


Figure 22. Average SIP for each Test Section.

To examine the effect of binder modification on performance against rutting, MSCR test was conducted on extracted and recovered binder of each plant-produced mixture after RTFO to determine the average Percent Recovery (3.2 kPa) and average Jnr (3.2 kPa). These two binder parameters were compared against average passes to 12.5 mm rut depth as shown in Figure 23. Both plots show significant effect of binder grade in terms of %R or Jnr on rutting resistance, higher %R and lower Jnr values improve resistance to rutting. However, no strong correlation between the value of these parameters and number of passes to 12.5 mm rut depth was discovered.



(a)

(b)

Figure 23. Average Passes to 12.5 mm Rut Depth versus (a) Average Jnr (3.2 kPa), and (b) Average % Recovery (3.2 kPa).

Although results of HWT clearly show effect of binder modification, it is clear that within each modification level, other mixture factors also significantly affect the results. This is expected and was a major finding of the completed WHRP 15-04 study (Bahia, et al., 2016) that HWT is extremely sensitive to asphalt binder properties (namely stiffness or Jnr).

6.1.2 SCB-IFIT Testing Results for Plant-Produced Mixtures

For SCB-IFIT testing, three pans from each plant-produced mixture (total 24 pans) were collected during production where one pan was used as is (PSTA) and the second one was aged in the 275°F oven for 6 hours (LTOA-6) and the last one was oven aged for 14 hours (LTOA-14). After aging, samples were cooled to room temperature and then pre-heated at 275°F for two hours before compaction; two 50 mm-thick slices were cut from the center of each compacted sample to achieve 7 ± 0.5% air voids as per Illinois Test Procedure 405 (AASHTO TP124, 2016). A minimum of four semi-circular samples were tested for each field section at each aging level and the calculated average Flexibility Index (FI) and Post-Peak Slope (PPS) values are presented in Figure 24 and Figure 25.

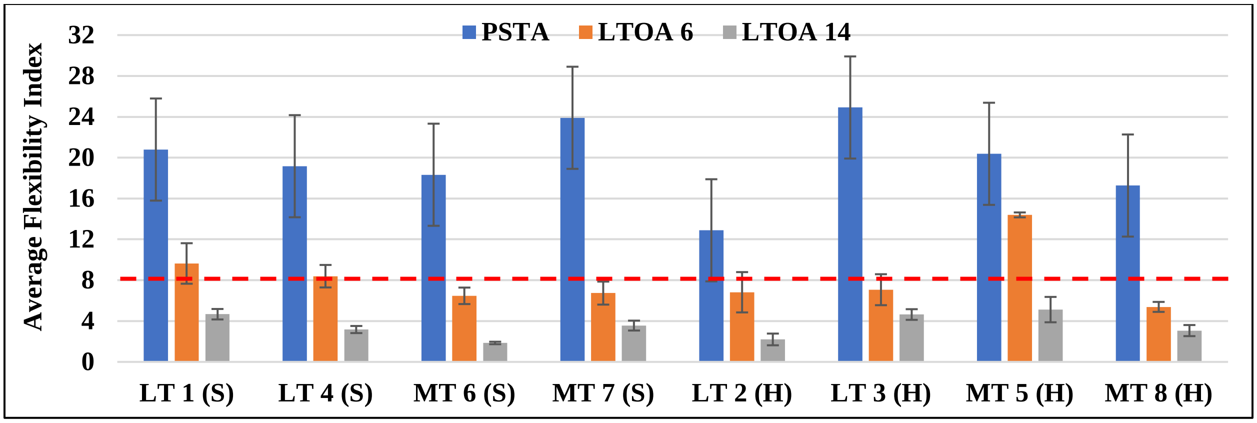


Figure 24. Average FI for each Plant-Produced Mixture at Different Aging Levels.

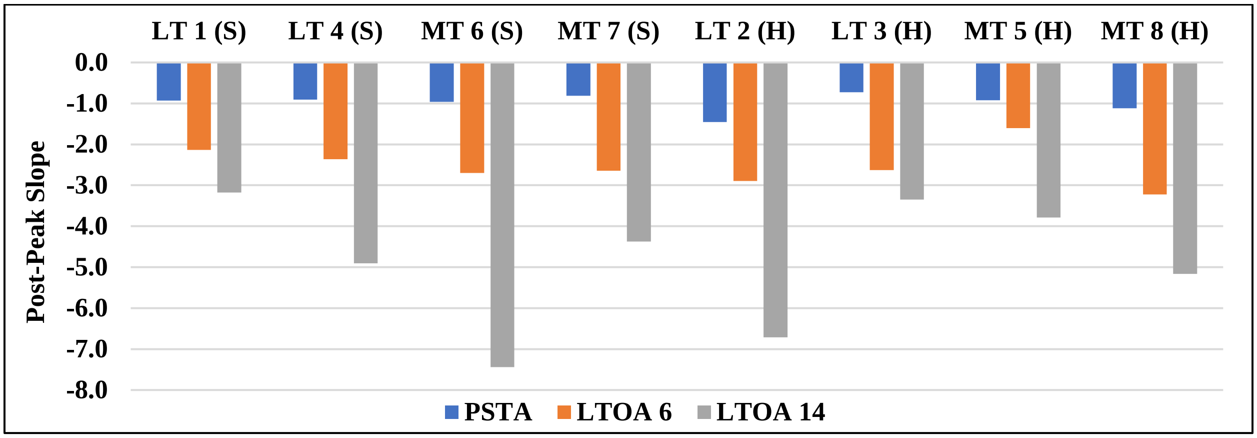


Figure 25. Average Post-Peak Slope for each Plant-Produced Mixture at Different Aging Levels.

According to the figures, average FI value of all eight PSTA mixtures is above the nominal value of eight recommended by Illinois (Circular Letter 2015-19, 2015). However, with more aging FI decreased significantly and most of results are below eight, particularly after 14 hours of oven aging. In addition, results showed no clear trend or effect for binder grade/modification on cracking resistance in terms of FI or Post-Peak Slope results.

Table 26 summarizes the effect of aging rate on FI results for the eight plant-produced mixtures of this study. The values depict that a clear distinction between mixtures can be found for PSTA and LTOA-6 aging data, however mixtures after 14 hours of oven aging (LTOA-14) show a narrow range of values (1.9 to 5.1), which is much smaller than the LTOA-6 range (5.4 to 15.4). In addition, the change in FI from PSTA to LTOA-6 ranges from 1.00 to 2.97 per aging hour while it is only from 0.29 to 1.16 for the LTOA-6 to LTOA-14 hours. Therefore, it is recommended to evaluate fatigue performance of mixtures at short-term and 6 hours long-term aging.

Table 26. Effect of Aging Rate on FI for the Plant-Produced Mixtures.

Mix ID	PSTA FI	LTOA-6 FI	LTOA-14 FI	ΔFI (ST-L6) Per Aging hr	ΔFI (L6-L14) Per Aging hr
LT 1 (S)	20.79	9.64	4.67	1.86	0.62
LT 4 (S)	19.16	8.39	3.17	1.80	0.65
MT 6 (S)	18.33	6.47	1.85	1.98	0.58
MT 7 (S)	23.90	6.74	3.56	2.86	0.40
LT 2 (H)	12.89	6.82	2.20	1.01	0.58
LT 3 (H)	24.91	7.07	4.64	2.97	0.30
MT 5 (H)	20.38	14.40	5.12	1.00	1.16
MT 8 (H)	17.27	5.39	3.07	1.98	0.29
Average	**19.70**	**8.12**	**3.54**	**1.93**	**0.57**
Range	**12.02**	**9.01**	**3.27**	**1.98**	**0.87**
Pooled Stdev.	**3.2**	**1.2**	**0.5**	**-**	**-**

In order to better study the effect of binder grade on cracking resistance, extracted and recovered binders from the control plant-produced mixtures (LT 1 “S” and MT 5 “H”) were subjected to the Linear Amplitude Sweep (LAS) test as per AASHTO TP101 (2016) since it is also conducted at 25°C similar to SCB-IFIT test. In the LAS test, binders are tested for frequency sweep in which the loading rate is changed from 0.1 to 30 Hz. As mentioned earlier, the Parameter B is calculated as follows:

$B = -2\alpha$; where α is calculated using the slope of log (w) -log $G'(\omega)$ plot,
where $G'(\omega)=|G^*|\cdot\cos\delta(\omega)$. The parameter $\alpha = 1 + 1 / m$, where m is slope of the log(w)-log $G'(\omega)$ plot.

For the S and H binders recovered after different mixture aging levels, the parameter B was determined and compared to average FI results from SCB-IFIT tests as shown in Figure 26. As shown in the figure, difference between values of Parameter B for S and H binders is not affecting the average FI results significantly. However, there is a strong relationship between the decrease in FI and the increase in LAS slope (Parameter B) of binder due to aging. More aging made both binders behaving almost the same, stiffer and less flexible against cracking.

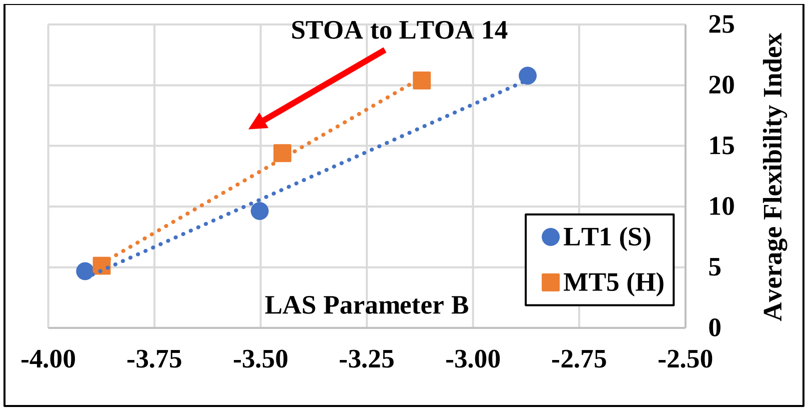


Figure 26. Average FI versus the LAS Parameter B at Different Aging Levels.

In addition, number of cycles to failure (N_f) at 5% strain from LAS test was compared to average FI results as shown in Figure 27. The plot shows that FI is decreasing while N_f is increasing with aging which is not logical. Therefore, relationship between N_f and strain level was studied as shown in Figure 28.

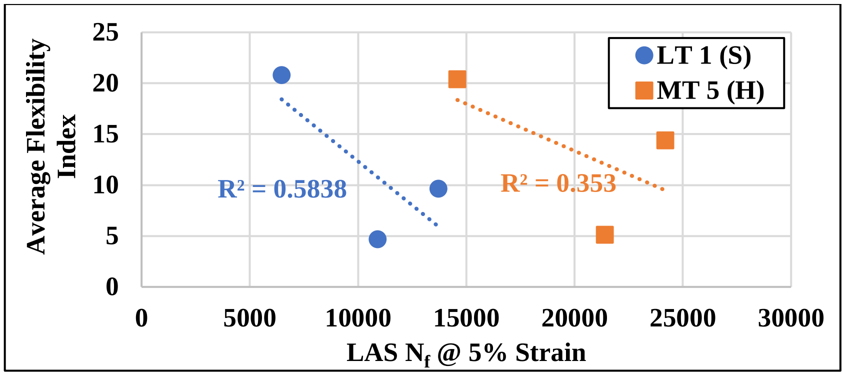


Figure 27. Average FI versus LAS Nf @ 5% Strain at Different Aging Levels.

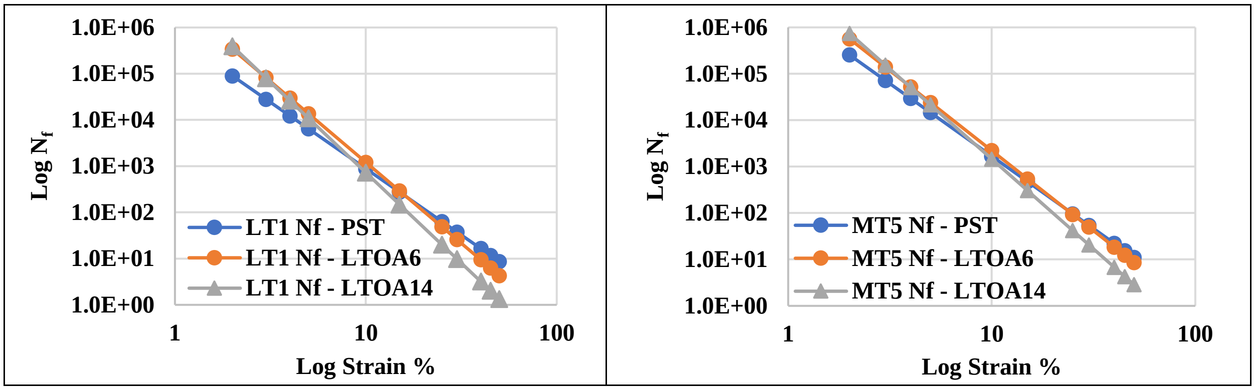


Figure 28. Effect of Strain % on Number of Cycles to Failure (Nf) in LAS test.

Figure 28 clearly shows that 10% is the critical strain level and after this strain percentage, aging reduces FI and N_f values similarly as shown in Figure 29. However, based on the results of this study, change in fatigue life (N_f at 25% Strain) between aging levels is not significant compared change in FI results.

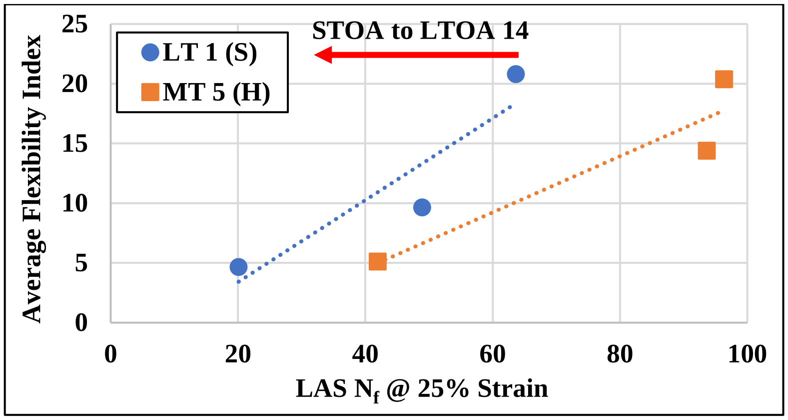


Figure 29. Average FI versus LAS Nf @ 25% Strain at Different Aging Levels.

Based on findings from this portion of the study, it can be concluded that Flexibility Index parameter as determined from AASHTO TP124/Illinois Test Procedure 405, is highly sensitive to mixture aging and magnitude of FI is controlled by post-peak slope during the test. Although FI did not show a clear distinction between S and H binders directly, FI is found to be highly correlated with LAS fatigue law "B" parameter for the control mixtures. This finding suggests that not only can binder properties be used to predict fatigue cracking resistance, but that current asphalt binder specification may be misleading in terms of fatigue performance since not all "H" binders in this study performed better than "S" binders.

6.1.3 DCT Testing Results for Plant-Produced Mixtures

For DCT testing, four pans from each plant-produced mixture (total 32 pans) were collected during production and two pans were aged in 275°F oven for 6 hours (LTOA-6) and the other two pans were aged for 14 hours (LTOA-14). After aging, samples were cooled to room temperature and then pre-heated at 275°F for two hours before compaction to 50 ± 5 mm targeting 7 ± 1% air voids. The compacted samples were prepared for testing at -18°C (LT PG + 10°C) as per ASTM D7313 (2013). Four replicates were tested for each test section at each aging level and average DCT Fracture Energy (FE) values are presented in Figure 30.

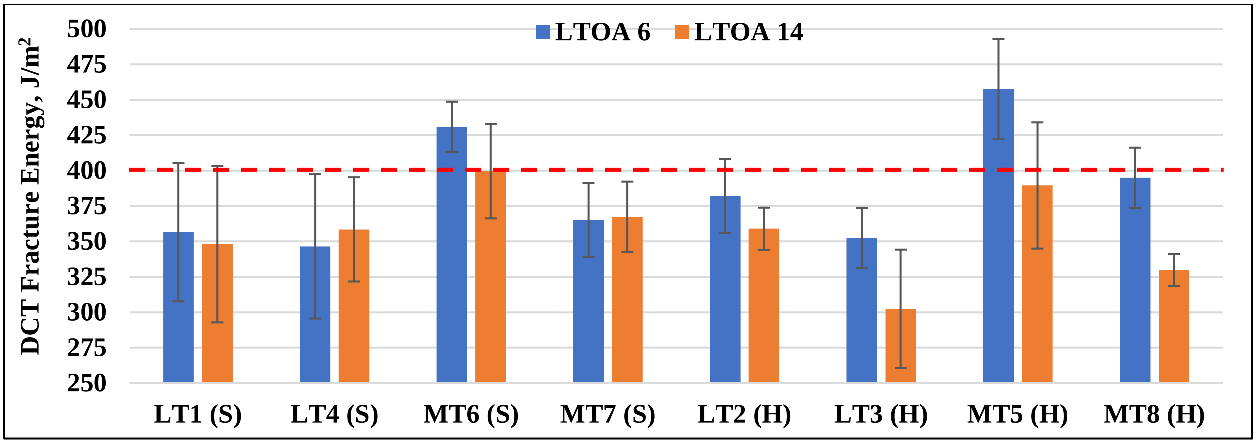


Figure 30. Average DCT Fracture Energy for each Plant-Produced Mixtures at Different Aging Levels.

The results in Figure 30 show high variability among DCT FE results with maximum Standard Deviation of results at 55 J/m^2, which is less than the ASTM Standard allowed limit of 78.5 J/m^2. However, this high variability is larger than the effect of aging measured for most of mixtures. Therefore, effect of aging on FE results from DCT test cannot be considered statistically significant. In addition, there is almost no logical distinction between mixtures from various field sections. The results show no clear effect of binder grade on FE results. Notably, most of mixtures had FE lower than 400 J/m^2 minimum limit proposed in literature at both aging levels, which indicates that these mixtures will not perform well in resistance to low-temperature fracture.

In order to better study the effect of binder grade on low-temperature cracking resistance, PAV residue of extracted and recovered binders from the control plant-produced mixtures (LT1 “S” and MT5 “H”) were tested in Bending Beam Rheometer (BBR) as per AASHTO T313 (2012) which was also conducted at -18°C similar to DCT test. From BBR test, slope (m-value) and creep stiffness (s), for S and H extracted and recovered binders of both aging levels (LTOA-6 & -14) were determined and compared to average FE results from DCT tests as shown in Figure 31 and Figure 32, respectively. As shown in the figures, difference between m-values or creep stiffness values for S and H binders is affecting average FE results (≈100 J/m^2 drop) after 6 hours of long-term oven aging. However, effect is much lower and negligible after 14 hours of oven aging.

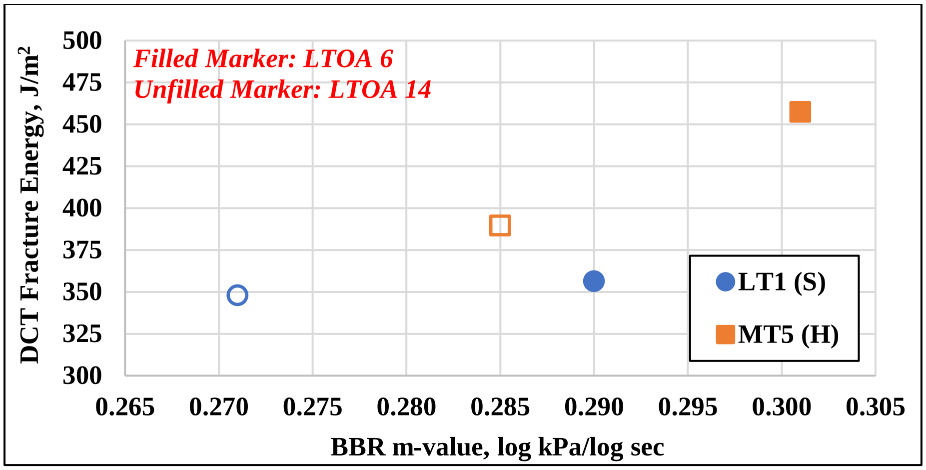


Figure 31. Average DCT Fracture Energy versus BBR m-value for Control Plant-Produced Mixtures at Different Aging Levels.

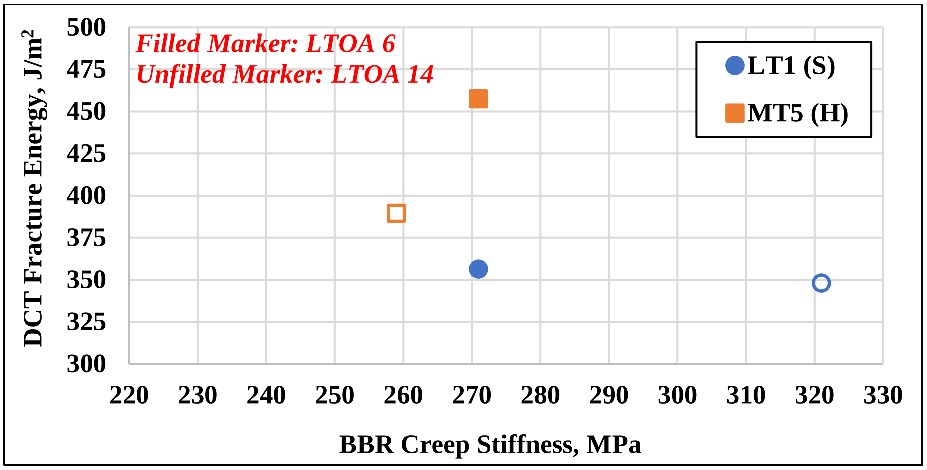


Figure 32. Average DCT Fracture Energy versus BBR Creep Stiffness for Control Plant-Produced Mixtures at Different Aging Levels.

Based on results presented in this section, Fracture Energy as determined by DCT test was not found to be significantly affected by aging, although on average a decrease in FE was observed for six of the eight plant-produced mixtures between the 6- and 14-hours aging conditions. Six of the eight plant-produced mixtures failed the proposed minimum FE limit of 400 J/m^2 at 6 hours aging, and all of plant-produced mixtures failed the same limit at 14 hours aging. Attempts to correlate low-temperature binder properties using BBR to FE results demonstrate that a general logical correlation exists for extracted binder m-value and FE, although changes observed in this study for FE were relatively small.

6.2 Effect of Filler and Asphalt Contents

For this part of the study, effect of filler or dust percentage (P200) and asphalt content on aging rate and performance of the eight plant-produced mixtures in terms of rutting and cracking is presented.

6.2.1 HWT Testing Results for the Plant-Produced Mixtures

In order to examine the effect of P200 percentage on rutting performance, average passes to 12.5 mm rut depth is plotted against P200 of the eight plant-produced mixtures as shown in Figure 33. The results of the HWT was sorted in two groups as mixtures with H binders showed much higher resistance to rutting than S binders. The P200 for mixes with both binder grades range from 4.4% to 6.2%, however average passes to 12.5 mm rut depth is not significantly affected by changing P200 when sorted by binder grade. The same conclusion can be drawn from Figure 34 and Figure 35 where AC% and Dust to Binder Ratio values are not affecting performance against rutting. It appears that binder grade is the most significant factor affecting performance of mixtures against rutting as discussed and concluded in the previous section of this report.

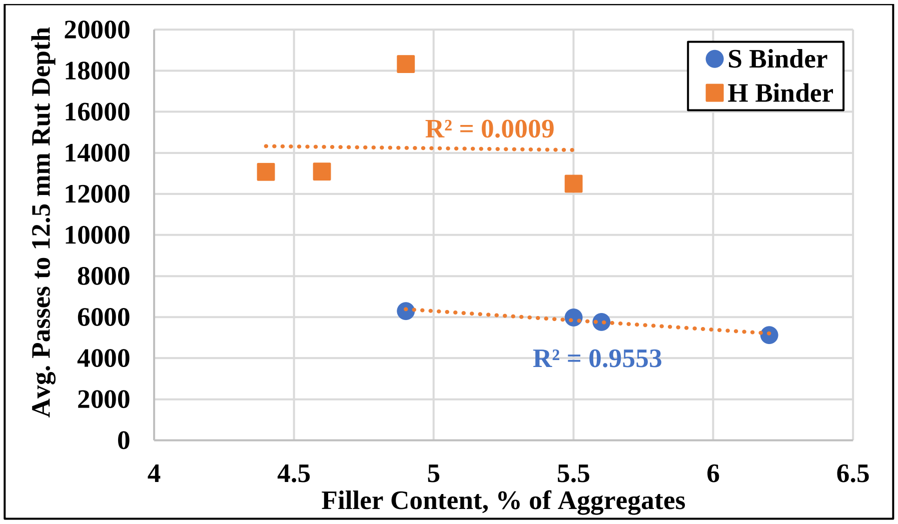


Figure 33. Average Passes to 12.5 mm Rut Depth versus P200 of Plant-Produced Mixtures.

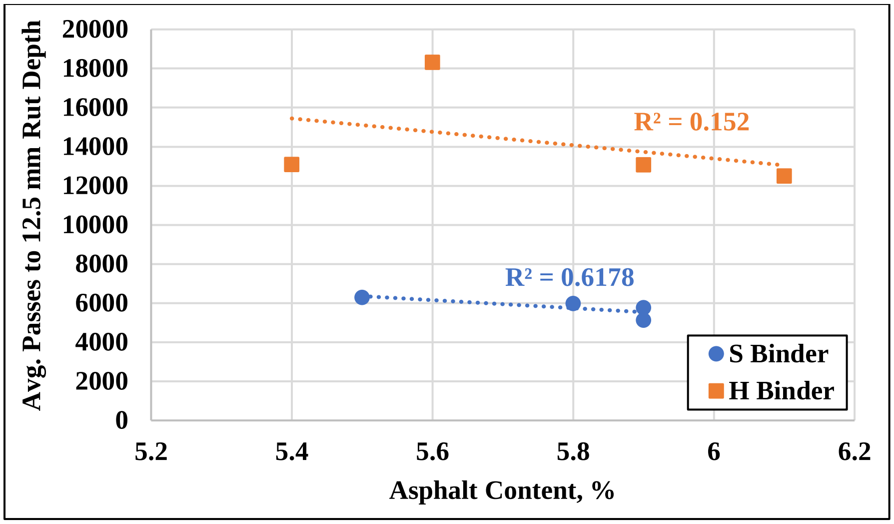


Figure 34. Average Passes to 12.5 mm Rut Depth versus Asphalt Content of Plant-Produced Mixtures.

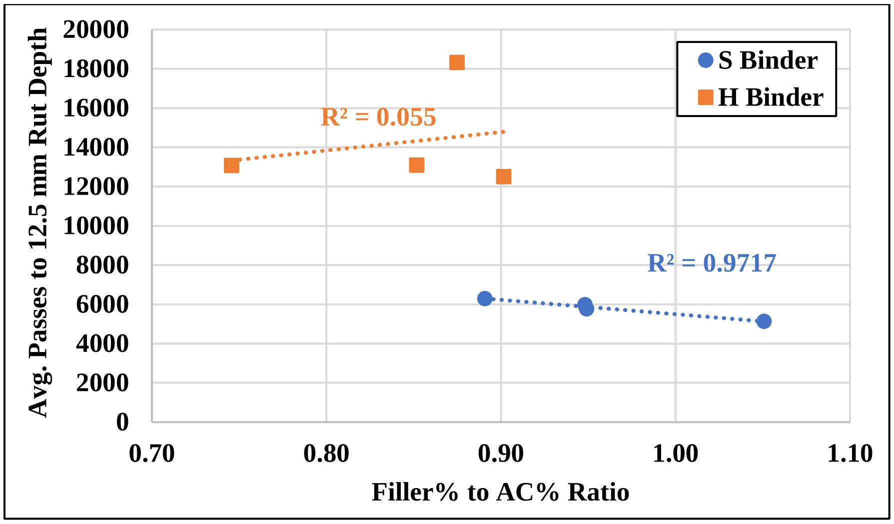


Figure 35 Average Passes to 12.5 mm Rut Depth versus Dust to Binder Ratio of Plant-Produced Mixtures

6.2.2 SCB-IFIT Testing Results for the Plant-Produced Mixtures

To evaluate the effect of P200 on cracking performance, average FI is plotted against P200 of the eight plant-produced mixtures at different aging levels as shown in Figure 36. The change in P200 in the plant-produced mixes does not appear to affect the resulting FI for either binder grade. Similarly, AC% and Dust to Binder Ratio values are not affecting resistance to cracking significantly as shown in Figure 37 and Figure 38.

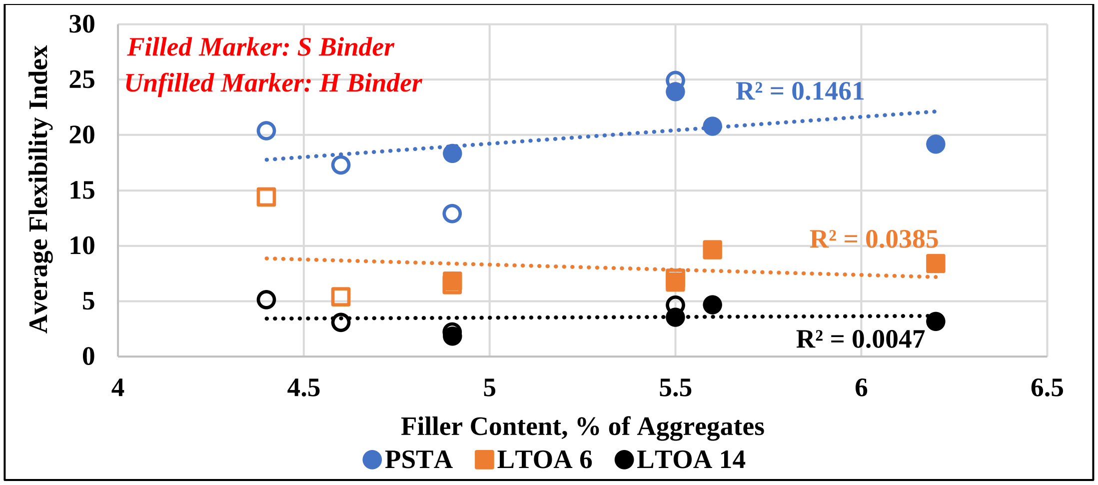


Figure 36. Average Flexibility Index versus P200 of Plant-Produced Mixtures.

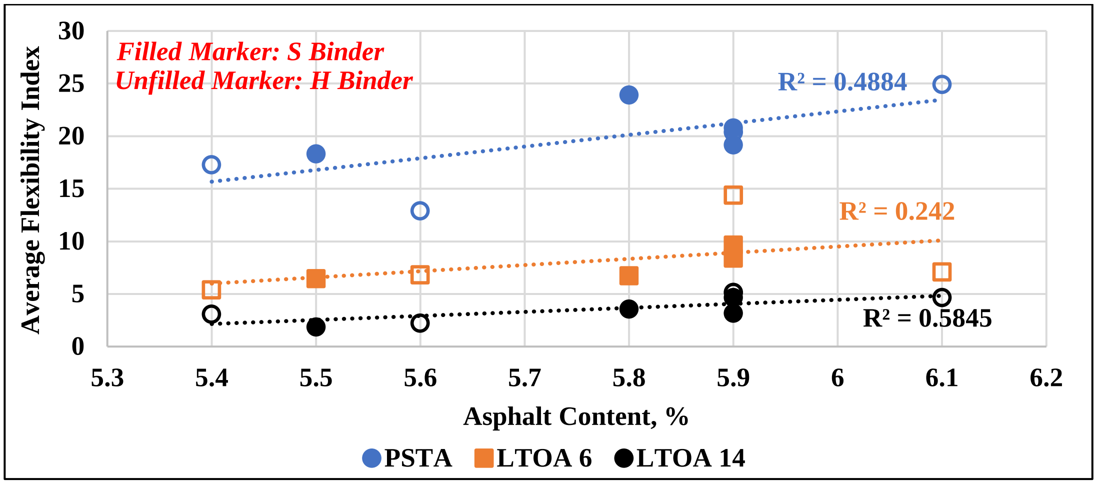


Figure 37. Average Flexibility Index versus AC% of Plant-Produced Mixtures.

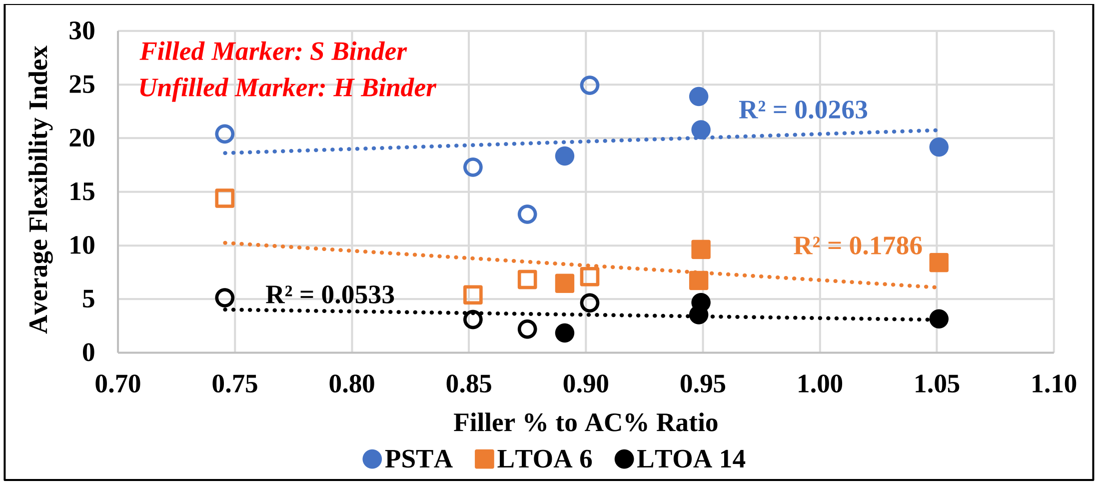


Figure 38. Average FI versus Dust to Binder Ratio of Plant-Produced Mixtures.

In addition, effect of the same factors on aging rate/extent for cracking was evaluated as shown in Figure 39 to Figure 41. The plots show that no major effect of filler content, asphalt content or ratio between both factors on ΔFI per aging hour.

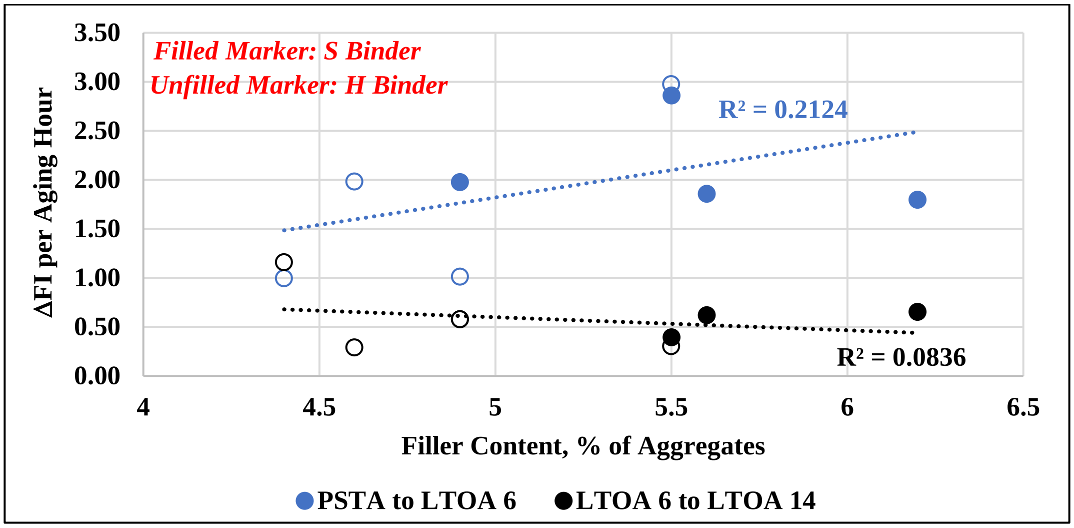


Figure 39. ΔFI per Aging Hour versus Filler % of Plant-Produced Mixtures.

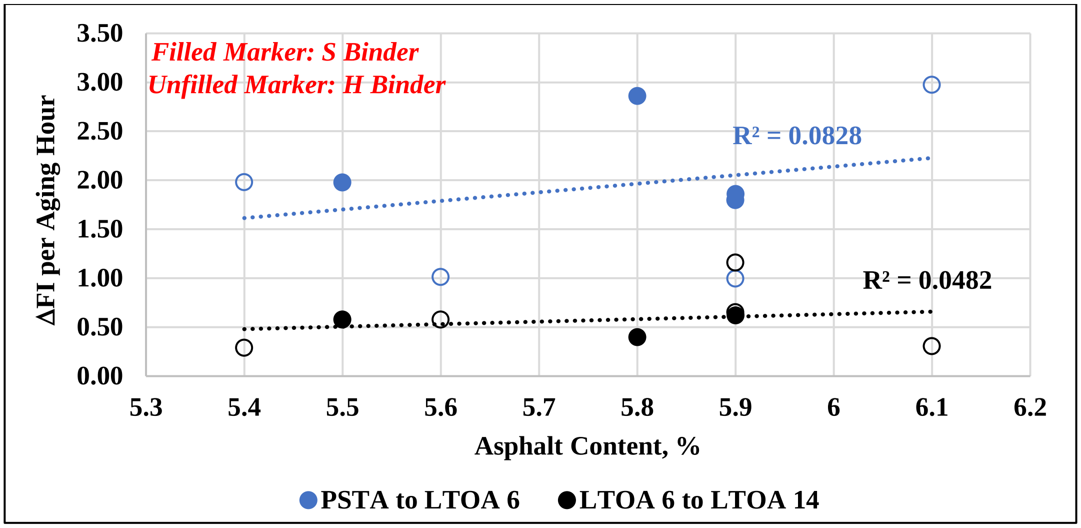


Figure 40. ΔFI per Aging Hour versus AC% of Plant-Produced Mixtures.

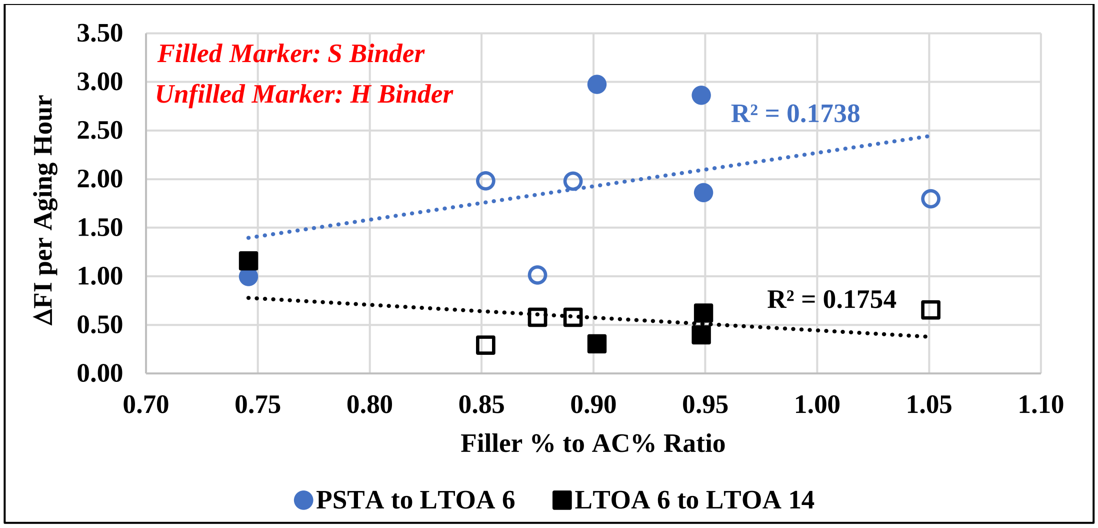


Figure 41. ΔFI per Aging Hour versus Filler % to AC% Ratio of Plant-Produced Mixtures.

Based on data presented in literature, it was expected that increase in binder content should result in better resistance to aging and less change in FI per hour of aging. However, this trend could not be seen in the study possibly due to limited data points and confounding effects of other factors, such as filler content changes. It is also worth mentioning that the trends between short-term aging to 6 hours are positive with increasing filler to binder ratio, while the trend is negative for aging rate between 6 and 14 hours. A positive trend with increased filler to binder ratio is logical and confirms trends reported in literature as it shows that more filler will reduce film thickness and results in more aging.

6.2.3 DCT Testing Results for the Plant-Produced Mixtures

In order to assess the effect of P200 on resistance to low-temperature cracking, average DCT FE values were plotted against P200 of the eight plant-produced mixtures at different aging levels as shown in Figure 42. The results show that increasing P200 (4.4% to 6.2%) results in lower FE for LTOA-6 mixtures (457 to 347 J/m^2), but effect is reduced and is almost negligible after 14 hours of aging. Similarly, Dust to Binder Ratio and Asphalt Content increase resulted in lower cracking resistance as measured by FE as shown in Figure 44 and Figure 43.

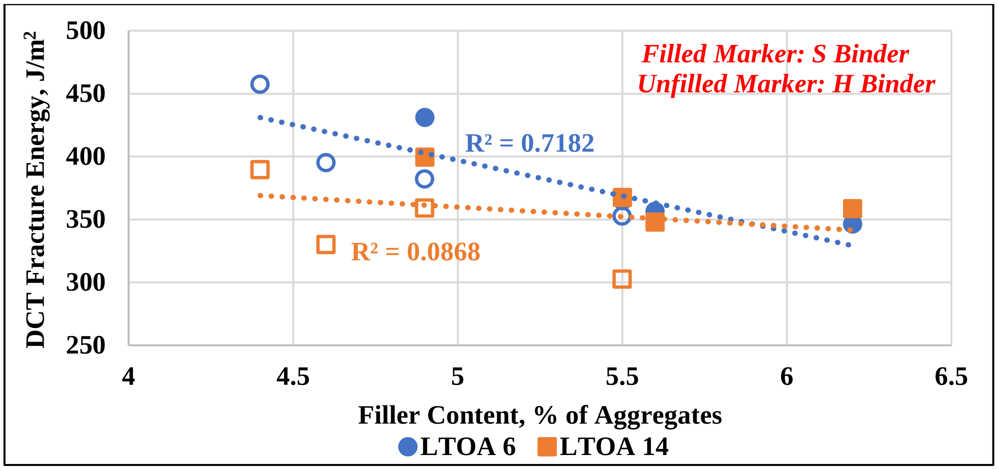


Figure 42. Average DCT Fracture Energy versus P200 of Plant-Produced Mixtures at LTOA-6 & -14 hrs.

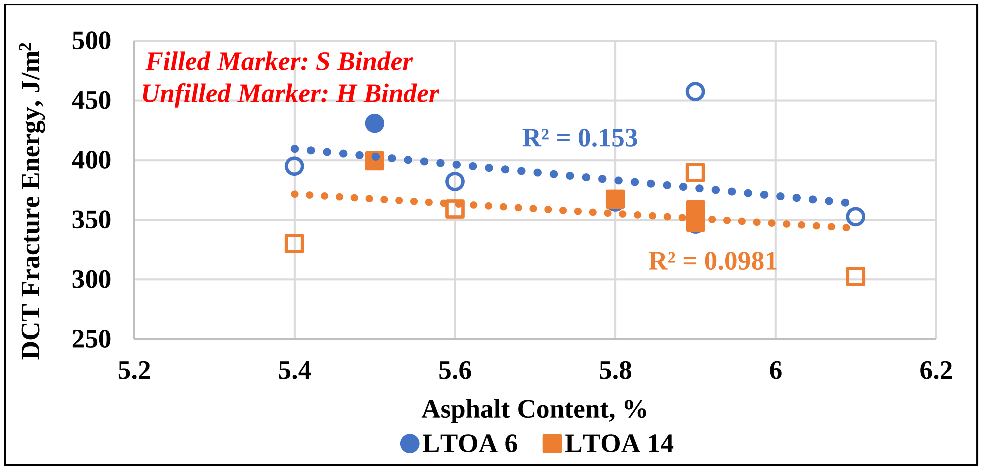


Figure 43. Average DCT Fracture Energy versus AC% of Plant-Produced Mixtures at LTOA-6 & -14 hrs.

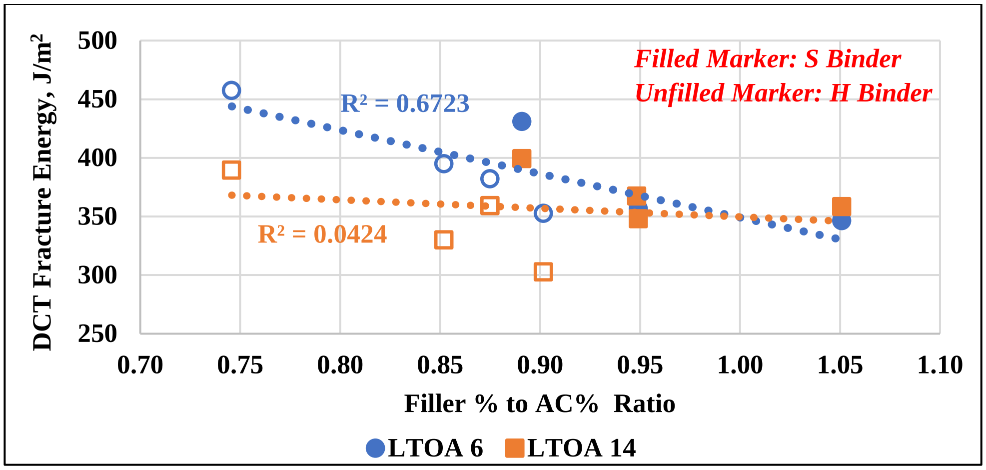


Figure 44. Average DCT Fracture Energy versus Dust to Binder Ratio of Plant-Produced Mixtures at LTOA-6 & -14 hrs.

The effect of same factors on aging rate/extent for low-temperature cracking was evaluated as shown in Figure 45 to Figure 47. The plots show that there is a significant effect of P200 content and Dust to Binder Ratio on change in FE values per aging hour. The higher the filler or dust to binder ratio, the lower is ΔFE per hour of aging. This was not expected since addition of filler will increase surface area and reduce film thickness resulting in faster aging. However, it is also possible that filler mineralogy is affecting the rate and it is known that some types of fillers, such as lime, can retard aging. Therefore, as per results of this study, P200 content and type of filler should be well controlled during production and WisDOT limits should be maintained.

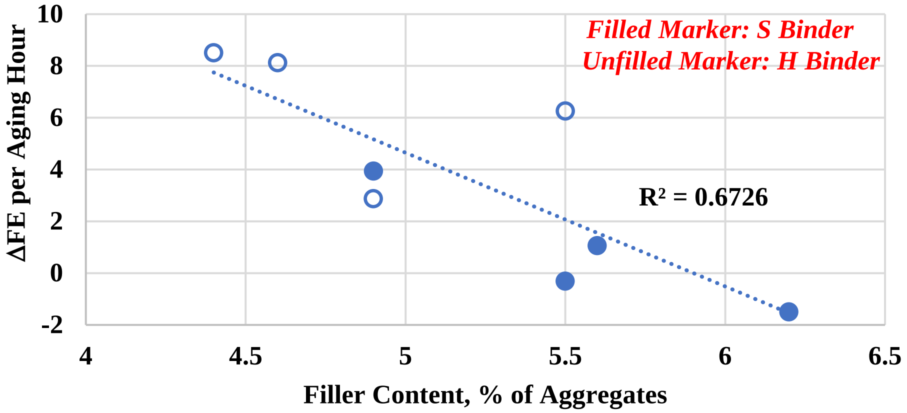


Figure 45. Change in Fracture Energy per Aging Hour versus P200 of Plant-Produced Mixtures.

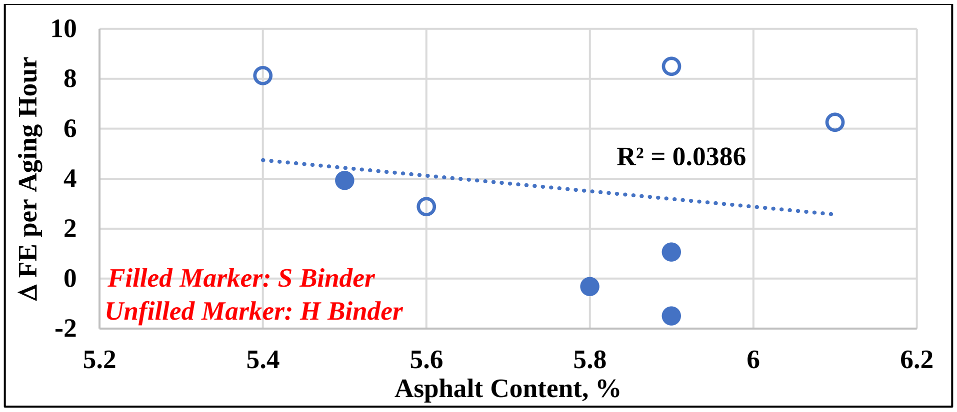


Figure 46. Change in Fracture Energy per Aging Hour versus AC% of Plant-Produced Mixtures.

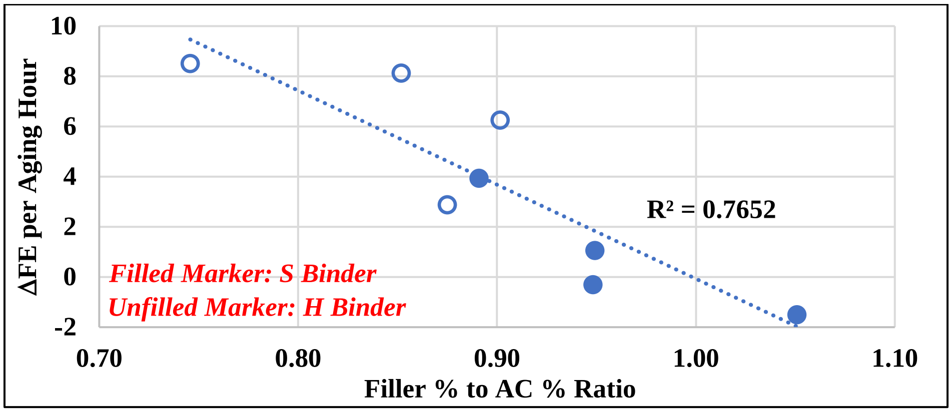


Figure 47. Change in Fracture Energy per Aging Hour versus Dust to Binder Ratio of Plant-Produced Mixtures.

6.3 Summary of Findings for Mix Design Factors Effect on Performance and Aging Study

Based on analysis of results presented in this section of the report, the following findings can be summarized:

A. HWT test results:

- HWT results of the eight plant-produced mixtures show significant effect of binder grade in terms of %R or Jnr on rutting resistance; higher %R and lower Jnr values of H grade improve resistance of short-term aged mixtures to permanent deformation. However, no strong correlation between value of these parameters and number of passes to 12.5 mm rut depth could be found.
- P200 content for mixtures with both binder grades range from 4.4% to 6.2%, however average passes to 12.5 mm rut depth is not significantly affected by changing P200. The same conclusion can be drawn for AC% and Dust to Binder Ratio values are not affecting performance against rutting.

B. SCB-IFIT test results

- Flexibility Index (FI) parameter is highly sensitive to mixture aging and magnitude of FI is controlled by post-peak slope during the test.
- A better distinction between mixtures can be found for PSTA and LTOA-6 data, however FI values of mixtures after 14 hours of oven aging are found to vary in a narrow range. Therefore, it is recommended to evaluate fatigue performance of mixtures at short-term and 6-hour long-term aging.
- FI results do not show a clear distinction between S and H binders, however FI is found to be highly correlated with LAS fatigue law "B" parameter for two binders used and to their changes with aging. This finding suggests that not only can binder properties be used to predict fatigue cracking resistance, but that current asphalt binder specification may be misleading in terms of fatigue performance since not all "H" binders in this study performed better than "S" binders.
- The change in P200 content, AC% or Dust to Binder Ratio values in the plant-produced mixes does not appear to affect the resulting FI for either binder grade.

C. DCT test results

- DCT Fracture Energy results are not found to be significantly affected by aging, although on average a decrease in FE was observed for six of the eight plant-produced mixtures between 6- and 14-hours aging conditions.
- Attempts to correlate low-temperature binder properties using BBR to DCT-FE results demonstrated that a general logical correlation exists for extracted binder m-value and FE, although changes observed in this study for FE were relatively small.
- The change in P200 content affected LTOA-6 FE results but the effect is reduced after 14 hours of aging. However, change in AC% is not affecting DCT-FE results.

7. Effect of Low-Temperature Modifiers on Mixture Aging and Performance

In this part of research study, effect of low-temperature modifiers on asphalt mixture aging and performance was investigated. The original LT mix design at design air voids of 3% was the mix design used for this part of the study. However, base binder, PG58S-28, was blended with two different oils and polymers in different dosages to prepare six blends of PG58-34 binder. The six blends produced with oils were compared to two binders of PG52S-34 grade with no oils. One of these no-oil blends is a commercial binder modified with Elvaloy to a PG58-34 and another was blended with SBS (D1101) and Sulfur as a cross-linker to prepare the other PG58-34 without oil. All eight blends are designed to exhibit similar AASHTO M320 continuous grades. Table 27 shows the composition of the eight blends prepared in laboratory to prepare PG58-34 mixtures of this part of the study and MSCR results of their RTFO residue at 58°C. The MSCR results shown in Table 27 indicate that % Recovery and Jnr (3.2 kPa) are different among the eight blends. This difference can contribute to difference in performance since these blends have different PG+ properties although PG grade targeted was similar.

Table 27. Compositions of the Eight Blends to Prepare PG58-34 Binder and MSCR Results of their RTFO Residue.

Mix Design	**Project “4-LT at design AV (3%) and design dust”**							
Target Binder	**PG58-34**							
Base Binder	**PG58S-28**						**PG52S-34**	
Oil Type	**Bio-Oil (Vegetable)**			**Re-Refined Oil (REOB)**			**-**	
Composition	**Blend 1**	**Blend 2**	**Blend 3**	**Blend 4**	**Blend 5**	**Blend 6**	**Blend 7**	**Blend 8**
PG58S-28 Base Binder	**94.5%**	**95.8%**	**96.5%**	**91.0%**	**90.8%**	**93.5%**		**Contractor Supplied PG58-34**
PG52S-34 Base Binder							**96.85%**	
SBS (Kraton D243)	**2.0%**			**2.0%**				
Elvaloy (4170)		**1.0%**			**1.0%**			
PPA (115)		**0.2%**	**0.5%**		**0.2%**	**0.5%**		
SBS (Kraton D1101)							**3.0%**	
Sulfur							**0.15%**	
Bio-Oil	**3.5%**	**4.0%**	**3.0%**					
REOB				**7.0%**	**8.0%**	**6.0%**		
OB C.G.	61.3	65.8	60.5	63.5	61.9	61.5	66.4	61.2
RTFO C.G.	62.4	66.3	60.7	64.8	63.1	61.8	67.8	62.2
LT S(60)	-26.8	-26.2	-25.4	-29.0	-27.1	-27.5	-25.9	-26.5
LT m(60)	-25.6	-28.5	-25.7	-25.1	-25.5	-25.1	-25.8	-28.3
ΔTc	**-1.2**	**2.3**	**0.3**	**-4.0**	**-1.6**	**-2.4**	**-0.1**	**1.8**
Continuous M320 PG	**61.3-35.6**	**65.8-36.2**	**60.5-35.4**	**63.5-35.1**	**61.9-35.5**	**61.3-35.1**	**66.4-35.8**	**61.2-36.5**
Avg. % Recovery (3.2 kPa) @ 58°C	**9.96**	**32.60**	**0.00**	**15.07**	**17.48**	**0.00**	**35.88**	**41.50**
Avg. Jnr (3.2 kPa) @ 58°C	**1.82**	**0.75**	**2.41**	**1.36**	**1.58**	**2.47**	**0.61**	**0.97**
MSCR Grade	**PG58S**	**PG58H**	**PG58S**	**PG58S**	**PG58S**	**PG58S**	**PG58H**	**PG58H**

SBS is Styrene-Butadiene-Styrene Elastomeric Polymer
PPA is Poly-Phosphoric Acid high temperature modifier.
REOB is Recycled (Refined) Engine Oil Bottoms
Elvaloy is trade name for an elastomeric terpolymer system trademarked by DuPont
O.B. is Original (unaged) Binder

RTFO is RTFO Residue
C.G. is Continuous (true) Binder Grade
L.T. is Low Temperature
OB and RTFO C.G. are Original Binder and RTFO Binder Continuous (True) Grade, respectively

After preparing the eight blends, eight mixtures were prepared using the same LT mix design binder content (5.8%), and same combined aggregate gradation. The only difference in these eight mixtures is composition or polymers/oils used to prepare the PG58-34 binder. These mixtures were tested for volumetric properties and resistance to fatigue damage using SCB-IFIT test at different aging levels (STOA, LTOA-6 & LTOA-14). The results are summarized and discussed in the following subsections.

7.1 Volumetric Properties and Workability

In order to evaluate the effect of oil rejuvenators and polymer types of the same PG58-34 binder on Theoretical Maximum Specific Gravity (Gmm) results, the eight mixtures prepared in this study with the eight blends were aged as per the procedure developed earlier and tested for Gmm as per ASTM D6857 (2011). Table 28 summarizes Gmm results for each mixture at three aging levels (STOA, LTOA-6 & LTOA-14). The results show that the eight mixtures have similar Gmm at a specific aging level. The standard deviations are 0.009, 0.007 and 0.008 for STOA, LTOA-6 and LTOA-14, respectively, which are around single operator precision standard deviation (0.007) mentioned in the standard (ASTM D6857). It is therefore concluded that effect of binder composition on Gmm for this study is minimal, however, Gmm value is increasing with aging as expected (more binder will be absorbed by aggregates). Therefore, it was decided to use average Gmm of each aging level to prepare SCB-IFIT samples of this part of the study.

Table 28. Results of Gmm for each Blend Mixture at Different Aging Levels.

Aging Level	Gmm of Mixture with								STD	Average
	Blend 1	Blend 2	Blend 3	Blend 4	Blend 5	Blend 6	Blend 7	Blend 8		
	58S-28 SBS-BioOil	58S-28 Elva-PPA-BioOil	58S-28 PPA-BioOil	58S-28 SBS-REOB	58S-28 Elva-PPA-REOB	58S-28 PPA-REOB	52S-34 SBS	58-34 (Elvaloy)		
STOA	2.475	2.475	2.467	2.468	2.456	2.453	2.481	2.468	0.009	2.468
LTOA-6	2.472	2.477	2.480	2.463	2.483	2.478	2.481	2.487	0.007	2.477
LTOA-14	2.484	2.481	2.498	2.475	2.490	2.484	2.494	2.492	0.008	2.487

In addition, effects of binder composition and aging on workability or compaction effort was assessed using Superpave Gyratory Compactor (SGC) data for samples compacted for SCB-IFIT tests. As shown in Table 29, number of gyrations required to compact SCB-IFIT samples to 135 mm height at different aging levels increases with aging while difference between blends reduces with aging. The average number of gyrations increased from seven for STOA to ten for mixtures aged for 14 hours (LTOA-14). This change in required gyrations is similar for all binders. The mixtures with binders without oils required slightly higher gyrations than mixtures with binders modified with oils.

Table 29. Number of Gyrations Required to 135 mm Height SCB-IFIT Sample.

Aging Level	No. of Gyrations to 135 mm Height								Average	Range
	Blend 1	Blend 2	Blend 3	Blend 4	Blend 5	Blend 6	Blend 7	Blend 8		
	58S-28 SBS-BioOil	58S-28 Elva-PPA-BioOil	58S-28 PPA-BioOil	58S-28 SBS-REOB	58S-28 Elva-PPA-REOB	58S-28 PPA-REOB	52S-34 SBS	58-34 (Elvaloy)		
STOA	7	7	7	6	7	8	10	7	7	4
LTOA-6	7	9	8	8	9	8	9	10	9	2
LTOA-14	9	11	9	11	11	11	10	11	10	2

7.2 SCB-IFIT Testing Results

For SCB-IFIT testing, three pans from each blend mixture (total 24 pans) were prepared and aged for short-term oven aging (STOA) in pans. Then, one pan was used as is (STOA) and second one was aged in 275°F oven for 6 hours (LTOA-6) and last one was aged for 14 hours (LTOA-14) following reheating and aging procedure developed earlier in this research study. After aging, samples were cooled to room temperature and then pre-heated at 275°F for two hours before compaction to 135 ± 1 mm. Then, two 50 mm-thick slices were cut from the center of each compacted sample to achieve 7 ± 0.5% air voids as per Illinois Test Procedure 405 (AASHTO TP124, 2016). A minimum of four half slices were tested for each mixture at each aging level and average Flexibility Index (FI) and average Post-Peak Slope are presented in Figure 48 and Figure 49, respectively.

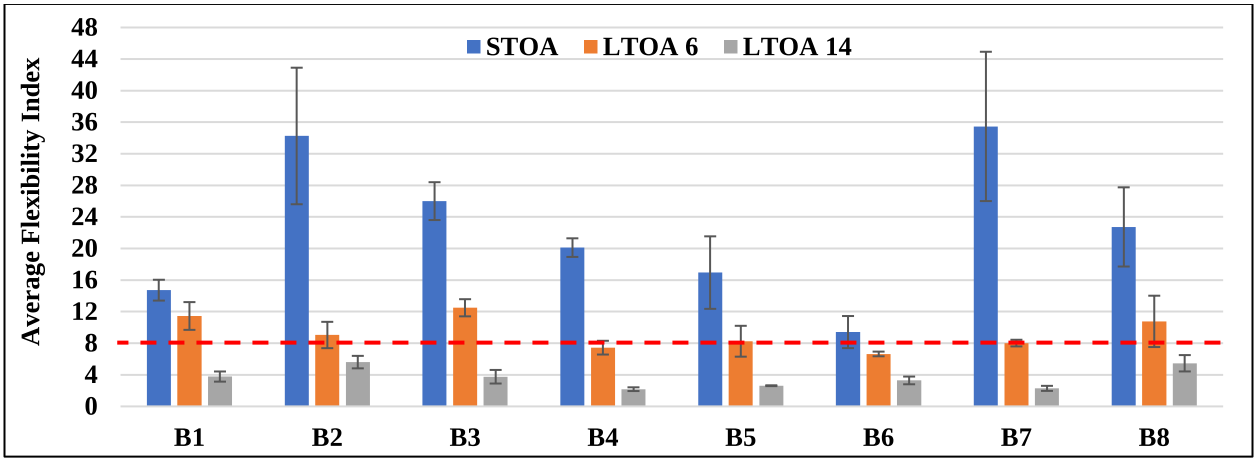


Figure 48. Average Flexibility Index for each Blend Mixture at Different Aging Levels.

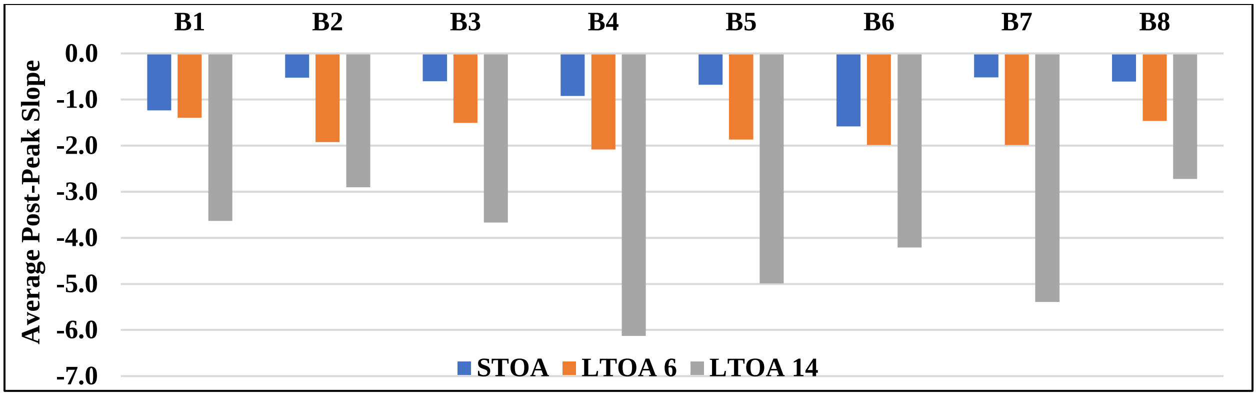


Figure 49. Average Post-Peak Slope for each Blend Mixture at Different Aging Levels.

7.2.1 Effects of Binder Formulations on FI and Aging Rates

According to results shown in Figure 48, mixtures vary in FI of STOA samples, with blends 2, 7, and 8 showing higher values than other mixtures. It is interesting to note that these three mixtures have the lowest Jnr values and higher %R from MSCR, and are graded as PG 58H. This finding indicates that binder MSCR grade is important and the more it improves, the higher the FI value is. The results in Figure 48 also indicate that average FI of all eight STOA mixtures is above the value of eight specified earlier by a study conducted in Illinois (Circular Letter 2015-19, 2015). However, with more aging (LTOA-6 & -14) FI decreased significantly and most of results are below eight.

Considering aging susceptibility of the eight mixtures, it can be seen that it is different as shown in Figure 48. To further evaluate the specific trends of aging rates, Table 30 is prepared to list and compare the change in FI values per hour of aging in the oven between STOA and LTOA-6, and between LTOA-6 and LTOA-14.

The FI values and aging rates in Table 30 indicate there is a significant effect of composition of each blend on initial FI values as well as aging rates. The range of FI for each aging condition reduces with more aging; FI-STOA results varies between 35.5 and 9.4, FI-LTOA-6 results varies between 12.5 and 6.6, while it varies between only 5.6 to 2.2 for FI-LTOA-14 results.

The aging rate of FI between STOA and LTOA-6 samples ranges from 0.46 to 4.20 per hour of aging. However, it ranges only from 0.42 to 1.09 per hour between LTOA-6 and LTOA-14 samples which shows LTOA-14 could be too severe to distinguish between cracking resistance of these mixtures after long-term aging. In addition, it shows clearly differences in aging sensitivity between mixtures.

The other interesting observation in Table 30 is no specific trend in FI values or aging rate that relates to one specific oil type nor polymer type is shown. As shown in the light blue shaded rows, mixtures containing REOB have higher or lower FI-STOA values than mixtures containing bio-oil. However, when mixtures aged for 6 extra hours, FI-LTOA-6 values for mixtures with REOB are significantly lower than those with bio-oil. Considering FI values after 14 hours aging (FI-LTOA-14) show that all mixtures including the one with and without oils are all low and within a range of +/- 1.7 units. This clearly indicates that the 14-hour aging could make it difficult to distinguish among mixtures with regards to cracking resistance.

Table 30. Effect of Aging Rate on FI for the Eight Blends Mixtures.

Blend #	PG Grade	Oil + Additive	STOA FI	LTOA-6 FI	LTOA-14 FI	ΔFI (ST-LT6) Per Aging hr	ΔFI (LT6-LT14) Per Aging hr	ΔT_c 20 hr PAV
Blend 1	61.3S-35.6	Bio-Oil + SBS	14.7	11.5	3.8	0.55	0.96	-1.2
Blend 2	65.8H-36.2	Bio-Oil + Elvaloy	34.3	9.0	**5.6**	4.20	0.43	**2.3**
Blend 3	60.5S-35.4	Bio-Oil + PPA	26.0	**12.5**	3.8	2.25	**1.09**	0.3
Blend 4	63.5S-35.1	REOB + SBS	20.1	7.4	**2.2**	2.11	0.66	**-4.0**
Blend 5	61.9S-35.5	REOB + Elvaloy	17.0	8.3	2.6	1.45	0.70	-1.6
Blend 6	61.3S-35.1	REOB + PPA	**9.4**	**6.6**	3.3	**0.46**	**0.42**	-2.4
Blend 7	66.4H-35.8	SBS	**35.5**	8.0	2.3	**4.57**	0.72	-0.1
Blend 8	61.2H-36.5	Elvaloy	22.7	10.8	5.5	1.99	0.66	1.8
		Average	**22.5**	**9.3**	**3.6**	**2.20**	**0.71**	**-0.61**
		Range	**26.1**	**5.9**	**3.4**	**4.11**	**0.67**	**6.3**
		Pooled Stdev.	**4.3**	**1.4**	**0.6**	**-**	**-**	**-**

To clarify the effect of oil modification on aging and performance, average effects of each oil rejuvenator type (i.e. bio-oil and REOB) on FI results and aging rate is summarized in Table 31. The results in the table show that REOB results in the lowest average values of FI for all aging levels, but it also shows the lowest aging rates. In contrast to REOB effect, the use of bio-oil significantly improved FI values at all aging levels but shows higher aging rates. In addition, results in Table 31 indicate clearly that using STOA mixtures could rank mixtures differently than LTOA-6 mixtures, while LTOA-14 results did not change the ranking. Although data set is limited, it shows that LTOA-6 is more than enough to distinguish between mixtures with oils. In fact, aging rate per hour is reduced significantly from LTOA-6 to -14 hours.

Table 31. Effect of Oil Type on FI and Aging Rate for the Eight Blends Mixtures.

Blend #	PG Grade	Oil	Additive	Avg. STOA FI	Avg. LTOA-6 FI	Avg. LTOA-14 FI	ΔFI (ST-LT6) Per Aging hr	ΔFI (L6-LT14) Per Aging hr
Blend 1	61.3S-35.6	Bio-Oil	SBS	24.99	11.00	4.38	2.33	0.83
Blend 2	65.8H-36.2		Elvaloy					
Blend 3	60.5S-35.4		PPA					
Blend 4	63.5S-35.1	REOB	SBS	15.49	7.45	2.70	1.34	0.59
Blend 5	61.9S-35.5		Elvaloy					
Blend 6	61.3S-35.1		PPA					
Blend 7	66.4H-35.8	No Oil	SBS	29.10	9.40	3.87	3.28	0.69
Blend 8	61.2H-36.5		Elvaloy					

7.2.2 *Relevance of binder ΔT_c and LAS-B Parameter*

In recent years, binder ΔT_c (pronounced "Delta Tee-See") parameter has been proposed as a possible indictor of durability and resistance to cracking. Although ΔT_c is measured at temperatures lower than the 25 °C used to measure FI, the concept of time-temperature equivalency has been used to explain the relevance of a low temperature parameter measured at long loading time (60 sec) to intermediate temperature cracking measured at a high loading rate (50 mm/min). Therefore, values of ΔT_c listed in Table 30 are plotted versus aging rate as expressed by ΔFI per hour of aging in Figure 50. As can be seen, there is no trend at all when FI change between LTOA-6 and LTOA-14 are plotted. However, there is a positive trend when ΔT_c is correlated with change in FI between STOA and LTOA-6. Although correlation is rather low, positive trend does not support concept that lower ΔT_c values are somewhat related to poor durability of asphalt mixtures. One of possible explanations to this lack of expected relationship is the fact that ΔT_c is measured at 20-hour PAV aging condition which is not severe enough to simulate extended aging.

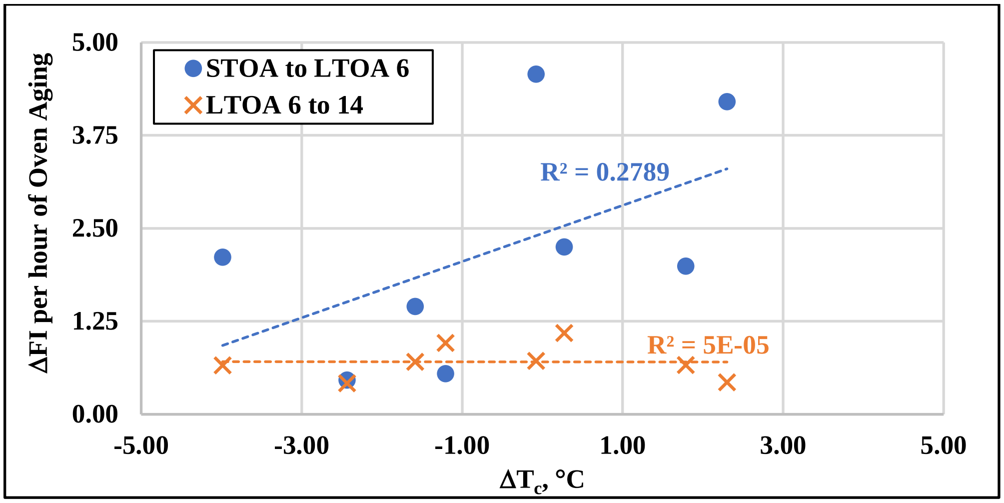


Figure 50. Change in FI as a function of Binder ΔTc.

In order to better understand effect of binder composition and aging on cracking resistance, extracted and recovered binders from the eight mixtures were subjected to Linear Amplitude Sweep (LAS) test as per AASHTO TP101 (2016), which was conducted at 25°C similar to SCB-IFIT test temperature. From LAS test, parameter B, which is directly calculated from frequency sweep part of LAS test, for the eight recovered binders of different aging levels was determined and compared to values of the original binders after RTFO aging and also to ΔT_c as shown in Table 32.

The results of LAS-B values show that extraction and recovery procedure could have significant effect on this parameter as RTFO LAS-B values show an average of 2.82 while values for binders extracted and recovered from the short-term aged mixtures (STOA-LAS-B) show an average of 3.15. It is not clear whether this is due to the difference in aging of binders or due to solvent effects. It is also shown in Table 32 that change due to aging in average values of LAS-B is 0.53 between STOA and LTOA-6, which increased to 0.63 when change from LTOA-6 to LTOA-14 is calculated. What is interesting to observe is there are some consistent trends for effect of oils on aging rates (ΔST-L6, and ΔL6-L14), as they show that binders with bio-oil show consistently lower aging rates than binders with REOB. This observation is in contradiction with results for FI of mixtures as they showed that mixtures with REOB have the lowest aging rates. Therefore, it could be concluded that testing extracted and recovered binders do not necessarily reflect results of FI testing of mixtures.

Table 32. Effect of Aging on Parameter B Value for the Eight Blends Mixtures.

Blend #	PG Grade	Oil + Additive	RTFO LAS-B	STOA LAS-B	LTOA-6 LAS-B	LTOA-14 LAS-B	ΔST-L6	ΔL6-L14	ΔT_c 20 hr PAV
Blend 1	61.3S-35.6	BioOil + SBS	**2.64**	3.17	3.68	4.21	0.51	0.53	-1.2
Blend 2	65.8H-36.2	BioOil + Elvaloy	2.80	3.09	**3.43**	**3.66**	**0.34**	**0.23**	**2.3**
Blend 3	60.5S-35.4	BioOil + PPA	2.69	3.00	3.44	3.96	0.45	0.51	0.3
Blend 4	63.5S-35.1	REOB + SBS	2.74	**3.38**	**4.10**	4.80	**0.72**	0.69	**-4.0**
Blend 5	61.9S-35.5	REOB + Elvaloy	2.76	3.19	3.74	**4.81**	0.55	**1.07**	-1.6
Blend 6	61.3S-35.1	REOB + PPA	2.71	3.09	3.74	4.40	0.66	0.66	-2.4
Blend 7	66.4H-35.8	SBS	2.94	3.20	3.77	4.49	0.56	0.72	-0.1
Blend 8	61.2H-36.5	Elvaloy	**3.31**	**3.05**	3.54	4.18	0.49	0.64	1.8
		Average	**2.82**	**3.15**	**3.68**	**4.31**	**0.53**	**0.63**	**-0.61**
		Range	**0.67**	**0.39**	**0.68**	**1.16**	**0.39**	**0.84**	**6.3**
		Pooled Stdev.	**0.013**	**0.021**	**0.006**	**0.017**	**-**	**-**	**-**

However, when average FI results from SCB-IFIT test are plotted versus LAS-B parameter of extracted and recovered binder, as shown in Figure 51, relatively acceptable correlations could be found.

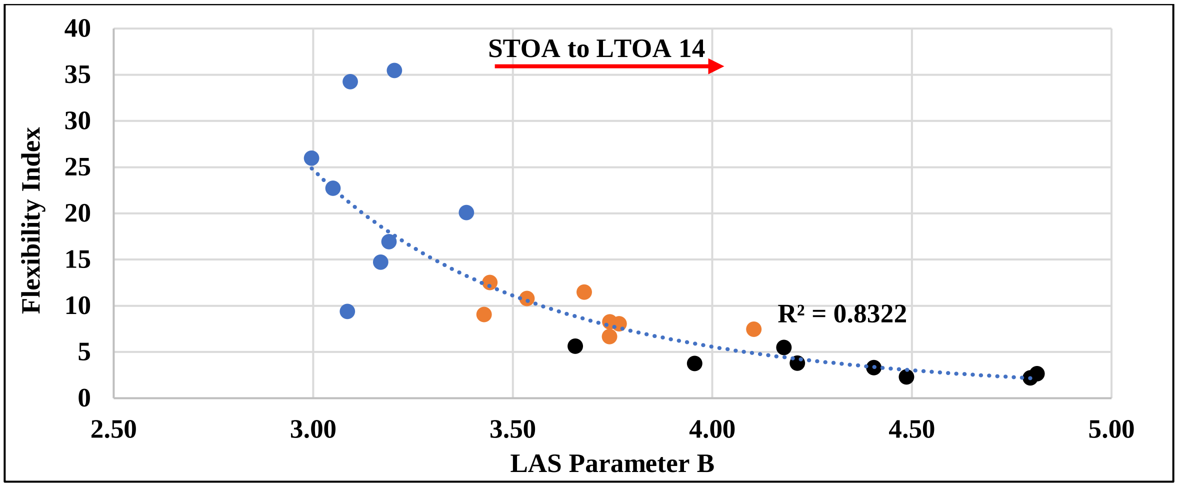


Figure 51. Average Flexibility Index versus LAS Parameter B of the Eight Blends Mixtures at Different Aging Levels.

As shown in Figure 51, values of LAS-B for extracted and recovered binders increase significantly (becomes more negative) with aging, and increase in B values correlates fairly well with decrease in FI values of mixtures. In addition, range of FI results are similar for all mixtures with longer aging of mixtures and no significant effect of B values on FI results.

The strong relationship ($R^2 = 83\%$) between the decrease in FI and the increase in LAS-B of binder due to aging also further demonstrates that FI is sensitive to aging and that influence of binders' composition on FI decreases with aging. In other words, influence of LAS-B parameter on FI decreases at a decreasing rate with increased aging time as binder becomes stiffer and less flexible against cracking. The results in Table 32 indicate that binders of a similar grade exhibit similar LAS-B parameters after short-term aging but vary much more after long-term aging. In addition, aging rates are significantly different and not linear where LTOA-6 to LTOA-14 hours show more change than STOA to LTOA-6 hours.

To further explore relationship of ΔT_c of binders with change in LAS-B parameter, the plot in Figure 52 is prepared to show the relationships with change between STOA and LTOA-6, and LTOA-6 and LTOA-14. There is an acceptable correlation between ΔT_c and change in LAS-B parameter for STOA to LTOA-6, but correlation is lost for change between LTOA-6 to LTOA-14. This could be explained by fact that ΔT_c is only measured for the 20-hours PAV aging which does not reflect extended aging of mixtures after 6 hours.

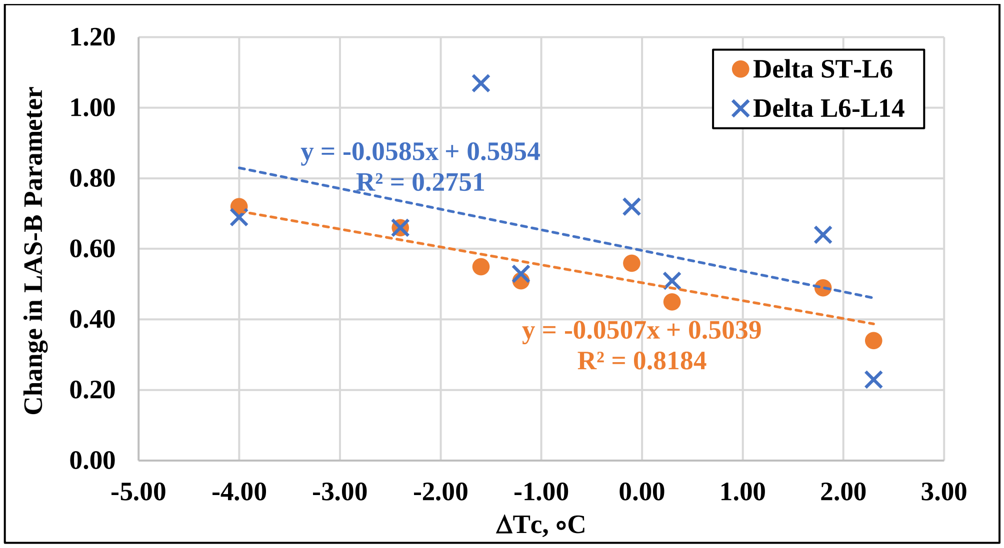


Figure 52. Correlation Between ΔTc and Change in LAS-B Parameter due to Extended Aging.

The main finding from the analysis of LAS-B parameter is that ΔT_c measured for the 20-hr PAV aging cannot be assumed to represent long term aging of mixtures, and that testing extracted and recovered binders could be confounded by extraction and recovery process, in particular by solvents used.

7.3 Summary of Findings for Effect of Low-Temperature Modifiers on Mixture Aging and Performance

Based on the analysis of results presented in this section, the following findings can be summarized:

- The eight blends prepared to target PG58-34 M320 grade with different compositions resulted in binders with different PG+ properties and characteristics (%R and Jnr). The difference is expected as only some formulations contained elastomeric polymers while others had only PPA. These differences in PG+ properties could affect performance of mixtures prepared with these blends.
- Gmm results for all mixtures prepared with the eight binders and aged for three different aging levels (STOA, LTOA-6 & LTOA-14) are similar at each aging level, but averages slightly increase with aging. The increase could be explained by increased absorption of binder with oven aging.
- The number of gyrations required to compact SCB-IFIT samples to 135 mm height at different aging levels increases marginally with aging, but difference in required gyrations between mixtures reduced with aging level.
- SCB-IFIT results showed different cracking resistance (range of FI values is more than 100% of average) among mixtures even though they have same aggregate gradation, binder PG grade and binder content. Also, aging susceptibility of the eight mixtures was significantly different (range for STOA to LTOA-6 is more than 180% of average FI units per hour of aging, and almost 90% of average rate per hour between LTOA-6 and LTOA-14).
- FI results and aging rates observed in this part of the study confirmed that LTOA-14 aging level is too severe for mixtures and cannot be considered suitable to distinguish between mixtures aging behavior.
- There is a strong relationship ($R^2 = 83\%$) between decrease in FI and increase in absolute value of LAS-B parameter of extracted and recovered binders due to aging. This finding shows that FI sensitivity to aging is driven by binder properties. With extended aging, binders showed more differences, but FI values become almost the same. This finding indicates that as binder becomes stiffer and less flexible against cracking, aggregates and volumetric properties dominate behavior of cracking.
- SCB-IFIT results show that oil modification significantly affects FI for a given mixture design. The mixtures with REOB have the lowest values of initial and aged FI values, but it had the lowest aging rates. In contrast, use of bio-oil resulted in high FI values than use of REOB, but higher (worse) aging rates than REOB mixtures. The mixtures with bio-oil show similar FI results and aging rates to the mixtures without oil modification.

8. Conclusions and Recommendations

This research study was focused on the development of asphalt mixture oven aging protocols to simulate field short-term and long-term aging. The study included collection of samples from a field section in which eight sub-sections were constructed using two mixture designs and a variation of asphalt contents and filler contents. The effects of binders' composition and interactions with other mix design components on physical and mechanical properties of asphalt mixtures before and after extended oven aging were measured. In addition, a study of effects of pre-heating and oven aging conditions were studied to define critical procedures that should be used to get better precision with regard to oven aging effects. Finally, effect of softening oils and polymers used to adjust binder grades on cracking resistance results of short- and long-term aging was evaluated. The following points provide a summary of the main findings of this study:

- Based on the oven comparison and pre-heating effects study, it is concluded that accuracy of the oven temperature during reheating and/or aging, even when slightly affecting percentage of air voids, does not affect performance of mixture tested in this study using HWT test and SCB–FI test significantly. The results however call for the standardization of mixture handling and aging procedures to minimize possible influence of variation in mixture temperature. Size of containers used for sampling, condition of container (open versus closed), and checking distribution of temperatures within the oven are important items that should be included in standard sampling, handling, and aging of field produced mixtures.
- Regarding comparison of lab versus field produced mixtures, mixtures produced in laboratory had comparable volumetric properties to plant-produced mixtures. Some notable variation in Gmm values for a few sections were recorded but they do not represent systematic bias. It is also noted that methods used for measuring Gmm could be variable and highly operator dependent. A careful look at details for measuring Gmm, and developing a more consistent protocol, is highly recommended.
- Properties at high temperatures (MSCR) and intermediate temperatures (LAS) of binders extracted and recovered from plant-produced mixtures are significantly different than properties of binders recovered from lab-produced mixtures. The same properties are also different than original binders collected from site. These differences could be due to solvent used in extraction as well as interaction with aggregates. This is particularly important for new MSCR parameters. It is highly recommended that this issue of solvent used in extraction and recovery be addressed to avoid disputes between suppliers and agency.
- In general, correlations between HWT and SCB-IFIT tests results of lab- and plant-produced mixtures are acceptable. This shows that difference in extracted binders' properties between lab and plant are not reflected in resistance of these mixture against permanent deformation or cracking. ***It is therefore not recommended to change number of aging hours or oven temperature in the laboratory short-term aging to simulate plant short-term aging***. However, differences in properties of recovered binders between lab and plant mixtures need to be studied further to define reasons for these differences.
- From mix design factors study, HWT results show significant effect of binder grade in terms of %R or Jnr on mixture rutting resistance; higher %R and lower Jnr values of H grade improve resistance of short-term aged mixtures to permanent deformation. However, no significant effect of P200 content or AC% on rutting resistance of mixtures could be found

- Flexibility Index (FI) parameter is highly sensitive to mixture aging and magnitude of FI is controlled by post-peak slope during test. However, change in P200 content, AC% or Dust to Binder Ratio values in plant-produced mixes does not appear to affect resulting FI for either binder grade.
- DCT Fracture Energy (FE) results were not found to be significantly affected by aging, although on average a decrease in FE was observed for six of the eight plant-produced mixtures between the 6- and 14-hours aging conditions.
- Attempts to correlate low-temperature binder properties using BBR to DCT-FE results demonstrated that a general logical correlation exists for extracted binder m-value and FE, although the changes observed in this study for FE were relatively small.
- The eight blends prepared with different oils and additives to target PG58-34 resulted in binders with different properties and characteristics (%R and Jnr) which could affect performance of mixtures prepared with these blends.
- SCB-IFIT results showed that mixtures with REOB oil have the lowest FI values at all aging levels, but also the lowest aging rates when compared to the mixture with no oils or with bio-oils. The use of bio-oil significantly improved FI values at different aging levels, but also increased aging rate of FI. The mixtures with no oils showed similar FI results and aging rates to mixtures with bio-oils.
- The collective results from the field samples and oil modification of this study confirm that ***long-term oven aging of 14 hours (LTOA-14) is too severe for asphalt mixtures and not suitable to distinguish between mixtures***. The use of 6 hours is therefore recommended as the standard long-term aging procedure for asphalt mixtures.
- Using binder testing on extracted and recovered or supplied binders to estimate effects of oil modification on mixture performance could be misleading. Although there are acceptable correlations between binder parameters and mixture FI results at extended aging, mixtures show narrow range of FI values after aging which makes all binders almost equal in performance.

9. References

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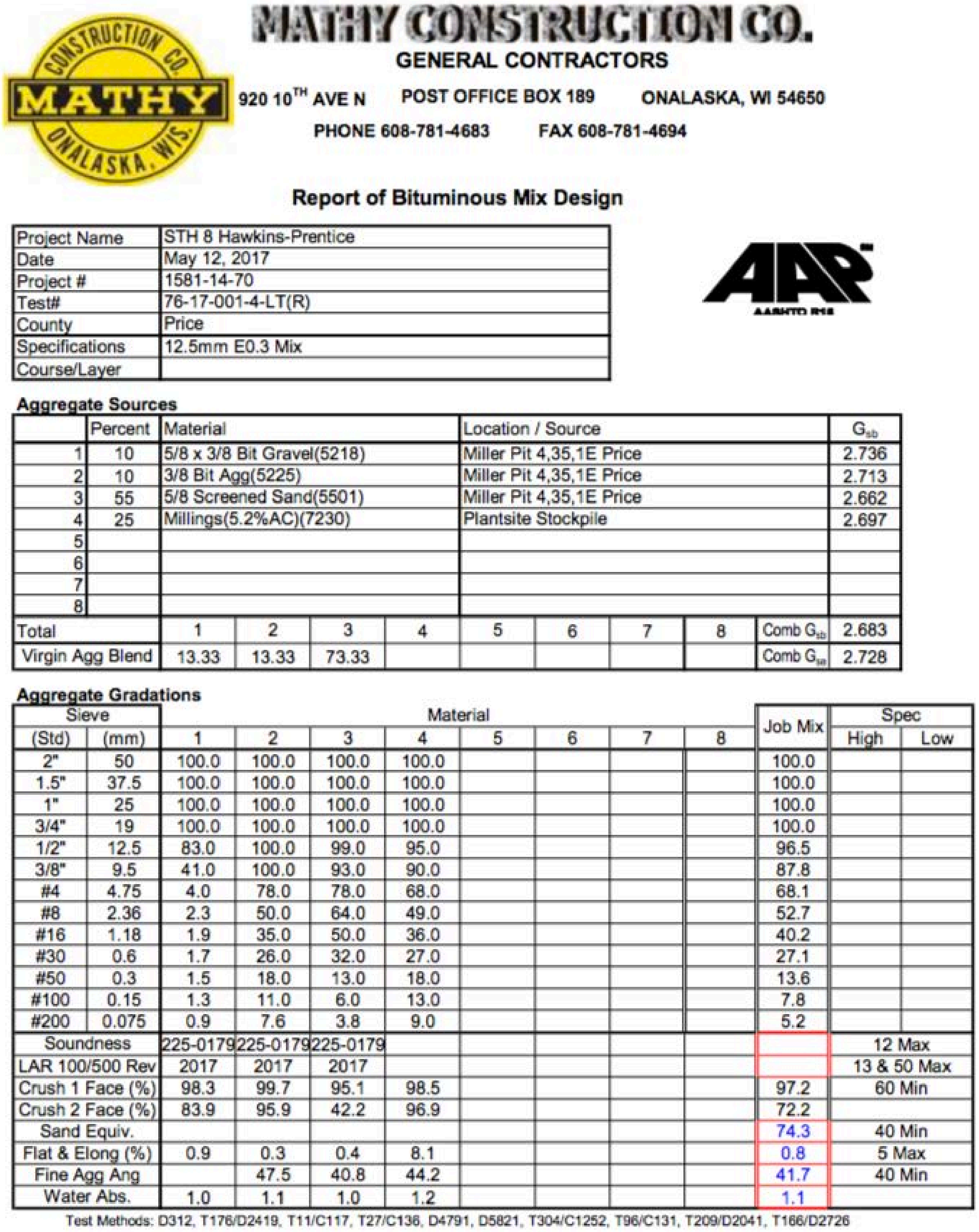
10. Appendix A: Mix Design for Control LT1 and MT5 Mixes

10.1 Control LT1 Mix Design



MATHY CONSTRUCTION CO.

GENERAL CONTRACTORS

920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650
PHONE 608-781-4683 FAX 608-781-4694

Report of Bituminous Mix Design

Project Name	STH 8 Hawkins-Prentice
Date	May 12, 2017
Project #	1581-14-70
Test#	76-17-001-4-LT(R)
County	Price
Specifications	12.5mm E0.3 Mix
Course/Layer	

Aggregate Sources

	Percent	Material	Location / Source	G_{sb}
1	10	5/8 x 3/8 Bit Gravel(5218)	Miller Pit 4,35,1E Price	2.736
2	10	3/8 Bit Agg(5225)	Miller Pit 4,35,1E Price	2.713
3	55	5/8 Screened Sand(5501)	Miller Pit 4,35,1E Price	2.662
4	25	Millings(5.2%AC)(7230)	Plantsite Stockpile	2.697
5				
6				
7				
8				

Total	1	2	3	4	5	6	7	8	Comb G_{sb}	2.683
Virgin Agg Blend	13.33	13.33	73.33						Comb G_{sa}	2.728

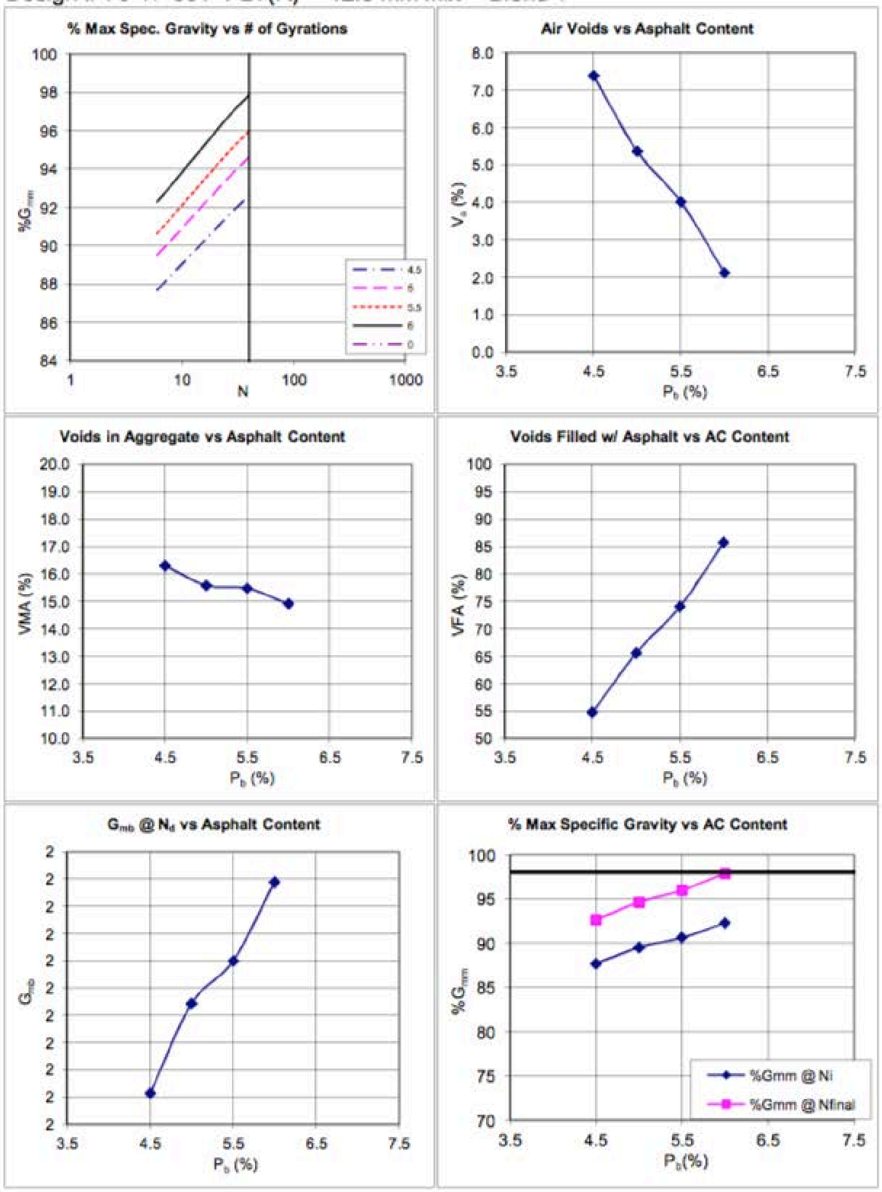
Aggregate Gradations

Sieve		Material								Job Mix	Spec	
(Std)	(mm)	1	2	3	4	5	6	7	8		High	Low
2"	50	100.0	100.0	100.0	100.0					100.0		
1.5"	37.5	100.0	100.0	100.0	100.0					100.0		
1"	25	100.0	100.0	100.0	100.0					100.0		
3/4"	19	100.0	100.0	100.0	100.0					100.0		
1/2"	12.5	83.0	100.0	99.0	95.0					96.5		
3/8"	9.5	41.0	100.0	93.0	90.0					87.8		
#4	4.75	4.0	78.0	78.0	68.0					68.1		
#8	2.36	2.3	50.0	64.0	49.0					52.7		
#16	1.18	1.9	35.0	50.0	36.0					40.2		
#30	0.6	1.7	26.0	32.0	27.0					27.1		
#50	0.3	1.5	18.0	13.0	18.0					13.6		
#100	0.15	1.3	11.0	6.0	13.0					7.8		
#200	0.075	0.9	7.6	3.8	9.0					5.2		
Soundness		225-0179	225-0179	225-0179							12 Max	
LAR 100/500 Rev		2017	2017	2017							13 & 50 Max	
Crush 1 Face (%)		98.3	99.7	95.1	98.5					97.2	60 Min	
Crush 2 Face (%)		83.9	95.9	42.2	96.9					72.2		
Sand Equiv.										74.3	40 Min	
Flat & Elong (%)		0.9	0.3	0.4	8.1					0.8	5 Max	
Fine Agg Ang			47.5	40.8	44.2					41.7	40 Min	
Water Abs.		1.0	1.1	1.0	1.2					1.1		

Test Methods: D312, T176/D2419, T11/C117, T27/C136, D4791, D5821, T304/C1252, T96/C131, T209/D2041, T166/D2726

STH 8 Hawkins-Prentice

Design # 76-17-001-4-LT(R) -- 12.5 mm Mix -- Blend 1



% Max Spec. Gravity vs # of Gyrations

Air Voids vs Asphalt Content

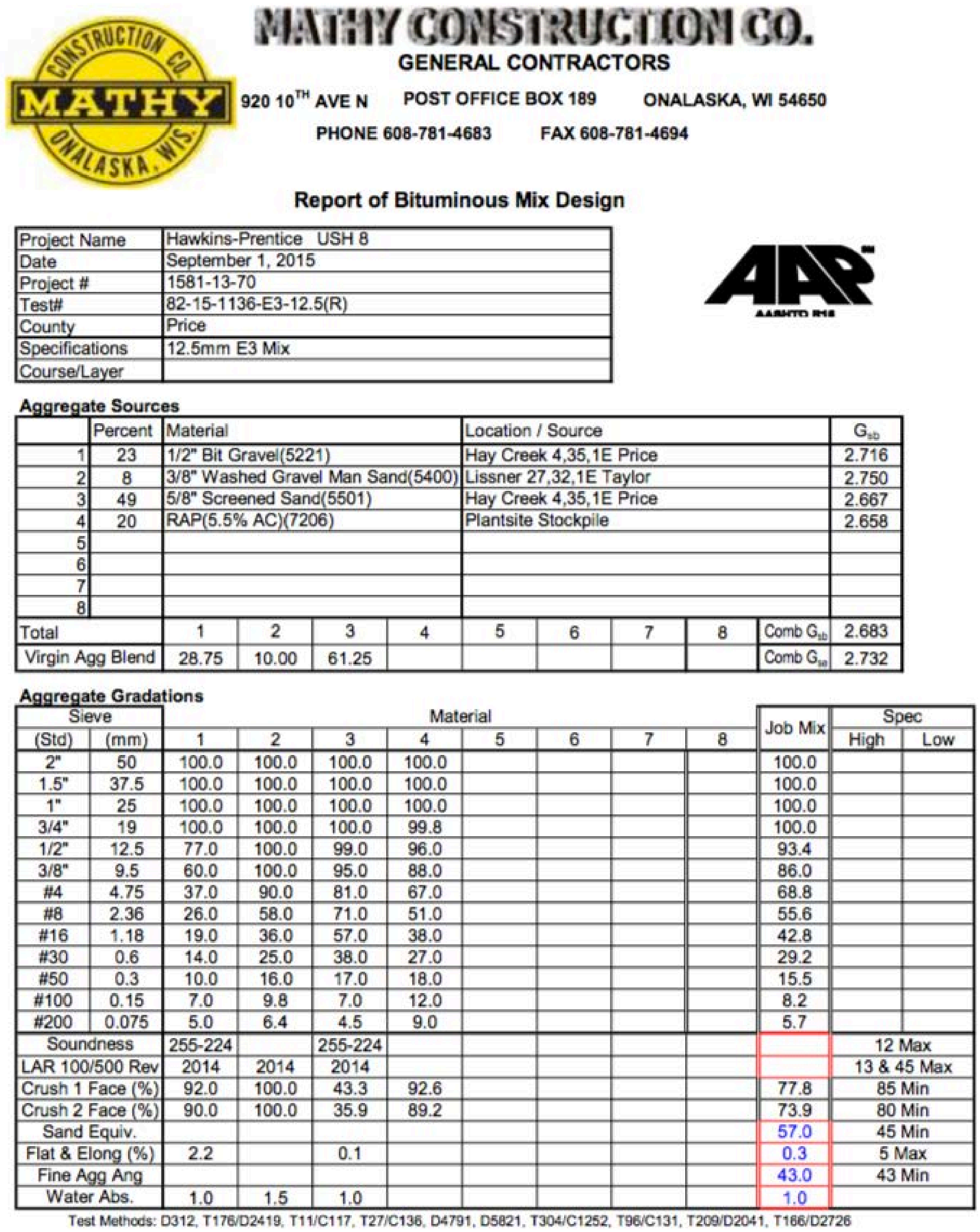
Voids in Aggregate vs Asphalt Content

Voids Filled w/ Asphalt vs AC Content

G_{mb} @ N_d vs Asphalt Content

% Max Specific Gravity vs AC Content

10.2 Control MT5 Mix Design



MATHY CONSTRUCTION CO.

GENERAL CONTRACTORS

920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650
PHONE 608-781-4683 FAX 608-781-4694

Report of Bituminous Mix Design

Project Name	Hawkins-Prentice USH 8
Date	September 1, 2015
Project #	1581-13-70
Test#	82-15-1136-E3-12.5(R)
County	Price
Specifications	12.5mm E3 Mix
Course/Layer	

Aggregate Sources

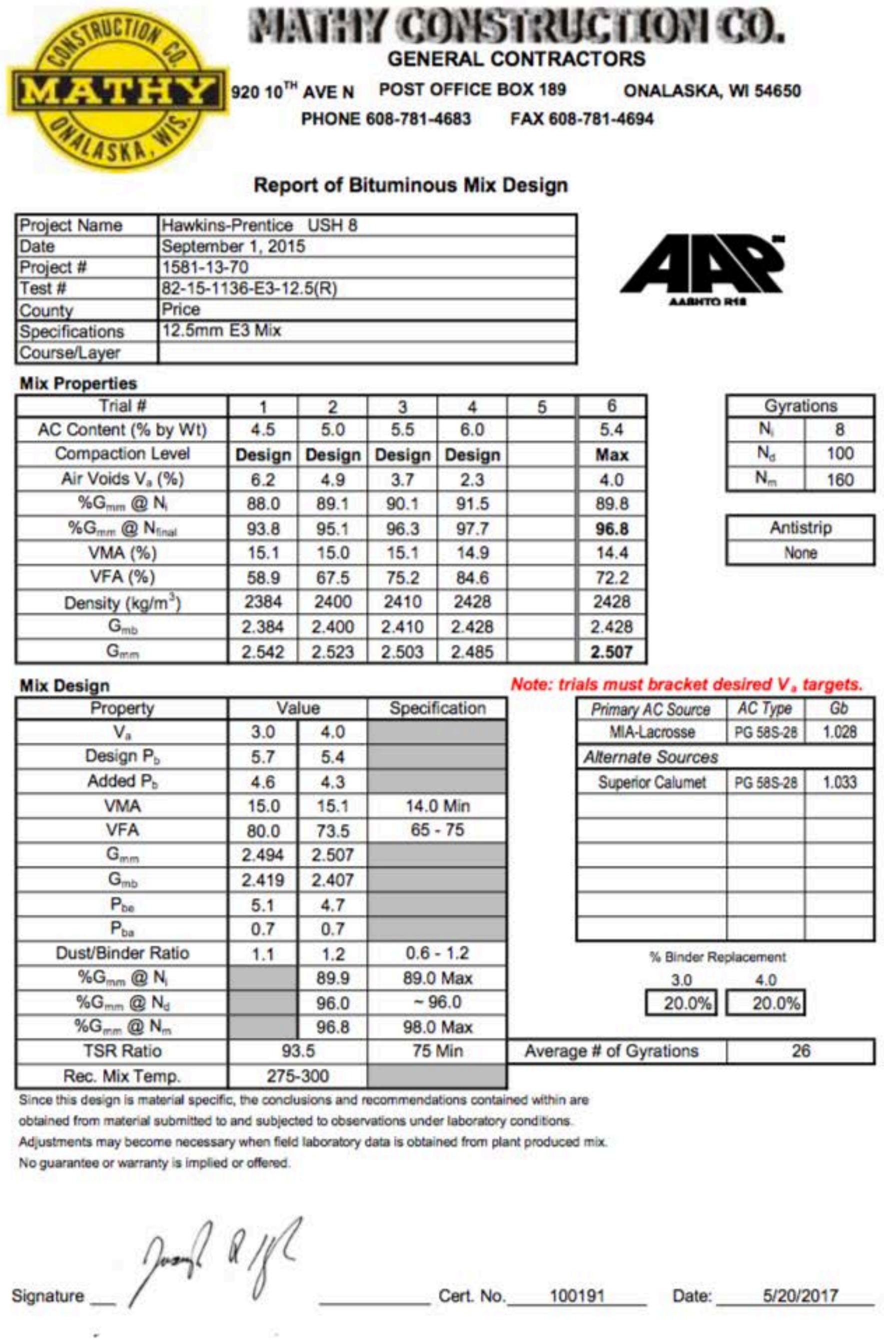
	Percent	Material	Location / Source	G_{sb}
1	23	1/2" Bit Gravel(5221)	Hay Creek 4,35,1E Price	2.716
2	8	3/8" Washed Gravel Man Sand(5400)	Lissner 27,32,1E Taylor	2.750
3	49	5/8" Screened Sand(5501)	Hay Creek 4,35,1E Price	2.667
4	20	RAP(5.5% AC)(7206)	Plantsite Stockpile	2.658
5				
6				
7				
8				

Total	1	2	3	4	5	6	7	8	Comb G_{sb}	2.683
Virgin Agg Blend	28.75	10.00	61.25						Comb G_{se}	2.732

Aggregate Gradations

Sieve		Material								Job Mix	Spec	
(Std)	(mm)	1	2	3	4	5	6	7	8		High	Low
2"	50	100.0	100.0	100.0	100.0					100.0		
1.5"	37.5	100.0	100.0	100.0	100.0					100.0		
1"	25	100.0	100.0	100.0	100.0					100.0		
3/4"	19	100.0	100.0	100.0	99.8					100.0		
1/2"	12.5	77.0	100.0	99.0	96.0					93.4		
3/8"	9.5	60.0	100.0	95.0	88.0					86.0		
#4	4.75	37.0	90.0	81.0	67.0					68.8		
#8	2.36	26.0	58.0	71.0	51.0					55.6		
#16	1.18	19.0	36.0	57.0	38.0					42.8		
#30	0.6	14.0	25.0	38.0	27.0					29.2		
#50	0.3	10.0	16.0	17.0	18.0					15.5		
#100	0.15	7.0	9.8	7.0	12.0					8.2		
#200	0.075	5.0	6.4	4.5	9.0					5.7		
Soundness		255-224		255-224							12 Max	
LAR 100/500 Rev		2014	2014	2014							13 & 45 Max	
Crush 1 Face (%)		92.0	100.0	43.3	92.6					77.8	85 Min	
Crush 2 Face (%)		90.0	100.0	35.9	89.2					73.9	80 Min	
Sand Equiv.										57.0	45 Min	
Flat & Elong (%)		2.2		0.1						0.3	5 Max	
Fine Agg Ang										43.0	43 Min	
Water Abs.		1.0	1.5	1.0						1.0		

Test Methods: D312, T176/D2419, T11/C117, T27/C136, D4791, D5821, T304/C1252, T96/C131, T209/D2041, T166/D2726



MATHY CONSTRUCTION CO.

GENERAL CONTRACTORS

920 10TH AVE N POST OFFICE BOX 189 ONALASKA, WI 54650
PHONE 608-781-4683 FAX 608-781-4694

Report of Bituminous Mix Design

Project Name	Hawkins-Prentice USH 8
Date	September 1, 2015
Project #	1581-13-70
Test #	82-15-1136-E3-12.5(R)
County	Price
Specifications	12.5mm E3 Mix
Course/Layer	

AASHTO R18

Mix Properties

Trial #	1	2	3	4	5	6
AC Content (% by Wt)	4.5	5.0	5.5	6.0		5.4
Compaction Level	**Design**	**Design**	**Design**	**Design**		**Max**
Air Voids V_a (%)	6.2	4.9	3.7	2.3		4.0
$\%G_{mm}$ @ N_i	88.0	89.1	90.1	91.5		89.8
$\%G_{mm}$ @ N_{final}	93.8	95.1	96.3	97.7		**96.8**
VMA (%)	15.1	15.0	15.1	14.9		14.4
VFA (%)	58.9	67.5	75.2	84.6		72.2
Density (kg/m^3)	2384	2400	2410	2428		2428
G_{mb}	2.384	2.400	2.410	2.428		2.428
G_{mm}	2.542	2.523	2.503	2.485		**2.507**

Gyrations	
N_i	8
N_d	100
N_m	160

Antistrip
None

Mix Design

Note: trials must bracket desired V_a targets.

Property	Value		Specification
V_a	3.0	4.0	
Design P_b	5.7	5.4	
Added P_b	4.6	4.3	
VMA	15.0	15.1	14.0 Min
VFA	80.0	73.5	65 - 75
G_{mm}	2.494	2.507	
G_{mb}	2.419	2.407	
P_{be}	5.1	4.7	
P_{ba}	0.7	0.7	
Dust/Binder Ratio	1.1	1.2	0.6 - 1.2
$\%G_{mm}$ @ N_i		89.9	89.0 Max
$\%G_{mm}$ @ N_d		96.0	~ 96.0
$\%G_{mm}$ @ N_m		96.8	98.0 Max
TSR Ratio	93.5		75 Min
Rec. Mix Temp.	275-300		

Primary AC Source	*AC Type*	*Gb*
MIA-Lacrosse	PG 58S-28	1.028
Alternate Sources		
Superior Calumet	PG 58S-28	1.033

% Binder Replacement

3.0	4.0
20.0%	20.0%

Average # of Gyrations	26

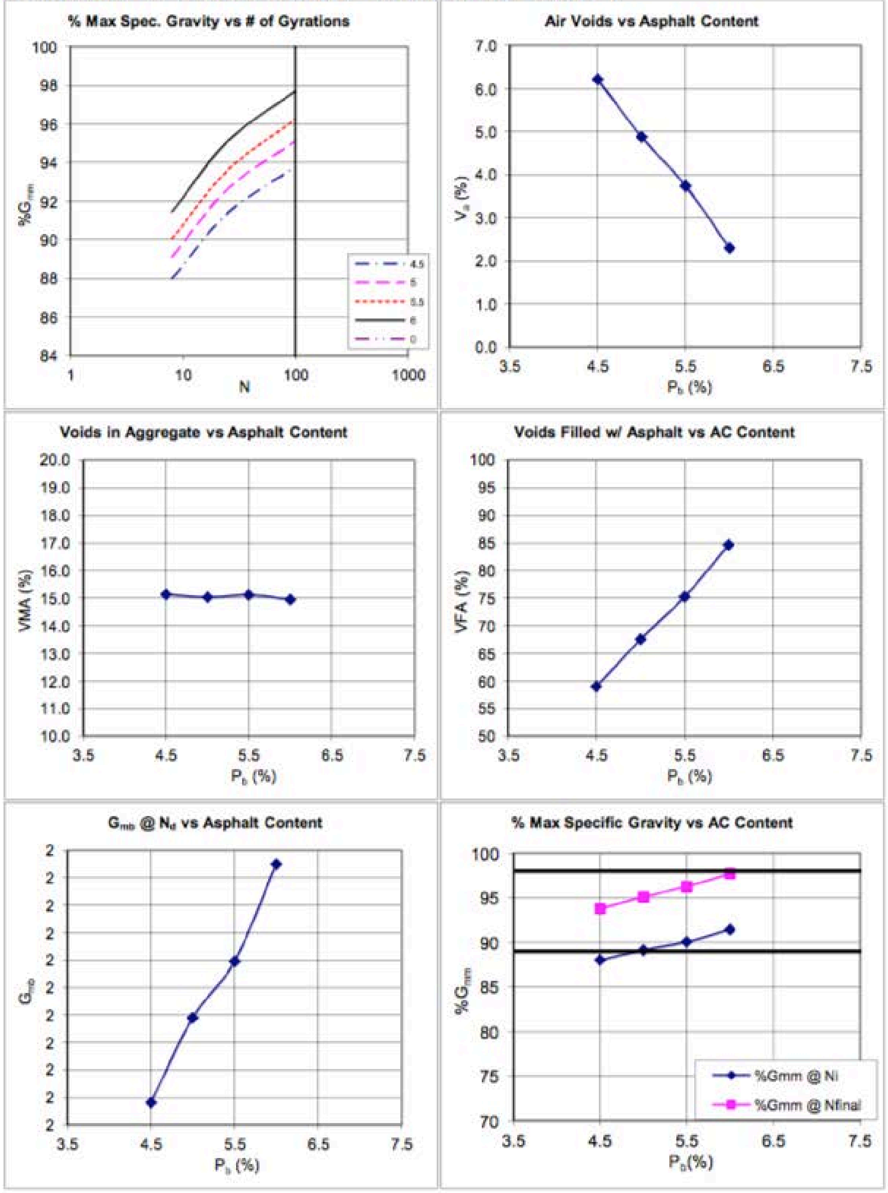
Since this design is material specific, the conclusions and recommendations contained within are obtained from material submitted to and subjected to observations under laboratory conditions. Adjustments may become necessary when field laboratory data is obtained from plant produced mix. No guarantee or warranty is implied or offered.

Signature __________ Cert. No. 100191 Date: 5/20/2017

Mathy Construction Co. -- MTE

Hawkins-Prentice USH 8

Design # 82-15-1136-E3-12.5(R) -- 12.5 mm Mix -- Blend 1



11. Appendix B: Station Locations of the Eight Field Test Sections

1580-29-70; USH 8 Hawkins - Prentice (Miller Road to Lustila Road), Price County Wisconsin

Construction of Field Aging and Moisture Sensitivity Test Section for HMA Pavement 4 LT 58-28 S

Behnke Materials Section #	WisDOT Section #	Mix Type	Station Range	Lane	Tons Placed	Paving Direction	Paved Date	Cored Date	Core Location
1	0	4 LT 58-28 S 3.0 Air Design Dust (Control)	585+00 - 608+27 LT	Westbound (LT)	499.7	West to East	7/5/17	7/5/17	589+00 5' LT
2	1	4 LT 58-28 H 4.0 Air Design Dust	632+45 - 660+93 LT	Westbound (LT)	519.81	West to East	7/5/17	7/7/17	651+00 6' LT
4	2	4 LT 58-28 S 4.0 Air +1% P200	660+93 - 686+13 LT	Westbound (LT)	497.48	West to East	7/7/17	7/7/17	672+00 6' LT
3	3	4 LT 58-28 H 3.0 Air +1% P200	608+27 - 632+45 LT	Westbound (LT)	497.03	West to East	7/5/17	7/5/17	622+00 6' LT
6	4	4 MT 58-28 S 4.0 Air Design Dust	711+05 - 736+00 LT	Westbound (LT)	522.22	West to East	7/7/17	7/7/17	723+00 6' LT
5	5	4 MT 58-28 H 3.0 Air Design Dust	681+50 - 700+65 RT	Eastbound (RT)	382.82	West to East	7/7/17	7/8/17	691+00 6' RT
8	6	4 MT 58-28 H 4.0 Air +1% P200	700+65 - 708+30 RT	Eastbound (RT)	159.13	West to East	7/7/17	7/8/17	703+00 6' RT
Not tested by Behnke	6	4 MT 58-28 H 4.0 Air +1% P200	708+30 - 738+00 RT	Eastbound (RT)	590.42	West to East	7/10/17	Not cored	See above
7	7	4 MT 58-28 S 3.0 Air +1% P200	686+13 - 711+05 LT	Westbound (LT)	498.25	West to East	7/7/17	7/7/17	702+00 6' LT

Notes:

+1% P200 is done with addition of Fly Ash.

Core numbers are based off WisDOT Section Numbers (as this numbering was started prior to knowing that Benke has a total different numbering system)

12. Appendix C: Proposed Standardized Sampling, Reheating and Aging Procedure for Performance Testing of Plant- and Lab-Produced Asphalt Mixtures

12.1 Apparatus

a. Oven: A thermostatically controlled forced-draft oven capable of maintaining the desired temperature setting within ± 5°F.
b. Thermometers: Thermometers having a range from 122°F to 500°F and readable to 1°F
c. Pans: approximately 16” × 11” × 2.5” aluminum foil pans

12.2 Sampling Procedure

Sampling of Plant-Produced HMA will be completed following WisDOT Standard Specification 460 in conjunction with WisDOT CMM 8-36. Total sample size may vary based on the required amount of material needed for additional required testing.

12.3 Splitting Procedure

HMA mixtures from plant production or laboratory should be quartered and split into approximately 5500 - 6000 g portions into the aluminum foil pans ensuring the maximum thickness does not exceed 2.5”.

12.4 Reheating Procedure

The following standardized reheating and aging procedure should be followed by any laboratory working for WisDOT projects. Reheating and aging will occur for all samples regardless of aging requirements.

a. Place the uncovered pan on the middle-center rack of a 275°F oven for 2 hrs ± 5 min. Do not stir or open the oven.
b. Once reheating time is achieved either continue with aging (Section 10.5 below), or compact specimens to the appropriate height and air void target based on pre-determined sample size calculation.

12.5 Aging Procedure

12.5.1 Short-Term Oven Aging (STOA)

a. STOA should only be completed as part of the mix design process, to simulate plant aging. All Plant-Produced HMA is considered STOA.
b. Follow appropriate reheating instructions above.
c. Keep the reheated pan for 2 hrs ± 5 min in an oven set at 275°F. Take the sample out of the oven and stir after 60 ± 5 min from start of the aging time. Stirring should be done within 1 to 2 minutes. Keep the oven closed before and after stirring throughout the aging time to avoid cooling of the oven.
d. Once aging time is achieved compact specimens to the appropriate height and air void target based on pre-determined sample size calculation.

12.5.2 Long-Term Oven Aging (LTOA)

a. Follow appropriate reheating instructions above.

b. Keep the reheated pan for 6 hrs ± 5 min (or 14 hrs if needed) in an oven set at 275°F. Take the sample out of the oven and stir after 60 ± 5 min from start of the aging time. Stirring should be done within 1 to 2 minutes. Keep the oven closed before and after stirring throughout the aging time to avoid cooling of the oven.
c. Once aging time is achieved compact specimens to the appropriate height and air void target based on pre-determined sample size calculation (weight required to achieve height/air void target)

13. Appendix D: Proposed Standardized Compacting, Cutting and Testing Procedure for Disc Shaped Compact Tester (DCT) and Illinois Flexibility Index Test (IFIT)

13.1 Compacting Procedure

13.1.1 Target Air Voids

a. See table below for specimen height and air void targets.

	DCT Target Air Voids	IFIT Air Voids
Specimen Height	135.0 mm	150.0 mm
JMF Air Void = 3.0 %	6.0% ± 0.5%	7.0% +/- 0.5%.
JMF Air Void = 3.5 %	6.5% ± 0.5%	
JMF Air Void = 4.0 %	7.0% ± 0.5%	

b. All air voids are calculated on cut specimen

NOTE: When targeting air voids for the full puck aim at least 0.5% high as air voids will be lower after cutting.

13.1.2 Cutting Procedure

a. DCT
  - Cut the 135.0 mm puck in half to create two 67.5 mm specimen
  - Then cut each 67.5 mm specimen to (test size) 50.0 mm +/-5.0 mm, cutting from the "face" to create two cut sides on each test specimen
  - Test the specimen for air void compliance
  - If the air voids are acceptable, use a template to cut the nose, ligament, and drill the holes conforming to ASTM D 7313 Section 6.

b. IFIT
  - Cut the 150.0 mm specimen in half to create two 75 mm specimen
  - Then cut each 75 mm specimen to (test size) 50.0 mm +/-5.0 mm, cutting from the "face" to create two cut sides on each test specimen
  - Test the specimen for air void compliance
  - If the air voids are acceptable, cut both specimens in half to create 4 "half-moon specimen"
  - Then, mark the center of the cut edge on each half-moon specimen and cut the notch to 15.0 mm +/- 1.0 mm

13.1.3 Conditioning Procedure

a. DCT
   - Dry the specimen, either by setting in front of a fan overnight, or using the CoreDry equipment
   - Condition the specimen at test temperature, not to exceed 0.2°C
   - Condition for a minimum of 2 hours before testing

b. IFIT
   - Dry the specimen, either by setting in front of a fan overnight, or using the CoreDry equipment
   - Condition the specimen in a waterbath or environmental chamber at 25°C +/- 0.5°C
   - Condition for 2 hours +/- 0.5 hours

13.1.4 Reporting

c. DCT
   - Test 4 specimen
   - Remove the highest and lowest results
   - Average the 2-remaining specimen
   - If the standard deviation is greater than 78.5, an additional puck is tested

d. IFIT
   - Test 4 specimen
   - Remove the furthest result from the average
   - Re-calculate the average of 3 remaining specimens