Civil and Environmental Engineering Department

Columbus Mississippi Field Aging and Laboratory Conditioning Study: Air Force Base and Single Aggregate Source Reference Asphalt Mixtures

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16. Abstract
This report's primary objective was to provide complimentary and supporting reference information for field aging of asphalt concrete in Mississippi. The primary data sets collected for this overall body of work are from full-scale constructed test sections where cores were collected over time (Volume 2), and from plant mixed asphalt containing warm mix technology that was field aged for four years or laboratory conditioned (Volume 3). Approximately 5,100 mixture specimens were tested as part of this three volume set of reports. When rounded to the nearest hundred mixture specimens, 300 were tested for Volume 1 (this report), 3,400 were tested for Volume 2, and 1,400 were tested for Volume 3. Binder testing was also performed in support of mixture testing. This report documents testing of mixtures produced with a single aggregate source to measure the interaction of binder and mixtures during aging. These mixtures showed the importance of aging within mixtures to capture environmental effects. This report also documents testing of air force base mixtures after being laboratory conditioned or after field aging in Columbus, MS. A summary table of how much field aging each laboratory conditioning protocol simulated is provided. Single aggregate source and air force base mixtures also provided information related to the suitability of indirect tensile strength and Cantabro mass loss testing for capturing intermediate temperature effects from environmental aging. All this information is intended for use within the more comprehensive volumes 2 and 3 of this report series. The information contained in this report is written so that it can be used in a standalone manner by others, or to compliment the remainder of this research effort.

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LIST OF SYMBOLS AND ACRONYMS

δ	Phase angle
AASHTO	American Association of State Highway Transportation Officials
Abs	Aggregate water absorption
AFB	Air Force Base
AL	Alabama
APA	Asphalt Pavement Analyzer
BBR	Bending beam rheometer
CAA	Coarse aggregate angularity
CAFB	Columbus Air Force Base
$CD_{fluctuation}$	Cumulative days of temperature fluctuation
CDD_{high}	High temperature cumulative degree days
CFI	Cumulative Freezing Index
CML	Cantabro Mass Loss
CO	Colorado
CP	Conditioning protocol
D:B	Dust to binder ratio
DGA	Dense Graded Asphalt
DSR	Dynamic shear rheometer
DSR_8	Dynamic shear rheometer testing with an 8 mm plate
DSR_{25}	Dynamic shear rheometer testing with a 25 mm plate
ERDC	Engineer Research and Development Center
FAA	Fine aggregate angularity
FE	Fracture energy
FE_{+20C}	Fracture energy at 20°C
FE_{-10C}	Fracture energy at -10°C
FT	Freeze Thaw
G^*	Complex shear modulus
G_{mb}	Bulk mixture specific gravity
G_{mm}	Maximum mixture specific gravity
G_{sa}	Apparent specific gravity of the aggregate
G_{sb}	Bulk specific gravity of the aggregate
G_{se}	Effective specific gravity of the aggregate
GR	Gravel
GTR	Ground tire rubber
HL	Hydrated lime
HLWT	Hamburg loaded wheel tracking
HMA	Hot mixed asphalt
IDT	Non-instrumented indirect tensile
LA	Los Angeles
LMLC	Laboratory-mixed and laboratory compacted
LS	Limestone
M01-M20	Mix 1-20
MAFB	March Air Force Base
MDOT	Mississippi Department of Transportation

ΔML	Change in mass loss
ML	Mass Loss
MS	Mississippi
MSU	Mississippi State University
NMAS	Nominal maximum aggregate size
$P_{12.5\text{-}HLWT}$	Number of passes at 12.5mm HLWT rut depth
P_{200}	Percent passing the number 200 sieve
P_b	Binder percent by mass
$P_{b,design}$	Design asphalt content
$P_{ba(mix)}$	Absorbed binder percent by mixture mass
P_{be}	Effective binder percent by mass
Pen	Penetration
PG	Performance grade
PMFC	Plant-mixed and field compacted
PMLC	Plant-mixed and laboratory compacted
PTSi	Paragon Technical Services, Inc.
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
ΔRD_{APA}	Change in APA rut depth
RD_{APA}	Rut depth from asphalt pavement analyzer
ΔRD_{HLWT}	Change in HLWT rut depth
RD_{HLWT}	Maximum rut depth from Hamburg loaded wheel tracking
S	Stiffness
ΔS_t	Change in tensile strength
S_t	Indirect Tensile Strength
SAS	Single aggregate source
SGC	Superpave Gyratory Compactor
SIDT	Instrumented indirect tensile
SIP	Stripping inflection point
SS	State Study
T_c	Critical temperature
$T_c(BBR_m)$	Critical low temperature based on *m*-value
$T_c(BBR_s)$	Critical low temperature based on stiffness
$T_c(DSR_8)$	Critical intermediate temperature
$T_c(DSR_{25})$	Critical high temperature
T_{design}	Design mixing temperature
T_{dlow}	Minimum daily temperature
T_{dmax}	Maximum daily temperature
$T_{production}$	Production mixing temperature
USACE	United States Army Corps of Engineers
V_a	Air voids
$V_{a,design}$	Design air voids
V_{be}	Volume of effective binder
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate
WMA	Warm mixed asphalt

CHAPTER 1-INTRODUCTION

1.1 General and Background Information

Characterization of the aging process of asphalt pavements is one of the most challenging and longstanding issues for industry and agencies alike. Aging studies date back several decades. Over this time period, there have been several changes to the types of asphalt mixtures produced. Examples that are of heightened interest in present day are warm mixed asphalt (WMA), and progressively increasing use of recycled or repurposed materials such as reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), or ground tire rubber (GTR). WMA has been a major advancement for asphalt paving, and use of recycled or repurposed materials has gained momentum due, at least in part, to challenging economic circumstances surrounding transportation infrastructure. With asphalt mixtures becoming progressively more complicated (e.g. WMA with RAP and/or RAS) relative to mixes of many years ago (e.g. all virgin materials and hot mixed), there are several needs with respect to the characterization of aging, and also of comparing hot mixed asphalt (HMA) to WMA.

In a paving environment where there are numerous materials and proportioning options, mixture conditioning and testing protocols that can represent mixture properties over time are more important than ever. Characterizing how aging occurs in a mixture is an essential step in predicting behavior over time. This report attempts to assist in improving understanding of aging, and to provide data for comparison or benchmarking of specific parameters of interest in companion reports in this research effort. One specific issue addressed in this report is how similar aggregate blends from noticeably different aggregate types interact with asphalt binder. These experiments isolate aggregate-binder interaction to assess how their interaction affects mixture behavior, especially after some level of aging. Single aggregate source (SAS) mixes were produced to determine if aging investigations are missing an important component when they don't incorporate mixture testing due to the role that aggregates and void structure have in the aging process. Some of the SAS aggregates were obtained from previous work on airfields (James, 2014). A second specific issue is how air force base (AFB) mixtures produced with and without RAP age over time as this is a useful benchmark for data presented in Volume 2 and Volume 3 of this research effort.

The data presented in this report is not for consideration for direct use by the Mississippi Department of Transportation (MDOT). Rather, the data and analysis of this report is intended to serve as reference information for work that could directly affect MDOT that is presented in Volume 2 and Volume 3 of this research effort, which is described in the remainder of this chapter.

1.2 Objectives and Scope

This report is part of a three volume series that investigated: 1) the effects field aging has on asphalt concrete produced at hot mix temperatures and hauled long distances; and 2) the effects field aging has on asphalt concrete produced at different mixing temperatures and hauled a moderate distance. This research effort utilized laboratory and field testing of asphalt mixtures and binders, literature review, and data analysis. The research program was funded by MDOT through Project 106526 101000, State Study 266 (SS266), and State Study 270

(SS270). The three report volumes do not coincide with MDOT funding mechanisms, rather are divided according to technical content. Collectively, these three reports contain all deliverables for these three funded endeavors (1 through Materials Division, 2 through Research Division).

Volume 1 (FHWA/MS-DOT-RD-18-266/270-Volume 1) includes data and analysis of reference mixtures that are intended largely for benchmarking and interpretation of Volume 2 and Volume 3 data. Volume 2 (FHWA/MS-DOT-RD-18-266/270-Volume 2) focused most of its effort on the effects field aging has on asphalt concrete produced at hot mix temperatures and hauled long distances. Volume 3 (FHWA/MS-DOT-RD-18-266/270-Volume 3) focused most of its efforts on the effects field aging has on asphalt concrete produced at different mixing temperatures and hauled a moderate distance.

The main objective of this report (Volume 1) is to provide data for benchmarking and general reference purposes that helps to interpret the findings from two much larger and more systematic data sets. Mixture and binder data is presented that includes field aging and laboratory conditioning. Chapter 2 presents an experimental program that divides the materials into SAS and AFB mixtures. SAS and AFB findings are separated by chapter, and SAS findings are supplemented by a literature review found in Hansen (2017) that is used for results interpretation.

1.3 Summary of Asphalt Mixtures Considered

There were a total of 20 asphalt mixtures (M01 to M20) tested as part of this research program (Project 106526 101000, SS266, and SS270). This section is repeated in all three volumes for clarity, and an asphalt mixture is defined as a unique combination of ingredients at consistent proportions. A single mixture could be produced in different ways and at different points in time using the same aggregate and asphalt binder sources at consistent proportions. For example, one mixture could be plant-mixed and field compacted (PMFC), plant-mixed and laboratory compacted (PMLC), or laboratory-mixed and laboratory compacted (LMLC). M01 to M13 were the focus of Volume 1 as an investigation of single aggregate source (SAS) and Air Force Base (AFB) mixtures which were often field aged on the full-scale test section described in Chapter 3 of Volume 2. M14 to M16 were the focus of Volume 2 which considers the full-scale and non-trafficked test section described in Chapter 3 of Volume 2. This report (Volume 3) relies on results from M17 to M20 which were also field aged on the full-scale test section. Tables 1.1 to 1.3 provide mixture design volumetric information, ingredient source information, and gradations, respectively. All terms used in Tables 1.1 to 1.3 are provided in the list of symbols.

Table 1.2 describes constituent materials in M01 to M20 by type, source, and sample (where documented). M01 to M10 were lab mixed from constituent materials and M11 to M20 were plant mixed. Aggregate sources which were sampled in more than one paving season are differentiated by year, and sample number differentiates binder samples. Notice that a single sample of asphalt binder was used for M01 to M10 and M17 to M20.

Table 1.1. Mixture Volumetric Properties Utilized During Research Program

Mix ID	T_{design} (°C)	$T_{production}$ (°C)	G_{mm}	G_{sb}	G_{se}	G_{sa}	P_b (%)	P_{be} (%)	$P_{ba\ (mix)}$ (%)	VMA (%)	Design V_a (%)	V_{be} (%)	P_{200} (%)	NMAS (mm)
M01	163	163	2.250	2.385	2.520	2.651	8.3	6.2	2.3	16.9	4	12.9	6.0	12.5
M02	163	163	2.250	2.385	2.520	2.651	8.3	6.2	2.3	16.9	4	12.9	6.0	12.5
M03	163	163	2.250	2.385	2.520	2.651	8.3	6.2	2.3	16.9	4	12.9	6.0	12.5
M04	129	129	2.248	2.385	2.505	2.651	8.0	6.1	2.1	16.8	4	12.8	6.0	12.5
M05	129	129	2.248	2.385	2.505	2.651	8.0	6.1	2.1	16.8	4	12.8	6.0	12.5
M06	129	129	2.248	2.385	2.505	2.651	8.0	6.1	2.1	16.8	4	12.8	6.0	12.5
M07	163	163	2.479	2.694	2.733	2.743	6.2	5.7	0.5	17.2	4	13.2	5.9	12.5
M08	129	129	2.481	2.694	2.735	2.743	6.2	5.7	0.5	17.0	4	13.0	5.9	12.5
M09	163	163	2.123	2.248	2.362	2.507	8.7	6.7	2.2	17.2	4	13.2	6.2	12.5
M10	129	129	2.125	2.248	2.351	2.507	8.3	6.5	2.0	16.8	4	12.8	6.2	12.5
M11	150	150	2.531	2.693	2.753	2.811	5.2	4.4	0.8	14.1	4	10.1	4.5	12.5
M12	166	160	2.370	2.484	2.560	2.653	6.0	4.8	1.2	14.3	4	10.3	4.0	12.5
M13	177	160	2.381	2.481	2.556	2.607	5.9	4.8	1.2	14.3	4	10.3	4.5	12.5
M14	160	164	2.378	2.515	2.567	2.663	5.4	4.6	0.8	14.1	4	10.1	5.9	12.5
M15	160	153	2.378	2.515	2.567	2.663	5.4	4.6	0.8	14.1	4	10.1	5.9	12.5
M16	160	148	2.378	2.515	2.567	2.663	5.4	4.6	0.8	14.1	4	10.1	5.9	12.5
M17	143	143	2.461	2.609	2.668	2.688	5.3	4.5	0.8	14.3	4	10.3	4.9	12.5
M18	129	132	2.461	2.609	2.668	2.688	5.3	4.5	0.8	14.3	4	10.3	4.9	12.5
M19	129	132	2.461	2.609	2.668	2.688	5.3	4.5	0.8	14.3	4	10.3	4.9	12.5
M20	129	132	2.461	2.609	2.668	2.688	5.3	4.5	0.8	14.3	4	10.3	4.9	12.5

Table 1.2. Mixture Components Information Utilized During Research Program

Mix ID	Aggregates: Gravel Source	Gravel (%)	Limestone Source	Limestone (%)	Sand Source	Sand (%)	RAP (%)	HL (%)	Asphalt Binder: PG Grade	Source	Warm Mix Technology	Sample
M01	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	---	1
M02	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	0.5% Evo.	1
M03	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	1.5% Sasobit	1
M04	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	---	1
M05	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	0.5% Evo.	1
M06	Hamilton, MS ('13)	100	---	---	---	---	---	---	67-22	Vicksburg, MS	1.5% Sasobit	1
M07	---	---	Tuscaloosa, AL ('13)	100	---	---	---	---	67-22	Vicksburg, MS	---	1
M08	---	---	Tuscaloosa, AL ('13)	100	---	---	---	---	67-22	Vicksburg, MS	---	1
M09	Creede, CO	100	---	---	---	---	---	---	67-22	Vicksburg, MS	---	1
M10	Creede, CO	100	---	---	---	---	---	---	67-22	Vicksburg, MS	---	1
M11	---	---	California	100	---	---	---	---	70-10	California	---	1
M12	Hamilton, MS ('13)	51	Tuscaloosa, AL ('13)	33	Hamilton, MS ('13)	15	---	1	76-22	Memphis, TN	---	1
M13	Hamilton, MS ('13)	41	Tuscaloosa, AL ('13)	25	Hamilton, MS ('13)	13	20	1	70-22	Memphis, TN	---	1
M14	Hamilton, MS ('11)	39	Tuscaloosa, AL ('11)	35	Hamilton, MS ('11)	10	15	1	67-22	Vicksburg, MS	---	2
M15	Hamilton, MS ('11)	39	Tuscaloosa, AL ('11)	35	Hamilton, MS ('11)	10	15	1	67-22	Vicksburg, MS	Foamed	2
M16	Hamilton, MS ('11)	39	Tuscaloosa, AL ('11)	35	Hamilton, MS ('11)	10	15	1	67-22	Vicksburg, MS	0.5% Evo.	2
M17	Undocumented	25	Calera, AL	60	Undocumented	15	---	---	67-22	Vicksburg, MS	---	1
M18	Undocumented	25	Calera, AL	60	Undocumented	15	---	---	67-22	Vicksburg, MS	Foamed	1
M19	Undocumented	25	Calera, AL	60	Undocumented	15	---	---	67-22	Vicksburg, MS	0.5% Evo.	1
M20	Undocumented	25	Calera, AL	60	Undocumented	15	---	---	67-22	Vicksburg, MS	1.5% Sasobit	1

Hydrated Lime (HL); Reclaimed Asphalt Pavement (RAP); Evotherm 3G^{TM} (Evo.)

Table 1.3. Mixture Gradations Utilized During Research Program

Mix ID	Percent Passing (%) 25 mm	19 mm	12.5 mm	9.5 mm	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
M01	100	100	96	88	70	53	37	27	14	7.6	6.0
M02	100	100	96	88	70	53	37	27	14	7.6	6.0
M03	100	100	96	88	70	53	37	27	14	7.6	6.0
M04	100	100	96	88	70	53	37	27	14	7.6	6.0
M05	100	100	96	88	70	53	37	27	14	7.6	6.0
M06	100	100	96	88	70	53	37	27	14	7.6	6.0
M07	100	100	96	87	67	48	25	17	12	8.4	5.9
M08	100	100	96	87	67	48	25	17	12	8.4	5.9
M09	100	100	96	87	67	48	29	17	12	8.6	6.2
M10	100	100	96	87	67	48	29	17	12	8.6	6.2
M11	100	100	95	83	64	49	33	22	13	7.0	4.5
M12	100	100	96	88	61	44	31	22	11	6.0	4.0
M13	100	100	93	85	57	38	27	21	11	6.0	4.5
M14	100	100	95	85	54	36	25	19	11	7.5	5.9
M15	100	100	95	85	54	36	25	19	11	7.5	5.9
M16	100	100	95	85	54	36	25	19	11	7.5	5.9
M17	100	100	96	85	68	54	38	28	15	6.8	4.9
M18	100	100	96	85	68	54	38	28	15	6.8	4.9
M19	100	100	96	85	68	54	38	28	15	6.8	4.9
M20	100	100	96	85	68	54	38	28	15	6.8	4.9

CHAPTER 2-EXPERIMENTAL PROGRAM

2.1 Overview of Experimental Program

Experiments were performed in two components and several aspects of this report utilized the same protocols as the companion Volume 2 and Volume 3 reports. As such, several descriptions, terminologies, photos, and so forth are used multiple times in the three report volumes to allow standalone use of any volume, while also maintaining continuity. The following sections present separately the Single Aggregate Source (SAS) and Air Force Base (AFB) material properties. Mixing, compaction, aging, and test method descriptions are discussed together for SAS and AFB experiments as some overlap existed. Mixture testing was performed for SAS and AFB mixtures, while binder testing was performed only for AFB mixtures.

2.2 Single Aggregate Source Materials

The following section discusses the materials used for the SAS portion of this report, alongside relevant mixture properties. Aggregate properties are given such as gradation, angularity, water absorption, and specific gravity. One binder source and two warm-mix additives were used (see Table 1.2).

2.2.1 Aggregate Properties

Three sources were sampled for mix designs: (1) Tuscaloosa, Alabama limestone, (2) Hamilton, Mississippi gravel, (3) Creede, Colorado gravel. Aggregates from a single source were dried, sieved, and recombined to the desired gradation. To account for fines on the aggregate surfaces, a washed gradation was performed in accordance with AASHTO T11, and for material in storage, moisture contents were determined for corrections in aggregate batching. Samples of the different aggregates can be seen in Figure 2.1.

Figure 2.1. Photos of Aggregates Used for Single Source Mixes

Fine and coarse aggregate angularity (FAA and CAA) were performed in accordance with AASHTO T304 Method A and AASHTO T335 Method A. Results can be seen in Table 2.1. Specific gravity and absorption values are included as well. The absorption percentage (Abs) is the amount of water the aggregate absorbs into the pores relative to its dry mass. The bulk specific gravity (G_{sb}) is based on the oven dry volume of aggregate over the total volume including all surface pores. The apparent specific gravity (G_{sa}) is based on only the volume of the solid portion of the aggregate ignoring surface pore space. For the specific gravities, G_{sa} is always greater than G_{sb}. Specific gravities were measured according to ASTM C127 and C128 for coarse and fine aggregate, respectively. Aggregate types are denoted GR for gravel and LS for limestone.

Table 2.1. Properties of Single Source Aggregates

Stockpile	FAA (%)	CAA (%)	Abs (%)	G_{sb}	G_{sa}
Tuscaloosa, AL LS (AL-LS)	48	100	0.7	2.694	2.743
Hamilton, MS GR (MS-GR)	48	96	4.2	2.385	2.651
Creede, CO GR (CO-GR)	47	99	4.6	2.248	2.507

Due to material quantity limitations of the Creede, CO gravel, a gradation was chosen that most closely resembled the existing Creede gradation that was within the limitations of AASHTO M323 and the Mississippi Department of Transportation (MDOT) gradation requirements (Table 2.2). The three aggregate gradations are given in Figure 2.2 along with the maximum density line. The maximum density line indicates the densest possible arrangement of aggregate particles.

Table 2.2. Gradations and Control Points

Sieve Size (mm)	M323		MDOT		Colorado GR (% Passing)	Alabama LS (% Passing)	Mississippi GR (% Passing)
	Min	Max	Min	Max			
19	100	---	100	---	100	100	100
12.5	90	100	90	100	96	96	96
9.5	---	90	---	89	87	87	88
2.36	28	58	20	60	48	48	53
0.075	2	10	2	10	6.2	5.9	6.0

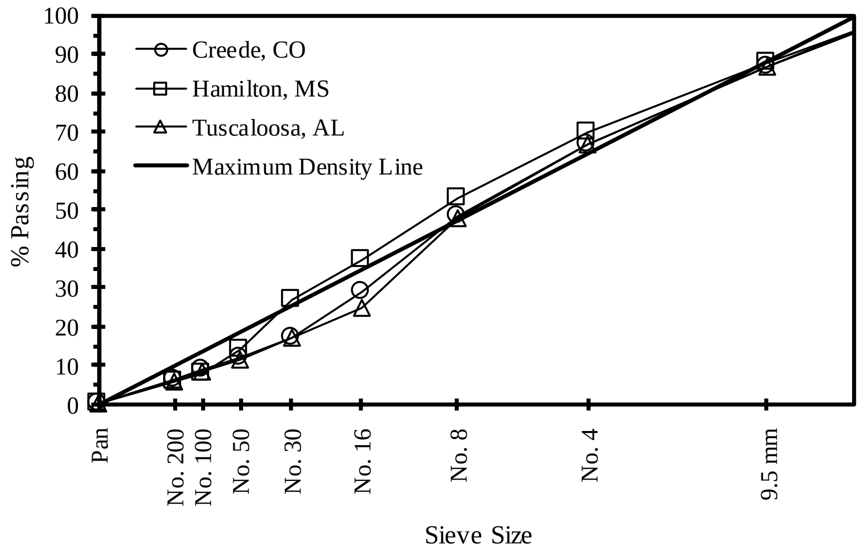


Figure 2.2. Creede, Hamilton, and Tuscaloosa Mixture Gradations

2.2.2 Binder Properties

One asphalt binder was chosen for testing: PG 67-22 from Ergon, Inc. refinery in Vicksburg, MS. Before specimen preparation, the binder was stirred and split from five-gallon buckets into multiple one gallon and one pint metal cans. Two additives were also used: Sasobit® and Evotherm^{3G}. Sasobit® comes from Sasol Wax in South Africa. The product is a long chain aliphatic hydrocarbon obtained from coal gasification (Zhang et al., 2015). Evotherm^{3G} is a chemical package used to improve coating and workability (Hurley and Prowell, 2006). Sasobit® was mixed in the laboratory by adding it directly to the heated binder (Figure 2.3), 1.5% by mass, while being stirred. Evotherm^{3G} additive was received premixed into the binder from Ergon, Inc. at a 0.5% dosage rate.

Figure 2.3. Sasobit® Being Mixed into Binder

2.2.3 Mixture Properties

Mixture volumetric properties were determined that correspond to bulk mixture specific gravity (G_{mb}) measured according to AASHTO T166 (Table 2.3). AASHTO T166 was used to align with most DOT mix designs. The aggregate is identified by source and type separated by a hyphen, e.g. MS-GR denotes Mississippi gravel. Table 2.3 also notes the production temperatures ($T_{production}$) and warm mix technology. G_{mm} and G_{se} denote the maximum mixture specific gravity and the aggregate effective specific gravity, respectively. Binder proportions were the percent of binder by mixture mass (P_b), the percent of binder absorbed into the aggregate pores by mixture mass ($P_{ba(mix)}$), and the volume of effective binder (V_{be}). The voids in mineral aggregate (VMA) is the void space between aggregates. The voids filled with asphalt (VFA) can be calculated as the percentage of VMA occupied by V_{be}. The dust to binder ratio (D:B) is the total percent passing the No. 200 sieve divided by the effective binder content (P_{be}). Mixing temperatures for hot and warm mix asphalt were 163°C and 129°C, respectively (see Table 1.1), and align with $T_{production}$.

Table 2.3. Mix Design Properties

Mix ID	Aggregate	$T_{production}$ (°C)	Warm Mix Technology	G_{mm}	G_{se}	P_b (%)	$P_{ba(mix)}$ (%)	VMA (%)	V_{be} (%)	D:B
M01	MS-GR	163	None	2.250	2.520	8.3	2.3	16.9	12.9	0.97
M02	MS-GR	163	Evotherm^{3G}	2.250	2.520	8.3	2.3	16.9	12.9	0.97
M03	MS-GR	163	Sasobit®	2.250	2.520	8.3	2.3	16.9	12.9	0.97
M04	MS-GR	129	None	2.248	2.505	8.0	2.1	16.8	12.8	0.98
M05	MS-GR	129	Evotherm^{3G}	2.248	2.505	8.0	2.1	16.8	12.8	0.98
M06	MS-GR	129	Sasobit®	2.248	2.505	8.0	2.1	16.8	12.8	0.98
M07	AL-LS	163	None	2.479	2.733	6.2	0.5	17.2	13.2	1.03
M08	AL-LS	129	None	2.481	2.735	6.2	0.5	17.0	13.0	1.04
M09	CO-GR	163	None	2.123	2.362	8.7	2.2	17.2	13.2	0.93
M10	CO-GR	129	None	2.125	2.351	8.3	2.0	16.8	12.8	0.96

The Creede gradation (M09-M10) led to a VMA of approximately 17% which is excessive for a NMAS of 12.5mm. The minimum VMA for a typical 12.5mm NMAS is 14% (e.g. AI, 2001). This mixture with a VMA of 17% was not meant for production due to the cost of extra binder required to fill the voids as well as tender mixture behavior and rutting concerns. Rather, these mixtures were meant to isolate aggregate and binder interaction effects. Based on limited Creede materials, the other two gradations had to be adjusted to reach the higher VMA. A key point in discussing VMA is when the same aggregate gradation and compactive effort are used with different shaped particles differences in VMA can be observed (AI, 1997). To account for these differences in VMA, certain sieve size passing percentages had to be adjusted for the M07-M08 and M01-M06 gradations to achieve a VMA of 17%.

An investigation into other mix designs that resembled the lab selected mix design was performed to determine what might have led to a very high VMA. In comparing a mix design performed by the United States Army Corps of Engineers - Engineer Research and Development Center (USACE-ERDC) of similar gradation (M17-M20), it was determined that, while the gradations were similar, certain sieve sizes could have changed VMA tremendously. The lab mix design (Figure 2.2) was much coarser in that it was lower on a 0.45 power chart than the ERDC mix after the No. 4 sieve. This indicated that the ERDC mix had finer materials, which can lead to a lower VMA. Additionally, common mix designs can include as much as 10% natural sand, which also usually leads to a lower VMA. No natural sand was used for the Creede gradation. The two mixture gradations have a VMA of approximately 14% and 17% for ERDC and Creede, respectively. For illustration, the 0.45 power chart can be seen in Figure 2.4.

When M01-M10 are compared to mixtures already used by MDOT, the differences are evident. Out of 167 12.5mm NMAS mixtures documented by Doyle et al. (2012), the maximum P_b and P_{ba} was 6.2% and 1.3%, respectively. M01-M06 and M09-M10 are comfortably over the max P_b by about 2% while 1% above the max P_{ba}. M07-M08 is at the maximum P_b while 0.8% below the max P_{ba}. Production of mixtures with these binder percentages is not the intent of this report. The intent of the SAS portion for this report is to control as many mixture properties as possible in order to isolate aggregate source effects on aging and mechanical properties.

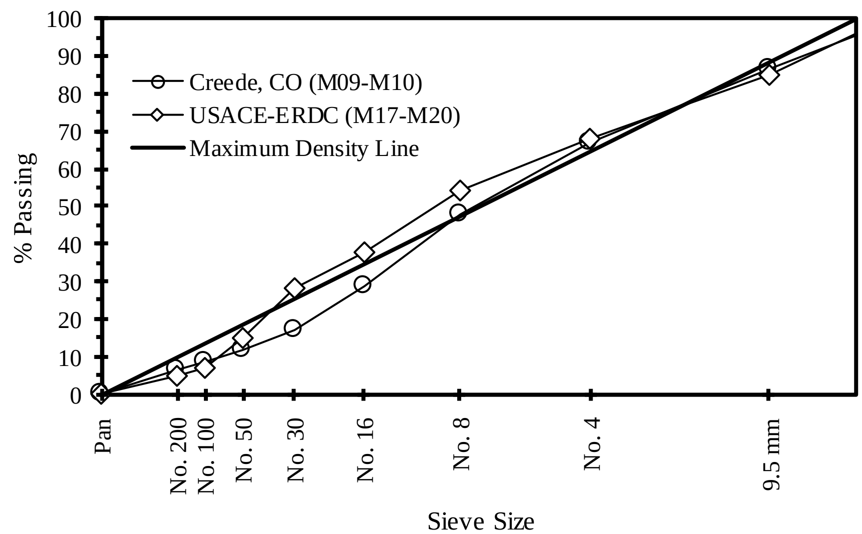


Figure 2.4. Creede and ERDC Gradation Comparison Chart

2.3 Air Force Base Materials

Mixture and extracted binder tests were conducted on three paving mixtures sampled from AFB paving projects at two locations. Two mixtures were sampled from the Columbus Air Force Base (CAFB) in Columbus, Mississippi, and one mixture was collected from the March Air Reserve Base (previously known as the March Air Force Base and denoted MAFB herein) in Moreno Valley, California. Fundamental properties of the three mixtures discussed (e.g., volumetric properties, mixture component details, and gradation) are provided in Tables 1.1 to 1.3, and pertinent details relative to material acquisition are discussed in the following subsections.

2.3.1 Columbus Air Force Base Materials

A CAFB runway was re-constructed during the summer of 2013, and the shoulders were constructed in two lifts using mixes M12 and M13 (Tables 1.1 to 1.3). Both mixes were designed using a Superpave Gyratory Compactor (SGC) with 75 gyrations and had 12.5 mm NMAS. Plant mixed materials were sampled on two occasions during the project: M13 plant mixed materials were sampled on July 19th, 2013, and M12 plant mixed materials were sampled on July 24th, 2013. Plant mixed materials from CAFB were sampled from the paving site using a front end loader (Figure 2.5), and materials were transferred to metal 5 gallon buckets with lids. Buckets containing plant mixed material were sealed and stored in the laboratory until compaction. Note that raw ingredients were obtained for M12 and laboratory mixed specimens were produced, but the laboratory mixed specimen properties are of no relevance to this report and are not included.

Figure 2.5. CAFB Material Sampling

2.3.2 March Air Reserve Base Materials

M11 was plant mixed material that was sampled 9 times by Rushing et al. (2014) from material transfer vehicle hoppers when paving the outer edges and shoulders of runway 14-32 at MAFB. Excess material from samples 3 and 4 was SGC compacted at USACE-ERDC and specimens were delivered to Mississippi State University (MSU) prior to October 30th, 2013 along with one 5 gallon bucket of loose material from sample 7. Measured binder content (P_b) and maximum specific gravity (G_{mm}) for the three samples were 5.18%, 5.18%, and 4.99% and 2.531, 2.531, 2.538 for samples 3, 4, and 7, respectively. Based on the information provided, measured P_b of 5.2% and G_{mm} of 2.531 were used for all M11 materials herein.

M11 was designed with a 75-blow Marshall procedure having an NMAS of 19 mm, PG 70-10 asphalt binder, and a design V_a of 4%. Two deviations between Rushing et al. (2014) and this report are the design asphalt content ($P_{b,design}$) and design air voids ($V_{a,design}$). Rushing et al. (2014) reported $P_{b,design}$ of 5.6% and $V_{a,design}$ of 3.5%, but this report provides a P_b of 5.2% and $V_{a,design}$ of 4.0%. These differences are based on conflicting information provided in the project mix design, which provides a 5.6% $P_{b,design}$ based on dry weight of aggregate and 5.3%

$P_{b,design}$ based on total weight of mix. This is likely the case as the average P_b reported from 9 samples in Rushing et al. (2014) was 5.24%. The V_a difference was likely caused by the mix design verification which had 3.5% V_a.

2.4 Specimen Preparation and Compaction

There were two methods of specimen preparation used in this report: laboratory mixed and laboratory compacted (Section 2.4.1) and plant mixed and laboratory compacted (Section 2.4.2). All compaction was performed using a Superpave Gyratory Compactor (SGC).

2.4.1 Lab Mixes

Single aggregate source mixtures (M01-M10) used two mixing and compacting temperatures. Hot mixed asphalt (HMA) was mixed at 163°C and compacted at 149°C while warm mixed asphalt (WMA) was mixed at 129°C and compacted at 116°C. Mixing was performed in accordance with AASHTO T312. After mixing, material was short term aged for 90 minutes at compaction temperature and SGC compacted.

One Columbus AFB mixture (M12) was lab mixed and compacted multiple times at a temperature of 166°C. Mixing was performed in accordance with AASHTO T312. After mixing, the material was short term aged for 120 minutes at compaction temperature and SGC compacted. All mix design properties for both SAS and CAFB mixtures can be found in Tables 1.1 to 1.3.

2.4.2 Plant Mixes

Plant mixed materials for M11, M12, and M13 were sampled from their respective paving sites during construction. M11 materials were compacted and measured for density per AASHTO T331 prior to delivery to MSU. M12 and M13 materials were sampled at the construction site by the authors and stored in sealed 5 gallon metal buckets for varying periods of time until compaction as described in the next paragraph.

M12 and M13 plant mixed and laboratory compacted specimens were prepared by heating 5 gallon buckets of plant mixed material until material could be sufficiently broken up to batch appropriate quantities of mix into individual pans with lids. Pans of material were returned to ovens systematically such that materials were compacted shortly after materials reached compaction temperatures. M12 plant mixed materials were compacted at 154 °C while M13 materials were compacted at 146 °C. Compacted specimens were thereafter cooled to room temperature and measured for G_{mb} according to AASHTO T331 prior to conditioning or testing.

2.5 Field Aging and Lab Conditioning

2.5.1 Field Aging

Field aging occurred at an asphalt test section in Columbus, MS between November 1, 2013 and October 30, 2015. During field aging, specimen tops were open to the atmosphere while specimen bottoms were in direct contact with the underlying parking lot, and specimen edges were surrounded by pvc sleeves (Figure 2.6). All AFB specimens were placed for field aging on November 1, 2013, and summaries of weather data over the two-year aging period are provided in Tables 2.4 and 2.5. The one year aging period for SAS specimens began on November 1, 2014. Note that the one year field aging period for SAS specimens was completed during the second year of aging for the AFB specimens.

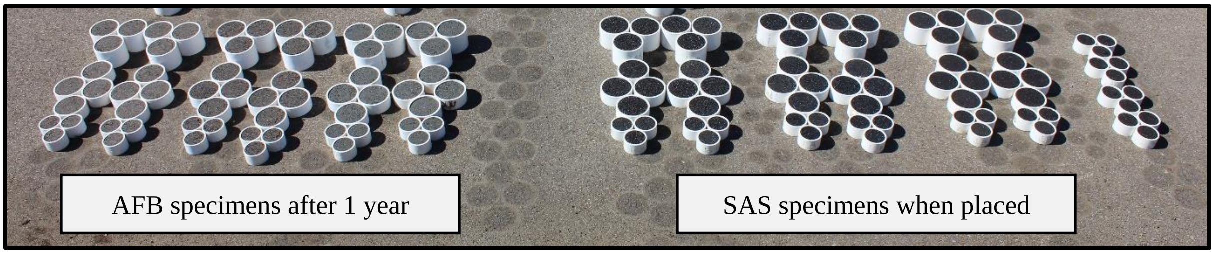


Figure 2.6. Field Aging (November 1, 2014)

Table 2.4. Weather Summary (November 1, 2013 and October 31, 2014)

		Avg. Daily Temp		High Daily Temp		Low Daily Temp		Rainfall		Relative Humidity	
Month	**Days**	**Mean (°C)**	**St. Dev (°C)**	**Mean (°C)**	**St. Dev (°C)**	**Mean (°C)**	**St. Dev (°C)**	**Total (cm)**	**Days of 1.25 cm+**	**Mean (%)**	**St. Dev (%)**
Nov-13	30	9.3	5.3	15.3	5.5	3.1	6.2	8.2	3	74.2	12.7
Dec-13	31	6.8	5.9	12.2	6.8	1.3	6.2	15.8	7	81.6	10.0
Jan-14	31	1.8	5.3	9.2	6.5	-5.7	5.2	5.2	1	60.4	16.2
Feb-14	28	6.6	5.1	12.4	6.8	0.7	4.6	9.2	2	75.6	11.8
Mar-14	31	10.4	4.4	17.7	5.7	3.0	4.2	9.0	2	71.8	14.1
Apr-14	30	16.5	4.0	23.3	4.5	9.7	4.5	20.2	4	74.9	13.7
May-14	31	21.2	3.4	28.0	3.7	14.8	4.3	11.2	3	72.9	11.2
Jun-14	30	25.4	1.5	30.7	2.3	20.4	1.3	15.2	3	80.6	7.0
Jul-14	31	24.6	2.3	30.1	2.8	19.2	2.4	9.5	3	78.5	8.7
Aug-14	31	26.3	1.7	32.4	2.0	20.3	2.0	7.7	1	77.1	8.3
Sep-14	30	24.3	2.6	30.4	2.4	18.4	3.4	4.1	2	76.9	6.7
Oct-14	31	18.1	4.2	25.3	4.1	11.0	5.2	11.4	3	80.5	9.7
All	***365***	**16.0**	**9.2**	**22.3**	**9.3**	**9.7**	**9.7**	**126.7**	**34**	**75.3**	**12.3**

Table 2.5. Weather Summary (November 1, 2014 and October 31, 2015)

Month	Days	Avg. Daily Temp Mean (°C)	Avg. Daily Temp St. Dev (°C)	High Daily Temp Mean (°C)	High Daily Temp St. Dev (°C)	Low Daily Temp Mean (°C)	Low Daily Temp St. Dev (°C)	Rainfall Total (cm)	Rainfall Days of 1.25 cm+	Relative Humidity Mean (%)	Relative Humidity St. Dev (%)
Nov-14	30	8.2	5.5	14.9	6.0	1.5	6.0	10.7	2	70.6	11.3
Dec-14	31	8.4	3.8	13.3	4.1	3.2	4.4	18.2	5	85.0	10.0
Jan-15	31	4.9	4.7	11.3	5.9	-1.5	4.8	12.2	4	72.0	16.5
Feb-15	29	3.6	4.6	9.1	6.2	-2.2	4.2	37.9	3	65.2	17.3
Mar-15	31	13.1	5.2	18.7	6.3	7.4	5.9	15.6	5	82.6	12.9
Apr-15	30	18.1	3.2	24.1	3.5	12.3	4.2	18.9	4	79.2	13.9
May-15	31	22.5	2.9	29.7	2.9	15.5	4.2	11.2	4	73.8	14.0
Jun-15	30	25.9	2.2	31.7	2.5	20.2	2.4	2.0	0	77.2	6.0
Jul-15	31	27.9	1.9	33.8	2.6	22.2	1.4	6.2	3	76.1	7.2
Aug-15	31	26.0	2.3	31.8	2.7	20.4	2.7	12.0	4	77.8	9.0
Sep-15	30	23.4	2.8	29.9	3.0	17.1	3.8	2.2	0	76.9	6.4
Oct-15	31	17.8	3.7	24.7	4.9	11.2	5.1	40.6	1	76.4	11.8
All	***366***	**16.7**	**9.1**	**22.8**	**9.6**	**10.7**	**9.4**	**187.9**	**35**	**76.2**	**12.8**

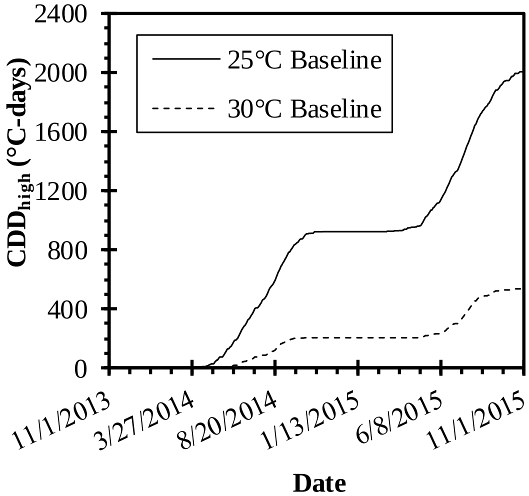
Some parameters are used herein to describe weather patterns over time are used throughout this effort. High temperature cumulative degree days (CDD_{high}) describes the accumulation of high temperature days over time, and CDD_{high} is defined in Equation 2.1. For example, a single day with a maximum temperature of 35 °C with a 25 °C baseline would contribute 10 °C – days to CDD_{high}. Cumulative freezing index (CFI) is used to describe the accumulation of low temperature days over time and is defined in Equation 2.2 (Figure 2.7b and 2.8b). Cumulative days of temperature fluctuation ($CD_{fluctuation}$) describes the accumulation of days where the difference in maximum and minimum temperature is greater than a defined baseline. For example, the 18 °C baseline in Figure 2.7c reaches a maximum of 85 days with at least an 18 °C temperature fluctuation in a single day. Cumulative precipitation was also used to describe the cumulative rainfall over time (Figure 2.7d and 2.8d).

$$\mathrm{CDD}_{high}\left(°\mathrm{C}-\mathrm{days}\right) = \sum(\mathrm{T}_{dmax} - \mathrm{Baseline}) \; if \; \mathrm{T}_{dmax} > \mathrm{Baseline} \qquad (2.1)$$

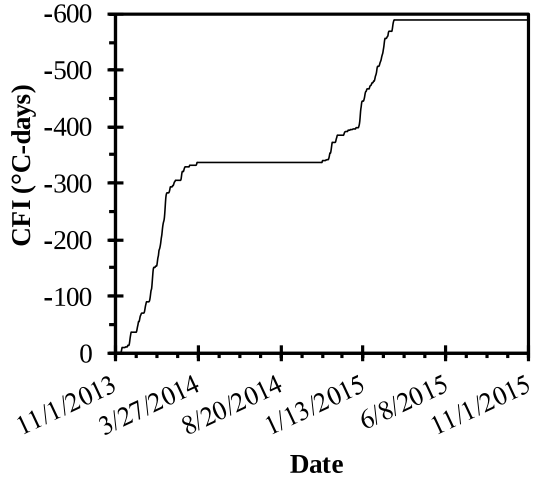
$$\mathrm{CFI}\left(°\mathrm{C}-\mathrm{days}\right) = \sum(\mathrm{T}_{dlow}) \; if \; \mathrm{T}_{dlow} < 0°\mathrm{C} \qquad (2.2)$$

Where,

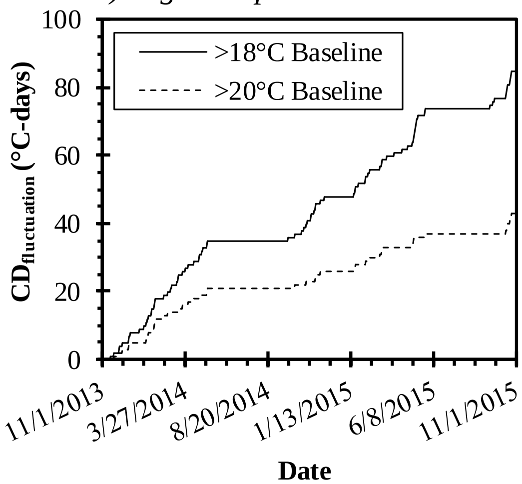
T_{dlow} = Minimum Daily Temperature (°C)
T_{dmax} = Maximum Daily Temperature (°C)



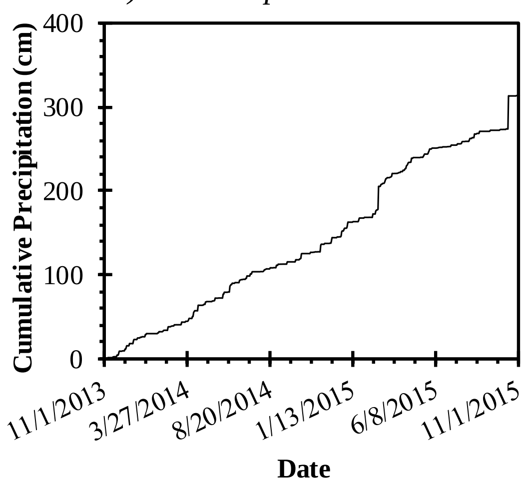
a) High Temperature Accumulation



b) Low Temperature Accumulation

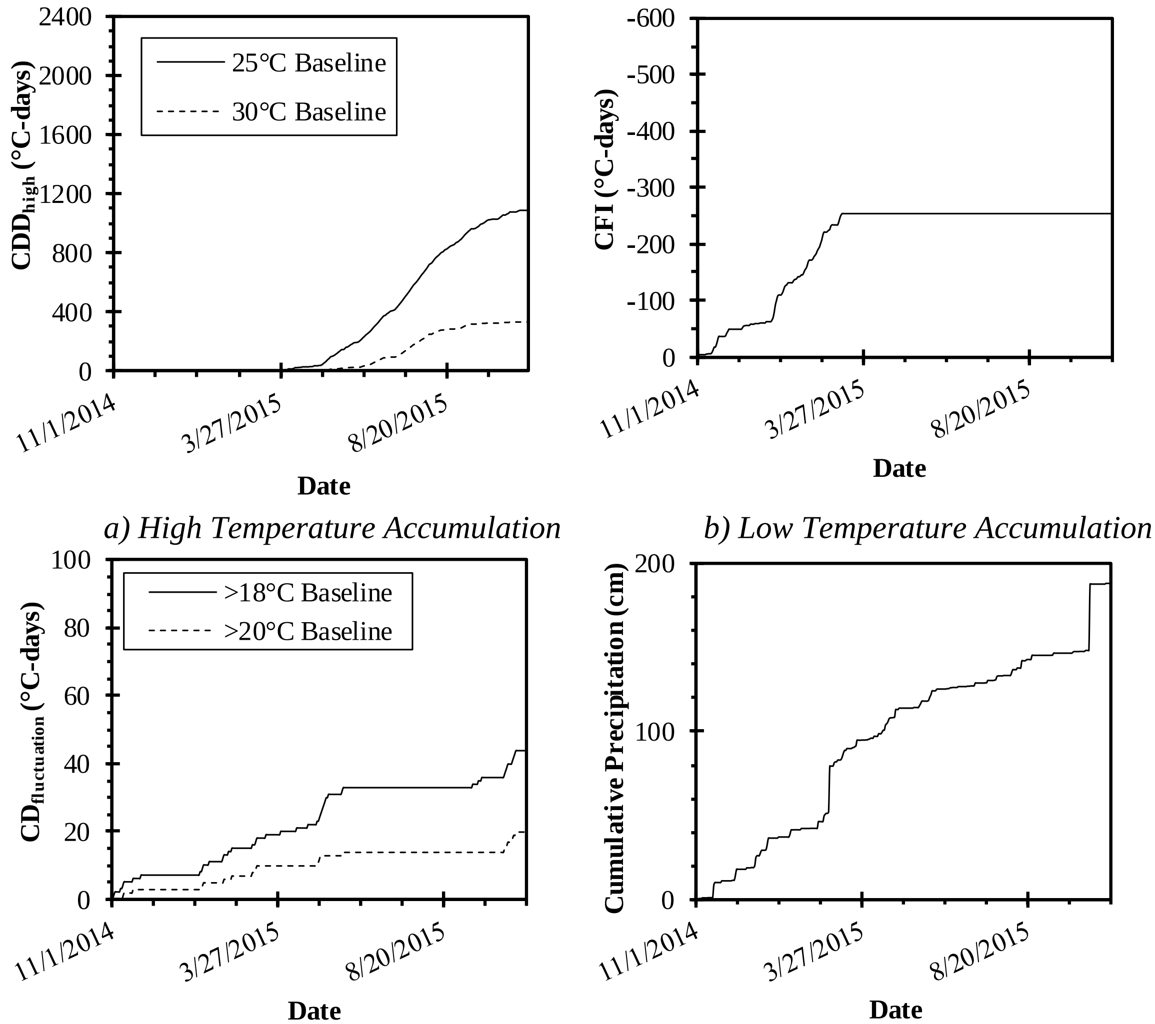


c) Temperature Fluctuation



d) Cumulative Precipitation

Figure 2.7. Cumulative Weather Summary – AFB Mixes



a) High Temperature Accumulation *b) Low Temperature Accumulation*

c) Temperature Fluctuation *d) Cumulative Precipitation*

Figure 2.8. Cumulative Weather Summary – SAS Mixes

2.5.2 Lab Conditioning

There were three conditioning mechanisms evaluated in a series of six conditioning protocols (CPs) with the intention to simulate different levels of field aging in AFB specimens: forced draft ovens, hot water, and freeze thaw (FT) cycles. Seven laboratory conditioning protocols were conducted for Volume 2 and Volume 3 of this effort, and the same CP designations are repeated here for consistency (Table 2.6). For CPs where more than one conditioning mechanism was applied, the mechanisms were applied in the order previously mentioned. A large capacity water bath and two upright freezers were used to conduct hot water and FT conditioning. Fabrication and calibration details for Figure 2.9 devices are provided in the companion Volume 2 report.

Table 2.6. Laboratory Conditioning Protocols

CP	Oven		Hot Water		Freeze Thaw	
	Time (days)	Temp. (°C)	Time (days)	Temp. (°C)	24 hr cycles	Temp (°C)
CP1	5	85	---	---	---	---
CP2	28	60	---	---	---	---
CP3*	---	---	14	64	---	---
CP4	---	---	14	64	1	-22
CP5	---	---	14	64	2	-22
CP6	---	---	28	64	---	---
CP7	5	85	14	64	1	-22

*CP3 was not conducted in this report.

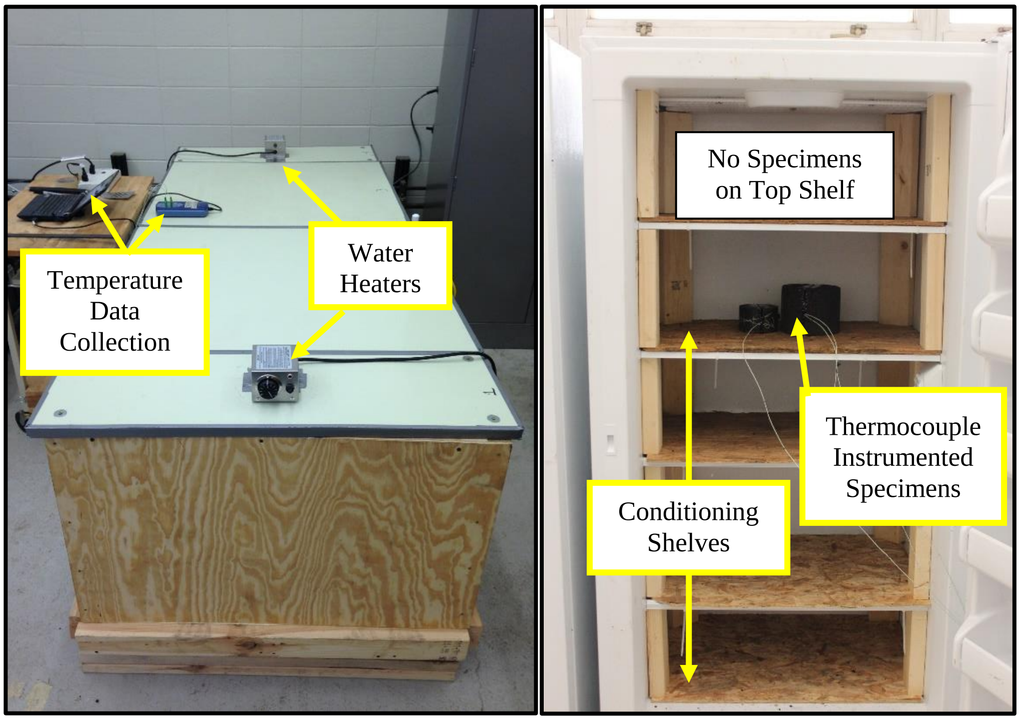


Figure 2.9. Water Bath and Freezer Laboratory Conditioning Equipment

2.6 Mixture Test Methods

Five mixture tests were used to measure mixture behaviors: Cantabro Mass Loss (CML), non-instrumented indirect tensile (IDT), Hamburg Loaded Wheel Tracking (HLWT), Asphalt Pavement Analyzer (APA), and instrumented indirect tensile (SIDT). The SAS specimens were subjected to CML, IDT, HLWT, and APA testing. March AFB specimens were subjected to CML, IDT, and SIDT. Columbus AFB specimens were subjected to CML, IDT, HLWT, and SIDT.

2.6.1 Cantabro Mass Loss

Cantabro Mass Loss testing was performed on 15 cm diameter lab compacted specimens after conditioning in air to 25°C. An initial specimen mass was recorded and then the specimen was subjected to 300 revolutions in a Los Angeles (LA) abrasion drum, brushed lightly, and the specimen's final mass was recorded. Mass Loss (*ML*) was determined by the change in initial to final specimen mass divided by the initial mass. The internal temperature of the LA abrasion drum was maintained at 25±2°C throughout testing, and all specimens were tested within 30 minutes of removal from the environmental chamber. A comprehensive state of knowledge paper for Cantabro testing of dense graded asphalt (DGA) is provided in Cox et al. (2017).

2.6.2 Indirect Tensile Testing (Non-Instrumented)

Non-instrumented indirect tensile (IDT) testing was performed on 10 cm diameter lab compacted specimens after conditioning in air at 25°C. IDT testing was performed in accordance with AASHTO T283. Specimens were loaded diametrically at a loading rate of 50mm/min until failure. The IDT strength (S_t) was determined using equation (2.3).

$$S_t = \frac{2000 \times P_{max}}{\pi \times t \times D} \times 100 \tag{2.3}$$

Where,

S_t = Indirect Tensile Strength (kPa)

π = 3.14159

P_{max} = Maximum Load (N)

t = Specimen Thickness (mm)

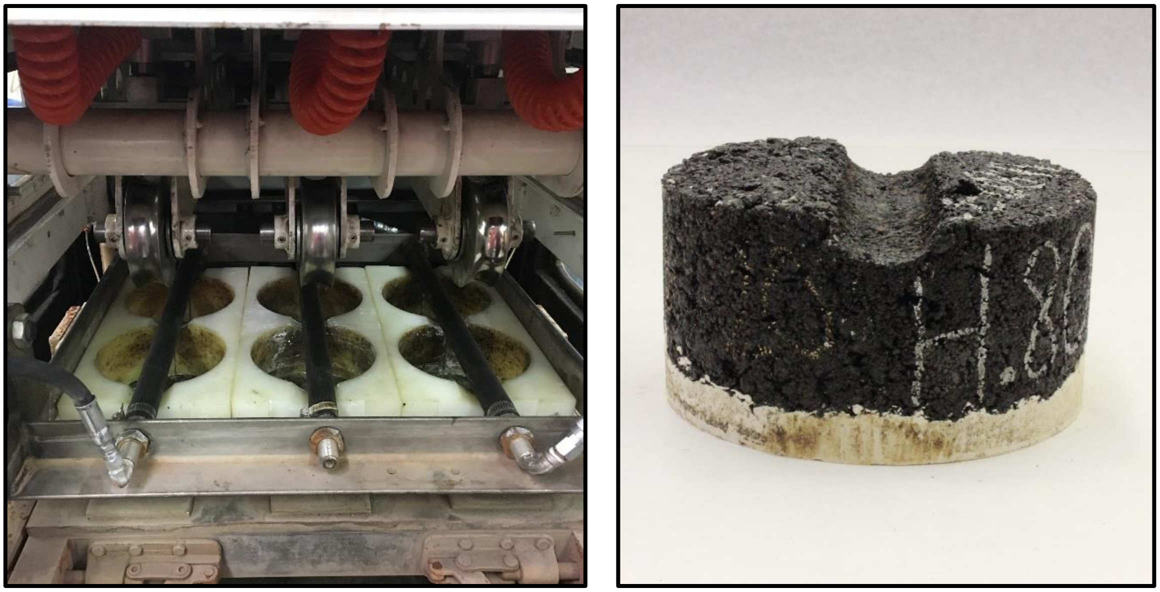
D = Specimen Diameter (mm)

2.6.3 Hamburg Loaded Wheel Tracking

Hamburg Loaded Wheel Tracking (HLWT) was performed in accordance with AASHTO T324. All HLWT specimens were compacted to 15 cm diameters with heights of 6.3 cm that were subsequently sliced to fit standard molds. Temperatures were maintained at 50°C throughout all HLWT testing, and wheel loads were maintained at 0.7 kN for 20,000 passes or a max rut depth of 12.5mm. HLWT results in indicate a measure of mixture stability based on maximum rut depth (RD_{HLWT}) and moisture induced damage based on the presence or absence of a stripping inflection point (SIP).

2.6.4 Asphalt Pavement Analyzer Rut Susceptibility

Asphalt Pavement Analyzer (APA) rutting susceptibility was performed in accordance with AASHTO T340. All APA specimens were laboratory compacted to 15 cm diameters with heights of 6.3 cm, and plaster of Paris was used to fill gaps below specimens during testing. The temperature was maintained at 64 °C throughout APA testing, and wheel loads were maintained at 0.4 kN for 8,000 passes. Hose pressure was maintained at 689 kPa. The APA test setup and example tested specimen are shown in Figure 2.10.



a.) APA Testing Setup *b.) APA Tested Specimen*

Figure 2.10. APA Rut Susceptibility Testing

2.6.5 Indirect Tensile Testing (Instrumented)

Instrumented IDT tests (aka SIDT) were conducted at 20°C and -10°C to determine fracture energy (FE). These parameters are referred to as FE_{+20C} and FE_{-10C}. Tests were conducted on 3.1 cm thick sections of 6.3 cm thick specimens which had previously had slices of equal thickness removed from tops and bottoms. These top and bottom slices were sometimes kept and used for extracted and recovered binder testing (further details are provided in Volume 2).

After specimens were sliced to the appropriate thickness, steel gage points were attached via epoxy gel as described in Volume 2. Specimens were then conditioned in air for a minimum of 2 hours for FE_{+20C} or 3 hours for FE_{-10C} testing. Loading rates during testing were applied at 50 mm/min and 12.5 mm/min for FE_{+20C} and FE_{-10C} tests, respectively. The data reduction process used to determine FE is described in Section 3.6.2 of Volume 2, which was based on section 4.5.11.4 of Cox et al. (2015).

2.7 Binder Test Methods

Properties were measured on nine binder samples extracted from AFB specimens after varying periods of field aging (Table 2.7). The binder recovery process is described in Section 2.7.1 while binder test methods are described in Section 2.7.2.

Table 2.7. Recovered Binder Test Matrix

Mix	Age (yr)	Depth from Top Surface (cm)
M11	0	---
M11	2	0.0 to 1.3
M11	2	5.0 to 6.3
M12	0	---
M12	2	0.0 to 1.3
M12	2	5.0 to 6.3
M13	0	---
M13	2	0.0 to 1.3
M13	2	5.0 to 6.3

2.7.1 Binder Extraction and Recovery

The binder extraction process completed for this report was identical to the process completed in Volume 2. While all details are provided therein, many details are excluded from this section for brevity. Binder extraction was performed using a Humboldt H-1471 centrifuge and a series of three solvents: 1) toluene which had been recovered from previous extractions, 2) virgin toluene, and 3) a blend of 85% toluene and 15% ethanol by volume. Mixes were initially submerged in toluene recovered from previous extractions and soaked for 45 ± 5 minutes. After initial soaking, a variable amount of 250 mL washes of virgin toluene were applied followed by a minimum of three 250 mL washes of the blended solvent. The binder extraction process was continued until extract reached a consistent amber color. Mineral fines smaller than 0.075 mm were removed from binder extract using a filter-less centrifuge conforming to ASTM D1856, and binders were recovered from the resulting filtrate using a BUCHI Rotavapor R-114.

2.7.2 Binder Test Methods

After recovery, binders were sealed to minimize oxygen access and stored in ambient conditions (i.e. approximately 21°C out of sunlight) until transportation to Paragon Technical Services, Inc. (PTSi) for testing. Binder properties were measured using three rheology tests without further conditioning prior to testing (i.e. rolling thin film ovens and pressure aging vessels were not used).

2.7.2.1 Penetration at 25°C

Binder samples were tested for penetration (*Pen*) per ASTM D5 in 3 oz. containers. Samples were conditioned to 25°C in water for a minimum of 1 hour, and testing was conducted with triplicate measurements while submerged.

2.7.2.2 Dynamic Shear Rheometer

Dynamic shear rheometer (DSR) testing was performed at intermediate (DSR_8) and high (DSR_{25}) temperatures to determine the complex shear modulus (G^*) and phase angle (δ) for each sample. Critical temperatures (T_c) were determined for intermediate temperatures using 8.0 mm plates with a 2.0 mm gap and high temperatures using 25.0 mm plates and a 1.0

mm gap. These critical temperatures are referred to as $T_c(DSR_8)$ and $T_c(DSR_{25})$, respectively. Testing was conducted per AASHTO T315 using Anton Paar SmartPave Plus 301 DSRs to determine $T_c(DSR_8)$ where $G^*\sin\delta$ was 5.0 MPa and $T_c(DSR_{25})$ where $G^*/\sin\delta$ was 2.20 kPa.

2.7.2.3 Bending Beam Rheometer

Bending beam rheometer (BBR) testing was conducted per AASHTO T313 to determine T_c when binder stiffness (S) reached 300 MPa or *m-value* reached 0.300. These critical temperatures are described herein as $T_c(BBR_S)$ and $T_c(BBR_m)$.

CHAPTER 3-SINGLE AGGREGATE SOURCE RESULTS

3.1 Overview of Single Aggregate Source Results

The SAS results are separated by specific test and then an overall discussion connecting all of the tests. All the results can be found in Table 3.1. These results are the same as a paper submitted for peer review (Hansen and Howard, 2018). Before the results are discussed a brief summary of relevant literature is given. A more comprehensive literature review can be found in Hansen (2017). Hansen (2017) reviews asphalt bonding and asphalt-aggregate interaction effects on aging and mechanical performance.

3.2 Summary of Relevant Literature

Finn (1967) noted that aggregate composition and reactivity can lead to asphalt stripping. Plancher et al. (1976) showed hydrated lime treatment helped mitigate stripping and limestone aggregate alone (no hydrated lime) can reduce asphalt hardening. Copas and Pennock (1979) identified selective aggregate absorption of asphalt components can lead to asphalt hardening. Bell (1989) summarized literature and observed: high average temperature was most significant aging factor, aggregate absorption effected aging to a greater extent in more volatile asphalts, and hydrated lime was effective against aging. Tarrer and Wagh (1991) found aggregate chemical composition and mineralogy affected asphalt moisture susceptibility. Specifically, acidic aggregates and basic aggregates tend to be hydrophilic and hydrophobic, respectively. Furthermore, acidic aggregates tend to have more moisture damage susceptibility problems than basic aggregates.

Curtis (1992) observed aggregate chemistry was much more influential than asphalt chemistry relative to adhesion and moisture sensitivity. Bell and Sosnovske (1994) found short and long term aging to be aggregate dependent, but asphalt binder had a greater significance. Bell and Sosnovske (1994) concluded asphalt aging susceptibility was a mixture problem with binder alone being unsatisfactory in predicting pavement aging. Abo-Qudais and Al-Shweily (2007) concluded the following: stripping resistance was significantly affected by aggregate type, aggregate gradation heavily effected stripping, and absorbed asphalt was able to detect differences within aggregate type, gradation, and asphalt type. Baek et al. (2012) determined greater adhesion yields better aging mitigation. Wu et al. (2014) found aggregate type significantly affected binder aging and at what point in the binder’s life it aged. Aguiar-Moya et al. (2015) stated some asphalt and aggregate combinations can develop adhesion issues even with adhesion promoter addition.

From literature it is evident aggregate interaction with asphalt binder can significantly affect performance. Literature consistently shows aggregate chemistry and physical properties affect bonding and aging. Aggregate chemistry mainly means chemical composition of the aggregate (e.g. basic or acidic). Physical aggregate properties which have shown to affect aggregate bonding include: surface roughness or texture, porosity, polarity, and shape.

3.3 Cantabro Mass Loss Results

The Cantabro mass loss (CML) test results are described by mass loss (*ML*) and change in mass loss (ΔML). CML results can be found in Table 3.1. The *ML* results for unaged mixtures show differences already exist with a *ML* range of 3.1%. Aging appeared to further increase these differences with the *ML* range increasing to 4.4%. These results indicate that asphalt-aggregate interaction and mixing temperature have an effect on mixture performance before and after aging. The ΔML supports the conclusion that differences exist before aging and are exacerbated by aging. Both $T_{production}$ and aggregate have a considerable effect on *ML*. MS-GR mixtures saw the largest increase in *ML* which indicates MS-GR experienced the most hardening. The gravel mixtures were more affected by $T_{production}$ than the limestone mixture. It is evident from CML results that differences exist between aggregate sources and $T_{production}$ indicating *ML* is affected differently depending on asphalt-aggregate interaction and mixing temperature in some cases.

3.4 Indirect Tensile Results

The indirect tensile (IDT) test results are described by tensile strength (S_t) and change in tensile strength (ΔS_t). These values are provided in Table 3.1. The ΔS_t value is defined as aged S_t minus unaged S_t. By comparing ΔS_t values, the relative changes can be compared between different aggregates to see if the mixtures aged consistently once initial S_t is considered. As seen in Table 3.1 this was not the case. MS-GR mixtures (M01-M06) started out strongest with a S_t of 1000 kPa and doubled to 1800-2000kPa after aging. The other mixtures, with M10 excluded, only increased about 1.5 times after aging. Warm mix additives had no measureable effect on S_t. $T_{production}$ seemed to considerably affect CO-GR mixtures (M09-M10) while AL-LS mixtures (M07-M08) were insensitive to $T_{production}$. It is also noteworthy that WMA displayed higher ΔS_t values than HMA in every case. It is evident from IDT results that differences exist between aggregate sources indicating S_t changes differently depending on asphalt-aggregate interaction.

3.5 Asphalt Pavement Analyzer Rut Susceptibility Results

The Asphalt Pavement Analyzer (APA) test results are described by rut depth (RD_{APA}) and change in rut depth (ΔRD_{APA}). APA results can be found in Table 3.1. Figure 3.1 shows MS-GR is the stiffest mixture. $T_{production}$ shows little effect on RD_{APA} for unaged MS-GR and AL-LS mixtures, but unaged CO-GR mixtures showed a considerable difference. The ΔRD_{APA} with respect to $T_{production}$ was approximately 1 mm for MS-GR and AL-LS mixtures, but CO-GR showed twice as large ΔRD_{APA}. The APA showed agreement with the other mixture tests with all tests showing that asphalt-aggregate interaction affects aging.

3.6 Hamburg Loaded Wheel Tracking Results

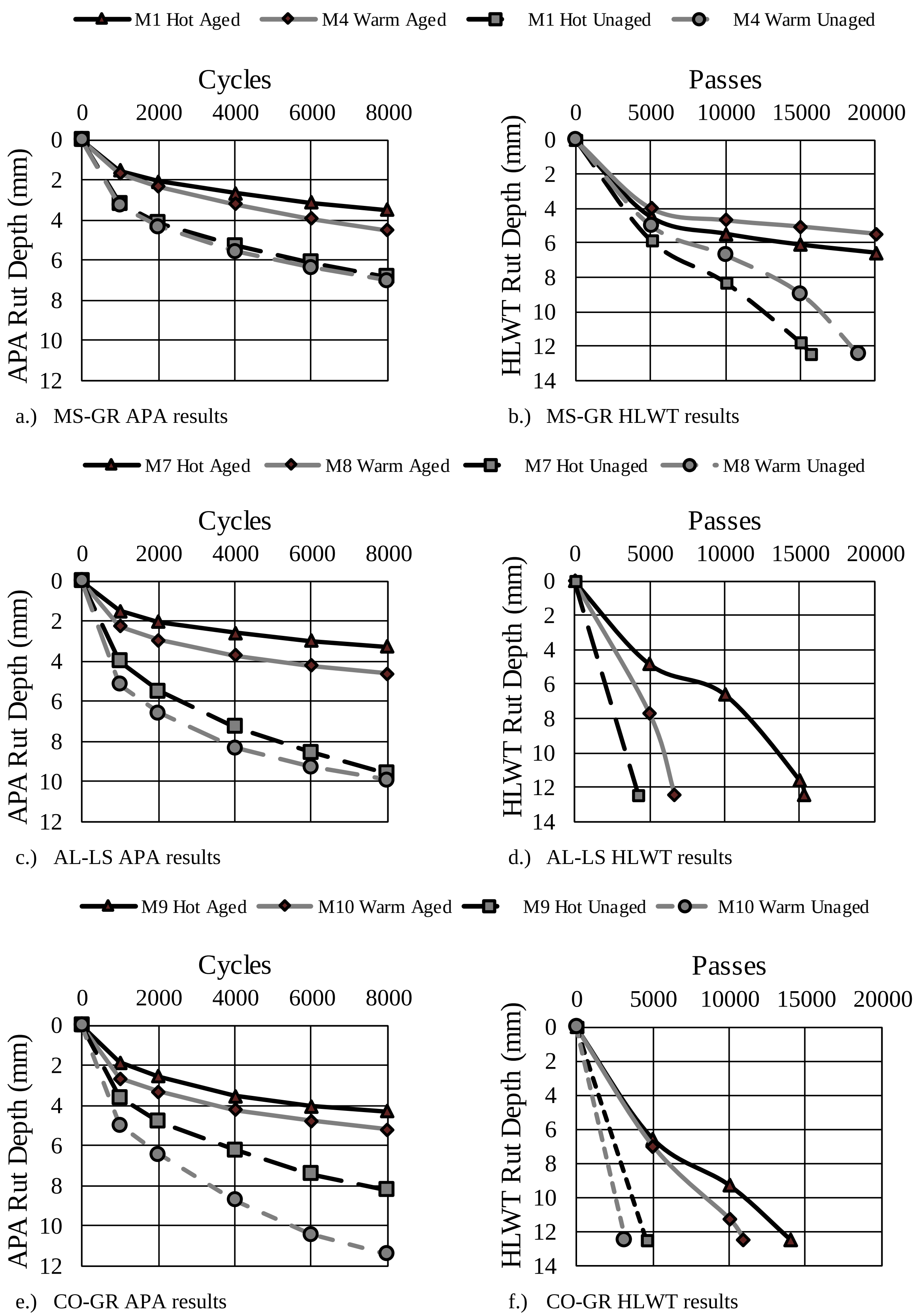
The Hamburg loaded wheel tracking (HLWT) test results are described by rut depth (RD_{HLWT}), change in rut depth (ΔRD_{HLWT}), number of passes to reach max rut depth of 12.5 mm ($P_{12.5\text{-}HLWT}$), and whether a stripping inflection point (SIP) was present. HLWT results can be found in Table 3.1. With a VMA of 17% these mixtures should be expected to experience significant rutting. Figure 3.1 plots the rut depth versus number of passes which shows all mixtures except aged MS-GR surpassed a 12.5 mm rut depth before the full 20,000 passes. Rut depth reduction for aged MS-GR mixtures indicates greater age hardening leads to decreased rutting. The WMA mixtures rutted more quickly according to $P_{12.5\text{-}HLWT}$. HLWT also gives indications of stripping potential via SIP. Stripping was present in the AL-LS and the unaged warm mixed gravel mixtures. One of the AL-LS tests was shut down early due to testing error, but it is assumed that stripping would most likely have occurred.

Table 3.1. All SAS Results

Mix	Agg.	Add.	$T_{production}$ (°C)	Aging	*ML* (%)	Δ*ML* (%)	S_t (kPa)	ΔS_t (kPa)	RD_{APA} (mm)	ΔRD_{APA} (mm)	RD_{HLWT} (mm)	ΔRD_{HLWT} (mm)	$P_{12.5\text{-}HLWT}$	SIP
M01	MS-GR	None	163	1 yr. Field None	11.1 5.9	5.2	1890 1032	858	3.5 6.9	-3.4	6.6 12.5	-5.9	20,000 15,672	No No
M02	MS-GR	Evo.[3G]	163	1 yr. Field None	---	---	1879 1082	797	---	---	---	---	---	---
M03	MS-GR	Sas.®	163	1 yr. Field None	---	---	1804 991	813	---	---	---	---	---	---
M04	MS-GR	None	129	1 yr. Field None	12.7 4.8	7.9	2047 1021	1026	4.5 7.0	-2.5	5.5 12.5	-7.0	20,000 18,862	No Yes
M05	MS-GR	Evo.[3G]	129	1 yr. Field None	---	---	2024 1045	979	---	---	---	---	---	---
M06	MS-GR	Sas.®	129	1 yr. Field None	---	---	1936 995	941	---	---	---	---	---	---
M07	AL-LS	None	163	1 yr. Field None	9.2 4.9	4.3	1071 719	352	3.3 9.6	-6.3	12.5 12.5	0	15,296 4,240	Yes Yes
M08	AL-LS	None	129	1 yr. Field None	9.1 5.2	3.9	1065 657	408	4.6 9.9	-5.3	12.5 *	---	6,686 *	Yes *
M09	CO-GR	None	163	1 yr. Field None	8.3 4.0	4.3	1114 770	344	4.3 8.2	-3.9	12.5 12.5	0	13,988 4,594	No No
M10	CO-GR	None	129	1 yr. Field None	8.6 2.8	5.8	1375 703	672	5.2 11.4	-6.4	12.5 12.5	0	10,932 3,170	No Yes

Note: IDT and CML results are a 3 specimen average while APA and HLWT are 2 specimens. A total of 144 specimens were tested. 40 were tested for each source with varying levels of aging, mixing/compaction temperatures, and testing procedures. An additional 12 specimens each were IDT tested with 2 warm mix additives

* Test shut down early, but specimen exhibited rutting.



a.) MS-GR APA results

b.) MS-GR HLWT results

c.) AL-LS APA results

d.) AL-LS HLWT results

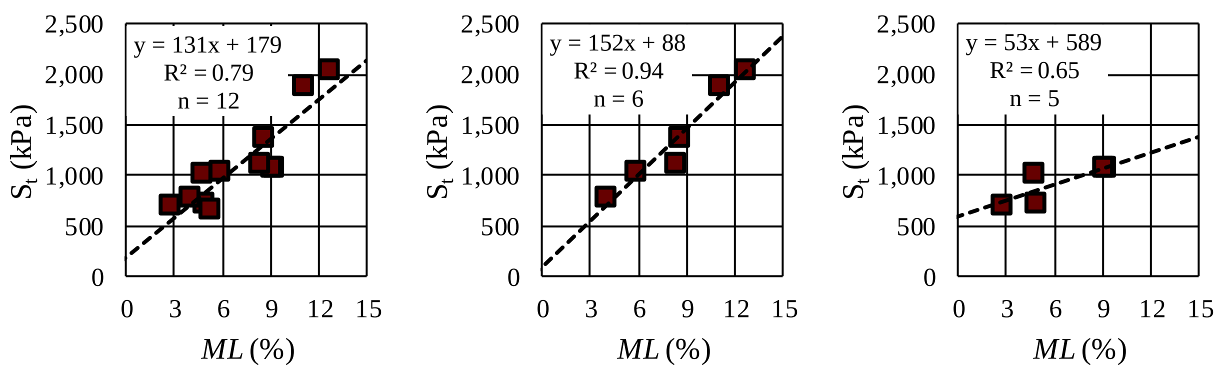
e.) CO-GR APA results

f.) CO-GR HLWT results

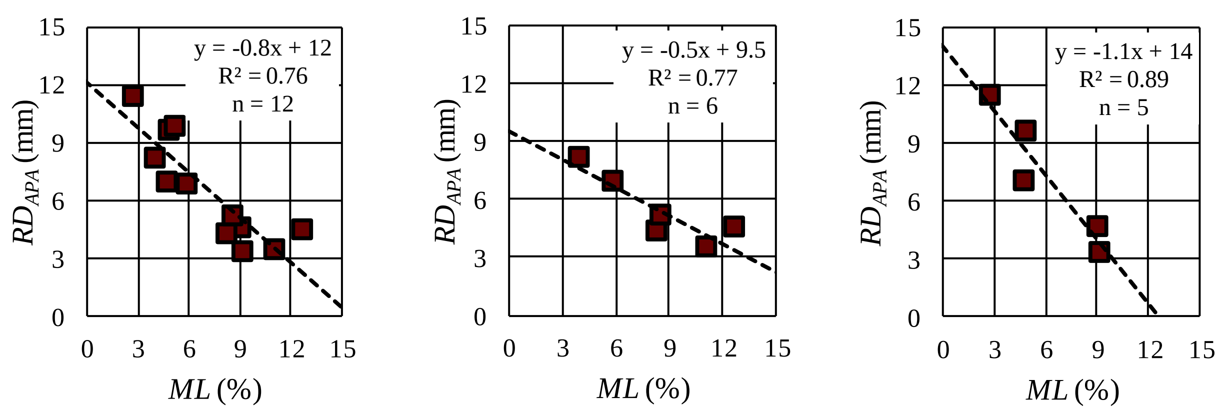
Figure 3.1. APA and HLWT Rutting Results

3.7 Discussion of Results

Figure 3.2 compares all four mixture test property results together to determine if a grouped analysis (all tests included) differs in findings than individual assessments (one test). Individual assessments indicated aggregate properties have probable meaningful implications on how the mixtures age. Figure 3.2a to 3.2c relate *ML* and S_t. Figure 3.2a plots all data together, while Figures 3.2b and 3.2c separate the data by presence of HLWT SIP. Figure 3.2a correlation was fairly reasonable, but the correlation substantially improved (R^2 increased from 0.79 to 0.94) when cases with a SIP were removed (Figure 3.2b). The correlation was lower (R^2 of 0.65) for cases that had a SIP (Figure 3.2c). Figure 3.2a to 3.2c trend line slopes show that moisture susceptibility appreciably affected tensile strength with higher moisture susceptibility leading to lower tensile strengths. Per unit increase in mass loss (*ML*), tensile strength (S_t) increased roughly three times faster when stripping did not occur. Stripping affected different aggregate types at varying levels which means the grouped assessment of HLWT, CML, and IDT is not meaningfully different than when the properties were individually assessed. Figures 3.2d to 3.2f relate CML and APA test results. As rut depth decreased, mass loss increased, which is expected since rutting is reduced by increased stiffness and mass loss increases when stiffening is caused by aging. When no stripping was present based on HLWT SIP data, rut depths decreased at a lower rate per unit increase in ML than when a SIP was present.



a.) S_t – All Data b.) S_t – No Stripping c.) S_t – Stripping



d.) RD_{APA} – All Data e.) RD_{APA} – No Stripping f.) RD_{APA} – Stripping

Figure 3.2. Between Property Comparisons of SAS Mixes

CHAPTER 4 - AIR FORCE BASE RESULTS

4.1 Overview of Air Force Base Results

Air Force Base (AFB) paving has stringent durability requirements, and as such this project made use of three plant mixed AFB materials as they are good references. The first was from the March Air Force Base (MAFB) in California. This material was selected since its binder grade is much different than used in traditional MDOT paving projects. The second AFB was in Columbus, MS (CAFB), which was selected since it is a short distance from the field test section described in Volume 2 of this report series.

4.2 Binder Testing Results

4.2.1 MAFB Binder Testing Results

Binder testing for MAFB (denoted M11 in Tables 1.1 to 1.3) was performed in three conditions: 1) 0 year field aged material (i.e. material to serve as a control that has only been short term aged in the plant and has not experienced any long term field aging), 2) tops of two year aged field specimens, and 3) bottoms of two year aged field specimens. Figure 4.1 is a photo of representative slices from the top (i.e. exposed to sunlight) and bottom (i.e. not exposed to sunlight) of MAFB two year field aged specimens. MAFB binder test results are provided in Table 4.1. Note that MAFB had a PG 70-10 binder and 0% RAP.

Figure 4.1. Photos of MAFB Core Slices Prior to Binder Recovery

Table 4.1. MAFB M11 Binder Test Results

Property	0 Year Field Aged	2 Year Field Aged Top	2 Year Field Aged Bottom
Pen (dmm)	21	17	18
T_c (DSR_{25}) (^oC)	79.9	81.9	80.4
T_c (DSR_8) (^oC)	24.8	24.3	25.0
T_c (BBR_S) (^oC)	-28.3	-28.0	-26.6
T_c (BBR_m) (^oC)	-28.3	-27.4	-27.3

Note: Air voids were 6.5 to 7.5% for these specimens during aging

4.2.2 CAFB Binder Testing Results

Binder testing for CAFB was performed on the same three conditions as MAFB. Figure 4.2 is a photo of representative slices from the top (i.e. exposed to sunlight) and bottom (i.e. not exposed to sunlight) of CAFB two year field aged specimens. The surface lift with PG 76-22 and 0% RAP is denoted M12, and the underlying base lift with PG 70-22 and 20% RAP is denoted M13 (Tables 1.1 to 1.3). CAFB binder results are in Tables 4.2 and 4.3.

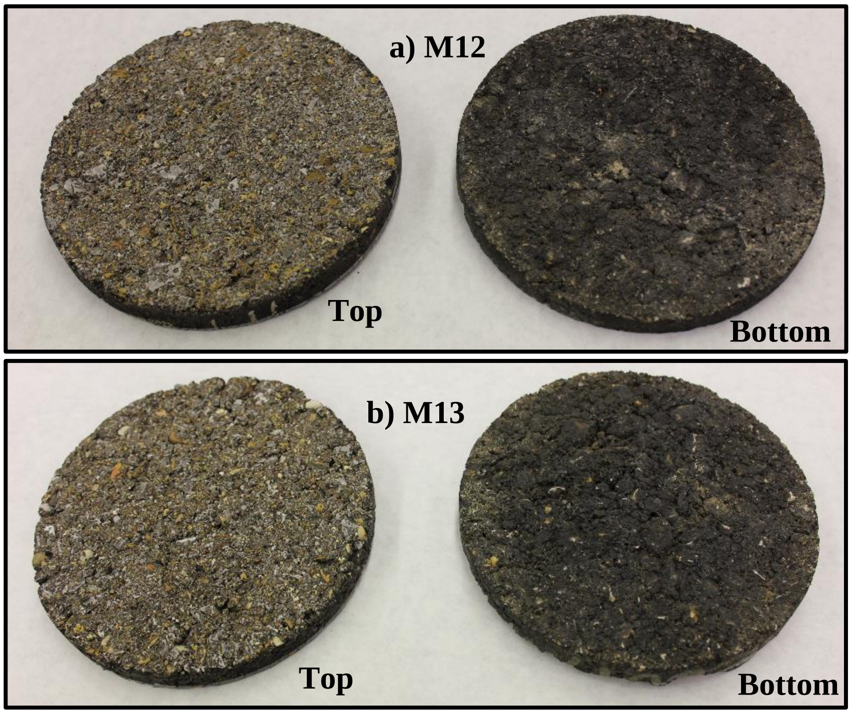


Figure 4.2. Photos of CAFB Core Slices Prior to Binder Recovery

Table 4.2. CAFB M12 Binder Test Results

Property	0 Year Field Aged	2 Year Field Aged Top	2 Year Field Aged Bottom
Pen (dmm)	27	17	17
T_c (DSR_{25}) (^oC)	82.7	90.5	88.1
T_c (DSR_8) (^oC)	21.8	22.7	20.9
T_c (BBR_S) (^oC)	-32.9	-31.5	-32.3
T_c (BBR_m) (^oC)	-30.1	-25.4	-28.1

Note: Air voids were 6.5 to 7.5% for these specimens during aging

Table 4.3. CAFB M13 Binder Test Results

Property	0 Year Field Aged	2 Year Field Aged Top	2 Year Field Aged Bottom
Pen (dmm)	22	9	11
T_c (DSR_{25}) (^oC)	86.5	100.9	96.4
T_c (DSR_8) (^oC)	22.7	27.7	26.8
T_c (BBR_S) (^oC)	-31.7	-32.5	-26.9
T_c (BBR_m) (^oC)	-28.0	-18.3	-20.9

Note: Air voids were 6.5 to 7.5% for these specimens during aging

4.3 Mixture Test Results

4.3.1 MAFB Mixture Test Results

Table 4.4 provides all MAFB mixture test results. Two laboratory items led to a non-symmetrical data set. In a few cases, CML specimens were compacted to two different air void levels as a result of initial terminology confusions. The specimens were properly compacted to the V_a levels shown in Table 4.4, but their densities bracketed that of specimens compacted for field aging, where a more ideal case would have been to compact all Table 4.4 CML specimens to the same air void level. The initial test plan also included SIDT testing after 2 years of field aging, but a slicing error prevented FE measurements at the two year interval. Binder testing after 2 years of field aging was not affected (see Section 4.2), but mixture testing was not possible on specimens that were sliced incorrectly.

Table 4.4. MAFB M11 Mixture Test Results

Conditioning	Sample	CML V_a (%)	CML *ML* (%)	IDT V_a (%)	IDT S_t (kPa)	SIDT V_a (%)	SIDT FE_{-10C} (kJ/m³)
0 Year Field Aged	3,4	7.4	10.5	7.1	2,439	7.0	0.58
0 Year Field Aged	3,4	5.9	10.5	---	---	---	---
1 Year Field Aged	3,4	7.5	12.6	7.1	2,475	6.8	0.85
1.5 Year Field Aged	3,4	7.4	14.1	7.1	2,475	---	---
2 Year Field Aged	3,4	7.4	13.9	7.1	2,533	---	---
CP1	3,4	6.2	11.9	---	---	---	---
CP1	7	8.4	16.5	---	---	---	---
CP6	3,4	6.2	12.4	---	---	---	---
CP6	7	8.3	13.6	---	---	---	---
CP2	3,4	6.1	13.3	---	---	---	---

-- Sample numbers refer to Rushing et al. (2014) and the corresponding information provided by ERDC with the samples received by MSU.
-- V_a was measured with T331.
-- Each measurement is based on three replicates; 48 mixture specimens were tested for this table.
-- 1 and 1.5 year field values coincidentally both had 7.1% air voids and the same tensile strength. Different measurements led to these average values.

Table 4.4 data was consolidated by, to the extent possible, estimating CML values at 7.4% air voids for the 0 year field aged material, CP1, and CP6. CP2 was only tested at 6.1% air voids, so adjustment was not possible in this case. Table 4.5 summarizes estimated CML values at as consistent as possible air void levels. The field aged data in Table 4.5 was plotted and a linear regression led to equation 4.1. Use of this equation for the three laboratory CP’s showed CP1 (AASHTO R30) simulating 2 years of field aging, CP6 simulating 1.3 years of field aging, and CP2 simulating 1.4 years of field aging. This assessment is approximate considering the air void adjustments needed to make this evaluation. It should also be noted that MAFB material was reported to be variable by Rushing et al. (2014) as APA testing with a 250 lb load and 250 psi hose pressure and found significant rutting variability.

ML = 1.9 (Years of Age) + 10.7 for M11 (R^2 of 0.92) (4.1)

Table 4.5. MAFB M11 Cantabro Results in Terms of Normalized Air Voids

Conditioning	CML	
	V_a (%)	*ML* (%)
0 Year Field Aged	7.4	10.5
1 Year Field Aged	7.5	12.6
1.5 Year Field Aged	7.4	14.1
2 Year Field Aged	7.4	13.9
CP1	7.4	14.4
CP6	7.4	13.1
CP2	6.1	13.3

a: sample numbers refer to ERDC report and information provided with the samples received by MSU

4.3.2 CAFB Mixture Test Results

Tables 4.6 and 4.7 provide plant mixed CAFB mixture test results. Equations 4.2 and 4.3 were produced from field aged data in a similar manner as equation 4.1. These equations were used to estimate the amount of field aging simulated by each of the laboratory conditioning protocols, which are summarized in Section 4.4.

Table 4.6. CAFB M12 Mixture Test Results

Conditioning	*ML* (%)	S_t (kPa)	FE_{+20C} (kJ/m^3)	FE_{-10C} (kJ/m^3)	RD_{HLWT} (mm)
0 Year Field Aged	11.6	1,812	3.05	0.71	2.1
1 Year Field Aged	13.5	2,008	---	0.65	---
1.5 Year Field Aged	13.6	2,102	---	---	---
2 Year Field Aged	15.7	2,209	---	---	1.4
CP1	16.8	---	---	---	---
CP2	14.5	---	---	---	---
CP4	19.1	---	---	---	---
CP5	21.1	---	---	---	---
CP6	18.4	---	---	---	---
CP7	24.6	---	---	---	---

-- V_a was 6.5 to 7.5% on a T331 basis for these specimens

Table 4.7. CAFB M13 Mixture Test Results

Conditioning	*ML* (%)	S_t (kPa)	FE_{-10C} (kJ/m^3)
0 Year Field Aged	15.1	2,271	0.54
1 Year Field Aged	17.9	2,405	0.49
1.5 Year Field Aged	17.5	2,514	---
2 Year Field Aged	19.4	2,667	---
CP1	19.0	---	---
CP2	18.7	---	---
CP6	22.9	---	---

-- V_a was 6.5 to 7.5% on a T331 basis for these specimens

$$ML = 1.9\,(\text{Years of Age}) + 11.5 \qquad \text{for M12} \qquad (R^2 \text{ of } 0.91) \tag{4.2}$$
$$ML = 2.0\,(\text{Years of Age}) + 15.3 \qquad \text{for M13} \qquad (R^2 \text{ of } 0.89) \tag{4.3}$$

4.4 Discussion of Results

Table 4.8 summarizes the amount of field aging simulated by each of the Table 2.6 laboratory conditioning protocols. These ages are approximate and are based on equations 4.1 to 4.3. Note that there are modest differences in the values reported in Table 4.8 and those reported in Table 6 of Cox et al. (2017) for the same mixture. Cox et al. (2017) did not use 1.5 year field aged data in their regressions, while Table 4.8 did make use of this data. There are no practical differences in the two sets of values as the ability to estimate field aging to the nearest year would be considered a major improvement relative to current capabilities and the differences between these two values are 0.3 years or less.

Table 4.8. Years of Field Aging Simulated by Laboratory Conditioning Protocols

	MAFB M11	CAFB M12	CAFB M13
CP1	2.0 years	2.8 years	1.8 years
CP2	1.4 years	1.6 years	1.9 years
CP4	---	4.1 years	---
CP5	---	5.2 years	---
CP6	1.3 years	3.7 years	3.9 years
CP7	---	7.0 years	---

Table 4.8 is a key piece of information from this report (Volume 1) that is utilized in the remaining reports (Volume 2 and Volume 3). The data suggests that laboratory conditioning protocols need to be severe to simulate environmental effects over many years in the Mississippi climate. Of particular interest is CP1 (AASHTO R30), which simulated less than 3 years in the Mississippi climate.

Figure 4.3 plots mass loss versus tensile strength for field aged mixes 11 to 13 from Tables 4.4, 4.6, and 4.7. Binder properties and supporting mixture data presented earlier in this chapter are used for assessment of Figure 4.3. MAFB (M11) had a very flat slope showing that tensile strength (S_t) did not change but *ML* increased. Binder properties stiffened slightly. M11's *ML* increase was less than that of CAFB (M12 and M13).

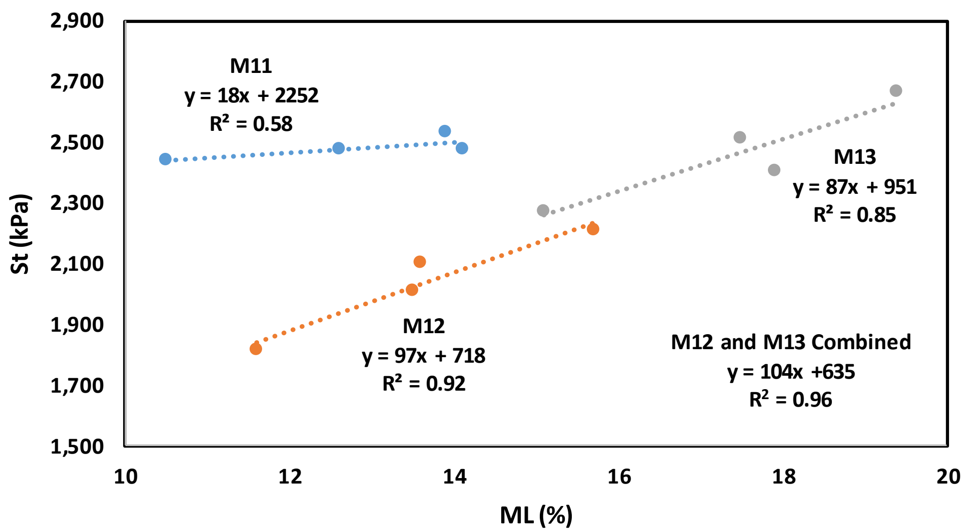


Figure 4.3. Tensile Strength versus Mass Loss for Field Aged AFB Mixtures

M11 did not behave in an intuitive way across all data collected. The PG 70-10 binder had measured properties rivaling the M12 PG 76-22, which was very surprising. As an example, the two year T_c (BBR_m) was -27.4 °C for M11 tops, which is better than the -25.4 °C for M12 in the same conditions. Also, FE increased after field aging, which is not intuitive. As measured, M11 S_t agreed better with binder properties than *ML*. S_t and binder suggested little to no aging, whereas *ML* suggested M11 became more brittle while outdoor aged. Data presented in Volume 2 and Volume 3 of this report are much more convincing and show *ML* to be a better intermediate temperature mixture property assessment to capture environmental aging effects than is tensile strength.

ML and S_t for the PG 70-22 and 20% RAP M13 was higher than the PG 76-22 and 0% RAP M12. These findings agree with intuition and also with measured binder properties. Polymer modification leading to a stiffer system would be expected to lead to less brittleness potential than use of RAP. There was a strong linear trend between tensile strength and mass loss for both CAFB mixes. Hamburg data for M12 showed no stripping and very modest rutting, and under these conditions it is not surprising that *ML* and S_t tracked with each other.

CHAPTER 5-SUMMARY AND CONCLUSIONS

5.1 Summary

This report contains supporting information intended to improve the characterization of aging within asphalt mixtures. This supporting information relates to the behavior of asphalt mixtures produced with a single aggregate type, and of air force base mixtures. The data presented is not for consideration for direct use by MDOT, rather this data is to serve as a reference for data contained in volumes 2 and 3 of this series where this report is Volume 1. The cumulative goal of all three report volumes is to investigate: 1) the effects field aging has on asphalt concrete produced at a hot mix temperature and hauled long distances; and 2) the effects field aging has on asphalt concrete produced at different mixing temperatures and hauled a moderate distance.

5.2 Conclusions

Conclusions relevant to the cumulative goal of this research that are relevant to the contents of volumes 2 or 3 of this report series are listed below. Volumes 2 and 3 contain the most meaningful findings from the work of State Study 266 and State Study 270.

1. Single aggregate source results showed there are differences in asphalt mixture mechanical properties before and after aging based on aggregate type, all other factors being essentially the same. All mechanical tests found asphalt-aggregate interaction to be considerably different based on aggregate type. Differences were amplified by field aging. Production temperature was a meaningful factor for mixture aging with some aggregate-asphalt combinations. Warm mix technology showed no detectable influence on tensile strength. Overall, aggregate properties were shown to have probable implications on mixture aging, thus volumes 2 and 3 of this effort focused on aging within mixtures.

2. Single aggregate source results showed Cantabro mass loss to indirect tensile strength relationships were affected by stripping. Absent stripping, tensile strength increased roughly three times faster relative to mass loss than when there was evidence of stripping. This is meaningful relative to tensile strength and/or mass loss's ability to capture environmental effects on mixture aging, which is more comprehensively addressed in volume 2 and volume 3 of this effort. Air force base mixture testing led to some additional supplementary information for comparing mass loss to tensile strength for purposes of evaluating environmental effects on mixture aging, but did not lead to any specific additional conclusions to add those from single aggregate source mixture testing.

3. Air force base mixture testing led to Table 4.8, which contains a summary of how many years of field aging various laboratory conditioning protocols were able to simulate. The data suggested that laboratory conditioning protocols need to be severe to simulate environmental effects over many years in the Mississippi climate. The laboratory conditioning protocols investigated in this report are further assessed in volumes 2 and 3 of this effort.

CHAPTER 6 - REFERENCES

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