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Performance Oriented Guidance for Mississippi Chip Seals-Volume I

Final Report

FHWA/MS-DOT-RD-13-211-Volume I

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Supplementary Notes: Work performed under Mississippi State University research project titled: *Laboratory Testing and Evaluation of Near Surface Properties of Flexible Pavements Due to Bituminous Surface Treatments.* The work performed for this report was under Mississippi Department of Transportation State Study 211 and principal investigator Isaac L. Howard. A second report was also written and performed as part of State Study 211, which was given the report number FHWA/MS-DOT-RD-13-211-Volume II. Volume II dealt primarily with testing chip seals fabricated on top of compacted asphalt concrete.

16. Abstract

A five year laboratory study was conducted to investigate near surface properties of flexible pavements in relation to how they are affected by bituminous surface treatments. Chip seals and scrub seals (a specialized type of chip seal) were the focus of the study. Seven emulsions, three aggregates, and four asphalt pavement types were tested. The overall objective was to provide MDOT with performance oriented guidance for chip seals. This overall objective was divided into aggregate retention and rejuvenation of the existing pavement's near surface. Repeated creep of mixture bars, viscosity change of recovered binder, and Bending Beam Rheometer (BBR) mixture beam responses were used to assess rejuvenation effects of chip seals on a pavement's near surface. Vialit adhesion, frosted marble, and sweep testing were used to assess aggregate retention behavior. Within the six test methods studied, some were used without modification, while others were modified during this research. Over 2,000 experiments were performed for this report. Key rejuvenation testing included: 24 repeated creep torsion bars, 168 viscosity change measurements, and 959 BBR mixture beams. Key aggregate retention testing included: 231 Vialit trays, 221 frosted marble trays, and 533 sweep pads. Key performance oriented recommendations included: requiring a minimum *m-value* increase of a BBR mixture beam due to emulsion application when rejuvenation is of high importance, monitoring moisture loss of a chip seal system for traffic opening determination, and specifying chip seal systems (i.e. aggregate and emulsion) as opposed to independently approving chip seal materials.

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LIST OF SYMBOLS

$\%_{total}$	Percentage of total number of attempted *BBR* beams for a given pavement
A	Percent of aggregate from 9.5 to 6.3 mm size
AASHTO	American Association of State Highway and Transportation Officials
Abs	Water absorption
ACT	Absolute cure time (hr)
ADT	Average daily traffic
AEMA	Asphalt Emulsion Manufacturers Association
AI	Asphalt Institute
ALD	Average least dimension
ANOVA	Analysis of variance
b	Width (mm)
B	Percent of aggregate from 6.3 to 4.75 mm size
BBR	Bending beam rheometer
C_i	Regression coefficient *i*
CCT	Critical cure time
C.I.	Confidence interval
COV	Coefficient of variation
CTI	Cure time interval (1, 2, 3, …, 13)
C_u	Coefficient of uniformity (D_{60} / D_{10})
D	Mass of asphalt felt disk (g)
df	Degrees of freedom
D_{10}	Particle diameter where 10% of the particles pass
D_{60}	Particle diameter where 60% of the particles pass
Dia.	Diameter
DOT	Texas Department of Transportation
DSR	Dynamic shear rheometer
E	Depth of embedment
E_{mass}	Mass of emulsion, target 83 ± 5, actual value recorded and used (g)
ERDC	US Army Research and Development Center
FAT	Factorial arrangements of treatments
FI	Flakiness index expressed as percent
FMT	Frosted marble test
FR	Frontage Road
FWD	Falling weight deflectometer
F_ε	Cumulative strain at failure
G_{mb}	Mixture bulk specific gravity (g/cm^3)
G_{sb}	Aggregate bulk specific gravity (g/cm^3)
gsy	Gallons per square yard
G_{mm}	Mixture maximum theoretical specific gravity (g/cm^3)
H	Average least dimension (in)
h	Thickness (mm)
H_a	Alternative hypothesis
HF	High float
HMA	Hot mixed asphalt

H_o	Null hypothesis
Hwy 17	Highway 17
Hwy 45	Highway 45
IDT	Indirect tensile
IRI	International roughness index
k	Permeability
L	Length (mm)
LTP	Long term performance
LTPP	Long Term Pavement Performance
LVM	Loose vehicle measure
M	Median particle size (inches) ($\geq$ 50% passing)
m	Slope
M_d	Mean difference
MDOT	Mississippi Department of Transportation
ME	Margin of error of the estimate
M_L	Mass loss (%)
$M_{L(CCT)}$	Critical mass loss
$M_L IP$	Mass loss inflection point
MnDOT	Minnesota Department of Transportation
Mod	Modified trays
MS	Medium set
m-value	Instantaneous slope of the creep stiffness curve
m-value$_T$	Emulsion treated *m-value*
m-value$_U$	Untreated *m-value*
n	Number of replicates
$n_{analysis}$	Number of replicates analyzed after outlier removal
NCPP	National Center for Pavement Preservation
NMAS	Nominal maximum aggregate size
N_{min}	Minimum number of replicates targeted
NS	Non-scraped specimens
N-S	Not significant
n_{tested}	Number of replicates tested
P	Load
PAV	Pressure aging vessel
PCR	Pavement condition rating
$p_{critical}$	Critical *p-value*
PG	Performance grade
Post-cure	Mass of specimen after curing but before initial brushing (g)
Post-sweep	Mass of specimen after sweep test and final brushing (g)
Pre-cure	Mass of specimen immediately after compaction and before curing (g)
Pre-sweep	Mass of specimen after initial brushing but prior to sweep test (g)
PTSi	Paragon Technical Services, Inc.
P-value	Normality statistic
p-value	Probability of observing a test statistic at least as extreme as that observed
R	Emulsion application rate (L/m^2)
R	Percent residual asphalt in the emulsion according to ASTM D244

R^2	Coefficient of determination
R^2_{adj}	Adjusted coefficient of determination
RAP	Reclaimed asphalt pavement
RC	Repeated creep
RH	Relative humidity
Roto-Vap	Rotational-vaporation
RS	Rapid set
RTFO	Rolling thin film oven
RTO	Linear regression through the origin
RVE	Representative volume element
S	Significant
SBR	Styrene butadiene rubber
SBS	Styrene-butadiene-styrene
SCR	Scraped specimens
$S_{D(\%)}$	Stiffness decrease (%)
S_e	Estimated creep stiffness
SFS	Saybolt Furol seconds
SHRP	Strategic Highway Research Program
S_m	Measured creep stiffness at a given time t
Spec	Specification
SPG	Surface PG system
SS	Slow set
SSD	Saturated surface dry
S_t	Indirect tensile strength at failure
S_T	Emulsion treated stiffness (GPa)
St. Dev.	Standard deviation
S_U	Untreated stiffness (GPa)
T	Cure time (hr)
T_c	Critical failure temperature
$T_{c,BBR\text{-}m\text{-}value}$	Critical failure temperature according to *BBR m-value*
$T_{c,BBR\text{-}S(t)}$	Critical failure temperature according to *BBR* Stiffness
$T_{c,PAV\ DSR}$	Critical failure temperature according to *PAV*-Aged *DSR* G*(sinδ)
$T_{c,\text{un-aged } DSR}$	Critical failure temperature according to Un-Aged *DSR* G*/sinδ
TCE	Trichloroethylene
TFF	Tertiary flow failure
T-I	Temperature interval
TL	Total loss
Torque	Torque (kg-cm)
T_s	Stress level used during the test
UFGS	Unified facilities guide specification
USACE	US Army Corps of Engineers
UTI	Useful temperature interval
V	Voids in the loose aggregate
V_a	Air voids (%)
$V_{a,crit}$	Air void level at which excessive permeability occurs
$V_{D\%}$	Viscosity decrease (%)

VMA	Voids in mineral aggregate
V_T	Emulsion treated viscosity
V_U	Untreated viscosity
W	Loose unit weight
W_L	Moisture loss (%)
$W_{L(CCT)}$	Critical moisture loss
y	Relative viscosity
Y	Amount of aggregate needed for sweep test (g)
$z_{\alpha/2}$	1.15 for 75% C.L.; 1.44 for 85% C.L.; 1.96 for 95% C.L
β	Coefficient of an independent variable for a multiple regression model
$(\Delta\varepsilon/\Delta T)^{-1}$	Inverse of slope in the secondary flow region
Δ*m-value*	Increase in *m-value*
δ	Deflection at a given time t (mm)
ε	Random error of the model
$\varepsilon(5\%)_T$	Time to 5% cumulative strain

CHAPTER 1-INTRODUCTION

1.1 General and Background Information

Pavement preservation refers to activities including corrective maintenance, preventive maintenance, and rehabilitation that are intended to extend life and enhance performance. The American Association of State Highway and Transportation Officials (AASHTO) defines preventive maintenance as a planned strategy of cost effective treatments to an existing roadway system that preserves the system, retards future deterioration, and maintains or improves functionality of the system without substantially increasing structural capacity. Preventive maintenance of asphalt concrete can often extend the pavement life for several years at relatively low costs (Brown, 1988). There are several types of preventive maintenance including rejuvenators, slurry seals, crack sealing, fog seals, scrub seals, and chip seals. Some treatments can be designed to serve multiple functions (e.g. chip seal with rejuvenating emulsion).

Construction of the Interstate Highway System commenced around 1956. Subsequent efforts focused on development of state highways and low volume roads that has developed one of the most advanced highway systems in the world. Decades ago, development was of primary concern, while preservation and maintenance were of much lesser scale. However, as the US highway system has aged, preservation and maintenance have become more of a priority. Toward this end, the National Center for Pavement Preservation (NCPP) was established in 2004. NCPP serves many functions, with one being to compile pavement preservation research.

In addition to the pavement network needs described in the previous paragraph, severe budget problems have led to enhanced focus on preservation activities. As an example, current budgets often prohibit asphalt overlays to be placed on low volume roads. According to Kuennen (2006), experience shows that spending $1 on pavement preservation before the point of rapid and precipitous deterioration can delay or eliminate spending $6 to $10 in future rehabilitation or reconstruction. Unfortunately, problems must develop prior to many agencies spending funds from their very limited budgets.

At the 2010 *Mississippi Quality Asphalt Conference* it was reported by the Mississippi Department of Transportation (MDOT) that 1,250 lane miles needed rehabilitation in District 1 alone at an estimated cost of $190 million. At the same conference, representatives of the Texas Asphalt Pavement Association indicated the Texas Department of Transportation (DOT) spends $350 million annually on seal treatments.

As preservation activities have yet to be studied to the extent of new construction since new construction activities have been of paramount interest to many for several decades, there is great advancement potential in the area of pavement preservation. Many parameters could be improved, notably optimal timing for treatment application, improved decision trees, and performance based material/construction specifications. A variety of preservation materials are available (several are propriety), and they can be tailored for items including rejuvenation, sealing, aggregate retention, or a combination. Performance oriented thresholds are especially useful for propriety products.

Of the pavement preservation techniques, chip seals are often the most cost effective and are commonly used. Chip seals cover more than 139,700 miles of pavement surfaces in the US, in addition to their extensive use in other areas such as Australia, Europe, and New

Zealand (Gransberg and James 2005). According to Roads and Bridges (2004), over 800 million m^2 of chip seals are applied yearly in the US.

A chip seal is constructed of a layer of asphalt binder or emulsion topped with a layer of embedded aggregate lying one stone thick. The primary role of a chip seal is to prevent water intrusion into the base and subgrade by sealing the fine cracks in the underlying pavement (Gransberg and James, 2005). The application of the aggregate protects the asphalt layer and creates a macrotexture creating a skid-resistant surface for vehicles. A scrub seal is similar to a chip seal except the asphalt binder or emulsion is scrubbed into the voids and cracks of the underlying pavement with a broom before aggregate application. An additional potential benefit of these treatments is the rejuvenation of the existing pavement surface to restore some desirable properties lost to aging.

1.2 Objectives

The primary objective of this report is to provide performance oriented guidance for chip and scrub seals used by MDOT. Generally speaking, the primary objective was divided into aggregate retention of the seal and rejuvenation of the existing pavement's near surface; areas (1) and (2) of Figure 1.1, respectively. The project's objectives were accomplished within the scope described in the next section.

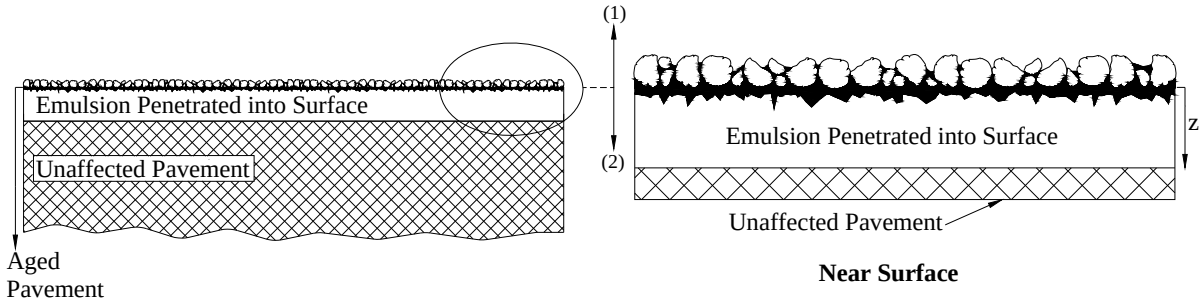


Figure 1.1. Schematic of Chip Seal and Pavement Near Surface

1.3 Scope

State Study 211 was reported in two volumes. This report (Volume I) contains most of the project's findings and focuses on laboratory testing and characterization. Volume II focuses on efforts to develop a long term performance (LTP) test for chip seals where two field projects (*Hwy 44* and *Hwy 366*) are a central component. LTP efforts focused on aggregate retention characteristics.

This report devoted most of its efforts to investigating (and in some cases modifying) test methods for their potential to add value to performance specifications. A literature review (Chapter 2) was performed and used as a guide during experimental program development and analysis. Findings from MDOT State Study 202 were part of the literature review and were leveraged during State Study 211 research. The same chip seal materials evaluated on *Hwy 17* and *Hwy 35* of State Study 202 were tested in this report, while findings from *Hwy 84* were used to guide certain test method protocols.

Emulsions were then selected to represent the Mississippi emulsion market, and candidate chip seal aggregates and existing pavement surfaces were also selected (Chapter

3). An extensive suite of laboratory tests was then developed for these materials (Chapter 4) where the two performance attributes of interest were rejuvenation (i.e. effect of chip seal on the existing pavement's near surface) and aggregate retention. Each behavior was investigated using multiple test methods as described below.

1. Investigate Effect of Emulsion on Existing Pavement Surface
    a. Repeated Creep testing of emulsion treated torsion bars (Chapter 5)
    b. Viscosity testing of binder extracted from emulsion treated surfaces (Chapter 6)
    c. Bending Beam Rheometer testing of emulsion treated mixture beams (Chapter 7)

2. Investigate Seal Treatment Aggregate Retention Characteristics
    a. Vialit adhesion testing of chip seal systems (Chapter 8)
    b. Frosted marble testing of emulsions adhered to standard materials (Chapter 9)
    c. Sweep testing of chip seal systems (Chapter 10)

Once all tests were evaluated individually, they were evaluated and discussed collectively in Chapter 11. This evaluation considered rejuvenation or aggregate retention, and then where applicable provided insight between rejuvenation and aggregate retention. From all findings, performance specification conclusions and recommendations were made in Chapter 12.

CHAPTER 2-LITERATURE REVIEW

2.1 Overview of Literature Review

Material properties, design methods, and construction practices are fundamental chip seal components. This report focuses largely on material properties, and Section 2.2 summarizes current information that describes many aspects of current practice as pertaining to chip seal materials. A conceptual overview of design methods (Section 2.3) is provided to complement chip seal material properties. Thereafter, the current state of practice within MDOT is described (Section 2.4), followed by a previous MDOT chip seal study largely based on field testing and focusing on construction practices (Section 2.5).

Performance is a key attribute for this report. To complement the broad assessments presented in Sections 2.1 to 2.5, Sections 2.6 and 2.7 focus on the two performance attributes of interest in this research. Early aggregate loss is often a chip seal failure mode. Binder stiffening can also be a deterioration factor. A treatment that can extend time before air and water can circulate within the pavement can delay stiffening and subsequent cracking. Rejuvenators are intended to replace lighter binder constituents that have been depleted with time to restore a softer consistency. A variety of fundamental concepts related to rejuvenation and aggregate loss as well as tests to characterize both are reviewed in Sections 2.6 and 2.7.

2.2 Chip Seal Material and Existing Pavement Properties

2.2.1 Emulsions

Chip seal materials consist of an asphalt binder (emulsions are of relevance to this report) and cover aggregates (chips). These materials are placed onto an existing pavement surface (asphalt concrete is the surface of relevance to this report). The remainder of this section describes pertinent properties of each of these materials and describes their corresponding performance characteristics.

Setting refers to the rate emulsions interact with chips and the pavement surface. Generally, emulsion designations as per ASTM D3628 are rapid set (RS), medium set (MS), and slow set (SS). Most surface treatments use rapid set emulsions to facilitate traffic opening (Roberts et al., 1996). High float (HF) is another emulsion category (ASTM D139) with modified rheology, increased flow time, and generally thicker consistency.

Emulsions are also described by their charge: cationic (positive charge); anionic (negative charge). McHattie (2001) indicated cationic emulsions outperformed anionic emulsions on chip seals, are less prone to stripping, are less sensitive to weather conditions, and have better electrostatic aggregate compatibility. Anionic emulsions break by evaporation and are not desired in humid conditions because curing is slowed (Shuler et al., 2011). Polymer modified emulsions are known for improving chip seal durability and providing earlier chip retention, which is ideal for higher volume roads. Styrene Butadiene Rubber (SBR) and Styrene-Butadiene-Styrene (SBS) are commonly used emulsion polymers. For example, CRS-2P is a polymerized CRS-2 emulsion; these two emulsions are commonly used for surface treatments.

Emulsion formulations from the same plant and supplier are often adjusted slightly depending upon the time of year and asphalt source available to the plant at the time of production. These emulsions would maintain the same category (e.g. CRS-2P), but their performance behavior may vary. As a result, specifying a desired outcome for a given application rather than an emulsion category appears to be a worthwhile area of study.

Chip seals rely heavily on the type of asphalt emulsion chosen, as different emulsions can have very different performance characteristics. The Minnesota Department of Transportation (MnDOT) requires CRS-2P emulsion and restricts use of latex modified emulsion to allow faster sweeping (Wood et al., 2006). In Ohio, polymer modified emulsion is used for average daily traffic (ADT) greater than 500 (ODOT, 2010).

Historically, two ASTM classification methodologies have been used repeatedly for bituminous materials: 1) penetration at 25 C (D946) and viscosity at 60 C (D3381). ASTM D244 (AASHTO T59 is equivalent) has historically been used for testing and evaluation of emulsified asphalts. Current methods of selecting emulsions (e.g. M140, M208, and M316) typically use empirical approaches. These specifications use tests such as viscosity, storage stability, demulsibility, coating ability, water resistance, sieve, and distillation residue to define asphalt emulsion type. Residue behavior is characterized by tests such as penetration, ductility, solubility, and elastic recovery. Though the properties obtained from the AASHTO test methods have many uses, they do not directly address application specific emulsion performance. These approaches provide useful information regarding material consistency and provide a communication medium between users and suppliers. They do not necessarily provide insight into viscoelastic behavior over the full in-service temperature spectrum, short-term and long-term aging, or interaction with existing pavement.

Epps et al. (2001) developed a modified performance grade (PG) system for binders and emulsions used in surface treatments using existing equipment. The new surface PG system (SPG) uses 3 C increments for both high and low temperature grades. It does not use the rolling thin film oven (*RTFO*) since surface treatment binders are generally not heated prior to construction to the extent of typical hot mix asphalt. It also forgoes the intermediate grading temperature because trends were not well established and, therefore, were non-discriminatory. Aging evaluations were performed using *FTIR* spectroscopy, the *PAV*, and a 60 C environmental chamber (1 mm thick films analyzed). The analysis concluded *PAV* aging or two months in the 60 C environmental chamber is equivalent to approximately one season of surface treatment exposure (the failure of the majority of surface treatments was stated to occur in either the first summer or winter). For application of the binder (i.e. spraying), rotational viscosity should be 0.1-0.15 Pa-s at the application temperature, not to exceed 180 C. The *DSR* was used to evaluate shear resistance at high temperature (controls aggregate loss). A minimum $G^*/\sin\delta$ of 0.75 kPa (traditionally measured) separated binders that performed well from those that did not. Low temperature binder behavior was measured on *PAV* samples (aged at 90 or 100 C depending on the grade) in the *BBR* at 8 seconds rather than 60 seconds since thermal cracking is of less concern for surface treatments and the fastest loading time would better simulate critical traffic loading conditions. Testing was conducted at the low temperature, as opposed to 10 C warmer as is typically performed. Threshold flexural stiffness and *m-values* were 500 MPa and 0.24, respectively.

2.2.2 Aggregates

In general, more uniformly-graded aggregate promotes long-term adhesion, higher surface friction, and better waterproofing (Wood et al., 2006). Chip seal performance improves with use of cubical aggregates having crushed faces, good abrasion and degradation resistance, and minimal adhered fines. Well-graded aggregates generally exhibit poor retention because smaller aggregates tend to inhibit proper embedment of larger aggregates. Larger particles are the first to be dislodged and are most likely to cause vehicle damage. In practice, chip seals are sometimes constructed using well-graded aggregates as they are less expensive, but shorter service life is expected as a result. Tables 2.1 and 2.2 present chip seal aggregate gradations from literature. Table 2.3 provides recommended aggregate property ranges from Shuler et al. (2011).

For chip seal aggregates, NCHRP Report 680 (Shuler et al., 2011) recommends an ASTM D2487 coefficient of uniformity (C_u) less than 4.0 (defines a uniformly-graded aggregate), high fractured faces, and low flakiness index (measure of particle's length compared to width). C_u is defined as the ratio of the particle diameter where 60% of the particles pass (D_{60}) to the particle diameter where 10% of the particles pass (D_{10}).

Table 2.1. Chip Seal Gradations Expressed in Percent Passing (1 of 2)

Source	MDOT (2004)	MDOT (2004)	MDOT (2004)	ODOT (2010)	Gransberg and James (2005)	Gransberg and James (2005)	Gransberg and James (2005)	Gransberg and James (2005)	Gransberg and James (2005)	Gransberg and James (2005)
Designation	*Size 7*	*Size 8*	*Size 89*	---	*Alaska E Chip*	*Arizona Low Traffic*	*Arizona High Traffic*	*Minnesota Aggregate*	*Minnesota Choke Stone*	*Montana Grade 4A*
19.0 mm	100	100	100	100	100	100	100	100	100	100
12.5 mm	90-100	100	100	100	100	100	100	100	100	100
9.5 mm	40-85	85-100	90-100	85-100	90-100	100	70-90	90-100	100	100
6.35 mm	---	---	---	---	---	70-90	0-10	40-70	100	---
4.75 mm	0-15	10-30	20-55	5-25	10-30	1-10	---	0-15	85-100	0-30
2.36 mm	0-5	0-10	5-30	0-10	0-8	0-5	0-5	0-5	10-40	0-15
1.18 mm	0-5	0-5	0-10	0-5	---	---	---	---	---	---
0.60 mm	---	---	---	---	---	---	---	---	---	---
0.42 mm	---	---	---	---	---	---	---	---	0-5	----
0.30 mm	---	---	---	---	---	---	---	---	---	---
0.075 mm	---	---	---	1.5 max	0-1	0-1	0-1	0-1	0-1	0-2

-- MDOT (2004) requirements from Section 703.14 of Mississippi's Standard Specifications.

-- ODOT (2010) requirements from specification Table 4.22.02-1. Washed limestone or dolomite is used in a uniform gradation for chip retention.

Table 2.2. Chip Seal Gradations Expressed in Percent Passing (2 of 2)

Source	Gransberg and James (2005)	Gransberg and James (2005)	Shuler et al. (2011)	Shuler et al. (2011)	Shuler et al. (2011)
Designation	*South Dakota Type 4A*	*South Dakota Type 1B*	*Gradation A*	*Gradation B*	*Gradation C*
19.0 mm	100	100	100	---	---
12.5 mm	100	100	90-100	100	---
9.5 mm	40-70	100	5-30	90-100	100
6.35 mm	---	---	---	---	---
4.75 mm	0-15	10-90	0-10	5-30	90-100
2.36 mm	0-5	0-30	---	0-10	5-30
1.18 mm	---	---	0-2	---	---
0.60 mm	---	---	---	0-2	---
0.42 mm	---	0-4	---	---	---
0.30 mm	---	---	---	---	0-2
0.075 mm	0-1	---	0-1	0-1	0-1

-- Shuler et al. (2011) are recommended gradations from NCHRP Report 680.

Table 2.3. Recommended Gradation Properties by Shuler et al. (2011)

Property	Gradation A	Gradation B	Gradation C
D_{60} (mm)	10.8-11.4	6.8-7.8	3.4-3.9
D_{10} (mm)	4.75-9.65	2.38-5.03	1.19-2.5
C_u	1.18-2.27	2.86-3.28	1.56-2.86
M (mm)	10.3-11.1	6.15-7.3	3.1-3.7

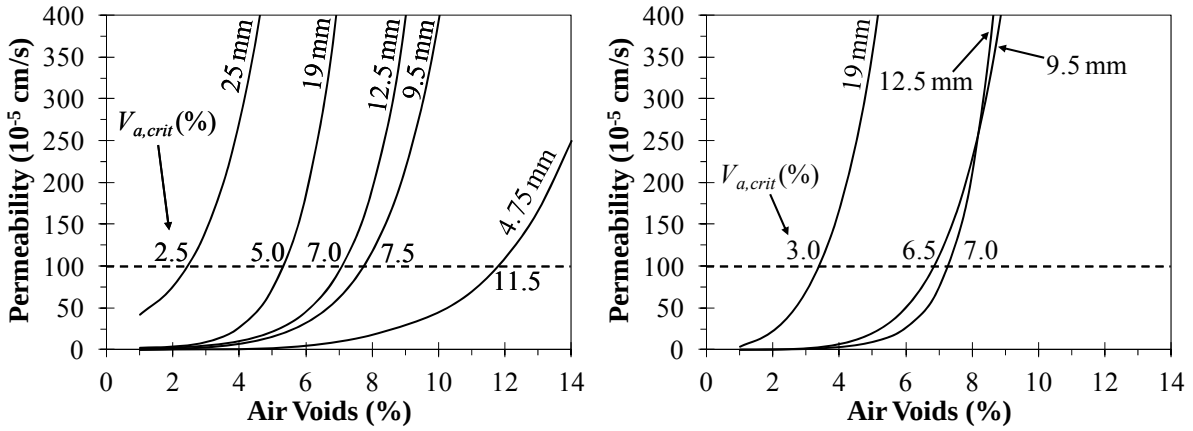
-- Gradations A, B, and C are those presented in Table 2.2.
-- Values provided for D_{60}, D_{10}, C_u, M are minimum interpolated requirements.
-- M = Median Particle Size

2.2.3 Existing Pavements

Generally pavements that are structurally sound and in good condition (minimal cracks, minimal raveling or aging) are candidates for good chip seal performance. The amount of oxidation, flushing, raveling, and so forth affect the amount of emulsion needed for a properly performing chip seal. Existing surface irregularities are an important consideration that can vary from one pavement to the next. More detailed information is provided later in this chapter that is directly related to aggregate retention and rejuvenation, while the remainder of this section addresses pavement permeability.

The rejuvenation potential of a chip seal emulsion may be affected by permeability of the existing pavement (may facilitate emulsion penetration); aging characteristics will also play some role in rejuvenation potential, though permeability can also affect aging. Numerous researchers have shown that permeability generally increases with nominal maximum aggregate size (NMAS) and air voids (Zube, 1962; Choubane et al., 1998; Cooley and Brown, 2000; Mallick et al., 2001, 2003). Excessive permeability from a durability and performance standpoint is commonly defined as permeability greater than 100×10^{-5} cm/s (Mallick et al., 1999, 2001; Maupin, 2001; Mogawer et al., 2002; Williams, 2006).

Figure 2.1a displays permeability as a function of air voids and NMAS constructed from literature sources (Mogawer et al., 2002; Cooley et al., 2002a, 2002b; Cooley, 2003; Cross and Bhusal, 2009; West et al., 2011). Figure 2.1b is a similar plot constructed using permeability data from Mississippi pavements (Cooley, 2003). The 9.5 mm and 12.5 mm plots overlap each other because 9.5 mm mixtures were coarse-graded and 12.5 mm mixtures were mostly fine-graded. All other factors being equal, fine gradations generally exhibit lower permeability than coarse gradations (Mogawer et al., 2002). The air void level at which excessive permeability occurs ($V_{a,crit}$) increases as NMAS decreases. Brown (1988), primarily addressing fog seals, concluded 7-8% V_a is necessary to provide adequate permeability to allow sufficient rejuvenator penetration. King and King (2008) suggested permeability testing may be a good measure for predicting emulsion infiltration, but there appears to be little published research to date to verify this concept.



a) All Mixtures in Literature *b) Mississippi Mixtures*

Figure 2.1. Average Permeability vs. Air Voids by Nominal Maximum Aggregate Size (Mogawer et al., 2002; Cooley et al., 2002a, 2002b; Cooley, 2003; Cross and Bhusal, 2009; West et al., 2011)

2.3 Chip Seal Design Methods

Chip seal design approaches are presented in this section and begin with pre-selected aggregate type, aggregate gradation, and emulsion. Chip seal design usually refers to selecting aggregate and emulsion application rates. One motivation for presenting design methods is to highlight aspects that are considered in design that may or may not be considered in performance-oriented laboratory testing.

According to Gransberg and James (2005), the two most common formal design methods are the Kearby/Modified Kearby and McLeod/Asphalt Institute. In the United States, agency methodology is as follows: Kearby/Modified Kearby (7%), McLeod/Asphalt Institute (11%), empirical method (37%), in-house method (19%), no method (26%).

Depth of embedment (E) is an important performance factor in McLeod (1969). The emulsion residue should, on average, embed aggregates approximately 70% of their depth (70% embedment). Even when the median particle size (M) is 70% embedded, gradation must be considered. Issues can arise particularly with well-graded aggregates as these have large percentages of particles larger or smaller than M. Particles that are larger than M such that embedment is 50% or less into emulsion residue are likely to be dislodged by traffic. Particles that are smaller than M such that embedment is 100% or more into emulsion residue will result in bleeding. For example, if M is equal to 10 mm, then E should ideally equal 7 mm; any particle that is 14 mm or larger (1.4M) is likely to be dislodged, and any particle 7 mm or less (0.7M) will result in bleeding. Uniformly-graded aggregates are much less susceptible to these failure modes given all other factors are equal.

The McLeod design method provides binder and aggregate application rate formulas (Equations 2.1 and 2.2) that are widely accepted (Gransberg and James, 2005) and adopted by the Asphalt Emulsion Manufacturers Association (AEMA) and the Asphalt Institute (AI). This design method was developed under two main premises: 1) the aggregate application rate should be equivalent to a one-stone-thick seal coat; and 2) depth of embedment for particles of median size should equal 70% for good performance under moderate traffic levels (McLeod, 1969).

$$C = 46.8\,(1 - 0.4V)\,[H]\,[G_{sb}]\,[E] \tag{2.1}$$

$$B = \frac{(2.244 * H * T * V) + S + Abs}{R} \tag{2.2}$$

Where,
C = aggregate application rate (lbs/yd^2)
V = voids in the loose aggregate expressed as a percentage
H = average least dimension (in)
G_{sb} = bulk specific gravity of the aggregate (G_{sb})
E = wastage factor for traffic whip-off
B = binder application rate (gsy)
T = traffic correction factor
S = surface condition factor (gsy)
Abs = aggregate absorption factor (gsy)
R = percent residual asphalt in the emulsion expressed as a decimal

McLeod's design method emphasizes aggregate particle shape, gradation, and void fractions. These properties are interrelated so that proper embedment, good stability, and maximum tire contact is achieved while avoiding excessive emulsion bleeding. Cubical, clean aggregates with low fines contents have approximately 50% embedment soon after they are initially dropped from the spreader, 70% embedment after rolling, and 80% embedment after traffic (Hanson, 1935; McLeod, 1969).

Emphasis is given to an aggregate's average least dimension (ALD). After considerable traffic, particles tend to re-orient until they lie on the flattest side (McLeod, 1969); consequently the average chip seal thickness equals the aggregate's ALD (Hanson, 1935). ALD significantly affects seal coat design in that cover aggregates with cubical shape (larger ALD) require larger emulsion application rates than flat and elongated aggregates (smaller ALD) to reach 70% embedment (McLeod, 1969).

High fractured faces ensure good aggregate interlock, and a low flakiness index (*FI*) is desired to prevent flushing under traffic. Additionally, "flaky" aggregates may break under heavy loads. Lower *FI* values indicate more cubical shaped particles. The *FI* is the percentage of particles whose least dimension (thickness) is less than three-fifths of their mean dimension, and it is measured with a metal plate approximately 1.6 mm thick with multiple slotted openings. Particles are divided according to sieve size fractions and are tested for flakiness by passing each individual particle through a slot corresponding to each sieve size. The passing particles are separated from those retained, and the *FI* is determined by calculating the percentage of particles passing from the total particles for each size fraction. *FI* calculations are performed relative to either weight or particle count (Shuler et al., 2011). Table 2.4 summarizes empirical fracture requirements and *FI* recommendations.

ASTM D1369-84 provides typical emulsion application rates used for surface treatments and suggests corrections for various conditions but is not a fully comprehensive guide for chip seal design. Agencies often merely use emulsion rates from the previous year's chip seal program as a means to determine application rates, where they are dependent on the condition of the pavement and past experiences (Gransberg and James, 2005). Texas used the modified Kearby method which included a "hunger factor" to characterize the

amount of oxidation or flushing present on the existing surface and consequently increase or decrease the application rate accordingly (Holmgreen et al., 1985). Emulsion application rates of 0.3 to 0.5 gsy (1.36 to 2.26 L/m^2) are reasonable rates in Texas based on discussion at the 2010 *Mississippi Quality Asphalt Conference*. Minnesota uses a modified version of the McLeod method to determine the amount of aggregate and initial emulsion estimates that can be adjusted with traffic and surface conditions (Wood and Olson, 2011).

Table 2.4. Requirements for Chip Seal Aggregates by Shuler et al. (2011)

		Vehicles/Day/Lane		
Parameter	**Test Method**	**<500**	**500-1,500**	**>1,500**
One Fractured Face	ASTM D5821	≥90	≥95	100
Two Fractured Faces	ASTM D5821	≥85	≥90	≥90
Flakiness Index[1]	Tex 224-F, FLH T508	≤35[2]	≤30[2]	≤25[2]

1) TxDOT (2004) and MnDOT (2005)
2) Value expressed as a percentage by mass for Tex 224-F and FLH T508.

2.4 Pertinent Review of Mississippi DOT Chip Seal Practices

2.4.1 Relevant Contents of MDOT Red Book

MDOT (2004) standard specifications are sometimes referred to informally as the *Red Book*. This document specifies road and bridge construction activities statewide and is divided into eight divisions. Divisions 100, 400, and 700 are applicable to this report. All specifications relevant to chip seals are provided in the following sub-sections.

2.4.1.1 Division 100-General Provisions

Section 106 describes materials control. Therein are descriptions for items such as inspection, storage, and handling. Nothing is solely applicable to chip seals. *Section 109* describes measurement and payment. A term of relevance for chip seals is Loose Vehicle Measure (LVM), as cover aggregates are purchased in this manner. LVM is measured loose in the vehicle by determining truck bed dimensions of a load that is "water level" on top.

2.4.1.2 Division 400-Bituminous Pavements

Section 410 is specific to bituminous surface treatments, and chip seals are primarily governed by the specifications in this section. Bituminous material type and grade are specified in the contract and must conform to applicable requirements of *Section 702* as per 410.02.1. Cover aggregates shall meet applicable requirements of *Section 703* and sub-section 14 (i.e. 703.14) as per 410.01.2., with the kind and type of aggregate specified in the contract. Crushed slag, crushed stone, gravel, or expanded clay aggregates are permitted (410.03.5 and also 703.14). Emulsion is purchased by the gallon and aggregates are purchased by the cubic yard on an LVM basis (410.05). Emulsion application rates can be varied by the engineer from 0.39 to 0.44 gsy (1.77 to 1.99 L/m^2) for size 7, 8, or 89 cover aggregate, and cover aggregates can be applied at 0.25 to 0.31 ft^3/yd^2 (410.03.5).

Emulsified asphalt cannot be applied unless the air temperature is above 60 F (15.6 C) (410.03.2). The time interval between emulsion and cover aggregate cannot exceed 20

minutes when air temperature is below 85 F (29.4 C) and cannot exceed 30 minutes when temperature is 85 F (29.4 C) or above (410.03.6). Once cover aggregate has been applied, pneumatic rollers having wheels mounted on two axles in a manner that the rear tires do not follow in the tracks of the forward group are used (410.03.3.4) These rollers must apply a minimum of 50 psi (344.7 kPa) contact pressure under each tire yet not be so heavy to cause damage (410.03.3.4). A minimum of five complete coverages of the entire surface treatment is required (410.03.6). During construction, traffic speed is to be regulated to avoid unnecessary damage (410.03.7).

2.4.1.3 Division 700-Materials and Tests

Section 702 is related to bituminous material testing. Anionic and cationic emulsion shall conform to AASHTO M140 and M208, respectively (702.07.2). CRS-2P emulsion shall conform to M316. Gradation requirements are provided in Table 2.1 of this report (703.14).

2.4.2 MDOT Special Provision 907-410-7

In April of 2013, MDOT revised their chip seal specifications by creating a special provision amending the *Red Book*. A mix design (e.g. McLeod) is not required in either the *Red Book* or the special provision. Key items in the special provision as they apply to this research are provided in the remainder of this section.

Air temperature requirements for chip seal placement were changed from 15.6 C (60 F) to an air and pavement temperature of 21.1 C (70 F) (907-410.03.2). Steel wheel rollers are no longer allowed (*Red Book* allows them) (907-410.03.3.4).

Emulsion and aggregate application rates changed relative to the *Red Book*. Optimum emulsion application rate is a function of gradation and existing pavement in the special provision. Emulsion application rate may be adjusted by the engineer based on field conditions. Target application rates are 0.38 $\pm$ 0.03 gsy (1.72 $\pm$ 0.14 L/m^2) for size 7 aggregate, and 0.35 $\pm$ 0.03 gsy (1.58 $\pm$ 0.14 L/m^2) for size 8 or size 89 aggregate (907-410.03.5). Cover aggregate application rates were modified to 0.30 $\pm$ 0.02 ft^3/yd^2 for size 7 and 0.25 $\pm$ 0.02 ft^3/yd^2 for size 8 or size 89. The special provision has a set of calculations to convert units, and when this formula is used with a default limestone G_{sb}, size 7 requirements are 17.2 $\pm$ 1.1 lb/yd^2 (9.33 $\pm$ 0.60 kg/m^2), and size 8 or size 89 requirements are 14.3 $\pm$ 1.1 lb/yd^2 (7.76 $\pm$ 0.60 kg/m^2) (907-410.03.6.1).

All traffic lanes are to be open at the end of each day (907-410.03.7). This same sub-section has the following quote related to traffic opening, which is much more restrictive than the *Red Book*. "After the surface treatment has been rolled and the bituminous material has cured a minimum of one (1) hour, or longer if necessary to sufficiently hold the aggregate in place, the Contractor shall perform an initial brooming operation consisting of lightly sweeping excess aggregate material from the surface. After the initial brooming has been completed, public traffic will be allowed on the roadway."

2.4.3 Non-Specified MDOT Chip Seal Practices

All information in this section was obtained from MDOT engineers or MDOT research reports and is current as of the date of this report. MDOT typically uses crushed

limestone as chip seal cover aggregate. Expanded clay (i.e. lightweight aggregate) is the only other aggregate type used by MDOT recently, and it was only used on a few projects in southwest Mississippi. Extremely dirty or dusty aggregate is prevented by means of visual evaluation.

Howard and Baumgardner (2009) documented a US Highway 84 (*Hwy 84*) project near Brookhaven, MS, constructed in 1989 as part of State Study 202. The primary objective for *Hwy 84* was to establish an approved products list of polymer modified CRS-2 emulsions using primary evaluation considerations of evaluating early chip retention set forth by MDOT internal memorandums. CRS-2 emulsion was governed by M208 at the time of construction as it still was as of the date of this report. Three products met approval requirements, though MDOT never established an official category for the approved polymers, and as of the date of this report there is no approved list for these types of products. MDOT approved producers and/or production facilities for asphalt emulsions as of the date of this report. Material certifications do not denote the specific modifier used for the products supplied.

2.5 Review of MDOT State Study 202 Field Testing

Howard (2009) is part of State Study 202, where the primary objective was to evaluate *Hwy 17* and *Hwy 35* chip and scrub seals. Aggregate retention, skid resistance, overall condition, and structural capacity using Falling Weight Deflectometer (FWD) testing were the primary evaluation mechanisms. *Hwy 17* and *Hwy 35* used limestone aggregate (material 1 from Table 3.8) and PASS-CR emulsion (material 3 from Table 3.1). Overall, test results showed scrub seals out-performed chip seals.

Hwy 17 results from State Study 202 that are relevant to State Study 211 are provided in this paragraph. The northbound lane contained significantly more bleeding/flushing than did the southbound lane. Loaded log trucks were observed to be more frequent in the northbound lane (note this was only a subjective assessment absent measured traffic data). Construction temperatures were 5.0 to 14.4 C (41 to 58 F), and traffic was allowed onto the seal immediately. *Hwy 17* may have been cracked too excessively for a seal treatment to be effective.

Hwy 35 contrasted *Hwy 17* in that bleeding/flushing was not significant. Construction temperatures were higher at 8.9 to 32.2 C (48 to 90 F). Overall, State Study 202 efforts indicated tools to improve construction practices could be useful (e.g. simple yet effective traffic opening guidance that can accommodate a range of conditions).

Howard (2011) used FWD test data from State Study 202 *Hwy 17* efforts and back-calculation techniques combining approaches from Arkansas, North Carolina, and Texas. Results showed chip and scrub seal treatments preserved the pavement's structural capacity better than control sections. *Hwy 17* was, overall, an unfavorable set of conditions for a chip or scrub seal.

2.6 Literature Pertinent to Rejuvenation

Asphalt cement is a term used to describe petroleum derived paving products absent modification with, for example, polymers. Asphalt binder is a more generic term referring to

either modified or unmodified asphalt cement. Asphalt binders are comprised mostly of petroleum derived constituents that differ in their volatility. These constituents can be characterized with different systems. One common method is to divide the petroleum based portions into two main fractions: 1) asphaltenes – hard and brittle component that is insoluble in pentane and not affected by oxidation; and 2) maltenes – oil and resin components that are soluble in pentane and affected by oxidation. Maltenes can also be divided into polar compounds, first acidiffins, second acidiffins, and saturated hydrocarbons. Oils in the maltene fraction are sometimes further divided into cyclics and saturates. Overall, resins keep asphaltenes dispersed in oils, and aging results in less oil (mostly) and resin (to some extent) components. Maltenes are more volatile than asphaltenes, which serve as the bodying agent in a binder system.

Rejuvenators (e.g. Reclamite®) are designed to penetrate an aged and oxidized pavement surface and restore the maltene fraction and, thus, flexibility and durability (Brownridge, 2010). Durable asphalt binder has a balanced oil-to-resins relationship, as weathering affects this balance. For rejuvenation to occur, the product must penetrate an adequate distance (i.e. 6 to 13 mm) into the pavement surface in a relatively short period of time. Thereafter, the rejuvenating product must combine with the existing binder in a way to restore flexibility and durability without causing adverse adhesion or stability effects. A typical rejuvenation candidate is a structurally sound pavement 3 to 7 years old showing early signs of distress (Brownridge, 2010).

Historically, viscosity changes have been the predominant method to measure rejuvenation. Alternative measurement approaches, however, are worth considering and are reviewed in this section alongside viscosity techniques. Literature is also reviewed to assess effectiveness of rejuvenation techniques.

2.6.1 Test Methods to Characterize Rejuvenation

2.6.1.1 Repeated Creep Testing

The repeated creep (*RC*) test was developed by Mathy Technology and Engineering in 2000, with pertinent early work from the developers found in Reinke and Dai (2001), Reinke and Glidden (2004), and Reinke et al. (2005). The *RC* test has traditionally been used to evaluate high temperature deformation as the test is a measure of mixture strength due to aggregate structure and binder properties (stiffness and elasticity). For example, mixtures were tested at 58 C with a 34 kPa stress in Reinke et al. (2005).

Doyle et al. (2013) tested 144 torsion bars using the *RC* test to investigate the interaction of reclaimed asphalt pavement (RAP) binder and virgin binder in different mixtures. Specimens made from 100% RAP and virgin binder were tested. The primary finding was the *RC* test did not appear optimal for evaluating the interaction of 100% RAP mixed with virgin binder. Additionally, preparing torsion bars over a wide range of RAP materials and virgin asphalt contents was discovered to be particularly difficult.

Failure strain was the least variable output in Doyle et al. (2013) for traditional HMA and mixtures of 100% RAP and virgin binder. A Pearson correlation analysis using HMA materials indicated high correlations between the time to 5% strain ($\varepsilon(5\%)_T$), inverse of slope in the secondary flow region ($(\Delta\varepsilon/\Delta T)^{-1}$), and tertiary flow failure (TFF), whereas strain at failure (F_ε) was not strongly correlated with the other response variables. One-way analyses

of variance (ANOVAs) were also performed to investigate relationships to test stress level. The $\varepsilon(5\%)_T$, $(\Delta\varepsilon/\Delta T)^{-1}$, and TFF variables were dependant on stress level (*p-values* < 0.001). However, the relationship between F_ε and stress level was not significant (*p-value* = 0.122). F_ε was considered most appropriate for analyzing 100% RAP due to lower variability, lower between variable correlation, and relatively low sensitivity to test stress level.

2.6.1.2 Viscosity and Penetration Testing

Both viscosity and penetration have been used for many years to evaluate rejuvenation. Based on literature, it does not appear that one is recommended over the other. In general, viscosity is considered a more fundamental material parameter than penetration. In this report, penetration and viscosity are both discussed in literature review; however, only viscosity (rotational) is evaluated as a potential rejuvenation characterization test.

Penetration testing generally refers to ASTM D5 in which the depth of penetration of a 100 g needle at 25 C after 5 seconds is reported in decimillimeters. Use of penetration testing has been documented by Brown and Johnson (1976), Pickett (1983), Corps of Engineers (1983), and others.

Viscosity tests for determining the rejuvenation effects on flexible pavements include kinematic, vacuum capillary, rotational, and Saybolt viscosity. Use of viscosity testing has been documented by Traxler and Schweyer (1936), Brown and Johnson (1976), Corps of Engineers (1983), Corps of Engineers (2008), and others. Corps of Engineers (1983) used Equation 2.3 to characterize rejuvenation based on viscosity results.

$$V_{D\%} = \frac{V_U - V_T}{V_U}(100) \tag{2.3}$$

Where,
$V_{D\%}$ = decrease in viscosity
V_U = untreated viscosity
V_T = treated viscosity

AASHTO T201 (D2170 is equivalent) measures kinematic viscosity of asphalt binder. Time is measured for a volume of liquid to flow through a glass capillary viscometer. The test is conducted at 60 C and 135 C with units of centistokes (mm^2/s).

AASHTO T202 measures viscosity of asphalt binder through vacuum capillary viscometers. Time is measured for a volume of liquid to flow through a capillary tube by means of a vacuum. The test is conducted at 60 C with units of poise (Pa-s).

AASHTO T316 measures viscosity of recovered asphalt binder using a rotational viscometer. Resistance to rotation is measured for a cylindrical spindle that is submerged in an asphalt binder specimen of constant temperature. This test is conducted at 60 to 200 C with units of poise (Pa-s).

AASHTO T72 measures viscosity of bituminous materials through the Saybolt viscosity procedure. Time is measured for volume of liquid to flow through an orifice at controlled conditions. It is conducted at 21 to 99 C with units of seconds (s).

2.6.1.3 Bending Beam Rheometer Testing

For asphalt binders, the Bending Beam Rheometer (*BBR*) is used to indicate ability to resist low temperature cracking by measuring low temperature stiffness and relaxation properties. In accordance with AASHTO T313-09 (D6648-08 is equivalent), binders are tested in the *BBR* to determine flexural creep stiffness or compliance and *m-value* of the material at specified temperatures. Binder specimens are conditioned for one hour at the desired temperature, and, then, a constant load is applied to the simply supported asphalt binder beam for a period of time. Measured creep stiffness (S_m) is the ratio found by dividing the maximum bending stress in the mixture beam by the maximum bending strain at a given time (Equation 2.4). An estimated creep stiffness (S_e) curve is obtained by fitting a second order polynomial to a plot of the logarithm of measured stiffness versus logarithm of time ($log(S_m)$ vs. $log(t)$). The S_e at 60 seconds is generally reported. The *m-value* is the absolute value of the slope of the S_e curve and is typically reported at a given time (generally 60 seconds).

$$S_m = \frac{PL^3}{4bh^3\delta} \tag{2.4}$$

Where:
S_m = measured creep stiffness at a given time t
P = load (mN)
L = length (mm)
b = width (mm)
h = thickness (mm)
δ = deflection at a given time t (mm)

Research in this report investigates use of the *BBR* to measure changes in flexural creep stiffness on mixture beams sawn from the surface of emulsion treated asphalt pavement so that stiffness changes due to surface treatments can be investigated. The practice of testing mixture beams in the *BBR* is a relatively recent development in the pavement industry but has been studied to some extent (Marasteanu et al., 2009; Velasquez, 2009; Zofka et al., 2005, 2008; Doyle and Howard, 2013). Also, some studies have compared *BBR* use to indirect tensile (*IDT*) testing in measuring creep stiffness in asphalt mixtures (Marasteanu et al., 2009; Velasquez, 2009; Zofka et al., 2008). Marasteanu et al. (2009) evaluated feasibility of testing asphalt mixture beams and noted potential uses and areas for further study included using the *BBR* to investigate surface aging, microcracking, creep stiffness from different layers in the pavement, and the effectiveness of surface treatments.

Given the *BBR* was not intended for testing asphalt mixture beams, concerns exist with the nature of testing and corresponding results. Multiple studies have suggested testing beams sawn from within the center of the specimen to avoid variability and aged characteristics of pavement surfaces (Marasteanu et al., 2009; Velasquez, 2009; Zofka et al., 2005, 2008).

Another concern is that mixture beam thicknesses are smaller than the mixture nominal maximum aggregate size (NMAS), which violates the representative volume element (*RVE*) concept and may result in inconsistent data (Zofka et al., 2008; Weissman et

al., 1999). Zofka et al. (2008) contests that the *RVE* concept is more important for asphalt mixture testing at higher temperatures. At lower temperatures, the disparity in stiffness between aggregates and asphalt binder significantly reduces. As temperatures approach a binder's glass transition temperature, the binder begins to behave as a brittle co-elastic material (Zofka et al., 2008). At these temperatures, the binder and aggregate have similar responses, and the bulk properties of the asphalt mixture become much less dependent on size and aggregate distribution (Zofka et al., 2008). Velasquez (2009) also supports this conclusion on the *RVE* concept for low-temperature asphalt mixture applications. Velasquez (2009) confirmed the ability to measure creep stiffness in mixture beams using the *BBR* at low temperatures while remaining above the low limit of the binder performance grade. In mixture beams with dimensions double and triple that of traditional *BBR* beams, the volumetric fraction and size distribution of aggregates were similar.

Zofka et al. (2005) initially removed the upper 10 mm of gyratory specimens in order to create a smooth surface. Six 12 mm thick slices were then cut (parallel to specimen surface) beginning at the smooth surface and progressing downward. From these slices, seven rectangular beams each 6 to 8 mm thick and 101 mm long were cut. The thickness cut was the most difficult (thicknesses ranged from 6 to 9 mm); for this reason, thickness should be directly measured for use in calculations. Marasteanu et al. (2009) developed a beam preparation procedure in which beams were sawn from the center of tall gyratory specimens.

Marasteanu (2004) investigated the relationship between stiffness and *m-value* calculated in the *BBR* and the development of thermal stresses in asphalt pavements. Neat and modified binders were tested. Results showed thermal stress development was controlled by the binder stiffness.

Zoftka et al. (2005) tested three replicates of each unique combination of binder, *RAP* percentage, and *RAP* source conditioned for one hour and tested at -18 C and -24 C. The coefficient of variation (COV) for replicate measurements was in the range of 3.6% to 19% which was deemed acceptable for mixture testing at low temperatures.

Marasteanu et al. (2009) investigated the idea of performing creep tests on asphalt mixture beams in the *BBR* due to the many apparent advantages compared to the current *IDT* specification. Acceptable results were obtained using the *BBR* with test loads of 1961 mN at the PG low temperature + 22 C and 4413 mN at the PG low temperature + 10 C. For the PG low temperature – 2 C, the authors recommended to use predictions formed from the higher two temperatures. Marasteanu et al. (2009) also concluded that the cooling medium and reasonable variation in air voids do not significantly affect asphalt mixture creep stiffness results when tested at low temperatures.

2.6.2 General Findings on Rejuvenation

Traxler and Schweyer (1936) provided the first conclusive statements regarding viscosity increase with time while temperature was held constant. Simpson et al. (1959) found that, in general, the asphalt in the top 6.3 mm of a pavement had a higher viscosity than the rest of the pavement, including both the surface and base. A microviscometer was used to study 32 and 35 month old cores. Less change in viscosity was observed for depths greater than 12.5 mm than depths less than 12.5 mm.

Coons and Wright (1968) studied pavement viscosity with depth. Cores of pavements with no surface treatments applied and varying in age from 1 to 13 years were

obtained from Georgia and sliced parallel to the pavement surface. The parallel slices were first dried for 20 minutes at 121 C, broken into small pieces, returned to the oven for 10 minutes, and then the binder was extracted with reagent grade benzene. Recovered binder was tested to determine absolute viscosity related to depth, age, and original viscosity. Each 150 mm diameter slice was extracted separately. The total mass (aggregate and binder) of the slices was on the order of 275 g.

Viscosity versus depth profiles showed the greatest hardening occurred in the top 12.5 mm of the pavement. The top slices (0 to 6.3 mm pavement depth) had an average viscosity that was approximately 50% greater than that of the second depth of slices (9.5 to 15.9 mm pavement depth). Investigation within the top slice indicated most of the hardening occurred in a layer less than 4.8 mm thick.

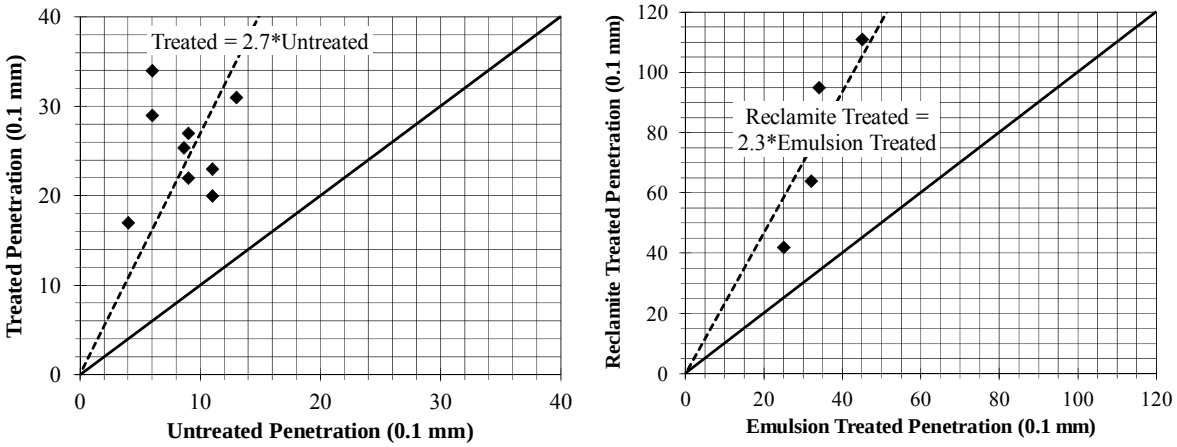
Relative viscosity was also investigated by Coons and Wright (1968) and is defined as the viscosity after a period of time divided by the original viscosity. The hardening of the top layer with time was characterized by Equation 2.5. For example, relative viscosity is 19 after approximately 10 years. Coons and Wright (1968) concluded aging of flexible pavements is a significant function of age and depth.

$$X = e^{(y+1.07)/4.21} \tag{2.5}$$

Where,
X = age in months
y = relative viscosity

Pickett (1983) evaluated an airfield in Arizona where three 150 mm diameter cores were taken prior to Reclamite® treatment from eight locations and three additional 150 mm diameter cores were taken after Reclamite® treatment (application rate varied from 0.053 to 0.074 gsy) from within 1.5 m of the original core location. The top 9.5 mm of the cores were removed, the binder extracted and recovered, and penetration (25 C, 100 g, 5 s) was measured. Test results are provided in Figure 2.2a. Treated penetration was 2.7 times higher than untreated penetration based on a linear fit with a zero intercept.

Figure 2.2b plots penetration values of binder extracted from various airports and roads nationwide where the top 6.3 mm of a core was removed and tested after receiving Reclamite® and emulsion treatment (data obtained from company literature with no reference). Reclamite® and emulsion application rates were not provided, nor were details of the emulsion used. Reclamite® treated penetration was 2.3 times higher than emulsion treated penetration based on a linear fit with a zero intercept.



a) Results of Pickett (1983) *b) Reclamite vs. Emulsion Treatments*

Figure 2.2. Rejuvenation Measured by Penetration

Brown and Johnson (1976) noted that full documentation of rejuvenation effectiveness was not available at the time. Additionally, the definition of a pavement which is capable of rejuvenation was not (and still is not) fully defined. Brown and Johnson (1976) investigated rejuvenation capability by means of decrease in viscosity or increase in penetration for five materials (Table 2.5) at three airfields.

Table 2.5. Properties of Rejuvenators Used by Brown and Johnson (1976)

Material	Type	Saybolt[1] Viscosity (s)	Residue (%)[2]	Residue Viscosity (Poises)[3]
A: Koppers BPR	Tar Products	22	51	0.70
B: Reclamite®	Asphalt Emulsion	22	67	1.47
C: Petroset	Asphalt Emulsion	22	62	14.27
D: Gilsabind	Cutback Asphalt	42	20	---
E: SS-1	Asphalt Emulsion	89	65	---

1) Saybolt viscosity at 25 C on as received rejuvenator.
2) Material (A) performed with ASTM D20, (B, C, and D) with ASTM D244, and (E) with ASTM D402.
3) Residue viscosity performed at 60 C according to ASTM D2170.

Brown and Johnson (1976) sought to test three airfields from different climates approximately ten years old that were free of maintenance; unfortunately, nearly all pavements ten years old or more had been maintained with a surface treatment. The taxiways of three air force bases were ultimately tested: Eglin in Florida, Malmstrom in Montana, and Williams in Arizona. Eglin had many longitudinal and transverse cracks up to 12.5 mm and had a surface asphalt content of 5.8%; Malmstrom had a slurry seal placed several years before testing and had a surface asphalt content of 6.3%; and Williams had been treated two or three times previously with a diluted fog seal and had a surface asphalt content of 5.3%.

The optimum rejuvenator application rate was determined with 0.9 meter square patches with application rates of 0.23, 0.46, and 0.69 L/m^2. The rate was selected as the amount that would entirely absorb into the surface in 24 hours. If the material did not penetrate into the pavement, the minimum amount needed to completely cover the surface was selected as the application rate. At each airfield, the rejuvenator was applied at the optimum rate and half the optimum rate.

Penetration and viscosity tests were performed on cores taken at 0.07, 6, 12, 24, and 36 months by slicing the top 9.5 mm of the pavement and recovering the binder. Viscosity was reported to be a better indicator of rejuvenation than penetration. At each airfield, treated viscosity was expressed as a percentage of untreated viscosity of the control sections at 135 C (other temperatures parallel these behaviors). Results of the work of Brown and Johnson (1976) applicable to the current effort are provided in Table 2.6. As seen, the effect of rejuvenation was varied with two of the materials stiffening the aged asphalt at 0.07 and 36 months. Materials A, B, and C softened the binder at 0.07 and 36 months, though the extent of softening decreased with time. Brown and Johnson (1976) recommended rejuvenators at the first sign of pavement deterioration such as cracking, raveling, and/or loss of fines from the surface.

Table 2.6. Select Test Results of Brown and Johnson (1976)

Material	Application Rate (L/m^2)	Percent of Control Viscosity (0.07 months)	(36 months)
A	0.27 to 0.54	17 to 42	60 to 66
B	0.27 to 0.45	38 to 84	67 to 96
C	0.27 to 0.45	61 to 81	95 to 99
D	0.27	146 to 178	138 to 164
E	0.27	107 to 111	132 to 146

The US Army Corps of Engineers (USACE) unified facilities guide specification (UFGS) for Bituminous Rejuvenation (UFGS 02787) is heavily based on the work of Brown and Johnson (1976). This guide required a 40% decrease in viscosity of the upper 9.5 mm of the pavement from rejuvenation, as defined by Equation 2.3 (Corps of Engineers, 1983). This remains unchanged (Corps of Engineers, 2008). Rejuvenation may be temporary and be followed by a subsequent viscosity increase that may or may not exceed that of the original pavement (Corps of Engineers, 1983).

Fog seals appear to be the most common rejuvenation application where near surface materials are extracted and the penetration or viscosity of recovered binder is evaluated. This is significant in multiple contexts; one of pertinence to this report is that fog seal application rates are less than for chip and/or scrub seals where not all the bituminous material is intended to penetrate into the pavement. For example, fog seal application rates of 0.18 to 0.91 L/m^2 were allowed with tolerances of $\pm$ 5% from the intended value in Corps of Engineers (1983).

Shoenberger (2003) continued the work of Brown and Johnson (1976) by focusing on propriety rejuvenator and sealer materials for airfield pavements. The premise of the work was that performance based requirements were preferred over material property specifications. Shoenberger (2003) evaluated eleven rejuvenator materials and five seal coat materials at two airfields: MacDill in Florida (representative of hot, humid conditions) and McGuire in New Jersey (representative of cold, humid conditions). Eight of the rejuvenator materials were coal-tar based, while three of the rejuvenator materials were petroleum based. Properties of select materials are shown in Table 2.7.

Cores (150 mm diameter) were taken pre- and post-treatment, with post-treatment cores taken at one month and twelve months. Cores were not taken until one month to allow evaporation of excess volatile materials and for rejuvenation to occur. Cores were taken from areas with minimal cracking or surface distresses.

Table 2.7. Properties of Rejuvenators (Shoenberger, 2003)

			Application Rate		Viscosity[2]	
Type	**Product**	***R*[1]**	**MacDill (L/m^2)**	**McGuire (L/m^2)**	**Saybolt (s)**	**Brookfield (cP)**
Coal-Tar	BCR	---	0.23	0.23	171	130
	CBRT-SO	---	0.30	0.25	---	---
	RejuvaSeal	---	0.23	0.23 to 0.27	31	---
Petroleum	APR-100	84	0.27	0.31	82	---
	GSB	63	0.54 to 0.63	0.61 to 0.91	159	670
	Reclamite®	61	0.23 to 0.45	0.27 to 0.68	31	153

1) Residue from ASTM D244
2) Viscosity tested at 25 C and as obtained with no dilution

To investigate effects of the coating on overall rejuvenation performance, the top 1 mm was removed and discarded and subsequently the next 9 mm removed, the binder extracted, and testing performed. Other cores had the entire 10 mm removed, the binder extracted, and testing performed. Removal of 1 mm consistently was reported to be difficult by Shoenberger (2003). Three cores were required per test. Kinematic viscosity testing was performed according to ASTM D2170 at 135 C (Table 2.8).

Penetration tests did not show a consistent pattern for either MacDill or McGuire airfield, while viscosity tests at one month and twelve months showed a lowering of viscosity at both airfields (Table 2.8). Removal of the top 1 mm appeared to affect results, but the effect was not reported to be conclusive by Shoenberger (2003). All rejuvenator materials reduced binder viscosity, but the extent of the reduction varied. Sample cores were arbitrarily obtained within taxiways, and as such are an indication of behavior that does not necessarily account for variability of untreated viscosity.

Table 2.8. Viscosity Results from Rejuvenators (Shoenberger, 2003)

$V_{D\%}$	MacDill Airfield			McGuire Airfield	
Thickness (mm)	**10**	**10**	**9**	**10**	**9**
Months Sealed	**1**	**12**	**12**	**1**	**1**
BCR	32	63	56	49	---
CBRT-SO	48	56	---	59	55
RejuvaSeal	76	---	---	14	57
APR-100	75	35	---	26	41
GSB Emulsion	36	16	4	43	14
Reclamite®	62	57	60	18	57

-- Thickness of 10 mm was top 10 mm and 9 mm had top 1 mm removed.

Due to the proprietary nature of emulsified asphalt products, performance specifications are recommended (Shoenberger, 2003; Boyer, 2000). It is common to find some specifications calling for a stiffness reduction at or near the surface of the pavement and others including a certain application rate (Shoenberger, 2003; Boyer, 2000). Specifying certain application rates should be avoided due to the rejuvenator products' varying performance depending on the environment (Boyer, 2000). Penetration, viscosity, ductility, and dynamic shear rheometer (*DSR*) results are common material property alternatives used to gauge changes in stiffness or performance (Shoenberger, 2003).

Boyer (2000) stated that rejuvenator products perform differently among themselves in a given environment and differently within themselves in changing environments. Therefore, a given application rate does not ensure a desired end product, and satisfactory

performance guidelines or targets should be based on the capability of the material to decrease the viscosity and increase the penetration value of the asphalt binder. For example, a performance specification was used at Kincheloe AFB, Michigan, which required a 30% increase in penetration for the top 6.3 mm of the pavement 60 days subsequent to application. In the case of pavements less than 2 years old, the minimum viscosity reduction of 20% and minimum penetration increase of 10 percent were reported. For asphalt pavements more than 2 years old, the minimum viscosity reduction of 40% and minimum penetration increase of 20% were reported. Testing was recommended to be performed on recovered asphalt binder from the pavement to a depth of 9.5 mm. Requiring the rejuvenator to achieve a given measure of standard penetration or measure of viscosity should ensure a more satisfactory result than simply specifying a given rate of application, especially prior to fully developed performance specification.

Boyer (2000) concluded that an asphalt rejuvenator in the form of an emulsion offers three beneficial reactions: 1) increases penetration values and lowers the viscosity of the asphalt binder in the top portion of the surface layer, which extends the pavement's life cycle, 2) seals the pavement against intrusion of air and water, thereby slowing oxidation, preventing stripping and raveling and protecting the pavement in-depth, and 3) increases the durability of the asphalt binder in the top portion of the pavement by improving the balance of chemical fractions of the asphalt binder.

Sholar et al. (2000) evaluated a coal tar product as a rejuvenator on an in-service shoulder of I-295 in Florida. On the day of application, six cores were obtained at random locations within the test section. The top 12.5 to 19 mm were sliced and used to obtain pretreatment viscosity of the recovered binder. The process was repeated with 29 day cores. There was no significant change between the before treatment asphalt binder viscosity (106,846 Pa-s) and the asphalt binder 29 days after treatment (106,329 Pa-s). The results indicate that the use of coal tar does not significantly reduce the viscosity of the pavement.

Fog sealed pavement sites were tested once per year for two years and extracted binder properties were compared to untreated sections of the same sites using paired *t*-testing (Prapaitrakul et al., 2008). Effects were restricted to the top 6.3 mm of the pavement. Slow setting, medium setting hard residual emulsion, polymer modified emulsion, and coal tar sealers were tested with application rates from 0.18 to 0.72 L/m^2. It was stated that fog seals with rejuvenators have been used for maintenance and preservation activities, but evidence to date is not sufficient to prove that sealants rejuvenate in-place binders. Three 6.3 mm layers were sliced parallel to the pavement surface. A solvent of 15% ethanol and 85% toluene by volume was used for extraction via 3 or 4 washes of 20 minutes each which removed practically all binder from the aggregate. Recovery was performed with a Roto-vap apparatus. Fog seal effects were noticeable in the top 6.3 mm, but not at other depths, providing evidence of approximately 6.3 mm penetration.

2.6.3 Asphalt Extraction and Recovery

Over the past few decades, several methods have relied upon asphalt extraction and recovery to produce test specimens for rejuvenation assessment. As a result, pertinent literature was reviewed to identify characteristics that should be included in test protocols, data analysis, and interpretation of literature.

Burr et al. (1993) discusses the history of asphalt extraction and recovery that dates back over 100 years. Highlights include centrifuge extraction leaving 2 to 4% of asphalt on aggregate when trichloroethylene (TCE) is used. Centrifuge extraction using 15% ethanol in the TCE reduces the percent asphalt remaining on the aggregate by approximately half. Binder recovery using rotary evaporation has been reported to leave residual solvent in the binder, which could be problematic since low solvent concentrations (e.g. 0.2%) can cause physical property testing errors. Modification of D2172 Method A (centrifuge) with toluene (85% toluene and 15% ethanol by volume for the last several washes) was comparable to the procedure developed for Strategic Highway Research Program (SHRP). More solvent was used than in the standard procedure and all washes were collected in one container until extraction was complete. The researchers used a very high number of washes (eleven) versus many standard practices (e.g. 4 to 6 washes). Previous work by the same researchers reported tank asphalts that were dissolved and recovered immediately hardened between 10 and 40% (Burr et al., 1990). Cipione et al. (1991) cites coefficients of variation from nationwide asphalt extraction to be 25% as early as 1989.

Cipione et al. (1991) focused on removal of "hard-to-remove" binder (i.e. strongly adsorbed asphalt material). Results indicated TCE with 15% ethanol was superior for this purpose and concluded many solvents do not remove the bulk of the asphalt binder. It could be argued that "hard-to-remove" material as described by Cipione et al. (1991) is not key to rejuvenation of the surface since active material (i.e. P_{be}) is the key material to be rejuvenated. Material within the aggregates if undisturbed has no effect on performance of the surface. Therefore, there may be little need to extract the "hard-to-remove" binder from within the aggregates when assessing rejuvenation.

Selecting solvents used in extracting the asphalt binder from a mixture is important in determining the properties of the recovered binder. Burr et al. (1994) reported up to 50% softening of asphalts in solutions while using a modified Roto-vaporation recovery technique. The rate at which softening occurred increased a considerable amount as a function of oil bath temperature (102 to 149 C were investigated) and decreased in a solvent of toluene with 15% ethanol. It was recommended to exercise care with asphalts in dilute solutions for extended periods of time at temperatures exceeding 93 C, especially polar solvents such as TCE/ethanol. Solvent softening was reported to vary widely with asphalt source and solvent type. Using toluene/ethanol as the solvent resulted in softening in the most severe conditions (high oil bath temperature with low asphalt concentration). Toluene/ethanol solvents were recommended, but it should be noted they are not as efficient at removing absorbed material from aggregate. Softening reactions can occur in dilute solutions at high temperatures and low asphalt concentrations. Solvent hardening was said to occur at high asphalt concentrations in diluted solutions. Up to 50% viscosity decrease was said to occur from softening, while up to 15% viscosity increase was mentioned due to hardening. Using toluene/ethanol with oil bath temperatures below 110 C with solutions having concentrations exceeding 0.15 g/ml was recommended.

Burr et al. (1991) stated that asphalt recoveries by the Abson and Roto-vap methods were performed at various temperatures and for several asphalt viscosities from tank, oven aged, and solvent exposed asphalt to evaluate the effectiveness of the procedures and operating parameters. It was found that small amounts of solvent cause significant decreases in viscosity and that recovery methods of the time period did not remove solvent adequately. High viscosities and larger HMA samples hinder solvent removal rates in the Abson Method.

Asphalt hardens significantly on extended exposure to TCE at both 93 C and 127 C; however, removal at a reduced temperature through use of a vacuum can inhibit hardening.

In Burr et al. (1991), the volatiles loss from virgin or unaged tank asphalts during solvent removal was shown to produce 7-10% hardening of the original asphalt viscosity. *RTFO* asphalts do not exhibit this hardening, apparently because of the loss of volatiles during aging. The same asphalts show hardening from 10 to 40% on contact with TCE and subsequent solvent removal. Short times and moderate temperature for incubation of the asphalt with solvent produce little hardening; extended times at elevated temperature can produce significant hardening.

Burr et al. (1991) conducted experiments with the Abson and Roto-vap solvent removal methods to evaluate their effectiveness in removing solvents. The Abson method, taken to its standard recovery time, can leave enough solvent to produce significant softening, especially for larger quantities of recovered material and for hardened asphalts such as those obtained from aged pavement cores (in general, the more aged the asphalt binder, the more difficult it is to recover). Increasing the solvent temperature and the recovery time can reduce residual solvent concentration, although the previously mentioned solvent hardening effects must be considered. The Roto-vap method appears to be less consistent and less reproducible than the Abson method, but it may have some solvent removal advantages. For the Abson procedure at 163 C, a minimum recovery time after the last drop is about 25 minutes, and for the Roto-vap procedure, 15 minutes past the last drop is adequate.

An 85% toluene and 15% ethanol solvent blend appears applicable to extraction of near surface bituminous material consisting of the original aged binder and newly applied bituminous material. This blend was reported to only soften bituminous materials under high oil bath temperature and low asphalt concentration and was not as effective at removing absorbed asphalt. Recovering asphalt is a critical process in which short recovery time, reduced temperature at early stages, and a use of a vacuum can reduce the effects of hardening on binder.

2.7 Aggregate Retention

Aggregate retention test methods have been used for many years and include the Frosted Marble Test (Benedict, 1990), Vialit Adhesion Test (EN 12272-3; CalTrans, 2008; ODOT, 1998), Sweep Test (ASTM D7000), third-scale accelerated pavement test device (Lee and Kim, 2008), accelerated pavement testing with pneumatic tires (Lee et al., 2006), Texas DOT aggregate retention test (Tex-216-F; Hank and Brown, 1949), Adhesion-Cohesion Test Esso (Serfass et al., 1998), and Nynas Spin Test (Redelius and Stewart, 1992). The loading mechanism of each of these methods varies in approach and applied energy. Also, the extent to which the test methods simulate traffic action can be debated.

2.7.1. Test Methods to Characterize Aggregate Retention

2.7.1.1 Vialit Adhesion Testing

The Vialit Adhesion Test (referred to hereafter as *Vialit* test) was developed in France during the 1960s to evaluate aggregates and binders. Throughout the years, the *Vialit* test

frame has been kept essentially the same, though a few modifications in the drop height have been implemented. Most methods have implemented a 50 cm fall height; however, some studies have determined that lower heights produced similar results. In 1987, Coyne (1988) used a 40 cm drop height which was found to be useful to evaluate emulsion rate of set and early performance characteristics.

The *Vialit* specimen tray has been modified many times throughout the years. Several current standards use a square tray that has dimensions of 20 cm by 20 cm that is 0.20 cm thick. Paint can lids (3.78 L) have been used as trays and showed useful results (Coyne, 1988). Tray texture has been indicated to play a role in aggregate loss. Plates have been modified using 40-grit sandpaper. At lower temperatures, these textured plates tend to perform better than smooth plates, though this plate modification did not improve reliability (Louw et al., 2004).

Glass marbles have been used as a substitute for aggregates in *Vialit* testing to reduce variability (Shuler, 1990). Rollers (25 kg is typical) have been incorporated to embed aggregates and simulate construction. Usually 3 passes in each perpendicular direction on the tray is used. Other means have been used such as self-weight of a person standing on the tray (Coyne, 1988) or placing a 3800 g mass on the tray (Shuler, 1990). The spherical mass has been changed in some studies. The French Standard (EN 12272-3) specifies a spherical mass of 500 $\pm$ 10 g and 5 $\pm$ 0.05 cm diameter, while the California (CalTrans, 2008) and Oregon (ODOT, 1998) DOT standards specify a 500 $\pm$ 5 g sphere that has a 5.08 cm diameter. Other methods and standards have implemented masses of 534.5 $\pm$ 1 g (B301-89T) and 510 $\pm$ 5 g (Asphalt Academy, 2007).

Conditioning was the most widely varied parameter. Table 2.9 provides different conditioning methods from literature. Internal information provided by one laboratory indicated a conditioning period of 50 C for 19 days was used to simulate the breaking and curing of emulsion on the road. Internal information from another laboratory indicated three freeze-thaw cycles were used prior to testing.

Table 2.9. *Vialit* Conditioning Protocols From Literature

Source	Test Type	Cure Time (hr)	Conditioning Temp. (C)
CalTrans (2008)	Laboratory	48	60 then -22
ODOT (1998)	Laboratory	48	60 then -22
Coyne (1988)	Field & Lab	0.25 to 2	Field Temps
Louw et al. (2004)	Laboratory	24	0 to 50
Asphalt Academy (2007)	Laboratory	1	5 or 25
B301-89T	Laboratory	2.5	25
Davis et al. (1991)	Laboratory	0.2, 0.5, 2, 5, 24	0
Shuler (1990)	Laboratory	0.17, 0.25, 0.42	60

The *Vialit* test has been stated to be suitable to evaluate temperature characteristics of binder and aggregate combinations (Coyne, 1988). Epps et al. (2001) reported the *Vialit* test was inconclusive in terms of distinguishing performance between materials. Another study stated *Vialit* test results have been noted to create confusion and controversy, mainly due to variability and reliability (B301-89T). The test method, though, is still referenced in active specifications (e.g. TNZ M/13:1989).

Lee and Kim (2008a) studied granite aggregates and CRS-2 emulsion for chip seal construction using samples obtained from the field. *Vialit* test samples were placed on 20 cm square plates (thickness not noted by authors), and three drops from a height of 50 cm were

administered during testing. The samples were cured at 35 C for 24 hours prior to testing. Aggregate loss was expressed as a percentage by mass of material dislodged from the plates (both aggregate and emulsion would be dislodged from the plate) and corrected for emulsion loss. Aggregate losses of 17, 7, and 5% were reported for one, three, and five roller coverages, respectively.

Hollearn and Motina (2006) performed D7000 sweep testing and *Vialit* cure testing on binders (130/150 pen) in the presence of granite and basalt aggregates. D7000 was said to show effect of binder coalescence on stone retention. The series of tests from D7000 and the *Vialit* cure procedures produced the same overall performance results in terms of both emulsion and aggregate behavior.

Past experiences with the *Vialit* test were investigated; especially from the perspective of asphalt emulsion producers and state DOTs. Three producers supplying emulsion into Mississippi for MDOT activities in the 2010 time frame were contacted related to past experiences regarding the test. Perspectives of the test as it is typically conducted were not favorable as indicated by the following paragraphs.

Laboratory 1 used the test in the mid-to-late 1990s but abandoned the use of the method several years ago. When materials and trays were warm when tested, no noticeable aggregate loss occurred regardless of the circumstance. In general, the laboratory never achieved aggregate loss quantities suitable to differentiate quality of asphalt emulsions. The only way appreciable loss could be achieved was to lower the temperature significantly. Test temperatures on the order of -50 C were used, and the test was conducted immediately after removal from the freezer. Under these conditions, the most common mechanism of failure was sheet failure (emulsion de-bonding from the metal tray). This failure is not representative of actual conditions. The laboratory no longer has any *Vialit* test data or the test equipment.

Laboratory 2 used the test as early as two decades ago but has not used it for some time. An internal seal coat design procedure was used to determine emulsion and aggregate application rates; 100% of the design emulsion and 75% of the design aggregate (project gradation including dust) application rates were applied to the plate. Curing consisted of: 1) 60 C in oven for 24 hr; 2) 25 C in water bath for 16 hr; 3) -18 C in air for 3 hr; 4) 25 C in water bath for 3 hr; 5) -18 C in air for 3 hr; and 25 C in water for 3 hr. After conditioning, a 506 g sphere was dropped 30 cm onto the plate three times, and aggregate loss was recorded. The laboratory used 0.20 cm thick plates which they provided to the research team for testing in this project.

Conversation with the Oregon DOT revealed they used trays with 0.20 cm thick bottoms that had edge lips that were 0.635 cm thick. The Oregon DOT also indicated they had abandoned the method primarily because, during a typical test, emulsion was often dislodged from the metal tray in many areas rather than the aggregate. Conversation with the California DOT revealed they (at a minimum) used the test four to five years ago, but it did not appear significant activity was occurring at present. The equipment was not readily on hand to check the thicknesses of the trays used which would seem to indicate very little to no activity with the test method.

When the *Vialit* test was in use in Oregon, aggregate retention versus curing time (0.5, 1, 2, and 3 hours) was often plotted. Also, uniform cure time with variable temperatures and variable cure time with constant temperatures were incorporated in some instances. The Oregon DOT performed testing at 5 and -22 C and found the effect of polymer was not clear

at 5 C. At -22 C, the test was reported superior to 5 C in determining the presence of polymer in the binder.

2.7.1.2 Frosted Marble Testing

The Frosted Marble Test (*FMT*) is not a common test method. Some groups, however, use the test for internal information and equivalent purposes. C.R. Benedict developed the original test method (Benedict, 1990).

Guiles (1995) implemented the *FMT* but modified the curing regime to capture early torque data that could indicate the ability to withstand brooming action and early traffic. The test was also used for assisting in the determination of the minimum amount of emulsifier needed to produce a stable CRS-2P emulsion. For this test, CRS-2 and three versions of CRS-2P with 3% emulsion residue polymer were tested in a manner similar to Benedict (1990) with the exception of curing protocol and test repetition. The curing protocol provided 4 data points: 2, 4, 6 hrs of 37.8 C and 16 hrs of ambient conditions. At 6 hours, emulsion leveled off and was said to indicate full curing. Thirty tests were averaged and recorded as the chip retention strength. The polymer appeared to soften this type of material or retard its ability for early strength gain. The study reported polymers did not increase set time during the first 6 hours, and that polymers decreased set at 2 hours. CRS-2P had significantly improved properties relative to the CRS-2 at 16 hours.

Kucharek et al. (2006) focused on early chip retention using the *FMT* and Sweep tests; Section 2.7.1.3 provides more information. The major departure of Kucharek et al. (2006) from Benedict (1990) was the curing protocol, which consisted of ambient temperature (22 to 25 C) for periods of 2, 4, 6, and 24 hours.

Howard and Baumgardner (2009) summarize the original *FMT* test method and also document full scale chip seal test sections described in more detail elsewhere in this report. Table 2.10 provides *FMT* results from the polymer modified emulsions evaluated on *Hwy 84*, alongside CRS-2 data. Some CRS-2 data was also taken from Long Term Pavement Performance (LTPP) sections. Moisture contents of the LTPP materials were around 33% initially. After the 15 hr air drying period, moisture contents were 3.8 to 6.0%. Moisture contents were believed to have dropped to 1 to 2% after the 4 hr oven curing period and to near zero after the 15 hr oven curing period.

Howard et al. (2009) compared the original *FMT* method (Benedict, 1990) to a modified method that was developed at Paragon Technical Services, Inc. (PTSi). Both methods are described in a step by step manner in Howard et al. (2009), and the modified method is described in sections 4.5.5 and 4.6.5 as it was employed in State Study 211. Moisture loss was not measured in Howard et al. (2009) as it was for portions of State Study 211. Modifications were mostly to curing protocols and specimen testing schedules. The output curves produced by the modified *FMT* were reported more promising relative to evaluating a chip seal emulsion's purpose of achieving high early adhesion for aggregate retention followed by a leveling off period to allow long term flexibility.

Howard et al. (2009) also found *FMT* test variability was an area of potential improvement. The shaft not being vertical during the torsional process can be problematic. Also, the marble contacting the tray can cause artificially high readings. Values in excess of 40 kg-cm are often considered suspect. Inexperienced operators were indicated to be more prone to artificially high readings.

Table 2.10. *FMT* Data Using Benedict (1990) Method

kg-cm		Curing Condition		
Location	**Emulsion**	**15 hr Air**	**4 hr oven + 2 hr air**	**15 hr oven + 2 hr air**
LTPP-SPS-Midwest	CRS-2	10.5	17.0	21.5
LTPP-SPS-Northeast	CRS-2	16.0	19.0	21.0
LTPP-SPS-South	CRS-2	17.5	21.0	31.5
Hwy 84	CRS-2	13.2	19.0	34.1
Hwy 84	Modified-A	12.7	22.3	36.3
Hwy 84	Modified-B	16.6	22.5	36.1
Hwy 84	Modified-C	17.2	22.6	36.0
Hwy 84	Modified-D	12.0	13.5	17.2
Hwy 84	Modified-E	28.9	25.5	39.3
Hwy 84	Modified-F	20.1	24.3	28.6
Hwy 84	Modified-G	19.6	24.9	38.0
Hwy 84	Modified-H	22.9	28.0	32.3
Hwy 84	Modified-I	33.0	29.8	35.0

-- Data taken from Howard and Baumgardner (2009), which was part of State Study 202.
-- Modified A to I were polymer modified emulsions from field trials generically labeled A to I.
-- LTPP is Long Term Pavement Performance.
-- SPS is LTPP Specific Pavement Study-Class 3 in this case.
-- Base asphalt of US 84 products was approximately 150 pen at 25 C, and target polymer contents were 3% in terms of residue mass.

2.7.1.3 Sweep Testing

The ASTM D7000 sweep test was developed to model a chip seal's early performance by simulating brooming in the field through the abrasive force of a rotating brush head on a laboratory specimen. Specimen fabrication consists of applying emulsion by means of a template on a felt disk, followed by manual spreading of aggregate onto the specimen. The emulsion is applied at a fixed rate of 1.42 L/m^2 (0.31 gsy), and the aggregate application rate is determined by its gradation and specific gravity. The aggregates used in the sweep test are limited to specific sizes: 100% passing the 9.5 mm sieve (3/8 in) to less than 1% passing the 4.75 mm sieve (No. 4 sieve).

The specimen is conditioned in an oven at 35 C and 30 to 40% relative humidity prior to testing. Sweep testing is conducted by a brush head attached to a mixer, which abrades the surface. Performance of chip seals is measured in terms of percent aggregate mass loss after a test period of one minute.

Kucharek et al. (2006) focused on early chip retention using the *FMT* and sweep tests. Ten cationic and anionic emulsions with different polymers were evaluated at 2, 4, 6, and 24 hr of room temperature (22 to 25 C) curing. These emulsions were evaluated with three aggregates (granite, limestone, and trap rock) with less than 1% fines. The term total loss (*TL*) was identified for the sweep test. *TL* was defined as the percent mass loss from preparation until after the sweep test was complete including moisture, un-embedded chips, stone loss during hand brushing, and stone loss during the sweep test. Chemical compatibility with the aggregate was reported to be more important once the emulsion residue begins gaining strength and the failure mechanism begins shifting from cohesive towards adhesive. Results showed that cationic emulsions cure at a faster rate relative to the anionic emulsions. Strength gain rate was fastest with use of CRS-2P emulsions making them more advantageous.

Islam and Hossain (2011) conducted sweep testing to evaluate lightweight aggregates in chip seal projects with the purpose of reducing vehicular damage. Four lightweight aggregates, each from different states, were tested; G_{sb} ranged from 1.17 to 1.53 and *Abs* ranged from 10.9 to 19.6%. Four blends were developed for each aggregate. Two emulsions, CRS-1HP and CRS-2P, were evaluated. ANOVA results indicated a significant interaction between aggregate and emulsion existed for three of the four aggregate blends at 5% level of significance (the non-significant blend had a *p-value* of 0.051). These results suggest that aggregate and binder selections should not be made independently. The highest and lowest aggregate losses were obtained when using CRS-1HP emulsion, depending on the aggregate source. Therefore, selecting materials based on aggregate-emulsion compatibility was recommended to reduce aggregate loss.

Islam and Hossain (2011) and Rahman et al. (2012) performed D7000 testing of lightweight aggregates. Rahman et al. (2012) and Musty and Hossain (2013) performed D7000 testing of reclaimed ultra-thin bonded bituminous surface (UBBS or Novachip) millings used as pre-coated aggregates in chip seals. Results showed that lightweight aggregates outperformed normal weight aggregates and UBBS millings generally performed worse than normal weight aggregates (pre-coated). Further, Rahman et al. (2012) found no significant difference in uncoated versus pre-coated aggregates with respect to sweep test mass loss. Islam and Hossain (2011) observed that aggregate retention depends on the prevailing charges of emulsion particles and aggregate surfaces.

Shuler and Lord (2009) state that even though the sweep test successfully captures adhesive bonding through the formation of a cohesive film of emulsion over aggregate, it cannot differentiate between different aggregate gradations with the same emulsion. The reason is that only one template is used and each test specimen possesses approximately the same film thickness, regardless of the emulsion type. Also, the repeatability and variability of the test results are affected due to varying embedment levels caused by lack of gradation control. It ultimately affects the potential use of this test method to determine the proper time required for the chip seal to cure before reopening to traffic. Researchers recommend modifying the sweep test procedure so that application rates are applied based on design calculations, and so that different emulsion rates are applied by means of templates with varying thicknesses (Shuler and Lord, 2009).

Johannes et al. (2011) performed 216 D7000 tests to evaluate the effects of emulsion application rate, aggregate gradation, and material type (i.e. different aggregates [limestone and granite] and emulsions [CRS-2, HFRS-2L, HFRS-2]). Results showed that D7000 was not sensitive to emulsion application rates yielding 35 to 70% embedment (corresponding to 0.85 to 2.00 L/m^2 for aggregates tested) according to a modified version of McLeod's method applicable to sweep test conditions. Variations in application rates were performed based on McLeod (1969). There was a general trend of aggregate loss reduction with additional emulsion, but the trend was not statistically significant (*p-value* of 0.09). Wasiuddin et al. (2012), however, found that D7000 was sensitive to increases in application rate from 2.04 to 2.72 L/m^2 (0.45 to 0.60 gsy). Aggregate gradation was a statistically significant factor (*p-value* of 0.00); coarse-graded aggregates resulted in more aggregate loss than fine-graded aggregates (Johannes et al., 2011). This could be because the clearance distance between the sweep head brush and the top of the aggregate particles is less for larger aggregates, which could result in larger shear forces. The sweep test was sensitive to the combination of emulsion type, aggregate mineralogy, and gradation. It was recommended

that the sweep test with minor modifications be used for evaluating compatibility between aggregates and emulsions. The properties of the aggregates tested are shown in Table 2.11, and material application rates are provided in Table 2.12.

Table 2.11. Aggregate Properties from Johannes et al. (2011)

Aggregate Properties	Testing Procedure	Fine Gradation		Coarse Gradation	
		Granite	Limestone	Granite	Limestone
Median Particle Size (mm)	McLeod (1969)	6.3	6.3	9.5	9.5
Flakiness Index (%)	FLH T 508	18.75	13.37	25.85	10.45
Average Least Dimension (mm)	McLeod (1969)	4.34	5.53	4.89	6.29
Loose Unit Weight (kg/m^3)	ASTM C29	1440	1441	1408	1410
Voids in Loose Aggregate	ASTM C29	0.455	0.474	0.474	0.474
Aggregate Absorption (%)	ASTM C127	0.26	0.95	0.26	0.95
Bulk Specific Gravity	ASTM C127	2.64	2.70	2.64	2.70

Table 2.12. Material Application Rates of Johannes et al. (2011)

		McLeod's Design Method			ASTM D7000
		% Embedbment			---
	Application Rate	**70**	**50**	**35**	---
Fine Granite	Aggregate Rate (kg/m^2)	7.31	7.31	7.31	7.50
	Binder Rate (L/m^2)	1.71	1.22	0.85	1.44
	Plate Thickness (mm)	1.71	1.22	0.85	1.41
Fine Limestone	Aggregate Rate (kg/m^2)	8.20	8.20	8.20	7.67
	Binder Rate (L/m^2)	2.00	1.43	1.00	1.44
	Plate Thickness (mm)	2.00	1.43	1.00	1.44
Coarse Granite	Aggregate Rate (kg/m^2)	10.92	10.92	10.92	N/A
	Binder Rate (L/m^2)	2.72	1.94	1.36	N/A
	Plate Thickness (mm)	2.70	1.94	1.36	N/A
Coarse Limestone	Aggregate Rate (kg/m^2)	13.01	13.01	13.01	N/A
	Binder Rate (L/m^2)	3.17	2.26	1.58	N/A
	Plate Thickness (mm)	3.17	2.26	1.58	N/A

Johannes et al. (2011) studied two aggregate types (granite and limestone) at two gradations: a fine gradation with all particles passing 9.5 mm sieve as specified by D7000 and a coarse gradation with all particles passing the 12.5 mm sieve. Results indicated coarse gradations resulted in higher mass loss than fine gradations. The trend was consistent across different curing times, application rates, and emulsion types, as an ANOVA at 5% level of significance found significant variation. Furthermore, the ANOVA showed that aggregate mineralogy (*F* value of 253) was more significant than aggregate gradation (*F* value of 106). It was reported that the effects of the chemical interaction between aggregate and emulsion overshadowed the effects of aggregate gradation. For example, the HFRS-2 emulsion was more compatible with limestone than granite.

Overall, limestone and granite performed best with CRS-2. Latex modified (HFRS-2L) performed slightly better than unmodified (HFRS-2). CRS-2 gained strength faster with limestone than granite at 2 hr cure; however, between 2 and 6 hr cure, granite gained strength faster. At 6 hours, mass loss was insignificant across all aggregate types. The authors concluded that 1) the sweep test should not be used as a design tool because it is not capable of capturing variations in emulsion application rates which vary in normal practice, 2) the actual emulsion rate used in the sweep test should not be modified since it is sufficient, 3) the sweep test should be revised to allow aggregate sizes that are representative of actual

practice, 4) sweep test is sensitive to emulsion and aggregate type, and 5) sweep test could be modified to determine bond development and allowance to traffic by controlling curing conditions and time restraints (Mahmoud et al., 2011).

Several modified sweep tests have also been presented. Islam and Hossain (2011) and Rahman et al. (2012) developed a modified sweep test which tested a rectangular area. It yielded higher mass loss than D7000 but better distinguished chip seal systems of varying quality because of the larger overall range of mass loss results. Shuler and Lord (2009) developed a test method with the primary objective of measuring chip loss as a function of aggregate type, aggregate water content, and moisture loss in order to predict adequate chip seal strength for traffic opening. D7000 was the basis of the research, and it was modified to apply different aggregate and emulsion application rates, while reducing variability. The test was also modified to provide means of determining cure levels (water remaining in emulsion) of different emulsions with the purpose of correlating moisture loss with performance in terms of aggregate loss.

Shuler and Lord (2009) tested four emulsions at 40 and 80% moisture loss and four different aggregate sources at dry and SSD conditions (Tables 2.13 and 2.14). Multiple aggregate and emulsion application rates were considered based on McLeod (1969) calculations. A new assembly was developed to systematically drop aggregates onto the circular template as an alternative to hand placement. Emulsion application rates were incorporated by means of different emulsion templates of varying thicknesses (Shuler and Lord, 2009). The moisture content of the test specimen was adjusted based on emulsion moisture content and final aggregate moisture at SSD (based on a reasonable estimation of unexposed aggregate pores).

Table 2.13. Emulsion Properties by Shuler and Lord (2009)

Test	RS-2P	RS-2	CRS-2	CRS-2P
Residue (%)	65.1	68.0	68.0	68.0
Pen, 25 C	115	--	125	--
Ductility, 25 C	150+	--	55	--
DSR, G* **(kPa)**	1.11	--	1.12	--
PAV, DSR, G* **(MPa)**	1210	--	3170	--

Results show that, overall, aggregate type, aggregate moisture content, and system moisture loss significantly and independently affect mass loss. Shuler and Lord (2009) found 80% moisture loss performed significantly better than 40%. Similarly, SSD aggregates outperformed dry aggregates under the premise that damp aggregates improve the emulsion absorption into the aggregate pores, thus improving its adhesive and cohesive properties (Shuler and Lord, 2009; Shuler, 2011). Wasiuddin et al. (2012) confirmed some moisture in aggregates is beneficial to aggregate retention performance, but Islam and Hossain (2011) found SSD aggregates generally, but not statistically, resulted in higher mass loss. Emulsion charge was not a significant factor since there was no significant difference in mass loss between cationic and anionic emulsions when tested with calcareous and siliceous aggregates. Shuler and Lord (2009) further concluded that the revised sweep test method has potential to determine traffic opening with less risk of vehicular damage by correlating sweep test results to moisture content.

Table 2.14. Aggregate Properties by Shuler and Lord (2009)

Sieve (mm)		Limestone	Granite	Basalt	Alluvial
12.5	Percent Passing	100	100	100	100
9.5		100	99	100	99
8.0		100	50	79	73
6.35		48	9	30	33
4.75		1	1	1	2
0.075		1	1	1	2
Bulk specific gravity		2.615	2.612	2.773	2.566
Loose unit weight (lb/ft^3)		78.31	83.97	92.20	86.05
Median size (in)		0.252	0.315	0.277	0.277
ALD (in)		0.170	0.265	0.218	0.222
McLeod (lb/yd^2)		16.48	26.11	22.95	21.73
ASTM D7000 (lb/yd^2)		13.31	14.98	14.96	13.56

Miller et al. (2010) found that curing time, aggregate mineralogy, and curing temperature significantly affect chip seal retention in terms of emulsion residue stiffness (these factors contribute to moisture loss and moisture loss rates). Miller et al. (2010) conducted a research study to define acceptable performance standards of chip seals needed to allow the re-opening of traffic by measuring emulsion residue stiffness at various curing conditions. CRS-2 emulsion was tested with limestone and granite aggregates using a modified version of the *DSR* and D7000.

Strain sweep tests conducted with the *DSR* using CRS-2 emulsion cured on limestone and granite substrates were used to establish whether the emulsion residue develops enough stiffness to prevent excessive loss of aggregate and raveling. It consisted of pouring 2.5 g of emulsion in circular shapes on large rock aggregate plates with a film thickness of approximately 1 mm. Specimens were set to cure at 30 and 70% humidity, 15 and 35 C temperatures, and allowed to set for 2, 6, and 24 hrs. Strain sweeps were conducted at 25 C.

Sweep tests were conducted to measure the curing performance characteristics of specimens fabricated in laboratory settings; specimens were made with CRS-2 emulsion and limestone aggregate according to D7000 except the application temperature of the base binder was 135 C. Specimens remained undisturbed for one hour before testing to equalize to laboratory temperature.

Miller et al. (2010) conducted an ANOVA to identify the factors that affect the development of emulsion stiffness, and found that curing time and temperature were more important than other factors considered. CRS-2 emulsion significantly increased resistance to permanent deformation over time and also gained the most stiffness when cured at higher temperatures. Overall, highest aggregate retention levels were found after 24 hours of curing at 35 C and 30% relative humidity. Limestone aggregate had better compatibility with CRS-2 emulsion and outperformed granite aggregate.

Johannes et al. (2011) proposed a chip seal was generally considered ready for traffic when D7000 mass loss was less than 10%. Each aggregate tested required 6 hours minimum of laboratory conditioning in order to reach this threshold value. Furthermore, Johannes et al. (2011) noted that, in reality, this threshold might not indicate traffic readiness since aggregate sizes used in the field are often larger than those used in D7000 (9.5 mm aggregates maximum).

Sweep test limitations include fixed emulsion application rates and narrow ranges of aggregate sizes which are not representative of actual chip seal construction. Literature review suggests moisture loss is correlated to strength gain and that the sweep test could be useful in evaluating the extent and nature of the correlation.

2.7.2 Moisture Effects on Aggregate Retention and Traffic Opening

Two versions of the sweep test (specimens cured up to 4 hr at 35 C) were performed alongside the frosted marble test (*FMT*) by Howard et al. (2011). Eight emulsion types were tested; three of the emulsions are also evaluated in this report (Emulsions 1, 2, and 4 in Table 3.1). Nine aggregates were evaluated, which were different than those described in Table 3.8. The nine aggregates tested included the following aggregate types: alluvial, basalt, granite, limestone, sandstone, and trap rock.

Test results correlated moisture loss to strength gain and indicated that as moisture loss (calculated by referencing the total initial water mass in the specimen) approached 75 to 90% strength gain was significantly enhanced. *FMT* results showed a modest strength gain up to approximately 80% moisture loss and more substantial moisture loss between 80 to 90% moisture loss. Sweep test moisture loss was 65 to 80% when mass loss was 10 to 15%; for some emulsion-aggregate combinations, moisture loss of 65 to 80% produced mass loss above 15%. The same emulsion combined with different aggregates was observed to be the best performing and the worst performing product. Howard et al. (2011) favored D7000 (or the modified D7000) over the *FMT* for evaluating chip seal systems. Since sweep test data indicated moisture loss values on the lower end of the 75 to 90% moisture loss window recommended using *FMT* and sweep data, additional sweep tests should be performed to determine if the recommended moisture loss value could be lowered while still achieving acceptable field performance.

The timing to broom or to allow traffic onto a freshly placed chip seal is, at best, difficult as over ten factors affect the decision (Shuler, 2011). In general, the residual binder strength after emulsion breaking is directly related to the amount of moisture remaining in the emulsion (Shuler and Lord, 2009). Traffic too soon can cause vehicle damage, while traffic too late is inefficient. Brooming too soon can damage the seal by dislodging aggregates.

Shuler (2011) and Shuler et al. (2011) conducted three field trials and found chip seals were capable of resisting brooming and traffic damage at 75 to 85% moisture loss, which correlated well to laboratory sweep testing. Table 2.15 provides time required to reach 75 to 80% moisture loss as well as weather conditions for each field site.

The amount of moisture remaining in each chip seal was measured and subsequently compared with the relative residue strength on a 1 to 10 scale (1 being no strength and 10 being ready for traffic). Relative residue strength was evaluated by pulling three aggregates from the fresh seal after rolling and qualitatively assessing dislodgement potential.

Moisture remaining was determined using 61 cm square plywood pads covered with aluminum foil. The pads were placed in front of the distributor. Pads were weighed before and after spraying and chipping, and mass loss was determined periodically until approximately 95% of the water had evaporated.

Shuler (2011) and Shuler et al. (2011) recommended the critical moisture content be that which corresponded to 10% D7000 mass loss. Uncontrolled traffic could be allowed

onto the chip seal field test sections once the critical moisture loss was achieved. The research used a qualitative index to judge when field test sections could withstand brooming and uncontrolled traffic; research is needed to develop a quantitative measure for evaluating chip seal binder adhesive strength in the field (e.g. a field sweep test that is conceptually similar to D7000).

Table 2.15. Shuler (2011) Pavement Summaries

Project	State	Ambient Temp (F)	Pavement Temp (F)	Weather	Time to 75 to 80% Moisture Loss (hr)
Frederick	CO	85 to 90	100 to 110	Full Sun, 45% RH	2.5 hr
Arches Nat. Park	UT	90 to 100	110 to 120	Full Sun, 30% RH	2.0 hr
Forks	WA	60 to 75	80 to 90	Little Sun, 95% RH	12.0 hr

-- *RH = relative humidity*

CHAPTER 3-MATERIALS TESTED

3.1 Overview of Materials Tested

The aggregates, emulsions, and asphalt pavements tested are described in this chapter. Material sources, general descriptions, test methods, and test results of each material individually are described in this chapter. Subsequent testing evaluates properties of combinations of these materials, which is the primary emphasis of this report.

3.2 Asphalt Emulsions

Emulsions were selected to encompass products available for chip/scrub seals in Mississippi as of beginning of State Study 211 (January 2009). All producers supplying emulsion to MDOT on a routine basis were contacted to select emulsion formulations needed to represent the entire state. The producers were: 1) *Blacklidge Emulsions, Inc.*; 2) *Ergon Asphalt & Emulsions, Inc.*; and 3) *Road Science, LLC* (formerly *SemMaterials LP*). Seven emulsions were selected, and their formulations were used in this report.

Ideally, all emulsions would have been sampled at the same time and all testing conducted very soon thereafter. For a project of this size, the ideal was not possible. Instead, multiple samples of the same emulsion type were obtained from the same producer. Table 3.1 summarizes the emulsions tested, and assigns emulsion identification numbers.

Table 3.1. Identification System for Emulsions Tested

Emulsion ID	Polymer Modified	Type	Supplier	Sources
E1	No	CRS-2	Ergon	Plant-Pleasanton, TX
E2	Yes	CRS-2P-SBR	Ergon	Pleasanton-TX & Vicksburg-MS Plants; Lab
E3	Yes	PASS-CR	Ergon	Pleasanton-TX & Memphis-TN Plants; *Hwy 17*[a]
E4	Yes	CHFRS-2P	Ergon	Pleasanton-TX Plant and Lab
E5	Yes	CRS-2P-SBS	Road Science	Lab
E6	Yes	Road Armor	Road Science	Garden City-GA Plant; Lab
E7	Yes	CFS-2HP	Blacklidge	Lab

a) Emulsion sampled during MDOT State Study 202 in Carroll County at coordinate 6.090 (Howard, 2009).

Figure 3.1 is representative of field sampling and handling used in this report. Note that most sampling was from plants. The sample was taken from the distributor nozzle, cooled to room temperature, re-heated to 60 C (12 to 18 hr), agitated with a hand drill and standard mixing attachment (2 min), and transferred to heated 1.9 or 3.8 L plastic containers for future testing.

Emulsion stored more than one month was stirred monthly with wooden dowels after heating to 60 C; emulsions were stored at room temperature. A sieve test (ASTM D6933) was performed just prior to use, and if the emulsion passed the sieve test and did not have any visual defects, it was used for testing. Emulsion was re-heated a minimal number of times (one re-heat in most cases), and while hot, the emulsion remained covered to minimize evaporation. Many of the protocols tested the emulsion within a few weeks of production.

Ergon and Blacklidge emulsions were heated in a 60 C oven for at least 4 hours. Thereafter, the emulsion was slowly rolled end-over-end to restore consistency after verifying the temperature by placing a thermometer into the container. Road Science

emulsions were heated in a 60 C water bath approximately 75% covered in 3.8 liter containers placed on a 6.3 mm spacer to prevent overheating due to direct contact with the water bath. The emulsion was slowly stirred with a rod to restore consistency.

Figure 3.1. Hwy 17 Sampling of PASS-CR (Emulsion 3)

Table 3.2 provides properties from samples taken at the same time as the emulsions tested. Properties shown are for the emulsions in the state used during sealing. Note that Saybolt Furol Seconds (*SFS*) viscosity values can be affected by sample age and can drift up or down over time depending on the asphalt, emulsifier, and polymer modifier used. *SFS* values varied considerably for some emulsions as observed in Table 3.2.

Table 3.2. Emulsion Properties According to AASHTO T59, T72, and T200

ID	pH	Particle Size (µm)	Sieve (%)	Demulsibility (%)	Oil by Vol. (%)	24 hr Storage (%)	*SFS* Visc. @ 50 C (s)
E1	3.68 to 4.20	1.77 to 4.01	0.01 to 0.01	84 to 100	0.13 to 0.25	0.03 to 0.10	114 to 452
	3.94	**2.89**	**0.01**	**93**	**0.17**	**0.07**	**283**
E2	3.70 to 3.91	4.67 to 7.29	0.00 to 0.04	56 to 94	0.00 to 0.13	0.09 to 0.14	73 to 397
	3.81	**5.98**	**0.02**	**78**	**0.09**	**0.11**	**207**
E3	1.90 to 2.66	1.47 to 5.29	0.00 to 0.03	20 to 61	0.63 to 0.63	0.01 to 1.05	94 to 101
	2.35	**3.38**	**0.02**	**46**	**0.63**	**0.52**	**98**
E4	2.44 to 2.62	4.56 to 7.12	0.02 to 0.02	55 to 81	0.25 to 0.25	0.04 to 2.50	59 to 143
	2.53	**5.84**	**0.02**	**72**	**0.25**	**1.27**	**101**
E5	1.78 to 3.29	2.58 to 2.91	0.00 to 0.00	59 to 61	0.00 to 0.10	-0.20 to 0.18	65 to 189
	2.54	**2.75**	**0.00**	**60**	**0.05**	**-0.01**	**126**
E6	2.00 to 2.26	5.48 to 9.50	0.01 to 0.05	100 to 101	0.00 to 0.50	0.01 to 0.02	119 to 252
	2.13	**7.59**	**0.04**	**101**	**0.27**	**0.02**	**172**
E7	2.80 to 3.00	4.51 to 8.24	0.01 to 0.01	67 to 100	0.10 to 0.50	0.00 to 0.60	36 to 228
	2.90	**6.04**	**0.01**	**89**	**0.37**	**0.21**	**155**

-- pH is according to T200, SFS according to T72, and all remaining tests are according to T59 except for particle size. Particle size was determined using a Malvern Mastersizer Micro-P and manufacturer protocols.
-- A range of values from multiple tests are shown with the average value bolded on the next line.

Table 3.3 provides penetration, ductility, and elastic recovery properties tested on emulsion residue, alongside the residue values. AASHTO M208 was followed using the protocol for emulsion 1 since there is no polymer/latex modified emulsion specification in M208. Emulsion 1 distillation was conducted at 260 C, while the polymer modified emulsion distillations were conducted at 177 C. Penetration was performed with a 100 g mass and 5 second duration, while elastic recovery was performed on specimens elongated 20 cm and held 5 minutes.

Table 3.3. Emulsion Properties According to AASHTO T49, T51, and T301

ID	Residue (%)	T49 Penetration at 25 C (dmm)	T51 Ductility at 25 C (cm)	T301 Elastic Recovery at 10 C (%)
E1	67.3 to 69.9	130 to 130	87 to 117	5 to 8
	68.7	**130**	**102**	**6**
E2	66.9 to 68.1	104 to 126	47 to 146	50 to 65
	67.6	**116**	**81**	**63**
E3	65.3 to 67.9	214 to 250	58 to 60	55 to 65
	66.6	**232**	**59**	**60**
E4	68.6 to 69.8	93 to 129	89 to 150	48 to 59
	69.1	**111**	**120**	**53**
E5	66.6 to 68.5	122 to 151	145 to 150	64 to 69
	67.6	**137**	**148**	**67**
E6	69.8 to 73.7	69 to 84	100 to 114	65 to 68
	71.4	**77**	**107**	**66**
E7	70.3 to 72.5	68 to 71	60 to 97	63 to 65
	71.7	**70**	**79**	**64**

Note: A range of values from multiple tests are shown with the average value bolded on the next line.

Dynamic Shear Rheometer (*DSR*) and Bending Beam Rheometer (*BBR*) testing was performed on emulsion residue obtained for grading via oven evaporation at 110 C (Tables 3.4 to 3.6). Specified values are provided as notes at the bottom of each table. Table 3.7 shows critical temperatures calculated with the data and specified values in Tables 3.4 to 3.6. Table 3.7 provides the temperature interval (T-I) for each emulsion based on unaged *DSR* and either *BBR m-value* or stiffness values. The T-I concept parallels the useful temperature interval (UTI) of the PG system (Asphalt Institute, 2012). T-I and UTI should not be used interchangeably since T-I is specific to the grading of emulsions in this report where true AASHTO M320 grading was not performed.

Table 3.4. Unaged *DSR* Results of Emulsion Residue (AASHTO T315)

Emulsion ID	Test Temp. (C)	G^* (kPa)	δ (deg)	$G^*/\sin\delta$ (kPa)
E1	58	1.15	82.6	1.16
	64	0.58	84.1	0.59
E2	64	1.34	78.3	1.37
	70	0.71	79.3	0.73
E3	58	1.19	82.8	1.19
	64	0.60	84.4	0.60
E4	70	1.60	74.5	1.66
	76	0.91	76.0	0.94
E5	64	1.23	76.6	1.27
	70	0.66	79.2	0.67
E6	64	3.57	68.1	3.84
	70	1.95	70.6	2.07
	76	1.08	73.8	1.13
	82	0.61	77.5	0.62
E7	64	4.08	72.7	4.28
	70	2.18	74.1	2.26
	76	1.24	75.1	1.28
	82	0.73	75.6	0.76

Note: Specified minimum value is $G^*/\sin\delta$ of 1.0 kPa.

Table 3.5. *PAV* Aged (100 C) *DSR* Results of Emulsion Residue (AASHTO T315)

Emulsion ID	Test Temp. (C)	G^* (kPa)	δ (deg)	$G^*(\sin \delta)$ (kPa)
E1	10	5830	46.3	4220
	7	9220	43.7	6370
E2	13	5290	42.6	3580
	10	8080	40.3	5220
E3	10	6890	44.5	4840
	7	10800	41.9	7190
E4	13	5900	40.2	3800
	10	8160	38.6	5100
E5	22	1108	50.8	858
	19	1720	48.6	1291
	16	2645	46.5	1918
	13	3930	45.1	2782
	10	5992	42.7	4065
	7	9039	40.3	5848
E6	22	2773	48.3	2070
	19	4298	45.8	3081
	16	6577	43.2	4505
	13	9971	40.6	6488
E7	22	3120	47.0	2280
	19	4780	44.8	3370
	16	7150	42.7	4850
	13	10900	40.3	7070

Note: Specified maximum value is $G^*(\sin \delta)$ of 5,000 kPa.

Table 3.6. *PAV* Aged (100 C) *BBR* Results of Emulsion Residue (AASHTO T313)

Emulsion ID	Test Temp (C)	Stiffness (MPa)	*m-value* (---)
E1	-18	92	0.398
	-24	198	0.334
	-30	546	0.273
E2	-18	109	0.337
	-24	232	0.298
	-30	539	0.246
E3	-18	78	0.391
	-24	160	0.332
	-30	575	0.268
E4	-18	105	0.328
	-24	257	0.290
	-30	443	0.220
E5	-18	63	0.390
	-24	152	0.345
	-30	332	0.287
E6	-18	170	0.332
	-24	343	0.289
E7	-18	192	0.328
	-24	399	0.269

Note: Specified maximum stiffness of 300 MPa and minimum m-value of 0.3.

Polymer cross linking can occur at temperatures above approximately 135 C and since the emulsions will not be exposed to these temperatures they were not used during recovery for *DSR* and *BBR* testing (110 C was used as stated in the previous paragraph). In

general, 50 g of emulsion was placed into 1000 ml beakers. ASTM D6934 was followed with exception of the temperature and additional time required to achieve constant mass. Beakers filled with emulsion were placed into the oven at 110 C for 2 hours, stirred, and placed back into the oven for an additional hour. The beakers containing emulsion were cooled and weighed, and thereafter the beakers were placed back into the oven for 1 hour intervals, cooled and weighed until constant mass was obtained. It took eight hours to obtain constant mass for most emulsions.

No Rolling Thin Film Oven (*RTFO*) Test was performed on this residue since they would never experience these conditions during manufacture, construction, or service. Pressure aging vessel (*PAV*) aging (AASHTO R28 at 100 C) was performed for some testing since it could give an indication of emulsion properties after a period of service. Unaged emulsion testing was also performed to compliment *PAV* aged data.

Table 3.7. Emulsion Critical Temperatures (C)

Emulsion ID	T315 Unaged *DSR*	T315 PAV Aged *DSR*	T313 PAV Aged *BBR* Stiffness	T313 PAV Aged *BBR m-value*	T-I
E1	59.3	8.8	-36.5	-37.3	95.8
E2	67.0	10.3	-35.8	-33.7	100.7
E3	59.5	9.8	-36.9	-37.0	96.4
E4	75.3	10.2	-35.7	-32.4	107.7
E5	66.2	8.3	-39.2	-38.7	104.9
E6	77.2	15.1	-32.9	-32.5	109.7
E7	78.8	15.8	-31.7	-30.8	109.6

Note: Critical temperature (T_c) was calculated with the approach presented on pages 107 to 109 of AI (2011).

3.3 Aggregates

Three aggregates were tested with properties provided in Table 3.8. Aggregate 1 was sampled during State Study 202 from the *Hwy 17* project (Howard, 2009). Aggregate 2 is not native to Mississippi or commonly imported; it was used in this research for comparison purposes. Aggregate 3 is produced by APAC Mississippi, Inc. for sealing activities as demand warrants. Washed and crushed gravel such as aggregate 3 was placed in Sunflower County on or before January 2009 according to the material supplier.

Gradation was measured through sieve analysis according to ASTM C117 and C136. The coarse aggregate bulk specific gravity (G_{sb}) and water absorption (*Abs*) were measured according to ASTM C127. Median particle size (50% or more passing a particular sieve size) was calculated by means of interpolation between sieve sizes closest to those corresponding to 50% passing. Flakiness Index (*FI*) was calculated according to Texas DOT standard Tex-224-F with one deviation: the metal gage used belongs to British standard BS 812, which is slightly different than used in Tex-224-F (refer to section 2.3). The BS 812 metal gage has smaller slot openings, being 1.1 mm off at most. Loose unit weight (*W*) was found according to ASTM C29 by means of the rodding procedure. Average least dimension (*H*) and voids in aggregates (*V*) were calculated using Equations 3.1 and 3.2, respectively.

$$H = \frac{M}{1.139285+(0.011506)FI} \tag{3.1}$$

Where,
H = average least dimension, which is also referred to as ALD (inches)
M = median particle size (inches)
FI = flakiness index as percent

$$V = \frac{1-W}{62.4[G_{sb}]} \quad (3.2)$$

Where,
V = voids in loose aggregate as decimal
W = loose unit weight of cover aggregate (lbs/ft^3)
G_{sb} = bulk specific gravity

Table 3.8. Properties of Aggregates Tested

Aggregate ID		**1**	**2**	**3**
Source		Hoover, AL (*Hwy 17*)	Wedowee, AL	Sidon, MS
Type		Limestone	Granite	Gravel
ASTM C33		Size 89	Size 8	Size 8
Percent Passing	**19.0 mm**	100.0	100.0	100.0
	12.5 mm	99.7	99.6	100.0
	9.5 mm	95.2	88.2	94.4
	8.0 mm	85.1	63.7	81.0
	6.7 mm	73.3	44.5	59.4
	6.35 mm	70.0	37.6	52.8
	5.6 mm	62.9	29.2	38.4
	4.75 mm	52.2	18.9	19.0
	2.36 mm	14.2	3.9	0.5
	1.16 mm	2.4	2.2	0.3
	0.6 mm	1.3	1.5	0.3
	0.3 mm	1.0	1.1	0.2
	0.15 mm	0.8	0.8	0.2
	0.075 mm	0.7	0.5	0.2
Coarse G_{sb}		2.537	2.653	2.538
***Abs* (%)**		1.8	0.8	1.3
M		4.61	7.07	6.20
FI		25.85	32.89	14.91
H		0.126	0.183	0.186
W		1484	1510	1468
V		0.415	0.431	0.421
D_{60}		5.37	7.75	6.74
D_{10}		1.93	3.33	3.59
C_u		2.8	2.3	1.9

Note: These gradations are slightly off with respect to size designation of the project.
Note: Typical Abs. values from the Hoover, AL source are 1.6 to 1.9% in MDOT records.

Legend
Coarse G_{sb}: Coarse bulk specific gravity
Abs: Absorption
M: Median particle size (≥ 50% passing)
FI: Flakiness Index
H: Average least dimension (inches)
W: Loose unit weight (kg/m^3)
V: Voids in Aggregate
D_{60}: Particle diameter size where 60% passes
D_{10}: Particle diameter size where 10% passes
C_u: Coefficient of Uniformity (D_{60} / D_{10})

3.4 Asphalt Concrete Pavements

Four asphalt concrete mixtures were tested. Three were field aged pavements, and the other was a plant mixed sample used to compact specimens in the laboratory. The three field aged pavements were: 1) frontage road adjacent to Highway 25 in Starkville, MS (*FR*), 2) abandoned portion of Highway 45 in Crawford, MS (*Hwy 45*), and 3) Highway 17 in Carroll County, MS sampled during State Study 202 (*Hwy 17*). The plant mix pavement was sampled from APAC-Columbus in Lowndes County, MS in September 2010 (*Plant Mix*).

The field aged pavements were selected because: a) they had different permeability; b) their conditions differed as *FR* was less cracked than *Hwy 45* (Figure 3.2); and c) they were different functional classifications. Slabs approximately 76 cm square were sawn from the pavements in areas free of large cracks, pot holes, and other large distresses using a walk behind wet saw. The slabs were removed with a backhoe and loaded into a trailer. Slabs were taken across the full lane width.

Figure 3.2. Field Aged Pavements Tested

The field aged slabs were leveled, supported around the edges to prevent movement, and cored (150 mm diameter) at the laboratory; each slab produced approximately 15 cores. Coring avoided sizeable cracks, irregularities, or other isolated deficiencies. After a core was cut, it was washed and placed under a fan to dry at room temperature. Once dry, cores were stored at room temperature and humidity out of sunlight. Cores were numbered in a random fashion; all cores taken from each pavement were assumed to have the same properties. Well over 1,000 cores were obtained from the field aged pavements in all.

Plant Mix was sampled at the plant (plant operating temperature of 160 C), allowed to cool, re-heated, and then compacted in the Superpave Gyratory Compactor (SGC) to produce test specimens. Specimens were compacted to a target air void content of 7 ± 1% air voids measured by AASHTO T331 (Corelok®). The aggregate blend was 37% gravel, 37% limestone, 15% RAP, 10% sand, and 1% hydrated lime with a combined aggregate absorption of 2.1%. Design voids in mineral aggregate (*VMA*) was 15.5%, and the dust to effective binder ratio was 1.13. In some instances, specimens were sliced horizontally to make use of the top and bottom face of the specimens.

FR and *Hwy 45* cores that were equal to the thickness of the surface lift were broken up, and the asphalt was extracted with an 85% toluene-15% ethanol solvent, recovered, and evaluated according to AASHTO M320. Test results are provided in Table 3.9. Properties were measured at two temperatures and the critical temperature (T_c) was calculated according to the procedure in MS-26 (2011), which is similar to the procedure in the appendix of M323-07. The low temperature T_c values shown have been reduced by 10 C to account for the warmer low temperature test conditions. Also provided in Table 3.9 are the binder grade

and asphalt content used during production of the *Plant Mix* sample; no other grading was performed on the *Plant Mix*. *Hwy 17* asphalt content was determined by extraction, but no binder grading was performed. Aggregate gradations and nominal maximum aggregate size (NMAS) are provided in Table 3.10. ASTM C117 and C136 were performed for *FR* and *Hwy 45*. The mix design gradation is provided for *Plant Mix*, and no gradation was performed for *Hwy 17*.

Table 3.9. Binder Properties of Asphalt Concrete Pavements

	Conditioning Test Method	**None T315**	**T240 Res. T315**	**R28 Res. T315**	**R28 Res. T313**	**R28 Res. T313**
Pavement	**Test Temp (C)**	**$G^*/\sin\delta$ (kPa)**	**$G^*/\sin\delta$ (kPa)**	**$G^*(\sin\delta)$ (kPa)**	**Stiffness (MPa)**	***m-value* (---)**
FR	-12	---	---	---	306	---
	-6	---	---	---	169	0.228
Asphalt	0	---	---	---	---	0.300
Content **5.8%**	34	---	---	7190	---	---
	37	---	---	4203	---	---
Continuous	82	7.75	16.54	---	---	---
Grade	88	3.58	7.69	---	---	---
PG 98-10	T_c	97.9	97.8	36.0	-21.8	-10.0
Hwy 45	-12	---	---	---	398	---
	-6	---	---	---	237	0.257
Asphalt	0	---	---	---	---	0.299
Content **6.8%**	37	---	---	9235	---	---
	40	---	---	3868	---	---
Continuous	82	4.82	13.49	---	---	---
Grade	88	2.31	6.44	---	---	---
PG 95-10	T_c	94.8	96.7	39.1	-18.7	-9.9
Plant Mix	Virgin Binder Grade **PG 67-22** Asphalt Content **6.0%**					

Note: Asphalt content determined according to AASHTO T164.
*Note: Hwy 17 binder grading not conducted; asphalt content was **5.8**%.*

Table 3.10. Asphalt Concrete Aggregate Gradations

Sieve Size (mm)	***FR***	***Hwy 45***	***Plant Mix*[a]**
12.5	99	100	100
9.5	91	95	95
4.75	56	63	58
2.36	39	42	36
1.18	29	30	25
0.60	23	23	19
0.30	16	15	12
0.15	12	11	8
0.075	10.9[b]	9.6	6.0
NMAS (mm)	9.5[c]	9.5	9.5

Note: Hwy 17 gradation not conducted.
a) Mix Design Gradation
b) High fines content possible causes: test variability, dust filling voids during service, particle breakdown.
c) 99% passing 12.5 mm sieve, 91% passing 9.5 mm sieve so could be defined 9.5 or 12.5 mm NMAS.

Table 3.11 provides density data for each asphalt concrete material tested. Field aged cores were tested with multiple methods to provide a better representation of in place air voids. Five cores were selected at random from *FR*, and five more were selected from *Hwy 45*. These cores were tested with T166 and T331. Three of the five cores that represented the range of air voids obtained were sawn smooth on all sides (Figure 3.3) with the saw used to prepare *BBR* and *RC* mixture specimens. G_{mm} (T209) was determined by testing field aged slabs that had been heated and separated (saw-cut faces were trimmed off the edge of the slabs).

Table 3.11. Asphalt Concrete Density Test Results

Test Method	Specimen Type	Term	Pavement *FR*	*Hwy 45*	*Plant Mix*
T209	Loose Mix	G_{mm}	2.380	2.382	2.358
T166	Cores	G_{mb} (Range)	2.071-2.146	2.152-2.220	---
		G_{mb} (Avg)	2.119	2.183	---
		V_a (Range)	9.8 to 13.0	6.8 to 9.7	---
		V_a (Avg)	10.9	8.4	---
T331	Cores or SGC	G_{mb} (Range)	2.053-2.129	2.130-2.203	2.169-2.217
		G_{mb} (Avg)	2.102	2.161	2.193
		V_a (Range)	10.5 to 13.7	7.5 to 10.6	6.0 to 8.0
		V_a (Avg)	11.7	9.3	7.0
T331	Blocks (Fig 3.3)	G_{mb} (Range)	2.084-2.160	2.181-2.252	---
		G_{mb} (Avg)	2.130	2.216	---
		V_a (Range)	9.2 to 12.4	5.4 to 8.4	---
		V_a (Avg)	10.5	7.0	---

Note: all but one T166 specimen absorbed more than 2% moisture, and it absorbed 1.7%.
Note: Hwy 17 density tests were not conducted.
-- G_{mm} = maximum theoretical specific gravity (g/cm^3)
-- G_{mb} = bulk specific gravity (g/cm^3)
-- V_a = air voids (%)

Figure 3.3. Blocks Sawn From Field Aged Pavement for G_{mb} Measurement

Permeability (*k*) of pavement cores and laboratory compacted asphalt is provided in Table 3.12. ASTM PS129-01 was performed on multiple specimens obtained randomly, and the resulting values were averaged. In PS129-01, the test is terminated after thirty minutes, but the test was taken beyond 30 minutes in this report in a few cases.

Table 3.12. Asphalt Pavement Permeability at 20 C

	Field Cores			Lab Compacted
PS 129-01	***FR***	***Hwy 45***	***Hwy 17***	***Plant Mix***
k (10^{-5}) (cm/sec)	66	< 1	18	4

Note: Permeability of Plant Mix was at 7% T331 air voids.

As a means of variability comparison for *BBR* testing, indirect tensile (*IDT*) strength tests, which are commonly used, were conducted using an Interlaken universal testing machine to establish baseline variability. The thickness was recorded for all specimens, and loading versus time data was recorded at a frequency of 30 Hz to determine indirect tensile strength (S_t) at failure. Testing was performed on thirty 150 mm diameter (Dia.) and thirty 100 mm diameter specimens from *FR*, *Hwy 45*, and *Plant Mix* pavements. Cores with noticeable surface cracks and uneven edges were not used in testing as they were not used in *BBR* testing. SGC-compacted *Plant Mix* specimens were at 7 ± 1% T331 air voids. Before testing began, specimens were placed inside an environmental chamber (Figure 3.4a) for 12 hours to achieve thermal equilibrium of -12 C. This temperature was chosen since *BBR* specimens were also tested at this temperature. Specimens were tested inside the environmental chamber as shown in Figure 3.4b. Results (with outliers removed) were generally normally distributed and are summarized in Table 3.13. COV values are generally around 11% but ranged from 9.1% to 19.1%.

a) Conditioning Cores *b) Indirect Tensile Strength Testing*

Figure 3.4 Indirect Tensile Strength Test Procedure

Table 3.13. Indirect Tensile Strength Test Results at -12 C

Pavement	Dia. (mm)	n_{tested}	$n_{analysis}$	P-value	Normality Fit	Avg S_t (kPa)	St. Dev. (kPa)	COV (%)	95% CI (kPa)
FR	150	30	26	0.70	Excellent	1885	172	9.1	1548 to 2221
	100	30	30	0.86	Excellent	1943	261	13.4	1432 to 2453
Hwy 45	150	30	30	0.14	Good	1708	296	17.3	1129 to 2288
	100	30	29	0.05	Acceptable	1911	215	11.3	1489 to 2333
Plant Mix	150	30	30	0.48	Good	3604	370	10.3	2878 to 4330
	100	30	30	0.71	Excellent	3034	579	19.1	1898 to 4170

-- n_{tested} = number of replicates tested *-- $n_{analysis}$ = number of replicates after outlier removal*
-- P-value = Normality statistic *-- S_t = IDT strength* *-- St. Dev. = Standard Deviation*
-- COV = coefficient of variation *-- 95% CI = 95% Confidence Interval*

For field aged pavement viscosity testing, only the effective asphalt binder (i.e. no absorbed binder) was tested. Preliminary extraction testing was performed to determine the number of washes each pavement needed in order to extract only the effective binder from a sample. *FR* and *Hwy 45* both with no emulsion were used for this experiment. Eight washes for *FR* and seven washes for *Hwy 45* completely removed all binder from a 1000 g sample and resulted in the total asphalt contents of 5.8% and 6.8%, respectively. Thereafter, 1 and 2 wash tests were performed to determine the minimum number of washes needed to extract the effective binder only. Two washes resulted in 89.7% extraction of the total asphalt for *FR* and 85.3% extraction of the total asphalt for *Hwy 45*. A database of 228 MDOT 9.5 mm NMAS mix designs assembled during State Study 212 revealed that, on average, 0.7% asphalt (mixture mass basis) is typically absorbed (Doyle and Howard, 2010). This value corresponds to approximately 11% of the total asphalt content, meaning 89% of the total asphalt acts as effective asphalt. Therefore, a two-wash extraction best estimates the removal of only the effective binder for the pavements tested.

CHAPTER 4-EXPERIMENTAL PROGRAM

4.1 Experimental Program Overview

The experimental program was developed to test a variety of materials used for chip/scrub seals with a variety of test methods. Testing goals were to determine which tests have potential with regards to performance specifications and to determine applicable performance specification information. The remainder of this chapter discusses specimen preparation, test methods, and quantities of specimens tested using the materials described in Chapter 3.

4.2 Treating Asphalt Pavement with Emulsion

Asphalt emulsion was applied to 150 mm diameter compacted asphalt specimens at four application rates: 0.00 (no emulsion, NE, or untreated control), 0.91, 1.36, and 1.81 L/m^2 (0.00, 0.20, 0.30, and 0.40 gsy). Heated (60 C) emulsion was kept covered adjacent to a scale where cores were treated. An untreated core was placed onto the scale above tin foil or wax paper, leveled, and the desired amount of emulsion was applied to the surface of the core using plastic spoons and knives that were disposed after each core. The amount of emulsion required to produce a desired application rate was calculated and this number was adjusted slightly based on preliminary testing. The application rates used for a 150 mm diameter core are below, which should be interpreted as $\pm$ 0.05 L/m^2 ($\pm$ 0.01 gal/yd^2). Figure 4.1 illustrates the emulsion application process, which took around one minute once emulsion first contacted the core.

- 0.91 L/m^2: apply 17.5 $\pm$ 0.1 g
- 1.36 L/m^2: apply 25.5 $\pm$ 0.1 g
- 1.81 L/m^2: apply 33.4 $\pm$ 0.1 g

Figure 4.1. Applying Emulsion to Cores

An emulsion consists of bituminous binder and water, both of which can penetrate into a pavement's void structure. The rejuvenation portion of an emulsion is usually oil based, which in some cases can continue to penetrate even after the water has evaporated. Fifteen to twenty days were typically allowed for the cores to cure after emulsion treatment in ambient laboratory conditions that were free of dust or other disturbances. Treated cores were left undisturbed for a minimum of 96 hours after application, and thereafter, the cores were

stored on shelves or in cabinets until a constant mass was obtained (verified by monitoring mass loss with time). After obtaining a constant mass, the cores sat for a minimum of 96 additional hours and thereafter the cores were ready for conditioning and/or specimen preparation. Prior to conditioning and/or specimen preparation, cores were stored out of sunlight and away from moisture at 18 to 25 C; storage varied from a few days to several weeks.

4.3 Conditioning Emulsion Treated Asphalt Pavement

Conditioning of cores treated with emulsion as described in Section 4.2 was conducted for some, but not all, tests. Two types of conditioning were performed on specimens that had not been scraped or otherwise altered relative to their state at the end of the Section 4.2 protocol. The first conditioning type consisted of placing specimens in a 60 C oven for a given amount of time (3, 7, 14, 30, 45, or 60 days). After the prescribed conditioning time, all specimens were removed from the oven. Some cores were immediately prepared for testing, and other cores were returned to storage out of sunlight and away from moisture at 18 to 25 C until needed, at which time they were also prepared for testing.

The second conditioning type consisted of placing cores outdoors on the grounds of an asphalt production facility just outside of Starkville, MS. Only *Hwy 45* cores treated with 1.81 L/m^2 of emulsion 3 underwent this conditioning protocol. Thirty specimens were prepared with a single emulsion sample; fifteen of these were placed outside on the afternoon of February 1, 2012, and the remaining fifteen were placed outside on the afternoon of May 1, 2012. Specimens were placed on a pallet in a free draining condition with direct exposure to rain and sunlight (i.e. no shade from trees or buildings) and left undisturbed for the aging period. All thirty specimens were retrieved on the morning of August 1, 2012. Nominal aging times were 6 months (February through July) and 3 months (May through July). Figure 4.2 shows representative photos at each stage of interest; specimens that were aged 6 months were photographed after 3 months of aging and again after 6 months of aging. Table 4.1 provides summary weather information during the aging period which was obtained from a weather station at George M. Bryan Airfield in Starkville, MS (approximately 8.1 km [5 mi] from the outdoor aging location). Once outdoor conditioning ended, specimens were placed under fans at room temperature until dry. Once dry, the specimens were prepared for testing as described in subsequent sections.

No Aging ***Feb 1 to May 1*** ***Feb 1 to Aug 1*** ***May 1 to Aug 1***

Figure 4.2. Photos of Outdoor Aged *Hwy 45* Cores with 1.81 L/m^2 of Emulsion 3

Table 4.1. Outdoor Aging Weather Conditions

	Avg. Daily Temp		High Daily Temp		Low Daily Temp		Rainfall		Relative Humidity	
Time Period	**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 (%)**
Feb (*29*)	9.6	5.5	15.1	5.7	4.0	6.1	7.6	1	75.6	13.7
Mar (*31*)	17.2	4.4	23.5	4.4	11.0	20.7	15.1	5	71.4	11.8
Apr (*30*)	17.5	3.7	24.1	3.9	10.7	4.4	8.7	1	74.2	8.6
May (*31*)	22.1	2.4	28.6	2.9	51.0	21.3	8.2	2	77.6	7.0
Jun (*30*)	24.3	2.7	30.8	4.0	17.7	2.6	5.3	1	69.9	9.9
Jul (*31*)	26.6	1.4	32.3	2.6	58.8	22.2	16.0	3	79.7	8.2
Feb-Apr (90)	***14.9***	***5.8***	***21.0***	***6.2***	***8.7***	***6.1***	***31.5***	***7***	***73.6***	***11.6***
Feb-Jul (182)	***19.6***	***6.6***	***25.8***	***6.9***	***13.4***	***6.8***	***60.9***	***13***	***74.7***	***10.5***

-- Number of days in each Time Period are provided in parentheses beside the Time Period.
-- 95% Confidence Intervals (C.I.s) for 90-day and 182-day data using Mean ± 1.96(St. Dev.) are as follows:*
90-Day Aging
-Avg. Daily Temp C.I. = 3 to 26 C
-High Daily Temp C.I. = 9 to 33 C (Max Recorded Value 30.6 C, or 87 F)
-Low Daily Temp C.I. = -3 to 21 C (Min Recorded Value -7.2 C, or 19 F)
-Humidity C.I. = 43 to 94%
182-Day Aging
-Avg. Daily Temp C.I. = 7 to 33 C
-High Daily Temp C.I. = 12 to 39 C (Max Recorded Value 36.7 C, or 98 F)
-Low Daily Temp C.I. = 0 to 27 C (Min Recorded Value -7.2 C, or 19 F)
-Humidity C.I. = 54 to 95%

4.4 Scraping Emulsion Treated Cores

Some emulsion treated cores were scraped prior to producing test specimens. Scraped specimens are denoted *SCR* and non-scraped specimens are denoted *NS*. Scraping removed emulsion that did not penetrate the core (i.e. emulsion that would hold cover aggregate in place). Cores were heated in a 60 C oven for one hour, and, thereafter, the non-penetrated emulsion was scraped with a putty knife (Figure 4.3). Next, P 60 grade sandpaper was used to remove excess emulsion left by the putty knife. Sanding continued until at least ten aggregates were visible, at which point the core was considered fully scraped. Fully scraped cores were stored out of sunlight and away from moisture in a cabinet at 18 to 25 C prior to being used to prepare test specimens.

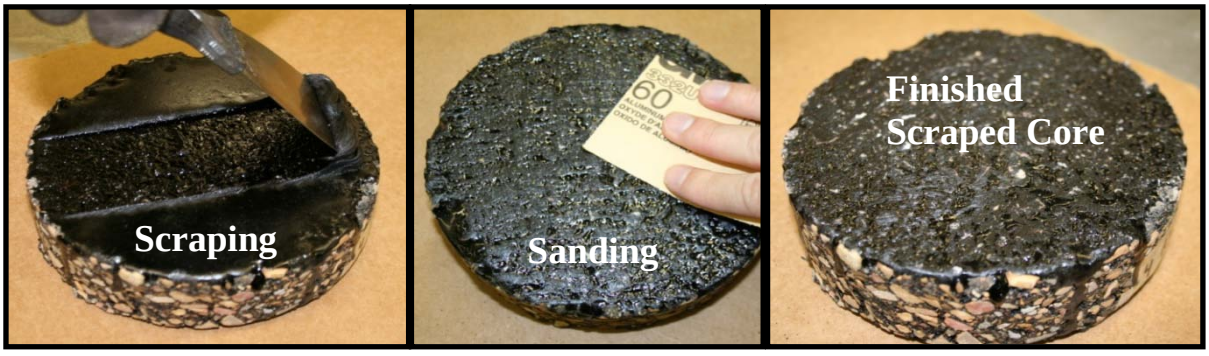


Figure 4.3. Scraping Emulsion Treated Core

4.5 Preparation of Test Specimens

4.5.1 Preparation of Repeated Creep Torsion Bars

Un-conditioned cores (either untreated or scraped emulsion treated) were sawn into torsion bars. Figure 4.4 shows a core sawing pattern. Sawing was performed with a Buehler Delta® Abrasimet® Abrasive Cutter and Troxell Premium Diamond Blades. One core can produce sixteen torsion bars. Sawing specimens directly from the surface of aged pavement is not common as most torsion bar or mixture beam work that has been performed over the past few years has used the interior portions of laboratory compacted specimens.

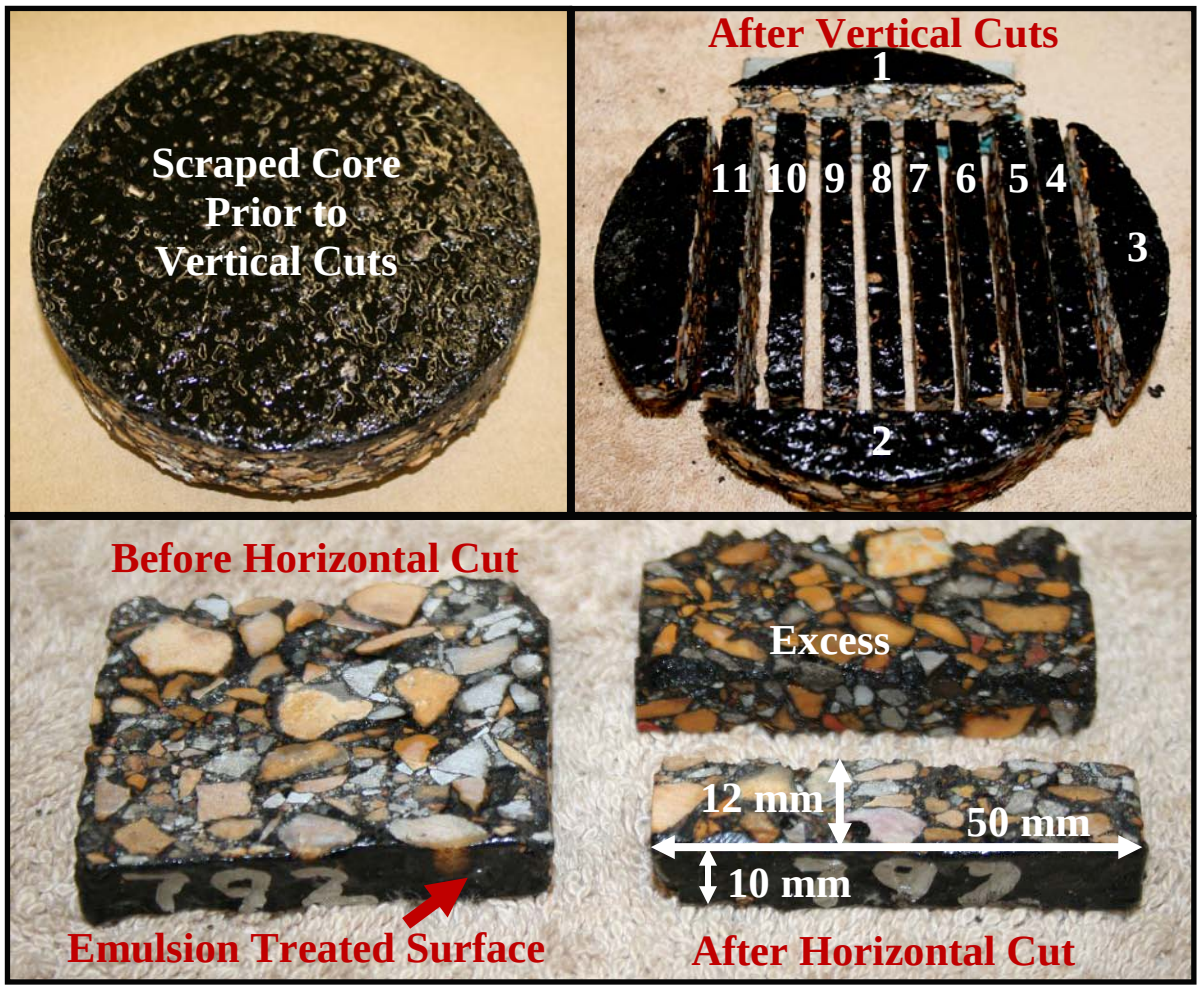


Figure 4.4. Preparation of Repeated Creep Torsion Bars

Cuts 1 and 2 are made first. Thereafter, the removed material is discarded, and the core is rotated in the saw and clamped on the parallel faces made by cuts 1 and 2, which are 100 mm apart. Cut 3 removes excess material, and afterward, cuts 4 through 11 remove 10 mm slices (each slice produces two bars). Cut 11 also removes excess material.

The 10 mm wide by 100 mm long pieces produced with cuts 4 to 11 are turned on their side and cut in half to 50 mm, while their thickness is still that of the original core. The

final cut removes the excess from the bottom of the core by trimming the bar to a 12 mm thickness. The final torsion bar is nominally 10 mm wide (parallel to core surface), 12 mm thick (parallel to core thickness), and 50 mm long. A torsion bar that is ready to test is shown in the bottom right of Figure 4.4 with nominal dimensions labeled. This orientation allows the bar to be gripped in the *DSR* on the 12 mm face to avoid emulsion sticking to the fixture. When tested, the 10 mm direction is usually referred to as thickness and the 12 mm direction referred to as width.

Time required to produce torsion bars was small compared to testing time. Sawing one core easily provided enough successfully produced torsion bars for a given combination for this project. As a result, torsion bar specimen fabrication rates were not recorded.

4.5.2 Preparation of Viscosity Test Specimens

4.5.2.1 Near Surface Slices for Viscosity Testing

Slicing for viscosity testing was performed on three types of unconditioned cores: untreated cores, emulsion treated cores that had been scraped (*SCR*), and emulsion treated cores that had not been scraped (*NS*). Cores treated with E1 to E7 were tested in a scraped condition. In addition, non-scraped cores were tested with E1 to E4. All emulsion treated cores were sliced and tested within 45 days of being fully cured. Cores were marked around their circumference at the appropriate depth (6.3, 9.5, or 12.5 mm), aligned, and sliced with an MK Diamond Chop Saw (Figure 4.5). Multiple slices from replicate cores were combined, placed under a fan to dry, and then placed into a 60 C oven for one hour to slightly soften the binder to facilitate breaking apart the slices so they could be placed into an asphalt extraction centrifuge. Once broken into a loose state, the bituminous material in the slice was extracted and recovered for further testing.

Figure 4.5. Slicing Cores for Viscosity Testing-Untreated Core Shown

4.5.2.2 Extraction and Recovery Procedures for Viscosity Testing

Bituminous material was extracted from composite samples of broken up slices and then recovered according to AASHTO T319-08. An 85% toluene and 15% ethanol mixture by volume was used instead of a trichloroethylene (TCE) or a TCE/ethanol mixture since: 1) the selected solvents tend to be less aggressive than solvents such as TCE, and 2) extraction of only the non-absorbed bitumen in an asphalt mixture is more easily accomplished. Two 45 ± 5 minute solvent washes were conducted in order to extract the non-absorbed (effective) bitumen only.

Figure 4.6 shows both centrifuges used during the extraction procedure. The protocol in this report differed from T319-08 in that a filter was placed on the bowl inside Centrifuge 1 to prevent the finer aggregates from escaping the bowl when the centrifuge was in operation. The filtrate from Centrifuge 1 consisted of asphalt binder, aggregate fines (minus No. 200 sieve), and solvent. Centrifuge 2 was used to remove the aggregate fines; the cup in Centrifuge 2 has a small lip at its opening which prevents aggregate fines from escaping. The filtrate from Centrifuge 2 consisted of asphalt binder and solvent only. The extraction process typically required two hours to complete.

Figure 4.6. Asphalt Extraction Equipment

After extraction, the asphalt binder was recovered using the rotational-vaporation (Roto-Vap) equipment shown in Figure 4.7. Filtrate was drawn into the bulb in the 140 C oil bath (number 1 in Figure 4.7) through the tubing denoted number 2. This was accomplished via vacuum (600 mm of Hg) which, along with high temperature, also facilitated solvent evaporation. A mixture of ice and water was circulated through the condenser coils (number 3) to aid solvent condensation. A bag of ice placed into a 19 L bucket and filled with water was used herein; a submersible pump circulated the water through the condenser coils. As solvent evaporated from the filtrate and condensed, it was collected in the condensate flask (number 4).

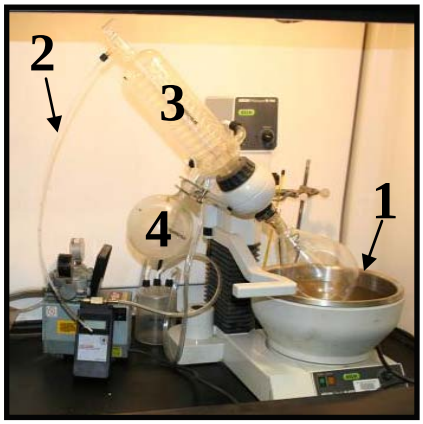


Figure 4.7. Recovery Apparatus Set-up

After 500 mL of solvent had evaporated, the temperature and vacuum was slowly increased to 180 C and 150 mm of Hg, respectively. When the solvent dripped from the condensing coils less than one drop per 30 seconds, recovery continued an additional 30

minutes at these conditions to ensure complete solvent evaporation. After 30 minutes, asphalt binder was poured from the recovery bulb into an open container and placed in a 165 C oven for 10 minutes as a final measure to ensure that all the solvent was removed from the asphalt binder. Thereafter, 9.5 to 10 grams of recovered binder was poured from the container into viscosity cups. Typically, each extraction and recovery yielded enough binder to fill four viscosity cups.

4.5.3 Preparation of Bending Beam Rheometer Mixture Beams

Untreated and emulsion treated cores (both unconditioned and conditioned) were used to produce *BBR* beams. All emulsion treated cores were scraped before sawing. Non-scraped cores could be sawn into mixture beams, but the presence of the surplus emulsion would have likely created difficulties with precise cutting and storage. The effects of varying emulsion thicknesses could have also had adverse affects during *BBR* testing. Any scraping performed after sawing would likely permanently damage the specimens. Therefore, all treated cores were scraped in the same manner, before sawing, which resulted in comparable sawing and testing conditions for mixture beams regardless of emulsion application rate. Sawing was performed with a Buehler Delta® Abrasimet® Abrasive Cutter and Troxell Premium Diamond Blades. The approximate size of a final mixture beam is 120 mm long by 12 mm wide by 7-8 mm thick.

This study developed a procedure to produce consistent, appropriately sized mixture beams for testing. Beams were produced from both SGC specimens and field cores. SGC specimens were compacted to a height of 75 mm and sawn into two approximately 35 mm thick halves so that *BBR* beams could be sawn out of the top and bottom surface. Asphalt cores used were approximately 38 mm thick, and beams were sawn from the top surface only. Cores with relatively smooth bases were chosen for *BBR* testing as jagged or uneven bases can affect consistency of specimen production. After making any cut, the saw was checked for small pieces of aggregate or debris that could have affected cut precision or alignment within the clamps. Also, ice was typically placed in the water bath of the saw to cool the cores during cutting which minimized smearing of binder or other undesirable behaviors.

There is a limited area within each core from which beams of sufficient length can be cut; therefore, a wood template was fabricated and used to mark cut 1 as seen in Figure 4.8 which shows a typical 5-beam sawing pattern. In the beginning of the study, five beams were always attempted from a core, but in some cases, six beams were attempted. Given the limited success of cutting a sixth beam during the early stages of the study, a decision was made to limit the number of beams cut from a single core to five for consistency.

Figure 4.9 demonstrates the first three cuts required in the sawing process. First, the edge marked by the wood template was removed by cut 1 as shown in Figure 4.9a. After this edge was removed, the sample was rotated 180° in the saw, aligning the edge of cut 1 with the left side of the saw base as shown in Figure 4.9b. The left edge of the saw base conveniently produced a 119 mm long beam, which is a satisfactory length, and ensured a parallel edge to cut 1. Once aligned, cut 2 was made (Figure 4.9c). The core was then rotated 90° so that the saw clamps could firmly contact the parallel sides produced from cuts 1 and 2 and firmly secure the core for cut 3 (Figure 4.9d).

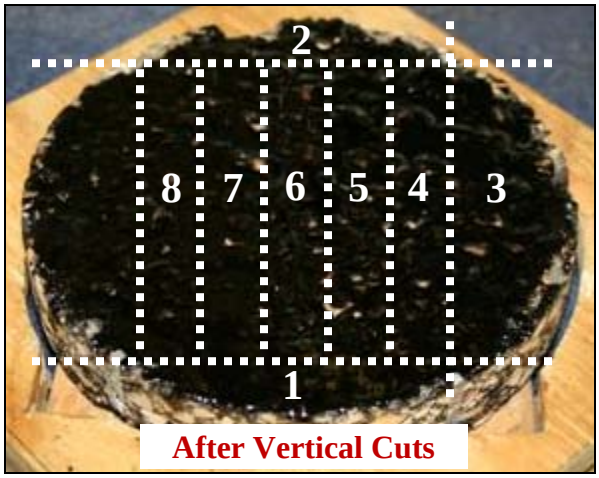
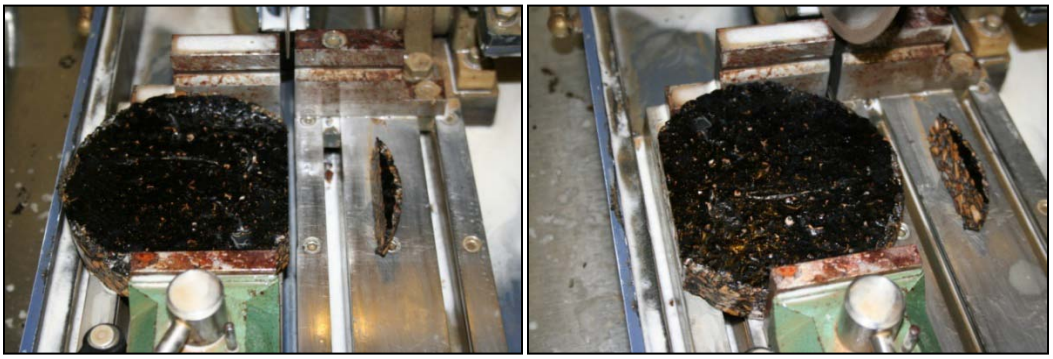
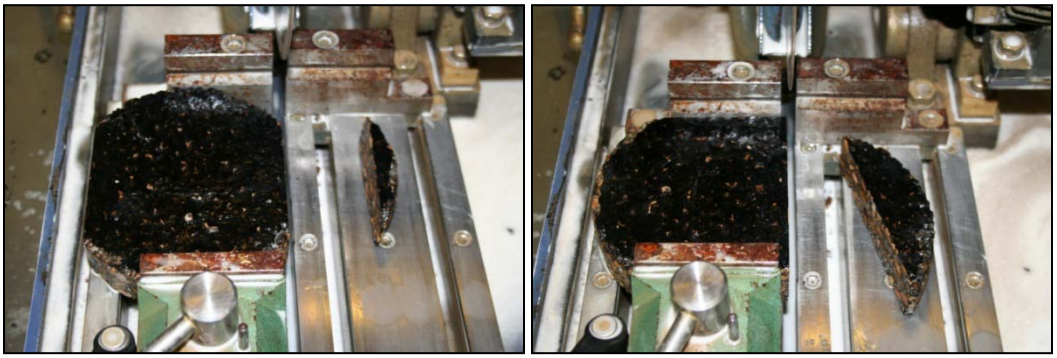


Figure 4.8. *BBR* Mixture Beam Sawing Pattern



a) Cut One *b) Positioning for Cut Two*

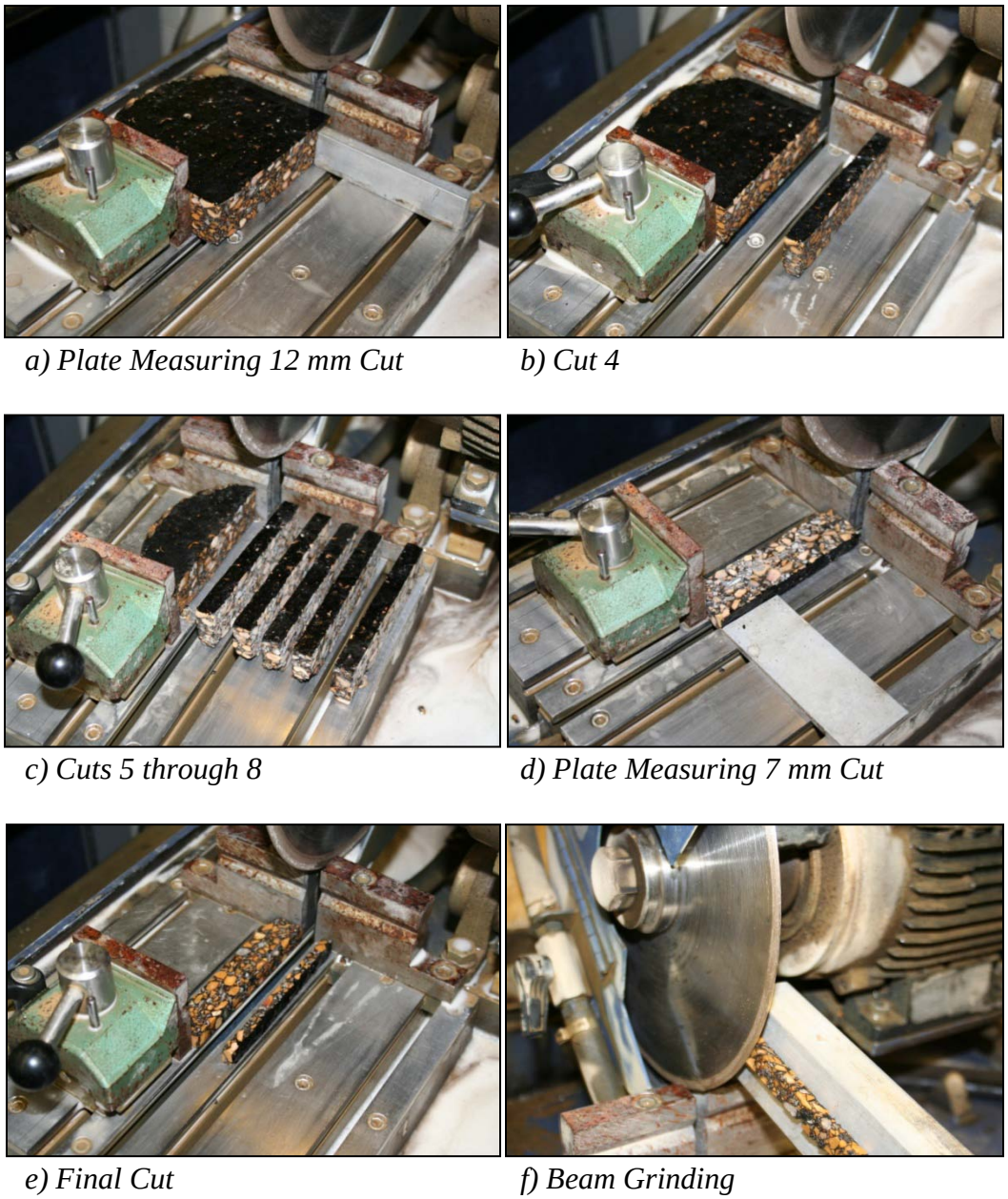


c) Cut Two *d) Cut Three*

Figure 4.9. Initial Emulsion Treated Core Preparations for Sawing

Figure 4.10 demonstrated the final cuts in the sawing process. As shown in Figure 4.10a, an aluminum plate was used to assist with cutting the 12 mm wide mixture beams. The plate was 107 mm long and was placed flush with the right edge of the saw base which produced a nominal 12 mm wide slice during cut 4 (Figure 4.10b). It was important to ensure the adjustable clamp was square, the core did not move when levers were tightened, and the plate was flush with the saw base before this and all subsequent cuts. Figure 4.10c shows the final four vertical cuts which produces five 12 mm wide slices. Each slice was

then laid on its side as shown in Figure 4.10d. A second aluminum plate measuring 112 mm long was placed flush with the right edge of the saw base to align the slice and produce a nominal 7 mm thick beam as shown in Figure 4.10e. It was not uncommon for beams to break during the 7 mm cut. Small burs were typically left on one end of successfully cut beams which were ground smooth as shown in Figure 4.10f. This was performed by starting the saw, stopping it, raising the lid, and placing the beam against the blade while it was still spinning with sufficient speed. It was necessary to fully support the beam during grinding as shown to prevent it from breaking. This process was repeated for each of the 12 mm wide slices.



a) Plate Measuring 12 mm Cut *b) Cut 4*

c) Cuts 5 through 8 *d) Plate Measuring 7 mm Cut*

e) Final Cut *f) Beam Grinding*

Figure 4.10. *BBR* Mixture Beam Cutting Procedure

Once specimens were sawn, they were immediately labeled to identify various treatment combinations (e.g. emulsion and application rate). Upon being labeled, the mixture beams were individually measured with a caliper at five equally spaced locations along the beam (Figure 4.11a). Both thickness and width were recorded and averaged to form representative values for that beam to be input into the *BBR* software. The average measurements are the only *BBR* software inputs prior to testing. At this point, beams were also inspected for damage and evaluated to ensure no beams with obvious dimensional flaws were tested (e.g. thickness or width did not vary too greatly from one end of the beam to the other).

All mixture beams were stored in plastic tackle boxes to protect the somewhat delicate test specimens (Figure 4.11b). Tackle boxes provided convenient storage as they are transparent and have small compartments; they also prevent free air flow over the specimens, retarding oxidation. Mixture beams with emulsion should be stored upright and should not be stacked because the emulsion surface will adhere to other beams or the tackle box. Prying these free would stress and potentially damage the mixture beams.

a) Mixture Beam Measuring *b) Mixture Beam Storage*

Figure 4.11. Labeling and Storage of *BBR* Mixture Beams

4.5.4 Preparation of *Vialit* Test Specimens

Vialit test specimens were prepared using various combinations of emulsions and aggregates. Figure 4.12 shows testing equipment and a fully prepared specimen tray. Two tray types were used to prepare specimens: specification tray and modified tray. The specification trays were made of metal, did not have a textured surface, measured 20 cm by 20 cm, had a bottom plate thickness of 0.20 cm, and had a 0.435 cm lip around the edge making the total thickness around the edge 0.635 cm. The specification trays were so named in this report because they meet requirements of traditionally performed *Vialit* tests. The modified trays were made of hot rolled steel, had a textured surface, measured 20 cm by 20 cm, had a bottom plate thickness of 0.635 cm, and had a 0.635 cm lip around the edge making the total thickness around the edge 1.27 cm. Modified trays were so named because they were fabricated specifically for this research.

To prepare a specimen tray, emulsion and empty trays were heated at 60 C for 5-6 hours; then, 79 g of emulsion was applied to each tray. The tray was tilted back and forth to provide a homogenous layer of emulsion prior to application of 100 washed and dried aggregates that were applied by hand in a 10 by 10 matrix. Aggregates tested passed a 9.5

mm sieve and were retained on a 4.75 mm sieve. A fully prepared specimen tray that is ready for conditioning is shown in Figure 4.12.

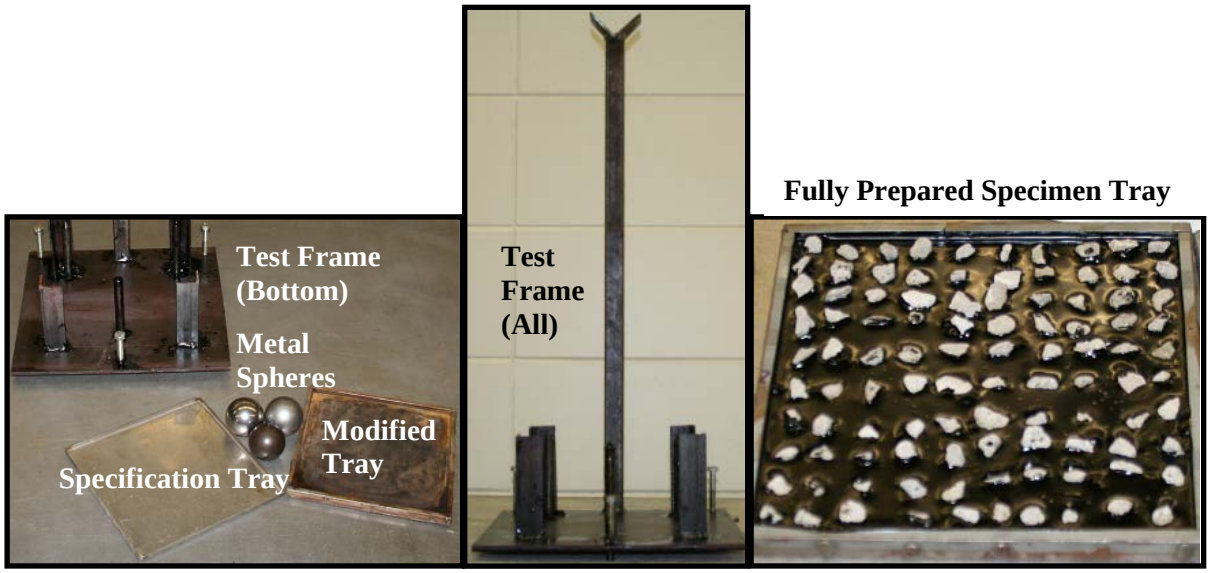


Figure 4.12. *Vialit* Test Equipment and a Prepared Specimen Tray

4.5.5 Preparation of Frosted Marble Test Specimens

Flat steel trays containing three independent machined troughs are used to prepare *FMT* test specimens (Figure 4.13). Emulsion is contained in each trough at 1.5 L/m^2; troughs are 1.55 $\pm$ 0.05 mm deep. Each trough contains five 14.3 mm acid etched (i.e. frosted) glass beads (i.e. marbles).

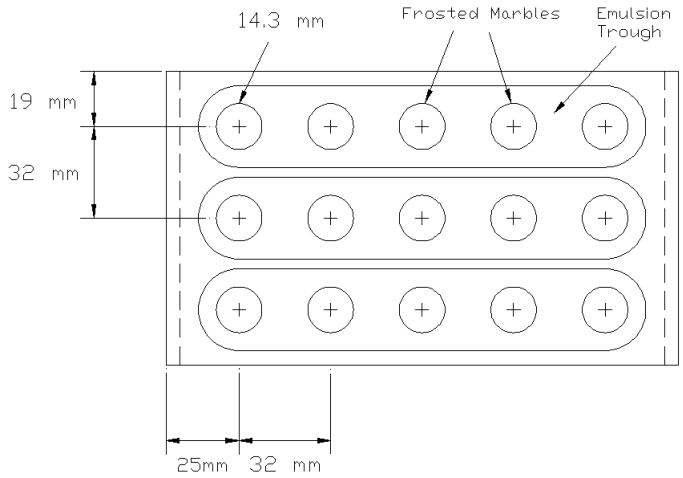


Figure 4.13. Frosted Marble Specimen Tray

To prepare a specimen tray, 9.0 to 9.5 g of emulsion heated to 60 C is placed in each of the three plate troughs. Plates are heated to 60 C. Heated emulsion is placed into heated

trays in ambient conditions using a 10 mL syringe (Figure 4.14a). The tray with emulsion is placed on a level surface to allow the emulsion to seek a level position.

As soon as a level position is obtained within the emulsion, an acrylic template is placed (Figure 4.14b) and 15 frosted marbles are added (Figure 4.14c). The tray is immediately taken into a 4 m by 2 m environmental chamber (54 to 57 C) with the template attached. Note that the only rationale for this curing condition is that pavement temperatures approach these values in Mississippi summer conditions. Once in a stable position in the chamber, the template is removed and the tray remains in the chamber for continuous curing. Marbles are embedded quickly to allow emulsion wicking up their sides to prevent skin formation within the emulsion. Heat lamps provide needed temperatures, and a minimum of 75 mm is left between all curing trays. Trays were positioned so that there was no direct heat from the lamps.

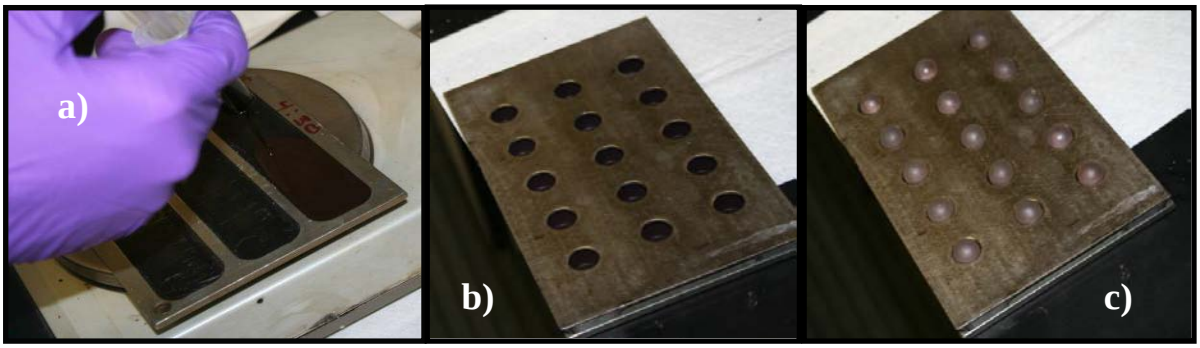


Figure 4.14. Preparation of Frosted Marble Specimen Tray

4.5.6 Preparation of Sweep Test Specimens

Sweep test specimens were prepared according to ASTM D7000 using various combinations of emulsions and aggregates. Figure 4.15 shows key specimen fabrication components used. Figure 4.16 summarizes fabrication of sweep test specimens, which was completed within 5 minutes. First, 83 ± 5 g of emulsion (heated to 60 C) was applied to a circular asphalt felt disk by means of a steel strike-off mold. Aggregates were then applied by hand across the specimen surface and seated with the sweep test compactor so aggregates became oriented evenly and set to one-stone thickness. The aggregate application rate for each specimen was calculated according to Equation 4.1. The only size fraction used from each aggregate source to produce specimens was that finer than the 9.5 mm sieve but greater than the 4.75 mm sieve so that 100% passed the 9.5 mm sieve and <1% passed the 4.75 mm sieve. After fabrication, specimens were ready for conditioning.

$$Y = \frac{A(202.1G_{sb} - 15.8)}{100} + \frac{B(146.4G_{sb} - 4.7)}{100} \quad (4.1)$$

Where,
Y = amount of aggregate needed for sweep test (g)
A = percent of aggregate from 9.5 to 6.3 mm size
B = percent of aggregate from 6.3 to 4.75 mm size
G_{sb} = aggregate bulk specific gravity

a) Strike-off Template *b) Strike-off Rod* *c) Sweep Test Compactor*

Figure 4.15. ASTM D7000 Specimen Preparation Equipment

a) Emulsion Application *b) Emulsion Strike-off*

c) Aggregate Spreading *d) Aggregate Compaction*

Figure 4.16. Sweep Test Specimen Preparation Procedure

4.6 Test Methods and Specimens Tested

4.6.1 Repeated Creep Test Methods and Specimens Tested

A dynamic shear rheometer (*DSR*) was used that had been modified to perform the *RC* test (Figure 4.17). Specimens are tested using the solids testing fixture provided by the manufacturer as opposed to traditional binder testing between parallel plates. The specimen length during testing is the distance between the two mounting points, which was on the order of 37 mm.

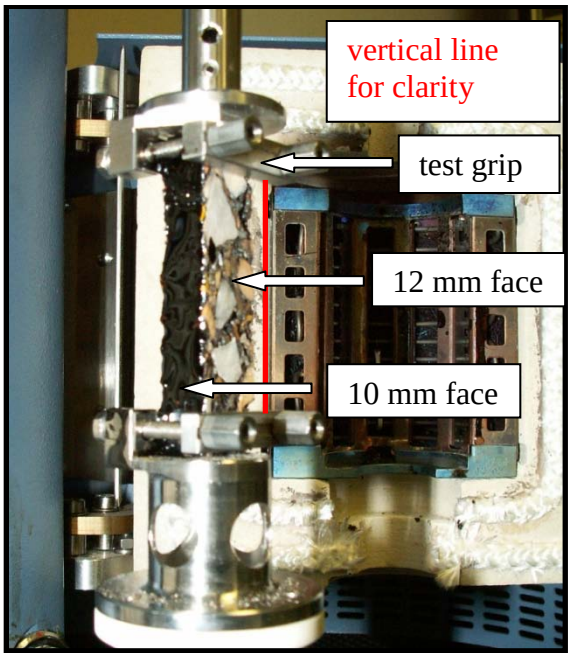


Figure 4.17. Torsion Bar Mounted in *DSR*

DSR control software computed the force required to produce a target torsional stress level based on measured torsion bar dimensions. The control software then recorded the strain history experienced by the specimen during testing. The loading sequence consisted of repeated cycles of 1 second of loading followed by 9 seconds of recovery (i.e. one test cycle corresponded to ten seconds). Up to 990 test cycles were performed. The stress level used during the test (T_s) was a function mixture properties. Values of T_s were selected to produce specimen failure generally within 100 to 990 cycles, and the loading sequence was repeated until failure occurred.

Specimens from *Hwy 45* and *FR* were tested at T_s levels of 68, 136, and 272 kPa to select an appropriate test condition for each pavement. T_s was selected as 136 kPa for *FR* since 68 kPa did not provide a pronounced flow in the tertiary region (i.e. rapid strain increase over a few load cycles) and since 272 kPa produced flow at too few cycles. T_s was selected as 272 kPa for *Hwy 45* as 68 and 136 kPa did not produce any tertiary flow.

ASTM D7552-09 (traditional binder *DSR* test method) typically tests materials at the high PG grade temperature representative of the climate region as determined by LTPP-BIND v3.1. This was incorporated herein as the *RC* test temperature was 64 C. Specimen test temperature is maintained by air circulation through a temperature controlled oven surrounding the specimen. Specimens are temperature conditioned for 30 minutes prior to testing.

One torsion bar tested in the *DSR* was defined as one test. Twenty-four torsion bars were tested (two pavements, one emulsion, four application rates, three replicates) for the primary experimental matrix. A small number of additional specimens were tested to establish stress thresholds as described previously.

4.6.2 Viscosity Test Methods and Specimens Tested

Testing was in accordance with AASHTO T316-04 which measures rotational dynamic viscosity. The Brookfield Viscometer was calibrated using N450000 fluid. Results showed the viscometer was within AASHTO and ASTM specifications of ±2% and ±1%, respectively. Testing was performed at 135 C and 165 C using an S27 spindle. For a given test condition, one replicate was made for each temperature. During testing, three readings were taken at each temperature.

A total of 168 viscosity tests were performed. Seven of these experiments were performed on *Hwy 17* at 135 C. Seventy-seven of these experiments were performed on *Hwy 45* (39 at 135 C; 38 at 165 C). Eighty-four of these experiments were performed on *FR* (42 at 135 C; 42 at 165 C).

4.6.3 Bending Beam Rheometer (*BBR*) Test Methods and Specimens Tested

A CANNON Thermoelectric *BBR* (Figure 4.18) was used to perform flexural creep testing of mixture beams. Due to the varying surface characteristics of the pavements tested, the thickness and width of the mixture beams were the average of five, evenly distributed measurements along the beam. During this process, mixture beams were also examined for visible deformations such as surface cracks or missing aggregate which may have had adverse affects on the testing data. Mixture beams found to have extreme deformations were discarded and recorded as beams broken during sawing. Examples of acceptable and unacceptable mixture beams are shown in Figure 4.18.

Figure 4.18. Bending Beam Rheometer Testing

All acceptable mixture beams were immersed in the cooling bath containing methanol for 60 ± 5 minutes prior to testing as shown in Figure 4.18. This ensured the specimens reached thermal equilibrium at -12 C before being tested. The test parameters for mixture

beams are different than for a standard binder test; they consisted of a 4.9 N constant load applied to the midpoint of the beam for 1,000 seconds. Specimen deflection at the center of the beam was recorded by the test equipment throughout the test. Figure 4.18 shows a beam being tested (a cover normally present is removed in the photo) as well as an example of a beam breaking during a test. The desired outcome of the test was a consistent, uninterrupted collection of deflection data. A broken beam during testing was deemed a failed test. Representative values of creep stiffness and *m-value* (the instantaneous slope of the creep stiffness curve) were calculated from deflection data at three discrete loading times over the test period: 8, 60, and 960 seconds.

Each treatment combination of pavement, emulsion, and application rate is identified by a detailed Mix ID labeling system of the form of Equation 4.2.

1-2-3-4 (4.2)

Where,

1: The first position designates pavement type. Possible values for this label are:
- H45: *Hwy 45* asphalt pavement
- FR: *Frontage Road* asphalt pavement
- PM: Laboratory-compacted *Plant Mix* asphalt pavement

2: The second position designates emulsion type. Possible values for this label are in Table 3.1, with examples shown below.
- NE: No emulsion
- E1: Emulsion 1
- E2: Emulsion 2

3: The third position designates application rate. This position is not included for untreated specimens (i.e. 2nd position equals NE). Possible values for this label are:
- R0.91: Emulsion applied at 0.91 L/m^2
- R1.36: Emulsion applied at 1.36 L/m^2
- R1.81: Emulsion applied at 1.81 L/m^2

4: The fourth position designates the number of days the specimen was conditioned (or aged) before sawing into beams and testing. Aging periods of 0 to 60 days correspond to laboratory conditioning, and aging periods of 90 or 180 days correspond to field conditioning. Examples for this label are:
- A0: 0-day aging period (laboratory-conditioned)
- A7: 7-day aging period (laboratory-conditioned)
- A90: 90-day aging period (field-conditioned)

Hwy 45, *FR*, and *Plant Mix* were tested with no emulsion application and after emulsion application. Unconditioned, laboratory-conditioned, and field-conditioned cores were tested. Three emulsion application rates were tested. Table 4.2 provides a brief summary of the specimens tested; greater resolution of the testing matrix is located in Section 7.3 where results are presented.

The ability to produce mixture beams varied with material type; sawing and testing resulted in broken beams in some instances. A minimum number of replicates were targeted (N_{min}), and every core sawn was completely tested. N_{min} of 5, 30, and 60 were used. Typically, for a field aged core, N_{min} of 5 required 2 cores (10 potential beams) to be

completely sawn and tested. In some cases, more than N_{min} were successfully tested; for example, 9 successful tests could have resulted from 2 *FR* cores (10 attempted beams). In some cases, more than 2 cores would be necessary to achieve N_{min} of 5. In other cases, all cores for a given Mix ID were completely sawn and tested with such low success rates that N_{min} was not able to be satisfied; however, this was uncommon. Because of this method, varying numbers of replication (successfully tested beams) resulted, but this approach was felt to be more consistent than other options.

Table 4.2. Summary of *BBR* Specimens Successfully Tested

	Number of Beams Tested				
	Untreated		Emulsion Treated		
Pavement	Unconditioned	Conditioned	Unconditioned	Conditioned	Total
Hwy 45	64	0	169	283	516
FR	65	0	152	44	261
Plant Mix	27	45	30	80	182
Total	156	45	351	407	959

Testing was separated into two major components. Component 1 testing evaluated the field pavements, *FR* and *Hwy 45*. The purpose of the first component was largely to determine the amount of rejuvenation typical Mississippi emulsions can provide for aged pavements. Component 2 testing evaluated *Plant Mix*. The purpose of the second component was to provide insight regarding potential specification development.

Testing of control specimens was performed to investigate material variability and to establish baseline properties for comparison to emulsion treated specimens. This classified as part of Component 1 testing. In general, more testing was performed on control specimens than other emulsion treated specimens. The target replication (N_{min}) for control testing was 60 beams for *Hwy 45* and *FR* and 30 beams for *Plant Mix*. *Plant Mix* was expected to be less variable than the field aged pavements; therefore, fewer replicates were tested.

Testing of unconditioned, or un-aged, emulsion treated specimens was performed to investigate performance effects of the various emulsions or application rates. This classified as part of Component 1 testing. Both *Hwy 45* and *FR* pavements treated with each of the seven emulsions at each application rate were tested. A minimum target of five replicates (N_{min} = 5) were tested for all 42 treatment combinations. There were two exceptions. N_{min} for H45-E3-R1.81-A0 was 30 because it was part of a larger experiment with *Hwy 45* treated with 1.81 L/m^2 of E3 in which greater replication was desired. With only four replicates, FR-E5-R1.81-A0 was the only specimen group which did not satisfy N_{min} (the fifth replicate was originally accepted but was later found to be questionable and was discarded).

Testing of 7-day aged emulsion treated specimens was performed to investigate performance effects of the various emulsions after some period of aging. This classified as part of Component 1 testing. Both *Hwy 45* and *FR* pavements treated with each of the seven emulsions at only the 1.81 L/m^2 application rate were tested. The highest application rate was chosen as this was believed to provide the greatest opportunity for an emulsion to rejuvenate the aged pavement surface. A minimum target of five replicates (N_{min} = 5) were tested for all 14 treatment combinations that were conditioned for 7 days. There were two exceptions. N_{min} for H45-E3-R1.81-A7 was 30 because it was part of a larger aging experiment with *Hwy 45* treated with 1.81 L/m^2 of E3 in which greater replication was

desired. With only four replicates, FR-E6-R1.81-A7 was the only 7-day aged specimen group which did not satisfy N_{min} (the fifth replicate was originally accepted but was later found to be questionable and was discarded).

Testing of *Hwy 45* treated with 1.81 L/m^2 of E3 was conducted at eight conditioning times to provide a greater understanding of extended-term emulsion rejuvenation. Both laboratory and field conditioning protocols were used to evaluate the feasibility of specification oriented laboratory aging protocols. This classified as part of Component 1 testing. A minimum target of 30 replicates (N_{min} = 30) were tested for all nine treatment combinations. The 60-day and the 90-day aged groups did not satisfy N_{min} but provided sufficiently large data sets nonetheless.

Testing of *Plant Mix* was performed to investigate the feasibility of a standard specification for defining whether or not a given emulsion classifies as a rejuvenator. This classified as part of Component 2 testing. *Plant Mix* treated with 1.81 L/m^2 of E3 was tested un-aged and at 7, 30, and 60 days of laboratory conditioning. This was performed to investigate the long-term effects of emulsion on *Plant Mix*. Since *Plant Mix* was not significantly aged prior to emulsion application like the field aged pavements, it was expected that performance changes of *Plant Mix* over time would be due partly to emulsion aging and partly to the asphalt mixture aging. Therefore, *Plant Mix* with no emulsion applied was tested at identical aging times in order to separate the effects of the asphalt mixture aging from the effects of the emulsion aging. Due to much higher success rates with sawing and testing mixture beams from *Plant Mix* relative to the field aged pavements, the N_{min} protocol was not used for Component 2 testing. Instead, the number of cores needed to produce 30 mixture beams (6 cores) were sawn and tested. It was concluded that, although some beams may break, it would be a minimal number which would not affect the overall quality of the data set. The only exception to this was PM-NE-A30 and PM-NE-A60 which had 10 and 9 replicates, respectively. Insufficient material quantities were available to compact the necessary specimens for 30 targeted replicates for these treatment combinations.

4.6.4 *Vialit* Test Methods and Specimens Tested

Figure 4.12 shows testing equipment and a fully prepared specimen tray (specimen trays were discussed in Section 4.5.4). The test frame was made of steel and had a drop height of 50 cm. The three masses used during testing were: the standard 4.68 cm diameter steel sphere used during the ASTM C131 LA Abrasion Test (416 g); a 5.08 cm diameter steel sphere machined by the research team (501 g); and a 5.08 cm steel sphere without any machining (527 g). In order to obtain a 501 g metal sphere that met the properties of the California and Oregon DOT test methods, the research team had to purchase a sphere and have it machined.

The equivalent test protocols of California and Oregon (CalTrans, 2008; ODOT, 1998) were selected as the baseline protocols for testing. Where protocols are not stated, these methods were followed. The primary factor that led to their selection in favor of the French method (EN 12272-3) was that they had previously been used by other state DOT's.

After a specimen was prepared and conditioned, the tray was inverted on the test frame and the spherical mass of interest was dropped three times within 10 seconds. The operator counted the number of aggregates lost and reported the value as aggregate loss (e.g. 3 aggregates would be 3% aggregate loss).

A total of 231 *Vialit* tests were performed with one tested tray defined as one test. A minimum of 3 replicate trays were tested, and up to 12 replicate trays were tested. Specific experimental matrices are described in the following paragraphs which focus on the conditioning protocol used.

To investigate the effects of tray type, the test method was conducted as specified by (CalTrans, 2008; ODOT, 1998) with no modifications. In addition, the test was conducted using the modified tray and keeping all other parameters constant. In general, this required test specimens to be placed in a 60 C oven for 48 hours, placed at room temperature for 30 minutes, placed in a -22 C freezer for 30 minutes, and tested immediately upon removal from the freezer. Forty-eight trays were tested in this manner, 18 using the modified tray and 30 using the specification tray.

To compare different emulsions, the protocols described in the previous paragraph were used in conjunction with the modified tray. All seven emulsions were tested. Twenty-one trays were tested in this manner.

To investigate spherical mass effects, all three spheres were used in conjunction with the modified tray. Test specimens were placed in a 60 C oven for 48 hours, placed at room temperature for 30 minutes, placed in either a -15 C or -22 C freezer for thirty minutes, and tested immediately upon removal from the freezer. Remaining parameters followed CalTrans (2008) and ODOT (1998). Seventy-two trays were tested in this manner.

A minimum curing time at low temperatures was suggested to the research team by one laboratory that was contacted. To determine the effects of freezer time and temperature, specimens were made using modified trays, placed at room temperature for 30 minutes (the step with oven was omitted), and then placed into a -15 C or -22 C freezer for a given time (up to 20 hours). The specimens were tested immediately upon removal from the freezer using the 501 g sphere. Forty-five specimens were tested in this manner.

To determine the effects of freeze thaw cycles, specimens were made using modified trays, placed at room temperature for 30 minutes (step with oven was omitted), and then placed into a -15 C or -22 C freezer for three hours. The specimens were allowed to come to room temperature and then exposed to additional freeze thaw cycles as needed (up to 6 cycles were used). Trays were tested immediately upon removal from the last freeze thaw cycle using the 501 g sphere. Forty-five specimens were tested in this manner.

4.6.5 Frosted Marble Test Procedure and Specimens Tested

There are no ASTM or AASHTO *FMT* specifications. An *ISSA Technical Bulletin No. 139* modified cohesion tester is the primary piece of equipment used in the *FMT* test, which is shown in Figure 4.19 alongside labeled items relevant to the protocol described in the remainder of this section. Frosted marbles are already in the specimen tray described in Section 4.5.5. Figure 4.20 is a schematic of the *FMT* set-up, and the following steps are used to perform a test.

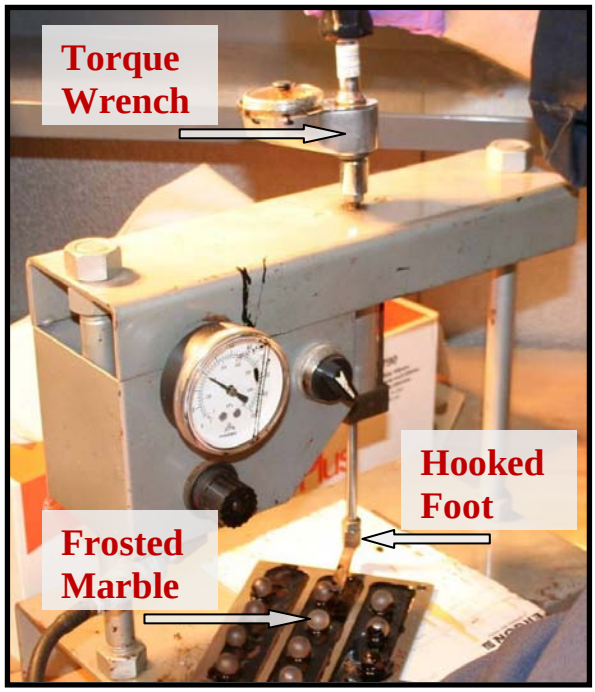


Figure 4.19. Cohesion Tester, Torque Wrench, Hooked Foot, and Frosted Marble Tray

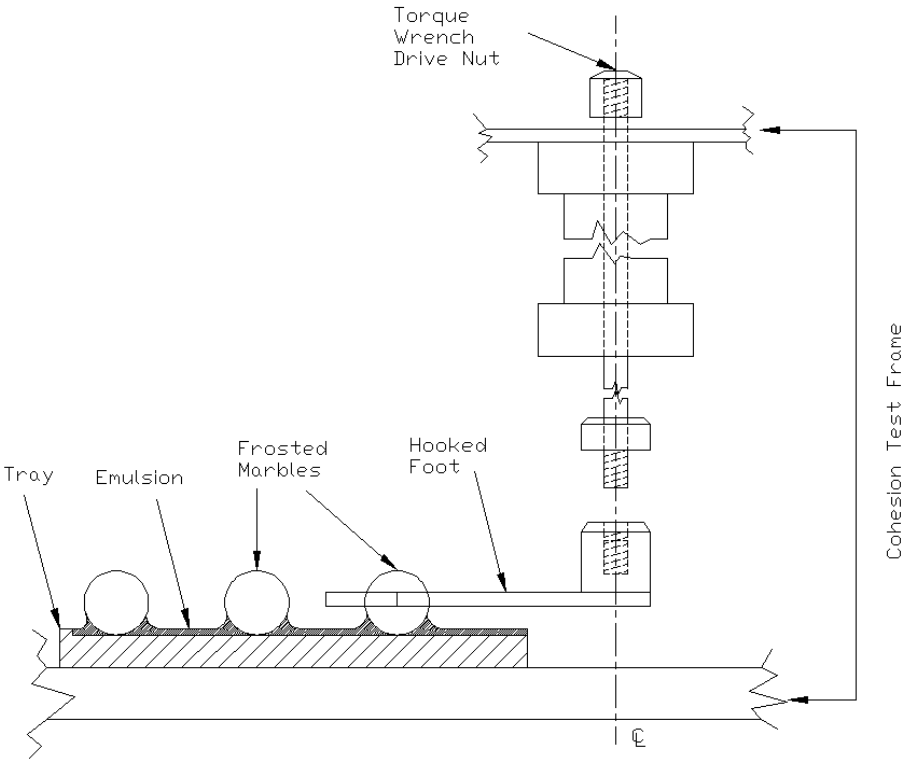


Figure 4.20. Frosted Marble Test Schematic

1. Replace the standard 28.6 mm diameter cohesion tester foot with the 50 mm hooked foot (Figure 4.21) and adjust to contact the frosted marbles slightly below the center of the marble. Lock in place with the jamb nut.

2. Adjust the air pressure just enough to raise and lower the foot which reduces potential for testing errors such as the torque shaft not being vertical.
3. Specimen trays remain in the environmental curing chamber during testing. The operator enters the chamber for testing. Trays are tested after 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 24, 48, and 120 hours of curing.
4. After each curing period the tray is positioned on the cohesion tester base with a hooked foot for a 2-point static contact. The tray is held firmly in place while the torque wrench is applied to the upper rod end and twisted in a quick and firm horizontal motion. The torque required to dislodge the marble from the emulsion is recorded as a data point. Fifteen data points are recorded per tray, the highest and lowest two data points are discarded, and the remaining eleven data points are averaged and recorded as one test (i.e. one tray is one test).
5. When moisture loss versus time is desired, step 5 is performed. State Study 211 was the first of the *FMT* efforts from the research team where moisture loss was measured, so it is a third iteration of the *FMT* protocol. A tray was prepared with 27 to 28.5 g of emulsion (9.0 to 9.5 g per trough) without frosted marbles. The tray was weighed before and after emulsion application and moisture loss was determined over time using initial moisture determined with the emulsion's residue. Moisture loss was calculated by referencing the total initial water mass in the specimen. For example, if 28 g of emulsion was in all three trays and the emulsion residue was 69%, 8.68 g of moisture was initially present. If 4 g of moisture was lost up to a given time, 46% moisture loss had occurred.

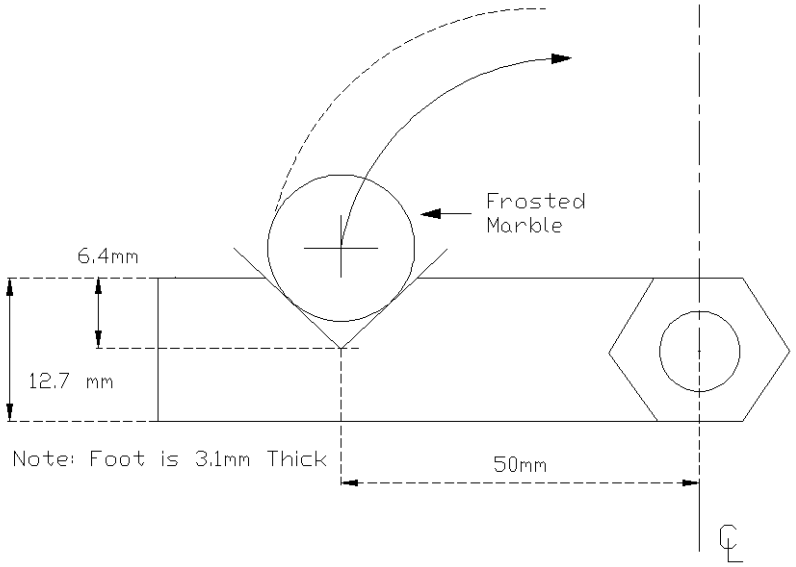


Figure 4.21. *FMT* Hooked Foot Assembly

A total of 221 *FMT* trays were tested for torque readings. Emulsions 1 to 7 were first tested by a single operator, which with 13 cure times equates to 91 trays. Emulsions 1, 2, and 4 were then re-tested by the same operator using a different sample of the same emulsion type in triplicate, which equates to 117 trays. Emulsion 6 was also tested by a different operator, requiring 13 trays. An additional 78 trays were tested absent frosted marbles for moisture loss measurements.

4.6.6 Sweep Test Procedures and Specimens Tested

Figure 4.22 shows key sweep test equipment and a sweep test in progress. Two sweep test protocols were used in this research: ASTM D7000 and *Sweep-M* (modified). ASTM D7000 tests were performed by Paragon Technical Services, Inc. and Road Science, LLC. Specimens were cured at 35 C and 30-40% relative humidity for a specified period of time prior to testing. Oven humidity was accomplished by placing pans filled with water in the bottom of the oven; it was monitored with a digital heat and humidity pen, model PTH 8708. After conditioning, specimens were removed from the oven and allowed to cool for three minutes. Next, they were held vertically by one edge, and a gentle brushing was used to remove any loose aggregate (initial brushing). The specimens were swept for 60 seconds on the low-speed setting and then held vertically and brushed again (final brushing).

a) Quick-clamp Mounting Base *b) ASTM D7000 Brush and Brush Head*

c) Hobart N50 Mixer, Base, Brush Head *d) Sweep Test in Progress*

Figure 4.22. Sweep Test Equipment

Sweep-M testing was performed in general accordance with D7000, with one notable exception. When researchers attempted to buy the equipment of the D7000 sweep test, it was found that the Hobart A120 mixer was discontinued. Instead, researchers bought and used the Hobart N50 mixer, thought at the time to be equivalent to the A120 model. It was learned during the data analysis phase that the N50 model is not equivalent to the A120; the HL120 model is a closer equivalent to the A120 (Table 4.3). This was an oversight on the part of the researchers. All else was in compliance with D7000 (e.g. brush type, brush head dimensions and weight, strike-off template dimensions, strike-off rod specifications,

compactor weight and radius of curvature, etc). Sweep testing with the N50 mixer is referred to as *Sweep-M* herein.

An experiment was conducted to investigate the mixer's sweep head influence area. Nylon brushes were damped in red ink, attached to the abrasion heads, and the abrasion heads were set to sweep for one minute on top of clean and unused felt disks. Sweeping revealed the N50 mixer sweeps approximately 83% of the A120 area (285 cm^2 versus 345 cm^2, respectively).

Table 4.3. Hobart Mixer Specifications

Model	Horsepower	Low Agitator (RPM)	Intermediate Agitator (RPM)	High Agitator (RPM)
A120	1/3	104	194	353
HL120	1/2	107	198	365
N50	1/6	136	281	580

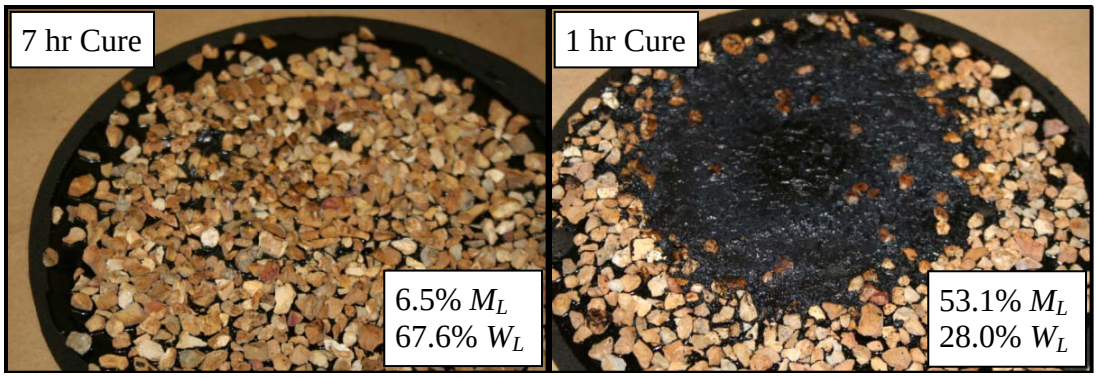
Sweep test response variables used in this study were mass loss and moisture loss. Mass loss (%) of each test specimen was calculated according to Equation 4.3 (Note: 1.33 magnifying factor accounts for the surface area of the specimen not swept by the brush head when using the A120 mixer or equivalent). Moisture loss (%) calculations were performed according to Equation 4.4. For D7000, only mass loss was recorded; for *Sweep-M*, both mass and moisture loss were recorded. Figure 4.23 illustrates test samples yielding low and high mass loss.

$$M_L\ (\%) = 1.33\left[\frac{Pre\text{-}sweep - Post\text{-}sweep}{Pre\text{-}sweep - D}\right](100) \tag{4.3}$$

Where,
M_L = mass loss (%)
Pre-sweep = mass of specimen after initial brushing but prior to sweep test (g)
Post-sweep = mass of specimen after sweep test and final brushing (g)
D = mass of asphalt felt disk (g)

$$W_L\ (\%) = \left[\frac{Pre\text{-}cure - Post\text{-}cure}{E_{mass}\,(1 - R)}\right]\ (100) \tag{4.4}$$

Where,
W_L = moisture loss (%)
Pre-cure = mass of specimen immediately after compaction and before curing (g)
Post-cure = mass of specimen after curing but before initial brushing (g)
E_{mass} = mass of emulsion, target 83 ± 5, actual value recorded and used (g)
R = emulsion residue as decimal (Table 3.3)



e) Example of Low Mass Loss *f) Example of High Mass Loss*

Figure 4.23. Example Sweep Test Results

The capability of emulsions to retain aggregate was evaluated by the *Sweep-M* test. D7000 sweep tests were performed in order to correlate *Sweep-M* results to D7000 results. D7000 and *Sweep-M* tests were performed on three aggregates and seven emulsions to analyze material compatibility and short term performance primarily related to traffic opening.

An identification system was developed for sweep test specimens. The treatments considered are emulsion, aggregate, and curing time. Treatment combinations were labeled according to Equation 4.5

1-2-3 (4.5)

Where,

1: The first position corresponds to the emulsion type. Possible values for this label are in Table 3.1, with examples shown below.
- E1: Emulsion 1
- E2: Emulsion 2
- E3: Emulsion 3

2: The second position corresponds to aggregate type. Possible values for this label are in Table 3.8 as shown below.
- A1: Aggregate 1
- A2: Aggregate 2
- A3: Aggregate 3

3: The third position corresponds to the curing time. Example values for this label are shown below.
- T0.5: 0.5 hour cure time
- T1: 1 hour cure time
- T4: 4 hour cure time

For example, E5-A3-T6 corresponds to a sweep test treatment combination of emulsion 5 and aggregate 3 at six hours of curing.

A total of 123 D7000 tests were performed. There were 63 specimens tested at 1 hr cure (3 replicates) using all seven emulsions and all three aggregate types. There were 60

additional specimens tested at ten different curing times (2 replicates); curing times were 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, and 8 hours. All three aggregates were tested but with emulsion 2 only.

Sweep-M variability was investigated by conducting sweep tests at 1 and 2 hr cure (20 replicates each). Test specimens were made with aggregate 3 and emulsions 1 and 2. A total of 80 variability sweep tests were conducted.

Sweep-M testing was performed using seven emulsions, three aggregates, and ten curing times to investigate possible relationships between performance and strength gain in terms of mass loss and moisture loss for a range of aggregates, emulsions, and curing times. A total of 410 sweep tests were conducted. Insufficient aggregate 1 was available to perform two replicates for emulsion 7, but, otherwise, two replicates were performed.

Extended duration *Sweep-M* testing was conducted to investigate moisture loss of specimens over time and to identify a reasonable range of curing times needed for near 100% asphalt emulsion moisture loss under laboratory conditions. Sweep test specimens were cured for 96 hrs and then tested. Moisture loss readings were taken on all test specimens throughout the 96 hr curing period. These moisture loss readings were obtained every hour for the first 12 hrs and, thereafter, every 12 hrs for the next 84 hrs. Specimens were tested for mass loss at the 96 hr cure time only. A total of 14 specimens were fabricated using all seven emulsions and aggregate 3 only (2 replicates each).

CHAPTER 5-REPEATED CREEP TEST RESULTS

5.1 Overview of Repeated Creep Test Results

Repeated Creep (*RC*) testing conducted in the *DSR* was performed to determine the test protocol's ability to characterize the effect of emulsified asphalt on aged asphalt concrete surfaces. One emulsion (E3) and two pavements (*FR* and *Hwy 45*) were tested in this chapter. The data in this chapter has not been previously presented in a citable document.

5.2 Torsion Bar Dimensions

Table 5.1 provides torsion bar dimension results from this study alongside results from the companion work presented in Doyle et al. (2013). It is noteworthy that inability to fabricate torsion bars over a range of properties of interest was reported by Doyle et al. (2013) as a drawback for 100% RAP mixed with virgin binder. Specimens were producible for *FR* and *Hwy 45* at all conditions investigated. Widths and thicknesses for traditional hot mixed asphalt (HMA) and 100% RAP were within the 95% confidence intervals of the tolerance listed in D7552-09, even though thicknesses targeted 10 mm as opposed to 9 mm.

Five of the twenty-four *FR* and *Hwy 45* beams investigated had thicknesses greater than 10.5 mm, with the thickest being 10.8 mm. The targeted State Study 211 thickness was also 10 mm as opposed to 9 mm. The thinnest *FR* or *Hwy 45* beam was 9.0 mm, making the range of beam thicknesses tested 1.8 mm. A thickness range of 1.8 mm is well within the 3.0 mm range used by D7552-09. There were no meaningful problems with producing functional torsion bars.

Table 5.1. Dimensional Results for Preparing Torsion Bars

Property	ASTM D7552-09	Doyle et al. (2013) HMA	Doyle et al. (2013) RAP	SS 211 *FR*	SS 211 *Hwy 45*
Width Tolerance (mm)	12 $\pm$ 2	---	---	---	---
Width Mean (mm)	---	12.4	11.9	12.2	11.9
Width COV (%)	---	2.3	7.3	3.2	5.1
Width 95% C.I. (mm)	---	11.9 to 13.0	10.2 to 13.6	11.5 to 13.0	10.7 to 13.1
Thickness Tolerance (mm)	9 $\pm$ 1.5	---	---	---	---
Thickness Mean (mm)	---	9.8	9.9	10.0	10.0
Thickness COV (%)	---	2.9	3.1	5.4	4.4
Thickness 95% C.I. (mm)	---	9.2 to 10.3	9.3 to 10.5	9.0 to 11.1	9.1 to 10.9

-- D7552-09 dimensions are measured with a caliper to nearest 0.01 mm.
-- COV = coefficient of variation, or Standard Deviation divided by the Mean.
*-- A 95% Confidence Interval (C.I.) was determined as the Mean $\pm$ 1.96*Standard Deviation.*

5.3 Repeated Creep Data Analysis Methods and Test Outputs

Individual torsion bar results were characterized using three sequential regions as described in the example data presented in Figure 5.1. Primary flow is the region where the strain rate decreases with loading time. Secondary flow is the region where the strain rate becomes constant with loading time. The tertiary flow region occurs after the failure point and is differentiated from the secondary flow region in that the strain rate increases with time instead of remaining constant. Throughout the tertiary flow region the specimen starts to fail

quickly and experiences large permanent deformations. Four response variables were utilized to describe *RC* specimen behavior: 1) time to 5% cumulative strain (denoted $\varepsilon(5\%)_T$); 2) inverse of slope in the secondary flow region (expressed as an inverse for convenience and denoted $(\Delta\varepsilon/\Delta T)^{-1}$); 3) tertiary flow failure (number of cycles to tertiary failure denoted TFF); and 4) cumulative strain at failure (denoted F_ε).

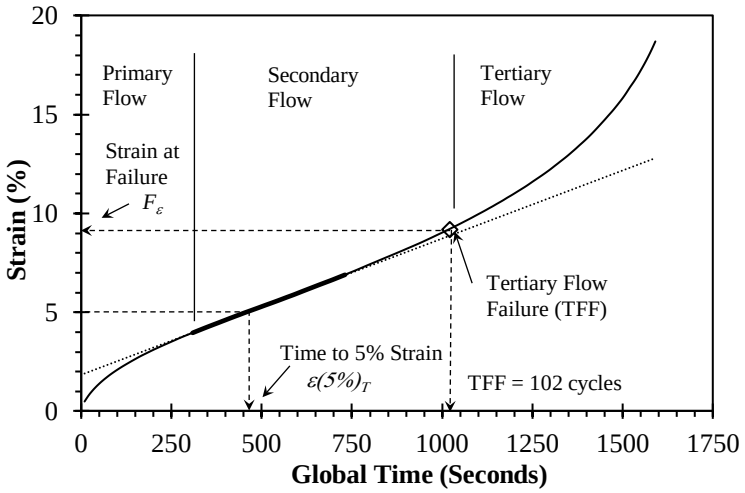


Figure 5.1. Example Repeated Creep Test Data and Associated Terminology

5.4 Repeated Creep Test Results

RC test results are plotted in Figure 5.2, and the results calculated from the Figure 5.2 curves are summarized in Table 5.2. Figure 5.2 plots were truncated at 8000 seconds as no meaningful behaviors occurred between 8000 and 9900 global seconds. All *FR* specimens lasted 100 cycles, whereas some *Hwy 45* specimens did not last 100 cycles. One *Hwy 45* specimen did not fail during the 990 cycles used during this testing protocol.

A visual observation from Figure 5.2 is behaviors are somewhat erratic within and between emulsion application rates. In some cases, the replicates produce similar curves (e.g. *Hwy 45* at 0.00 L/m^2 and *FR* at 1.81 L/m^2), but in other cases the curves are dissimilar for all three replicates (e.g. *FR* at 0.91 L/m^2 and *Hwy 45* at 1.36 L/m^2). This level of variability for a test method that requires fairly expensive equipment alongside a noticeable amount of labor and equipment time is somewhat problematic. Total *DSR* equipment time is from 45 to 195 minutes per torsion bar, and the variability observed herein indicates several replicates would be necessary to make any meaningful statements.

Table 5.3 summarizes linear regressions performed with the Table 5.2 data. Failure strain was the only term where the directional behavior of the slope (m) was the same between pavement types. Failure strain also had the highest R^2 values, though they were extremely low for all variables indicating increasing emulsion did not appear to have any meaningful effect that was measured by the *RC* test.

Table 5.4 further consolidates the data by averaging all data that was emulsion treated (9 specimens per pavement type) and comparing it to the 3 specimens tested without emulsion treatment. Failure strain decreased 0.6% on average due to emulsion application for *FR* and *Hwy 45*. Decreased failure strain indicates the material was able to flow at lower strains, which would be a logical effect of adding unaged bitumen to an aged pavement.

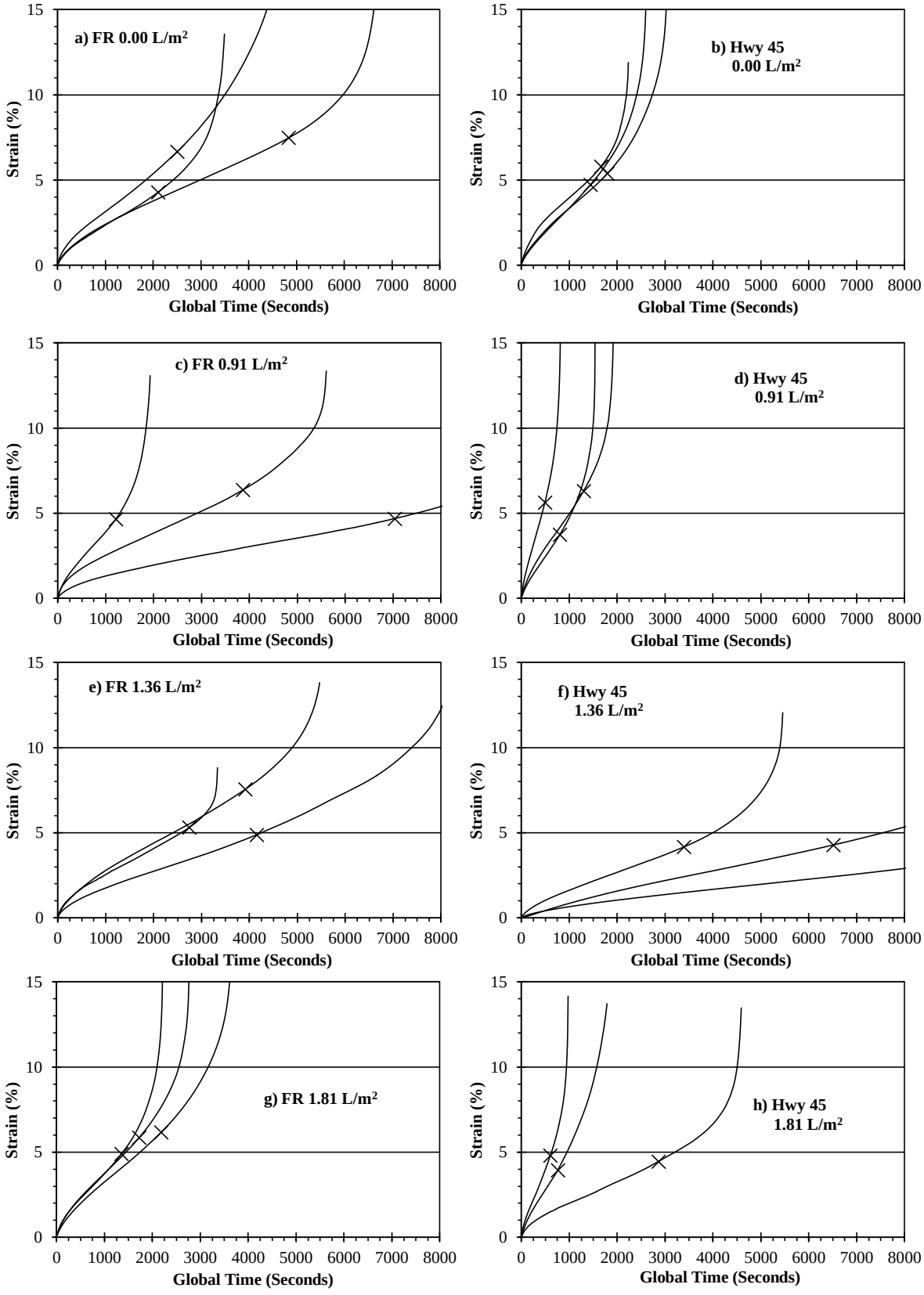


Figure 5.2. Repeated Creep Curves with Failure Strain (F_{ε}) Denoted with an "X"

Table 5.2. Repeated Creep Test Results

Pavement ID	Emulsion Rate (L/m^2)	T_s (kPa)	Rep No.	$\varepsilon(5\%)_T$ (sec)	$(\Delta\varepsilon/\Delta T)^{-1}$ (sec per % strain)	TFF (cycles)	F_ε (%)
FR	0.00	136	1	2970	785	483	7.5
			2	1850	473	250	6.7
			3	2420	574	210	4.3
	0.91	136	1	7490	2000	703	4.7
			2	2910	769	386	6.4
			3	1300	323	121	4.7
	1.36	136	1	2400	667	391	7.6
			2	4250	1111	415	4.9
			3	2570	625	274	5.3
	1.81	136	1	1750	426	218	6.2
			2	1440	359	172	5.9
			3	1380	345	135	4.9
Hwy 45	0.00	272	1	1410	400	166	5.8
			2	1660	412	179	5.4
			3	1530	349	144	4.7
	0.91	272	1	1010	255	130	6.3
			2	440	100	49	5.6
			3	1040	241	80	3.8
	1.36	272	1	7560	1667	651	4.3
			2	---[a]	3333	---[a]	---[a]
			3	3390	1000	339	4.2
	1.81	272	1	630	152	60	4.8
			2	3210	833	286	4.5
			3	960	227	76	3.9

a) specimen did not fail within 990 cycles, or within 9900 global test seconds.

Table 5.3. Correlations of *RC* Outputs to Application Rate

Pavement	y	m	R^2
FR	$\varepsilon(5\%)_T$ (sec)	-358	0.02
	$(\Delta\varepsilon/\Delta T)^{-1}$ (sec per % strain)	-92	0.02
	TFF (cycles)	-58	0.06
	F_ε (%)	-0.21	0.02
Hwy 45	$\varepsilon(5\%)_T$ (sec)	620	0.05
	$(\Delta\varepsilon/\Delta T)^{-1}$ (sec per % strain)	325	0.06
	TFF (cycles)	40	0.03
	F_ε (%)	-0.57	0.25

-- Linear regression was performed where $y = m(x) + b$, x = emulsion rate in L/m^2, and b = the intercept which is not relevant for the present discussion.

Table 5.4. Average *RC* Data Comparing Emulsion to No Emulsion

Pavement	Emulsion	$\varepsilon(5\%)_T$ (sec)	$(\Delta\varepsilon/\Delta T)^{-1}$ (sec per % strain)	TFF (cycles)	F_ε (%)
FR	No	2413	611	314	6.2
	Yes	2832	736	313	5.6
Hwy 45	No	1532	387	163	5.3
	Yes	2280	868	209	4.7

Note: All emulsion application rates (0.91 to 1.81 L/m^2) from Table 5.2 were averaged.

The remaining three parameters have a considerable time component. The high time associated variability is visually observed in Figure 5.2 and numerically denoted in Table 5.2, which makes all three of these parameters difficult to use with only three replicates. As an example, *FR* at 0.91 L/m^2 had $\varepsilon(5\%)_T$ values from 1300 to 7490 seconds and TFF values from 121 to 703 cycles. Any trends in Table 5.4 for any of these three parameters are likely coincidence. For example, $\varepsilon(5\%)_T$ values were higher when specimens were emulsion treated, but removing one specimen converged the values for practical purposes. Findings were similar (though values did not converge as much) for $(\Delta\varepsilon/\Delta T)^{-1}$.

5.5 Repeated Creep Test Results Summary

Torsion bars were successfully sawn from the surface of field aged pavements. Thereafter, characterization of an emulsion's effect on an aged pavement surface became more difficult. Stress levels needed to be varied to obtain reasonable results, a behavior also observed in Doyle et al. (2013) for 100% RAP mixed with virgin binder, which makes direct comparison more difficult. Failure strain appears the least sensitive to this behavior, and was the most promising output variable. A modest trend was identified for failure strain, but there was considerable time associated variability that seemed to affect the remaining three test outputs. Overall, the *RC* test does not appear to be an ideal choice for evaluating the effect of emulsion on aged asphalt surfaces when considering test results and variability presented herein in conjunction with equipment and labor investments required.

CHAPTER 6-VISCOSITY TEST RESULTS

6.1 Overview Viscosity Test Results

Jordan (2010) provides preliminary viscosity testing and example calculations, in addition to the viscosity data in this chapter. Raw data used herein comes from Tables A.1 to A.10 of Jordan (2010). Note that Table A.11 was not used as additional investigation resulted in the data being questionable. In a few cases minor discrepancies were identified in the data from Jordan (2010); in the event of a discrepancy, the data in this chapter governs.

Brookfield viscosity is used in many applications to assess the ability to pump bituminous materials. In this chapter, it assessed the effect of an emulsion on the near surface of existing pavements. Most of the viscosity test data presented is within 6.3 mm of the pavement surface. The percent decrease in viscosity ($V_{D(\%)}$) for each application rate at each thickness was determined using Equation 2.3. Materials tested in this chapter were three pavements (*FR*, *Hwy 45*, and *Hwy 17*) and seven emulsions (E1 to E7).

6.2 Viscosity of Existing Pavement Prior to Emulsion Application

Viscosity of existing pavements prior to emulsion application is provided in Table 6.1 as a function of depth. *FR* has a noticeable viscosity versus depth of material gradient, whereas *Hwy 45* does not. *Hwy 17* was only tested at one depth and temperature, yet it had a noticeably lower viscosity than *FR* or *Hwy 45*.

Table 6.1. Existing Pavement Viscosity Profiles with Depth

	Viscosity (cP) at Indicated Test Temperature & Pavement Depth					
	135 C			165 C		
Pavement	**6.3 mm**	**9.5 mm**	**12.5 mm**	**6.3 mm**	**9.5 mm**	**12.5 mm**
FR	10,550	6,578	4,913	1,494	1,219	734
Hwy 45	9,216	8,991	9,044	1,318	1,496	1,467
Hwy 17	6,943	---	---	---	---	---

6.3 Preliminary Testing of Emulsion Treated Pavements

Jordan (2010) evaluated *NS* cores at 0.91 and 1.36 L/m^2 application rates with E3 alongside pavement depths of 6.3, 9.5, and 12.5 mm. Results showed $V_{D(\%)}$ steadily decreased with slice depth. Figure 6.1 plots scraped (*SCR*) versus non-scraped (*NS*) cores at a 135 C test temperature using *Hwy 45* and *FR* with E1 to E4. Results clearly indicate non-scraped specimens have a viscosity peak and are much lower than scraped viscosities. Results are intuitive and indicate no advantage to testing non-scraped specimens. Scraped specimens also more reasonably represent the combination of conditions where a chip seal emulsion could affect the existing pavement surface. Given the top 6.3 mm of a pavement is most prone to aging, it was selected as the depth to slice specimens for the remaining testing presented. These specimens were also scraped, making the final configuration testing 6.3 mm thick slices with emulsion scraped prior to slicing. Jordan (2010) also measured the amount of bitumen residue that penetrated scraped cores and found no correlation between the amount of bitumen residue penetrated and $V_{D(\%)}$ for the seven emulsions tested.

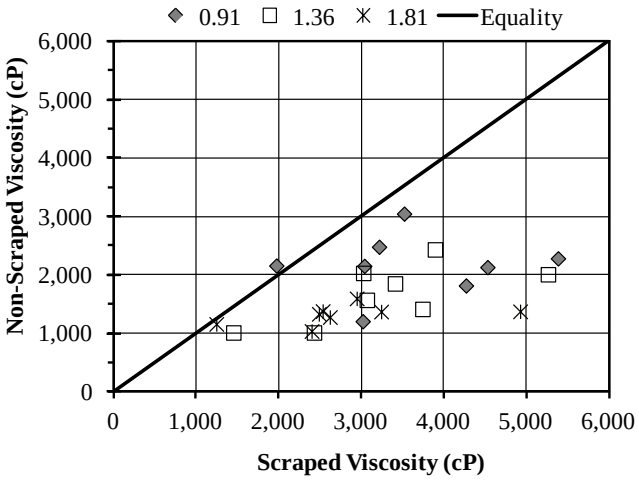


Figure 6.1. Comparison of Scraped and Non-Scraped Viscosities at 135 C

6.4 Percent Viscosity Change Test Results

Table 6.2 provides all viscosity change test results. *Hwy 45* and *FR* specimens were not conditioned prior to testing. *Hwy 17* specimens were field aged prior to testing.

Table 6.2. Percent Viscosity Change ($V_{D(\%)}$) Test Results

	Application	*Hwy 45*		*FR*	
Emulsion	**Rate (L/m^2)**	**135 C**	**165 C**	**135 C**	**165 C**
1	0.91	65	54	71	46
	1.36	67	48	71	57
	1.81	73	52	75	61
2	0.91	51	36	67	53
	1.36	58	44	68	52
	1.81	73	53	72	57
3	0.91	67	65	81	69
	1.36	74	66	86	75
	1.81	74	66	88	75
4	0.91	54	39	49	47
	1.36	59	29	50	17
	1.81	65	55	53	32
5	0.91	71	52	75	59
	1.36	72	51	78	65
	1.81	73	57	80	66
6	0.91	53	34	58	38
	1.36	57	33	61	44
	1.81	60	36	59	46
7	0.91	60	39	60	24
	1.36	64	47	61	34
	1.81	67	51	68	38

-- All specimens were scraped (SCR), and a 6.3 mm slice was taken from all cores.
-- Hwy 17 $V_{D(\%)}$ values were 19% and 25%, respectively, for chip and scrub seals using emulsion 3 after 18 months of service life in Carroll County, MS.
-- Test temperature was 135 C for Hwy 17.

Table 6.3 summarizes results of a paired *t*-test performed on the data presented in Table 6.2. A two tailed test was performed with a null hypothesis (H_o) that the mean difference (M_d) was zero and an alternative hypothesis (H_a) that M_d does not equal zero. Three cases were compared to allow comparison of all three application rates. A *p-value* of 0.05 or less indicates the two data sets compared were statistically different, or in general terms that emulsion application rate affected the percent change in viscosity ($V_{D(\%)}$).

Table 6.3. Paired *t*-Test Results Comparing $V_{D(\%)}$ Means for Different Application Rates

Pavement	Temperature of Test (C)	Application Rates Compared (L/m^2)	*p-value*	Statistically Different?
Hwy 45	135	0.91 and 1.36	0.0026	Yes
		1.36 and 1.81	0.0427	Yes
		0.91 and 1.81	0.0083	Yes
FR	135	0.91 and 1.36	0.0388	Yes
		1.36 and 1.81	0.0382	Yes
		0.91 and 1.81	0.0013	Yes
Hwy 45	165	0.91 and 1.36	0.9566	No
		1.36 and 1.81	0.0632	No
		0.91 and 1.81	0.0454	Yes
FR	165	0.91 and 1.36	0.8771	No
		1.36 and 1.81	0.0466	Yes
		0.91 and 1.81	0.1889	No

-- Seven pairs were present per pavement, one for each emulsion.

At 135 C, application rate statistically affected $V_{D(\%)}$ for all six cases considered. Mean values increased with application rate indicating increased emulsion applied had increased effect on the existing pavement. Mean values at 135 C from Table 6.3 are shown in Table 6.4, and they show a lessening difference of pavement type as emulsion application rate increases. *FR* is softened more than *Hwy 45* for all application rates, though the effect is more pronounced as the application rate decreases.

Table 6.4. Mean $V_{D(\%)}$ Values Using Combined Data from All Emulsions

	135 C			165 C		
Pavement	0.91 L/m^2	1.36 L/m^2	1.81 L/m^2	0.91 L/m^2	1.36 L/m^2	1.81 L/m^2
Hwy 45	60.1	64.4	69.3	45.6	45.4	52.9
FR	65.9	67.7	70.7	48.0	48.9	53.6
Difference	5.8	3.3	1.4	2.4	3.2	0.7

At 165 C, there were no clear statistical trends with respect to emulsion application rate, as statistical differences were detected in two of six cases (both of these cases had *p-values* near the 0.05 threshold). Mean values generally increased with emulsion application rate, though there was not an increase for *Hwy* 45 between 0.91 and 1.36 L/m^2. Mean values at 165 C were also shown in Table 6.4, and there is a lessening effect of pavement type between 0.91 to 1.81 L/m^2 and 1.36 to 1.81 L/m^2, but not from 0.91 to 1.36 L/m^2. *FR* was softened more than *Hwy 45* for all application rates as was the case at 135 C.

Test data at 165 C was not as consistent as 135 C data. This is perhaps because at higher temperatures aged binder in the original pavement has more opportunity to affect behavior. For seal treatments, lower temperatures seem more intuitive to characterize

behavior, and since the data was more consistent, test data at 135 C was relied upon more heavily when coupled with other test methods.

Table 6.5 averages all application rate data in Table 6.2 to compare viscosity change potential of all emulsions. Emulsion rank is listed in parenthesis for each pavement and test temperature. E3 decreased viscosity more than any of the other emulsions. E6 decreased viscosity the least for *Hwy 45*, and E4 decreased viscosity the least for *FR*.

Table 6.5. Viscosity Decrease Potential Evaluated With Combined Application Rates

	Hwy 45		***FR***	
Emulsion	**135 C**	**165 C**	**135 C**	**165 C**
1	68 (3rd)	51 (3rd)	72 (3rd)	55 (3rd)
2	61 (5th)	44 (5th)	69 (4th)	54 (4th)
3	72 (1st)	66 (1st)	85 (1st)	73 (1st)
4	59 (6th)	41 (6th)	51 (7th)	32 (7th)
5	72 (1st)	53 (2nd)	78 (2nd)	63 (2nd)
6	57 (7th)	34 (7th)	59 (6th)	43 (5th)
7	64 (4th)	46 (4th)	63 (5th)	32 (7th)

CHAPTER 7-BENDING BEAM RHEOMETER TEST RESULTS

7.1 Overview of Bending Beam Rheometer Test Results

Creep stiffness and *m-value* determined from the Bending Beam Rheometer (*BBR*) test are widely accepted for use in the Superpave asphalt binder grading specification, and in recent years, *BBR* testing of asphalt mixture beams has seen increased use as well (see Section 2.6.1.3 of literature review). *BBR* outputs were used in this chapter to evaluate an emulsion's effect on the near surface of field aged pavements and plant mixed laboratory compacted asphalt. In general, *BBR* results are analyzed in this chapter relative to control data sets (i.e. no emulsion and no aging) and are characterized by two values (Equations 7.1 and 7.2). This was performed to quantify the effect of an emulsion relative to the *m-value* or stiffness of a pavement prior to emulsion application. Materials tested in this chapter were three pavements (*FR*, *Hwy 45*, and *Plant Mix*) and seven emulsions (E1 to E7).

$$\Delta m\text{-}value = m\text{-}value_T - m\text{-}value_U \tag{7.1}$$

$$S_{D(\%)} = \frac{S_U - S_T}{S_U}(100) \tag{7.2}$$

Where,
$\Delta m\text{-}value$ = increase in *m-value* (negative value represents decrease)
$m\text{-}value_U$ = untreated *m-value*
$m\text{-}value_T$ = treated *m-value*
$S_{D(\%)}$ = decrease in stiffness (negative value represents stiffness increase)
S_U = untreated stiffness (GPa)
S_T = treated stiffness (GPa)

Barham (2011) is a thesis that provides data from 773 successfully tested beams which compose the bulk of the data presented in this chapter. Braham et al. (2013a) and Braham et al. (2013b) also include parts of the Barham (2011) data. After additional investigation of Barham (2011), 12 discrepancies were identified, and the questionable 12 beams were removed from the data set. In addition, 40 beams from Barham (2011) were not used in this chapter for stiffness or *m-value* calculations as the specific treatment combinations did not benefit the test matrix. A total of 721 of the 773 beams presented in Barham (2011) were used in this report for stiffness and *m-value* investigations. Further testing [post-Barham (2011)] of 238 beams was used to compile the final State Study 211 *BBR* data set of 959 successfully tested beams as presented and analyzed in this chapter. In the case of a discrepancy, the data in this chapter governs. The discrepancies identified had no meaningful effect on *BBR* findings.

7.2 Analysis of *BBR* Beam Fabrication and Variability

To the knowledge of the research team, *BBR* testing of emulsion treated field aged pavement surfaces had not been attempted in a comprehensive manner prior to these research

efforts. Therefore, fundamental investigations evaluating feasibility of such testing were necessary. Braham et al. (2013b) details feasibility concepts for testing field aged asphalt surface beams in the *BBR*. This paper performed specimen fabrication and dimensional variability analysis on the data set from Barham (2011) where 773 *BBR* beams were successfully tested; 1,387 beams were attempted. This section summarizes key findings of Braham et al. (2013b) (phase 1) and also provides a similar feasibility/variability analysis for the total State Study 211 data set (phase 2).

7.2.1 Phase 1 Beam Fabrication and Variability Investigation

All information in this section was from the work of Braham et al. (2013b) using a partial data set. It has thus been labeled as a phase 1 investigation. *BBR* success rates were as follows. For the 535 *FR* beams, 115 (21.5%) broke during fabrication, and 140 (26.2%) broke during testing. For the 692 *Hwy 45* beams, 150 (21.7%) broke during fabrication, and 197 (28.5%) broke during testing. For the 160 *Plant Mix* beams, 9 (5.6%) broke during fabrication, and 3 (1.9%) broke during testing. In general terms, five of ten beams were successfully sawn and tested from field aged surfaces, and nine of ten beams were successfully sawn and tested from plant mixed laboratory compacted asphalt.

Dimensional variability of the beam sawing process was also evaluated. The average beam thickness and width for all successfully tested beams was 7.7 and 12.3 mm, respectively. Between-beam thickness COV values for *FR* and *Hwy 45* were 4.1% and 3.8%, respectively, while the *Plant Mix* had a slightly lower COV of 3.1%. Width variability was slightly less than that of the thickness. Between-beam width COV values for *FR* and *Hwy 45* were 2.5% and 3.3%, respectively, while the *Plant Mix* again had a slightly lower COV of 1.3%.

Within-beam variability was evaluated by two methods: COV and range (maximum minus minimum) of the five dimension measurements. Within-beam variability was not limited only to beams that were successfully tested but also included beams that were successfully sawn yet broke during testing. Laboratory data recording protocols in Barham (2011) did not consistently log all five dimension measurements and occasionally reported only the average dimension. Therefore, the number of within-beam variability specimens (996 total) in Braham et al. (2013b) was greater than the number of successfully tested beams (773) but less than the sum of successfully tested and broken during testing beams (1,108). Approximately 13% of the 1,108 beams were unusable for this part of the investigation because all five dimension measurements had not been recorded. The set of 996 beams that was used to assess within-beam variability was sufficiently large, however, to provide a reasonable analysis.

The average within-beam thickness COV values for *FR* and *Hwy 45* were 2.2% and 2.8%, respectively, while the *Plant Mix* had a COV of 2.2%. Width variability was slightly less than that of the thickness. Average within-beam width COV values for *FR* and *Hwy 45* were 1.0% and 1.1%, respectively, while the *Plant Mix* had a slightly lower COV of 0.6%. Approximately 73% of the *FR* beams, 53% of the *Hwy 45* beams, and 70% of the *Plant Mix* beams had a range of maximum to minimum thickness of 0.50 mm or less. Approximately 87% of the *FR* beams, 88% of the *Hwy 45* beams, and 97% of the *Plant Mix* beams had a range of maximum width to minimum width of 0.50 mm or less.

7.2.2 Phase 2 Beam Fabrication and Variability Investigation

All information in this section is from the full State Study 211 data set. It has thus been labeled as a phase 2 investigation. Table 7.1 provides a summary of the outcome of all *BBR* beams. As in Braham et al. (2013b), the rate of success for field aged pavements was considerably less than that of the *Plant Mix*. Likewise, five of ten beams were generally successfully sawn and tested from field aged surfaces, and nine of ten beams were successfully sawn and tested from plant mixed laboratory compacted asphalt.

Laboratory data recording protocols in Barham (2011) did not consistently log dimensional characteristics of each beam that was attempted to be sawn and tested, rather only the final summary percentages were preserved. This approach was suitable for the Barham (2011) objectives but prevented dimensional properties of the 52 beams not used for stiffness or *m-value* calculations to be isolated in this report. For this reason, Table 7.1 includes all Barham (2011) data as well as all data associated with the later testing (1,011 beams successfully tested in all). Whether or not a beam was removed from further analysis, however, would not affect the overall significance of Table 7.1 as it is essentially independent of the factors that led to the removal of the 52 Barham (2011) beams.

Table 7.1. *BBR* Specimen Fabrication Outcome Summary

		Broke During Fabrication		Broke During Testing		Successfully Tested	
Pavement	***n* Total**	***n***	**$\%_{total}$**	***n***	**$\%_{total}$**	***n***	**$\%_{total}$**
FR	571	122	21.4	149	26.1	304	53.2
Hwy 45	1027	235	22.9	270	26.3	522	50.8
Plant Mix	200	11	5.5	4	2.0	185	92.5
All	1798	368	---	423	---	1011	---

-- $\%_{total}$ = percentage of total number of attempted BBR beams for a given pavement.
-- Note: 52 of the successfully tested beams were not used for stiffness or m-value analysis.

Table 7.2 provides statistical analysis for between-specimen dimensions for all beams in the final State Study 211 *BBR* data set (successfully tested beams only). The average thickness and width was 7.67 and 12.24 mm, respectively. Thickness COV values for *FR* and *Hwy 45* were 3.9% and 3.7%, respectively, while the *Plant Mix* had a slightly lower COV of 3.0%. Width variability was slightly less than that of the thickness. Width COV values for *FR* and *Hwy 45* were 2.5% and 3.3%, respectively, while the *Plant Mix* again had a slightly lower COV of 1.5%. Results in Table 7.2 did not change meaningfully from that of Braham et al. (2013b) and the phase 1 investigation.

Table 7.2. Analysis of *BBR* Beam Between-Specimen Dimensions

		Thickness			Width		
Pavement	***n***	**Avg (mm)**	**St. Dev. (mm)**	**COV (%)**	**Avg (mm)**	**St. Dev. (mm)**	**COV (%)**
FR	261	7.70	0.30	3.9	12.27	0.30	2.5
Hwy 45	516	7.67	0.29	3.7	12.21	0.40	3.3
Plant Mix	182	7.64	0.23	3.0	12.26	0.18	1.5
All	959	7.67	0.28	3.7	12.24	0.35	2.8

Tables 7.3 and 7.4 provide COV values for all successfully tested within-beam dimensions. The average within-beam thickness COV values for *FR* and *Hwy 45* were 2.2% and 2.9%, respectively, while the *Plant Mix* had a COV of 2.3%. Width variability was slightly less than thickness variability. Average within-beam width COV values for *FR* and *Hwy 45* were 1.0% and 0.9%, respectively, while the *Plant Mix* had a slightly lower COV of 0.6%. Results in Table 7.3 and 7.4 did not change meaningfully from that of Braham et al. (2013a).

Table 7.3. Analysis of *BBR* Beam Within-Specimen COV Values for Thickness

	FR		***Hwy 45***		***Plant Mix***	
	n = 244, Avg = 2.2%		*n* = 492, Avg = 2.9%		*n* = 180, Avg = 2.3%	
COV (%)	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**
0 to 0.25	0.0	0.0	0.0	0.0	0.6	0.6
0.26 to 0.50	1.6	1.6	0.2	0.2	0.0	0.6
0.51 to 0.75	2.9	4.5	2.0	2.2	4.4	5.0
0.76 to 1.00	8.2	12.7	2.0	4.3	6.7	11.7
1.01 to 1.25	6.1	18.9	3.7	7.9	9.4	21.1
1.26 to 1.50	9.0	27.9	6.9	14.8	8.3	29.4
1.51 to 1.75	7.4	35.2	6.7	21.5	8.9	38.3
1.76 to 2.00	10.2	45.5	6.3	27.8	8.9	47.2
2.01 to 2.25	11.5	57.0	7.9	35.8	5.0	52.2
2.26 to 2.50	8.2	65.2	9.1	44.9	6.1	58.3
2.51 to 2.75	7.0	72.1	8.5	53.5	10.0	68.3
2.76 to 3.00	5.3	77.5	7.5	61.0	5.6	73.9
3.01 to 3.25	7.4	84.8	7.3	68.3	4.4	78.3
3.26 to 3.50	4.5	89.3	4.7	73.0	2.8	81.1
3.51 to 3.75	3.7	93.0	5.3	78.3	5.6	86.7
3.76 to 4.00	1.2	94.3	4.3	82.5	3.3	90.0
>4	5.7	100.0	17.5	100.0	10.0	100.0

Table 7.4. Analysis of *BBR* Beam Within-Specimen COV Values for Width

	FR		***Hwy 45***		***Plant Mix***	
	n = 244, Avg = 1.0%		*n* = 492, Avg = 0.9%		*n* = 180, Avg = 0.6%	
COV (%)	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**
0 to 0.25	6.6	6.6	10.6	10.6	15.0	15.0
0.26 to 0.50	18.9	25.4	22.8	33.3	34.4	49.4
0.51 to 0.75	21.3	46.7	17.9	51.2	23.3	72.8
0.76 to 1.00	14.3	61.1	16.7	67.9	15.6	88.3
1.01 to 1.25	11.9	73.0	8.9	76.8	6.1	94.4
1.26 to 1.50	10.2	83.2	6.1	82.9	1.7	96.1
1.51 to 1.75	4.5	87.7	5.5	88.4	0.6	96.7
1.76 to 2.00	3.3	91.0	3.9	92.3	1.7	98.3
>2	9.0	100.0	7.7	100.0	1.7	100.0

Tables 7.5 and 7.6 provide ranges for successfully tested within-beam dimensions. Approximately 71% of the *FR* beams, 50% of the *Hwy 45* beams, and 66% of the *Plant Mix* beams had a range of maximum thickness to minimum thickness of 0.50 mm or less. Approximately 87% of the *FR* beams, 87% of the *Hwy 45* beams, and 96% of the *Plant Mix* beams had a range of maximum width to minimum width of 0.50 mm or less. Results in Table 7.5 and 7.6 did not change meaningfully from that of Braham et al. (2013b).

There is increased variability associated with cutting beam thickness. Because less overall material is being cut, less material is present to support the saw blade. When there is not substantial material on either side of the blade, the blade tends toward the side of lesser support and results in a larger range of thickness values within a beam.

Table 7.5. Analysis of *BBR* Beam Within-Specimen Max-Min Values for Thickness

Max-Min	***FR*** *n* = 244, Avg = 0.4%		***Hwy 45*** *n* = 492, Avg = 0.5%		***Plant Mix*** *n* = 180, Avg = 0.4%	
(mm)	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**
0 to 0.10	1.6	1.6	0.4	0.4	0.6	0.6
0.11 to 0.20	11.1	12.7	4.9	5.3	13.9	14.4
0.21 to 0.30	17.6	30.3	12.4	17.7	19.4	33.9
0.31 to 0.40	19.3	49.6	14.4	32.1	14.4	48.3
0.41 to 0.50	20.9	70.5	18.3	50.4	17.8	66.1
0.51 to 0.60	15.2	85.7	16.7	67.1	9.4	75.6
0.61 to 0.70	3.7	89.3	11.0	78.0	10.6	86.1
0.71 to 0.80	5.3	94.7	6.5	84.6	8.9	95.0
0.81 to 0.90	2.9	97.5	4.7	89.2	2.2	97.2
0.91 to 1.00	0.4	98.0	4.1	93.3	2.2	99.4
>1	2.0	100.0	6.7	100.0	0.6	100.0

Table 7.6. Analysis of *BBR* Beam Within-Specimen Max-Min Values for Width

Max-Min	***FR*** *n* = 244, Avg = 0.3%		***Hwy 45*** *n* = 492, Avg = 0.3%		***Plant Mix*** *n* = 180, Avg = 0.2%	
(mm)	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**	**Rel. Freq.**	**Cum. Freq.**
0 to 0.10	13.5	13.5	17.7	17.7	25.0	25.0
0.11 to 0.20	27.9	41.4	26.2	43.9	45.0	70.0
0.21 to 0.30	20.5	61.9	24.8	68.7	17.8	87.8
0.31 to 0.40	13.5	75.4	10.8	79.5	7.8	95.6
0.41 to 0.50	11.1	86.5	7.9	87.4	0.6	96.1
0.51 to 0.60	5.7	92.2	5.3	92.7	2.8	98.9
0.61 to 0.70	4.1	96.3	2.6	95.3	0.6	99.4
0.71 to 0.80	1.6	98.0	1.2	96.5	0.6	100.0
0.81 to 0.90	0.4	98.4	1.4	98.0	0.0	100.0
0.91 to 1.00	0.8	99.2	1.0	99.0	0.0	100.0
>1	0.8	100.0	1.0	100.0	0.0	100.0

7.3 Summary of *BBR* Stiffness and *m-value* Results for All Mixtures

Tables 7.7 through 7.14 provide *BBR* results for all mixtures in the final State Study 211 *BBR* data set. Averages, standard deviations, and coefficients of variation are provided for stiffness and *m-value* at loading times of 8, 60, and 960 seconds. Additionally, calculated Δ*m-value* and $S_{D(\%)}$ are provided. Results at three times (beginning, middle, and near end of the test) are used to provide an overall representation of the creep response. Example plots of *m-value* and stiffness versus time (log scale) for *FR* are provided in Figure 7.1. They illustrate varying amounts of emulsion rejuvenation on the existing pavement (Category 1, 2, or 3). Category 1 represents the greatest rejuvenation, Category 2 represents moderate rejuvenation, and Category 3 represents the least preferred behavior in the context of rejuvenation. In some cases, increasing application rate resulted in greater Δ*m-value* and $S_{D(\%)}$, while in others it did not. Laboratory aging appeared to inconsistently affect results.

Table 7.7. Summary Table of *BBR m-value* Results for *FR* Mixture Beams

Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg *m-value*			Test Time (s) and St. Dev. of Avg *m-value*			Test Time (s) and COV of *m-value*			Test Time (s) and Δ*m-value*		
				8	60	960	8	60	960	8	60	960	8	60	960
NE	---	0	65	0.063	0.086	0.118	0.054	0.027	0.081	85.7	31.4	69.0	---	---	---
1	0.91	0	8	0.099	0.128	0.168	0.023	0.041	0.093	23.1	32.3	55.4	0.036	0.042	0.050
	1.36	0	5	0.105	0.153	0.219	0.030	0.055	0.122	28.2	36.1	55.5	0.042	0.067	0.101
	1.81	0	8	0.120	0.146	0.181	0.040	0.047	0.062	33.2	32.0	34.0	0.057	0.060	0.063
		7	8	0.108	0.115	0.125	0.027	0.033	0.050	24.8	28.8	40.2	0.045	0.029	0.007
2	0.91	0	6	0.093	0.117	0.149	0.017	0.023	0.043	18.0	19.8	29.1	0.030	0.031	0.031
	1.36	0	8	0.101	0.120	0.147	0.024	0.039	0.066	24.3	32.8	44.6	0.038	0.034	0.029
	1.81	0	12	0.121	0.143	0.173	0.029	0.032	0.041	24.3	22.2	23.6	0.058	0.057	0.055
		7	5	0.113	0.153	0.208	0.027	0.030	0.040	24.0	19.5	19.3	0.050	0.067	0.090
3	0.91	0	6	0.108	0.122	0.142	0.049	0.051	0.062	45.5	41.9	43.9	0.045	0.036	0.024
	1.36	0	7	0.131	0.156	0.191	0.051	0.040	0.028	38.9	25.4	14.5	0.068	0.070	0.073
	1.81	0	5	0.137	0.176	0.228	0.020	0.017	0.014	14.5	9.4	6.2	0.074	0.090	0.110
		7	7	0.154	0.163	0.174	0.042	0.042	0.062	27.3	25.7	35.8	0.091	0.077	0.056
4	0.91	0	8	0.082	0.108	0.143	0.020	0.022	0.037	24.6	20.4	25.6	0.019	0.022	0.025
	1.36	0	9	0.091	0.133	0.190	0.030	0.030	0.056	32.8	22.6	29.6	0.028	0.047	0.072
	1.81	0	7	0.115	0.142	0.179	0.048	0.041	0.035	41.6	29.1	19.7	0.052	0.056	0.061
		7	5	0.096	0.125	0.166	0.018	0.015	0.023	18.3	11.7	13.6	0.033	0.039	0.048
5	0.91	0	8	0.158	0.171	0.190	0.055	0.050	0.053	34.8	29.3	28.1	0.095	0.085	0.072
	1.36	0	9	0.132	0.151	0.176	0.061	0.064	0.074	46.3	42.4	42.2	0.069	0.065	0.058
	1.81	0	4	0.147	0.177	0.219	0.051	0.029	0.001	34.5	16.5	0.4	0.084	0.091	0.101
		7	9	0.107	0.141	0.188	0.040	0.035	0.041	37.0	24.9	21.6	0.044	0.055	0.070
6	0.91	0	5	0.128	0.156	0.196	0.016	0.013	0.018	12.5	8.0	9.2	0.065	0.070	0.078
	1.36	0	10	0.140	0.160	0.189	0.047	0.046	0.051	33.5	28.5	27.2	0.077	0.074	0.071
	1.81	0	5	0.151	0.170	0.196	0.025	0.012	0.018	16.5	7.0	9.2	0.088	0.084	0.078
		7	4	0.111	0.139	0.176	0.039	0.059	0.087	35.0	42.7	49.3	0.048	0.053	0.058
7	0.91	0	7	0.087	0.104	0.126	0.046	0.033	0.054	52.4	31.7	42.8	0.024	0.018	0.008
	1.36	0	9	0.086	0.142	0.219	0.025	0.053	0.129	28.9	37.6	58.9	0.023	0.056	0.101
	1.81	0	6	0.100	0.129	0.170	0.007	0.015	0.027	7.0	11.3	16.2	0.037	0.043	0.052
		7	6	0.070	0.089	0.116	0.028	0.034	0.047	40.0	38.6	40.4	0.007	0.003	-0.002

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged

Table 7.8. Summary Table of *BBR m-value* Results for *Hwy 45* Mixture Beams (No Emulsion through Emulsion 4)

Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg *m-value*			Test Time (s) and St. Dev. of Avg *m-value*			Test Time (s) and COV of *m-value*			Test Time (s) and Δ*m-value*		
				8	**60**	**960**	**8**	**60**	**960**	**8**	**60**	**960**	**8**	**60**	**960**
NE	---	0	64	0.058	0.090	0.134	0.016	0.027	0.058	27.3	30.5	42.8	---	---	---
1	0.91	0	5	0.116	0.139	0.169	0.046	0.047	0.051	39.5	34.1	30.3	0.058	0.049	0.035
	1.36	0	7	0.132	0.165	0.211	0.045	0.042	0.039	34.5	25.4	18.5	0.074	0.075	0.077
	1.81	0	8	0.111	0.137	0.174	0.044	0.044	0.053	39.6	32.4	30.3	0.053	0.047	0.040
		7	7	0.151	0.181	0.222	0.015	0.012	0.025	9.8	6.5	11.4	0.093	0.091	0.088
2	0.91	0	7	0.134	0.151	0.174	0.015	0.012	0.019	11.5	7.7	10.9	0.076	0.061	0.040
	1.36	0	7	0.116	0.138	0.168	0.047	0.037	0.038	40.4	27.0	22.5	0.058	0.048	0.034
	1.81	0	8	0.130	0.156	0.192	0.027	0.025	0.043	21.1	15.9	22.5	0.072	0.066	0.058
		7	6	0.138	0.165	0.203	0.021	0.014	0.022	15.5	8.7	10.7	0.080	0.075	0.069
3	0.91	0	8	0.141	0.148	0.157	0.052	0.060	0.085	36.9	40.7	54.4	0.083	0.058	0.023
	1.36	0	7	0.130	0.149	0.176	0.072	0.086	0.106	55.4	57.4	60.4	0.072	0.059	0.042
	1.81	0	30	0.150	0.160	0.174	0.064	0.062	0.066	42.2	38.4	38.1	0.092	0.070	0.040
		3	30	0.123	0.142	0.168	0.056	0.056	0.065	46.0	39.7	38.6	0.065	0.052	0.034
		7	39	0.098	0.118	0.145	0.058	0.058	0.069	59.6	48.9	47.8	0.040	0.028	0.011
		14	30	0.142	0.158	0.180	0.125	0.098	0.076	87.9	61.9	42.2	0.084	0.068	0.046
		30	31	0.139	0.153	0.173	0.058	0.053	0.072	41.9	34.7	41.4	0.081	0.063	0.039
		45	30	0.144	0.161	0.186	0.080	0.043	0.070	55.6	26.7	37.6	0.086	0.071	0.052
		60	29	0.130	0.145	0.166	0.074	0.056	0.063	57.2	38.4	37.8	0.072	0.055	0.032
		90*	26	0.186	0.208	0.239	0.150	0.154	0.165	80.4	74.0	69.3	0.128	0.118	0.105
		182*	33	0.127	0.153	0.189	0.037	0.039	0.058	29.1	25.4	30.4	0.069	0.063	0.055
4	0.91	0	5	0.096	0.120	0.152	0.036	0.041	0.056	37.5	34.2	37.0	0.038	0.030	0.018
	1.36	0	5	0.100	0.136	0.184	0.029	0.047	0.074	28.5	34.4	40.0	0.042	0.046	0.050
	1.81	0	9	0.097	0.121	0.154	0.028	0.031	0.041	29.0	25.6	26.4	0.039	0.031	0.020
		7	5	0.100	0.126	0.162	0.022	0.020	0.031	22.4	15.8	19.2	0.042	0.036	0.028

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged except E3-R1.81-A90 and E3-R1.81-A182, which were field aged (*)

Table 7.9. Summary Table of *BBR m-value* Results for *Hwy 45* Mixture Beams (Emulsion 5 through 7)

Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg *m-value*			Test Time (s) and St. Dev. of Avg *m-value*			Test Time (s) and COV of *m-value*			Test Time (s) and Δ*m-value*		
				8	60	960	8	60	960	8	60	960	8	60	960
5	0.91	0	9	0.138	0.158	0.184	0.043	0.034	0.033	31.3	21.4	18.1	0.080	0.068	0.050
	1.36	0	9	0.146	0.149	0.154	0.047	0.058	0.085	32.2	38.6	55.1	0.088	0.059	0.020
	1.81	0	7	0.152	0.173	0.202	0.052	0.040	0.026	34.0	23.0	12.7	0.094	0.083	0.068
		7	6	0.151	0.167	0.189	0.024	0.023	0.022	16.2	13.7	11.8	0.093	0.077	0.055
6	0.91	0	7	0.136	0.163	0.200	0.019	0.035	0.062	13.7	21.5	31.0	0.078	0.073	0.066
	1.36	0	5	0.132	0.160	0.198	0.051	0.065	0.090	39.0	40.8	45.5	0.074	0.070	0.064
	1.81	0	9	0.150	0.168	0.192	0.041	0.042	0.051	27.0	25.1	26.7	0.092	0.078	0.058
		7	5	0.127	0.153	0.189	0.030	0.027	0.032	23.8	18.0	17.0	0.069	0.063	0.055
7	0.91	0	5	0.102	0.122	0.150	0.011	0.009	0.012	10.5	7.5	7.8	0.044	0.032	0.016
	1.36	0	5	0.109	0.147	0.199	0.022	0.024	0.031	20.1	16.5	15.6	0.051	0.057	0.065
	1.81	0	7	0.109	0.148	0.201	0.020	0.030	0.051	18.5	20.4	25.2	0.051	0.058	0.067
		7	6	0.100	0.141	0.197	0.022	0.022	0.036	21.9	15.3	18.1	0.042	0.051	0.063

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged

Table 7.10. Summary Table of *BBR m-value* Results for *Plant Mix* Mixture Beams

Emulsion	Rate (L/m^2)	Age (days)	*n*	Test Time (s) and Avg *m-value*			Test Time (s) and St. Dev. of Avg *m-value*			Test Time (s) and COV of *m-value*			Test Time (s) and Δ*m-value*		
				8	60	960	8	60	960	8	60	960	8	60	960
NE	---	0	27	0.103	0.160	0.238	0.021	0.031	0.065	20.1	19.7	27.4	---	---	---
		7	26	0.091	0.135	0.196	0.026	0.032	0.047	28.7	23.9	23.8	-0.012	-0.025	-0.042
		30	10	0.038	0.078	0.132	0.007	0.015	0.029	17.4	19.4	22.0	-0.065	-0.082	-0.106
		60	9	0.076	0.119	0.177	0.017	0.028	0.045	22.2	23.3	25.4	-0.027	-0.041	-0.061
3	1.81	0	30	0.157	0.211	0.285	0.033	0.027	0.039	21.2	12.6	13.8	0.054	0.051	0.047
		7	29	0.146	0.216	0.312	0.034	0.045	0.072	23.2	21.0	23.2	0.043	0.056	0.074
		30	27	0.130	0.177	0.241	0.031	0.031	0.073	23.8	17.4	30.5	0.027	0.017	0.003
		60	24	0.139	0.166	0.204	0.043	0.039	0.063	31.2	23.7	30.9	0.036	0.006	-0.034

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged

Table 7.11. Summary Table of *BBR* Stiffness Results for *FR* Mixture Beams

Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg Stiffness (Gpa)			Test Time (s) and St. Dev. of Avg Stiffness (Gpa)			Test Time (s) and COV of Stiffness			Test Time (s) and $S_{D(\%)}$		
				8	60	960	8	60	960	8	60	960	8	60	960
NE	---	0	65	5.68	4.85	3.60	2.06	1.72	1.23	36.3	35.4	34.2	---	---	---
1	0.91	0	8	6.79	5.46	3.80	1.58	1.54	1.65	23.3	28.2	43.3	-19.5	-12.6	-5.6
	1.36	0	5	5.94	4.60	2.86	0.58	0.66	0.94	9.8	14.4	32.8	-4.6	5.2	20.6
	1.81	0	8	6.26	4.77	3.05	2.05	1.46	0.94	32.8	30.6	30.8	-10.2	1.6	15.3
		7	8	8.52	6.83	4.99	1.20	1.21	1.37	14.1	17.7	27.4	-50.0	-40.8	-38.6
2	0.91	0	6	5.58	4.54	3.16	1.75	1.49	1.08	31.3	32.8	34.2	1.8	6.4	12.2
	1.36	0	8	5.76	4.66	3.32	1.91	1.76	1.62	33.2	37.7	48.9	-1.4	3.9	7.8
	1.81	0	12	6.72	5.16	3.37	1.29	1.08	0.89	19.3	21.0	26.5	-18.3	-6.4	6.4
		7	5	4.26	3.27	2.00	1.14	0.97	0.70	26.8	29.5	34.9	25.0	32.6	44.4
3	0.91	0	6	5.43	4.30	3.03	1.60	1.20	1.04	29.4	27.9	34.4	4.4	11.3	15.8
	1.36	0	7	6.30	4.74	2.97	1.04	0.92	0.80	16.5	19.5	27.0	-10.9	2.3	17.5
	1.81	0	5	4.56	3.34	1.92	1.35	1.07	0.66	29.6	32.0	34.4	19.7	31.1	46.7
		7	7	6.13	4.45	2.81	1.24	0.84	0.65	20.2	18.9	23.1	-7.9	8.2	21.9
4	0.91	0	8	8.15	6.75	4.85	2.45	2.09	1.88	30.0	31.0	38.8	-43.5	-39.2	-34.7
	1.36	0	9	5.13	4.05	2.57	1.66	1.18	0.70	32.4	29.1	27.3	9.7	16.5	28.6
	1.81	0	7	6.05	4.71	3.07	0.65	0.78	0.77	10.8	16.6	25.1	-6.5	2.9	14.7
		7	5	8.42	6.73	4.49	0.89	0.58	0.30	10.6	8.6	6.7	-48.2	-38.8	-24.7
5	0.91	0	8	5.04	3.74	2.40	1.90	1.86	1.58	37.7	49.7	65.8	11.3	22.9	33.3
	1.36	0	9	4.60	3.46	2.23	1.71	1.43	1.13	37.1	41.3	50.8	19.0	28.7	38.1
	1.81	0	4	5.31	3.88	2.26	1.11	1.01	0.65	21.0	26.2	28.7	6.5	20.0	37.2
		7	9	6.00	4.71	3.04	1.17	1.07	0.92	19.5	22.7	30.2	-5.6	2.9	15.6
6	0.91	0	5	6.65	5.00	3.08	2.07	1.59	1.01	31.1	31.8	32.8	-17.1	-3.1	14.4
	1.36	0	10	5.93	4.47	2.87	1.60	1.55	1.32	26.9	34.8	45.9	-4.4	7.8	20.3
	1.81	0	5	4.71	3.41	2.06	1.04	0.76	0.50	22.1	22.2	24.2	17.1	29.7	42.8
		7	4	6.33	5.01	3.44	2.11	1.93	1.88	33.3	38.5	54.7	-11.4	-3.3	4.4
7	0.91	0	7	5.23	4.28	3.00	2.68	2.15	1.35	51.2	50.2	45.1	7.9	11.8	16.7
	1.36	0	9	6.83	5.43	3.37	1.53	1.18	0.99	22.4	21.7	29.5	-20.2	-12.0	6.4
	1.81	0	6	6.09	4.85	3.23	1.01	0.87	0.71	16.6	18.0	22.2	-7.2	0.0	10.3
		7	6	6.60	5.56	4.11	2.57	2.05	1.35	39.0	37.0	32.9	-16.2	-14.6	-14.2

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged

Table 7.12. Summary Table of *BBR* Stiffness Results for *Hwy 45* Mixture Beams (No Emulsion through Emulsion 4)

Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg Stiffness (Gpa)			Test Time (s) and St. Dev. of Avg Stiffness (Gpa)			Test Time (s) and COV of Stiffness			Test Time (s) and $S_{D(\%)}$		
				8	60	960	8	60	960	8	60	960	8	60	960
NE	---	0	64	6.31	5.43	4.03	2.18	1.87	1.59	34.5	34.5	39.4	---	---	---
1	0.91	0	5	7.17	5.58	3.74	2.26	1.97	1.72	31.5	35.3	46.1	-13.6	-2.8	7.2
	1.36	0	7	6.63	4.99	3.04	2.13	1.81	1.31	32.1	36.3	43.2	-5.1	8.1	24.6
	1.81	0	8	5.41	4.19	2.73	1.63	1.21	0.83	30.2	28.8	30.3	14.3	22.8	32.3
		7	7	6.21	4.44	2.56	1.71	1.22	0.79	27.5	27.6	30.8	1.6	18.2	36.5
2	0.91	0	7	4.94	3.71	2.38	1.68	1.25	0.84	33.9	33.7	35.1	21.7	31.7	40.9
	1.36	0	7	6.37	4.95	3.24	2.48	1.94	1.26	39.0	39.3	38.9	-1.0	8.8	19.6
	1.81	0	8	5.48	4.10	2.52	1.58	1.14	0.62	28.8	27.9	24.8	13.2	24.5	37.5
		7	6	7.36	5.45	3.30	2.26	1.77	1.14	30.7	32.4	34.7	-16.6	-0.4	18.1
3	0.91	0	8	6.37	4.76	3.22	1.83	1.42	1.35	28.7	29.9	41.8	-1.0	12.3	20.1
	1.36	0	7	5.52	4.25	2.91	1.68	1.66	1.62	30.3	39.1	55.7	12.5	21.7	27.8
	1.81	0	30	5.98	4.49	2.99	2.28	2.00	1.62	38.0	44.6	54.2	5.2	17.3	25.8
		3	30	6.92	5.38	3.61	2.67	2.36	1.83	38.5	43.9	50.8	-9.7	0.9	10.4
		7	39	4.67	3.67	2.54	2.58	1.84	1.23	55.2	50.3	48.5	26.0	32.4	37.0
		14	30	5.85	4.34	2.76	2.22	1.81	1.30	37.9	41.8	47.1	7.3	20.1	31.5
		30	31	7.29	5.58	3.70	2.45	2.27	1.86	33.7	40.8	50.4	-15.5	-2.8	8.2
		45	30	5.84	4.36	2.77	1.89	1.65	1.26	32.4	38.0	45.4	7.4	19.7	31.3
		60	29	6.21	4.78	3.16	2.57	2.12	1.49	41.4	44.4	47.2	1.6	12.0	21.6
		90*	26	5.10	3.71	2.29	2.07	1.84	1.40	40.6	49.6	61.2	19.2	31.7	43.2
		182*	33	5.87	4.47	2.84	1.56	1.34	1.06	26.5	30.1	37.4	7.0	17.7	29.5
4	0.91	0	5	6.03	4.78	3.27	2.17	1.56	1.10	36.0	32.7	33.6	4.4	12.0	18.9
	1.36	0	5	7.06	5.58	3.65	0.63	0.61	0.82	8.9	11.0	22.5	-11.9	-2.8	9.4
	1.81	0	9	7.26	5.87	4.09	1.92	1.75	1.56	26.5	29.8	38.0	-15.1	-8.1	-1.5
		7	5	8.26	6.58	4.45	1.41	1.13	0.89	17.1	17.1	20.1	-30.9	-21.2	-10.4

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged except E3-R1.81-A90 and E3-R1.81-A182, which were field aged (*)

Table 7.13. Summary Table of *BBR* Stiffness Results for *Hwy 45* Mixture Beams (Emulsion 5 through 7)

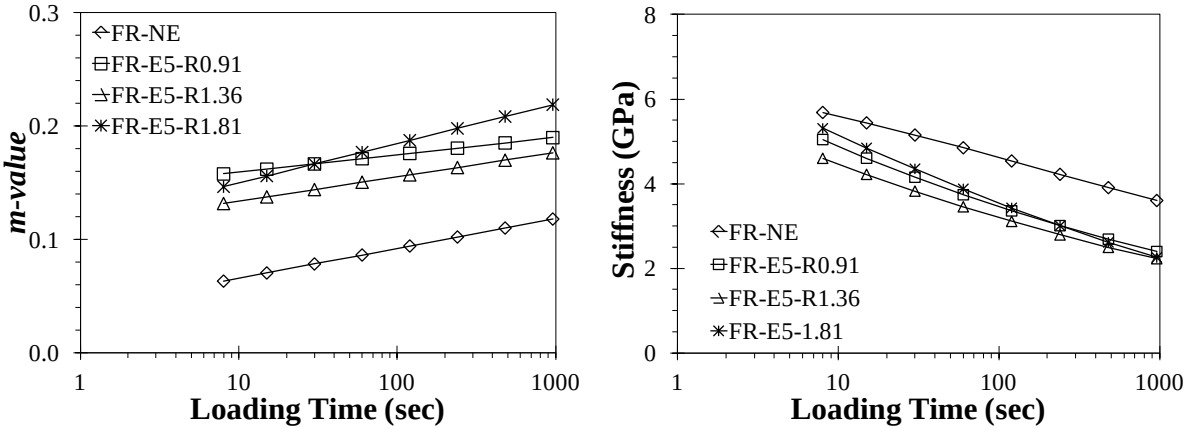
Emulsion	Rate (L/m^2)	Age (day)	*n*	Test Time (s) and Avg Stiffness (Gpa)			Test Time (s) and St. Dev. of Avg Stiffness (Gpa)			Test Time (s) and COV of Stiffness			Test Time (s) and $S_{D(\%)}$		
				8	60	960	8	60	960	8	60	960	8	60	960
5	0.91	0	9	5.98	4.53	2.88	2.60	2.23	1.56	43.5	49.2	54.1	5.2	16.6	28.5
	1.36	0	9	4.37	3.25	2.18	1.77	1.41	1.10	40.6	43.2	50.6	30.7	40.1	45.9
	1.81	0	7	7.44	5.43	3.29	1.78	1.66	1.27	24.0	30.6	38.7	-17.9	0.0	18.4
		7	6	5.28	3.87	2.39	1.58	1.30	0.95	29.9	33.7	39.6	16.3	28.7	40.7
6	0.91	0	7	5.66	4.22	2.63	0.97	0.92	0.91	17.1	21.9	34.6	10.3	22.3	34.7
	1.36	0	5	3.09	2.25	1.35	1.15	0.72	0.33	37.3	32.0	24.4	51.0	58.6	66.5
	1.81	0	9	4.56	3.29	2.00	1.19	0.89	0.61	26.0	27.1	30.5	27.7	39.4	50.4
		7	5	7.32	5.60	3.55	2.49	2.13	1.49	34.0	38.1	42.1	-16.0	-3.1	11.9
7	0.91	0	5	6.48	5.17	3.55	1.78	1.41	0.99	27.4	27.3	27.9	-2.7	4.8	11.9
	1.36	0	5	6.30	4.87	3.03	0.93	0.74	0.53	14.8	15.2	17.6	0.2	10.3	24.8
	1.81	0	7	5.82	4.52	2.83	1.10	0.96	0.78	18.9	21.3	27.6	7.8	16.8	29.8
		7	6	7.75	6.04	3.79	2.96	2.18	1.40	38.2	36.1	37.0	-22.8	-11.2	6.0

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged

Table 7.14. Summary Table of *BBR* Stiffness Results for *Plant Mix* Mixture Beams

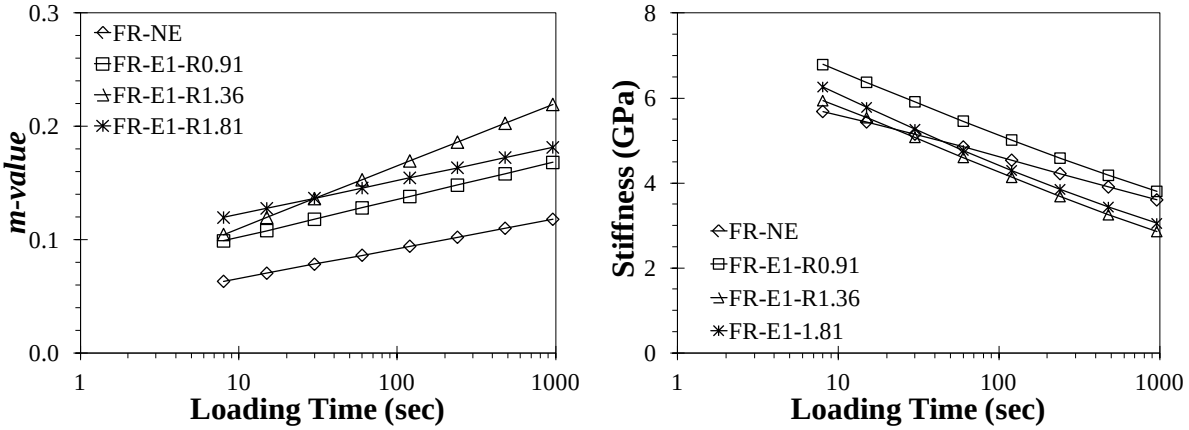
Emulsion	Rate (L/m^2)	Age (days)	*n*	Test Time (s) and Avg Stiffness (Gpa)			Test Time (s) and St. Dev. of Avg Stiffness (Gpa)			Test Time (s) and COV of Stiffness			Test Time (s) and $S_{D(\%)}$		
				8	60	960	8	60	960	8	60	960	8	60	960
NE	---	0	27	4.65	3.58	2.09	0.89	0.71	0.50	19.1	19.9	23.8	---	---	---
		7	26	4.71	3.71	2.30	1.31	0.94	0.47	27.8	25.4	20.4	-1.3	-3.6	-10.0
		30	10	2.48	2.21	1.65	0.29	0.26	0.22	11.9	11.7	13.1	46.7	38.3	21.1
		60	9	5.47	4.47	2.94	1.44	1.10	0.66	26.2	24.6	22.4	-17.6	-24.9	-40.7
3	1.81	0	30	4.59	3.19	1.62	1.01	0.78	0.45	22.0	24.5	27.6	1.3	10.9	22.5
		7	29	4.02	2.80	1.37	1.06	0.77	0.45	26.4	27.5	32.8	13.5	21.8	34.4
		30	27	4.94	3.64	2.07	1.43	1.10	0.76	28.8	30.3	36.4	-6.2	-1.7	1.0
		60	24	4.50	3.29	1.94	1.42	1.08	0.63	31.7	32.8	32.6	3.2	8.1	7.2

-- NE = no emulsion, or control data set -- All aged beams were 60 C laboratory aged



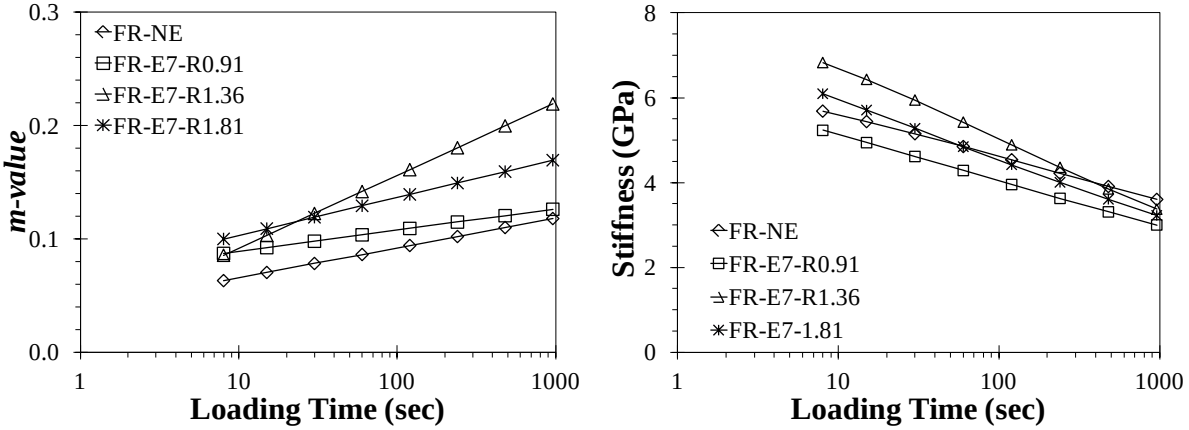
a) Emulsion 5 m-value (Category 1)

b) Emulsion 5 Stiffness (Category 1)



c) Emulsion 1 m-value (Category 2)

d) Emulsion 1 Stiffness (Category 2)



e) Emulsion 7 m-value (Category 3)

f) Emulsion 7 Stiffness (Category 3)

Figure 7.1. Example of Varying Amounts of Emulsion Rejuvenation on *m-value* and Stiffness

In the context of rejuvenating of existing asphalt surfaces, an emulsion should increase *m-value* and/or decrease stiffness as this would increase the pavement's susceptibility to distresses associated with aged pavements (e.g. raveling or cracking). A

precursory assessment of Figure 7.1 indicates that *m-value* appears to better distinguish between emulsions than stiffness for all levels of influence (Categories 1 through 3). The *m-value* term is the slope of the stiffness versus time curve at a given time. Conceptually, the *m-value* indicates a mixture's ability to change stiffness when stressed (i.e. its ability to dissipate stress). Furthermore, *m-value* can be thought of as a term that is independent of the actual numerical value of stiffness but instead is only dependent on the relative stiffness change over time. This aspect of the *m-value* term may make it better suited for specifying rejuvenation effects of an emulsion for all pavements as it would be less sensitive to the initial stiffness of the untreated pavement.

7.4 Overview of Analysis of Variance Testing

The statistical analysis performed in this report is based on methods from Ott and Longnecker (2010) using the statistical package SAS for most calculations. Analysis of variance tests (ANOVA) with factorial arrangements of treatments (FAT) are used in this chapter to statistically analyze the influence of factors such as emulsion, application rate, and emulsion aging on aged pavements. The response variable is the variable that is used to evaluate the performance of these treatments. In this chapter, the response variable is either Δ*m-value* or $S_{D(\%)}$, depending on the analysis. In this type of ANOVA, treatments are arranged factorially into treatment combinations where each level of each treatment occurs once and only once with all other levels of all other treatments. For example, a 7x3 FAT using 7 emulsions and 3 application rates implies that each of the 7 emulsions is used with all 3 application rates for a total of 21 treatment combinations.

With this arrangement of treatments, there exists a hierarchal system of testing that must be followed. First, the interaction between different treatments must be explored. For example, if increasing application rate increased Δ*m-value* (the response variable) for one emulsion but decreased Δ*m-value* with another emulsion, there would be interaction between emulsion and application rate (i.e. the effect of application rate was dependent on which emulsion is applied). If there is significant interaction, the hierarchal testing does not proceed further, but the influence of the emulsion and the influence of the application rate, for example, cannot be separated – they must be evaluated as a combination of emulsion and application rate. If there is not significant interaction, the hierarchal testing proceeds to testing the individual treatments, which is statistically desired. In the above example, if application rate and emulsion type did not interact significantly, they would be tested individually to determine whether either one or both significantly affected Δ*m-value*.

When a treatment or treatment combination (in the case of significant interaction) significantly affects the response variable, this only indicates that at least one pair of treatment levels significantly differs in its effect on the response variable. For instance, if the treatment application rate significantly affects Δ*m-value*, this could mean that 1.81 L/m^2 provides a significantly higher Δ*m-value* than both the 1.36 and 0.91 L/m^2 rates; however, the 1.36 L/m^2 rate may not provide a significantly different Δ*m-value* than the 0.91 L/m^2 rate.

In order to explore the ranking of significant treatments such as application rate, multiple comparisons analysis can be performed in which each level of the treatment is assigned a letter (*t*-group). Treatment levels with different letters indicate they are significantly different, while levels with identical letters indicate they are not significantly different. Chaining of treatment levels can also occur where a level may be assigned two or

more letters. For example, if a treatment level is assigned both letters *A* and *B*, that indicates that the *A* group and the *B* group are chained together. If a treatment has no significant effect on the response variable, N-S replaces the *t*-grouping letters to signify non-significance. Discussion of multiple comparisons and chaining is presented here to introduce the concept, which will be developed more throughout the chapter.

The multiple comparisons analyses in this chapter were performed in SAS using the LSMEANS statement in PROC GLM. This is a unique function capable of handling unbalanced replication as is present in the data set analyzed herein. This function computes approximated, corrected mean values for each treatment group based on its number of replicates. These corrected mean values are used in all tables and discussion in Sections 7.5 to 7.8. This is of little significance other than noting that Δ*m-values* and $S_{D(\%)}$ values in Sections 7.5 to 7.8 will not equate exactly to values presented in Tables 7.7 to 7.14. Values in Tables 7.7 to 7.14 are simple arithmetic calculations (i.e. the average *m-value* for an untreated mixture is subtracted from the average *m-value* for a given emulsion treated mixture to obtain Δ*m-value* for that mixture).

The following sections are laid out in similar formats. Analyses where Δ*m-value* is the response variable are always performed first, followed by $S_{D(\%)}$. Additionally, the research team felt that it may be necessary to evaluate the entire *m-value* or stiffness curve because a factor (e.g. emulsion or application rate) may not have the same effect at short loading times as it does at long loading times. This phenomenon can be observed in Figure 7.2. While *m-value* at all loading times consistently increased when 1.81 L/m^2 of E1 was applied to *FR* (pure translation), it did not when 1.36 L/m^2 was applied (translation and rotation). The slope of the *m-value* or stiffness curve is not incorporated into the analysis when evaluation is performed at only 60 seconds. Only evaluating 60-second data may be misleading in some cases as it cannot account for any rotation effects. Therefore, two classes of ANOVA tests are performed in the following order for comparison: 1) an analysis including all three test times and 2) an analysis including only the 60-second test time.

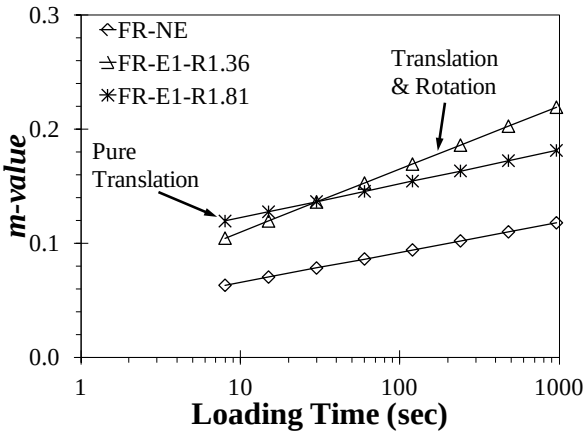


Figure 7.2. Example of Translation and Rotation of *BBR* Response Curves

7.5 Analysis of Un-Aged Emulsion Treated Field Mixtures

This section provides ANOVA results for all emulsion treated field mixtures that are 0-day aged in Tables 7.7 through 7.14. *FR* and *Hwy 45* are analyzed separately. When all three test times are considered, a 7x3x3 factorial arrangement of treatments is used where the

treatments are emulsion (7 levels), application rate (3 levels), and loading time (3 levels). When only the 60-second time is considered, a 7x3 factorial arrangement of treatments is used where the treatments are emulsion (7 levels) and application rate (3 levels). These results are presented in ANOVA summary tables. Following the ANOVA summary tables, treatment summary tables are provided where the levels of treatments or treatment combinations are ranked in order from best to worst measured response. If the treatment levels were significantly different, *t*-grouping letters are provided.

7.5.1 Analysis with Respect to Δ*m-value*

Table 7.15 provides ANOVA results for *FR* and *Hwy 45* Δ*m-value* for the full 8, 60, and 960-second analysis. There is no significant interaction among any of the treatments for either pavement; therefore, each treatment can be individually evaluated. For either pavement, at least two emulsion types are significantly different with respect to Δ*m-value*, which was expected. Application rate has a significant effect on Δ*m-value* for *FR* but not for *Hwy 45*. Loading time has no significant effect on Δ*m-value* for *FR* but does for *Hwy 45*. This indicates that the effect of emulsion application on *FR* is consistent regardless of loading time (i.e. no significant rotation occurs as demonstrated in Figure 7.2) but is not for *Hwy 45* (i.e. translation and rotation occur as demonstrated in Figure 7.2).

Table 7.16 provides ANOVA results for *FR* and *Hwy 45* Δ*m-value* for the 60-second analysis. There is no significant interaction between emulsion and application rate for either pavement as in Table 7.15. For *FR*, both emulsion and application rate significantly affect Δ*m-value*. For *Hwy 45*, neither emulsion nor application rate significantly affect Δ*m-value*. It was expected that the emulsion used would affect Δ*m-value* as it did in Table 7.15.

Table 7.15. ANOVA Summary for Un-Aged 8, 60, and 960-Second Δ*m-value*

	FR			***Hwy 45***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	455			509		
Emulsion x Rate x Time	24	0.9886	No	24	1.0000	No
Emulsion x Rate	12	0.0771	No	12	0.4370	No
Emulsion x Time	12	0.9453	No	12	0.7983	No
Rate x Time	4	0.4109	No	4	0.9184	No
Emulsion	6	<0.0001	Yes	6	0.0033	Yes
Rate	2	<0.0001	Yes	2	0.2578	No
Time	2	0.2132	No	2	0.0012	Yes
Error	393			447		

-- $p_{critical} = 0.05$

Table 7.16. ANOVA Summary for Un-Aged 60-Second Δ*m-value*

	FR			***Hwy 45***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	151			169		
Emulsion x Rate	12	0.7637	No	12	0.9777	No
Emulsion	6	0.0016	Yes	6	0.2223	No
Rate	2	0.0132	Yes	2	0.6304	No
Error	131			149		

-- $p_{critical} = 0.05$

Table 7.17 provides emulsion ranking with respect to un-aged mean Δ*m-values* for *FR* and *Hwy 45*. The emulsions are ranked similarly but not identically between pavements. Both the full analysis and the 60-second analysis rank the emulsions in the same order with only slightly different mean values for either pavement.

For *FR*, the full analysis and the 60-second analysis statistically group the emulsions slightly differently; however, there is a great deal of chaining for either analysis. For the full analysis, the *t*-grouping can be interpreted as either E5, E6, and E3 are significantly better than E2, E4, and E7 with respect to Δ*m-value*, E5, E6, E3, and E1 are significantly better than E2 and E7, or E5 and E6 are significantly better than E1, E2, E4, and E7. The chaining of E3 and E1 and also E1 and E4 adds complexity to the interpretation of the *t*-grouping results. The *t*-grouping for the 60-second analysis is similar. For *Hwy 45*, there are statistical differences in emulsion for the full analysis, but there are not for the 60-second analysis even though the mean values are nearly identical.

For both *FR* and *Hwy 45*, slight resolution within *t*-groups is lost when downsizing from the full analysis to the 60-second analysis. The ranking of emulsions is identical, but the clarity at which they are ranked is diminished. This is likely due to the fact that the full analysis accounts mostly for the entire test curve, whereas the 60-second analysis selects a single discrete value from the curve. In reference to the *Hwy 45* ranking of emulsions being non-significant for the 60-second analysis, it should be noted that the significant chaining within the full analysis indicates that emulsions were only barely significantly different (almost all emulsions were classified in the *A* group). When coupled with the loss of resolution occurring when downsizing to the 60-second analysis, it is not unreasonable that the emulsions become statistically indifferent. Given that the mean values range from 0.035 to 0.073, the emulsions appear practically different; they are likely not statistically different due to variation in results. As variability increases, statistically definitive conclusions become increasingly difficult to infer.

Table 7.17. Ranking of Emulsions With Respect to Un-Aged Δ*m-value*

FR					***Hwy 45***				
	8, 60, 960 Sec		**60 Sec**			**8, 60, 960 Sec**		**60 Sec**	
E	**Mean**	***t*-Group**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**Mean**	***t*-Group**
5	0.080	A	0.080	A	6	0.072	A	0.073	N-S
6	0.076	A	0.076	A	5	0.067	A	0.070	
3	0.065	AB	0.065	AB	3	0.060	AB	0.062	
1	0.057	BC	0.056	ABC	2	0.057	AB	0.058	
4	0.042	CD	0.041	BC	1	0.056	AB	0.057	
2	0.040	D	0.040	BC	7	0.049	BC	0.049	
7	0.040	D	0.039	C	4	0.035	C	0.035	

Table 7.18 provides ranking of application rate with respect to un-aged mean Δ*m-values* for *FR* and *Hwy 45*. Both the full analysis and the 60-second analysis rank the application rates similarly with approximately similar mean values for both pavements. Although the mean values are similar, application rate does not have a significant effect on *Hwy 45* Δ*m-value*. Application rate does have a significant effect on *FR* Δ*m-value*. Because *FR* and *Hwy 45* have almost identical mean values, it would be expected that, if application rate significantly affects *FR* Δ*m-value*, it would also significantly affect *Hwy 45* Δ*m-value*, which was not the case. This likely indicates greater variability with the *Hwy 45* data that

prevents statistical conclusions from being inferred; practically, however, it seems reasonable to conclude that different application rates likely yielded different Δ*m-values* for *Hwy 45*.

Table 7.18. Ranking of Application Rate With Respect to Un-Aged Δ*m-value*

FR					***Hwy 45***				
	8, 60, 960 Sec		**60 Sec**			**8, 60, 960 Sec**		**60 Sec**	
R	**Mean**	***t*-Group**	**Mean**	***t*-Group**	**R**	**Mean**	***t*-Group**	**Mean**	***t*-Group**
1.81	0.069	A	0.068	A	1.81	0.060	N-S	0.062	N-S
1.36	0.060	A	0.059	AB	1.36	0.058		0.059	
0.91	0.043	B	0.043	B	0.91	0.051		0.053	

Table 7.19 provides the un-aged mean Δ*m-values* for each loading time. For *FR*, the mean values for Δ*m-value* change with loading time but not significantly (total range of mean values is 0.011). For *Hwy 45*, the mean values for Δ*m-value* change significantly with loading time (total range of mean values is 0.022). The mean Δ*m-value* for *FR* is larger at the 960-second loading time (0.063) than it is at the 8-second loading time (0.052). It is of interest to note that the opposite is true of *Hwy 45*; the mean Δ*m-value* for *Hwy 45* is greatest at the 8-second loading time. Therefore, it can be concluded that 1) loading time has an insignificant effect on Δ*m-value* for *FR*, meaning insignificant rotation (refer to Figure 7.2 for example) occurs in the *m-value* curve due to emulsion treatment and 2) loading time has a significant effect on Δ*m-value* for *Hwy 45*, meaning significant rotation occurs in the *m-value* curve due to emulsion treatment.

The implications of rotation occurring in the *m-value* curve after emulsion treatment (as opposed to pure translation) are not fully understood. It does indicate that simply ranking emulsions based on 60-second Δ*m-value* may misrepresent the overall curve since a single discrete value cannot account for slope of the curve in any way. However, 60-second mean Δ*m-values* in Table 7.17 are nearly identical to those of the full analysis; therefore, it is likely that the error associated with ranking emulsions based only on a 60-second analysis is relatively small.

Table 7.19. Ranking of Loading Time With Respect to Un-Aged Δ*m-value*

FR			***Hwy 45***		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
960	0.063	NS	8	0.067	A
60	0.057		60	0.058	A
8	0.052		960	0.045	B

7.5.2 Analysis with Respect to $S_{D(\%)}$

Table 7.20 provides $S_{D(\%)}$ ANOVA results for *FR* and *Hwy 45* for the full 8, 60, and 960-second analysis. There is no significant three-way interaction for either pavement, but there is no two-way interaction between emulsion and loading time or application rate and loading time. However, there is significant interaction between emulsion and application rate for both pavements. Loading time is the only treatment that did not interact with any other treatment; therefore, it can be evaluated separately. Loading time has a significant effect on $S_{D(\%)}$ for either pavement, which indicates there is, on average, some rotation occurring as

demonstrated in the Figure 7.2 example. Emulsion and application rate significantly interact and must be considered as a pair, or a treatment combination, in the multiple comparisons analysis.

Table 7.20. ANOVA Summary for Un-Aged 8, 60, and 960-Second $S_{D(\%)}$

	FR			*Hwy 45*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	455			509		
Emulsion x Rate x Time	24	1.0000	No	24	1.0000	No
Emulsion x Rate	12	<0.0001	Yes	12	<0.0001	Yes
Emulsion x Time	12	0.9999	No	12	1.0000	No
Rate x Time	4	0.8836	No	4	0.9976	No
Emulsion	6	<0.0001	n/a	6	<0.0001	n/a
Rate	2	0.0028	n/a	2	0.1212	n/a
Time	2	<0.0001	Yes	2	<0.0001	Yes
Error	393			447		

-- $p_{critical} = 0.05$

Table 7.21 provides $S_{D(\%)}$ ANOVA results for *FR* and *Hwy 45* for the 60-second analysis. There is significant interaction between emulsion and application rate for *FR* but not for *Hwy 45*. For *FR*, emulsion and application rate must be evaluated as a pair, or a treatment combination, in the multiple comparisons analysis. For *Hwy 45*, the emulsion used significantly affected $S_{D(\%)}$ but the application rate did not. It is of interest to note that the interaction between emulsion and application rate became insignificant from the full analysis to the 60-second analysis which may indicate the need for representation of the entire curve for more meaningful results.

Table 7.21. ANOVA Summary for Un-Aged 60-Second $S_{D(\%)}$

	FR			*Hwy 45*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	151			169		
Emulsion x Rate	12	0.0269	Yes	12	0.1317	No
Emulsion	6	0.0143	n/a	6	0.0029	Yes
Rate	2	0.1585	n/a	2	0.5280	No
Error	131			149		

-- $p_{critical} = 0.05$

Table 7.22 provides ranking of emulsion and application rate treatment combinations with respect to mean $S_{D(\%)}$ for those cases in which emulsion and application rate significantly interact. For *FR*, the full analysis and the 60-second analysis rank treatment combinations in almost the same order. Treatment combinations rank differently for *Hwy 45*, but similar trends are observed. Generally, E3, E5, and E6 exhibit higher $S_{D(\%)}$, whereas E1, E4, and E7 exhibit lower $S_{D(\%)}$. Chaining in either analysis is quite significant, and while some statistical conclusions could be made, they would likely be too specific to be useful or applicable to materials outside those in this research. The key implication of Table 7.22 is that it supports the case for using *m-value* increase rather than stiffness reduction as the means by which emulsions are evaluated for rejuvenation. Both statistically and by casual observation, Δ*m-value* provides more distinguishable results than $S_{D(\%)}$.

Table 7.22. Ranking of Emulsion and Application Rate With Respect to Un-Aged $S_{D(\%)}$

FR				*FR*				*Hwy 45*			
8, 60, 960 Sec				**60 Sec**				**8, 60, 960 Sec**			
E	**R**	**Mean**	***t*-Group**	**E**	**R**	**Mean**	***t*-Group**	**E**	**R**	**Mean**	***t*-Group**
3	1.81	32.5	A	3	1.81	31.1	A	6	1.36	58.7	A
6	1.81	29.9	AB	6	1.81	29.7	A	6	1.81	39.1	B
5	1.36	28.7	AB	5	1.36	28.8	A	5	1.36	38.9	B
5	0.91	22.5	ABC	5	0.91	22.9	A	2	0.91	31.4	BC
5	1.81	21.3	ABCD	5	1.81	20.0	AB	2	1.81	25.0	BCD
4	1.36	18.3	ABCD	4	1.36	16.4	AB	1	1.81	23.0	BCDE
7	0.91	12.1	BCDE	7	0.91	11.7	AB	6	0.91	22.4	BCDE
3	0.91	10.6	BCDEF	3	0.91	11.4	AB	3	1.36	20.6	CDE
6	1.36	8.0	CDEF	6	1.36	7.9	AB	7	1.81	18.0	CDEF
1	1.36	7.1	CDEFG	2	0.91	6.3	AB	5	0.91	16.7	CDEF
2	0.91	6.8	CDEFG	1	1.36	5.1	AB	3	1.81	16.1	CDEF
4	1.81	3.8	DEFGH	2	1.36	3.9	AB	7	1.36	11.8	CDEFG
2	1.36	3.5	DEFGH	4	1.81	3.0	AB	4	0.91	11.8	CDEFG
3	1.36	3.0	DEFGH	3	1.36	2.3	AB	3	0.91	10.5	DEFG
1	1.81	2.3	DEFGH	1	1.81	1.7	AB	2	1.36	9.2	DEFG
7	1.81	1.1	DEFGH	7	1.81	0.1	AB	1	1.36	9.1	DEFG
6	0.91	-1.8	EFGH	6	0.91	-3.0	AB	7	0.91	4.7	EFGH
2	1.81	-6.0	FGH	2	1.81	-6.5	B	5	1.81	0.1	FGH
7	1.36	-8.5	GH	7	1.36	-11.9	BC	4	1.36	-1.8	FGH
1	0.91	-12.5	H	1	0.91	-12.5	BC	1	0.91	-3.1	GH
4	0.91	-39.0	I	4	0.91	-39.1	C	4	1.81	-8.3	H

Table 7.23 provides emulsion rankings for the *Hwy 45* 60-second analysis. Emulsions are ranked in a somewhat similar fashion to the general ranking of emulsions in Table 7.22 with E6, E2, and E5 providing the greatest mean $S_{D(\%)}$. Statistically, chaining again limits meaningful inferences regarding emulsion rank.

Table 7.23. Ranking of Emulsion With Respect to 60-Second Un-Aged $S_{D(\%)}$

Hwy 45		
E	**Mean**	***t*-Group**
6	40.0	A
2	21.7	B
5	18.9	B
3	17.0	BC
7	10.7	BC
1	9.3	BC
4	0.3	C

Table 7.24 provides ranking of application rate for the *Hwy 45* 60-second analysis. It is interesting to note that the 1.36 L/m^2 application rate provided the greatest mean $S_{D(\%)}$. The value of that observation is miniscule, however, as it was not a statistically significant outcome. Again, Tables 7.22 through 7.24 support the case for using Δm-*value* rather than $S_{D(\%)}$ as the means by which emulsions are evaluated for rejuvenation. Both statistically and by casual observation, Δm-*value* provides more distinguishable results than stiffness.

Table 7.24. Ranking of Application Rate With Respect to 60-Second Un-Aged $S_{D(\%)}$

Hwy 45		
R	**Mean**	***t*-Group**
1.36	20.7	N-S
1.81	16.1	
0.91	13.8	

Table 7.25 provides the mean $S_{D(\%)}$ values for each loading time. Each loading time is significantly different with respect to $S_{D(\%)}$ which means that there is not only translation occurring with emulsion treatment but also considerable rotation as well (as depicted in Figure 7.2). As previously stated in Section 7.5.1, the consequence of this occurrence may possibly, but not likely, lead to misleading conclusions if only the 60-second analysis is conducted.

Table 7.25. Ranking of Loading Time With Respect to Un-Aged $S_{D(\%)}$

FR			*Hwy 45*		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
960	17.5	A	960	27.2	A
60	6.1	B	60	16.9	B
8	-3.1	C	8	6.5	C

7.5.3 Summary of Analysis of Un-Aged Emulsion Treated Field Mixtures

For the *FR* and *Hwy 45* un-aged field mixtures, there are several overall findings. In terms of Δ*m-value*, E6, E5, and E3 were consistently ranked highest for both pavements with mean Δ*m-values* ranging from 0.060 to 0.080. Although these three emulsions did not necessarily perform statistically different than all other emulsions, they were all classified as group *A* in multiple comparisons analyses. E2, E4, and E7 generally ranked lowest (not necessarily statistically). It should be noted that the rejuvenation behavior of E1, which is the only non-modified CRS-2 material, generally ranked in the middle of the other six emulsions. This will be discussed further in Chapter 11 but is worth noting in this section. In terms of $S_{D(\%)}$, emulsions are much more difficult to classify as they often interact with the application rate making reliable analysis less feasible.

From this section's un-aged *BBR* testing, Δ*m-value* is recommended as the criteria by which an emulsion's rejuvenation potential is evaluated. Relative to the untreated control tests, *m-value* increases with emulsion application more than stiffness decreases; therefore, a greater range exists from no rejuvenation to maximum potential rejuvenation. This greater range in Δ*m-value* allows for more distinct differences to be observed between emulsions; whereas stiffness differences between emulsions were less distinguishable. Fundamentally, the *m-value* is independent of the initial pavement stiffness as it is only a measure of the time change in stiffness. In terms of developing a specification for chip seal emulsion performance, evaluating emulsions with respect to Δ*m-value* appears more universally applicable for pavements with a wide range of initial stiffnesses.

The 1.81 L/m^2 application rate provides the highest degree of rejuvenation as measured by Δ*m-value*. However, for *Hwy 45*, the application rates are not statistically different, and for *FR*, the 1.81 L/m^2 rate is statistically better than the 0.91 L/m^2 rate only. It is possible that the significance of application rate for *FR* and lack thereof for *Hwy 45* is due

to the higher permeability of *FR* (66×10^{-5} cm/sec) which could facilitate greater penetration of the emulsion into the pavement surface.

In the *FR* Δ*m-value* analysis, Δ*m-value* increases as loading time increases; however, the increases were not significant (i.e. insignificant rotation as depicted in Figure 7.2). *FR* Δ*m-value* follows the expected trend in which the emulsion would have a greater influence as the *BBR* beam is loaded for a longer period. *Hwy 45* does not follow this trend, rather the opposite is observed. In this discussion, care should be taken to differentiate between *m-value* and Δ*m-value*. All mixtures tested demonstrate an increase in *m-value* with loading time. However, relative to the untreated control, emulsion treated *FR m-value* increases with loading time at a greater rate, meaning Δ*m-value* is not constant increases with loading time. When *Hwy 45* Δ*m-value* decreases with loading time, *m-value* is still increasing but at a slower rate relative to the untreated control.

Whether rotation of the *m-value* curve contributes to emulsion rejuvenating performance is not known at this time. There are perhaps interactions of greater complexity between emulsion and aged binder that lead to different Δ*m-values* at different loading times. It is interesting to note that, despite the loss of resolution in terms of *t*-grouping when shifting from the full analysis to the 60-second analysis, the emulsions are still ranked identically with similar mean Δ*m-values*. Considering the emulsions tested in this report were selected to represent the range of emulsions available in Mississippi, it is plausible to suggest that, for typical Mississippi emulsions, the ranking from 60-second Δ*m-values* provides sufficient results relative to the full analysis even though it may not be as statistically definitive. Additionally, given the current lack of understanding of emulsion and aged binder interaction, evaluating emulsions at the 60-second loading time would be most logical at present as it is heavily documented and is the most widely used time in *BBR* testing. Additional potential implications of the finding that Δ*m-value* is not constant with loading time are beyond the scope of this research but could be an avenue for further research.

7.6 Analysis of 7-Day Aged Emulsion Treated Field Mixtures

This section provides ANOVA results for all field mixtures treated with 1.81 L/m^2 of emulsion and aged seven days in an oven (located in Tables 7.7 to 7.9 and 7.11 to 7.13). *FR* and *Hwy 45* are analyzed separately. When all three test times are considered, a 7x3 factorial arrangement of treatments is used where the treatments are emulsion (7 levels) and loading time (3 levels). When only the 60-second time is considered, the only treatment is emulsion (7 levels). Results are presented in ANOVA summary tables, followed by treatment summary tables where treatment levels or treatment combinations are ranked in order from best to worst measured response. If the treatment levels were significantly different, *t*-grouping letters are provided to distinguish significance from non-significance.

7.6.1 Analysis with Respect to Δ*m-value*

Table 7.26 provides ANOVA results for 7-day aged *FR* and *Hwy 45* Δ*m-value* for the full 8, 60, and 960-second analysis. Note that Δ*m-value* is relative to the untreated control *m-value* just as when un-aged specimens were analyzed. There is no significant interaction between emulsion and loading time for either pavement; therefore, each treatment can be individually evaluated. For either pavement, at least two emulsion types are significantly

different with respect to Δ*m-value*, which is largely to be expected. Loading time has no significant effect on Δ*m-value* for either pavement. This indicates the effect of emulsion application is consistent regardless of loading time (i.e. no significant rotation). Table 7.27 provides ANOVA results for 7-day aged *FR* and *Hwy 45* Δ*m-value* for the 60-second analysis. The emulsion used has a significant effect on 7-day aged Δ*m-value*.

Table 7.26. ANOVA Summary for 7-Day Aged 8, 60, and 960-Second Δ*m-value*

	FR			***Hwy 45***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	131			221		
Emulsion x Time	12	0.5304	No	12	0.9889	No
Emulsion	6	<0.0001	Yes	6	<0.0001	Yes
Time	2	0.9868	No	2	0.4499	No
Error	111			201		

-- $p_{critical} = 0.05$

Table 7.27. ANOVA Summary for 7-Day Aged 60-Second Δ*m-value*

	FR			***Hwy 45***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	43			73		
Emulsion	6	0.0195	Yes	6	0.0070	Yes
Error	37			67		

-- $p_{critical} = 0.05$

Table 7.28 provides the mean 7-day aged Δ*m-value* for each emulsion. The amount of chaining limits the statistical merit of the rankings. When interpreting Table 7.28, it should be noted that *Hwy 45* values for E1 and E3 are questionable. No specific problems were identified, but the behavior of these two emulsions does not generally align with the overall data set presented in this report.

Table 7.28. Ranking of Emulsions With Respect to 7-Day Aged Δ*m-value*

FR					***Hwy 45***				
	8, 60, 960 Sec		**60 Sec**			**8, 60, 960 Sec**		**60 Sec**	
E	**Mean**	***t*-Group**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**Mean**	***t*-Group**
3	0.075	A	0.076	A	1	0.090	A	0.090	A
2	0.069	AB	0.067	AB	5	0.075	AB	0.077	AB
5	0.056	AB	0.055	AB	2	0.074	AB	0.075	AB
6	0.053	ABC	0.052	AB	6	0.062	ABC	0.063	ABC
4	0.040	BC	0.039	ABC	7	0.052	BC	0.051	ABC
1	0.027	CD	0.029	BC	4	0.035	CD	0.036	BC
7	0.002	D	0.003	C	3	0.026	D	0.027	C

For *FR*, E3, E5, and E6 remain in the upper half of the ranking relative to un-aged emulsion treated *FR* Δ*m-value*. Additionally, E2 exhibits a more desirable response after aging. For *Hwy 45*, E3 ranks lowest after aging, but E1 and E2 both move up considerably in the ranking. The value of these *Hwy 45* observations is minimal absent additional investigation. All other emulsions rank relatively similarly to the un-aged emulsions.

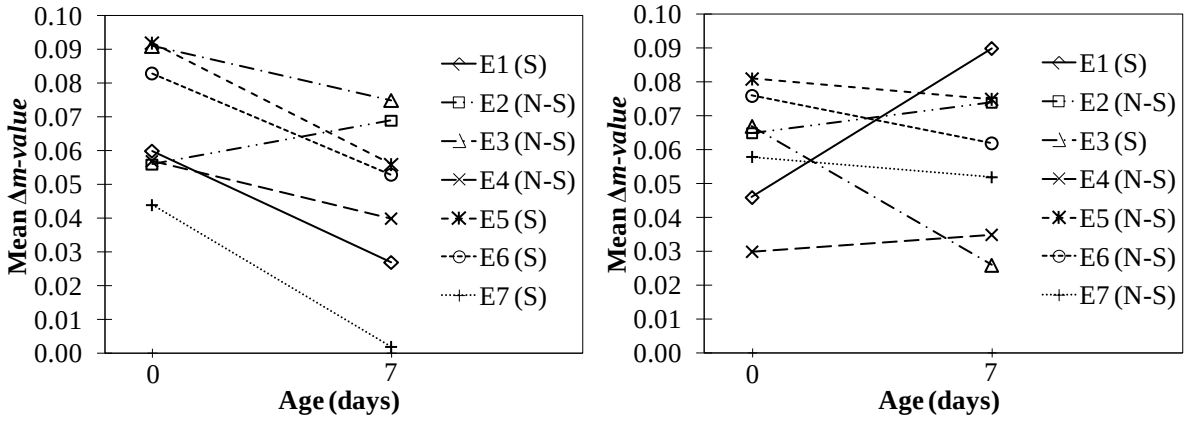
Table 7.29 provides the mean 7-day aged Δ*m-value* for each loading time. The trends observed and the overall ranges of mean Δ*m-value* are similar to that of the un-aged Δ*m-*

value analysis. On average, emulsions have a greater effect on *FR m-value* at longer loading times than at shorter loading times, and vice versa for *Hwy 45*. These observations, however, are not statistically significant, which is likely due to an increase in variability since the range of mean Δ*m-values* did not change meaningfully.

Table 7.29. Ranking of Loading Time With Respect to 7-Day Aged Δ*m-value*

FR			***Hwy 45***		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
960	0.047	N-S	8	0.065	N-S
60	0.046		60	0.060	
8	0.045		960	0.052	

In order to compare un-aged emulsion behavior to 7-day aged emulsion behavior, an additional ANOVA was performed using a 7x3x2 factorial arrangement of treatments where treatments were emulsion (7 levels), loading time (3 levels), and age (2 levels, un-aged and 7-day aged). ANOVA results are not shown for brevity, but interaction between emulsion and age was significant at a 0.05 significance level. Figure 7.3 provides the interaction plot for the full 8, 60, and 960-second analysis for each pavement. The symbols (S) and (N-S) are used to denote significant changes in Δ*m-value* from 0-day to 7-day aging. Generally, Δ*m-value* decreases after 7 days of 60 C oven aging with some exceptions. For *FR*, E2 Δ*m-value* increases after aging although not significantly. For *Hwy 45*, E1 increases significantly while E2 and E4 increase insignificantly. With respect to Δ*m-value*, it appears that some emulsions improve, some worsen, and some are relatively unaffected by aging.



a) FR *b) Hwy 45*

Figure 7.3. Comparison of Un-Aged and 7-Day Aged Δ*m-values* by Emulsion

7.6.2 Analysis with Respect to $S_{D(\%)}$

Table 7.30 provides $S_{D(\%)}$ ANOVA results for 7-day aged *FR* and *Hwy 45* for the full 8, 60, and 960-second analysis. There is no significant interaction between emulsion and loading time for either pavement; therefore, each treatment can be individually evaluated. For either pavement, at least two emulsion types are significantly different with respect to $S_{D(\%)}$, which was expected. Loading time significantly affected $S_{D(\%)}$ for both pavements. This indicates effect of emulsion application is not consistent with loading time (i.e.

significant rotation occurs). Table 7.31 provides $S_{D(\%)}$ ANOVA results for 7-day aged *FR* and *Hwy 45* for the 60-second analysis. The emulsion used has a significant effect on 7-day aged $S_{D(\%)}$.

Table 7.30. ANOVA Summary for 7-Day Aged 8, 60, and 960-Second $S_{D(\%)}$

	FR			*Hwy 45*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	131			221		
Emulsion x Time	12	0.9990	No	12	0.9944	No
Emulsion	6	<0.0001	Yes	6	<0.0001	Yes
Time	2	0.0193	Yes	2	0.0013	Yes
Error	111			201		

-- $p_{critical} = 0.05$

Table 7.31. ANOVA Summary for 7-Day Aged 60-Second $S_{D(\%)}$

	FR			*Hwy 45*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	43			73		
Emulsion	6	0.0002	Yes	6	0.0015	Yes
Error	37			67		

-- $p_{critical} = 0.05$

Table 7.32 provides the mean 7-day aged $S_{D(\%)}$ for each emulsion. For the *FR* full analysis, E2; E3, E5, and E6 generally exhibit higher $S_{D(\%)}$ which is consistent with Δ*m-value* rankings in Table 7.28. Although not as statistically definitive, results are also similar for the *FR* 60-second analysis. For *Hwy 45*, E3, E5, and E6 still rank higher than E7 and E4, but E1 and E2 improve with respect to $S_{D(\%)}$ after aging (recall the questionable nature of E1 and E3). Considerable chaining is present which limits the number of statistical observations that can be made.

Table 7.32. Ranking of Emulsions With Respect to 7-Day Aged $S_{D(\%)}$

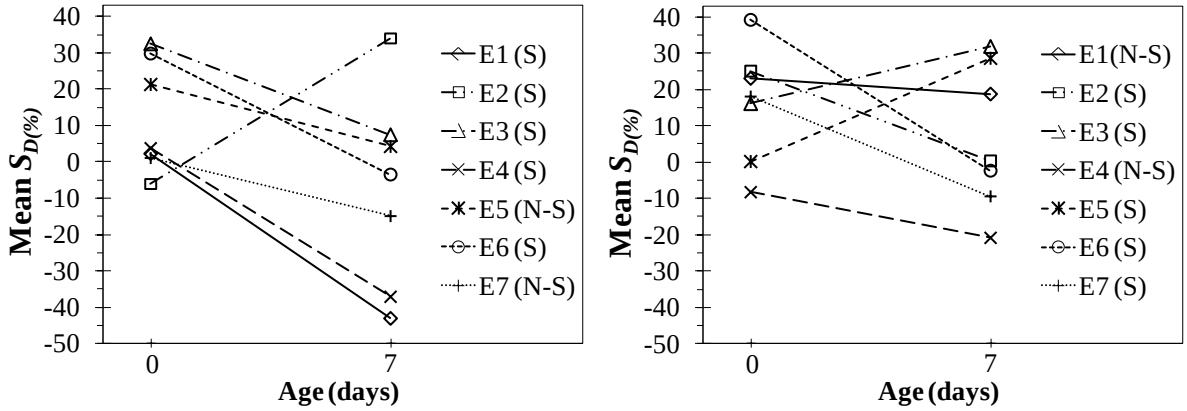
FR						***Hwy 45***					
8, 60, 960 Sec			**60 Sec**			**8, 60, 960 Sec**			**60 Sec**		
E	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**
2	34.0	A	2	32.6	A	3	31.8	A	3	32.4	A
3	7.5	B	3	8.3	AB	5	28.6	A	5	28.8	AB
5	4.3	B	5	2.9	AB	1	18.7	AB	1	18.2	ABC
6	-3.4	BC	6	-3.4	BC	2	0.3	BC	2	-0.5	BCD
7	-14.9	C	7	-14.6	BCD	6	-2.4	BC	6	-3.1	BCD
4	-37.1	D	4	-38.7	CD	7	-9.4	C	7	-11.2	CD
1	-43.0	D	1	-40.9	D	4	-20.9	C	4	-21.2	D

Table 7.33 provides the mean 7-day aged $S_{D(\%)}$ for each loading time. The trends observed and the overall ranges of mean $S_{D(\%)}$ are similar to that of the un-aged $S_{D(\%)}$ analysis. On average, emulsions have a greater effect on stiffness at longer loading times than at shorter loading times for both pavements.

Table 7.33. Ranking of Loading Time With Respect to 7-Day Aged $S_{D(\%)}$

FR			*Hwy 45*		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
960	1.4	A	960	19.9	A
60	-7.7	AB	60	6.2	AB
8	-16.2	B	8	-6.1	B

In order to compare un-aged emulsion behavior to 7-day aged emulsion behavior, an additional ANOVA was performed using a 7x3x2 factorial arrangement of treatments where treatments were emulsion (7 levels), loading time (3 levels), and age (2 levels, un-aged and 7-day aged). ANOVA results are not shown for brevity, but interaction between emulsion and age was significant at a 0.05 significance level. Figure 7.3 provides the interaction plot for the full 8, 60, and 960-second analysis for each pavement. Generally, $S_{D(\%)}$ decreases after aging with some exceptions. For *FR*, E2 $S_{D(\%)}$ increases significantly after aging. For *Hwy 45*, E2 increases significantly while E4 increase insignificantly. With respect to $S_{D(\%)}$, it appears that some emulsions improve, some worsen, and some are relatively unaffected by 7days of 60 C oven aging.



a) FR *b) Hwy 45*

Figure 7.4. Comparison of Un-Aged and 7-Day Aged $S_{D(\%)}$ by Emulsion

7.6.3 Summary of 7-Day Aged Emulsion Treated Field Mixtures

When 7-day aging was introduced, Δ*m-value* results become rather erratic relative to the un-aged analysis. Generally, E3, E5, and E6 exhibit the most desirable response with no aging. For *FR*, E2, E3, E5, and E6 exhibit the most desirable response after 7 days of laboratory aging, and for *Hwy 45*, E1, E2, E5, and E6 exhibit the most desirable response after 7-day aging (recall the questionable nature of E1 and E3). After 7-day aging of *FR*, E1 moved from an average performer to one of the least desirable performers while E3 remained one of the most desirable performers. For *Hwy 45*, 7-day aging produced the opposite result. E1 moved from a least desirable performer to a most desirable performer, and E3 moved from one of the most desirable performers to the least desirable. Overall, 7-day aging resulted in lower Δ*m-values* for most emulsions. Similarly, 7-day aging generally resulted in lower overall $S_{D(\%)}$ values as well.

In general, 7-day laboratory aging had negative effects on *m-value* and stiffness relative to no aging. It was proposed that the aging could positively influence *m-value* and stiffness as the prolonged time at elevated temperature might facilitate positive interaction of the emulsion and aged binders. The results of this section indicate that the aging period stiffened the emulsion treated pavement more than it was softened by the emulsion so that the net result was a decrease in rejuvenation.

7.7 Analysis of Extended-Term Laboratory and Field Aged Emulsion Treated Mixes

This section provides ANOVA results for *Hwy 45* treated with 1.81 L/m^2 of E3. These specimens were subjected to extended-term aging in the laboratory and field (Tables 7.8 and 7.12). Field and laboratory aged specimens are analyzed separately. When all three test times are considered, a 3x3 or 7x3 factorial arrangement of treatments is used where the treatments are age (3 levels for field aging and 7 levels for laboratory aging) and loading time (3 levels). When only the 60-second time is considered, age (3 levels for field aging and 7 levels for laboratory aging) is the only treatment. These results are presented in ANOVA summary tables. Following the ANOVA summary tables, treatment summary tables are provided where the levels of treatments or treatment combinations are ranked in order from most desirable to least desirable behavior. If the treatment levels were significantly different, *t*-grouping letters are provided to distinguish significance from non-significance.

7.7.1 Analysis with Respect to Δ*m-value*

Table 7.34 provides ANOVA results for extended-term *Hwy 45* Δ*m-value* for the full 8, 60, and 960-second analysis. Age and loading time do not significantly interact. At least two aging times are significantly different with respect to Δ*m-value* for either aging protocol. Loading time is not significant for field aged *Hwy 45* but is for laboratory aged *Hwy 45*. Table 7.35 provides ANOVA results for extended-term *Hwy 45* Δ*m-value* for the 60-second analysis. Aging time does not significantly affect Δ*m-value* for the field aged *Hwy 45* but it does for the laboratory aged *Hwy 45*.

Table 7.34. ANOVA Summary for Extended-Term Aged 8, 60, and 960-Second Δ*m-value*

	Field Aged			***Laboratory Aged***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	266			653		
Age x Time	4	0.8507	No	12	0.9537	No
Age	2	0.0004	Yes	6	0.0143	Yes
Time	2	0.1149	No	2	<0.0001	Yes
Error	258			633		

-- $p_{critical} = 0.05$

Table 7.35. ANOVA Summary for Extended-Term Aged 60-Second Δ*m-value*

	Field Aged			***Laboratory Aged***		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	88			217		
Age	2	0.0629	No	6	0.0482	Yes
Error	86			211		

-- $p_{critical} = 0.05$

Table 7.36 provides ranking of aging times with respect to mean Δ*m-value* for field aged *Hwy 45*. Un-aged, Δ*m-value* equals 0.067. At 90 days of field aging, Δ*m-value* significantly increases to 0.117. After 182 days of field aging, Δ*m-value* significantly decreases to 0.062, which is not significantly different from the un-aged Δ*m-value*. The 60-second analysis does not significantly distinguish between the aging times because of the resolution lost, but it does result in similar mean Δ*m-values*.

Table 7.36. Ranking of Aging With Respect to Extended-Term Field Aged Δ*m-value*

	8, 60, 960 Sec		**60 Sec**	
Age	**Mean**	***t*-Group**	**Mean**	***t*-Group**
90	0.117	A	0.118	N-S
0	0.067	B	0.070	
182	0.062	B	0.063	

Table 7.37 provides ranking of aging times with respect to laboratory aged *Hwy 45* Δ*m-value*. The full 8, 60, and 960-second analysis and the 60-second analysis do not rank the aging times consistently. For either analysis, there does not appear to be any trend that progresses from 0-day aging to 60-day aging, rather results are sporadically dispersed.

Table 7.37. Ranking of Aging With Respect to Extended-Term Laboratory Aged Δ*m-value*

8, 60, 960 Sec			**60 Sec**		
Age	**Mean**	***t*-Group**	**Age**	**Mean**	***t*-Group**
45	0.085	A	45	0.071	A
60	0.069	AB	0	0.070	A
0	0.067	AB	14	0.068	A
14	0.066	AB	30	0.063	A
30	0.061	AB	60	0.055	AB
3	0.050	BC	3	0.051	AB
7	0.026	C	7	0.027	B

Table 7.38 provides the mean Δ*m-value* for each loading time. For field aged *Hwy 45*, loading times are not significantly different, but they do result in mean Δ*m-values* that are relatively widely spaced. Although no significant rotation occurs as depicted in Figure 7.2, considerable rotation appears to occur from a practical perspective. For laboratory aged *Hwy 45*, mean Δ*m-value* is significantly greater at short loading times than at long loading times. The differences in Δ*m-value* with each loading time increment for Table 7.38 are the most significant observed of any loading time tables in this chapter. This may contribute to the vast differences observed between the full analysis and the 60-second analysis in Table 7.37.

Table 7.38. Ranking of Loading Time With Respect to Extended-Term *Hwy 45* Δ*m-value*

Field Aged			***Laboratory Aged***		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
8	0.096	N-S	8	0.087	A
60	0.084		60	0.058	B
960	0.066		960	0.036	C

7.7.2 Analysis with Respect to $S_{D(\%)}$

Table 7.39 provides $S_{D(\%)}$ ANOVA results for extended-term aged *Hwy 45* for the full 8, 60, and 960-second analysis. Age and loading time do not significantly interact. At least two aging times are significantly different with respect to $S_{D(\%)}$ for either aging protocol. Loading time is also significant for either aging protocol. Table 7.40 provides ANOVA results for long-term *Hwy 45* $S_{D(\%)}$ for the 60-second analysis. Aging time does not significantly affect $S_{D(\%)}$ for field aged *Hwy 45* but it does for laboratory aged *Hwy 45*.

Table 7.39. ANOVA Summary for Extended-Term Aged 8, 60, and 960-Second $S_{D(\%)}$

	Field Aged			*Laboratory Aged*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	266			653		
Age x Time	4	0.9981	No	12	0.9998	No
Age	2	0.0051	Yes	6	<0.0001	Yes
Time	2	<0.0001	Yes	2	<0.0001	Yes
Error	258			633		

-- $p_{critical} = 0.05$

Table 7.40. ANOVA Summary for Extended-Term Aged 60-Second $S_{D(\%)}$

	Field Aged			*Laboratory Aged*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	88			217		
Age	2	0.1709	No	6	0.0020	Yes
Error	86			211		

-- $p_{critical} = 0.05$

Table 7.41 provides ranking of aging times with respect to field aged *Hwy 45* $S_{D(\%)}$. Un-aged, $S_{D(\%)}$ equals 16.1. At 90 days of field aging, $S_{D(\%)}$ significantly increases to 31.3. After 182 days of field aging, $S_{D(\%)}$ significantly decreases to 18.0, which is not significantly different from the un-aged $S_{D(\%)}$. The 60-second analysis does not significantly distinguish between the aging times but results in similar mean $S_{D(\%)}$ values.

Table 7.41. Ranking of Aging With Respect to Extended-Term Field Aged $S_{D(\%)}$

	8, 60, 960 Sec		**60 Sec**	
Age	**Mean**	***t*-Group**	**Mean**	***t*-Group**
90	31.3	A	31.6	NS
182	18.0	B	17.7	
0	16.1	B	17.2	

Table 7.42 provides ranking of aging times with respect to laboratory aged *Hwy 45* $S_{D(\%)}$. Both the full analysis and the 60-second analysis rank aging times identically with similar mean $S_{D(\%)}$ values. For either analysis, there does not appear to be any trend that progresses from no aging to 60-day aging, rather results are sporadically dispersed.

Table 7.43 provides the mean $S_{D(\%)}$ for each loading time. For either aging protocol, mean $S_{D(\%)}$ is significantly greater at long loading times than at short loading times (i.e. significant rotation).

Table 7.42. Ranking of Aging With Respect to Extended-Term Laboratory Aged $S_{D(\%)}$

	8, 60, 960 Sec		60 Sec	
Age	**Mean**	***t*-Group**	**Mean**	***t*-Group**
7	31.8	A	32.4	A
45	19.5	B	19.8	AB
14	18.7	B	19.3	AB
0	16.1	B	17.2	AB
60	11.7	BC	11.9	BC
3	0.6	CD	0.9	BC
30	-3.9	D	-3.6	C

Table 7.43. Ranking of Loading Time With Respect to Extended-Term Aged $S_{D(\%)}$

Field Aged			***Laboratory Aged***		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
960	32.8	A	960	23.5	A
60	22.2	B	60	14.0	B
8	10.4	C	8	3.0	C

7.7.3 Summary of Long-Term Aged Emulsion Treated Mixtures

Section 7.6 (7 day oven aging) seems to indicate that rejuvenation performance of emulsion treated mixtures decreases after aging. Data presented in Section 7.7 (a variety of aging conditions) sometimes suggests otherwise. The 90-day and 182-day field aged mixtures indicate that Δ*m-value* and $S_{D(\%)}$ increase with age in the field up to some threshold and then decrease. The laboratory aging times presented do not mimic field aging with respect to Δ*m-value*. The maximum Δ*m-value* attained in the laboratory is the 45-day aging value of 0.085; whereas, the 90-day field aging Δ*m-value* is 0.117. The maximum $S_{D(\%)}$ value attained by laboratory aging is the 7-day aging value of 31.8% which is similar to the 90-day field aging value of 31.3%. Although the $S_{D(\%)}$ values are similar, $S_{D(\%)}$ has shown that it may not be the most reliable means of evaluation. Overall, this data indicates field aging of emulsion treated mixtures was not accurately simulated in a laboratory oven as per the protocols in this report.

7.8 Effects of Emulsion Application and Aging on Plant Mixed Asphalt

This section provides ANOVA results for *Plant Mix* laboratory aged mixtures that contain no emulsion and additional mixtures that are treated with 1.81 L/m^2 of E3. Test results are located in Tables 7.10 and 7.14. Untreated *Plant Mix* and emulsion treated *Plant Mix* are analyzed separately. When all three test times are considered, a 3x3 or 4x3 factorial arrangement of treatments is used where the treatments are age (3 levels for untreated *Plant Mix* and 4 levels for emulsion treated *Plant Mix*) and loading time (3 levels). When only the 60-second time is considered, age (3 levels for untreated *Plant Mix* and 4 levels for emulsion treated *Plant Mix*) is the only treatment. These results are presented in ANOVA summary tables. Following the ANOVA summary tables, treatment summary tables are provided where the levels of treatments or treatment combinations are ranked in order from most desirable to least desirable behavior. If the treatment levels were significantly different, *t*-grouping letters are provided to distinguish significance from non-significance.

7.8.1 Analysis with Respect to Δ*m-value*

Table 7.44 provides ANOVA results for *Plant Mix* Δ*m-value* for the full 8, 60, and 960-second analysis. For untreated (i.e. no emulsion applied) *Plant Mix*, age (i.e. time in a 60 C oven) and loading time do not significantly interact. At least two aging times and two loading times are significantly different with respect to Δ*m-value*. For emulsion treated *Plant Mix*, age and loading time significantly interact and must be evaluated as a treatment combination. Table 7.45 provides ANOVA results for *Plant Mix* Δ*m-value* for the 60-second analysis. Age significantly affects Δ*m-value* for untreated and emulsion treated *Plant Mix*.

Table 7.44. ANOVA Summary for *Plant Mix* 8, 60, and 960-Second Δ*m-value*

	Untreated			*Emulsion Treated*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	134			329		
Age x Time	4	0.9806	No	6	<0.0001	Yes
Age	2	<0.0001	Yes	3	<0.0001	n/a
Time	2	<0.0001	Yes	2	0.0327	n/a
Error	126			318		

-- $p_{critical} = 0.05$

Table 7.45. ANOVA Summary for *Plant Mix* 60-Second Δ*m-value*

	Untreated			*Emulsion Treated*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	44			109		
Age	2	<0.0001	Yes	3	<0.0001	Yes
Error	42			106		

-- $p_{critical} = 0.05$

Table 7.46 provides ranking of age treatments with respect to mean Δ*m-value* for untreated laboratory aged *Plant Mix*. Both the full analysis and the 60-second analysis rank the aging times identically with slightly differing mean Δ*m-values*. Aging of untreated *Plant Mix* results in a decrease in *m-value* for all aging times which is reasonable. It is expected that *Plant Mix* asphalt would exhibit considerable stiffening during aging given that it has not undergone considerable aging previously. It would not be expected, however, that the 30-day aging lends to more *m-value* decrease than the 60-day aging.

Table 7.46. Ranking of Aging With Respect to Untreated *Plant Mix* Δ*m-value*

	8, 60, 960 Sec		**60 Sec**	
Age	**Mean**	***t*-Group**	**Mean**	***t*-Group**
7	-0.026	A	-0.025	A
60	-0.043	B	-0.041	A
30	-0.084	C	-0.082	B

Table 7.47 provides mean Δ*m-values* for untreated laboratory aged *Plant Mix* at each loading time. Mean Δ*m-value* is significantly smaller in magnitude at short loading times than at long loading times. It is of interest to note that this rotation occurs in conjunction with translation for mixtures that are not emulsion treated but are laboratory aged.

Table 7.47. Ranking of Loading Time With Respect to Untreated *Plant Mix* Δ*m-value*

Time (s)	Mean	*t*-Group
8	-0.035	A
60	-0.049	A
960	-0.069	B

Table 7.48 provides ranking of aging time and loading time treatment combinations with respect to full analysis of emulsion treated laboratory aged *Plant Mix* Δ*m-value*. Despite complex chaining, it can be concluded that 0-day and 7-day aging generally yields the highest Δ*m-value*. The 30-day and 60-day aging generally yields the lowest Δ*m-value*. For the 7-day aging, the 960-second loading time yields the highest Δ*m-value*, but for all other aging times, the 8-second loading time yields the highest Δ*m-value*. However, these trends are not necessarily statistically significant.

Table 7.48. Ranking of Aging and Loading Times With Respect to Emulsion Treated *Plant Mix* 8, 60, and 960-Second Δ*m-value*

Age	Time (s)	Mean	*t*-Group
7	960	0.074	A
7	60	0.056	AB
0	8	0.054	AB
0	60	0.051	AB
0	960	0.047	BC
7	8	0.043	BC
60	8	0.035	BCD
30	8	0.026	CDE
30	60	0.017	DE
60	60	0.006	E
30	960	0.004	E
60	960	-0.033	F

Table 7.49 provides ranking of aging time with respect to 60-second Δ*m-value* for emulsion treated laboratory aged *Plant Mix*. With no aging, emulsion application increases *m-value* 0.051. After 7 days of aging, Δ*m-value* does not change significantly. After 30 days of aging, Δ*m-value* decreases significantly to 0.017. From 30 to 60 days of aging, Δ*m-value* decreases insignificantly to 0.006. Therefore, after approximately 60 days of laboratory aging, *m-value* of emulsion treated *Plant Mix* is essentially equal to the *m-value* of un-aged *Plant Mix* with no emulsion (i.e. Δ*m-value* equals zero). However, some of the gradual decrease in *m-value* is contributed to aging of the *Plant Mix* mixture itself as indicated by Table 7.46 results.

Table 7.49. Ranking of Aging Time With Respect to Emulsion Treated *Plant Mix* 60-Second Δ*m-value*

Age	Mean	*t*-Group
7	0.056	A
0	0.051	A
30	0.017	B
60	0.006	B

Figure 7.5 compares 60-second Δ*m-value* for untreated and emulsion treated *Plant Mix* and supplements Tables 7.46 and 7.49. Data from the 60-second analysis was used to construct Figure 7.5 since aging time and loading time significantly interacted in the full analysis. As noted in the discussion of Table 7.46, the Δ*m-value* at the 30-day aging time does not follow the expected trend based on other aging times. Aside from the 30-day aging, trends appear reasonable and as expected. Although the emulsion treated Δ*m-value* at 7 days is not greatly different than the un-aged value, the effective Δ*m-value* (emulsion treated Δ*m-value* minus untreated Δ*m-value*) should be evaluated since aging of the untreated *Plant Mix* must be considered (a factor that is much less prominent in an already-aged existing pavement). Effective Δ*m-value* at 7 days increases relative to the un-aged value (0.081 versus 0.051). At 60 days, emulsion treated Δ*m-value* is nearly zero, but, at 0.047, effective Δ*m-value* remains nearly 0.050. From an overall perspective, un-aged Δ*m-value* is approximately 0.050. After a few days of aging, the effective Δ*m-value* increase to 0.081 suggests that some amount of conditioning was beneficial for this mix as it promoted blending interaction between the emulsion and *Plant Mix* binder, which is desired. After some longer period of aging, the effective Δ*m-value* decreased to 0.047 suggesting that the rejuvenation effects of the emulsion diminish as the aging of the emulsion becomes a more prominent factor in the overall rejuvenation behavior.

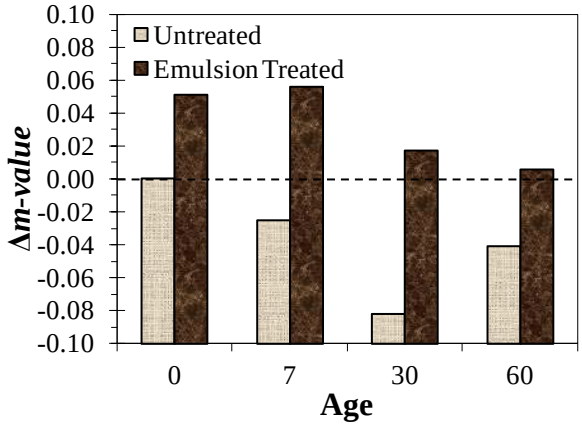


Figure 7.5. *Plant Mix* 60-Second Δ*m-value* Response as a Function of Aging

7.8.2 Analysis with Respect to $S_{D(\%)}$

Table 7.50 provides $S_{D(\%)}$ ANOVA results for *Plant Mix* for the full 8, 60, and 960-second analysis. Age and loading time do not significantly interact for either untreated or emulsion treated *Plant Mix*. At least two aging times and two loading times are significantly different with respect to $S_{D(\%)}$ for both untreated and emulsion treated *Plant Mix*. Table 7.51 provides ANOVA results for *Plant Mix* $S_{D(\%)}$ for the 60-second analysis. Age significantly affects $S_{D(\%)}$ for both untreated and emulsion treated *Plant Mix*.

Table 7.52 provides ranking of aging treatments with respect to mean *Plant Mix* $S_{D(\%)}$. For untreated *Plant Mix*, the 30-day aging time ranks significantly highest which is contrary to the Δ*m-value* results in Table 7.46 and is contrary to expectations. It would be expected that for untreated *Plant Mix*, $S_{D(\%)}$ would decrease with aging (i.e. *Plant Mix* would stiffen). For emulsion treated *Plant Mix*, $S_{D(\%)}$ increases from 0-day to 7-day aging, which is a reasonable expectation. After some period of aging, $S_{D(\%)}$ decreases as expected. However,

the 30-day aging results in the lowest $S_{D(\%)}$, which is of particular interest considering 30-day aging resulted in the highest $S_{D(\%)}$ before emulsion treatment.

Table 7.50. ANOVA Summary for *Plant Mix* 8, 60, and 960-Second $S_{D(\%)}$

	Untreated			*Emulsion Treated*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	134			329		
Age x Time	4	0.6694	No	6	0.5651	No
Age	2	<0.0001	Yes	3	<.0001	Yes
Time	2	0.0037	Yes	2	0.0017	Yes
Error	126			318		

-- $p_{critical} = 0.05$

Table 7.51. ANOVA Summary for *Plant Mix* 60-Second $S_{D(\%)}$

	Untreated			*Emulsion Treated*		
Source	***df***	***p-value***	**Sig?**	***df***	***p-value***	**Sig?**
Total (Corrected)	44			109		
Age	2	<0.0001	Yes	3	0.0115	Yes
Error	42			106		

-- $p_{critical} = 0.05$

Table 7.52. Ranking of Aging With Respect to *Plant Mix* $S_{D(\%)}$

Untreated					***Emulsion Treated***				
	8, 60, 960 Sec		**60 Sec**			**8, 60, 960 Sec**		**60 Sec**	
Age	**Mean**	***t*-Group**	**Mean**	***t*-Group**	**Age**	**Mean**	***t*-Group**	**Mean**	***t*-Group**
30	35.3	A	38.3	A	7	23.3	A	21.9	A
7	-5.0	B	-3.7	B	0	11.5	B	10.7	AB
60	-27.7	C	-24.9	C	60	6.3	B	8.1	AB
0	---	---	---	---	30	-2.4	C	-1.8	B

Table 7.53 provides the mean *Plant Mix* $S_{D(\%)}$ for each loading time. Mean $S_{D(\%)}$ is greater at short loading times than at long loading times for untreated *Plant Mix*. Similar to the loading time rankings by Δm-*value* (Table 7.47), the slope of the stiffness curve is significantly affected by aging even without the presence of emulsion. For emulsion treated *Plant Mix*, this trend is reversed; mean $S_{D(\%)}$ is greater at long loading times than at short loading times.

Table 7.53. Ranking of Loading Time With Respect to *Plant Mix* $S_{D(\%)}$

Untreated			***Emulsion Treated***		
Time (s)	**Mean**	***t*-Group**	**Time (s)**	**Mean**	***t*-Group**
8	9.3	A	960	16.2	A
60	3.3	A	60	9.7	AB
960	-9.9	B	8	3.1	B

Figure 7.6 compares 60-second $S_{D(\%)}$ results for untreated and emulsion treated *Plant Mix* with and without emulsion treatment and supplements 60-second data in Table 7.52. Data from the 60-second analysis was used to construct Figure 7.6 to be consistent with

Figure 7.5. As previously discussed, the 30-day data appears questionable for both untreated and emulsion treated *Plant Mix*. Aside from the 30-day aging time, progressive stiffening (i.e. negative $S_{D(\%)}$ values progressively increasing in magnitude) occurs with age for the untreated *Plant Mix*. Emulsion treatment provides rejuvenation where the effects of the emulsion increase after a short period of aging and taper after a long period of aging. However, this trend is most clearly observed by the Δ*m-value* results in Figure 7.5.

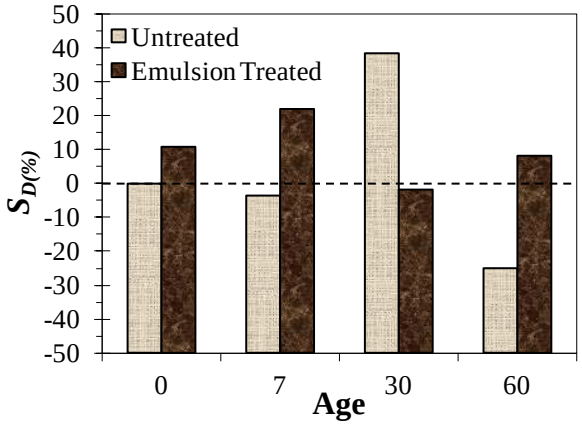


Figure 7.6. *Plant Mix* 60-Second $S_{D(\%)}$ Response as a Function of Aging

7.8.3 Summary of Effects of Emulsion Application and Aging on Plant mixed Asphalt

With no aging, the 60-second Δ*m-value* for emulsion treated *Plant Mix* was 0.051. The corresponding Δ*m-value* for *Hwy 45* or *FR* is approximately 0.070 or greater (note that this corresponds to the 1.81 L/m^2 application rate). This indicates the rejuvenation effect of the emulsion is detectable for the *Plant Mix*, but the emulsion does not have as much effect on the *Plant Mix* as it does for the field aged *Hwy 45* and *FR*. This is probably due to the greater initial *Plant Mix m-value* of 0.160 compared to an average initial *m-value* for the field aged pavements of 0.088. Similar, but not as noticeable, trends were observed in terms of $S_{D(\%)}$. Therefore, the measurable rejuvenation effect of emulsion appears, at least to some extent, dependent on the initial *m-value* or stiffness of the pavement to be treated, and it potentially has a maximum rejuvenation threshold in that the emulsion can only rejuvenate a pavement to a certain degree. An interesting supplement study could involve aging *Plant Mix* various increments of time, applying emulsion, and then measuring the 0-day *BBR* response. Testing of this emulsion treated mixture which was aged prior to emulsion addition may better simulate emulsion treatment of an existing, previously-aged pavement. It seems to reason that the un-aged Δ*m-value* and $S_{D(\%)}$ would increase relative to testing emulsion treated *Plant Mix* that was not aged prior to emulsion addition.

7.9 Performance Related Specification Guidance

In order to develop a standard specification for classifying emulsions as rejuvenators or non-rejuvenators, the asphalt mixture to be rejuvenated should be standardized or considered on a case by case basis. This approach lends to three options: 1) test untreated and emulsion treated mixture beams from a field aged pavement on a project by project basis; 2) obtain significant quantities of cores from a field aged pavement to use as a standard

mixture, test untreated mixture beams to establish a control set, test emulsion treated mixture beams as needed to approve or disapprove rejuvenators; and 3) perform option 2 with laboratory compacted asphalt.

Although cores cut from field aged pavements could be used either project by project or as a standard mixture, these approaches would be least practical. The success rate of sawing and testing mixture beams cut from field aged pavements is approximately 50% (compared to approximately 90% for laboratory compacted asphalt). Further, COV for field aged mixture beams is, on average, 28% (compared to approximately 20% average for laboratory compacted asphalt) which suggests greater testing replication would be required to acquire a reliable mean Δ*m-value*. These factors translate to increased labor, cost, and time demands. Additionally, if a field aged pavement was to be used as a standard mixture, hundreds of cores must be cut in order to sustain laboratory testing for any meaningful period of time. Also, all cores would have to be collected at the same time so that the in-service life of each would be consistent.

Although any of the three options could be employed, testing of laboratory compacted asphalt should provide a more practical, as well as cost-effective, alternative to testing field aged pavements. The sawing and testing success rate is approximately 90% and COV is, on average, 20% which corresponds to less overall fabrication and testing. Compared to testing field aged pavements, it would be relatively easy to obtain a large sample of plant mixed asphalt (or raw ingredients to produce the material in the lab), compact an abundance of specimens in the laboratory, and test as needed. The envisioned approach would test mixture beams cut from the faces of laboratory compacted specimens to produce a large untreated control data set and establish baseline properties. Only one control set would be required per asphalt mixture. Given that enough specimens were initially compacted as to sustain testing of emulsion treated beams for a substantial amount of time, time between testing of new control data sets could be significant (e.g. measured in years). Guidance on testing replication is provided later in this section.

Rejuvenation properties would be measured by testing specimens treated with emulsion. Based on testing presented in this report, an emulsion application rate of 1.81 L/m^2 is recommended. Results from Section 7.5 demonstrated that application rate can have a considerable effect on the measured response in the *BBR*. Because rejuvenation is of interest in this case, recommending 1.81 L/m^2 appears reasonable as this provides the greatest opportunity for an emulsion to rejuvenate an asphalt mixture. Since specimens are scraped, the presence of excess surface emulsion appears of little concern so long as specimen preparation protocols are consistently managed in the laboratory.

Based on current experience with testing specimens that were aged following emulsion treatment, testing of un-aged specimens is recommended. When 90-day and 182-day field aged specimens were tested (Section 7.7), rejuvenation increased from 0-day to 90-day testing and then decreased from 90-day to 182-day testing. For *Plant Mix* testing (Section 7.8), rejuvenation followed a similar trend. These two data sets indicate that some amount of conditioning may be beneficial for rejuvenation as it facilitates positive interaction of the emulsion and the asphalt binder. After some point, rejuvenation effects decrease as aging becomes a considerable factor. However, these trends were not observed for laboratory conditioning of field aged *FR* and *Hwy 45*; results were erratic and unpredictable. Although testing of laboratory conditioned specimens is currently inconclusive relative to use

in specifications, test results indicate that it is not necessary to test conditioned specimens to achieve potentially useful results.

The 60-second Δ*m-value* is recommended as the standard measure of rejuvenation. First, relative to untreated control tests in this research, *m-value* increases with emulsion application more than stiffness decreases; therefore, a greater range exists from no rejuvenation to maximum potential rejuvenation. This greater range in Δ*m-value* allows for more distinct differences to be observed between emulsions; whereas the differences in stiffness between emulsions would be less distinguishable. Fundamentally, the *m-value* is independent of the initial pavement stiffness as it is only a measure of the change in stiffness with time. In terms of developing a specification for rejuvenation performance, evaluating emulsions with respect to Δ*m-value* appears more universally applicable for pavements with a wide range of initial stiffnesses. Secondly, the 60-second loading time is recommended because of its current prevalent use. The data in this report shows that both aging and emulsion treatment do not affect Δ*m-value* consistently at all loading times. On the contrary, Δ*m-value* is generally affected differently at short and long loading times (i.e. rotation occurs in addition to translation as depicted in Figure 7.2). This is likely due to behaviors occurring within the asphalt binder as it ages or interactions between the asphalt binder and applied emulsion; these appear complex and are not fully understood as of present. For this reason and given that the 60-second loading time is well established, the 60-second Δ*m-value* is recommended as of the date of this report.

Based on test results of un-aged emulsion treated field pavements in this report, a Δ*m-value* of 0.060 or greater (60-second Δ*m-value* for 1.81 L/m^2 application rate) is attainable for emulsions that have been known to yield desirable performance in the field. This value was slightly less for *Plant Mix*, which is reasonable given that the initial *m-value* of *Plant Mix* was almost double that of *FR* or *Hwy 45*. Therefore, when using a laboratory compacted asphalt to evaluate rejuvenation, the minimum Δ*m-value* criteria should be reduced. Based on results in this chapter, it appears that an initial Δ*m-value* criteria of 0.060 for field aged pavements and 0.040 for laboratory compacted asphalts could be appropriate. These values are initial recommendations for consideration and should be modified to align with agency goals and field performance results if future data warrants such a change.

To achieve reliable results, the amount of replication required should be based on testing variability. In order to determine recommended replication for field pavements or laboratory compacted asphalt, Equation 7.3 was used to solve for *n* based on the desired margin of error and reliability, or confidence level. Data sets tested in this report where the number of replicates was nearly thirty or more were used to determine the required replication. Due to the large sample size of nearly thirty specimens, the standard deviations of these sample sets provide a reasonable estimate of the population standard deviation.

$$ME = z_{\frac{\alpha}{2}} \frac{St.\ Dev.}{\sqrt{n}} \tag{7.3}$$

Where,
ME = margin of error of the estimate
$z_{\alpha/2}$ = 1.15 for 75% confidence level (C.L.); 1.44 for 85% C.L.; 1.96 for 95% C.L.
St. Dev. = sample or population standard deviation
n = number of replicates

Several means of data refinement were investigated such as outlier removal, discarding the two highest and two lowest extremes, and trimming 10% of the data points from either end of the data set. These methods were investigated to prevent extreme values from adversely and artificially affecting the number of replicates required. Analysis showed that trimming 10% of the data points from either end of the data set proved most effective in removing outlying values. For example, if 30 replicates were tested, trimming 10% would require discarding the three highest and the three lowest extremes. The amount of replication is shown in Table 7.54 for a given reliability and margin of error. Average results are shown for untreated and emulsion treated *Hwy 45* and *Plant Mix*. As an example, when testing untreated *Hwy 45*, the minimum number of replicates should be 14 in order to be 75% confident that the true population mean is ±0.005 that of the 10% trimmed sample mean tested. Greater replication is required when testing field aged pavements or emulsion treated mixtures. As margin of error increases, replication decreases, and as confidence level increases, replication increases.

Table 7.54. Recommended Replication for a Given *ME* and Confidence Level

Margin of Error		**0.005**			**0.010**			**0.012**		
Confidence Level		**75%**	**85%**	**95%**	**75%**	**85%**	**95%**	**75%**	**85%**	**95%**
Hwy 45	**Untreated**	14	21	39	4	6	10	3	4	7
	E3	70	110	203	18	28	51	13	19	36
Plant Mix	**Untreated**	12	19	35	3	5	9	3	4	7
	E3	21	33	61	6	9	16	4	6	11

In the context of a performance related specification, the acceptable level of reliability (confidence level) and margin of error should be established. In general, less error and higher reliability would be desired for the untreated control set. For example, testing untreated laboratory compacted asphalt (the standard mixture) at a 0.005 margin of error and 95% confidence level would require 35 replicates. This implies that six specimens would be compacted and five *BBR* mixture beams would be sawn from each face and tested. With a 90% sawing and testing success rate, this process would produce 54 useable data points. In order to trim 10% of the data, the six highest extremes and the six lowest extremes would be discarded. After trimming, 42 data points would be used to calculate the untreated *m-value* rounded to three decimal places. This amount of replication meets the minimum replication necessary to satisfy the specified margin of error and confidence level.

When evaluating an emulsion, testing of emulsion treated laboratory compacted asphalt could be conducted at a 0.010 margin of error and 95% confidence level, requiring a minimum of 16 replicates. This implies three specimens could be compacted and tested. After trimming 10% of the data, 21 data points would remain and be used to calculate emulsion treated *m-value* rounded to three decimal places. Δ*m-value* should be calculated by simply subtracting the average untreated *m-value* from the average emulsion treated *m-value*. If Δ*m-value* rounded to three decimal places is greater than the specified minimum Δ*m-value* criteria (e.g. 0.040), then the emulsion can be approved as a rejuvenator.

CHAPTER 8-VIALIT TEST RESULTS

8.1 Overview of *Vialit* Test Results

This chapter evaluates *Vialit* test suitability for characterizing aggregate retention. Several test protocols were investigated and in some cases protocols were modified. Protocols investigated and/or modified were influenced by literature review and information from emulsion producers and state DOT's. Test parameters investigated were tray type, spherical mass properties, and conditioning. Emulsions were also compared to each other using select test combinations. Two complimentary papers (Jordan and Howard, 2010; Jordan and Howard, 2011) use the data presented herein, but their material identification numbers do not match the system used herein. Materials tested in this chapter were seven emulsions (1 to 7 from Table 3.1) and two aggregates (1 and 2 from Table 3.8).

8.2 Comparison of Specification and Modified Trays

Table 8.1 compares the specification (Spec) and modified (Mod) trays. Three cases directly compare the two trays, and the average aggregate loss was 53.5 to 98.2% with the specification tray and 2.5 to 6.3% with the modified tray. Two more combinations were tested with the specification tray that also had very high losses. Aggregate loss for the specified tray is too high to have physical meaning, especially when the mode of failure is considered (Figure 8.1). As noted in the literature review by opponents of the existing method, significant areas of emulsion de-bonded from the tray (a behavior that makes test results physically meaningless) resulting in the specification tray being deemed inadequate. Emulsion de-bonding occurred on practically all tests conducted with the specified trays. The modified tray's performance was reasonable, and it was used hereafter in this chapter.

Table 8.1. *Vialit* Results Comparing Tray Types

			***Vialit* Aggregate Loss Results**						
Tray	**Emulsion**	**Aggregate**	**Tray 1**	**Tray 2**	**Tray 3**	**Tray 4**	**Tray 5**	**Tray 6**	**Avg.**
Spec	6	1	98	97	97	100	99	98	98.2
	6	2	84	90	88	92	93	90	89.5
	5	1	51	59	53	44	57	57	53.5
	2	2	100	95	95	87	93	96	94.3
	2	1	100	97	95	100	99	93	97.3
Mod	6	1	0	0	2	1	5	7	2.5
	6	2	5	5	8	6	6	8	6.3
	5	1	3	1	8	2	7	3	4.0

-- A 501 g sphere was used in conjunction with 48 hr at 60 C and -22 C freezing for 0.5 hr.

Figure 8.1. *Vialit* Specification Trays After Testing

8.3 Comparison of Emulsions Using Modified Tray

Table 8.2 compares aggregate loss of all seven emulsions when tested with the modified tray. The aggregates were dislodged from the emulsion and not from the tray. The *Vialit* test with the modified tray was able to detect a noticeable performance difference between CRS-2 emulsion (13% aggregate loss) and the six polymer modified emulsions (4% or less aggregate loss) but the differentiation between polymer modified emulsions for the purposes of specifications does not appear useful.

Table 8.2. Test Results With Modified Tray and Aggregate 1

	***Vialit* Aggregate Loss (%)**			
Emulsion	**Tray 1**	**Tray 2**	**Tray 3**	**Average**
1	15	14	10	13.0
2	2	4	6	4.0
3	1	0	0	0.3
4	2	0	0	0.7
5	0	0	0	0.0
6	1	2	5	2.7
7	2	1	3	2.0

-- A 501 g sphere was used in conjunction with 48 hr at 60 C and -22 C freezing for 0.5 hr.

8.4 Effects of Sphere Properties

Table 8.3 summarizes spherical mass effects. Changing only the spherical mass did not have appreciable effect on aggregate loss. Aggregate loss was relatively low, which is in general agreement with Table 8.2 for polymer modified emulsion. The effect of spherical mass was not investigated in conjunction with modifications to specimen conditioning. This combination of variables could prove informative. Based on the information in this experimental program, changing the spherical mass while using a modified tray does not appear to meaningfully affect test results; a constant mass should, however, be used.

Table 8.3. Effects of Spherical Mass on Aggregate Loss

	-15 C Test Temp.			**-22 C Test Temp.**		
Tray	**416 g (%)**	**501 g (%)**	**527 g (%)**	**416 g (%)**	**501 g (%)**	**527 g (%)**
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	1	0	0	0	1
7	0	1	0	0	0	1
8	0	1	0	0	0	1
9	0	1	0	0	0	2
10	0	1	0	0	1	2
11	1	1	0	1	1	3
12	1	4	1	2	1	6
Avg	*0.17*	*0.83*	*0.08*	*0.25*	*0.25*	*1.33*

-- Emulsion 2 and aggregate 1 were used throughout.
-- Conditioning was 48 hr at 60 C and -22 C freezing for 0.5 hr.

8.5 Effects of Conditioning Protocols

Figure 8.2 plots the effect of freezer time and temperature on aggregate loss with emulsion 3 and aggregate 1 (limestone). The modified tray and 501 g steel sphere were used in conjunction with modified conditioning incorporating effects of freezer time and temperature. The typically specified -22 C temperature was used, alongside a warmer temperature of -15 C that should be achievable with any typical freezer.

Figure 8.2 shows freezer time and freezer temperature have a pronounced effect on aggregate loss. It is clear the specified temperature of -22 C needs to be maintained since only a moderate temperature increase produced a noticeably lower aggregate loss. It should be noted that aggregate loss at -22 C begins to level off at 4 hours and essentially remains constant after 8 hours of freezer time. For specification purposes, a freeze time of 4 hours in conjunction with the modified tray appears more logical than the currently specified 0.5 hr.

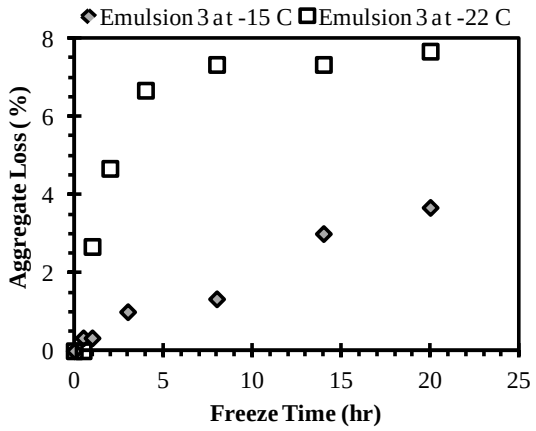


Figure 8.2. Effect of Freeze Time and Temperature on *Vialit* Results

Figure 8.3 plots *Vialit* loss results with two emulsions and aggregate 1 (limestone) using the modified protocol absent oven conditioning and incorporating freeze-thaw cycles. The modified tray and 501 g steel sphere were used. As seen in Figure 8.3, the importance of freezer temperature is even more heightened than it was in Figure 8.2. The data shows it is imperative to achieve the specified temperature and that any freezer may not be sufficient.

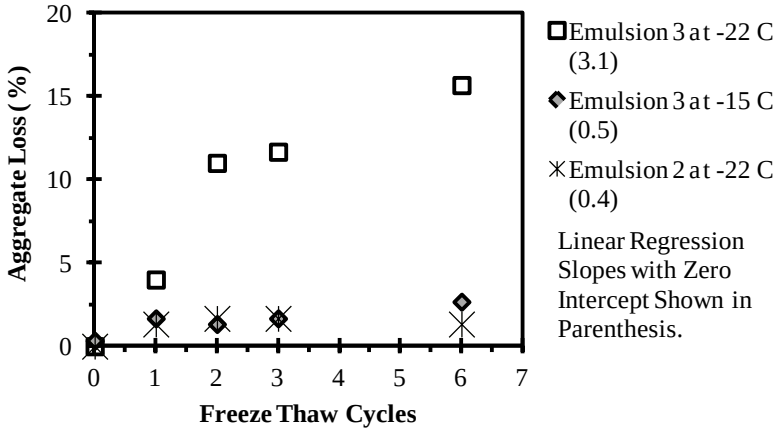


Figure 8.3. *Vialit* Test Results Investigating Freeze-Thaw Cycle Effects

Figure 8.3 also compares two polymer modified emulsions and shows that freeze-thaw cycles in conjunction with the modified tray differentiated between their measured responses in terms of *Vialit* aggregate loss. Three hour freeze times were incorporated, which are feasible to incorporate into the daily activities of a testing laboratory. Aggregate loss on the order of 15% was achieved with freeze-thaw cycles, whereas, in Figure 8.2, aggregate loss on the order of half this amount was achieved with only freezer time.

8.6 *Vialit* Test Results Summary

The *Vialit* test as it is currently performed in citable test methods does not appear adequate for use in a performance oriented specification. With the 0.20 cm thick tray that is currently specified, the results should be questioned regardless of the use. Use of the modified tray was able to differentiate between polymerized and non-polymerized emulsions with no other testing modifications. Identification of polymer modification has value, but by itself does not constitute a means for a comprehensive specification.

Using a modified test tray alongside a freeze time of 4 to 8 hours at -22 C was shown promising. Using a modified test tray in conjunction with freeze-thaw cycles was able to differentiate between two polymer modified emulsions. Spherical mass tolerance appears to be expandable, though additional testing would be needed to make a definitive statement. Use of a sphere of constant mass is recommended for consistency. The *Vialit* test seems to be improved with modified trays and longer freezing durations, and possibly with freeze-thaw cycles. For routine testing, the use of only freeze time will likely be more practical; whereas, for allowing use of a new material (or similar), freeze-thaw cycles could be more informative.

CHAPTER 9-FROSTED MARBLE TEST RESULTS

9.1 Overview of Frosted Marble Test Results

Four documents have been written by members of the research team where the Frosted Marble Test (*FMT*) was used. Two of these documents evaluated the same emulsions presented in this report (Jordan, 2010; Howard et al., 2011), while the other two documents evaluated different emulsions (Howard and Baumgardner, 2009; Howard et al., 2009) during MDOT State Study 202. Both State Study 202 documents were described in the literature review portion of this report. Some of the data reduction techniques used herein differed relative to Jordan (2010) and Howard et al. (2011). These differences were for consistency in this report and did not result in large differences in the assessments made. The key difference was this report discarded the two highest and two lowest data points per test tray and used the other eleven measurements absent any judgment, whereas previous works used a few different methods such as discarding the highest and lowest reading and any value deemed questionable based on judgment. All seven emulsions were tested in this chapter absent aggregates or asphalt pavement.

9.2 Frosted Marble Test Results

Table 9.1 provides all *FMT* torque values measured, and Table 9.2 provides all moisture loss values measured. Four of the seven emulsions were tested two times. Emulsions 1, 2, and 4 were a different sample of the same formulation tested by a different operator, while emulsion 6 was the same sample tested by a different operator. Emulsions 1, 2, and 4 denoted with (#2) are repeat tests that occurred in August of 2009. All other testing, including emulsion 6(#2), occurred in May of 2009.

Table 9.1. *FMT* Torque Results

Cure	Emulsion - (#2) Indicates Test Repeated with Same Emulsion ID										
Time (hr)	1	1 (#2)	2	2 (#2)	3	4	4 (#2)	5	6	6 (#2)	7
0.5	7.1	13.7	5.7	12.5	11.2	13.9	16.4	7.9	7.4	13.6	6.3
1	11.5	14.5	17.7	13.8	14.5	13.1	15.1	12.5	13.9	12.0	13.9
1.5	9.3	15.4	10.9	15.2	11.2	15.3	15.5	15.8	11.2	14.7	11.7
2	13.1	16.5	13.9	15.7	13.4	13.4	17.1	14.2	9.0	15.5	13.1
3	16.6	17.1	14.7	16.5	15.8	15.3	17.4	15.8	18.5	17.7	20.7
4	13.6	17.9	15.3	16.8	13.1	12.3	18.5	15.0	17.2	17.5	16.4
5	13.1	19.0	13.1	17.0	13.1	12.3	19.7	15.3	14.5	17.7	13.9
6	15.3	20.2	14.7	17.5	15.5	16.9	19.1	15.8	13.4	18.3	16.1
7	13.4	21.5	13.4	18.0	13.1	14.7	20.6	15.3	15.5	18.8	14.5
8	15.8	21.7	17.5	21.5	14.2	15.8	21.8	13.1	12.5	19.6	17.5
24	15.3	24.8	16.9	21.4	15.0	17.7	22.6	16.4	16.4	18.0	18.3
48	15.3	23.9	17.7	19.9	15.5	18.3	25.5	16.4	15.5	19.9	19.4
120	15.5	23.9	19.9	28.7	15.0	19.6	29.3	17.7	18.5	23.2	19.6

-- Values shown are measured torque (kg-cm), and each value encompasses one tested tray.

-- Emulsions 1, 2, and 4 testing repeated by same operator, but with different sample of same emulsion ID.

-- Tests 1(#2), 2(#2), and 4(#2) were performed in triplicate and the results of all 3 trays were averaged.

-- Emulsion 6 testing repeated with same sample of this emulsion ID, but by a different operator.

Table 9.2. *FMT* Percent Moisture Loss Results

Cure	Emulsion		
Time (hr)	1 (#2)	2 (#2)	4 (#2)
0.5	59.8	54.3	56.3
1	63.2	59.7	65.7
1.5	73.0	67.2	72.7
2	81.8	72.7	79.0
3	85.9	80.6	87.7
4	88.9	84.4	92.2
5	90.4	90.4	95.1
6	92.0	91.7	96.5
7	92.4	92.9	96.6
8	92.6	94.2	96.6
24	94.0	95.3	96.9
48	94.0	95.3	96.9
120	94.0	95.3	96.9

-- Emulsion numbers correspond to Table 9.1.
-- Two trays were tested and the average value was reported.

9.3 *FMT* Repeatability Evaluation

Figure 9.1 compares all four Table 9.1 cases where *FMT* testing was repeated. Recall that emulsions 1, 2, and 4 were tested on different samples by the same operator and that emulsion 6 was the same sample tested with a different operator. Linear regression through the origin (*RTO*) was performed on each emulsion represented in Figure 9.1. Slopes were: E1 = 1.41, E2 = 1.20, E3 = 1.30, and E6 = 1.20, which indicates repeat testing produced torque values that were, generally speaking, 20 to 41% higher than original testing. Interestingly, all repeat testing measured higher strengths than original testing. It is possible that the new samples of emulsions 1, 2, and 4 were stronger than the previous samples, though even if that were the case it does not explain emulsion 6 as it was the same sample.

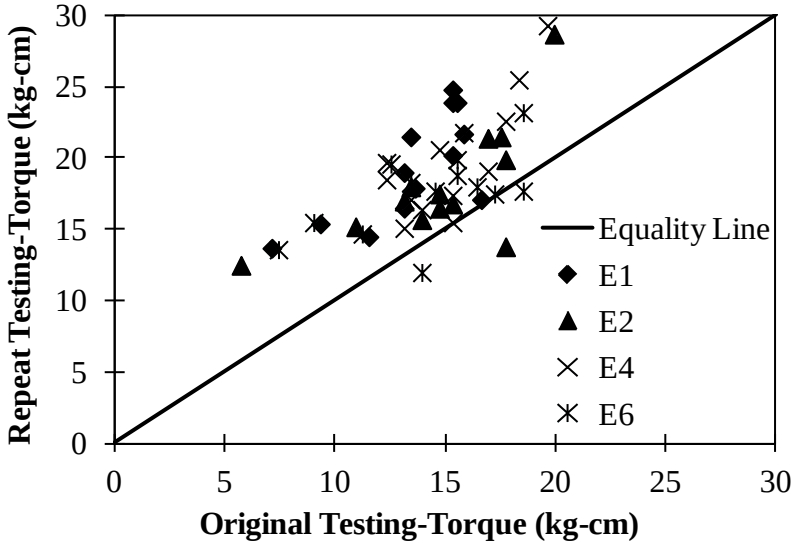


Figure 9.1. Comparison of Original and Repeat *FMT* Data

This data set is not comprehensive enough to make any definitive assessments, though it does pose a potential concern, especially when this approach only incorporates one of the three materials of interest in a chip seal system (emulsion; aggregates and existing pavement are not considered). There are other possible repeatability issues such as placement location within the environmental chamber. Heat lamps invariably cause temperature fluctuation with location that cannot be avoided absent sophisticated procedures. Figure 9.1 indicates *FMT* repeatability needs improvement prior to use as a standalone performance test.

9.4 *FMT* Torque Measurement Evaluation

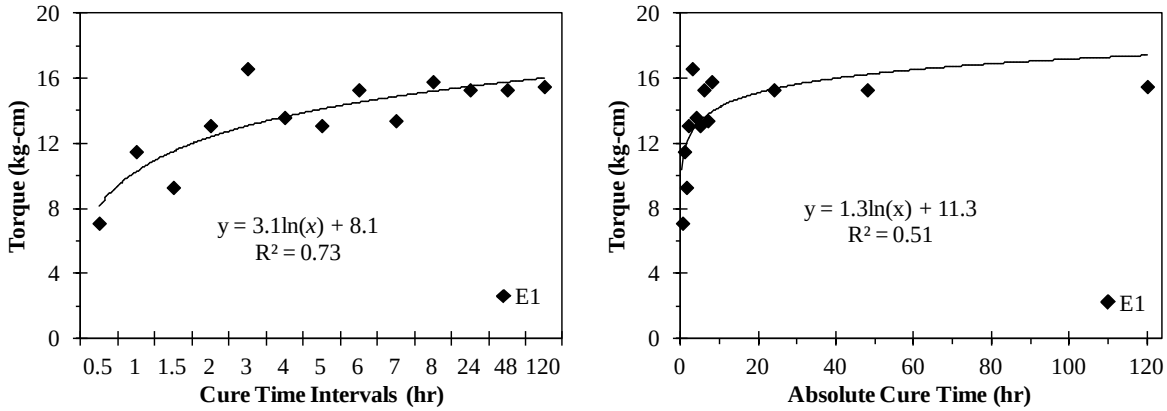
The original tests by a single operator during May of 2009 are compared in this section. In that these experiments were performed in a relatively short amount of time, they were deemed reasonable for general comparison so long as the behaviors of section 9.3 are noted when interpreting results.

Figure 9.2 demonstrates a typical torque versus cure time plot. Note that Figure 9.2a is a line graph where *x* in the trendline equation is cure time interval (e.g. cure time interval 3 corresponds to a cure time of 1.5 hr). Jordan (2010) provides plots for all seven emulsions using the Figure 9.2a analysis method following Equation 9.1. For use in this report, *FMT* data is presented as shown in Figure 9.2b where cure time (hr) is the *x* variable for the trendline equation following Equation 9.2. Table 9.3 summarizes the regression coefficients of each emulsion following the general form of Figure 9.2 and Equations 9.1 and 9.2.

$$Torque = C_1 \ln[CTI] + C_2 \quad (9.1)$$

$$Torque = C_3 \ln[ACT] + C_4 \quad (9.2)$$

Where,
Torque = torque (kg-cm)
CTI = cure time interval (1, 2, 3, …, 13)
ACT = absolute cure time (hr)
C_1, C_2, C_4, C_5 = regression coefficients



a) Cure Time Interval *b) Absolute Cure Time*

Figure 9.2. Example of *FMT* Strength Gain versus Cure Time Using Emulsion 1

Table 9.3. Emulsion Curing Patterns from *FMT*

	Cure Time Interval			Absolute Cure Time		
Emulsion	**C_1**	**C_2**	**R^2**	**C_3**	**C_4**	**R^2**
1	3.1	8.1	0.73	1.3	11.3	0.51
2	3.4	8.8	0.51	1.7	11.8	0.53
3	1.2	11.7	0.38	0.6	12.9	0.37
4	1.8	12.2	0.35	1.2	13.3	0.62
5	2.6	10.2	0.65	1.2	12.7	0.54
6	3.0	9.0	0.44	1.5	11.6	0.43
7	4.1	8.3	0.65	1.9	12.2	0.57

Table 9.4 provides ANOVA results for the *FMT* data. The trimmed data sets of 11 replicates per treatment combination were analyzed. Emulsion and cure time significantly interact to affect results. Significant interaction suggests that different emulsions gain strength at different rates, test variability is considerably high, or a combination of both. Because there is significant interaction between cure time and emulsion, a multiple comparisons analysis cannot be performed on emulsion alone since emulsion performance is dependent on the cure time evaluated.

Table 9.4. ANOVA Summary for *FMT* Torque Results

Source	***df***	***p-value***	**Sig?**
Total Corrected	1000		
Emulsion x Cure Time	72	<0.0001	Yes
Emulsion	6	<0.0001	n/a
Cure Time	12	<0.0001	n/a
Error	200		

-- $p_{critical} = 0.05$

Given the significant interaction between emulsion and cure time, ANOVAs were performed again for each cure time. Tables 9.5 and 9.6 provide rankings of the emulsions at each cure time. The emulsion tested had a significant effect on torque at all cure times except the 3, 5, 6, and 7 hr cure times. There is little established physical interpretation of torque values from the *FMT*; however, in terms of relative behavior, strong performance at early cure times is of more significance than strong performance at late cure times. At later cure times, strength gain of an emulsion is likely due partially to emulsion curing and partially due to aging of the emulsion residue. Additionally, behavior at early cure times is likely of greater interest in terms of insight into traffic opening guidance. At each cure time, chaining is present, and the ranking of emulsions generally changes considerably between cure times. Therefore, formulating a conclusion becomes relatively difficult as there are no clearly identifiable strong performers. The most significant observation is the overall variability of the *FMT* over time.

Table 9.5. Emulsion Ranking With Respect to Torque for 0.5 hr to 5 hr Cure Times

0.5 hr Cure Time (*p-value*: <0.0001)		1 hr Cure Time (*p-value*: 0.0050)		1.5 hr Cure Time (*p-value*: <0.0001)		2 hr Cure Time (*p-value*: 0.0010)		3 hr Cure Time (*p-value*: 0.1608)		4 hr Cure Time (*p-value*: 0.0272)		5 hr Cure Time (*p-value*: 0.6138)	
E	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**
4	A	2	A	5	A	5	A	7	N-S	6	A	5	N-S
3	B	3	B	4	A	2	A	6		7	AB	6	
5	C	7	B	7	B	3	A	1		2	ABC	7	
6	CD	6	B	6	BC	4	A	5		5	ABC	2	
1	CD	4	B	3	BC	1	A	3		1	BC	1	
7	CD	5	B	2	BC	7	A	4		3	C	3	
2	D	1	B	1	C	6	B	2		4	C	4	

-- $p_{critical}$ = 0.05 -- N-S = not significant

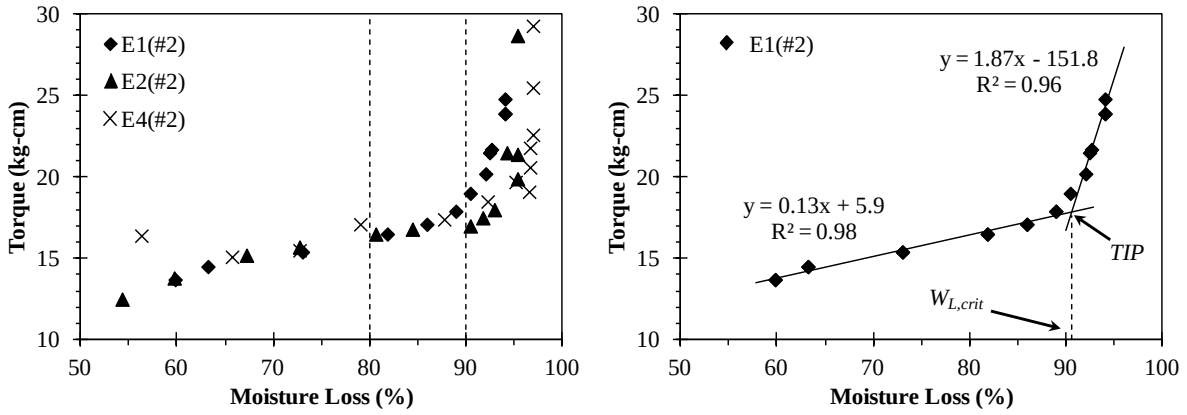
Table 9.6. Emulsion Ranking With Respect to Torque for 6 hr to 120 hr Cure Times

6 hr Cure Time (*p-value*: 0.0644)		7 hr Cure Time (*p-value*: 0.5231)		8 hr Cure Time (*p-value*: 0.0008)		24 hr Cure Time (*p-value*: 0.0028)		48 hr Cure Time (*p-value*: 0.0011)		120 hr Cure Time (*p-value*: <0.0001)	
E	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**	**E**	***t*-Group**
4	N-S	6	N-S	7	A	7	A	7	A	2	A
7		5		2	A	4	AB	4	AB	7	A
5		4		1	AB	2	ABC	2	ABC	4	A
3		7		4	AB	5	BCD	5	BCD	6	AB
1		1		3	BC	6	BCD	3	CD	5	B
2		2		5	C	1	CD	6	CD	1	C
6		3		6	C	3	D	1	D	3	C

-- $p_{critical}$ = 0.05 -- N-S = not significant

9.5 *FMT* Moisture Loss to Strength Gain Correlations

Figure 9.3a plots *FMT* torque as a function of moisture loss. Howard et al. (2011) compared cure time and moisture loss as two ways of evaluating strength gain and showed moisture loss provides greater insight than cure time for the *FMT*. Howard et al. (2011) also observed that strength gain rose sharply between 80 to 90% moisture loss. Figure 9.3a uses some of the Howard et al. (2011) data and displays similar trends as torque curves begin to rise sharply around 90% moisture loss. The torque inflection point (*TIP*) was determined for each emulsion (Figure 9.3b) by plotting straight lines for the two distinct slopes such that R^2 values were maximized for each. The moisture loss at the *TIP* is denoted the critical moisture loss ($W_{L,crit}$). Table 9.6 provides $W_{L,crit}$ values for each emulsion as well as the corresponding critical cure time (*CCT*) which is rounded to the nearest half hour.



a) All Results *b) Torque Inflection Point Determination*

Figure 9.3. *FMT* Strength Gain versus Moisture Loss

Table 9.7. Critical Values at *TIP*

Emulsion	*CCT* (hr)	$W_{L,crit}$ (%)
1(#2)	5	91
2(#2)	6	92
4(#2)	6	96

CHAPTER 10-SWEEP TEST RESULTS

10.1 Overview of Sweep Test Results

This chapter evaluates the sweep test for characterizing chip seal aggregate retention performance. Two test protocols were used: ASTM D7000 and a modified version denoted *Sweep-M*. Test parameters investigated were emulsion, aggregate, and cure time. Alvarado (2012) is a thesis which presents all data used herein; the material identification system used herein is similar to Alvarado (2012) but not identical. Data presented herein was also used by Alvarado and Howard (2014). Materials tested in this chapter were seven emulsions (E1 to E7 from Table 3.1) and three aggregates (A1 to A3 from Table 3.8).

10.2 Summary of Sweep Test Results

Tables 10.1 and 10.2 present results of the 123 D7000 sweep tests. Seven emulsions and three aggregates were tested at one hour cure time in Table 10.1. Three aggregates were tested with emulsion E2 at ten cure times in Table 10.2. D7000 testing was conducted for means of comparison to *Sweep-M*. The D7000 treatment combinations were selected in order to approximately represent all *Sweep-M* factors: aggregate, emulsion, and cure time.

Table 10.1. ASTM D7000 Mass Loss at 1 hr Cure

	Aggregate and Mass Loss (%)		
Emulsion	**1**	**2**	**3**
1	26.2	18.1	32.5
2	36.8	17.6	51.8
3	56.0	61.7	58.0
4	31.1	16.3	31.6
5	29.9	14.2	39.8
6	17.6	14.2	13.5
7	21.8	9.5	15.5

-- Each result is the average of three replicates.
-- Raw data is presented in Tables A.1-A.2 of Alvarado (2012).

Table 10.2. ASTM D7000 Mass Loss for Emulsion 2 at Multiple Cure Times

	Aggregate and Mass Loss (%)		
Cure Time (hr)	**1**	**2**	**3**
0.5	54.2	51.0	54.7
1	39.0	26.1	40.2
1.5	27.5	12.5	30.3
2	20.3	12.1	24.6
3	11.1	9.4	12.8
4	6.4	6.2	7.9
5	5.1	5.8	4.3
6	5.1	5.3	4.3
7	2.7	5.1	5.1
8	4.0	4.9	2.0

-- Each result is the average of three replicates.
-- Raw data is presented in Tables A.1-A.2 of Alvarado (2012).

Table 10.3 presents *Sweep-M* variability results for moisture loss and mass loss. E1 and E2 were tested with aggregate A3 at both 1 and 2 hr cure times (20 replicates each). In all, 80 *Sweep-M* variability tests were conducted. All variability sets appear reasonably normally distributed (good or excellent normality fits) except for E2-A3-T1 (poor normality fit). At the one hour cure time, COV for moisture loss is 16.6% and 12.5% for emulsions 1 and 2, respectively. The COV decreases slightly after two hours of curing to 10.5% and 8.8% for E1 and E2, respectively. For mass loss, the COV after one hour of curing is 7.6% and 9.1% for E1 and E2, respectively. After two hours of curing, COV increases to 16.3% and 18.4% for E1 and E2, respectively.

Table 10.3. *Sweep-M* Variability Results

Mix ID	P-value	Normality Fit	Mean	St. Dev.	COV (%)	95% C.I.
Moisture Loss						
E1-A3-T1	0.57	Excellent	33.7	5.6	16.6	11.7 to 55.7
E1-A3-T2	0.25	Good	51.9	5.5	10.5	30.3 to 73.5
E2-A3-T1	0.50	Excellent	27.2	3.4	12.5	13.9 to 40.5
E2-A3-T2	0.03	Poor	42.2	3.7	8.8	27.7 to 56.7
Mass Loss						
E1-A3-T1	0.76	Excellent	61.5	4.7	7.6	43.1 to 79.9
E1-A3-T2	0.57	Excellent	41.8	6.8	16.3	15.1 to 68.5
E2-A3-T1	0.47	Good	60.5	5.5	9.1	38.9 to 82.1
E2-A3-T2	0.57	Excellent	44.4	8.2	18.4	12.3 to 76.5

-- 95% C.I. = 95% Confidence Interval

-- Each result corresponds to 20 replicates.

-- Raw data is presented in Tables B.1-B.2 of Alvarado (2012).

Table 10.4 provides data for 410 *Sweep-M* tests in which seven emulsions, three aggregates, and ten cure times were tested (two replicates each). Moisture loss and mass loss are provided. In general, moisture loss increased rapidly during the first two hours of curing, and mass loss decreased rapidly during the first two to four hours of curing. After these initial periods, moisture loss increased and mass loss decreased in a generally linear fashion. Figure 10.1 demonstrates examples of desirable and undesirable material response and compatibility via mass loss versus cure time, moisture loss versus cure time, and mass loss versus moisture loss plots. Plots are shown with regression trend lines included which are discussed further in subsequent sections. Plots similar to Figure 10.1 are shown in Appendix C of Alvarado (2012) for all 21 emulsion-aggregate combinations.

Table 10.5 provides data for 14 *Sweep-M* tests which underwent extended-duration curing with the primary objective of investigating reasonable curing times needed for near 100% moisture loss. All seven emulsions were tested with aggregate A3 only. Moisture loss results were calculated for each specimen every hour up to 12 hours and then every 12 hours up to 96 hours. After the 96 hour curing time, *Sweep-M* testing was performed, and mass loss results were calculated for each of the seven emulsions (two replicates each).

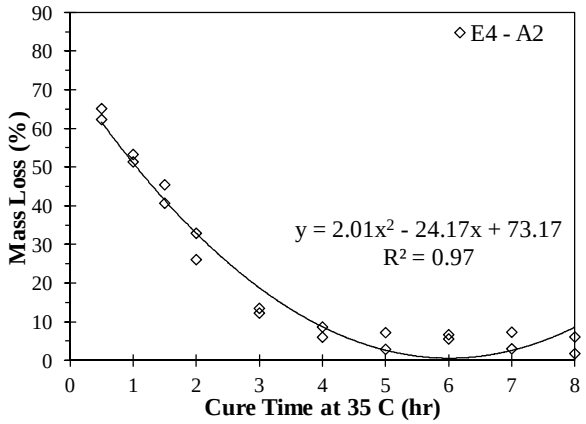
Table 10.4. *Sweep-M* Results for 0.5 to 8 hr Cure Times

		Cure Time (hr) and Average Moisture Loss (%)										Cure Time (hr) and Average Mass Loss (%)									
E	**A**	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1	14.0	36.0	54.1	61.3	67.0	69.4	70.3	71.7	72.7	76.8	52.3	48.8	30.7	19.9	18.6	19.9	13.6	17.0	17.5	16.4
	2	19.9	40.4	54.6	67.6	71.8	75.8	71.8	75.2	75.7	79.9	62.0	48.6	32.0	24.0	18.9	17.0	9.4	9.4	10.0	8.9
	3	12.5	32.6	43.8	54.7	62.2	66.5	67.9	68.5	71.9	76.0	50.6	47.0	25.9	34.7	22.5	9.8	6.3	7.3	5.3	2.8
2	1	9.7	23.9	39.4	43.1	51.9	58.6	61.2	62.9	62.2	68.1	67.7	63.4	46.6	38.7	27.5	17.8	10.9	11.2	5.5	4.1
	2	11.8	26.2	39.2	46.2	57.7	63.3	65.2	65.4	64.0	70.5	71.6	70.1	55.2	47.0	21.4	12.7	6.0	7.1	6.6	6.2
	3	9.2	24.7	32.7	41.5	52.3	61.6	59.6	61.6	64.3	72.8	77.7	75.8	64.9	62.2	28.5	23.8	34.8	26.2	12.2	16.9
3	1	20.0	28.9	37.9	44.6	52.4	58.3	59.5	64.6	67.9	71.9	40.9	44.8	31.1	34.1	30.2	31.4	24.2	23.0	15.7	17.4
	2	15.9	30.1	39.3	48.6	58.4	65.2	67.4	69.4	71.4	74.0	58.7	42.7	46.7	29.7	26.9	29.7	19.9	16.8	17.9	19.4
	3	17.0	30.4	37.4	43.2	50.2	58.8	61.0	62.9	65.5	70.9	58.1	50.8	43.6	35.6	31.5	27.8	24.2	23.4	15.6	16.5
4	1	15.0	31.2	46.1	51.9	68.0	70.9	72.4	74.2	75.0	79.3	52.4	48.2	45.0	36.7	11.3	16.8	8.3	8.9	7.7	5.3
	2	17.4	34.3	48.2	61.3	69.1	74.9	75.4	78.1	78.5	81.8	63.7	52.3	43.0	29.5	12.9	7.3	5.1	6.1	5.2	4.0
	3	13.6	30.4	40.1	52.2	64.2	70.3	71.7	73.3	75.0	80.5	67.5	48.7	52.7	35.5	25.0	12.6	12.0	9.5	1.5	1.5
5	1	18.8	27.4	38.6	42.4	50.2	56.1	57.1	59.1	62.8	66.1	45.1	44.8	34.6	28.1	25.2	26.8	31.1	30.5	32.0	28.1
	2	19.3	31.2	44.6	52.0	59.7	61.1	66.3	66.1	67.9	73.9	61.7	42.3	29.3	27.6	26.6	30.1	20.7	17.6	19.3	22.1
	3	15.0	27.5	41.5	46.7	55.9	62.3	64.4	68.3	67.5	72.2	63.1	61.7	43.5	37.9	27.5	32.6	25.2	24.5	26.9	16.9
6	1	16.2	27.6	36.7	47.1	50.7	47.5	49.8	50.9	50.6	54.1	58.0	41.4	20.5	16.6	11.0	8.0	6.1	6.9	7.1	4.3
	2	18.9	34.2	44.1	49.1	50.6	52.1	53.6	52.3	54.9	61.4	58.4	32.9	19.3	11.7	11.4	12.5	6.9	6.4	5.7	6.4
	3	17.7	27.5	35.8	39.0	43.4	47.6	43.2	46.5	49.9	54.6	50.7	39.4	36.5	28.9	19.2	16.8	10.5	6.0	4.8	9.1
7	1[a]	11.2	29.6	45.6	52.3	56.4	59.5	63.2	62.6	63.0	68.6	41.5	41.6	34.0	28.3	6.1	4.1	8.2	6.6	6.4	3.3
	2	13.5	30.2	45.4	52.8	61.4	62.3	65.8	65.0	66.3	68.9	53.3	46.7	24.7	25.3	11.0	10.7	10.2	9.6	9.9	9.0
	3	11.5	26.1	38.4	45.1	50.6	56.6	57.9	60.6	63.1	65.4	59.0	53.9	37.0	38.3	33.8	21.5	16.9	8.6	6.5	6.1

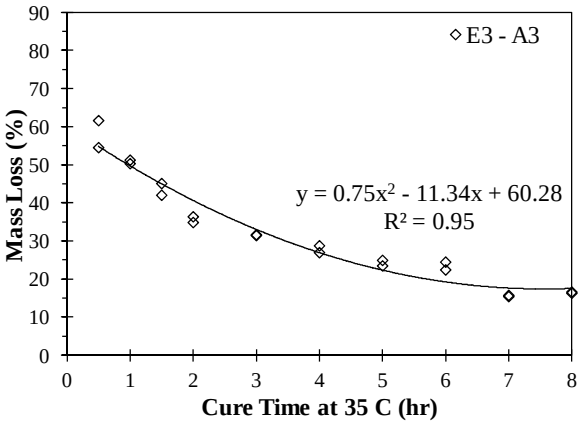
a) Insufficient A1 to test two replicates. Result is based on a single replicate.

-- Each result is the average of two replicates.

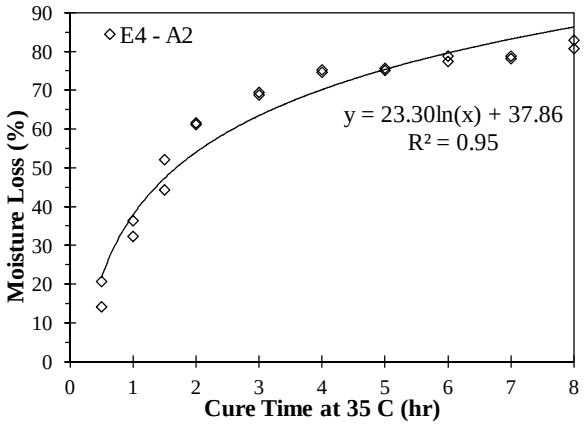
-- Raw data is presented in Tables B.3-B.23 of Alvarado (2012).



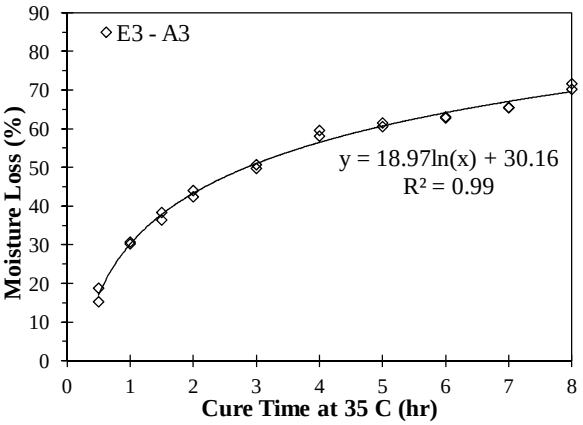
a) Mass Loss vs. Cure Time (Desirable)



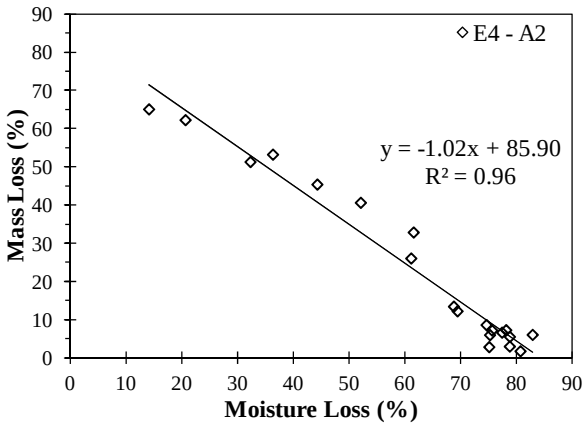
b) Mass Loss vs. Cure Time (Undesirable)



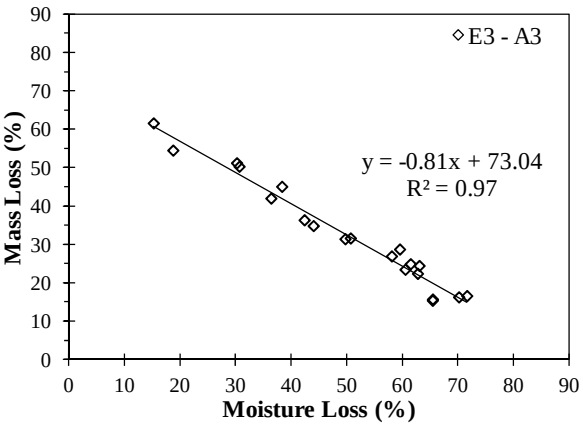
a) Moisture Loss vs. Cure Time (Desirable)



b) Moisture Loss vs. Cure Time (Undesirable)



a) Mass Loss vs. Moisture Loss (Desirable)



b) Mass Loss vs. Moisture Loss (Undesirable)

Figure 10.1. Example of Desirable and Undesirable Material Performance and Compatibility as Measured by the *Sweep-M* Test

Table 10.5. *Sweep-M* Results for Extended Cure Times with Aggregate 3

Cure Time (hr)	Moisture Loss (%)						
	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**
1	36.1	16.2	31.6	25.5	30.9	31.6	33.0
2	58.1	31.4	44.0	45.3	48.5	39.2	47.7
3	67.8	43.7	50.1	57.9	58.4	43.8	54.8
4	70.9	52.1	55.0	64.9	63.0	47.9	59.7
5	73.6	58.0	58.7	69.8	66.9	52.0	62.2
6	75.8	60.8	61.9	72.5	69.1	54.4	65.4
7	76.9	64.4	64.0	75.0	71.6	57.3	67.7
8	78.7	66.7	66.4	76.7	73.0	58.7	68.9
9	79.5	68.6	67.6	78.4	75.5	61.8	71.1
10	81.2	70.4	69.0	79.5	76.9	63.1	72.4
11	82.2	71.8	70.5	80.9	77.6	64.3	73.2
12	83.2	72.7	71.9	82.2	78.7	65.7	74.6
24	88.6	78.7	77.2	87.7	85.8	72.7	80.3
48	93.5	83.4	84.1	92.9	90.0	80.3	84.6
72	95.4	87.4	89.8	96.1	92.7	85.0	86.4
96	96.2 (***2.6***)	89.2 (***1.5***)	91.2 (***3.7***)	98.7 (***3.0***)	94.6 (***1.9***)	88.3 (***2.6***)	87.8 (***2.5***)

-- Each result is the average of two replicates.
-- Raw data is presented in Table B.24 of Alvarado (2012).
-- Italicized bold values in parentheses are mass losses at 96 hr cure times.

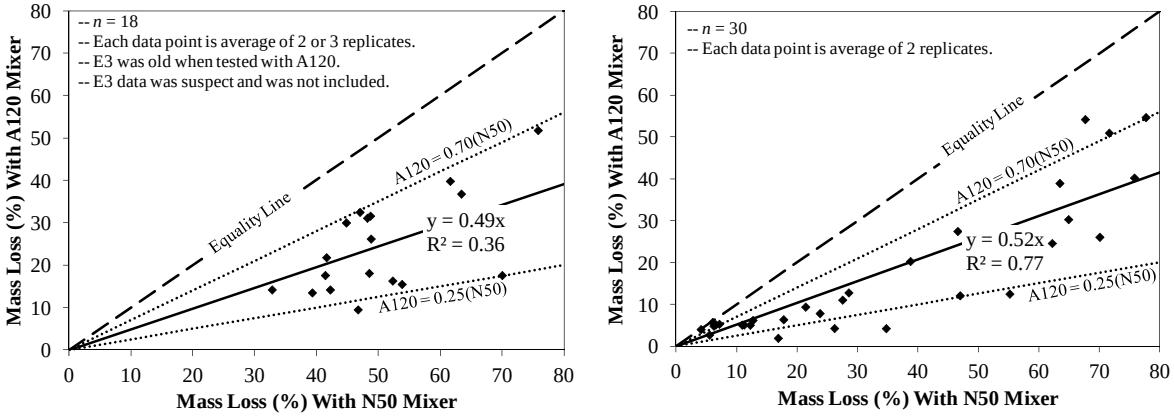
10.3 Comparison of ASTM D7000 and *Sweep-M* Protocols

Figure 10.2 provides equality plots comparing mass loss between the D7000 A120 mixer and the *Sweep-M* N50 mixer. Figure 10.2a data is located in Table 10.1, and Figure 10.2b data is located in Table 10.2. The best-fit trend lines have slopes of 0.49 and 0.52 which indicates the A120 mixer, on average, induces approximately half of the mass loss of the N50 mixer. Both plots show similar amounts of scatter around the trend line as indicated by the dotted line slopes. The dotted lines were subjectively selected to encompass most of the data; slopes were 0.25 and 0.70. The data indicates there is a reasonable correlation between D7000 and *Sweep-M* over a large number of tests (i.e. D7000 produces approximately half the mass loss of *Sweep-M*), but it also shows, that for any one test, the results can vary considerably (i.e. D7000 can produce as little as 25% and as much as 70% of the *Sweep-M* mass loss for any one test).

Longer cure times do not explain the scatter present in the data (i.e. scatter does not necessarily reduce with cure time). This is evidenced by the observation that scatter in Figure 10.2b did not decrease relative to that of Figure 10.2a. During analysis, Figure 10.2b was divided into three additional plots based on aggregate type (n = 10 for each plot). The trend line slopes for aggregates A1, A2, and A3 were 0.64, 0.45, and 0.50, respectively, with corresponding R^2 values of 0.92, 0.67, and 0.79. Therefore, the differences in slope between the three aggregates may explain some of the Figure 10.2 scatter.

A small additional experiment was performed with the *Sweep-M* N50 mixer. Two emulsion-aggregate combinations were tested at several cure times and two test duration times (60 seconds as normal and 46 seconds). With the N50 mixer, 60 seconds resulted in

136 revolutions; whereas, 46 seconds resulted in 104 revolutions which is equivalent to the number of A120 revolutions in 60 seconds. For one emulsion-aggregate combination, mass loss at 46 seconds was 70% of the mass loss at 60 seconds. While reducing number of revolutions to that of the A120 mixer did have a noticeable effect, it appears that reducing revolutions cannot necessarily replicate the A120 mixer (mixer speed is another likely factor to be considered). For the second emulsion-aggregate combination, reducing the number of revolutions did not noticeably affect the mass loss. The data appears to indicate that for some chip seal systems and the N50 mixer, most of the mass loss occurs prior to 46 seconds of sweeping (visual observations during testing also support this position).



a) Comparison at 1 hr Cure Time *b) Comparison at 10 Cure Times (0.5-8 hrs)*

Figure 10.2. Comparison of ASTM D7000 (A120 Mixer) and *Sweep-M* (N50 Mixer)

The overall findings of this section suggest there is a correlation between the A120 and N50 mixers; however, the correlation is likely to change (at least to some extent) depending on the emulsion-aggregate combination. The data in this section ultimately influenced the decision to analyze *Sweep-M* data directly rather than apply any correction factors relative to D7000.

10.4 *Sweep-M* Variability Results

Table 10.6 provides ANOVA results for mass loss variability. Emulsion and cure time did not interact to significantly affect mass loss. Emulsion type did not significantly affect mass loss, but cure time did, which was expected. Since there was no emulsion and cure time interaction, E1 and E2 mass losses were averaged at each cure time which showed mass loss was reduced significantly (from 61% to 43% on average) from a 1 hr cure to a 2 hr cure.

Table 10.6. ANOVA Summary for Mass Loss Variability

Source	*df*	*p-value*	Sig?
Total Corrected	79		
Emulsion x Cure Time	1	0.2278	No
Emulsion	1	0.5752	No
Cure Time	1	<0.0001	Yes
Error	76		

-- $p_{critical} = 0.05$

Table 10.7 provides ANOVA results for moisture loss variability. Emulsion and cure time did not interact to significantly affect mass loss. Both emulsion type and cure time significantly affected moisture loss. E1 demonstrated significantly higher moisture loss than E2. It is of interest to note that, although E2 demonstrated significantly less moisture loss, the mass losses of E1 and E2 were not significantly different. This finding indicates a given mass loss can occur at differing moisture loss levels for different aggregate-emulsion combinations. On average, moisture loss increased from 30% to 47% at the 1 and 2 hr cure times, respectively.

Table 10.7. ANOVA Summary for Moisture Loss Variability

Source	***df***	***p-value***	**Sig?**
Total Corrected	79		
Emulsion x Cure Time	1	0.1261	No
Emulsion	1	<0.0001	Yes
Cure Time	1	<0.0001	Yes
Error	76		

-- $p_{critical} = 0.05$

The most significant observation from the *Sweep-M* variability testing is the spread of the 95% confidence intervals from Table 10.3. Generally speaking, the range of the confidence interval is larger for mass loss results than moisture loss results. The average range for the mass loss confidence intervals is 49%, and the average range for the moisture loss confidence intervals is 36%. This result is somewhat expected, however, as any variability within the moisture loss results would be carried over and compounded by the variability within the sweep test itself.

10.5 *Sweep-M* Results

Mass loss in Table 10.4 shows an initial rapid decrease in mass loss with cure time which equalizes after some period of time. Initial mass loss readings range from 41% (E3-A1-T0.5) to 78% (E2-A3-T0.5), and final readings range from 2% (E4-A3-T8) to 28% (E5-A1-T8). Moisture loss in Table 10.4 shows an initial rapid increase with cure time which also equalizes after some period of time. In some cases, moisture loss appears to depend on emulsion-aggregate compatibility as moisture loss varied between aggregates while using a single emulsion (e.g. approximately 13% difference between E1-A2-T2 and E1-A3-T2).

Table 10.8 provides regression coefficients and R^2 values for each emulsion-aggregate combination tested. The Figure 10.1 examples display how these regression coefficients were derived from trend lines in each plot. Regression coefficients follow the form of Equations 10.1, 10.2, and 10.3 for mass loss versus cure time, moisture loss versus cure time, and mass loss versus moisture loss, respectively. In some cases, Equation 10.1 M_L versus cure time models increased at later cure time, which is not reasonable. An improved, yet succinct method of presenting this data might be useful.

$$M_L = C_5 [T]^2 + C_6 [T] + C_7 \quad (10.1)$$

$$W_L = C_8 \ln[T] + C_9 \quad (10.2)$$

$$M_L = C_{10} [W_L] + C_{11} \quad (10.3)$$

Where,
M_L = mass loss (%)
W_L = moisture loss (%)
C_5, C_6, C_7, C_8, C_9, C_{10}, C_{11} = regression coefficients
T = Cure time (hr)

Table 10.8 provides critical values from the *Sweep-M* analysis curves. The point at which mass loss began to equalize with further curing was referred to as the mass loss inflection point (M_LIP). The cure time at which the M_LIP occurred was denoted the critical cure time (*CCT*) and was determined graphically by plotting two straight lines over the portions of mass loss versus cure time data in which change in mass loss relative to change in cure time was both high and low. Figure 10.3 provides an example plot of *CCT* determination; all other *CCT* plots can be found in Appendix D of Alvarado (2012). All *CCT* values were rounded to the nearest half hour. Equations 10.1 and 10.2 were used to calculate critical mass loss ($M_{L(CCT)}$) and critical moisture loss ($W_{L(CCT)}$), respectively, using the corresponding *CCT* for each emulsion-aggregate combination.

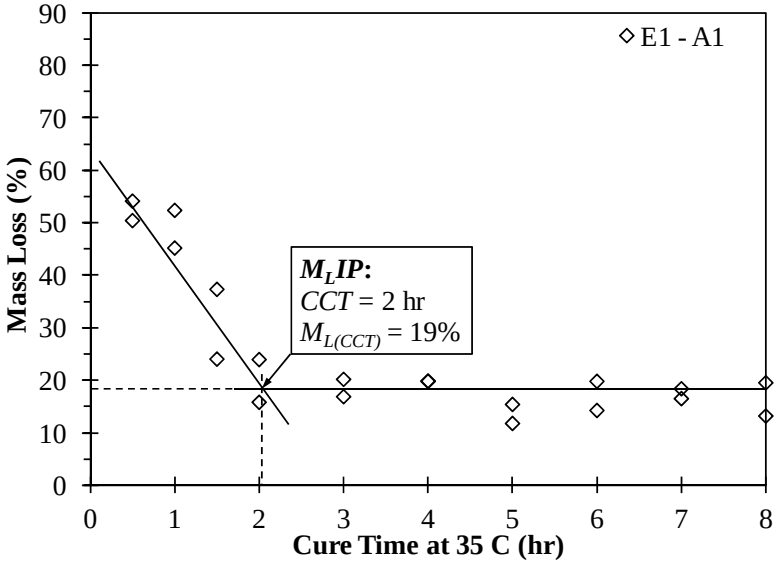


Figure 10.3. Example of *CCT* Plot

The critical values in Table 10.8 provide insight to the emulsion-aggregate interaction. *CCT* values range from 1.5 to 4.5 hours of cure time; note that Howard et al. (2011) found moisture loss is better correlated to mass loss than cure time. On average, the moisture loss at M_LIP ($W_{L(CCT)}$) was 52%, and the critical mass loss ($M_{L(CCT)}$) was 16%.

Trends in $W_{L(CCT)}$ and $M_{L(CCT)}$ vary by chip seal system. For example, critical moisture loss with E6 ranges from 41-43% (lowest critical moisture loss of all emulsions) which results in an average critical mass loss of 9.3%. E4 results in an average critical mass loss of 9.7% (similar to E6) but requires 60-63% moisture loss. E5, on the other hand, demonstrates similar moisture losses at the mass loss inflection point as E6, but average critical mass loss is 26.3% which is 17% greater than that of E6. Essentially, aggregate retention as a function of moisture loss can vary significantly for different combinations of emulsions and aggregates.

Table 10.8. Summary of *Sweep-M* Analysis Curves

		Mass Loss vs. Cure Time Fig 10.1				Moisture Loss vs. Cure Time Fig 10.2			Mass Loss vs. Moisture Loss Fig 10.3			Critical Values		
E	**A**	C_5	C_6	C_7	R^2	C_8	C_9	R^2	C_{10}	C_{11}	R^2	***CCT* (hr)**	$M_{L(CCT)}$ **(%)**	$W_{L(CCT)}$ **(%)**
1	1	1.43	-15.88	56.16	0.80	20.62	38.06	0.90	-0.68	65.60	0.88	2	19	52
	2	1.62	-19.32	64.03	0.89	19.98	42.65	0.87	-0.93	82.88	0.95	2	15	56
	3	1.14	-15.61	57.04	0.90	21.72	33.24	0.96	-0.82	66.94	0.84	3	8	57
2	1	1.48	-20.67	77.39	0.97	20.62	26.83	0.97	-1.21	87.59	0.94	4	11	55
	2	2.15	-27.28	89.69	0.97	21.07	29.21	0.91	-1.29	96.01	0.88	4.5	7	61
	3	1.42	-20.48	90.69	0.87	22.04	25.28	0.98	-1.18	98.75	0.87	3.5	22	53
3	1	0.13	-4.41	43.39	0.78	18.87	31.14	0.98	-0.49	54.24	0.74	3	24	52
	2	1.05	-13.35	59.92	0.87	21.53	31.75	0.98	-0.68	67.71	0.88	2	24	47
	3	0.75	-11.34	60.28	0.95	18.97	30.16	0.99	-0.81	73.04	0.97	2.5	23	48
4	1	1.34	-17.62	63.42	0.92	23.27	34.40	0.96	-0.84	72.91	0.89	3	12	60
	2	2.01	-24.17	73.17	0.97	23.30	37.86	0.95	-1.02	85.90	0.96	3	5	63
	3	1.36	-19.56	72.88	0.94	24.16	32.20	0.98	-1.02	84.69	0.93	3.5	12	62
5	1	0.77	-7.90	46.73	0.48	17.11	30.21	0.99	-0.37	50.37	0.51	2	28	42
	2	1.16	-13.43	56.75	0.72	18.98	34.63	0.97	-0.70	67.63	0.81	1.5	24	42
	3	1.06	-13.97	67.20	0.87	20.78	30.68	0.98	-0.80	77.47	0.94	2.5	27	50
6	1	1.74	-19.66	56.86	0.85	12.66	30.06	0.81	-1.31	74.31	0.88	2.5	8	42
	2	1.58	-17.78	52.01	0.77	12.61	34.10	0.87	-1.30	78.49	0.91	2	9	43
	3	1.12	-14.86	55.49	0.98	11.74	28.40	0.93	-1.33	75.89	0.86	3	11	41
7	1	1.34	-16.41	52.65	0.91	18.94	31.66	0.93	-0.81	59.24	0.79	3	8	52
	2	1.62	-18.46	57.75	0.86	19.38	33.16	0.93	-0.87	67.52	0.91	2.5	12	51
	3	0.82	-13.79	63.71	0.95	19.01	27.91	0.98	-1.05	77.90	0.90	4	19	54

10.5.1 Investigation of Interaction Effects on *Sweep-M* Mass Loss

Analysis of variance tests (ANOVA) with factorial arrangements of treatments are used in this section to statistically analyze the influence of factors such as emulsion, aggregate, and cure time on *Sweep-M* mass loss. A detailed overview of ANOVA testing is provided in Section 7.4. Aside from different treatment factors, the ANOVA protocol in this section is identical to that of Section 7.4.

Table 10.9 provides ANOVA results for all *Sweep-M* mass loss results. There is significant three-way interaction between emulsion, aggregate, and cure time. Because there is interaction, the treatments cannot be analyzed separately; however, a multiple comparisons analysis of 210 treatment combinations would be so large that it would not be practical. For this reason, two-factor interaction was investigated between emulsion and aggregate at each cure time.

Table 10.9. ANOVA Summary for *Sweep-M* Mass Loss Results

Source	*df*	*p-value*	Sig?
Total Corrected	409		
Emulsion x Aggregate x Cure Time	108	<0.0001	Yes
Aggregate x Cure Time	18	<0.0001	n/a
Emulsion x Aggregate	12	<0.0001	n/a
Emulsion x Cure Time	54	<0.0001	n/a
Aggregate	2	<0.0001	n/a
Emulsion	6	<0.0001	n/a
Cure Time	9	<0.0001	n/a
Error	200		

-- $p_{critical} = 0.05$

Table 10.10 provides an overview of emulsion-aggregate interaction at each cure time. ANOVA summaries at each cure time are provided in Table 10.11. The results show that mass loss was largely unaffected by emulsion and aggregate interaction at early cure times. In cases where emulsion and aggregate interaction was not significant, emulsion and aggregate significantly and independently affected mass loss (except at the 8 hr cure time). Multiple comparisons were performed for each cure time and are discussed in the following paragraphs. In many cases where there was significant interaction between emulsion and aggregate, there was also significant chaining within the multiple comparisons. This indicates a single emulsion-aggregate combination that performs statistically significantly better than other combinations over a wide range of cure times may not exist.

Table 10.10. Mass Loss Emulsion and Aggregate Interaction at each Cure Time

Cure Time (hr)	Emulsion x Aggregate	Emulsion	Aggregate
0.5	Not Significant	Significant	Significant
1	Not Significant	Significant	Significant
1.5	Significant Interaction	n/a	n/a
2	Not Significant	Significant	Significant
3	Significant Interaction	n/a	n/a
4	Significant Interaction	n/a	n/a
5	Significant Interaction	n/a	n/a
6	Significant Interaction	n/a	n/a
7	Significant Interaction	n/a	n/a
8	Not Significant	Significant	Not Significant

Table 10.11. ANOVA Summary for Mass Loss at each Cure Time

Cure Time (hr)	Source	*df*	*p-value*	Sig?
0.5	Total Corrected	40		
	Emulsion x Aggregate	12	0.1056	No
	Emulsion	6	< 0.0001	Yes
	Aggregate	2	0.0003	Yes
	Error	20		
1	Total Corrected	40		
	Emulsion x Aggregate	12	0.1231	No
	Emulsion	6	< 0.0001	Yes
	Aggregate	2	0.0064	Yes
	Error	20		
1.5	Total Corrected	40		
	Emulsion x Aggregate	12	0.0054	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	< 0.0001	n/a
	Error	20		
2	Total Corrected	40		
	Emulsion x Aggregate	12	0.0685	No
	Emulsion	6	< 0.0001	Yes
	Aggregate	2	< 0.0001	Yes
	Error	20		
3	Total Corrected	40		
	Emulsion x Aggregate	12	0.0090	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	< 0.0001	n/a
	Error	20		
4	Total Corrected	40		
	Emulsion x Aggregate	12	0.0070	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	0.0494	n/a
	Error	20		
5	Total Corrected	40		
	Emulsion x Aggregate	12	< 0.0001	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	< 0.0001	n/a
	Error	20		
6	Total Corrected	40		
	Emulsion x Aggregate	12	0.0060	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	0.0040	n/a
	Error	20		
7	Total Corrected	40		
	Emulsion x Aggregate	12	0.0002	Yes
	Emulsion	6	< 0.0001	n/a
	Aggregate	2	0.0092	n/a
	Error	20		
8	Total Corrected	40		
	Emulsion x Aggregate	12	0.0610	No
	Emulsion	6	< 0.0001	Yes
	Aggregate	2	0.7545	No
	Error	20		

-- $p_{critical} = 0.05$

Table 10.12 and 10.13 provide multiple comparisons rankings for emulsions and aggregates, respectively, in the cases in which there was insignificant interaction between emulsion and aggregate. Note that results are ranked by mean mass loss in descending order; therefore, those emulsions or aggregates with more favorable measured responses are located towards the lower portion of the ranking. For those cases in which there was significant two-factor interaction between emulsion and aggregate, multiple comparisons rankings were performed for each emulsion-aggregate combination and are provided in Tables 10.14 and 10.15.

Table 10.12. Ranking of Emulsion With Respect to Mass Loss for Various Cure Times

0.5 hr Cure Time			1 hr Cure Time			2 hr Cure Time			8 hr Cure Time		
E	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**	**E**	**Mean**	***t*-Group**
2	72.3	A	2	69.7	A	2	49.3	A	5	22.4	A
4	61.2	B	4	49.7	B	4	33.9	B	3	17.8	A
5	56.6	BC	5	49.6	B	3	33.1	B	1	9.3	B
6	55.7	BC	1	48.1	B	5	31.2	BC	2	9.1	BC
1	54.9	BC	7	47.4	B	7	30.6	BC	6	6.6	BC
3	52.5	C	3	46.1	B	1	26.2	C	7	6.1	BC
7	51.3	C	6	37.9	C	6	19.1	D	4	3.6	C

-- Mean values are mass loss for each emulsion averaged across aggregate.

Table 10.13. Ranking of Aggregate With Respect to Mass Loss for Various Cure Times

0.5 hr Cure Time			1 hr Cure Time			2 hr Cure Time			8 hr Cure Time		
A	**Mean**	***t*-Group**	**A**	**Mean**	***t*-Group**	**A**	**Mean**	***t*-Group**	**A**	**Mean**	***t*-Group**
2	61.3	A	3	53.9	A	3	39.0	A	1	11.3	N-S
3	60.9	A	2	47.9	B	1	28.9	B	2	10.8	
1	51.1	B	1	47.6	B	2	27.8	B	3	9.9	

-- Mean values are mass loss for each aggregate averaged across emulsion.

At early cure times, E6 develops noticeably better aggregate retention relative to other emulsions. E6 becomes somewhat overshadowed at later cure times as other emulsions begin to gain strength and improve within the rankings, but aggregate retention of E6 remains satisfactory. E5 progressively worsens relative to other emulsions. This indicates that it maintains average behavior at early cure times but does not improve at later cure times as other emulsions. Generally, A3 is the worst performing aggregate of the three except when used with E1. Overall, E4, E6, and E7 provide the best aggregate retention towards the end of curing, especially with A1 and A2.

There are two issues of overall interest pertaining to Tables 10.12 to 10.15. First, emulsions, aggregates, or combinations which display strong aggregate retention behavior at early cure times are of interest in relation to timing of traffic opening. Second, overall aggregate retention behavior after some considerable amount of curing is of interest to the overall performance of an emulsion or aggregate as well as the compatibility of the two. For any aggregate, but especially with A1 or A2, E6 appears to be useful for cases where timely return to traffic is of central priority. In terms of overall performance at later cure times when considerable moisture has been lost, E4, E6, and E7 exhibit the most desirable aggregate retention. This suggests that emulsion should be selected to meet specific performance objectives. If early traffic opening is of great concern, E6 appears to be a good selection; if not, E4 or E7 could be more practical depending on cost factors.

Table 10.14. Ranking of Emulsion-Aggregate Combinations With Respect to Mass Loss for 1.5, 3, and 4 Hour Cure Times

1.5 hr Cure Time				3 hr Cure Time				4 hr Cure Time			
E	**A**	**Mean**	***t*-Group**	**E**	**A**	**Mean**	***t*-Group**	**E**	**A**	**Mean**	***t*-Group**
2	3	64.9	A	7	3	33.8	A	5	3	32.6	A
2	2	55.2	B	3	3	31.5	AB	3	1	31.4	AB
4	3	52.7	BC	3	1	30.2	ABC	5	2	30.1	AB
3	2	46.7	BCD	2	3	28.5	ABCD	3	2	29.7	AB
2	1	46.6	BCD	5	3	27.5	ABCD	3	3	27.8	ABC
4	1	45.0	CDE	2	1	27.5	ABCD	5	1	26.8	ABCD
3	3	43.6	DE	3	2	26.9	ABCDE	2	3	23.8	BCDE
5	3	43.5	DE	5	2	26.6	ABCDEF	7	3	21.5	CDE
4	2	43.0	DE	5	1	25.2	BCDEFG	1	1	19.9	DEF
7	3	37.0	EF	4	3	24.5	BCDEFG	2	1	17.8	EFG
6	3	36.5	EF	1	3	22.5	CDEFG	1	2	17.0	EFGH
5	1	34.6	EFG	2	2	21.4	DEFG	6	3	16.8	EFGH
7	1	34.0	FGH	6	3	19.2	EFGH	4	1	16.8	EFGH
1	2	32.0	FGH	1	2	18.9	FGHI	2	2	12.7	FGHI
3	1	31.1	FGH	1	1	18.6	GHIJ	4	3	12.6	FGHI
1	1	30.7	FGH	4	2	12.9	HIJK	6	2	12.5	FGHI
5	2	29.3	FGHI	6	2	11.4	IJK	7	2	10.7	GHI
1	3	25.9	GHIJ	4	1	11.3	IJK	1	3	9.8	HI
7	2	24.7	HIJ	7	2	11.0	JK	6	1	8.0	I
6	1	20.5	IJ	6	1	11.0	JK	4	2	7.3	I
6	2	19.3	J	7	1	6.1	K	7	1	4.1	I

Table 10.15. Ranking of Emulsion-Aggregate Combinations With Respect to Mass Loss for 5, 6, and 7 Hour Cure Times

5 hr Cure Time				6 hr Cure Time				7 hr Cure Time			
E	**A**	**Mean**	***t*-Group**	**E**	**A**	**Mean**	***t*-Group**	**E**	**A**	**Mean**	***t*-Group**
2	3	34.8	A	5	1	30.5	A	5	1	32.0	A
5	1	31.1	AB	2	3	26.2	A	5	3	26.9	B
5	3	25.2	BC	5	3	24.5	AB	5	2	19.3	C
3	1	24.2	C	3	3	23.4	ABC	3	2	17.9	C
3	3	24.2	C	3	1	23.0	ABC	1	1	17.5	C
5	2	20.7	CD	5	2	17.6	BCD	3	1	15.7	CD
3	2	19.9	CDE	1	1	17.0	CDE	3	3	15.6	CD
7	3	16.9	DEF	3	2	16.8	CDEF	2	3	12.2	DE
1	1	13.6	EFG	2	1	11.2	DEFG	1	2	10.0	EF
4	3	12.0	FGH	7	2	9.6	EFG	7	2	9.9	EF
2	1	10.9	FGHI	4	3	9.5	FG	4	1	7.7	EFG
6	3	10.5	FGHI	1	2	9.4	FG	6	1	7.1	FG
7	2	10.2	FGHI	4	1	8.9	G	2	2	6.6	FG
1	2	9.4	GHI	7	3	8.6	G	7	3	6.5	FG
4	1	8.3	GHI	1	3	7.3	G	7	1	6.4	FGH
7	1	8.2	GHI	2	2	7.1	G	6	2	5.7	FGH
6	2	6.9	GHI	6	1	6.9	G	2	1	5.5	FGH
1	3	6.3	HI	7	1	6.6	G	1	3	5.3	GH
6	1	6.1	HI	6	2	6.4	G	4	2	5.2	GH
2	2	6.0	HI	4	2	6.1	G	6	3	4.8	GH
4	2	5.1	I	6	3	6.0	G	4	3	1.5	H

10.5.2 Aggregate Property Evaluation

Table 3.8 aggregate properties, such as H, M, and C_u, can be used to formulate performance expectations. A1 was expected to perform better compared to A2 and A3 since more voids are filled for aggregates with smaller average least dimension (given the same emulsion application rate and the same compaction efforts) (McLeod, 1969). A1 has a noticeably smaller average least dimension than A2 and A3 (3.2, 4.7, and 4.7 mm, respectively).

By comparison, A1 has a smaller M value (4.6 mm) and, thus, possesses more particles embedded than A2 and A3 (7.1 and 6.2 mm, respectively). Therefore, less mass loss is expected. A2 and A3 have larger particles which, by comparison, are more prone to becoming dislodged (McLeod, 1969).

By comparison, A1 (C_u of 2.8) is expected to have slightly better aggregate interlock than A2 (C_u of 2.3), while A3 (C_u of 1.9) should have the worst interlock. According to Shuler et al. (2011), aggregates with coefficient of uniformity (C_u) less than 4.0 are defined as uniformly-graded and are expected to perform better than well-graded aggregates.

These properties (H, M, and C_u) are derived from the overall gradation. However, the sweep test (both D7000 and *Sweep-M*) only tests a narrow band of the overall gradation (the 4.75 mm to 9.5 mm material). Therefore, the sweep test may not be able to account for or detect factors such as these properties which relate to the overall gradation.

A1 and A2 are also expected to perform better than A3 because they posses more fines which accelerate breaking of the emulsion (MS-19, 1997). According to MS-19 (1997), aggregates with higher absorption perform better because they drive water out of the emulsion at a faster rate. Based on absorption, A1 is expected to perform best, while A3 should perform better than A2.

Table 10.16 provides a qualitative means of evaluating aggregates that provide the most and least desirable measured responses. Aggregates were analyzed with each emulsion and at each cure time. It should be noted this is not a statistical analysis but a subjective assessment. A1 performed best 40% of the time, followed by A2 which performed best 36% of the time. A3 performed best the least number of times and performed worst the greatest number of times. Although A1 performed best the greatest number of times, it performed worst more times than A2. This indicates that at any given cure time and for any given emulsion, A1 generally performs best, but there remains a high chance that either of the other two aggregates could outperform A1. The opposite is true of A3.

Table 10.16. Percentage of Cases in Which Aggregates Are Most or Least Desirable

Aggregate	Most Desirable (%)	Least Desirable (%)
1	40	27
2	36	16
3	24	57

10.5.3 Investigation of Interaction Effects on *Sweep-M* Moisture Loss

Analysis of variance tests (ANOVA) with factorial arrangements of treatments (FAT) are used in this section to statistically analyze the influence of factors such as emulsion, aggregate, and cure time on *Sweep-M* moisture loss. A detailed overview of ANOVA testing

is provided in Section 7.4. Aside from different treatment factors, the ANOVA protocol in this section is identical to that of Section 7.4.

Table 10.17 provides ANOVA results for all *Sweep-M* moisture loss results. There is no significant three-way interaction between emulsion, aggregate, and cure time, but there is significant two-way interaction between aggregate and cure time, emulsion and aggregate, and emulsion and cure time. For this reason, each two-factor interaction is explored in more detail in subsequent paragraphs.

Table 10.17. ANOVA Summary for *Sweep-M* Moisture Loss Results

Source	*df*	*p-value*	Sig?
Total Corrected	409		
Emulsion x Aggregate x Cure Time	108	0.8485	No
Aggregate x Cure Time	18	0.0010	Yes
Emulsion x Cure Time	54	<0.0001	Yes
Emulsion x Aggregate	12	<0.0001	Yes
Emulsion	6	<0.0001	n/a
Aggregate	2	<0.0001	n/a
Cure Time	9	<0.0001	n/a
Error	200		

-- $p_{critical} = 0.05$

Aggregate and cure time interaction was investigated to analyze moisture loss results by aggregate source. Analysis was performed by averaging all emulsion moisture loss results for any given aggregate at each cure time. Consequently, an interaction plot was developed to graphically represent moisture loss for each aggregate during an eight hour period. Figure 10.4 shows the rapid, initial moisture loss increase at early cure times; during this time, all aggregates yielded relatively equal moisture loss. Overlapping suggests that moisture loss occurs similarly during 0.5-1.5 hr cure time, regardless of aggregate source.

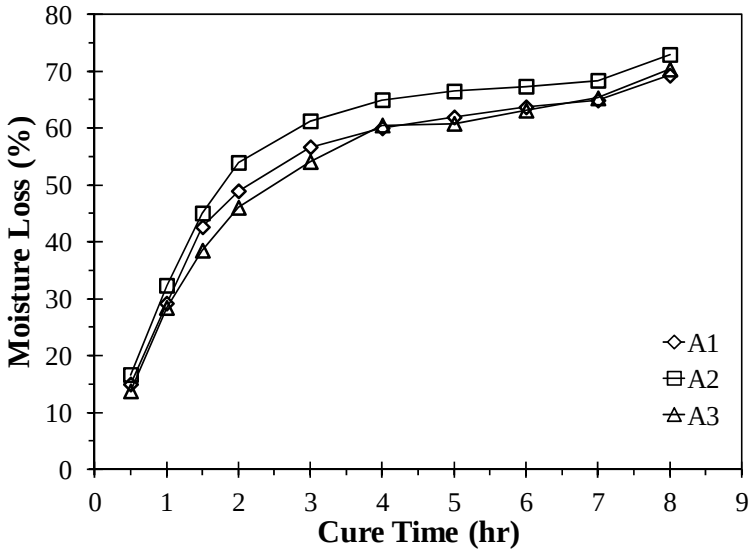


Figure 10.4. Moisture Loss Aggregate and Cure Time Interaction Plot

During the range of cure times which *CCT* was observed (1.5-4.5 hr), A2 (0.8% *Abs*) exhibited higher moisture loss results while A1 (1.8% *Abs*) and A3 (1.3% *Abs*) had

approximately equal moisture loss. Overall, A2 demonstrated greater moisture loss, being at most 7% higher.

During the remaining curing period (5-8 hr), A2 continued to exhibit the greatest moisture loss; however, the difference between A2 and A1 or A3 decreased with increasing cure time. Even though absorption can be differentiated at *CCT* cure levels, Figure 10.4 shows that moisture loss begins to converge at later cure times for all aggregates. Overall, not much interaction is observed.

Emulsion and cure time interaction was investigated to analyze moisture loss results by emulsion. Analysis was performed by averaging all aggregate moisture loss results for any given emulsion at each cure time. Consequently, an interaction plot was developed to graphically represent moisture loss for each emulsion during an eight hour period. Figure 10.5 shows that at 0.5 hour cure, moisture loss results cannot differentiate between emulsion sources. At this time, 10-17% moisture loss occurred regardless of the emulsion.

From 1-2 hr cure, E1 (non-polymer modified) had noticeably higher moisture loss than the other emulsions. At *CCT* cure levels, E6 yielded noticeably lower moisture loss, while E2, E3, E5, and E7 had mid-level moisture loss, and E1 and E4 had higher moisture loss. During late cure times, moisture loss results cannot differentiate between E2, E3, E5, and E7. Similarly, E6 yielded noticeably lower moisture loss, while E1 and E4 were comparatively higher than the all other emulsions. It appears that E4, having higher float and higher viscosity, is capable of approximately the same rate of moisture loss at 35 C as E1.

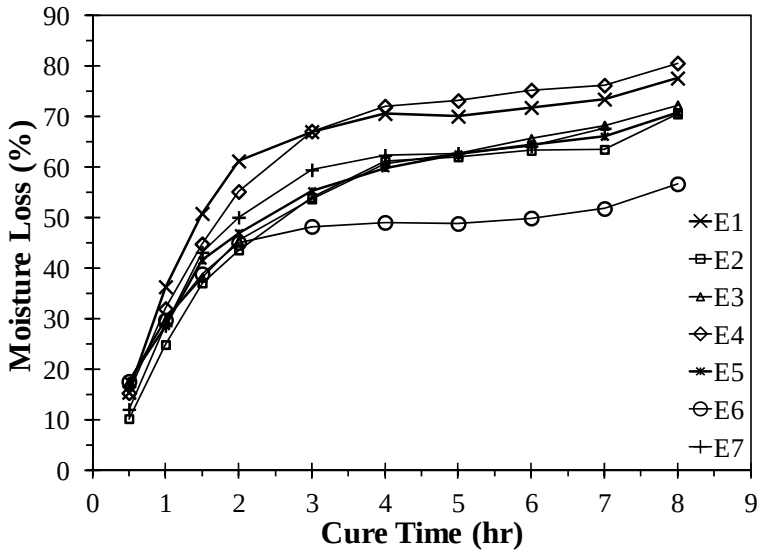


Figure 10.5. Moisture Loss Emulsion and Cure Time Interaction Plot

Table 10.18 provides the multiple comparisons rankings for each emulsion and aggregate combination. Moisture loss for each emulsion-aggregate combination was averaged across all curing times. This resulted in 21 treatment combinations total.

Either E1 or E4 with A2 yield significantly higher moisture loss than all other combinations. This is not surprising as A2 and both E1 and E4 yielded the highest moisture loss in Figure 10.4 and 10.5, respectively. Fairly significant chaining exists for all other combinations, but several observations can be made from a subjective viewpoint (note that the following observations are not necessarily statistically conclusive). First, E1 and E4 rank

the higher than all other emulsions with respect to moisture loss regardless of aggregate source. For E2, E3, E5, and E7, moisture loss appears more dependent on aggregate type with A2 generally producing the greater moisture loss than other aggregates for a given emulsion. E6 produced the lowest moisture loss regardless of aggregate type. Overall, E1, E4, and A2 yield higher moisture loss; whereas, E6 yields the lowest moisture loss.

Table 10.18. Ranking of Emulsion and Aggregate With Respect to Moisture Loss

Emulsion	Aggregate	Mean	*t*-Group
1	2	62.67	A
4	2	58.03	A
1	1	55.97	B
4	1	51.77	BC
4	3	39.80	CD
1	3	36.83	DE
5	2	32.47	EF
3	2	31.57	F
7	2	31.07	FG
5	3	29.93	GH
7	1	26.17	GHI
2	2	21.83	HI
3	1	18.07	HI
3	3	17.57	I
2	1	17.57	J
2	3	16.27	J
5	1	15.53	J
7	3	14.23	J
6	2	14.20	J
6	1	13.50	K
6	3	9.47	L

10.5.4 Comparison of *Sweep-M* Moisture Loss and Mass Loss Results

Table 10.19 provides overall ranking of each emulsion-aggregate combination with respect to both mass loss and moisture loss (averaged over all cure times). This ranking is not a statistical grouping but rather a means of comparing mass loss and moisture loss for each emulsion-aggregate combination simultaneously. The emulsion and aggregate are treated as a combination rather than individually as there was generally, although not always, significant two-factor interaction.

Table 10.19 demonstrates that E6 ranked least desirable in terms of moisture loss but one of the most desirable in terms of mass loss. This indicates there is not necessarily a universal moisture loss level that can be used to indicate when mass loss levels become acceptable. If there was a universal critical moisture loss level, E6 would likely fail to even though it performs best in terms of mass loss. This finding suggests that, in practice, sweep testing should be conducted for each combination of emulsion and aggregate in order to establish the critical moisture loss level for each specific combination. In the field, the moisture loss could then be monitored and used for guidance on traffic opening.

Table 10.19. Ranking of Emulsion-Aggregate Combinations

Mass Loss Ranking			Moisture Loss Ranking		
E	**A**	**Avg M_L (%)**	**E**	**A**	**Avg W_L (%)**
6	2	17.2	1	2	63.3
6	1	18.0	4	2	61.9
7	1	18.0	1	1	59.3
7	2	21.0	4	1	58.4
1	3	21.2	4	3	57.1
6	3	22.2	1	3	55.7
4	2	22.9	5	2	54.2
1	2	24.0	3	2	54.0
4	1	24.1	7	2	53.2
1	1	25.5	5	3	52.1
4	3	26.7	7	1	51.2
7	3	28.2	2	2	51.0
3	1	29.3	3	1	50.6
2	1	29.3	3	3	49.7
5	2	29.7	2	1	48.1
2	2	30.4	2	3	48.0
3	2	30.8	5	1	47.9
5	1	32.6	7	3	47.5
3	3	32.7	6	2	47.1
5	3	36.0	6	1	43.1
2	3	42.3	6	3	40.5

Note: M_L and W_L for each emulsion-aggregate combination are averaged over all ten cure times.

In Table 10.19, E1 and E4 rank highest in terms of moisture loss but slightly less (average to high) in terms of mass loss. It appears that other emulsions which rank average in terms of moisture loss can either move up (E7) or down (E5) in terms of mass loss rank. This further affirms the theory that moisture loss, although probably a better indicator of mass loss than cure time, is not necessarily a consistent indicator of mass loss performance.

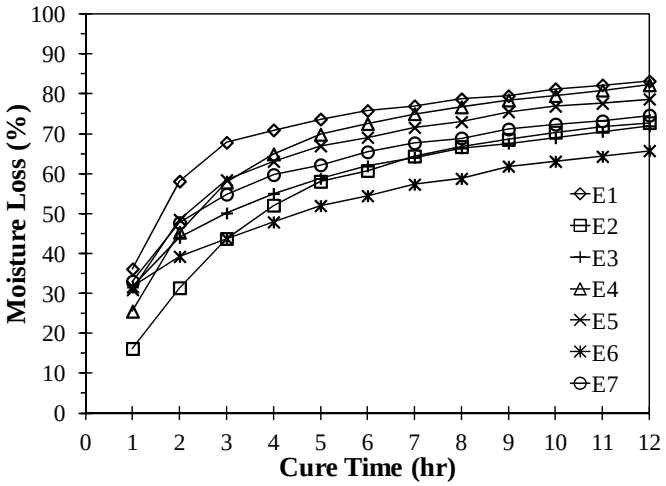
10.5.5 *Sweep-M* Results for Extended Cure Times

Figure 10.6 provides results of the *Sweep-M* tests that underwent extended-duration curing. At the 96 hr cure time, all specimens were tested for mass loss to investigate each emulsion's strength at high moisture loss. Figure 10.6a shows that water evaporates from each emulsion differently during the first twelve hours of curing. E3 and E6 never experienced rapid moisture loss. Conversely, E1 experienced rapid initial moisture loss.

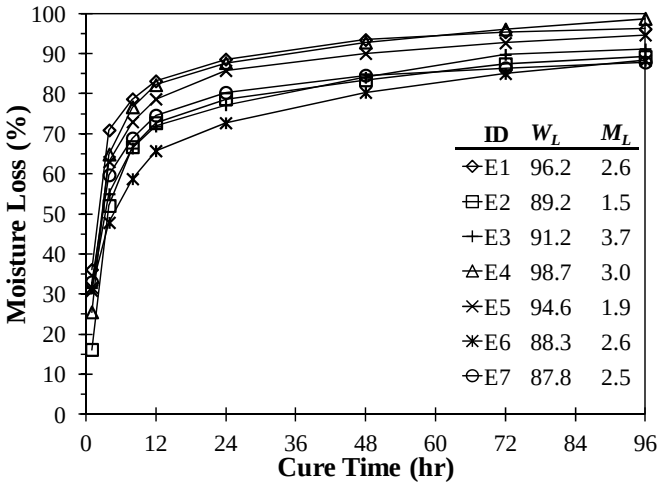
During the first 3 hours of curing, E1 and E4 exhibit predominantly higher moisture loss while E2 exhibits lower moisture loss. During the 4-12 hr cure period, E6 shows noticeably lower moisture loss, while E2, E3, and E7 exhibit comparatively mid-level moisture loss. At 12 hours of curing, moisture loss ranged from 66-83%.

Figure 10.6b shows that after the first 12 hours of curing, all emulsions had steady, essentially linear moisture loss throughout the remaining 84 hours of curing. Similarly, E1 and E4 exhibit higher moisture loss values during this period while E6 exhibits the lowest moisture loss. At 96 hours of curing, E1, E4, and E5 had higher moisture loss than E2, E3, E6, and E7. The average 96 hr moisture loss was 92.3% with an 11% range from 87.8% (E7)

to 98.7% (E4). The data suggests specimens should be cured 96 hrs or more at 35 C and 30% humidity to achieve near 100% moisture loss. Low and practically indistinguishable mass loss resulted at 96 hr cure, with values ranging from 1.5 to 3.7%.



a) Moisture Loss During First 12 Hours of Extended Duration Curing



b) Moisture Loss During Extended Duration Curing (W_L and M_L at 96 hr provided)

Figure 10.6. *Sweep-M* Results for Extended Cure Times

10.6 Discussion and Conclusions

In general, there is a correlation between the ASTM D7000 A120 mixer and the *Sweep-M* N50 mixer. On average, the N50 mixer is twice as aggressive as the A120 mixer although this correlation could vary significantly for any one test. For discussion purposes, the *Sweep-M* mass loss results were assumed to be twice the value that D7000 would provide. Consequently, any maximum mass loss values recommended in literature were halved in order to compare with *Sweep-M* results.

Regarding *Sweep-M* variability, twenty replicates generally were sufficient to provide a normally-distributed sample population. Overall, COV for moisture loss ranged from 8.8-16.6%, and COV for mass loss ranged from 7.6-18.4%. Moisture loss COV tended to decrease with longer curing time, but mass loss COV tended to increase with longer curing

time. Although only two emulsions were tested, it should be noted that the two emulsions resulted in significantly different moisture loss results but insignificantly different mass loss results. This reinforces the notion that mass loss is not a function of moisture loss alone but is likely to also be dependent on the specific emulsion and aggregate used.

Evaluation of the *Sweep-M* results both at the M_LIP and on average indicates that moisture loss alone is not capable of predicting the relative mass loss. The data demonstrates with some emulsion-aggregate combinations, moisture loss can be relatively low, but the system can yield similar mass loss results as another system with relatively high moisture loss. This finding advances the findings of Howard et al. (2011) and suggests that, for some chip seal systems, the moisture loss criteria of 80 to 90% can be reduced and still lead to good early traffic opening performance. Statistical analysis revealed significant interaction between emulsions and aggregates; therefore, it would be ideal to analyze each combination of emulsion and aggregate as a system. To reach near 100% moisture loss, approximately 96 hours of curing were required as a minimum. After 96 hours of curing, moisture loss values ranged from approximately 88-98%, but mass loss values were not greatly different (total mass loss range of 2.2% for all emulsions).

CHAPTER 11-DISCUSSION OF RESULTS

11.1 Overview of Discussion of Results

Chapters 5 to 10 discuss individual test methods and specific issues related only to the results of a single method. This chapter builds on Chapters 5 to 10 and focuses on analysis between test methods. Two categories of discussion are presented: rejuvenation and aggregate retention. In addition, the interrelation between rejuvenation and aggregate retention are also discussed.

11.2 Rejuvenation Discussion

Three test methods to evaluate rejuvenation were studied in this report: repeated creep (*RC*) test, rotational viscosity test, and the bending beam rheometer (*BBR*) test. *RC* testing does not appear to be an ideal means of evaluating rejuvenation and is not discussed further in this chapter. Viscosity and *BBR* testing appear promising although viscosity testing may be limited in its flexibility and long-term usefulness. Viscosity and *BBR* testing were generally able to detect changes in application rate; therefore, for the purposes of discussion and clarity of overall trends, results shown in this chapter are the average of all three application rates.

Figure 11.1 provides the relationship between $V_{D(\%)}$ from viscosity testing and Δ*m-value* from *BBR* testing. For 135 C and 165 C viscosity testing, there is a correlation to Δ*m-value*; however, the correlation is fairly weak (*p-values* are 0.1796 and 0.1519 for 135 C and 165 C, respectively). In general, Figure 11.1 suggests $V_{D(\%)}$ increases range from 2 to 4% for every 0.01 increase in Δ*m-value*. The scatter around the trendline should not be overlooked. Although the general trend is 2 to 4% $V_{D(\%)}$ to 0.01 Δ*m-value*, any one result could violate this trend considerably. Overall, the 135 C viscosity data exhibited less variability than the 165 C data, and use of the lower temperature appears more intuitive for characterizing rejuvenation behavior of seal treatments. For these reasons, only the 135 C viscosity data is used for further comparison and discussion.

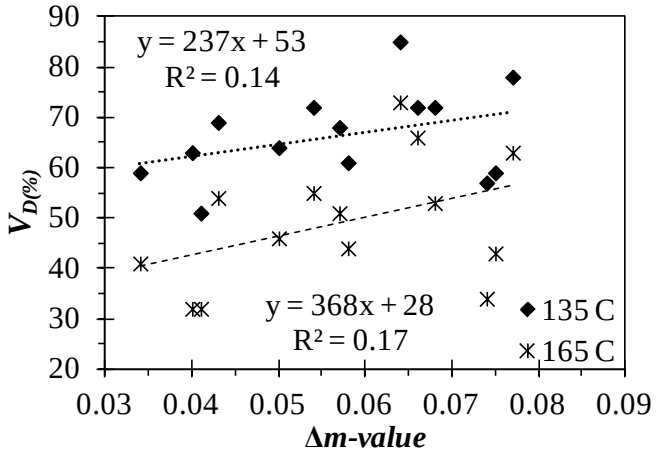
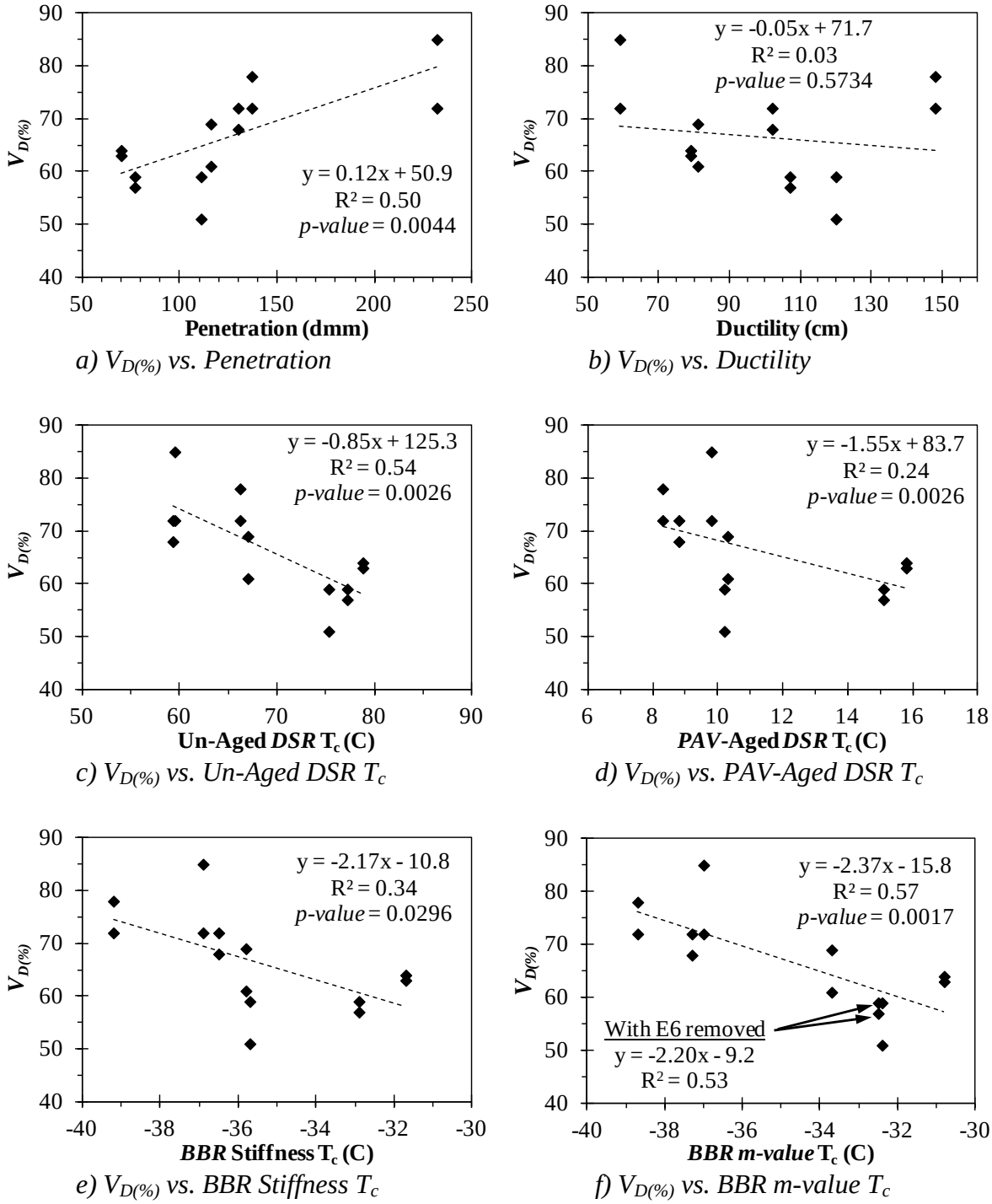


Figure 11.1. Relationship Between $V_{D(\%)}$ and Δ*m-value*

Given there is no strong relationship between viscosity and *BBR* results, the relationship between emulsion properties and $V_{D(\%)}$ or Δ*m-value* are explored in Figures 11.2 and 11.3. Relationships with pavement properties from Chapter 3 (e.g. permeability and asphalt content) were not shown because a correlation analysis revealed poor correlation to $V_{D(\%)}$ or Δ*m-value* for all pavement properties (*p-values* were 0.5 to 0.9).

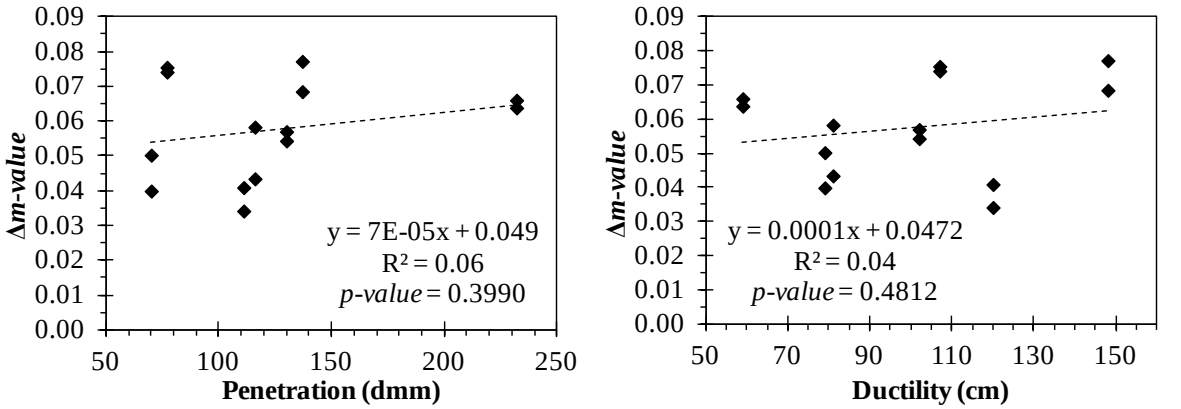


a) $V_{D(\%)}$ vs. Penetration *b) $V_{D(\%)}$ vs. Ductility*

c) $V_{D(\%)}$ vs. Un-Aged DSR T_c *d) $V_{D(\%)}$ vs. PAV-Aged DSR T_c*

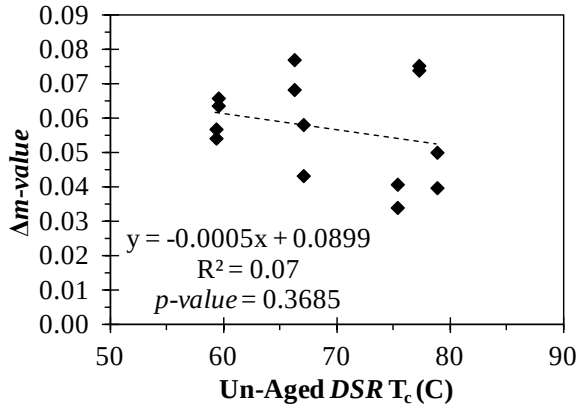
e) $V_{D(\%)}$ vs. BBR Stiffness T_c *f) $V_{D(\%)}$ vs. BBR m-value T_c*

Figure 11.2. 135 C $V_{D(\%)}$ Correlation to Various Emulsion Properties

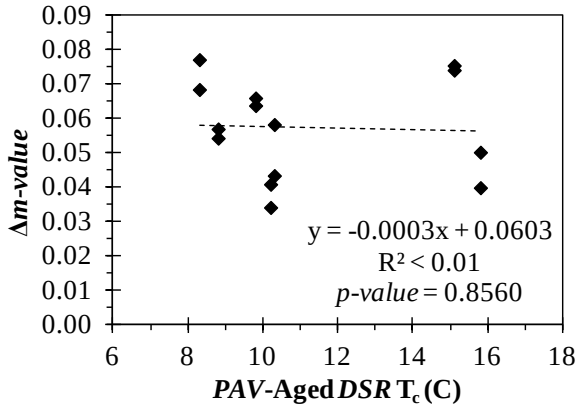


a) Δm-value vs. Penetration

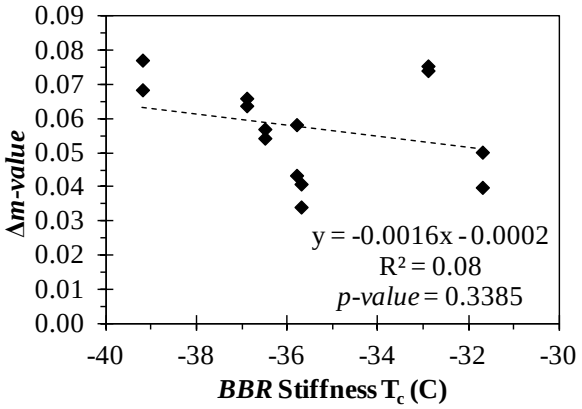
b) Δm-value vs. Ductility



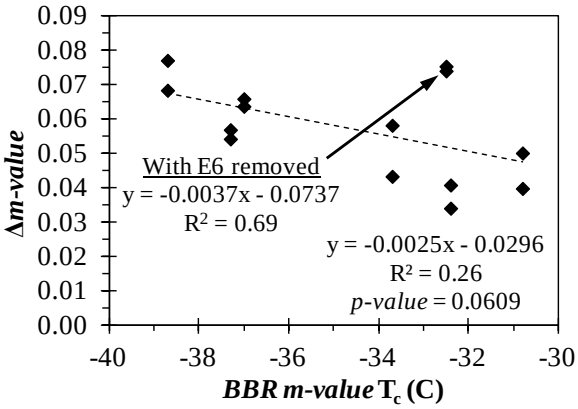
c) Δm-value vs. Un-Aged DSR T_c



d) Δm-value vs. PAV-Aged DSR T_c



e) Δm-value vs. BBR Stiffness T_c



f) Δm-value vs. BBR m-value T_c

Figure 11.3. Δ*m-value* Correlation to Various Emulsion Properties

Based on Figures 11.2 and 11.3, $V_{D(\%)}$ exhibits better correlation to more emulsion properties than Δ*m-value*, indicating viscosity testing appears capable of detecting high, intermediate, and low temperature emulsion properties. This finding, however, is not beyond reason since viscosity testing only evaluates the recovered blend of aged binder and applied emulsion binder, whereas *BBR* testing accounts for the entire emulsion treated pavement system absent unrealistic and forced blending. For this reason, it seems likely that viscosity results would show more direct relationships to emulsion properties than *BBR* results.

Overall, behavior of E6 was somewhat unique in that it generally responded favorably in both rejuvenation and aggregate retention contexts, which generally was not the case for other emulsions. This observation is discussed in more detail in later discussion but is of interest to note at this point because of the behavior observed in Figure 11.3f. The critical failure temperature based on emulsion residue *m-value* correlates fairly well to Δ*m-value* measured on emulsion treated mixture beams with the exception of E6. This suggests the common perception that emulsions with softer base asphalts are better rejuvenators is supported by this research but is not universal to all emulsions. Even though E6 residue is harder than most other emulsion residues, it provides one of the highest Δ*m-values*. The implication of this observation is that rejuvenating emulsions should be produced, bought, and sold based on the actual properties desired (e.g. Δ*m-value*) rather than properties that generally correlate well (e.g. *m-value* failure temperature). If product specifications relied on properties such as *m-value* failure temperature, E6 would likely be underestimated and possibly kept off approved product lists, despite its favorable performance in terms of rejuvenation characteristics. General trends, such as that shown in Figure 11.3f, could be useful to emulsion producers but, based on the results of this research, are not the most efficient specification approach in terms of rejuvenation.

The behavior of E6 supports use of a test to directly measure rejuvenation rather than material properties that generally, but not always, correlate to rejuvenation. The test method selected should be capable of detecting unique cases such as E6. Based on Figure 11.2f, viscosity testing did not necessarily distinguish E6 from other emulsions. This brings to question whether use of a high temperature test is appropriate for characterizing rejuvenation since rejuvenation typically seeks to address issues most often associated with lower temperatures experienced in service (i.e. -22 to 64 C in Mississippi). If rejuvenation characterization is accomplished through a viscosity reduction specification, the outcome may not be that which is desired. Many techniques are capable of reducing viscosity (e.g. blending aged binder with used motor oil), but not all of these techniques provide desired behavior. Although viscosity testing does detect an emulsion, such as E3, which benefits rejuvenation, viscosity testing may also detect a different additive that may not actually positively rejuvenate the pavement. With a viscosity reduction specification, both materials have satisfied the specification, but only one has truly rejuvenated the pavement. This is an inherent deficiency of the viscosity reduction system. Although viscosity reduction testing can be informative for rejuvenation characterization, it also appears limited in that it can provide a false sense of rejuvenation if not carefully controlled. The *BBR*, on the other hand, is directly measuring properties within temperatures of interest. Therefore, the *BBR* appears to have a greater ability to, not only measure the amount of rejuvenation, but also discriminate rejuvenators from non-rejuvenators. Given that there are no major labor and cost differences between viscosity reduction testing and *BBR* mixture beam testing, the *BBR* appears to be more promising for characterizing rejuvenation.

Although the *BBR* testing of emulsion treated mixture beams shows promise, there is likely potential for additional improvement with further study. For example, *m-value* curves exhibited not only translation but also rotation after emulsion treatment (depicted in Figure 7.2). This implies emulsion treatment affects pavements differently at different loading times, yet the causes or consequences of this are not currently understood. Additional research could improve areas within *BBR* testing such as the aforementioned. In contrast, viscosity testing has been studied and used for many years; therefore, most areas of

improvement have likely been explored previously. Additionally, the *BBR* tests beams sawn from the location of interest (i.e. the surface) of pavements; whereas, the viscosity test requires extraction and recovery and tests the bituminous material only. This results in a forced blending of emulsion residue and aged binder which produces a less realistic test sample than a *BBR* surface mixture beam. To date, *BBR* testing appears preferable to viscosity testing, and, with improvement, the disparity between the two is likely to increase.

Table 11.1 provides four multiple regression models for estimating Δ*m-value* based on emulsion properties for the field aged existing pavements. Ott and Longnecker (2010) was used for guidance on multiple regression techniques which were performed using PROC REG in SAS. As stated previously, Chapter 3 pavement properties correlated poorly to Δ*m-value* (*p-values* above 0.8) and were not included in the regression. Although only one emulsion property appears decently correlated to Δ*m-value*, all emulsion properties were included for consideration in the regression model. Equation 11.1 is the general form of the multiple regression model used in this report to estimate Δ*m-value*.

$$y_p = \beta_0 + \beta_1(x_1) + \beta_2(x_2) + ... + \beta_z(x_z) + \varepsilon \quad (11.1)$$

Where,
y_p = dependent or predicted variable (Δ*m-value*)
β_0 = constant
$\beta_1, \beta_2, \ldots, \beta_z$ = coefficients of the independent variables
$x_1, x_2, \ldots, x_z$ = independent variables
ε = random error of the model

In SAS PROC REG, an ANOVA was performed for each regression model which reported *p-value*, R^2, and R^2_{adj} to assess the model's usefulness in predicting Δ*m-value*. According to *p-value*, Equations 11.2 to 11.5 are useful for predicting Δ*m-value* at a 95% confidence level, R^2 and R^2_{adj} values are fair to good. Equations 11.2 and 11.3 were developed to have the highest R^2 values, which required the most independent variables. Equation 11.2 uses emulsion application rate as an independent variable while Equation 11.3 does not. Equations 11.4 and 11.5 were developed using a stepwise selection feature in PROC REG which systematically determines which independent variables significantly contribute to the overall model. Equation 11.4 uses emulsion application rate as an independent variable while Equation 11.5 does not. Figure 11.4 plots Equations 11.2 to 11.5.

In Figure 11.4, the predicted Δ*m-values* are plotted on an equality plot as a function of the corresponding measured Δ*m-values*. The plots visually depict how R^2 values decrease when removing application rate as a variable or when using the stepwise selection feature in SAS. Because application rate generally has a significant effect on Δ*m-value*, Equations 11.2 and 11.4 are more appropriate, but there is scatter around the equality line. When the average of all three application rates is used (Equations 11.3 and 11.5), scatter is reduced. With Equations 11.3 and 11.5, it is apparent that Δ*m-value* measurement in the *BBR* is at least related to and supported by base properties of the emulsion itself. Equations 11.2 to 11.5 are not currently recommended for use in specifications, though Figure 11.4 provides some validation for Δ*m-value* measurement in the *BBR*. Perhaps further research could refine prediction models such as those in Table 11.1, but at present, direct measurement of Δ*m-value* is recommended.

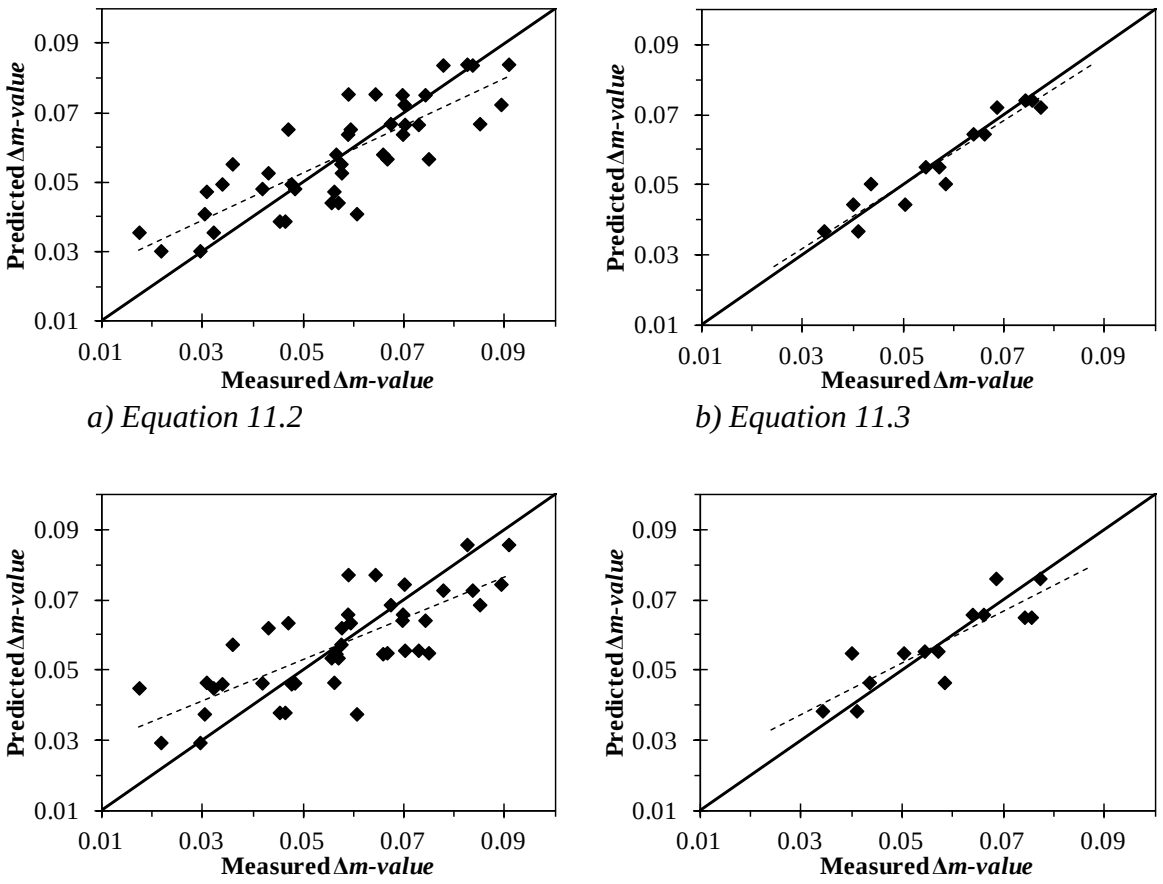
Table 11.1. Multiple Regression Models for Estimating Δ*m-value*

	Statistical Summary for Models						***β* Coefficients for Multiple Regression Equations (subscripts are listed below)**							
Eq.	***n***	***z***	***p-value***	**R^2**	**R^2_{adj}**		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
All variables used in regression.														
11.2	42	7	<0.0001	0.6791	0.6130	***β***	0.05868	0.0002183	0.00145	-0.01067	0.03232	-0.02617	0.02174	0.01901
						Variable	---	Pen	Ductility	$T_{c,\text{un-aged } DSR}$	$T_{c,PAV\ DSR}$	$T_{c,BBR\text{-}S(t)}$	$T_{c,BBR\text{-}m\text{-}value}$	R
						p-value	0.8004	0.0836	0.0042	0.0039	0.0003	0.0028	0.0194	0.0004
11.3	14	6	0.0022	0.9115	0.8357	***β***	0.07399	0.0002057	0.0014	-0.01086	0.03308	-0.02741	0.02241	---
						Variable	---	Pen	Ductility	$T_{c,\text{un-aged } DSR}$	$T_{c,PAV\ DSR}$	$T_{c,BBR\text{-}S(t)}$	$T_{c,BBR\text{-}m\text{-}value}$	---
						p-value	0.7197	0.0919	0.0106	0.008	0.002	0.0058	0.0217	---
Variables selected by stepwise selection function in SAS.														
11.4	42	4	<0.0001	0.5828	0.5377	***β***	-0.51023	0.00949	-0.00742	-0.00496	0.01901	---	---	---
						Variable	---	$T_{c,PAV\ DSR}$	$T_{c,BBR\text{-}S(t)}$	$T_{c,BBR\text{-}m\text{-}value}$	R	---	---	---
						p-value	0.0002	0.0002	0.0399	0.0031	0.0010	---	---	---
11.5	14	3	0.0028	0.7411	0.6634	***β***	-0.45874	0.0092	-0.00677	-0.00499	---	---	---	---
						Variable	---	$T_{c,PAV\ DSR}$	$T_{c,BBR\text{-}S(t)}$	$T_{c,BBR\text{-}m\text{-}value}$	---	---	---	---
						p-value	0.0082	0.0054	0.1153	0.0178	---	---	---	---

-- n = number of observations

-- z = number of independent variables

-- R^2_{adj} = adjusted R^2, accounts for the proportions of n and z as R^2 can be misleading when n is not considerably larger than z



a) Equation 11.2 *b) Equation 11.3*

c) Equation 11.4 *d) Equation 11.5*

Figure 11.4. Measured Versus Predicted Δ*m-value* Plots for Equations 11.2 to 11.5

Based on *BBR* testing of field aged mixture beams, Δ*m-value* of 0.060 for field aged pavements (emulsion application rate of 1.81 L/m^2) is a feasible value for initial discussion between agencies and suppliers. The assessment of each emulsion in this paragraph is based on this 0.060 Δ*m-value* criteria for field aged pavements. For both *FR* and *Hwy 45*, E3, E5, and E6 provide the best rejuvenation with Δ*m-values* ranging from 0.070 to 0.091. Mid-range rejuvenators are E2 and E7 for *Hwy 45* and E1 and E2 for *FR* with Δ*m-values* ranging from 0.057 to 0.067 overall. For *Hwy 45*, E1 and E4 provide the lowest Δ*m-values*, and for *FR*, E4 and E7 provide the lowest Δ*m-values* with Δ*m-values* ranging from 0.031 to 0.056 overall. It is imperative to remember that significant chaining existed within the multiple comparisons analyses. This indicates that many emulsions are not necessarily statistically better or worse than other emulsions with respect to Δ*m-value* (although some are). The rankings do, however, provide a general overview of trends within rejuvenation performance. In terms of specification guidance, statistical analyses should be more robust if the recommended guidelines for testing replication are followed.

The rejuvenation performance of E1 is of interest in that E1 generally fell in the mid-range rejuvenation category for each pavement and application rate. This supports the general premise that polymer modification often has limited effect on low temperature properties (all other emulsions were polymer modified). Based on the Δ*m-value* results, it appears that properties of an emulsion's base binder and the emulsifying formulation have a

greater impact on Δ*m-value* than polymer modification. Polymer modification is more heavily related to aggregate retention as addressed in the following section.

Based on *BBR* testing of *Plant Mix* mixture beams, Δ*m-value* of 0.040 for *Plant Mix* appears comparable to the Δ*m-value* criteria of 0.060 for field aged pavements. Testing of *Plant Mix* was conducted with E3 only; therefore, the 0.040 value is based on E3 results alone. For this reason, this value, like the value for field aged pavements, is suggested for initial discussion but should be adjusted as necessary to correspond to satisfactory field performance.

From a technical consideration, requiring an emulsion to meet a Δ*m-value* requirement for laboratory compacted asphalt of 0.040 is not greatly different than requiring an 0.060 Δ*m-value* for field aged pavements. However, from a practical consideration, evaluating emulsions with laboratory compacted asphalt would likely provide greater efficiency since a large stock of raw materials or plant mixed asphalt would be relatively easy to acquire and store. Further, sawing and testing success rates and variability of results indicate testing laboratory compacted asphalt is a more efficient approach for evaluating the rejuvenation potential of an emulsion. The proposed testing protocol would require testing of an untreated control group of large size to provide a reliable mean *m-value* and emulsion treated groups of smaller size to better facilitate routine testing. Based on the replication analysis in Section 7.9, the recommended minimum sample size after data processing should be 35 for the untreated control group and 16 for the emulsion treated groups. These sample sizes correspond to 95% reliability with margins of error of 0.005 and 0.010 for untreated and emulsion treated mixture beams, respectively.

11.3 Aggregate Retention Discussion

Three test methods to evaluate aggregate retention were studied in this report: *Vialit* test, frosted marble test (*FMT*), and sweep test (D7000 or *Sweep-M*). Each test provided some insight into aggregate retention characteristics; however, versatility, ability to account for variables, and clarity in terms of discrimination between materials varies between each test. Overall, the sweep test appears to be the most suitable choice for aggregate retention characterization based on these factors. As a result, discussion focuses on sweep testing with the *Vialit* and *FMT* evaluated in light of sweep testing.

All three tests are capable of measuring aggregate retention testing as a function of cure time so that various levels of moisture loss can be evaluated. This type of testing was performed in this report for *FMT* and *Sweep-M*. It was not explicitly performed for the *Vialit* test although testing protocols could be easily modified to conduct testing at different cure times. Where this testing was performed (*FMT* and *Sweep-M*), results from both tests demonstrate strong correlations between cure time and strength gain as was observed by Howard et al. (2011). In all cases, the performance indicator, either torque or mass loss, improved with cure time and, consequently, moisture loss as well. However, comparing data from the two tests methods reveals differences exist in each test's ability to differentiate between the multiple variables present during the actual field placement of a chip seal.

Howard et al. (2011) categorized differences between test methods into four key areas: 1) ability to evaluate aggregate properties and chemistry effects on a chip seal system, 2) ability to validate binder properties and emulsion chemistry on a chip seal system, 3) ability to address variables that affect performance achievement within the test method, and

4) ability of the methods to affect design, quality control, and quality assurance methods for improved chip seal system performance.

Chapter 10 *Sweep-M* results demonstrate the importance of aggregate in the evaluation of a chip seal system. Performance of a chip seal in the field is related to properties of both aggregate and emulsion, and it is heavily related to the interaction of the two. *Sweep-M* testing clearly indicates the need for system-specific aggregate sweep testing because of the emulsion-aggregate interaction. The *FMT* is deficient in this regard since it cannot address aggregate type or chemistry because it uses a standard cover material. Not only does varying the aggregate affect mass loss at a given time, but it also affects the rate of moisture loss from the system. This variability demonstrates the impact aggregate can have on both moisture loss and adhesion development.

Emulsion properties and chemistry also have significant effects on the chip seal system. *FMT* shows problems quantifying emulsion chemistry effects on the entire chip seal system when attempting to use *FMT* for benchmarking different chip seal systems. *FMT* data does demonstrate curing trends, but these are limited in evaluating how individual emulsions affect the entire system in the field since no aggregate is tested. D7000 or *Sweep-M* is better able to rank the emulsions for a given aggregate since aggregates are incorporated within the test method. The *Sweep-M* data shows that each emulsion performed differently with each aggregate. If emulsion chemistry did not affect chip seal performance, then all data from a given aggregate should be essentially identical; however, this was not the case.

Repeatability and variability are issues of concern with the *FMT*. Critical cure time and critical moisture loss values are both greater than that observed within the sweep test. This suggests interaction with aggregate may be a driving factor with respect to moisture loss rate. It is also possible the *FMT* could be entraining moisture and not allowing it to leave. The top of the emulsion in a tray dries first and possibly creates an essentially impermeable boundary that hinders moisture loss. Despite these current drawbacks, the *FMT* does clearly demonstrate the need to specify strength gain based on moisture loss rather than cure time. Prior to use as a standalone performance test, *FMT* repeatability needs improvement.

The *FMT* appears useful as a test to benchmark curing rates and residual binder characteristics of emulsions. In the appropriate context, it can be used by emulsion producers to refine their materials for acceptable use in chip seal systems. *FMT* was able to independently demonstrate the moisture loss concept absent the factor of aggregates. Performance of the entire chip seal is best characterized by sweep tests which have shown promise in their ability to measure differences in aggregate chemistry/properties and emulsion chemistry/properties. Sweep testing lends to similar moisture loss curing trends as the *FMT* but allows for a more robust characterization as it is capable of handling more variables. Sweep testing is able to differentiate performance according to moisture loss rate and aggregate retention at least as effectively as *FMT*.

Unlike the *FMT*, the *Vialit* test incorporates aggregates. *Vialit* results indicate that the 0.20 cm thick tray currently specified yields questionable results. Improvements resulted in the modified tray which was able to differentiate between non-polymerized and polymerized emulsions. With no modifications to the test other than the modified tray, the *Vialit* test did not distinguish response trends of polymer modified emulsions although the sweep test did (Table 11.2). *Sweep-M* demonstrates a more comprehensive assessment as it grouped emulsions into three general categories as opposed to two with *Vialit* testing. M_L values are greater in magnitude and range which should provide an enhanced level of discrimination.

Lastly, *Sweep-M* testing appears to better define behavior of polymer modified emulsions with softer base asphalts (E3 and E5).

Table 11.2. Comparison of *Vialit* and *Sweep-M* (8 hr Cure Time) with Aggregate 1

	***Vialit* Results**		***Sweep-M* Results**	
Category	**E**	**Agg Loss Range (%)**	**E**	**M_L Range (%)**
1	E2-E7	0-4	E2, E4, E6, E7	3-5
2	E1	13	E1, E3	16-17
3	---	---	E5	28

Overall, sweep testing appears to be the most suitable choice for evaluating aggregate retention. Based on results in this report, sweep testing proved capable of differentiating a wide array of emulsions and aggregates. The sweep test and sweep test concepts are also versatile and implementable in that they could be used to 1) approve chip seal materials as a system (i.e. a combination of aggregate and emulsion) based on acceptable mass loss in laboratory design, 2) determine the critical moisture loss value that corresponds to acceptable mass loss in the laboratory, and 3) determine traffic opening times in field construction by monitoring moisture loss until the critical moisture loss is achieved. Based on current practice, the moisture loss corresponding to 10% D7000 mass loss (approximately 20% *Sweep-M* mass loss) should be the critical moisture loss. The threshold D7000 mass loss of 10% is supported by literature (Johannes et al., 2011; Shuler, 2011; Shuler et al., 2011) but should be considered a trial value in Mississippi until supported by field projects monitored over time. This type of refinement would allow mass loss to take on more physical meaning.

Moisture loss values suggested to date to provide acceptable aggregate retention performance range from 75 to 90% (Howard et al., 2011; Shuler, 2011; Shuler et al., 2011). *Sweep-M* results in this report suggest acceptable moisture loss values could be considerably lower for some chip seal systems. For example, the mass loss of the E6-A1 combination was 8% (approximately 4% for D7000) at a moisture loss level of only 42%. This behavior indicates the need to rely on moisture loss rather than cure time to achieve a threshold mass loss. Emulsion moisture loss should be considered in performance based specifications and should be used to determine when to release traffic onto a chip seal in an informed manner. In terms of traffic opening times during construction, Shuler (2011) and Shuler et al. (2011) present procedures for monitoring moisture loss in the field which appear promising for implementation.

Information from sweep testing can also provide insight to projects with various priorities and interests. Chapter 10 results showed that almost all emulsion-aggregate systems performed satisfactorily at longer cure times (i.e. 8 hours); however, there remains various levels of performance as a function of moisture loss. Some emulsion-aggregate systems excel at low moisture loss levels which would be useful on projects where quicker return to traffic is of primary interest. Other emulsion-aggregate systems require greater moisture loss to reach similar mass loss levels. Although these may not be desired when traffic opening is of primary interest, use of these systems could be valuable when traffic opening is not of great concern (e.g. parking lots) and, consequently, could result in cost savings or other beneficial attributes.

Chapter 2 reviews literature related to chip seal gradations and design processes to select aggregates, emulsions, and application rates of both. Engineering properties (e.g.

durability, mechanical strength, and surface texture) of igneous, sedimentary, and metamorphic rocks can be used to establish general guidelines relating to aggregate retention behavior. However, mineralogy alone cannot predict performance because of other factors. The presence of deleterious material, dust coating, and unfavorable weather conditions can affect the bond between emulsion and aggregate and lead to early aggregate loss. Additionally, several aggregate properties (gradation in particular) are not fully addressed at present. The state of the art appears to, generally speaking, stop short of considering project gradations for performance testing purposes. The companion report (Volume II) of State Study 211 considers full aggregate gradation during Long Term Performance (LTP) testing.

11.4 Rejuvenation and Aggregate Retention Discussion

Although some further refinement could meaningfully improve protocols discussed herein, work in this report indicates *BBR* and sweep testing show promise for overall seal treatment evaluation. Further, these two testing procedures could be used to conduct material selection to accomplish fairly specific goals. These goals primarily focus on rejuvenation, traffic opening, and aggregate retention. According to *BBR* Δm*-value* and *Sweep-M* mass loss results, E6 is capable of providing upper end performance in all areas of interest. Other emulsions may only provide upper end performance in one performance category (i.e. rejuvenation or aggregate retention).

Table 11.3 provides a comparison of emulsions based on the three measured response categories. *BBR* Δm*-value* results shown are the average of the three application rates tested for *FR* and *Hwy 45*. *Sweep-M* results (M_L and W_L) shown are the average of the three aggregates. Equation 10.3 was used to calculate W_L at 20% M_L. Equation 10.3 should not be relied heavily upon, but it is useful in demonstrating general trends. For instance, E5 never reached 20% M_L during the 8 hour cure time; therefore, Equation 10.3 may not be reliable for determining W_L at 20% M_L for E5. Additionally, the interaction of emulsion and aggregate not only affects the W_L at which 20% M_L occurs, but also the time to reach that W_L. For this reason, cure times required to reach corresponding W_L values are provided (cured at 35 C and 30-40% relative humidity). Table 11.3 traffic opening rankings are based on W_L alone but are shown with laboratory cure times as well as they provide insight to the rate of moisture loss. For example, for 20% M_L, E1 and E4 required only 3.5 hours of curing, approximately, to reach the required 64% W_L; whereas, E2 required almost 5 hours of curing to reach 61% W_L. Despite this observation, moisture loss values are of greater importance for connecting laboratory and field performance since the required moisture loss is constant but required cure times can vary considerably in the field depending on numerous factors (e.g. temperature, humidity, and sun exposure).

Results in Table 11.3 show that, generally, emulsions which are ideal for rejuvenation are generally worst for aggregate retention at later cure times or traffic opening and vice versa. This trend aligns relatively well with emulsion low temperature critical failure temperatures. Emulsions with softer base asphalts are generally better for rejuvenation, and those with harder base asphalts are generally better for aggregate retention. E6 is a unique exception to this trend as it behaves favorably in the rejuvenation category as well as the aggregate retention categories. This observation emphasizes the need for direct measurement of properties of interest rather than relying on intuitive trends. Additionally, agencies should

specify desired performance properties (e.g. Δ*m-value*) rather than material properties as this could offer greater flexibility to producers while still delivering the desired performance.

Table 11.3. Comparison of Emulsions Based on Various Measured Response Categories

Rejuvenation		**Aggregate Retention (M_L at 8 hr Cure Time)**		**Traffic Opening (W_L at 20% M_L)**	
E	**Δ*m-value***	**E**	**M_L (%)**	**E**	**W_L (%)**
E5	0.076	E4	3.6	E6	43 (*2.7*) [a]
E6	0.072	E7	6.1	E7	53 (*3.2*)
E3	0.065	E6	6.6	E2	61 (*4.9*)
E1	0.056	E2	9.1	E4	64 (*3.4*)
E2	0.050	E1	9.3	E1	64 (*3.5*)
E7	0.046	E3	17.8	E3	69 (*6.7*)
E4	0.038	E5	22.4	E5	74 (*11.3*)

a) Italicized values in parentheses are cure times required to reach each W_L value calculated by Equation 10.2.

CHAPTER 12-SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

12.1 Summary

Six test methods were evaluated to determine their merit within performance based specifications for seal treatments. Three test methods were evaluated to investigate rejuvenation effects of emulsion on existing pavement surfaces: repeated creep test, viscosity test, and Bending Beam Rheometer test. Three test methods were evaluated to investigate aggregate retention characteristics: *Vialit* test, frosted marble test, and sweep test. Section 12.2 provides the most relevant project conclusions. Recommendations are divided into two categories. Section 12.3 provides overall project recommendations, while Section 12.4 isolates those recommendations applicable to specifications as of the date of this report.

The findings presented in the remainder of this chapter could be enhanced by exploring performance of Mississippi chip seals using the MDOT pavement management database. Parameters to consider include the international roughness index (IRI) and the pavement condition rating (PCR), which should be evaluated versus time and compared to data from similar pavements where no treatment was performed. Analysis such as regression and data mining could prove worthwhile for these endeavors.

12.2 Conclusions

The overall conclusions of the research are: 1) rejuvenation is better characterized by *BBR* Δ*m-value* than by the other methods considered; 2) aggregate retention is better characterized by sweep test M_L than by the other methods considered; and 3) traffic opening can be suitably characterized using moisture loss. Seal treatment specifications developed around these three items appear worthwhile. Repeated creep, viscosity, *Vialit*, and frosted marble testing are limited in their usefulness for performance related specifications. Of these, viscosity and *Vialit* testing likely offer greater value than repeated creep and frosted marble testing. Specific conclusions are as follows.

Repeated Creep: Test specimens can be successfully sawn from the surface of field aged pavements; however, stress levels must be varied to obtain reasonable results. *RC* results were sensitive to the stress level used and exhibited considerable time associated variability. Therefore, the *RC* test does not appear useful for characterizing rejuvenation.

Viscosity: Viscosity testing is capable of detecting viscosity gradients as a function of pavement depth (untreated) and $V_{D(\%)}$ increases with increasing emulsion application rate. Test results at 165 C were less consistent than test results at 135 C. Overall, $V_{D(\%)}$ from viscosity testing is generally correlated to commonly reported emulsion residue properties. It likely does not, however, most accurately represent a field aged pavement surface in that extraction and recovery processes result in forced blending of emulsion and aged binder.

BBR: *BBR* testing of emulsion treated mixture beams sawn from pavement surfaces or from gyratory specimen faces showed the most promise in terms of rejuvenation specifications. Mixture beams were successfully sawn and tested from laboratory compacted asphalt and field aged pavements with manageable variability. *BBR* testing was capable of detecting the presence of emulsion as well as distinguishing, sometimes statistically, between emulsions and emulsion application rates. Change in *m-value* between untreated and treated beams (Δ*m-value*) was more informative that $S_{D(\%)}$. *BBR* testing captured the effects of emulsion and binder interaction as a function of age for laboratory conditioned *Plant Mix* and field conditioned *Hwy 45*. Results of laboratory conditioned *Hwy 45* were generally erratic and sometimes inconclusive for 7-day conditioning and extended-term conditioning protocols. At 1.81 L/m^2 application rate, Δ*m-values* of 0.060 and 0.040 for field aged and laboratory compacted mixtures, respectively, appear to be reasonable initial discussion values for minimum rejuvenation thresholds for un-aged emulsion.

Vialit: As it is currently performed in citable test methods, the *Vialit* test does not appear useful for performance specifications. Use of the modified tray developed in this research and extended freeze times improved results. The modified *Vialit* test was able to differentiate non-polymerized from polymerized emulsion but was not able to greatly differentiate polymerized emulsions from each other.

FMT: The Frosted Marble Test (*FMT*) was useful in showing strength gain is more a function of moisture loss than cure time. For all emulsions tested, 80 to 90% moisture loss corresponded well to significant strength gain. Five to six hours of curing were required to reach this moisture loss. The *FMT*, as currently specified, is unable to account for emulsion application rate, and noticeable repeatability issues were also encountered.

Sweep: *Sweep-M* testing generally produced twice the mass loss of D7000. *Sweep-M* mass loss variability was reasonably low (COV: 8-18%). Mass loss values were generally a function of emulsion and aggregate, indicating chip seal materials should be evaluated as a system rather than individually. *Sweep-M* testing supported *FMT* findings that moisture loss is a better indicator of strength gain than cure time. Moisture loss values at a mass loss value of 20% (*Sweep-M* protocol) varied considerably between chip seal systems, indicating aggregates considerably affect moisture loss and strength gain. Because of this interaction, the minimum moisture loss for traffic opening could be as low as 40 to 50% in some cases but much higher in other cases. *Sweep-M* also demonstrated that some emulsion-aggregate systems could be incompatible even at later cure times. The greatest drawback to current sweep testing is the inability to account for aggregate factors such as gradation.

12.3 Overall Project Recommendations

The overall project recommendation is to use *BBR*, sweep, and moisture loss testing as described in Section 12.4. The repeated creep and frosted marble test are not recommended for performance oriented specifications, though the frosted marble test could be useful for internal operations of emulsion producers. Viscosity and *Vialit* testing could be useful in some cases but appear limited in their overall versatility. Additional recommendations for performance oriented specifications and future research are as follows.

Repeated Creep: The *RC* test is not recommended for use of any kind in a performance oriented specification.

Viscosity: Viscosity testing generally, but not always, provides similar conclusions to *BBR* testing. There are no apparent advantages which encourage viscosity over *BBR* testing. If used, a test temperature of 135 C is recommended. Abandoning viscosity testing for *BBR* testing should provide a vehicle for long term improvements since *BBR* testing has the potential to capture performance more than viscosity testing.

BBR: *BBR* testing is recommended within draft performance specifications as described in Section 12.4. Avenues for further *BBR* research include: evaluation of the effect of emulsion treatment on *BBR* mixture beams as a function of loading time, clarification of the effects of aging on *BBR* results, and refinement of threshold Δm-*values* based on field performance of pilot projects.

Vialit: At present, the *Vialit* test is only recommended as a simple procedure for distinguishing between polymerized and non-polymerized emulsions. If used, the modified tray developed in this report is recommended. The recommended conditioning protocol is 48 hours in a 60 C oven followed by -22 C freezing where freezing consists of 4 hours or two freeze-thaw cycles with 3 hour freeze times. A sphere of constant mass which can be economically obtained should be specified (e.g. 525 ± 5 g).

FMT: The *FMT* is not recommended for performance based specifications at the present time due to variability between emulsions and operators. The *FMT* can be a useful tool for producers and for product development (e.g. emulsion breaking and set times), and it is useful for documenting or supporting trends from other test methods.

Sweep: ASTM D7000 is recommended for sweep testing within draft performance specifications as described in Section 12.4.

12.4 Draft Performance Specification Recommendations

This section provides only those items specifically recommended for MDOT's immediate consideration as draft performance specifications. Several other items were learned from State Study 211 that have potential value at present or in the future, but as of the date of this report, the three most promising items are described below. It is important to interpret all items listed below as suggestions to begin discussion with all parties involved (i.e. MDOT, consultants, emulsion suppliers, aggregate suppliers, and contractors), and some of the protocols and property thresholds recommended may change as this process unfolds over time. Additionally, it is recommended to test the recommendations below with full-scale MDOT chip seal projects that are monitored over time.

1) Chip Seal Systems: Performance is a system level characteristic that cannot be fully characterized with current methods of evaluating individual materials (i.e. aggregate and emulsion). ASTM D7000 is recommended to qualify a chip seal system, as opposed to individual evaluation and approval of aggregates and emulsions. A mass loss of below 10 to 15% after 4 hours of curing at 35 C is suggested as a beginning acceptance criteria. This criteria should apply to any MDOT chip seal project, but should only be performed for acceptance of the system (and periodically thereafter), and not on individual projects.

2) Rejuvenation: For projects where rejuvenation is of first order importance, Δ*m-value* obtained from *BBR* testing is the recommended means of rejuvenation characterization. Use of a standard laboratory compacted asphalt mixture is recommended as the preferred medium for evaluating emulsions. The recommended testing protocol is provided below. Specific details regarding specimen preparation and testing are provided in Chapter 4.

A) Compact six laboratory specimens and slice in half (60 possible beams), saw and test five beams from each specimen face (approximately 54 successfully tested beams), trim 10% of the data to remove outliers (42 data points after outlier removal), compute the average 60-second *m-value* rounded to three decimal places ($m\text{-}value_U$). This process would calculate the 60-second $m\text{-}value_U \pm 0.005$ with 95% reliability.

B) Compact three laboratory specimens and slice in half (30 possible beams), apply 1.81 L/m^2 of emulsion to each surface face, cure on lab bench to constant mass, scrape excess emulsion from the surface, saw and test five beams from each face (approximately 27 successfully tested beams), trim 10% of the data to remove outliers (21 data points after outlier removal, compute the average emulsion treated 60-second *m-value* rounded to three decimal places ($m\text{-}value_T$). This process would calculate the 60-second $m\text{-}value_T \pm 0.010$ with 95% reliability.

C) Compute Δ*m-value* by subtracting $m\text{-}value_U$ from $m\text{-}value_T$. If Δ*m-value* is greater than 0.040 (this value is the initial recommendation and should be modified if future data warrants), the emulsion is a rejuvenator.

3) Traffic Opening: For projects where early traffic opening is of first order importance, moisture loss corresponding to 10% mass loss by D7000 is the recommended means of determining readiness for traffic. Moisture loss should be monitored during field construction as per the protocols outlined in Shuler (2011) and Shuler et al. (2011).

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