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Performance Oriented Guidance for Mississippi Chip Seals-Volume II

Final Report

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

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16. Abstract

A laboratory and field study was conducted related to long term chip seal performance. This report's primary objective was to initiate development of a long term performance (LTP) test protocol for chip seals focused on aggregate retention. Key components of the study were to: 1) develop laboratory equipment and protocols to place a chip seal onto asphalt concrete; 2) develop laboratory equipment and protocols to evaluate chip seal aggregate loss placed onto asphalt concrete; 3) monitor chip sealed pavements from construction through two years of service life while collecting cores to be tested for aggregate loss in the laboratory; 4) compare laboratory produced chip seals to cores taken from in service pavements when using the same aggregates and emulsion. The study evaluated two pavements: *Hwy 366* near Baldwyn, MS (Size 89 aggregates), and *Hwy 44* near Hattiesburg, MS (Size 7 aggregates). The primary objective was met, though the effort stopped short of long term performance prediction of in service chip seals. The primary conclusion from this report was that fabricating chip seals in the laboratory that represent those placed in the field was feasible to some extent. Chip seals fabricated using the equipment developed in this research with Size 7 aggregates and corresponding embedment/conditioning protocols did represent field applied chip seals taken from *Hwy 44* 6 days after construction. Chip seals fabricated using the equipment developed in this research with Size 89 aggregates and corresponding embedment/conditioning protocols did not represent field applied chip seals taken from *Hwy 366* 10 days after construction.

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LIST OF SYMBOLS

A, B	Regression coefficients
AADT	Annual Average Daily Traffic
AADT	Annual Average Daily Traffic
Abs	Water absorption
ADT	Average daily traffic
ALF	Accelerated Loading Facility
ANOVA	Analysis of Variance
BBR	Bending Beam Rheometer
C_u	Coefficient of Uniformity (D60 / D10)
COV	Coefficient of Variation (%)
D_{10}	Particle diameter size where 10% passes
D_{60}	Particle diameter size where 60% passes
DBST	Double bituminous surface treatment
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
FI	Flakiness Index
FWD	Falling Weight Deflectometer
G*	High complex shear modulus
G_{sb}	Bulk specific gravity
H	Average least dimension, which is also referred to as ALD (inches)
HSKSC	Accelerated chip seal simulation device
IRI	International Roughness Index
LAC	Linear Asphalt Compactor
LTP	long term performance
LTPP	Long Term Pavement Performance
M	Median particle size (inches)
Max	Maximum value
MDOT	Mississippi Department of Transportation
MFT	Mini Fretting Test
Min	Minimum value
MMLS3	Model Mobile Loading Simulator
MnDOT	Minnesota DOT
MQAC	Mississippi Quality Asphalt Conference
n	Number of data points
PAV	Pressure aging vessel
PCR	Pavement Condition Rating according to Mississippi Protocols
PCR_o	Pavement Condition Rating conducted as per Ohio protocols
R_{Agg}	Aggregate application rates calculated during the project
$R_{Agg\text{-}C}$	Aggregate application rates calculated during the project
R_E	Emulsion application rates calculated during the project
RH	Relative humidity (%)
RTFO	Rolling Thin Film Oven
SBST	Single bituminous surface treatment

SFS	Saybolt Furol Seconds
Stdev	Standard deviation
T1	Time from opening the oven doors to commencing abrasive forces
T2	Time when 100% mass loss was achieved
$T_{100\%}$	Time to 100% mass loss (T2 minus T1)
T_{max}	LTP test achieving 900 seconds (15 minutes)
T_{air}	Air temperature
t_{cover}	Time between applying emulsion and cover aggregate
$T_{E\text{-}cover}$	Emulsion temperature immediately before covering with aggregate
$T_{E\text{-}spray}$	Emulsion temperature exiting the spray bar
T-I	Temperature interval
T_{pvmt}	Pavement surface temperature
$t_{traffic}$	Time to traffic release
UTI	Useful temperature interval
V	Voids in loose aggregate as decimal
W	Loose unit weight
WB	Water bath
X	Percent aggregate retained
δ	Low phase angle

CHAPTER 1-INTRODUCTION

1.1 General and Background Information

It is well known that aggregate retention is a key performance characteristic for chip seals. Several test methods exist to characterize chip seal aggregate retention. A companion report (Howard et al. 2013) provides a review of literature and describes several of these methods. The aforementioned review led to the observation that a test method capable of evaluating chip seal aggregate retention placed on compacted asphalt concrete would have value, especially if the method could be used to assess long term performance in some way.

Over the last several years, multiple state highway agencies including departments of transportation (DOTs) have used surface treatments to prolong the life of pavements by protecting the surface. According to Gransberg (2005), chip seal surface treatments have gained popularity due to their performance and cost-effectiveness for low and high volume pavements. Construction usually involves surface preparation, emulsion application, aggregate spreading, compaction, and brooming of the chip seal surface. Under proper application, chip seals can successfully delay or prevent rehabilitation and reconstruction over large pavement areas.

1.2 Objectives

This report's primary objective was to initiate development of a long term performance (LTP) test protocol for chip seals focused on aggregate retention. To accomplish this objective, the project was divided into four key components: 1) develop laboratory equipment and protocols to place a chip seal onto asphalt concrete; 2) develop laboratory equipment and protocols to evaluate chip seal aggregate loss placed onto asphalt concrete; 3) monitor chip sealed pavements from construction through two years of service life while collecting cores to be tested for aggregate loss in the laboratory; 4) compare laboratory produced and field applied chip seals when using the same materials.

1.3 Scope

This report was part of State Study 211, which was reported in two volumes. This report (Volume II) focuses on efforts to develop a long term performance (LTP) test for chip seals where two field projects were a central component. Volume I contains most of the project's findings and focuses on laboratory testing and characterization. State Study 211 had an overall charge of developing performance based specification guidance for chip and scrub sealing activities for the Mississippi Department of Transportation (MDOT).

A driving component of the efforts performed in this report was the ability to characterize an actual chip seal placed on the surface of an actual asphalt pavement. A second driving component was to be able to produce a representative chip seal on compacted asphalt concrete in the laboratory. Most current protocols omit one or more components of an actual chip seal (e.g. test only part of the gradation, chip seal not applied to pavement, etc.).

CHAPTER 2-LITERATURE REVIEW

2.1 Overview of Literature Review

An abbreviated literature review was conducted that included chip seal economics, performance, and test method descriptions. Chip seal performance and performance oriented test methods applied to specimens representing a full chip seal were the primary items reviewed. The companion State Study 211 Volume I literature review was more comprehensive, which reduced the needed content in this document.

2.2 Chip Seal Economics

Initial chip seal cost is generally favorable. In 2008, chip seals were reported to cost \$10,565 per lane mile, while a thin asphalt overlay was reported to cost \$66,358 per lane mile (Rajagophal 2010). Gransberg and James (2005) reported the initial cost of chip sealing was low compared to a thin asphalt overlay. According to Temple et al. (2002), the average chip seal cost was \$1.35/yd^2 (\$1.61/m^2), which was reported to be \$0.50/yd^2 more than the national average. Maintenance costs were estimated at \$0.20/yd^2, making the average total cost \$1.55/yd^2. The equivalent annual cost or EAC (unit cost divided by expected treatment life) was reported to be \$0.35/yd^2 per year including maintenance. These costs were reported to be approximately twice those reported by Hicks et al. (1997).

Table 2.1 provides seal treatment cost data from Chen et al. (2002) that came from a 2001 Texas statewide survey. A thin overlay was reported to cost 2.2 to 2.4 times a chip seal. Chen et al. (2002) reported that all factors considered (pavement condition, distress score, ride score, and cost), chip seals were the most cost-effective alternative.

Table 2.1. Seal Treatment Cost Data of Chen et al. (2002)

Treatments	Cost per lane mile
Thin Overlay (25 mm)	\$17,000 to \$22,000
Slurry Seal	\$8,000 to \$11,000
Chip Seal	\$7,000 to \$10,000
Crack Seal	\$700 to \$1,000

Jordan (2012) reported the average MDOT asphalt overlay cost for 2 lane miles was \$275,000. Chip seal cost estimating was provided by MDOT and included the past 2-3 years. Cost estimating data provided was based on bid prices for pertinent pay items; the price index that commonly used for asphalt binders was not part of MDOT's cost estimating. MDOT mostly used CRS-2P over the time period considered, and the average bid price was \$2.89/gallon as applied, with individual bid prices generally ranging from \$2.50 to \$3.75/gallon. Price per unit area data for chip seals was not maintained within the data provided by MDOT.

2.3 Chip Seal Performance

Generally pavements that are structurally sound and in good condition (minimal cracks, minimal raveling or aging) facilitate chip seals to perform as designed. During the

SHRP program, SPS-3 in the Southern region indicated chip seals on pavements in poor condition increased failure risk by 2 to 4 times (Smith et al. 1993). A synthesis by Gransberg and James (2005) reported an average pavement life increase of 7 years when a chip seal was applied at the appropriate time on a structurally sound substrate. Islam and Hossian (2011) reported a generally expected chip seal life expectancy of 5 to 8 years. The average chip seal life was stated by Temple et al. (2002) be 4 to 6 years assuming proper design, materials, and construction procedures. As of 2011, Minnesota's average chip seal life exceeded both of the aforementioned references at 10 to 15 years before aggregates were worn off by traffic and snow plows (Wood and Olson 2011).

Irfan et al. (2009) synthesized past work alongside data from Indiana related to thin asphalt overlays and their service life. Chip seals were not a focus of Irfan et al. (2009), but thin overlay service lives make for good general comparisons to the chip seal service lives presented in the previous paragraph. Several performance indicators were used by Irfan et al. (2009), and the study confirmed past findings that thin HMA overlay effectiveness is dependent on the performance indicator used, highway functional class, level of traffic, and climate severity. In general, a thin overlay service life of 7 to 12 years was found, with service life as low as 3 years and as high as 24 years.

Additional performance oriented information was obtained from Louisiana, Michigan, Minnesota, Mississippi, New Zealand, and Ohio. This information is presented in the following sub-sections.

2.3.1 Chip Seal Performance in Louisiana

Temple et al. (2002) described a five year statewide study in Louisiana, which is summarized in this section. The study evaluated 40 chip seals from pre-treatment until 2001. Inventory, historical, pavement condition, and cost data were used in the investigation. Most chip seals investigated were on low volume roads (1,000 to 2,000 ADT). Expanded light weight shale was the predominant aggregate, while crushed stone and crushed gravel were used in some instances. CRS-2P was the primarily used emulsion. General observations from the study were: the median PCI was 75 after 52 months of service with a significant crack reduction; about 70% of the chip seals fell into the excellent to good category; 20% of the projects showed moderate to heavy bleeding; skid resistance was good.

2.3.2 Chip Seal Performance in Michigan

Galehouse and O'Doherty (2006) discussed Michigan SPS-3 sites from the Long Term Pavement Performance (LTPP) program. Benefits of multiple treatments (chip seals being one treatment) were investigated and a notable finding was chip seals performed well except in wet/freeze zones on poor pavements. Chip seals provided the best overall cracking performance when considering only sections evaluated for 14 years. In general, chip seals performed longer than expected, and in 2001 the annualized chip seal cost was $2,800 per lane mile.

2.3.3 Chip Seal Performance in Minnesota

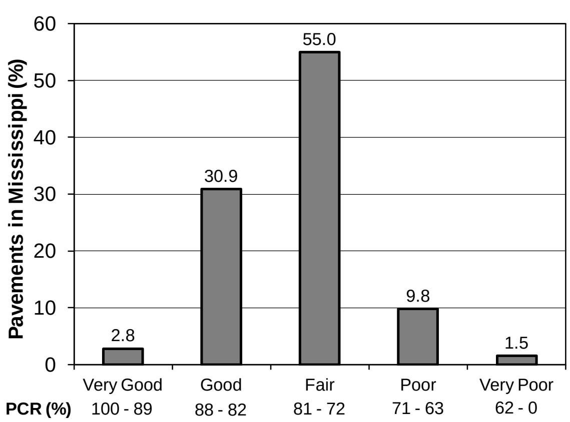
Wood and Olson (2011) described chip seal practices within the Minnesota DOT (MnDOT) and referenced MnDOT SP 2356 (2008). Chip seals were reported to be regularly applied to highways with average daily traffic (ADT) of more than 10,000 and speed limits greater than 89 km/h (55 mph). MnDOT's reported good performance documented in Wood and Olson (2011) prompted key activities reported therein to be presented in the following paragraph.

Over the past 10 years the average size of MnDOT chip seal aggregates has increased from 100% passing the 4.75 mm sieve to 100% passing the 9.5 mm sieve. Larger aggregates were reported to be more durable and to allow more binder. Desirable aggregates are clean (less than 1% fines), durable, single sized, and cubical. A flakiness index of 25% or less is required as per Federal Lands and Highway Method T508 on plus 4.75 mm material. Within MnDOT, emulsion is paid for by the gallon with the rest of the chip seal paid for by the square yard to allow in field emulsion application rate adjustments. Pavement temperatures must be 15.5 C (60 F) and rising to place a seal for MnDOT. MnDOT construction practices included aggregate being placed within 1 minute of the emulsion application, three roller passes occurring within 5 minutes of emulsion application, and sweeping occurring 20 minutes after placement in ideal conditions.

2.3.4 Chip Seal Performance in Mississippi

This section summarizes select chip seal presentations from the 3rd Annual Mississippi Quality Asphalt Conference (MQAC). In particular, two presentation given at the conference were obtained by the authors and are summarized in this section. One of the presentations was given by an MDOT representative (Jordan 2012), while the other was given by a material supplier representative (Ishee 2012).

Figure 2.1 summarizes actual statewide pavement conditions in Mississippi along with the estimated impact of commonly used pavement preservation techniques implemented throughout the state. Chip seals are reported capable of extending the pavement's service life up to 10 years if applied at the most appropriate time (i.e. at high PCR values).



a) Pavement Conditions in Mississippi

	Pavement Condition		
Treatment	Good	Fair	Poor
Fog Seal	1-3	0-1	0
Chip Seal	4-10	3-5	0-3
Thin HMA	4-10	3-7	2-4

According to the National Center for Pavement Preservation

b) Pavement Life Extensions (yrs.)

Figure 2.1. Pavement Preservation in Mississippi by Jordan (2012)

Ishee (2012) presented results of a survey that is described in the remainder of this section. Surveys on a 10 point scale rated chip seals 7 on average, which indicates users, contractors, and suppliers are not completely satisfied throughout the state. MDOT responses indicated frustration and possible limitations in some instances for chip seal applications due to unpredictable quality and chip seal performance throughout the state. Note that MDOT and State Aid have sealed 5,400 miles since 2009.

Possible solutions toward improving chip seal practices presented at MQAC included a revision to the current specification manual. At the time of Ishee (2012), MDOT specifications called for 1.77 to 1.99 L/m^2 (0.39 to 0.44 gal/yd^2) emulsion application rates (for aggregate size 7, 8, and 89 per ASTM C33), while surface area design calculations called for 1.50 to 1.99 L/m^2 (0.33 to 0.44 gal/yd^2) (for aggregate size 7). Other current construction and design-related inconsistencies presented included time allowed before applying cover stone, type of wheel rollers used for compaction, site selection, inspection, and ambient temperature during construction. Note that MDOT has recently made some updates to their specifications, and those updated are documented in Volume I of State Study 211 (Howard et al. 2013).

2.3.5 Chip Seal Performance in New Zealand

Aggregate surface texture is a chip seal performance and safety indicator according to Karasahin et al. (2011). In New Zealand, performance and acceptance of chip seals are determined by its texture depth; the lifetime of a chip seal is considered expired once the texture depth is less than 2 mm. The surface micro and macro texture are related to surface safety properties in that it can provide adequate surface frictional resistance.

2.3.6 Chip Seal Performance in Ohio

Rajagophal (2010) studied 225 chip seals in Ohio that were placed between 1999 and 2006, and the findings are summarized in the remainder of this section. Note a chip seal's average life is 5 to 8 years based on Ohio DOT maintenance guidelines. Seal lengths varied from 0.02 to 21.68 km, and were on roads with a general functional classification (i.e. largely 2 lane state routes). Most of the seals were in districts 1 to 3, which have similar climates.

Pavement Condition Rating conducted as per Ohio protocols (PCR_o) was used as a central evaluation component. PCR_o is a composite index of several distresses. Chip seal service life was monitored and corresponded to when another treatment was recorded in the database or when the PCR_o increased by 5 or more points (indicates a treatment was used but not recorded). Of the 225 chip seals, 111 had completed their service life and their weighted average life was 4 years.

PCR_o data was collected before treatment (i.e. untreated) and every year after treatment. Untreated PCR_o groups were created in five point intervals. Linear regression equations were developed for each untreated PCR_o group to determine the number of years to reach a PCR_o threshold of 60, with the results shown in Table 2.2. Note that service life completion did not correspond to a PCR_o of 60. Chip seals were reported to produce maximum benefits when the untreated pavement had a PCR_o of 66 to 80, and in those conditions a chip seal can extend service life up to seven years.

Table 2.2. PCR_o Results of Rajagophal (2010)

Untreated PCR_o	Years to PCR_o of 60	C_1	C_2	R^2	n
56-60	4.0	-7.2	89.7	0.70	59
61-65	4.5	-7.2	92.7	0.75	37
66-70	7.0	-4.7	93.1	0.60	132
71-75	7.5	-4.6	94.7	0.64	147
76-80	8.5	-4.0	94.2	0.53	203
81-85	7.5	-5.0	95.5	0.60	140
86-90	*Note 1*	-4.0	95.9	0.71	107

--Eqn: $PCR_o = C_1(\text{Age in years}) + C_2$

--Note 1: life was not predicted since all PCR_o's were above 70 and would have required considerable extrapolation beyond data measured to reach PCR_o of 60.

2.4 Performance Based Chip Seal Test Methods

Performance specifications are defined as a measurement of "how the finished product should perform over time" (Chamberlain 1995). TNZ P/17 (2002) is an example in that it states texture depth after 12 months of service is the most accurate indication of chip seal performance. Performance based specifications generally rely on a test method(s), which is the focus of this section as there isn't a test method for long term chip seal performance that has widespread use and acceptance. Note that the companion work presented in Howard et al. (2013) reviews several test methods for rejuvenation and aggregate retention, but none of those methods focus heavily on long term performance in terms of aggregate retention. The methods presented in the remainder of this section either investigate long term performance, or have attributes of potential relevance to investigating long term aggregate retention performance. All methods have a commonality in that they apply abrasive forces on the surface of a chip seal to simulate traffic.

2.4.1 Accelerated Chip Seal Simulation Device

The accelerated chip seal simulation device (*HSKSC*) was developed in Turkey to evaluate laboratory chip seal performance. The model consists of simulating traffic loads on a chip seal applied on a 60 cm thick unbound granular base. Chip seal performance is determined by surface texture and skid-resistance measurements (Karasahin et al. 2011). The prototype consists of four different components: 1) *HSKSC* paver, 2) *HSKCS* simulator, 3) climate cabin, and 4) sample mold. The paver is used to spread the chip seal on a 140 by 100 cm sample mold containing the unbound granular base, and the climate cabin is used to condition the sample to predetermined climate conditions. The *HSKSC* simulator applies a single wheel load of 600 kg that moves laterally back and forth at 1 m/sec.

Laboratory made, single-layer and double-layer specimens were prepared and tested. The double-layer chip seal was tested at 30 C and the single-layer chip seal was tested at 40 C. The single layer seal was made with 25 kg/m^2 limestone aggregate, 1.20 L/m^2 prime seal, and 1.77 L/m^2 of 100/150 pen bitumen. After *HSKSC* testing, skid measurements were taken with the British Pendulum test device (ASTM E303-93) and macro textures were determined with the sand-circle test (TNZ T/3:1981).

Results showed the *HSKSC* device had a realistic simulation of chip seal behavior on unbound granular base, and this was reinforced by field measurements where the same materials were used. Sand-circle test results showed a rapid decrease in texture depth at the beginning of the test, followed by a slowed decrease of texture depth. The wheel simulation also caused aggregate embedment over time, which is representative of in-situ conditions.

A correlation between loading cycles and macro texture was found (R^2 0.52 to 0.96). Pendulum tests showed relatively high skid-friction numbers at first, followed by a limited decrease in skid friction as cycles increased. Results showed the device capable of successfully simulating the rapid decrease of texture depth and skid friction as observed when chip seals are first opened to traffic, followed by a gradual, slow decrease as aggregates settled due to the effect of traffic.

2.4.2 Mini Fretting Test

The Mini Fretting Test (MFT) is a performance-based test used to predict chip seal performance by loading with a cylindrical piece of rubber that simulates tire loading. It is a modification to the Wet Track Abrasion test (ASTM D3910). This test method is capable of capturing differences between asphalt emulsions while predicting the chip seal's short term performance according to Khalid (2000). The MFT applies shear forces on a 190 mm prepared specimen mounted on a planetary mixer. Rotational movement of the adjustable rubber head simulates vehicle tire forces, causing the aggregates to dislodge from the specimen. The rotational force can be broken down into three forces that chip seals typically undergo in service: 1) vertical load that represents vehicle weight, 2) horizontal force that simulates friction and skidding action at the surface, and 3) rotational force resulting from both forces induced.

The MFT is considered a short term performance test since it is conducted where little to no aggregate embedment has taken place. The MFT measures binder performance because it evaluates the capability to develop early bonding with aggregates, thus preventing chip loss. Khalid (2000) conducted a laboratory study to correlate MFT and DSR results. Specimens were tested at 10, 20, 30, and 40 C temperatures, and at each temperature, specimens were tested at 1, 3, 5, and 24 hr conditioning. One conventional and two modified cutback binders were used.

DSR results showed the conditioning duration and test temperatures had a significant effect on performance. High complex shear modulus (G*) at 10 C indicates potential for brittle chip seal behavior, and low phase angle (δ) at 40 C indicates potential for viscous deformation under loading. It was concluded that 24 hr conditioning simulated full-strength development. MFT testing was conducted using the same binders, conditioning times, and test temperatures as the DSR. The aggregates used were 6 different granite gradations (6 mm max size with 0 to 5% passing the 1 mm sieve).

MFT test results showed sensitivity to temperature and conditioning time, similar to DSR test results. The percent aggregates retained increased with time; the cohesive strength was negatively impacted by the decreased binder stiffness. It was also observed that the chip seal increased aggregate retention over time. Khalid (2000) noted that at low temperature (10 C), SBS binder showed less brittleness while maintaining elastic behavior at 40 C. Khalid (2000) found correlations between MFT test procedures and DSR rheological properties (G*/sinδ). Eq. 2.1 describes the relationship between G*/sinδ and aggregate retention.

$Y = AX^B$ (2.1)

Where,

Y = G*/sinδ

X = Percent aggregate retained

A, B = Refer to Table 2.3

Table 2.3. Eq. 2.1 Coefficients by Khalid (2000)

Description	A	B	R^2
Conventional Cutback	$8x10^{-18}$	11.7	0.88
Rubber Modified Cutback	$3x10^{-38}$	22.0	0.91
SBS Modified Cutback	$5x10^{-87}$	46.5	0.95

2.4.3 Hamburg Wheel-Tracking Device

Islam and Hossian (2011) produced slabs (30 by 26 by 4 cm) with a kneading compactor (3 to 5% air voids) using a 9.5 mm NMAS mix. A chip seal was applied by heating the compacted slab to 70 C and placing thick tape around the slab to prevent emulsion leakage. Emulsion was manually applied on the slab surface with a brush, and a thin steel plate was used to smooth and even the surface. Aggregates were carefully applied to avoid overlapping, and 15 passes of a 37.2 kg concrete cylinder was used to compact chip seals on laboratory-compacted slabs. Each slab was swept after 3 hr to remove loose aggregates. Two slabs with chip seals applied were tested in the Hamburg wheel-tracking device with a 35 C water temperature. Results were used alongside modified sand circle data to perform an analysis of variance (ANOVA). Results showed that the interaction between aggregate and emulsion was significant for embedment at a 5% level of significance.

2.4.4 Model Mobile Loading Simulator

The Model Mobile Loading Simulator (MMLS3) is a 3rd scale vehicle wheel load simulator through which chip seal performance can be evaluated. Several publications have incorporated the MMLS3 over the past few years from North Carolina State University. Among them are: Lee (2007); Lee and Kim (2008); Kim and Lee (2008); and Lee and Kim (2009). The remainder of this section summarizes relevant information from these publications with respect to this report.

The MMLS3 test is conducted at predetermined temperatures and consists of applying a wheel load of 3.57 kN on a fabricated chip seal specimen (modified version of D7000 that has been trimmed). The tires used have a 30 cm diameter and a 34 cm^2 contact area. The wheel has a dynamic loading rate of 3.3 Hz which corresponds to a load rate approximately 5,500 wheel passes per hour. Aggregate loss is calculated as the change in aggregate mass divided by the original aggregate mass.

The MMLS3 procedure consists of curing and conditioning the specimen under predetermined climate conditions, followed by two different cycles of traffic loading. The first loading cycle simulates initial loading in the field, while the second loading cycle evaluates retention performance characteristics of surface treatments under traffic. A bleeding test finalizes the procedure.

The MMLS3 was used as part of a study to evaluate different surface treatment performance characteristics such as aggregate gradation, fines content, and aggregate type. Materials included were CRS-2 emulsion, light-weight slate (expanded), and granite. The emulsion was heated to 70 C, distributed evenly at 1.59 L/m^2, and cured at 35 C in 30 % relative humidity for 24 hrs. Once aggregates were placed, compaction was performed along the traffic direction with a kneading compactor. Specimens were conditioned for 3 hrs at 25 C prior to wheel loading. Initial MMLS3 loading was applied for 10 minutes, with 2 hours in the second loading. The bleeding test was conducted after conditioning the specimen at 50 C for 3 hrs, followed by wheel loading at 50 C for 4 hrs. Visual surveys and performance tests were conducted throughout the test procedure to measure aggregate retention and skid resistance.

Test results showed the MMLS3 is an effective procedure capable of evaluating aggregate loss of asphalt surface treatments due to several mixture factors. Research efforts found that aggregate gradation, fines content, aggregate application rate, and emulsion application rate have an effect on MMLS3 measured mass loss. Results showed the least mass loss can be obtained by decreasing aggregate application rate, increasing emulsion application rate, decreasing fines content, and using a more uniform gradation. Mass loss was also found sensitive to aggregate source changes. The light-weight slate was found to perform better than granite, showing a decrease in mass loss. The physical characteristics of both aggregate types differ in that slate had more cubical shape and more uniform gradation than granite. Also, the amount of fines appeared to have a lesser impact with slate than with granite. Overall, the most critical factor within the MMLS3 testing procedure was reported to be aggregate gradation.

2.4.5 Accelerated Loading Facility

Martin and Sharp (2009) used an Accelerated Loading Facility (ALF) to test full-scale seal treatments in Australia. Collected deterioration data was used to develop relative performance factors for roughness and rutting over a range of surface treatments and surface conditions (e.g. cracked, uncracked, wet, dry). This effort tested single and double chip seals as well as a geotextile seal over 150 mm of crushed rock. Other factors studied were cracked versus uncracked, continuously wet versus continuously dry, and maintained versus not maintained. All test sections were subjected to 9,000 ALF cycles at 40 kN from a dual wheel configuration to embed cover aggregate. After embedment, loads were increased to 50 kN and a pre-set transverse wander pattern was used to simulate in-service trafficking.

Deterioration was characterized by rutting, roughness, and falling weight deflectometer (FWD) measurements. Rutting and roughness limits were not dissimilar to field results suggesting ALF simulation was realistic. Relative performance between treatments and test conditions was accomplished by means of rut and roughness ratios where the rutting or roughness rate of one treatment was divided by the other. Given FWD determined strength did not change significantly over time, the ALF did not appear to simulate strength deterioration well, suggesting strength loss is a long-term phenomenon. Overall, relative performance factors for rutting and roughness were successfully determined but field validation was reported to be needed.

CHAPTER 3 – MATERIALS TESTED

3.1 Overview of Materials Tested

Properties of the emulsions, aggregates, and asphalt pavement surfaces tested are provided in this chapter. Some of the materials tested corresponded to the Hwy 44 and Hwy 366 field projects that are a focus of this report. Most of the remaining materials tested were the same as those in the Volume I State Study 211 report. Note that seven emulsions were tested in Volume I of State Study 211, and they were numbered 1 to 7.

3.2 Emulsions Tested

Three emulsions were tested in this report. Two of these emulsions were also tested in Volume I of State Study 211 (emulsions 2 and 3), though they served a secondary role in this report. The remaining emulsion (emulsion 8) was the primary emulsion tested in this report, and it was not used in Volume I of State Study 211. As seen in Table 3.1, these emulsions are labeled A, B, and C herein. Multiple samples of the same emulsion type were obtained from the same producer as testing in this project spanned a considerable amount of time. Emulsion handling procedures were the same as in Volume I (Howard et al. 2013).

Table 3.1. Emulsions Tested and Identification System

ID	ID - Volume I	Supplier	Type
A	2	Ergon Asphalt & Emulsions, Inc.	CRS-2P-SBR
B	3	Ergon Asphalt & Emulsions, Inc.	PASS-CR
C	---	Blacklidge Emulsions, Inc.	CRS-2P-SBR

-- Volume I refers to the companion State Study 211 report (Howard et al. 2013).

Table 3.2 provides representative properties from samples taken during the State Study 211 time frame. 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	Sieve (%)	Demulsibility (%)	Oil by Vol. (%)	SFS Visc. @ 50 C (s)
A	3.70 to 3.91	0.00 to 0.04	56 to 94	0.00 to 0.13	73 to 397
	3.81	**0.02**	**78**	**0.09**	**207**
B	1.90 to 2.66	0.00 to 0.03	20 to 61	0.63 to 0.63	94 to 101
	2.35	**0.02**	**46**	**0.63**	**98**
C	2.04 to 2.33	0.02 to 0.08	63 to 83	0.50 to 1.00	236 to 280
	2.19	**0.05**	**70**	**0.75**	**258**

Note: pH is according to T 200, SFS according to T 72, and all remaining tests are according to T 59.
Note: 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 CRS-2 emulsion since there is no polymer/latex modified emulsion specification in M 208. 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 (%)
A	66.9 to 68.1	104 to 126	47 to 146	50 to 65
	67.6	**116**	**81**	**63**
B	65.3 to 67.9	214 to 250	58 to 60	55 to 65
	66.6	**232**	**59**	**60**
C	69.9 to 70.4	112 to 130	150 to 150	51 to 56
	70.2	**121**	**150**	**54**

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 un-aged 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)
A	64	1.34	78.3	1.37
	70	0.71	79.3	0.73
B	58	1.19	82.8	1.19
	64	0.60	84.4	0.60
C	58	1.64	83.8	1.65
	64	0.83	85.2	0.83

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

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

Emulsion ID	Test Temp. (C)	G^* (kPa)	δ (deg)	$G^*(\sin \delta)$ (kPa)
A	13	5290	42.6	3580
	10	8080	40.3	5220
B	10	6890	44.5	4840
	7	10800	41.9	7190
C	22	1800	55.4	1480
	19	2980	52.3	2360
	16	4840	49.2	3660
	13	7740	46.0	5570

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* (---)
A	-18	109	0.337
	-24	232	0.298
	-30	539	0.246
B	-18	78	0.391
	-24	160	0.332
	-30	575	0.268
C	-18	176	0.344
	-24	363	0.280

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

Table 3.7. Emulsion Critical Temperatures (C)

Emulsion	T315 Unaged DSR	T315 PAV Aged DSR	T313 PAV Aged BBR Stiffness	T313 PAV Aged BBR *m-value*	T-I
A	67.0	10.3	-35.8	-33.7	100.7
B	59.5	9.8	-36.9	-37.0	96.4
C	62.4	13.8	-32.4	-32.1	94.5

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

3.3 Aggregates Tested

Properties of the limestone aggregates tested are in Table 3.8. Gradation was measured through sieve analysis according to ASTM C117 and C136. 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. 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 and voids in aggregates were calculated using equations 3.1 and 3.2, respectively.

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

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

Where,

G_{sb} = Bulk Specific Gravity
FI = Flakiness Index as Percent
H = Average Least Dimension, which is also referred to as ALD (inches)
M = Median Particle Size (inches)
V = Voids in Loose Aggregate as Decimal
W = Loose Unit Weight of Cover Aggregate (lbs/ft^3)

Table 3.8. Properties of Limestone Aggregates Tested

Source **Project** **ASTM C33**		**Hoover, AL** **Hwy 366** **Size 89**	**Calera, AL** **Hwy 44** **Size 7**	***Legend and Notes:***
Percent Passing	**19.0 mm**	100.0	100.0	* 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.
	12.5 mm	99.0*	94.8*	
	9.5 mm	85.6*	61.0*	
	8.0 mm	64.9	35.3	
	6.7 mm	51.1	21.9	
	6.35 mm	46.3	17.8	
	5.6 mm	38.1	11.7	
	4.75 mm	30.1	7.2*	
	2.36 mm	8.2	1.9	
	1.16 mm	2.6	1.3	
	0.6 mm	1.6	1.0	
	0.3 mm	1.0	0.9	
	0.15 mm	0.5	0.7	
	0.075 mm	0.3	0.2	
Coarse G_{sb}		2.530	2.735	*Coarse* G_{sb}: Coarse aggregate G_{sb}
Abs **(%)**		1.7	0.4	*Abs*: Absorption
M		6.62	8.86	M: Median particle size (≥ 50% passing)
FI		28.1	23.9	FI: Flakiness Index
H		0.18	0.25	H: Average least dimension (inches)
W		1494	1677	W: Loose unit weight (kg/m^3)
V		0.409	0.387	V: Voids in Aggregate
D_{60}		7.54	9.44	D_{60}: Particle diameter size where 60% passes
D_{10}		2.56	5.22	D_{10}: Particle diameter size where 10% passes
C_u		3.0	1.8	C_u: Coefficient of Uniformity (D_{60} / D_{10})

3.4 Asphalt Concrete and Pavements Tested

Six asphalt concrete mixtures were tested. Five of these mixtures were surface lifts taken from MDOT highways that either were in service or had previously been in service. The sixth was a plant produced mixture used to prepare laboratory compacted specimens.

Asphalt concrete was sampled from Dickerson & Bowen Inc. during construction of one section of a US highway 49 surface lift that is documented in State Study 250. This material had a PG 76-22 binder grade, a design asphalt content of 5.8%, and a 9.5 mm nominal maximum aggregate size. The sampled material was compacted using a Superpave Gyratory Compactor (*SGC*) into 150 mm diameter by 75 mm tall specimens with 7 ± 1 % air voids as per AASHTO T331. *SGC* specimens were essentially impermeable (< $1(10^{-5})$ cm/sec) as per ASTM PS129. Specimens were sliced in half so that their thickness was approximately 36 mm and used for testing. Specimens produced from this material are labeled *Hwy 49-S1* (*S1* = section 1) hereafter. The inside face of these specimens (i.e. sliced face) had essentially no surface texture.

The second asphalt concrete mix tested came from one section of an abandoned portion of Highway 45 in Crawford, MS. This pavement was a key State Study 211 Volume I material, and several additional properties not directly related to this report are provided in Howard et al. (2013). Figure 3.1 provides photographs of this pavement's surface texture. Cores and slabs of this material were tested; cores were 150 mm diameter, and slabs were 30 cm square. Specimens produced from this material were labeled *Hwy 45-S1* hereafter.

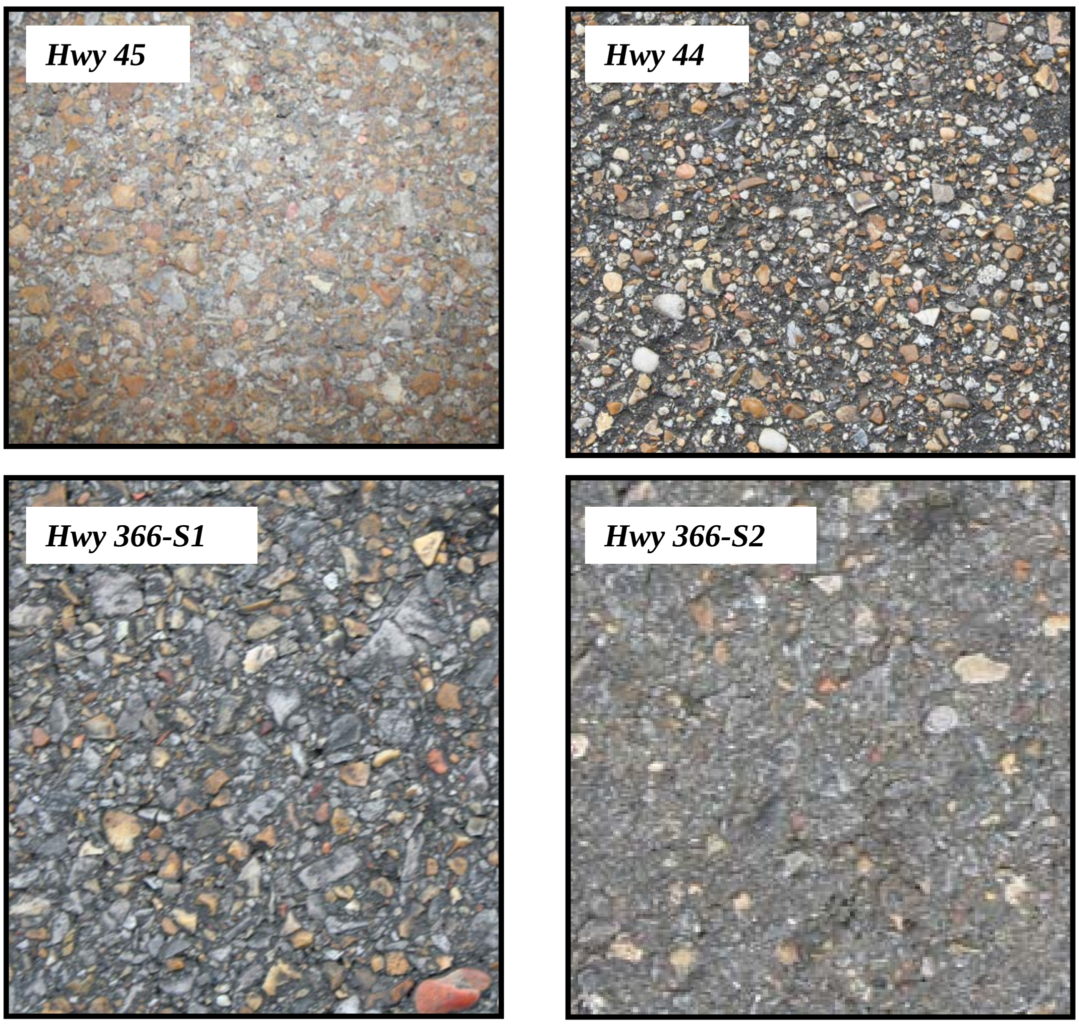
The third asphalt concrete mix tested came from highway 44 near Hattiesburg, MS. This one of the two pavements of primary emphasis in this report, and additional information is provided in Chapter 5. MDOT pavement management records show original construction occurred in 1961 and that three overlays have been placed resulting in a total pavement thickness of 40.6 cm (10.2 cm of bituminous material). The original surface was 1.9 cm of double bituminous surface treatment, which was overlaid with 3.8 cm of asphalt, which was sealed with a 0.6 cm single bituminous surface treatment, which was overlaid in June of 2000 with 3.8 cm of asphalt. The June 2000 overlay was the surface of the entire pavement prior to the September 2011 chip seal described in Chapter 5. This pavement was ultimately divided into three test sections for research purposes (note that all three sections are in MDOT pavement management section 1624), but each section had the same surface layer and thus would nominally have the same properties. The pavement surface was textured and aggregates were easily visible in (Figure 3.1). Cores were taken from this pavement as described in Chapter 5, and specimens produced from this material were labeled *Hwy 44-S1*, *Hwy 44-S2*, or *Hwy 44-S3* hereafter, depending on whether they were from section 1, 2, or 3.

The fourth, fifth, and sixth asphalt concrete mixes tested came from highway 366 near Baldwyn, MS. This is the second pavement of primary emphasis in this report, and additional information is provided in Chapter 5. Highway 366 varied more than highway 44, as seen in MDOT pavement management properties provided in Table 3.9. Highway 366 was divided into three test sections for purposes of this research, and each section had a different surface layer and thus each would have different properties. Sections 1 and 2 as defined in this report both lie in MDOT pavement management section 3802, and section 3 lies in MDOT pavement management section 3803. Discrepancies exist with respect to Table 3.9 and materials encountered on site; Chapter 5 provides more information. Surface texture varied between highway 366 test sections; section 1 was more textured than section 2 as seen in Figure 3.1. Cores were taken from this pavement as described in Chapter 5, and specimens produced from this material were labeled *<u>Hwy 366-S1</u>*, *<u>Hwy 366-S2</u>*, or *<u>Hwy 366-S3</u>*, depending on whether they were from section 1, 2, or 3.

Table 3.9. Highway 366 Pavement Management Material Properties

Test Sections	**1 and 2**	**3**
MDOT Section ID	3802	3803
Coordinates	0.000 to 1.453	1.453 to 1.920
Total Pavement Thickness (cm)	51.1	30.5
Total Asphalt Thickness (cm)	5.4	7.6
Bituminous Layers	1.9 cm DBST (1977) 2.5 cm Asphalt (1978) 1.0 cm SBST (1988)	7.6 cm Asphalt (1993)

Original construction occurred at the year shown for the first bituminous layer.
DBST = double bituminous surface treatment. *SBST = single bituminous surface treatment.*



Note: No photographs were taken of Hwy 366-S3 due to rainfall.

Figure 3.1. Surface Texture of Field Sampled Asphalt Concrete Highways Tested

CHAPTER 4 – SPECIMEN PREPARATION AND TEST METHODS

4.1 Overview of Specimen Preparation and Test Methods

This chapter presents specimen preparation and test methods, including developmental information for the long term performance (LTP) equipment and protocols. Generally speaking, use of the LTP equipment involves specimen fabrication, embedment, conditioning, and testing. Each of these steps, alongside the equipment developed or used to perform these steps, is presented in this chapter. Additionally, methods used to collect complimentary data is also provided in this chapter.

4.2 Distress Survey and Traffic Data Collection Methods

Several different automatic profilers were used to collect the distress data presented herein. MDOT provided all distress survey data from that collected according to their standard procedures. Data collected in this manner includes: Pavement Condition Rating (PCR), rut depths, International Roughness Index (IRI), Annual Average Daily Traffic (AADT), and any other data denoted in later chapters to come from pavement management records.

4.3 Preparation and Testing of Sweep Specimens

Sweep testing was performed according to the *Sweep-M* protocol in the Volume I State Study 211 report (Howard et al. 2013). *Sweep-M* specimens are prepared in the same manner as ASTM D7000, and cured in a 35 C oven in 30 to 40% relative humidity. A different mixer is used for *Sweep-M* relative to D7000 to apply abrasive forces to a prepared specimen; a Hobart N50 mixer was used for the testing in this report. *Sweep-M* outputs are mass loss and moisture loss, calculated using Equations 4.3 and 4.4 of Howard et al. (2013).

4.4 LTP Equipment Overview

Equipment was used for: 1) fabrication; 2) embedment; 3) conditioning; and 4) testing. The intent of this equipment is to be able to produce a laboratory chip seal specimen representative of a field core and to test either laboratory produced specimens or field cores. An overall test method and equipment such as the LTP does not exist to the knowledge of the authors. Some of the LTP components and/or concepts came from sources cited in literature review or from ASTM test methods. A considerable portion of the equipment was designed and fabricated for this research. When possible, protocols used existing components. Most of the LTP equipment (Table 4.1) was fabricated by a local machine shop. Items 1 to 6 were used during fabrication, and items 7 and 8 were used during testing. Embedment and conditioning was performed with additional equipment not fabricated for this research.

Table 4.1. LTP Equipment Components and Main Functions

Equipment Name	Main Function
1. *Spreader Base*	Overall item that allows fabrication process to occur
2. *Specimen Box*	Encloses four specimens during fabrication (cores only)
3. *Aggregate Spreader Sheet*	Facilitates uniform spreading of aggregate onto emulsion
4. *Aggregate Divider*	Divides aggregate into four quadrants to improve uniformity
5. *Aggregate Restrainer*	Keeps aggregate from lateral displacement during spreading fabrication
6. *Specimen Panhandle*	Allows handling of each specimen after emulsion application
7. *Abrasion Head*	Applies abrasive forces to specimen
8. *Adapter Base*	Contains individual specimens during abrasion test

Note: Total equipment cost (materials, fabrication) was approximately $4,100 (includes two adapter bases).

4.5 LTP Specimen Fabrication

Other than a very modest amount of initial exploratory work where results were not reported, the full project gradation was used for specimen fabrication. All pavements were treated the same for emulsion application rates; i.e. texture was not considered by changing application rates. Not accounting for pavement texture is a limitation of this research. Alvarado (2012) documents exploratory fabrication efforts not presented herein including cardboard boxes with circular holes cut for specimens, aggregates dropped with funnel assemblies made for other types of testing, and seating aggregates absent a rubber pad on the sweep test compactor.

4.5.1 LTP Specimen Fabrication Equipment

The LTP equipment used during laboratory specimen fabrication represents an assembly line that involves emulsion spread, aggregate spread, and chip seal surface seating (Figure 4.1). The equipment is capable of producing four chip seal circular specimens during each production cycle, or of producing one slab per production cycle that can be cored to produce two circular specimens. The fabrication assembly line equipment consists of six different assemblies, and each is described in the remainder of this section, while Figure 4.1 labels each of the six items to assist in understanding how they are used together.

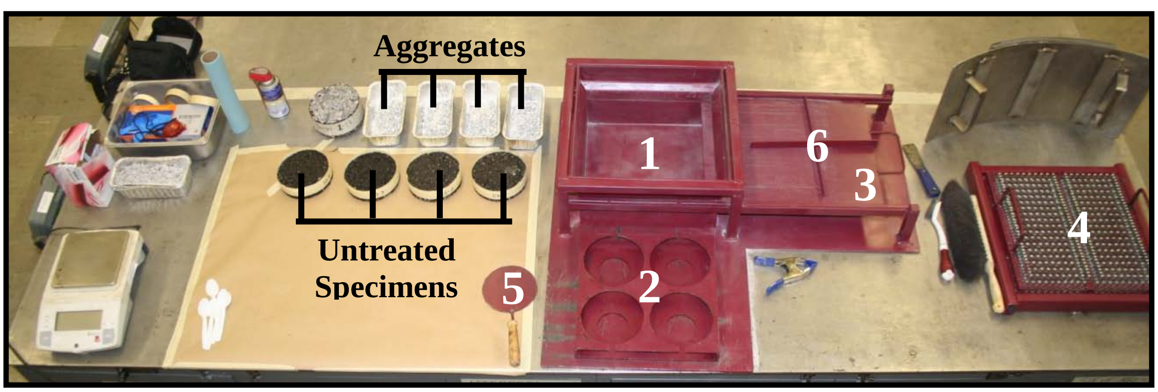
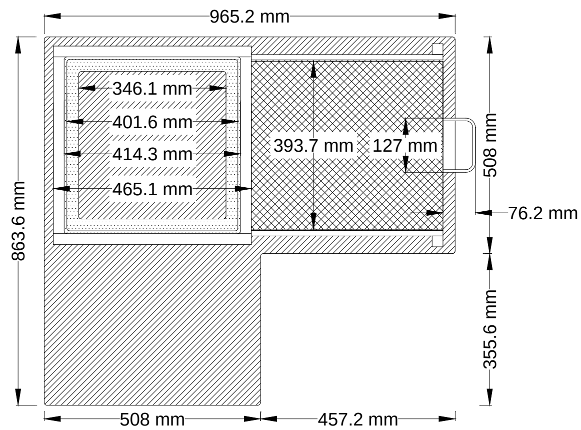


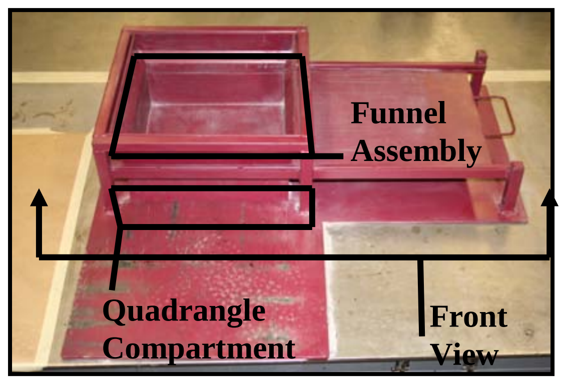
Figure 4.1. Overall View of LTP Specimen Fabrication Assembly Line

4.5.1.1 *Spreader Base*

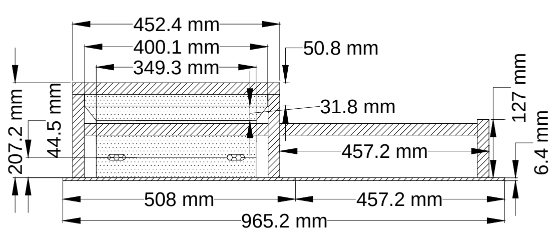
The *Spreader Base* consists of multiple parts, compartments, and platforms (Figure 4.2). It is a funnel-shaped assembly which contains the *Specimen Box* during aggregate spreading (only when circular specimens are fabricated). The front of the spreader base serves as a platform where the *Specimen Box* is placed before and after aggregate spreading. The platform allows for smooth motion of the *Specimen Box* in and out of the assembly without disturbing LTP specimens. The platform connects to a quadrangle compartment located under the funnel assembly where aggregate is dropped. The funnel assembly and spreader sheet are positioned 90 mm from the bottom platform, directly above the quadrangle compartment where the *Specimen Box* is introduced. Rails enable lateral movement of the *Aggregate Spreader Sheet* through which aggregate is spread into the specimen box.



a) Top View Schematic

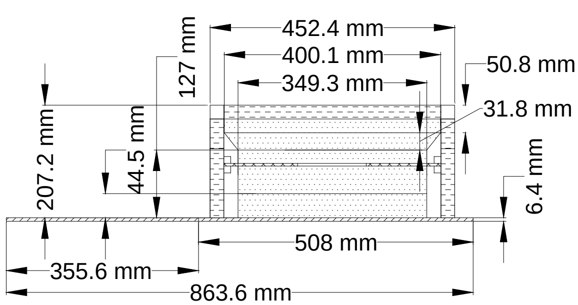


b) Top View Photo



c) Front View Schematic

d) Front View Photo



e) Side View Schematic

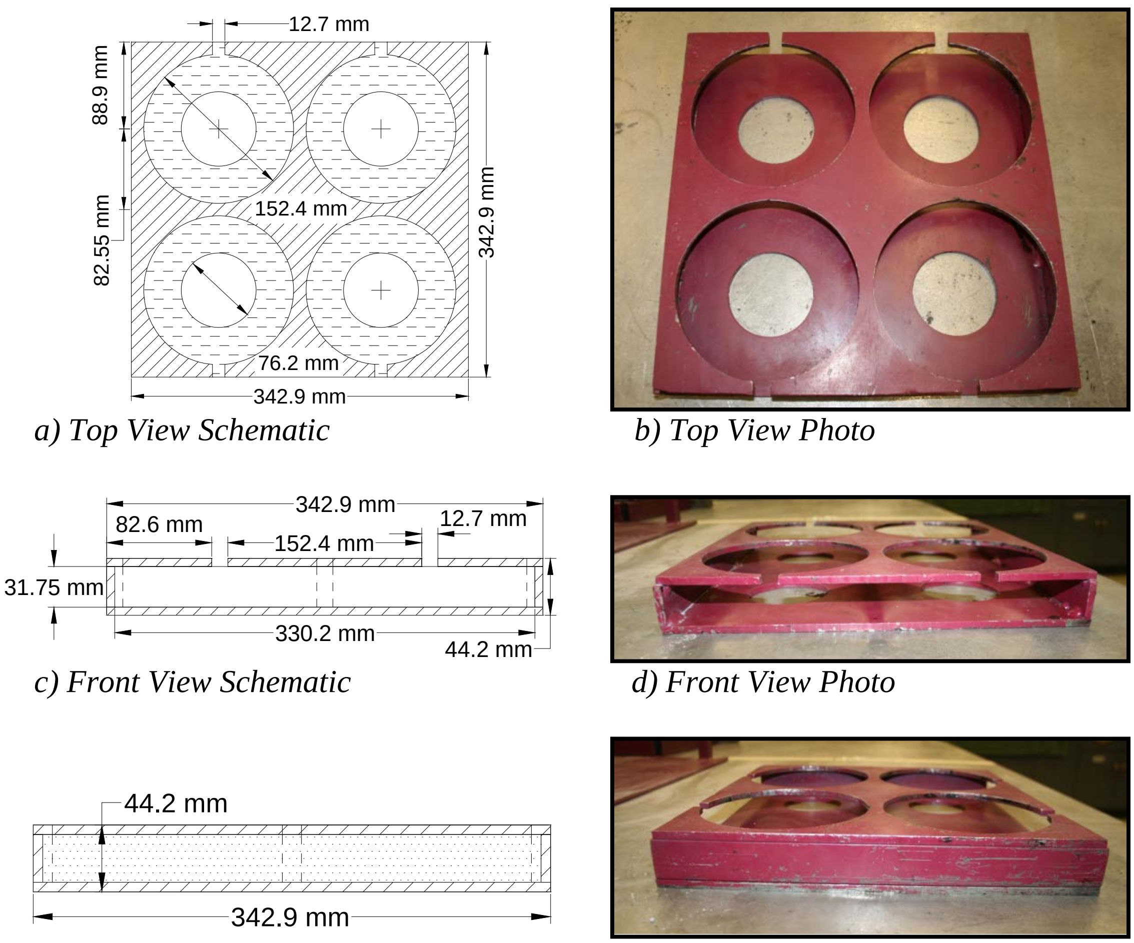
f) Side View Photo

Figure 4.2. ***Spreader Base***

Note the height of the *Spreader Base* opening into which the *Specimen Box* slides was not large enough to accommodate all aggregates. Periodically, larger pieces of aggregate would lodge in the opening as the *Specimen Box* was being removed. These aggregates would either roll over in the emulsion or prevent the *Specimen Box* from being removed from the *Spreader Base* altogether. This issue resulted in a few specimens being discarded without testing. Future fabrications should increase this opening a few millimeters to improve fabrication efficiency.

4.5.1.2 *Specimen Box*

The *Specimen Box* (Figure 4.3) has a main function of containing four compacted circular asphalt specimens during fabrication. It consists of multiple 6 mm plates welded into a 340 by 340 by 32 mm box. The upper plate of the box has four circular openings which hold specimens ready for aggregate application. Each opening contains a small slot to accommodate the *Specimen Panhandle* which facilitates insertion of each specimen into the box. The bottom plate has four 76 mm circular openings that enable specimen removal.



a) Top View Schematic *b) Top View Photo*

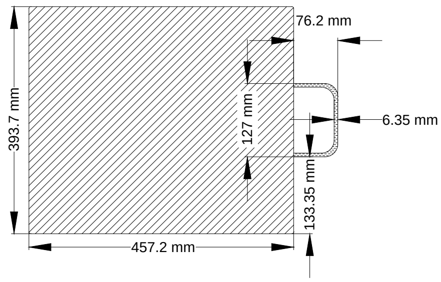
c) Front View Schematic *d) Front View Photo*

e) Side View Schematic *f) Side View Photo*

Figure 4.3. *Specimen Box*

4.5.1.3 *Aggregate Spreader Sheet*

The *Aggregate Spreader Sheet* (Figure 4.4) serves two purposes: 1) retain aggregates in the funnel assembly prior to dropping and 2) drop aggregates onto the surface of compacted asphalt that has already had emulsion applied to its surface. The sheet has a handle on one side which enables lateral sliding in and out of the funnel assembly. The sheet allows aggregates to be placed in a manner representing construction.



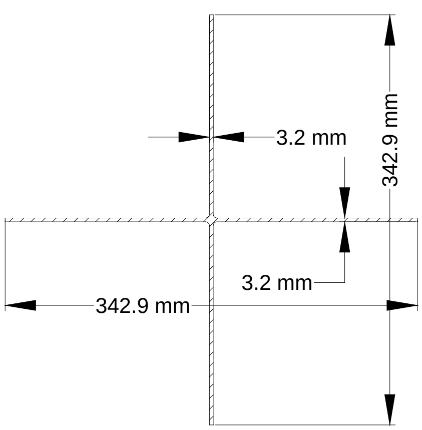
a) Schematic

b) Photo

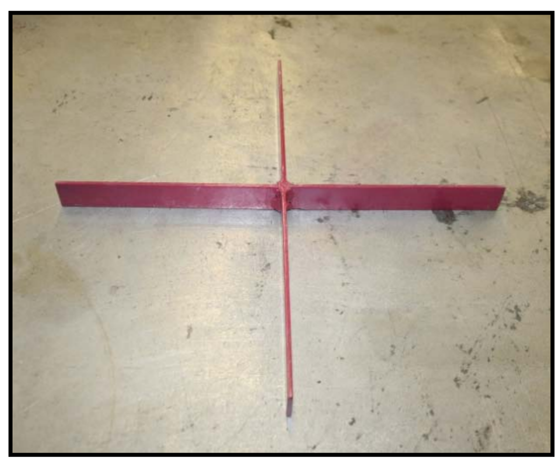
Figure 4.4. *Aggregate Spreader Sheet*

4.5.1.4 *Aggregate Divider*

The *Aggregate Divider* (Figure 4.5) is used to assist with uniformity during aggregate spreading. It consists of two 343 mm long by 25 mm wide by 3 mm thick steel shims welded at the center. It is placed on the *Aggregate Spreader Sheet* before aggregate is dropped and is removed before introducing the *Aggregate Restrainer*.



a) Schematic



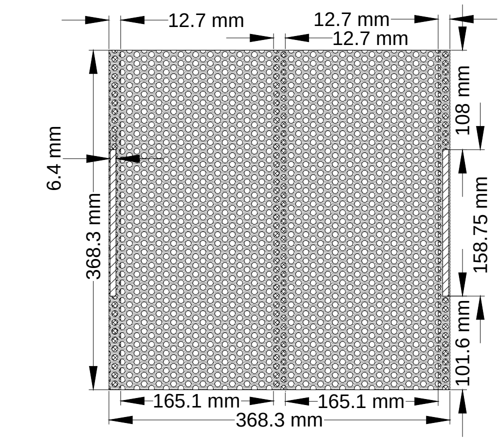
b) Top View Photo

Figure 4.5. *Aggregate Divider*

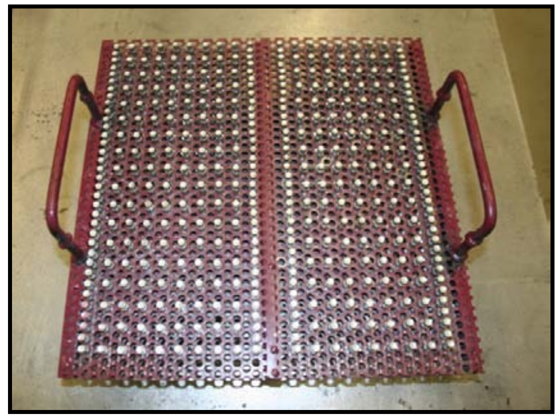
4.5.1.5 *Aggregate Restrainer*

The *Aggregate Restrainer* is an assembly that facilitates uniform and even aggregate spreading onto compacted asphalt specimens that have already had emulsion placed on them.

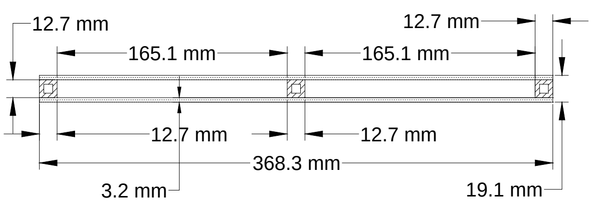
It consists of two sets of two welded and perforated steel plates with slots for approximately 730 anchor bolts fully penetrating each set of two plates (Figure 4.6), providing spaces for approximately 1460 total anchor bolts. The perforated plates are spaced 6-mm from each other by three 6-mm thick steel channels, spaced evenly between both plates.



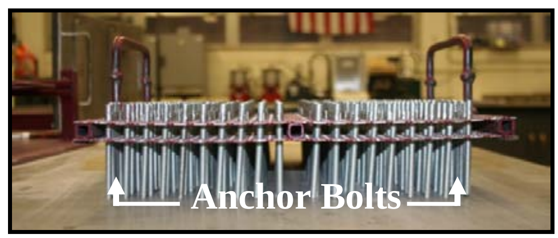
a) Top View Schematic



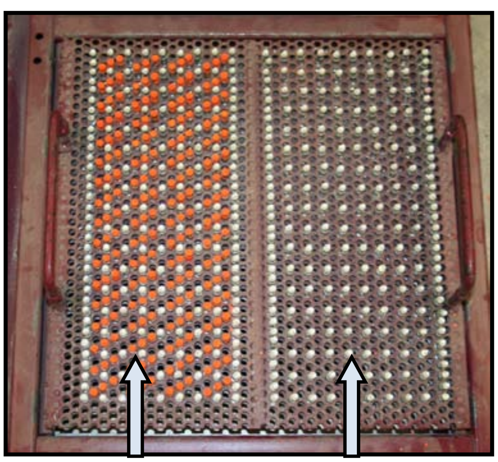
b) Top View Photo (Original Bolt Configuration)



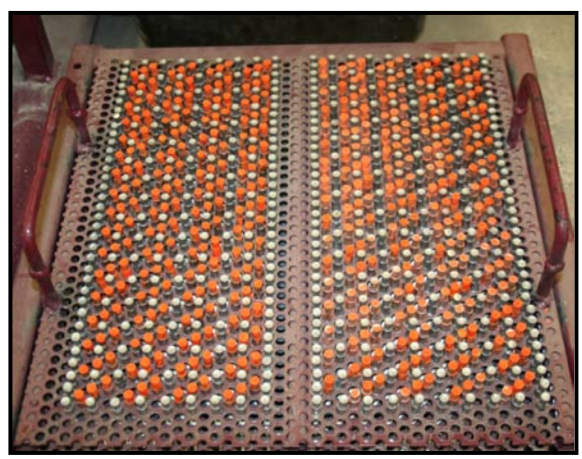
c) Front View Schematic (plates only)



d) Front View Photo



e) Modified Configuration, Original Configuration



f) Modified Bolt Configuration

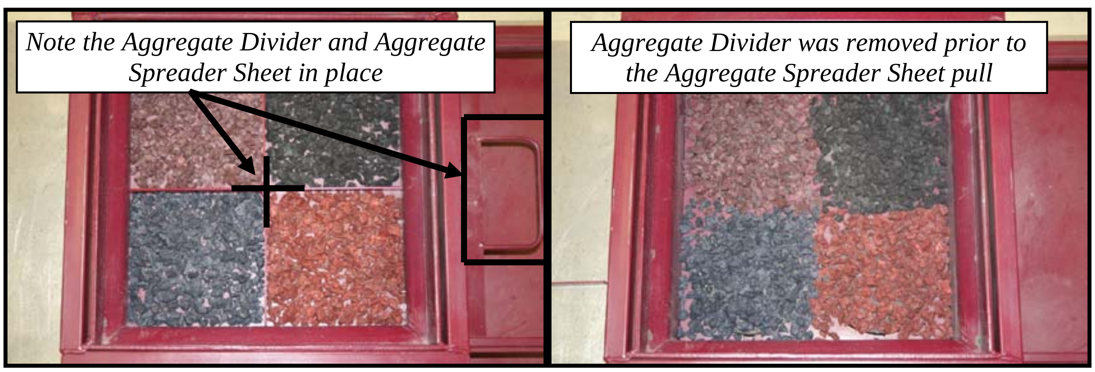
Figure 4.6. ***Aggregate Restrainer***

The anchor bolts are TRUBOLT® wedge anchor 6.4 by 82.6 mm that weigh 15 grams each. The restrainer is used by placing it on the rim of the funnel assembly of the *Spreader Base* after the aggregate is placed on the spreader sheet, while the anchor bolts penetrate both plates and drop approximately 83 mm, slightly touching the spreader sheet.

Only the self-weight of each individual anchor bolt is applied to the aggregates. All anchor bolts become free-floating upon contact and are capable of capturing the vertical profile of the aggregate layer. The purpose is to capture and retain aggregate from lateral movement during the lateral pull of the *Aggregate Spreader Sheet*.

An experiment was conducted to investigate the effectiveness of the *Aggregate Restrainer*. One trial chip seal specimen fabrication procedure was performed with aggregate that had been colored to visually examine the placement of aggregate before and after the aggregate spread. It was observed that the *Aggregate Restrainer* was effective in that aggregate did not have noticeable lateral movement during the aggregate spread. Figure 4.7 shows that aggregates travel vertically, dropping from the *Aggregate Spreader Sheet* directly to the *Specimen Box*.

The aforementioned experiment was performed on aggregate on the order of Size 7, and with the *Aggregate Restrainer* containing around 400 anchor bolts as shown in Figure 4.6b. Seeing that aggregates dropped as desired in Figure 4.7, specimen fabrication commenced this anchor bolt pattern. Early fabrication attempts with Size 89 aggregates observed that the aggregate restrainer was not effective at holding material smaller than 2.36 to 4.75 mm in place during *Aggregate Spreader Sheet* pulling. To address this issue, the number of anchor bolts was increased by approximately 800, and placed in the configuration shown in Figure 4.6f. Anchor bolts applied in the modified configuration are painted orange, while the original configuration is silver.



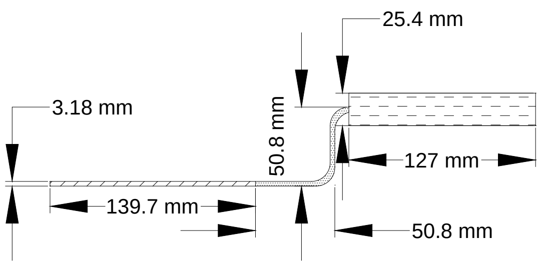
a) Before aggregate spread *b) After aggregate spread*

Figure 4.7. *Aggregate Restrainer* Uniformity Experiment

The modified configuration has bolts oriented to prevent even small aggregates from sliding during *Aggregate Spreader Sheet* pulling. Originally, bolts were not placed in every slot to minimize weight of the *Aggregate Restrainer*, though the extra slots were placed in case a given gradation required more bolts. Once the additional bolts were placed, they were not removed, so Size 7 gradations were prepared with both the original and modified configurations. This was deemed insignificant as more bolts would not cause negative dropping effects, though for Size 7 aggregates they provided no positive effects (Figure 4.7 provides evidence around 400 bolts were sufficient for Size 7 gradations). Size 89 gradations that were tested for non-preliminary efforts used the modified bolt configuration (Figure 4.6f).

4.5.1.6 *Specimen Panhandle*

The *Specimen Panhandle* is used to transfer each individual circular specimen from the scale into the *Specimen Box* (Figure 4.8). Each specimen rests on the panhandle during emulsion application, and then is transferred into the box. When slabs are fabricated, the *Specimen Panhandle* is not used.



a) Schematic

b) Photo

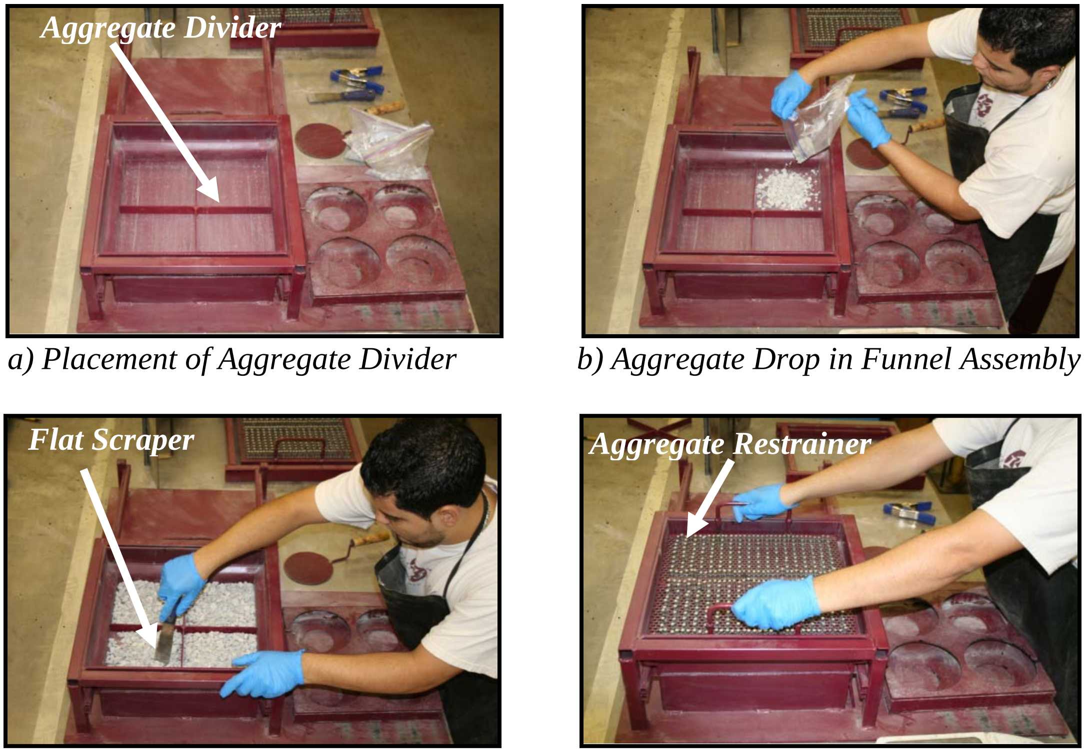
Figure 4.8. *Specimen Panhandle*

4.5.2 LTP Specimen Fabrication Procedure - Cores

Fabrication consists of 1) emulsion application, 2) aggregate application, and 3) seating aggregates. Target fabrication completion time was 7.5 minutes or less. This time corresponds to actual time to completion of *Hwy 44* chip seal construction where emulsion was applied, aggregate was spread, and the surface was compacted in approximately 7.5 minutes.

Preliminary steps consist of placing the *Aggregate Divider* on the *Aggregate Spreader Sheet* (Figure 4.9a), placing and spreading aggregate onto the sheet (Figure 4.9b and 4.9c), and placing the *Aggregate Restrainer* in place (Figure 4.9d). Aggregate is pre-batched in plastic bags equivalent to the desired application rate and equivalent to one-fourth the area of the *Spreader Sheet*. One aggregate batch is dropped and spread within each quarter area using a flat scraper to facilitate uniformity and single layer application. The *Aggregate Divider* is then removed, and the *Aggregate Restrainer* is set in place.

Prior to emulsion application, all specimens are taped around the sides to prevent emulsion runoff and assist with even emulsion distribution. Emulsion was heated to 60 C in an oven and gently agitated to produce uniform consistency (further details are provided in the State Study 211 Volume I report). The emulsion is applied by placing each individual specimen on a scale and evenly spreading a fixed mass of emulsion corresponding to a desired application rate over the surface with a plastic spoon as shown in Figures 4.10a and 4.10b. The *Specimen Panhandle* is then used to move each specimen from the scale and place it inside the *Specimen Box*. Once all four specimens are introduced in the *Specimen Box* (Figure 4.10c), the box is slid into the bottom compartment of the *Spreader Base* (Figure 4.10d).



a) Placement of Aggregate Divider *b) Aggregate Drop in Funnel Assembly*

c) Even Spread with Flat Scraper *d) Placement of Aggregate Restrainer*

Figure 4.9. Preliminary Aggregate Arrangement

The aggregate is spread onto the specimens by pulling the *Aggregate Spreader Sheet* laterally until all aggregate is dropped onto the specimen box (Figure 4.10e). The spreader sheet is pulled completely across the funnel in approximately one second. Afterwards the *Specimen Box* is pulled out of the funnel compartment prior to seating (Figure 4.10f).

Aggregate seating is performed on the surface of the *Specimen Box* so that all specimens are seated simultaneously (Figure 4.10g). The surface is seated in three passes first; then, the specimen box is rotated 90 degrees and the surface is seated again in three passes. The sweep test compactor (shown in the top right corner of Figure 4.1) is used during this procedure. In order to modestly represent in-situ rubber tire compaction, a 380 mm by 380 mm by 13 mm thick rubber pad was affixed to the face of the compactor. The rubber padding was changed periodically as needed during fabrication of specimens in this report. Initial seating attempts placed the rubber pad between the specimens and the compactor, but gluing the pad to the compactor was preferred and was used to produce useable specimens.

Removal of LTP specimens from the *Specimen Box* is performed by pushing the *Specimen Box* slightly off the *Spreader Base*, pushing up from the bottom of each specimen individually, and then carefully removing each specimen off the base (Figure 4.10h). The fully fabricated slab being removed in Figure 4.10h is ready for embedment, conditioning, or testing as desired.

a) Emulsion Poured on Core

b) Emulsion Spread with Spoons

c) Placement in Specimen Box

d) Insertion into Funnel Assembly

e) Aggregate Spread on LTP Specimens

f) Removal from Funnel Assembly

g) Seating

h) Removal of Fabricated Specimen

Figure 4.10. Specimen Fabrication Procedure - Cores

4.5.3 LTP Specimen Fabrication Procedure - Slabs

Slab specimens are fabricated in a similar manner to core specimens which are described in Section 4.5.2. However, some modifications to the core fabrication procedure were necessary. After preliminary aggregate arrangement (Figures 4.9a to 4.9c) but before placement of the *Aggregate Restrainer* (Figure 4.9d), small gaps left from the *Aggregate Divider* are closed by additional, minor spreading of the aggregate batches to form one continuous aggregate layer.

Figure 4.11 demonstrates slab specimen fabrication. Emulsion application for slabs is identical to that of cores. Once emulsion is applied, the slab is inserted into the funnel assembly without the use of the *Specimen Box*. After aggregates are spread and the slab is removed from the funnel assembly, the surface is seated in the same manner as for core specimens. Once fabricated, slabs went through embedment and conditioning prior to having test specimens cored from the slabs. Generally speaking, two circular test specimens were cored from each slab.

a) Emulsion Application *b) Funnel Assembly Removal* *c) Fabricated Slab*

Figure 4.11. Specimen Fabrication Procedure - Slabs

4.6 LTP Specimen Embedment

Generally speaking, embedment and conditioning occurred in multiple phases. The majority of the specimens tested were embedded after fabrication, though there were a fair number of specimens during earlier parts of this research that were not embedded. A total of eleven embedment protocols were used that are described in Table 4.2.

The Linear Asphalt Compactor, or LAC, (Doyle and Howard 2011) was a key embedment component. Figure 4.12 provides photographs of the LAC in various stages of the embedment processes described in Table 4.2. Under normal operation, the LAC has 47 steel plates with thicknesses of 12.7 to 14 mm that are placed side by side to produce kneading compactive effort. For this project, 46 plates were used. The plate removed is normally driven into the specimen mold to tighten the plates; there was concern this might damage specimens on one end prior to beginning embedment. The LAC mold's inside length and width are 62.4 and 29.3 cm, and each LAC plate weighs on the order of 6.7 kg (total mass on the order of 308 kg), producing a static pressure of approximately 0.17 kg/cm^2.

Figure 4.13 is a measured temperature versus time curve within the LAC cavity when under the Figure 4.12f heating element that was measured using a thermocouple inserted through the side of the steel mold by drilling a small hole (see Figure 4.12d). The Figure 4.13 curve began with the system at room temperature (as would occur for E-4) and continued for 60 hours. As seen, it took approximately 6 hours to achieve 30 C, but thereafter, temperatures were 30 to 35 C for practical purposes. Table 4.2 refers to a 30 to 35 C temperature condition on several instances, and this should be understood to come from Figure 4.13. For protocols E-4 to E-6 where specimens were under the LAC plates for 1 to 4 days, it should be noted that the first 6 hours of this duration was 25 to 30 C since all components began at room temperature. For protocols E-7 to E-11, all components had been pre-heated, so effectively they were beyond the 6 hour mark in Figure 4.13.

Table 4.2. Summary of Embedment Procedures

ID	Description
E-1	Room temperature specimens placed in room temperature Marshall mold with thin plastic membrane separating specimens from fine sand. Specimen and mold heated to 35 C in an oven, Marshall hammer left on specimen for 1 day as surcharge, and 6 hammer drops were performed.
E-2	Room temperature specimens placed in room temperature LAC cavity. Figure 4.12e infrared heater positioned above LAC plates until measured temperature inside LAC carriage cavity (Figure 4.12d) was 35 C. Thereafter, temperature cycled between approximately 30 to 42 C. LAC plates were on specimens for 2 to 2.5 days, but no roller passes occurred.
E-3	Room temperature specimens placed in room temperature LAC cavity. Figure 4.12e infrared heater was used initially for 2 days (cavity temperatures of 30 to 42 C), followed by the Figure 4.12f heating element (cavity temperatures of 30 to 35 C) for 4 additional days. LAC plates were on specimens for 6 days, but no roller passes occurred.
E-4	Room temperature specimens placed in room temperature LAC cavity. Figure 4.12f heating element (cavity temperatures of 30 to 35 C) used for 3 to 4 days. LAC plates were on specimens for this duration days, but no roller passes occurred.
E-5	Room temperature specimens placed in room temperature LAC cavity. Figure 4.12f heating element (cavity temperatures of 30 to 35 C) used for 1 to 3 days. LAC plates were on specimens for this duration, and in addition 6 roller passes occurred (Figure 4.12h) with plates resting directly on specimens (i.e. no rubber pad as shown in Figure 4.12g) at a hydraulic cylinder system pressure of 1551 kPa near the end of day 3.
E-6	Room temperature specimens placed in room temperature LAC cavity. Figure 4.12f heating element (cavity temperatures of 30 to 35 C) used for 3 days beginning with all components at room temperature. LAC plates were on specimens for this duration, and in addition 6 roller passes occurred near the end of day 3 (Figure 4.12h) with plates resting on Figure 4.12g rubber pad that was resting on the specimens. Hydraulic cylinder system pressure was set at 1551 kPa.
E-7	Specimens were placed in a 35 C oven overnight, while the full LAC configuration was heated as shown in Figure 4.12f (30 to 35 C). Specimens were then placed in LAC by briefly removing pre-heated plates, and left to sit under the plates for 2.5 hours with Figure 4.12f heating element in place to allow equilibrium temperatures of 30 to 35 C to be achieved. Specimens were then embedded using a 2413 kPa hydraulic cylinder system pressure and 100 roller passes. A five minute pause occurred between each group of 25 passes with hydraulic cylinder system pressure removed but LAC plates still in place. Specimens were under LAC plates for less than half a day.
E-8	Same as E-7 except 25 roller passes were used with a 2413 kPa hydraulic cylinder system pressure.
E-9	Same as E-7 except 100 roller passes were used with a 1551 kPa hydraulic cylinder system pressure.
E-10	Same as E-7 except 25 roller passes were used with a 1551 kPa hydraulic cylinder system pressure.
E-11	Same as E-7 except 200 roller passes were used with a 2413 kPa hydraulic cylinder system pressure.

-- LAC carriage capacity is seven core or SGC specimens or two slabs as seen in Figure 4.12b. Most embedment trials were conducted at full capacity, and in some cases a dummy specimen was used to occupy space in the LAC carriage.

-- Specimen cavity is between bottom of LAC carriage and LAC plates where specimens are placed.

-- The rubber silicone heating element (Figure 4.12f) is a commercially available product (McMaster Carr Product Number 35765K509) which emits 1,440 Watts. The unit was set to 100 C to maintain 30 to 35 C within the LAC specimen cavity.

-- The rubber pad used in E-7 is identical to that glued to the sweep test compactor (Figure 4.10g).

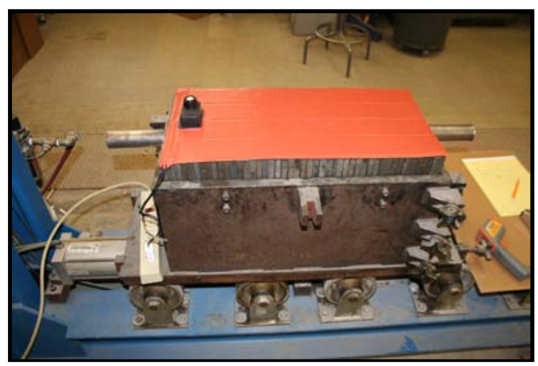
a) Overall view of LAC

b) Specimens in LAC Carriage

c) LAC Plates Resting on Specimens

d) Temperature Monitoring

e) Infrared Heat Lamp



f) Silicone Rubber Heating Element

g) Rubber Pad in Place

h) LAC in Operation

Figure 4.12. Embedment Using the Linear Asphalt Compactor

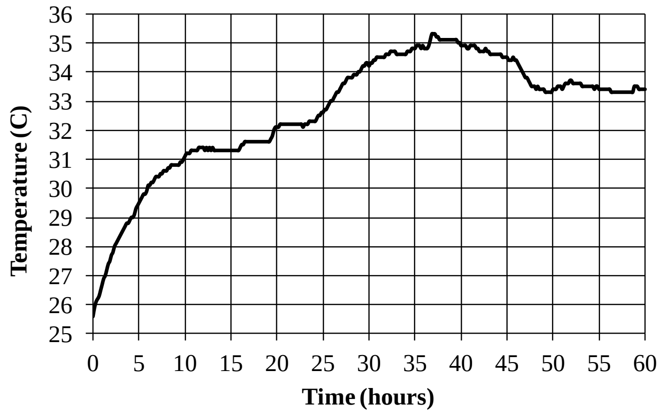


Figure 4.13. Temperature Versus Time Relationship Within LAC Chamber

The LAC was used to allow a range of embedment conditions to be applied to specimens, including crudely simulating embedment from vehicle traffic. It should be understood that the LAC is not ideal for embedding core or gyratory specimens since the carriage dimensions do not allow specimens to be placed side by side, and there is free space on the ends and around the specimens. On the other hand, it should also be understood that conceptually, equipment capable of providing temperatures that are reasonable for chip seals to experience during the construction season, and a combination of static pressure and additional pressure due to kneading action simulating traffic seems to be a reasonable approach to produce representative chip seal specimens in the laboratory.

Several specimens were damaged during embedment in that the pavement cores or gyratory specimens distorted during roller passes (Figure 4.14 provides a few example photographs). Embedment protocol E-5 broke chip seal aggregates, but otherwise there were no protocols that damaged the chip seal itself. Specimens that were damaged were easily identified visually, so the decision was made to continue with testing and discard damaged specimens as opposed to developing a support fixture that could be inserted into the Figure 4.12b LAC carriage to provide lateral support to cores (i.e. focus efforts on proof of concept rather than creating specimen fixture). Note that slab specimens were fully supported and were not damaged during LAC embedment. Some attempts to limit damage to cores or gyratory specimens included placing fine sand between cores and using small wood fixtures to provide some lateral support. In addition, spacers were used to regulate specimen height to some extent, but incorporating better height control into a support fixture should also improve specimen survivability during embedment.

Figure 4.14. Example Photographs of Specimens Damaged During LAC Embedment

4.7 LTP Specimen Conditioning

Eleven conditioning protocols were used (Table 4.3). These protocols generally relied upon ovens, though water baths were used in a few cases. Conditioning occurs after fabrication if no embedment was performed, or after embedment if performed. Most specimens were embedded and conditioned after fabrication but before testing. Some specimens were not embedded but were conditioned. After conditioning, specimens were usually cooled to room temperature and prepared for testing at a later date. In some cases, specimens were taken directly from conditioning to test preparation.

Table 4.3. Summary of Conditioning Procedures

ID	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**	**C-8**	**C-9**	**C-10**	**C-11**
Oven *RH*	**0%**	**0%**	**0%**	**0%**	**30%**	**30%**	**0%**	**0%**	**30%**	**30%**	**0%**
Day 1	85 C	35 C	35 C	35 C	35 C	60 C	35 C	35 C	60 C	60 C	64 C
Day 2	Note 1	35 C	35 C	35 C	35 C	60 C	35 C	35 C	60 C	60 C *WB*	64 C
Day 3	---	35 C	35 C	35 C	35 C	60 C	35 C	35 C	60 C *WB*	60 C	64 C
Day 4	---	---	35 C	35 C	35 C	60 C	40 C *WB*	40 C *WB*	60 C *WB*	60 C *WB*	---
Day 5	---	---	---	35 C	35 C	60 C	40 C *WB*	40 C *WB*	60 C *WB*	60 C	---
Day 6	---	---	---	35 C	35 C	---	40 C *WB*	40 C *WB*	---	---	---
Day 7	---	---	---	35 C	35 C	---	40 C *WB*	40 C *WB*	---	---	---
Day 8	---	---	---	---	---	---	40 C *WB*	40 C *WB*	---	---	---
Day 9	---	---	---	---	---	---	35 C	35 C	---	---	---
Day 10	---	---	---	---	---	---	35 C	35 C	---	---	---
Day 11	---	---	---	---	---	---	35 C	35 C	---	---	---
Day 12	---	---	---	---	---	---	---	35 C	---	---	---
Day 13	---	---	---	---	---	---	---	35 C	---	---	---
Day 14	---	---	---	---	---	---	---	35 C	---	---	---
Day 15	---	---	---	---	---	---	---	35 C	---	---	---

--Note 1: C-1 protocols varied a fair amount, but temperature was 85 C in all cases. Conditioning times ranged from 19 to 162 hr, and a few specimens were conditioned in a water bath.
--Note 2: 35 C for 168 hr (7 days) removes essentially all moisture based on Chapter 10 of Volume I State Study 211 report (Howard et al. 2013).
-- On days where not specified, an oven was used.
-- C-6, C-9, and C-10 were first subjected to C-5.
-- RH = relative humidity (%)
-- WB = water bath

4.8 LTP Specimen Testing

LTP testing equipment, test parameter development, and test protocols are described in this section. A few iterations were performed on some aspects of testing LTP specimens. Pertinent developmental and procedural details related to LTP testing are provided in the remainder of this section. Note that specimens were gently hand brushed prior to testing; i.e. hand brushing occurred after the last step prior to testing (either fabrication, embedment, or conditioning)

4.8.1 LTP Specimen Testing Equipment

4.8.1.1 *Abrasion Heads*

Two abrasion heads were used with the *LTP* test (Figure 4.15). The brush head (ASTM D7000) and the rubber abrasion hose head (ASTM D3910) were used. Ultimately, the abrasion hose head (D3910) was selected for use as described later in this report.

a) Brush Head (ASTM D7000) *b) Rubber Hose Head (ASTM D3910)*

Figure 4.15. Abrasion Heads

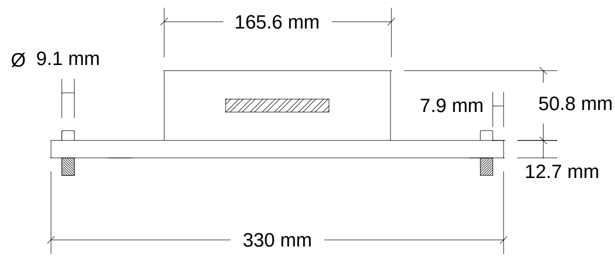
4.8.1.2 LTP Mixer

All testing was performed using the Hobart N50 planetary mixer which is discussed in detail in the State Study 211 Volume I report. The LTP abrasion test was conducted at mixer speed number 1. Figure 4.16 shows the Hobart N50 mixer with the sweep test mounting base and the Figure 4.15a brush head in place.

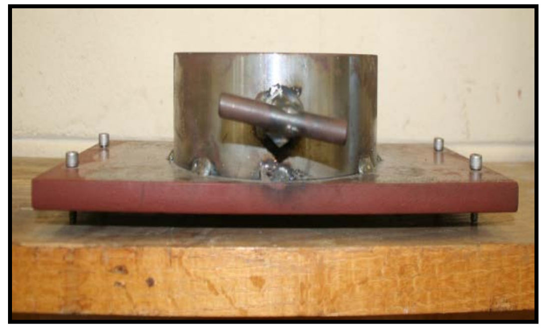
Figure 4.16. Hobart N50 Mixer with Mounting Base in Place

4.8.1.3 *Adapter Base*

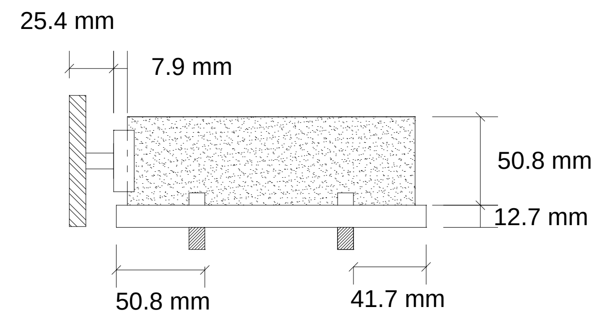
The *Adapter Base* was developed to fit onto the sweep test mounting base of the Hobart mixer (Figure 4.16) and to accommodate either head shown in Figure 4.15. The *Adapter Base* was made to contain chip seal specimens during abrasion testing. The planetary mixer mounting base was altered in order to clamp the specimen in place to prevent movement during testing. The *Adapter Base* (Figure 4.17) consists of a circular, steel ring welded onto a metal plate. The circular steel ring has an inner diameter of 152.4 mm and is positioned in the center of the metal plate. The metal plate has four equally spaced pins located at each corner that act as clamps to secure the *Adapter Base* to the quick-clamp mounting base, thus preventing movement.



a) Front View Schematic

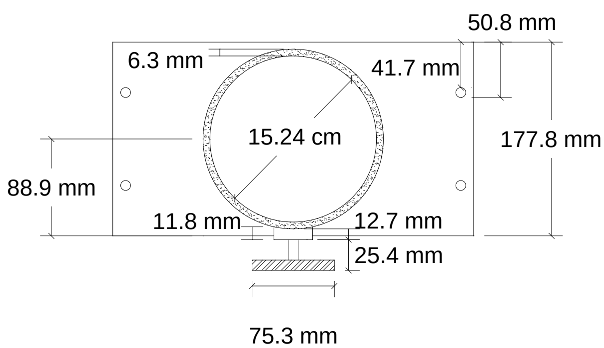


b) Front View Photo

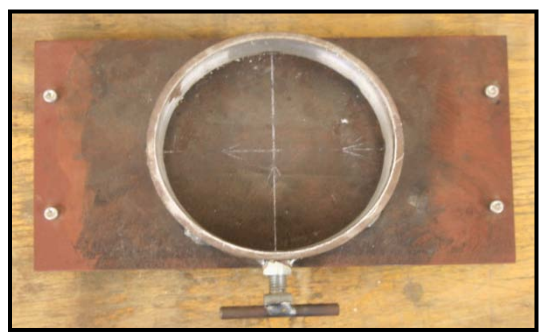


c) Side View Schematic

d) Side View Photo



e) Plan View Schematic



f) Plan View Photo

Figure 4.17. ***Adapter Base***

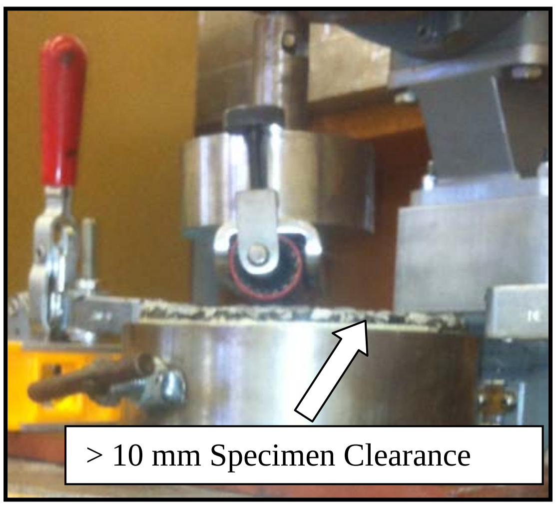
4.8.2 LTP Specimen Test Parameter Development and Testing

Figure 4.18 describes the LTP test protocol. Generally speaking, LTP testing occurred in three phases. All phase 1 efforts were preliminary investigations or testing to establish parameters for phases 2 and 3. The base plate for the mixer was leveled front to back with a series of spacers stacked below the base. The LTP *Adapter Base* was secured to the mixer base plate with clamps (this often occurred immediately before testing). A thin, rectangular piece of sheet metal was used to protect the specimen from the *Adapter Base* dial bolt. If the specimen was too short to be held in place by the dial bolt, a series of shims was used to secure the specimen. In later testing a new dial bolt was tapped into the back side of the LTP base assembly ¼ of the way from the top of the assembly to help alleviate this issue.

In phase 1, specimens were pre-heated from room temperature 1 hr in an oven set at the test temperature absent the *Adapter Base*. After pre-heating, specimens were carefully secured in the room temperature *Adapter Base* in less than 30 seconds. Aluminum spacers of different thicknesses were placed on the bottom, inside of the steel ring to adjust the specimen height so that the chip seal application was at least 10 mm above the *Adapter Base* (Figure 4.18c is an example).

a) 2.5 hr Pre-Heating in Adapter Base

b) Overall LTP Test View



c) Local View of Side Exposure and Abrasion Hose

d) Tested Specimen

Figure 4.18. LTP Specimen Testing

Additional investigation prior to phase 2 revealed that 1 hr of pre-heating absent the *Adapter Base* was not sufficient to achieve the oven set temperature. Figure 4.19 provides details of this investigation. A green dot was placed on the top of a field produced core to monitor its temperature gain with time while being brought to testing temperature. Following the first hour in the oven, the temperature was checked at the predetermined location (i.e. the green dot) at intervals of 15 minutes using a Gilson MA-372 infrared temperature device. Figure 4.19 shows that approximately 2.5 hours is necessary for the specimen to reach test temperature, which was the pre-heating time used in phases 2 and 3. Specimens were pre-positioned in the *Adapter Base* in a manner ready for testing during the Figure 4.19 investigation. Having specimens pre-positioned in the *Adapter Base* allowed the base to be taken directly from the oven to the mixer for testing and minimization of heat loss. The time from opening the oven doors to commencing abrasive forces (T1) from the LTP test (Figure 4.18c) was generally 50 seconds or less (a 60 second or less tolerance is reasonable and was achieved for almost all cases in this project). T1 was the beginning of the LTP test. The final pre-heating configuration for phases 2 and 3 was 2.5 hours while pre-positioned in the *Adapter Base* (Figure 4.18a).

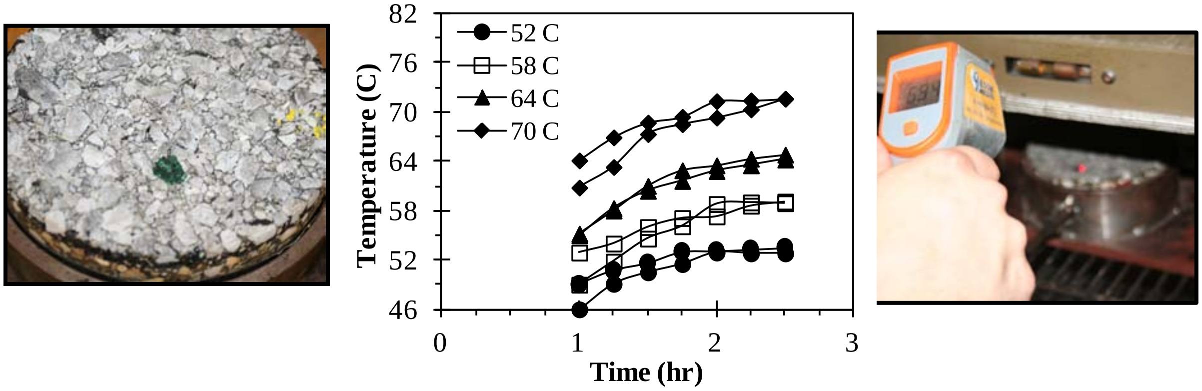


Figure 4.19. Development of Pre-Heating Protocol

During phase 1 efforts, a few LTP approaches were investigated. In all cases, abrasive forces were applied to a specimen using either the D7000 or D3910 abrasion heads. Figure 4.18b shows the overall LTP setup where a specimen has been secured in the Figure 4.17 *Adapter Base* that is sitting on the Figure 4.16 mixer mounting base. The specimen is secure, level, and has 10 mm or more of clearance above the *Adapter Base*. Thereafter the mixer is turned on to speed number 1 and abrasive forces are applied through the abrasion heads that are free-floating, capable of vertical movement, and are rotating on top of the specimen's surface to dislodge aggregates.

Early stage LTP protocols abraded specimens for a given amount of time (e.g. 1 minute) and attempted to evaluate mass loss in some quantifiable manner. These efforts are described in more detail in the phase 1 results presented in Chapter 6, but ultimately these efforts were unproductive, especially for specimens at higher temperatures as their cooling curves would be severely affected if testing stopped several times for evaluation. Overall, specimens were tested at temperatures from 21 to 85 C, with essentially all meaningful test results occurring at 52 to 70 C.

The final LTP protocol was to abrade a specimen until 100% mass loss was reached. 100% mass loss was defined as the surface condition at which all aggregates become dislodged from their original position regardless of the aggregate's location thereafter (e.g. if an aggregate becomes dislodged but moves to the other side of the specimen but does not fall off the specimen it would be considered dislodged). Time to 100% mass loss ($T_{100\%}$) was the only response variable of the LTP test during all of phase 2 and phase 3, and during most of phase 1.

During phases 2 and 3, $T_{100\%}$ was defined as T2 minus T1, with T2 being the time when 100% mass loss was achieved referencing the time the specimen was removed from the oven. For example, if the pre-heating oven doors were opened at time 0 (i.e. stop watch at 0 seconds), and LTP abrasion began 46 seconds later, T1 would be 46. At the conclusion of abrasion (i.e. specimen had 100% mass loss), the timer was stopped, and for example, was 106 seconds (T2). In this case, $T_{100\%}$ was 60 seconds, and the specimen was in transition from pre-heating to LTP testing for 46 seconds. Only $T_{100\%}$ needs reported so long as the transition time is 60 seconds or less.

Mass loss was assessed by means of visual examination; i.e. no calculations were performed. In cases where 100% mass loss was not reached in 900 seconds, the test was terminated early. This condition is defined as T_{max}. Note that T_{max} is equal to T1 plus 900 seconds. Figure 4.18d is an example of a specimen at 100% mass loss that also shows the abrasion hose at the conclusion of testing.

The D3910 abrasion hose was selected in favor of the D7000 abrasion brush during phase 1 testing efforts described in Chapter 6. The D3910 hose was used for all phase 2 and 3 testing. In most cases, abrasion hoses were used for two tests prior to being discarded; hoses were rotated between tests. A typical number of testes performed in a traditional work day period was 6 with two *Adapter Bases* (testing output could be increased with additional *Adapter Bases*).

CHAPTER 5 – FIELD TEST SECTIONS

5.1 General Information for Field Test Sections

Two test sections were evaluated in this study. The first was highway 366 (Hwy 366), which is in Prentiss County and east of Baldwyn, MS. The Hwy 366 project contained 14.0 km of two lane highway that had a total width of 6.55 m (91,700 m^2 to seal). The second was highway 44 (Hwy 44), which is in Lamar County and west of Hattiesburg, MS. The Hwy 44 project contained 9.5 km of two lane highway that had a 6.70 m total width (63,650 m^2 to seal). Table 5.1 summarizes key dates related to these test sections.

Table 5.1. Dates of Field Test Section Activities

Project	**Hwy 366**		**Hwy 44**	
Timing	**Date**	**Days[1]**	**Date**	**Days[1]**
Pre-Sealing Survey, Untreated Specimen Coring	09/10/2010	-4	09/19/2011	-1
Chip Seal Application	09/14/2010	0	09/20/2011	0
Post-Sealing Survey, Unaged Specimen Coring	09/24/2010	10	09/26/2011	6
Intermediate Survey	06/27/2011	286	09/10/2012	356
Two Year Survey, Aged Specimen Coring	09/19/2012	736	09/18/2013	729

1: Days with respect to chip seal being applied.

5.2 Condition of Existing Field Test Sections

Table 5.2 summarizes MDOT pavement management data collected prior to chip sealing. Figures 5.1 to 5.6 are photographs and visual observations of each test section that summarize the condition within the distance evaluated, which was approximately 60 m long.

Table 5.2. Pre-Sealing Pavement Management Properties

Highway Test Sections	**Hwy 366 1 and 2**	**Hwy 366 3**	**Hwy 44 1, 2, and 3**
Survey Date	02/28/2010	02/28/2010	02/17/2010
MDOT Section ID	3802	3803	1624
Coordinates	0.000 to 1.453	1.453 to 1.920	0.000 to 5.897
PCR	67	71	74
Rut Depth (mm)	6.4	2.8	2.3
IRI (mm/m [in/mi])	2.39 [151.4]	2.69 [170.4]	1.79 [113.4]

---Eastbound lane evaluated.

Several cracks ≈ 1 m long. Some wheel path fatigue cracking and numerous cracks ≈1 to 3 mm wide. Pavement appeared somewhat degraded as cores had to be handled carefully.

Figure 5.1. Hwy 44 Section 1 Pre-Sealing Survey (09/19/2011)

Several cracks ≈ 1 m long. Some wheel path fatigue cracking and numerous cracks ≈1 to 3 mm wide. Similar condition to Section 1.

Figure 5.2. Hwy 44 Section 2 Pre-Sealing Survey (09/19/2011)

Some cracks, but not as many as sections 1 or 2. Most cracks were evenly spaced and did not cover full pavement width. Typical cracks were 1 to 3 mm wide.

Figure 5.3. Hwy 44 Section 3 Pre-Sealing Survey (09/19/2011)

Oil and grease droppings were present in some areas, as well as a small amount of polished aggregate. Cracking was minor.

Figure 5.4. Hwy 366 Section 1 Pre-Sealing Survey (09/10/2010)

Surface was in good condition. No cracks were observed in the section.

Figure 5.5. Hwy 366 Section 2 Pre-Sealing Survey (09/10/2010)

Surface was in fair condition, with exception of large transverse cracks that were avoided when selecting section boundaries. Otherwise the section had some cracks, but was not highly cracked.

Figure 5.6. Hwy 366 Section 3 Pre-Sealing Survey (09/10/2010)

5.3 Chip Sealing Activities

5.3.1 Hwy 44 Chip Sealing Activities

Hwy 44 was sealed along with nine other routes. A total of 886,300 m^2 was sealed at \$2.06/m^2. CRS-2P was purchased for \$0.66 per liter (L) and size 7 limestone was purchased for \$72/m^3 and stockpiled on site. The project bid called for a CRS-2P application rate between 1.68 and 1.81 L/m^2 (0.37 to 0.40 gal/yd^2), and a size 7 aggregate application rate between 0.25 to 0.31 ft^3/yd^2, which for a unit weight of 110 pcf translates to 27.5 to 34.1 lb/yd^2. To place the seal, temperature had to be 21 ^oC and rising with no threat of rainfall.

The Hwy 44 chip seal was placed by TL Wallace Construction, Inc. out of Columbia, MS. At 8 AM on the west end of the project, the relative humidity was 95% and the air temperature was 26 ^oC. Sealing commenced later in the morning and the three test sections were sealed in the afternoon. Figure 5.7 provides example photographs of the Hwy 44 sealing process.

Figure 5.7. Hwy 44 Chip Seal Application (09/20/2011)

The pavement edge was scraped with a Cat® 12H blade, and the pavement surface was swept with a Broce Broom Model RCT 350 prior to emulsion application. Once swept, the emulsion was placed with an Etnyre® Black-Topper® Centennial Series Asphalt Distributor. Aggregates were placed with an Etnyre® QUAD Model Chip Spreader. Aggregates were seated into the emulsion with two Ingersoll Rand PT-125R rollers (water tanks were empty) that had four pneumatic tires in the front and five pneumatic tires in the back. The maximum tire pressure rating was 860 kPa (125 psi). The standard weight of PT-125R rollers is 4,082 kg (9,000 lb), or 454 kg (1,000 lb) per tire. Three passes were made with each roller. The chip seal was swept the next day to complete the process.

Data collection at each test section began just before the emulsion was applied to the pavement and continued until aggregates were placed. Table 5.3 summarizes test section locations and conditions when the sections were sealed. Air temperature (T_{air}) and pavement surface temperature (T_{pvmt}) were measured with a digital thermometer. Relative humidity was measured with a hand held device placed a few millimeters above the pavement.

Emulsion temperature exiting the spray bar ($T_{E\text{-}spray}$), and emulsion temperature immediately before covering with aggregate ($T_{E\text{-}cover}$) were measured with a hand held infrared temperature measurement device. Aggregate application rates calculated during the project (R_{Agg} or $R_{Agg\text{-}C}$) and emulsion application rates calculated during the project (R_E) are also provided in Table 5.3. Time between applying emulsion and cover aggregate (t_{cover}) and time to traffic release ($t_{traffic}$) were also collected.

Table 5.3. Hwy 44 Sealing Information

Data	Section 1	Section 2	Section 3
Distance From BOP	1.49	2.10	2.98
Date Placed	09/20/2011	09/20/2011	09/20/2011
Time Began	1:45 PM	1:14 PM	1:04 PM
GPS COORDINATES-North	N 31 23’ 21.5”	N 31 22’ 50.2”	N 31 22’ 21.8”
GPS COORDINATES-West	W 89 37’ 13.0”	W 89 37’ 49.9”	W 89 38’ 07.4”
Lane Tested	Eastbound	Eastbound	Eastbound
Cored Asphalt Thickness (cm)	10.8	10.0	12.7
Year Existing Surface Placed	2000	2000	2000
Emulsion ID (Table 3.1)	C	C	C
Aggregate ID (Table 3.8)	Size 7	Size 7	Size 7
Sky Conditions	Clouds w/ Some Sun	Clouds	Clouds w/ Some Sun
Wind Conditions	Slight Breeze	Calm	Calm
Relative Humidity (%)	41	49	48
T_{air} (^oC)	30.6	26.1	28.3
T_{pvmt} (^oC)	36.1	29.4	34.4
$T_{E\text{-}spray}$ (^oC)	52.2	46.7	47.2
$T_{E\text{-}cover}$ (^oC)	36.1	30.0	33.9
t_{cover} (sec)	251	225	150
$t_{traffic}$ (min)	A Few	A Few	A Few
Pilot Car	Yes	Yes	Yes
R_E (gsy)	0.38 to 0.39	0.38 to 0.39	0.38 to 0.39
R_{Agg} (ft^3/yd^2)	0.28 to 0.29	0.28 to 0.29	0.28 to 0.29
$R_{Agg\text{-}C}$ (lb/yd^2)	16.2 to 16.8	16.2 to 16.8	16.2 to 16.8

--- BOP is measured in miles from the Marion County Line.

--- Aggregate moisture was ≈1.1%

--- Visual identification of cores in all sections agreed with MDOT pavement management records. Layer thicknesses varied somewhat from section to section as indicated by the different pavement thicknesses in the sections. It was difficult to distinguish the interface between the double bituminous surface treatment and the overly directly above it.

--- $R_{Agg\text{-}C}$ values were calculated using project G_{sb} with MDOT’s formula in section 907-410.03.6.1 of special provision 907-410-7 dated April 9, 2013.

5.3.2 Hwy 366 Chip Sealing Activities

The seal was placed with MDOT forces, so no bid or specification information was obtained for this project. Figure 5.8 provides example photographs of the Hwy 366 sealing process. The pavement edge was scraped with a John Deere 570 B motor grader, and the pavement surface was swept with a Waldon Sweepmaster 250 prior to emulsion application. Once swept with a Rosco Maximizer asphalt distributor, aggregates (stockpiled on site) were placed with a Rosco Flaherty SPR-H chip spreader. Aggregates were seated into the emulsion with two rollers with empty water tanks that had five pneumatic tires on the front and six pneumatic tires on the back: BROS PS 2500 and Ferguson SP-1115. Three passes were made with each roller. The BROS roller had a maximum tire pressure rating of 860 kPa (125 psi), and the standard weight of the roller is 3,380 kg (7,450 lb), which is approximately

307 kg (675 lb) per tire. The Ferguson roller is similar except the tire pressure rating was 275 kPa (40 psi). The chip seal was swept on September 14, 2010 and again on September 16, 2010 to complete the process.

Figure 5.8. Hwy 366 Chip Seal Application (09/14/2010)

Data collection per section began just before emulsion was applied to the pavement and continued until aggregate placement. Table 5.4 summarizes test section locations and conditions when the sections were sealed. Table 5.4 terminology is the same as in Table 5.3.

Table 5.4. Hwy 366 Sealing Information

Data	**Section 1**	**Section 2**	**Section 3**
Distance From BOP	0.08	0.55	1.61
Date Placed	09/14/2010	09/14/2010	09/14/2010
Time Began	8:10 AM	8:31 AM	9:15 AM
GPS COORDINATES-North	N 34 d 30.5425 m	N 34 d 30.5827 m	N 34 d 30.9858 m
GPS COORDINATES-West	W 88 d 35.6224 m	W 88 d 35.1532 m	W 88 d 34.0655 m
Lane Tested	Eastbound	Eastbound	Eastbound
Cored Asphalt Thickness (cm)	12.2	8.2	14.0
Year Existing Surface Placed	2006	2010	1993
Emulsion ID (Table 3.1)	C	C	C
Aggregate ID (Table 3.8)	Size 89	Size 89	Size 89
Sky Conditions	Clear	Clear	Clear
Wind Conditions	Calm	Calm	Calm
Relative Humidity (%)	72	72	72
T_{air} (^{o}C)	18.3	22.8	22.8
T_{pvmt} (^{o}C)	19.4	25.6	30.0
$T_{E\text{-}spray}$ (^{o}C)	47.8	48.9	44.4
$T_{E\text{-}cover}$ (^{o}C)	32.2	30.0	35.0
t_{cover} (sec)	45	70	78
$t_{traffic}$ (min)	8	9	7
Pilot Car	No	No	No
R_E (gsy)	0.25	0.25	0.29
R_{Agg} (ft^3/yd^2)	0.31	0.31	0.28
$R_{Agg\text{-}C}$ (lb/yd^2)	16.6	16.6	15.0

--- BOP is measured in miles from the Intersection of Hwy 366 and Hwy 370.

--- Aggregate moisture was ≈2.5%.

--- Visual identification of cores in all sections did not agree with MDOT pavement management records. Section 1 was missing a surface overlay ≈5 cm thick and the layers that were identified were slightly thicker than shown by pavement management. Section 2 was missing an overlay at the surface≈3 cm thick, but the rest of the layers were in reasonable agreement with pavement management. Section 3 was significantly thicker than shown in pavement management. The years the existing surface were placed as shown in this table were provided by the District 1 Maintenance Engineer.

---$R_{Agg\text{-}C}$ values were calculated using project G_{sb} with MDOT's formula in section 907-410.03.6.1 of special provision 907-410-7 dated April 9, 2013.

5.4 Condition of Field Test Sections After Sealing

Each pavement was surveyed three times after chip seal application (Table 5.1). These surveys occurred as early as 6 days after sealing and as late as 736 days after sealing. The surveys occurred: 1) a few days after sealing; 2) several months after sealing; and 2) approximately two years after sealing. Photos and summary information from each survey is provided in the remainder of this section organized by test section.

5.4.1 Hwy 44 Condition Surveys

The seal was in good condition just after placement (Figure 5.9). Aggregate coverage was generally very good. Section 3 had a few areas that were not covered as well as other sections, but these areas were reasonably covered. The seal within a few centimeters of the centerline was not as well covered as the rest of the pavement. Neither Hwy 44 or Hwy 366 sealed the pavement's centerline prior to applying the chip seal. Wood and Olson (2011) state this practice can avoid excessive asphalt absorption at the joint. The centerline joint appeared to be the best in section 2, a little worse in section 1, and the worst in section 3.

Figure 5.9. Hwy 44 Post-Sealing (09/26/2011)

The Hwy 44 intermediate survey occurred 356 days after chip seal placement. The seal was evaluated by MDOT's acting District Maintenance Engineer who reported the seal to be in very good shape with no raveling or bleeding and good aggregate retention (Figures 5.10 to 5.12). Approximately two years after placement (729 days), the seal's condition was evaluated again (Figures 5.13 to 5.15). The seal was in reasonable to decent shape.

Figure 5.10. Hwy 44 Section 1 Intermediate Survey (09/10/2012)

Figure 5.11. Hwy 44 Section 2 Intermediate Survey (09/10/2012)

Figure 5.12. Hwy 44 Section 3 Intermediate Survey (09/10/2012)

There were signs of lack of texture/full embedment in wheel paths, but no meaningful bleeding/flushing. Centerline was in better shape than Section 2. There was some wheel path rutting.

Figure 5.13. Hwy 44 Section 1 Two Year Survey (09/18/2013)

Centerline had some noticeable problem areas. Aggregate loss and bleeding were a little worse visually than Section 3, but otherwise the same general observations were made. Seal was in decent shape.

Figure 5.14. Hwy 44 Section 2 Two Year Survey (09/18/2013)

There were noticeable areas where binder was visible; i.e. aggregate loss. Some areas were as large as 2.5 cm diameter. There were no signs of bleeding and overall the condition was about the same as Section 1 even though aggregate loss seemed a little worse than Section 1. Seal was in reasonable shape.

Figure 5.15. Hwy 44 Section 3 Two Year Survey (09/18/2013)

5.4.2 Hwy 366 Condition Surveys

The Hwy 366 seal was in good condition just after placement (Figure 5.16). Two-hundred and eighty-six days later the seal was in reasonable shape (Figures 5.17 to 5.19). No major failures were observed in the test sections. The pavement was plowed for snow three times in the winter of 2010. Approximately two years after placement (736 days), the seal's condition was evaluated again (Figures 5.20 to 5.22). The seal had degraded, but was still in reasonable shape and functional. The winder of 2011 was mild and no snowfall occurred, so there was no additional snow plow activity between the intermediate and two year surveys.

Figure 5.16. Hwy 366 Post-Sealing Survey (09/24/2010)

Slight aggregate loss, some popouts, and a little more aggregate loss in the wheel path. Some underlying cracks were beginning to be visible, but overall no major distresses were observed.

Figure 5.17. Hwy 366 Section 1 Intermediate Survey (06/27/2011)

Wheel path appeared slightly more polished than lane center. Very few popouts were observed; dark areas were from oil drippings and not bleeding/flushing. Aggregate loss was insignificant, and a few small cracks were beginning to be visible. Slightly better condition than Section 1.

Figure 5.18. Hwy 366 Section 2 Intermediate Survey (06/27/2011)

Several popouts and large cracks were easily visible. The large cracks are likely due to highly cemented base for bridge approach. Very little wheel path polishing was observed.

Figure 5.19. Hwy 366 Section 3 Intermediate Survey (06/27/2011)

Some aggregate loss and popouts; greater loss in wheel paths. Some cracks visible that were present pre-sealing. No major distresses; overall in good shape for two years old.

Figure 5.20. Hwy 366 Section 1 Two Year Survey (09/19/2012)

A few popouts. Wheel path was slightly darker than the rest of the pavement, but seal was in very good shape. No cracking observed; seal in a little better shape than Section 1.

Figure 5.21. Hwy 366 Section 2 Two Year Survey (09/19/2012)

Considerable popouts. Reflective cracks were easily visible. Some longitudinal cracking, but other than the large transverse cracks, there were no major distresses other than excessive binder in a few areas that did not appear to be traffic related.

Figure 5.22. Hwy 366 Section 3 Two Year Survey (09/19/2012)

5.4.3 Hwy 44 and Hwy 366 Traffic and Condition Indices

Annual Average Daily Traffic (AADT) estimates for Hwy 44 and Hwy 366 were obtained from MDOT (http://mdot.ms.gov/applications/trafficcounters/). Hwy 44's AADT was 1800 at site ID 370400. Hwy 366's AADT was 720 at site ID 590670 and 760 at site ID 590660. Table 5.5 summarizes condition indices after chip seal application; Table 5.2 has pre-seal test data.

Table 5.5. Post-Sealing Pavement Management Properties

Highway **Test Sections**	**Hwy 366** **1 and 2**	**Hwy 366** **3**	**Hwy 44** **1, 2, and 3**
Survey Date	07/02/2012	07/02/2012	02/23/2012
MDOT Section ID	3802	3803	1624
Coordinates	0.000 to 1.453	1.453 to 1.920	0.000 to 5.897
PCR	73	67	74
Rut Depth (mm)	7.8	4.3	6.3
IRI (mm/m [in/mi])	2.07 [131.1]	2.93 [185.6]	1.91 [121.0]

---Eastbound lane evaluated.

5.5 Field Test Section Coring Patterns

Test sections were approximately 60 m long and in the eastbound lane. Test sections had no significant distresses such as potholes or patches. Each highway had three test sections that were cored three times as per the Table 5.1 schedule; 2 highways, 3 sections, and 3 times result in 18 coring groups. Untreated cores were taken from the western most end of each section, unaged cores were taken from the eastern most end of each section, and aged cores were taken near the middle of each section since all sections were reasonably uniform and any one area was representative of the section. When cores with a chip seal were taken, ice was placed on the pavement surface to minimize damage that could occur if the chip seal stuck to the coring bit (Figure 5.23).

In the transverse direction, five core locations were marked in a row at 0.3, 0.9, 1.5, 2.1, and 2.7 m from the centerline. In the longitudinal (i.e. traffic) direction, rows of cores were spaced 3 m apart. Of the 18 coring groups: 13 took ten cores in two rows, 1 did not get cored due to rain, 1 took fifteen cores in three rows, and 3 took ten cores in two rows alongside two additional cores at 0.9 and 2.1 m from the centerline. The group that took fifteen cores allowed for some preliminary testing, and the groups that took twelve cores was as a result of finalized test plans that were ongoing at the time the other sections were cored.

Table 5.6 summarizes the cores taken. A total of 42 untreated cores were taken that were tested (note that five were damaged during laboratory embedment leaving 37 data points), and 126 treated (i.e. chip seal applied in the field) cores were taken that were tested. In some cases, cores taken were not tested for reasons such as they were damaged during coring or transport. Traffic control was only available for limited periods, and cores were not carefully inspected on site. In a few instances damage to a core was not identified until it was allowed to dry and was viewed in the laboratory.

Figure 5.23. Pre-Marked Locations With Ice Prior to Coring

Table 5.6. Summary of Hwy 44 and Hwy 366 Cores Taken

			Cores	
Location	**Type**	**Section**	**Total Taken**	**Tested**
Hwy 44	Untreated	1	10	10
		2	10	10
		3	10	6
96 total cores	Unaged	1	10	10
		2	10	10
		3	10	8
	Aged	1	12	12
		2	12	12
		3	12	12
Hwy 366	Untreated	1	10	8
		2	10	8
		3	0	0
85 total cores	Unaged	1	10	10
		2	10	10
		3	15	12
	Aged	1	10	10
		2	10	10
		3	10	10

-- Rainfall prevented coring of Hwy 366 section 3.
--Five of the untreated cores denoted to be tested were damaged during embedment.

CHAPTER 6 - TEST RESULTS

6.1 Overview of Test Results

Results of all LTP and sweep testing are provided in this chapter. A small amount of sweep testing was performed for general comparative purposes with respect to LTP test results. Laboratory prepared and field sampled LTP specimens make up the majority of the tests results, and their results are presented individually. The numbers of specimens tested and application rates (aggregates and emulsion) are described within each respective section.

6.2 *Sweep-M* Test Results

Table 6.1 provides test results performed with the *Sweep-M* protocol. As described in Howard et al. (2013), *Sweep-M* testing generally produced twice the mass loss of ASTM D7000. The *Hwy 366* limestone (Size 89) had lower mass loss and higher moisture loss than the *Hwy 44* limestone (Size 7) when tested with Emulsion C. In that the same general size fractions were tested as opposed to the entire gradation, this could suggest the *Hwy 366* limestone was somewhat more compatible with Emulsion C than the *Hwy 44* limestone.

Table 6.1. *Sweep-M* Test Results

Aggregate	Emulsion	Test Time (hr)	Mass Loss (%)	Moisture Loss (%)
Size 89	C	1	42	31
Hwy 366		2	31	41
		4	14	53
Size 7	C	1	51	27
Hwy 44		2	45	39
		4	26	48

--Values reported are the average of two tests.

6.3. LTP Results for Field Applied Chip Seals

A total of 126 specimens were successfully tested with the D3910 rubber hose and 2.5 hr pre-heating where the chip seal was applied during full scale activities and cored thereafter. These specimens were not embedded or conditioned beyond what occurred in the field. Table 5.6 summarizes the cores obtained where chip seals had been applied prior to coring. Figures 6.1 to 6.4 provide results for these specimens. Figures 6.5 and 6.6 provide representative photos of specimens from each highway, test section, and field aging time.

Detailed information regarding construction properties for each project are provided in Chapter 5, with key parameters summarized herein. *Hwy 44* used an emulsion application rate of 1.72 to 1.77 L/m^2 (0.38 to 0.39 gsy) in all three test sections. *Hwy 366* used 1.13 L/m^2 (0.25 gsy) in sections 1 and 2, and 1.31 L/m^2 (0.29 gsy) was used in section 3. Emulsion C was used for both projects.

Visually, $T_{100\%}$ increased from the specimens field aged 6 or 10 days to 729 or 736 days. There was also a fair amount of variability between test results. In a few cases, one small area not dislodging resulted in noticeably higher $T_{100\%}$ values. The remainder of this section evaluates *Hwy 44* (Size 7) and *Hwy 366* (Size 89) results separately.

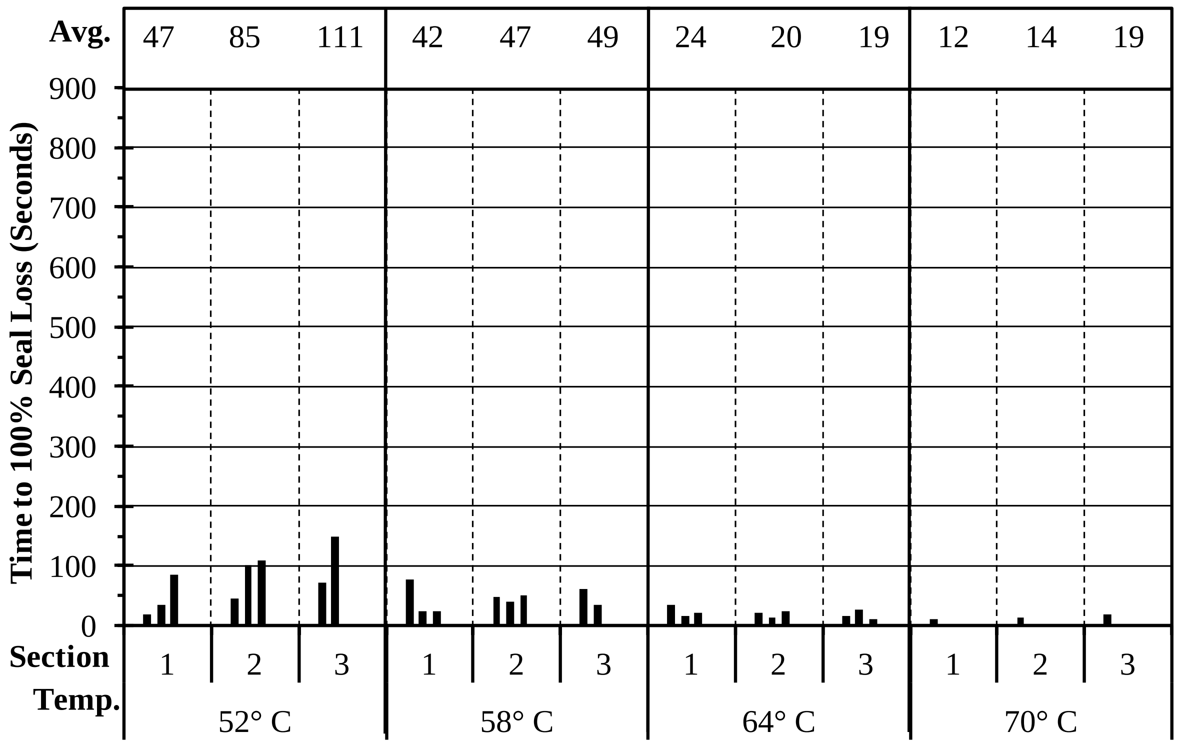


Figure 6.1. 6 Day Aged *Hwy 44* Field Core Test Results (Size 7 Aggregate)

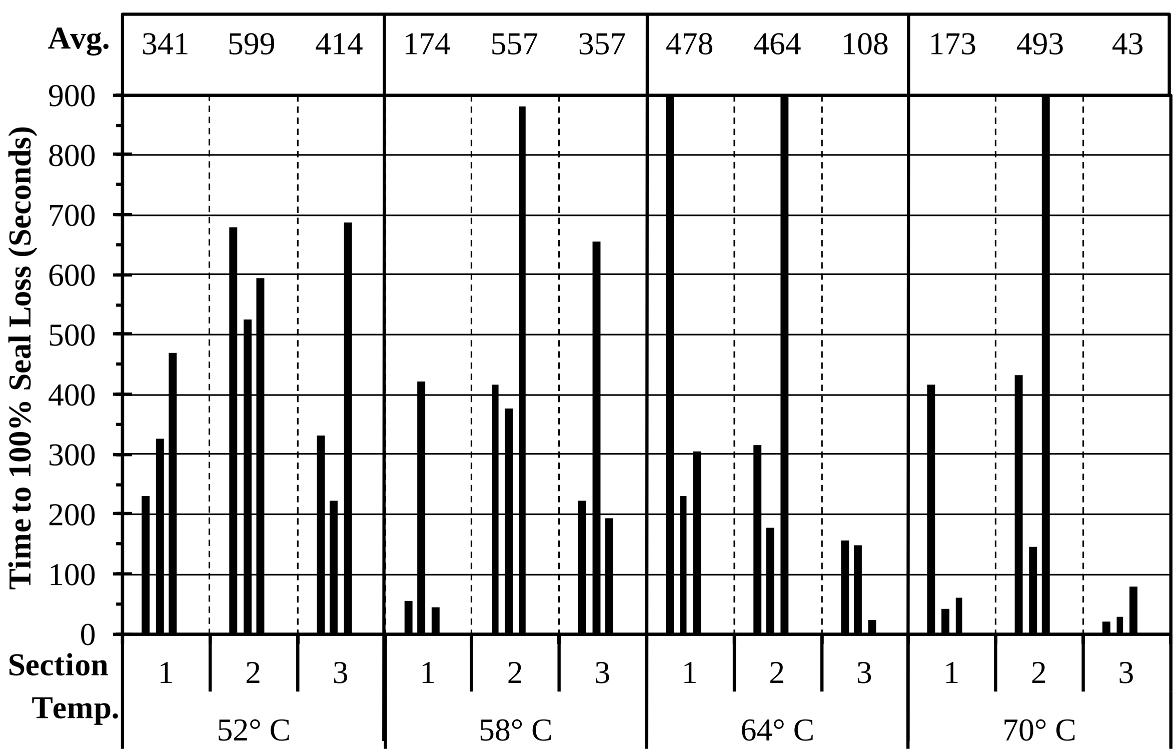


Figure 6.2. 729 Day Aged *Hwy 44* Field Core Test Results (Size 7 Aggregate)

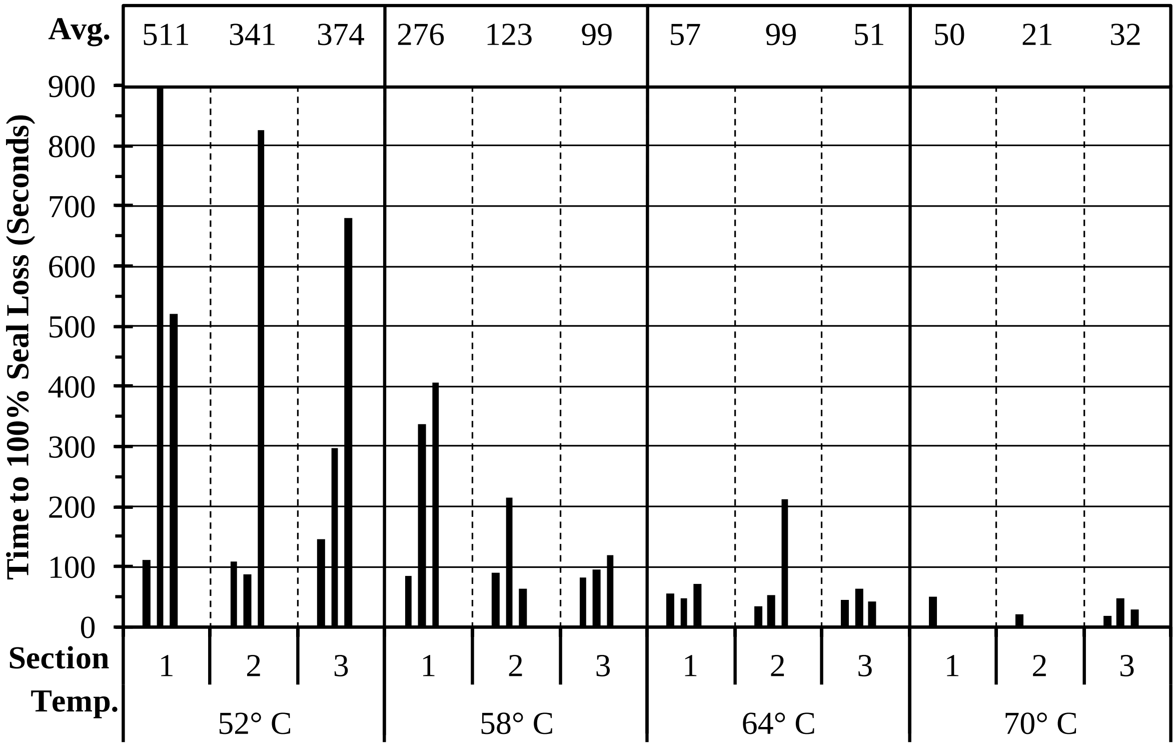


Figure 6.3. 10 Day Aged *Hwy 366* Field Core Test Results (Size 89 Aggregate)

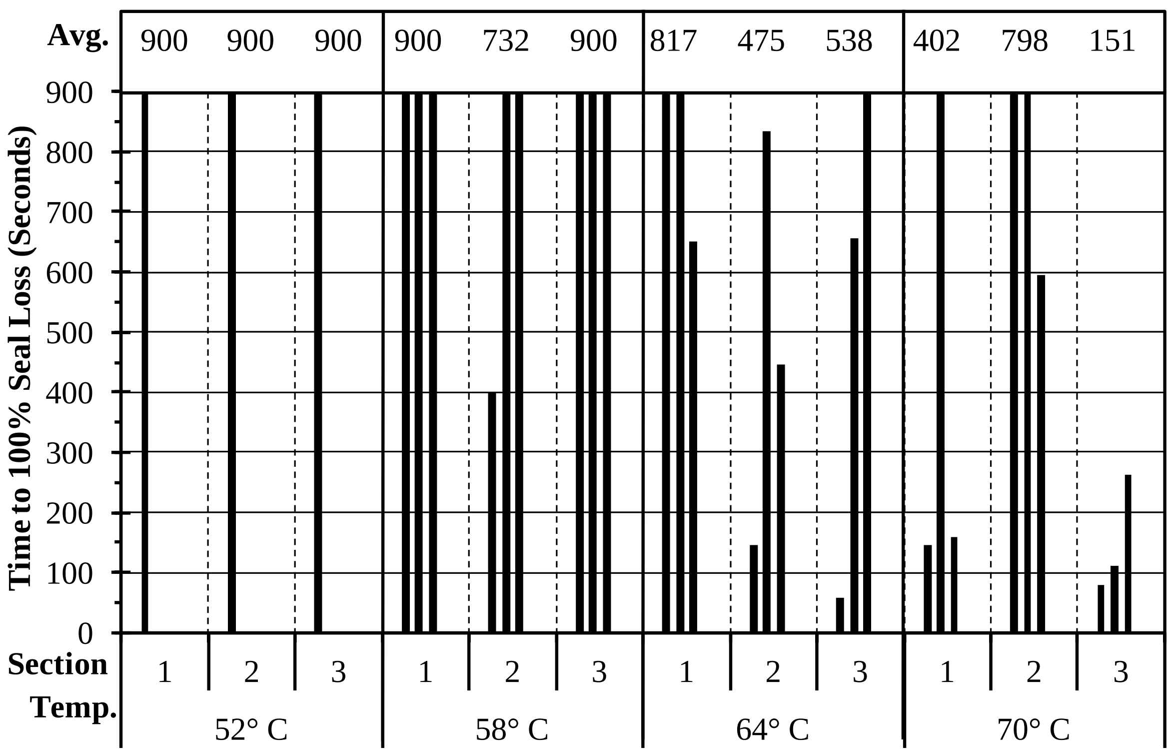


Figure 6.4. 736 Day Aged *Hwy 366* Field Core Test Results (Size 89 Aggregate)

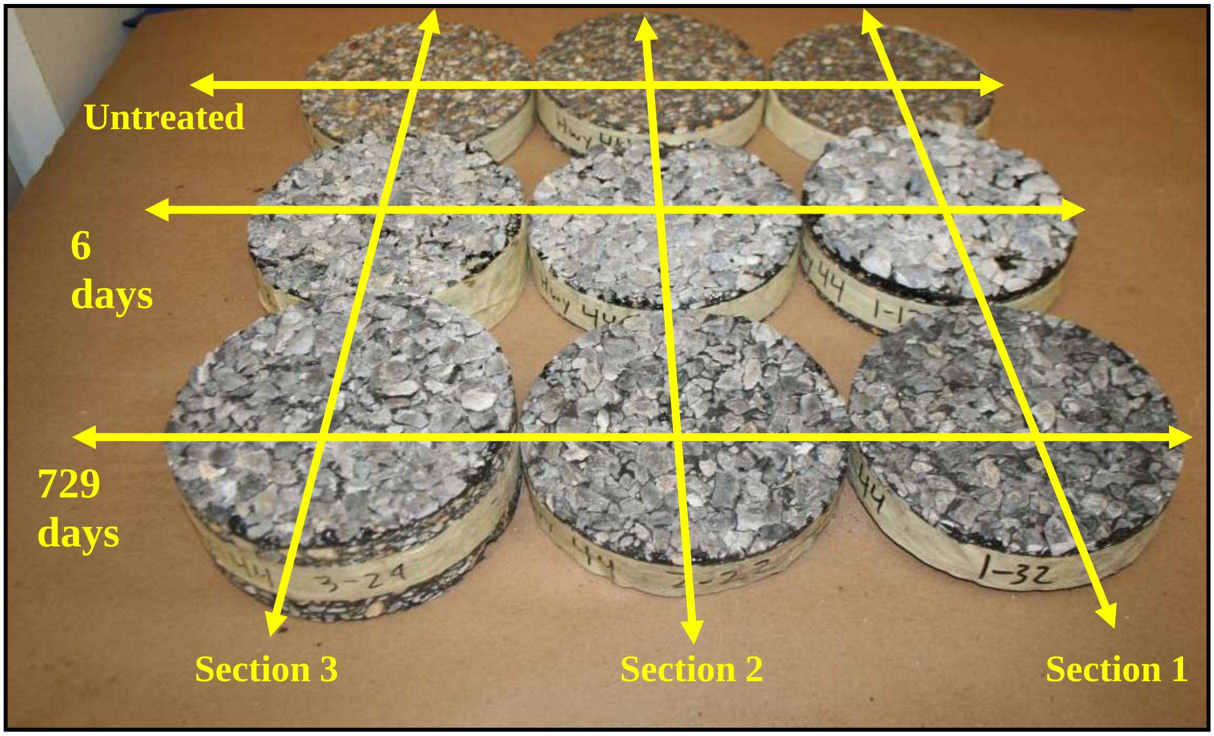
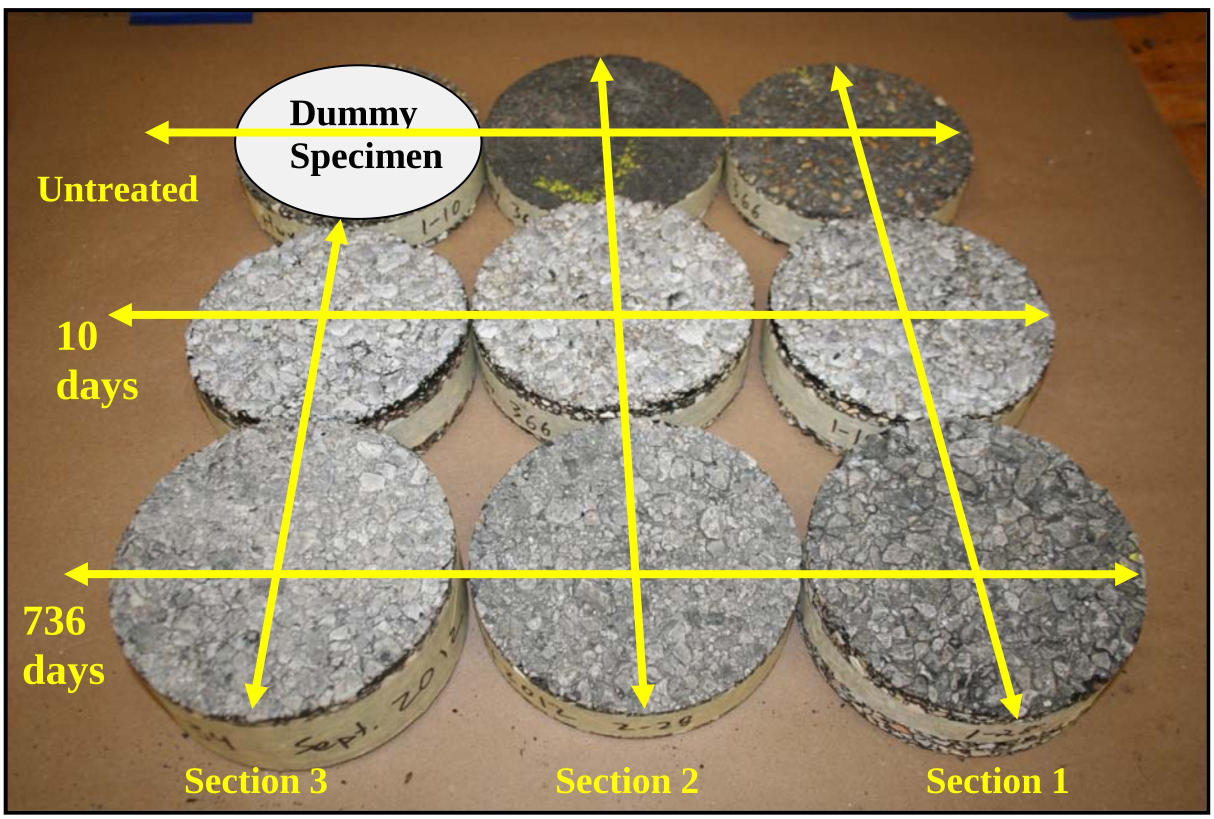


Figure 6.5. Photos of *Hwy 44* Specimens (Surfaces Are Only Relevant Aspect)



Note: Section 3 was not cored prior to sealing.

Figure 6.6. Photos of *Hwy 366* Specimens (Surfaces Are Only Relevant Aspect)

To provide an overall evaluation of Size 7 aggregates, all *Hwy 44* sections were combined into one data set. This was deemed reasonable for this study since the existing surface was placed in the same year and was reasonably consistent in terms of distresses prior to sealing. Consistent chip seal application rates were also used throughout the project.

Table 6.2 is a condensed form of the data presented in Figures 6.1 and 6.2. Average $T_{100\%}$ values decreased with test temperature, which is somewhat intuitive. Coefficient of Variation (COV) values were fairly high, and COV trends were not consistent with aging time. For example, 70 C testing for a 6 day age had the lowest COV of the four temperatures, but at a 729 day age 70 C had the highest COV of the four temperatures. At a 52 C level, COV values were 40 to 55%, which was the most desirable overall variability.

Table 6.2. Summary of *Hwy 44* (Size 7) LTP Results for Field Applied Chip Seals

Aging Time (days)	Test Temp (C)	n	$T_{100\%}$ (seconds) Average	Min	Max	Stdev	COV (%)
6	52	8	77	20	148	43	55
	58	8	46	23	78	19	41
	64	9	21	12	35	7	34
	70	3	15	12	19	4	24
729	52	9	451	222	688	182	40
	58	9	362	45	880	275	76
	64	9	350	23	900	324	93
	70	9	236	20	900	296	126

To provide an overall evaluation of Size 89 aggregates, all *Hwy 366* sections were combined to produce one data set. This is not an ideal approach with different surfaces and emulsion application rates in the test sections, though it does give a general idea of field behaviors for comparison of laboratory and field produced specimens. Table 6.3 is a condensed form of the data presented in Figures 6.3 and 6.4. Average $T_{100\%}$ values for *Hwy 366* Size 89 were higher than *Hwy 44* Size 7 in all cases. These results should be interpreted in light of Table 6.1 sweep test findings where *Hwy 366* aggregates appeared more compatible with Emulsion C for similar aggregate sizes. Average $T_{100\%}$ values decreased with test temperature, which also occurred for Size 7 aggregates. COV values were higher at earlier aging times, which is opposite to what occurred for Size 7 aggregates. There were no obvious observations related to COV values other than they were very high.

Table 6.3. Summary of *Hwy 366* (Size 89) LTP Results for Field Applied Chip Seals

Aging Time (days)	Test Temp (C)	n	$T_{100\%}$ (seconds) Average	Min	Max	Stdev	COV (%)
10	52	9	409	88	900	329	80
	58	9	166	64	406	126	76
	64	9	69	35	211	54	79
	70	5	33	18	50	15	45
736	52	3	900	900	900	0	0
	58	9	844	397	900	168	20
	64	9	610	57	900	327	54
	70	9	451	80	900	369	82

--Note that some of the Hwy 366 specimens with $T_{100\%}$ values of 900 seconds abraded the D3910 hose in a similar manner to that shown in Figure 6.7b.

6.4. LTP Results for Laboratory Applied Chip Seals

Laboratory specimens were evaluated in three phases. The first phase was also presented in Alvarado (2012), with phases two and three being unique to this report. Generally speaking, phase 3 produced the majority of the useful data collected from laboratory applied chip seals by utilizing findings from phases 1 and 2. A key component of this investigation was to compare properties of laboratory produced chip seals to those of field applied chip seals. The data in Tables 6.2 and 6.3 is compared to phase 3 laboratory specimens at the end of this section.

6.4.1 Phase 1 LTP Results for Laboratory Applied Chip Seals

All information in this sub-section is a consolidated form of Alvarado (2012). All phase 1 efforts were preliminary investigations or testing to establish parameters for phases 2 and 3. Emulsions B and C were used in phase 1, alongside Size 7 *Hwy 44* aggregate.

Fabrication protocols were evaluated by visually comparing laboratory produced specimens to *Hwy 44* field cores described in Chapter 5 and Section 6.3. When the non-sliced faces of *Hwy 49-S1* SGC specimens were used, excess emulsion loss occurred along the sides of and into the specimen. Pre-coating these specimens with 0.45 L/m^2 (0.1 gal/yd^2) of emulsion improved this problem, but ultimately it was decided to use sliced faces for chip seal application for the remainder of phase 1 and for all of phases 2 and 3. The inside or sliced surface of these specimens was more compacted than the outside surface, and it was smoother than any other surface evaluated. Visually, chip seals placed on the sliced surface were more representative than those placed on the outside surface that wasn't sliced.

Seven fabrication trials were performed in 7 minutes or less (five trials were performed with only one operator) indicating one operator can produce LTP specimens in less than 7.5 minutes. An aggregate application rate of 14 kg/m^2 appeared excessive, resulting in a non-uniform chip seal layer. Lowering aggregate application rates to 11 and 12 kg/m^2 resulted in an approximately even chip seal layer.

Initial comparisons of the brush (D7000) and abrasion hose (D3910) heads was performed by testing a specimen for a period of time, stopping the test and visually examining the specimens. These tests were performed at 21 to 35 C, and the brush head was less aggressive than the hose head, as expected. Observations from these initial tests led to abandoning intermediate observations and having a lone LTP test output as the time to achieve 100% chip seal aggregate mass loss. Time to 100% mass loss is somewhat subjective as aggregates can be dislodged from their original position, yet remain on the specimen surface (once dislodged from their original position, aggregates were deemed lost from the chip seal).

In conjunction with D7000 and D3910 abrasion head initial comparisons, test temperatures were evaluated. Figure 6.7 is an example chip seal placed on the sliced face of a *Hwy 49-S1* SGC specimen that demonstrates room temperature (near 21 C) testing did not cause 100% mass loss with either abrasion head (note the damage to the D3910 hose in Figure 6.7b). The specimen tested with D3910 at 21 C was re-tested at 35 C, which did result in 100% mass loss, albeit on a specimen that had not had any embedding. Exploratory testing was also performed by conditioning specimens that had not been embedded at 85 C (C-1 protocol from Chapter 4) and also testing those specimens at 85 C using the D3910 hose. Aggregate loss approached 100% very quickly, which led to the observation that test temperatures on the order of 85 C are likely too high, especially since they would not occur to an in-service chip seal.

a) D7000 Brush at 21 C   b) D3910 Hose at 21 C   c) D3910 Hose at 35 C

Figure 6.7. Phase 1 LTP Testing at Modest Temperatures

Findings presented in the previous paragraph resulted in temperatures above 21 C, but below 85 C to be further investigated; 35 and 50 C were chosen since they represent pavement temperatures that occur frequently on the surface of Mississippi highways during the summer. Figure 6.8 and Table 6.4 provides results of 48 LTP tests on specimens fabricated with 1.81 L/m^2 of emulsion C and 11 kg/m^2 of Size 7 aggregate. Specimens were not embedded, but were conditioned. Test temperatures reported were oven settings during 1 hr period in oven absent the *Adapter Base* as described in Section 4.8.

The D7000 abrasion head yielded higher time to 100% mass loss than D3910. D7000 was not as aggressive as D3910. The 35 C test temperature always yielded higher test times than 50 C, which was expected. There were no immediate observations relative to the different conditioning protocols. There was a phenomenon occurring mostly at 50 C where aggregates became dislodged from their original position, but yet not swept off the surface. This caused aggregates to become attached to the abrasion head (Figure 6.8a), which affected sweeping uniformity. In such cases, specimens reached 100% mass loss while leaving loose aggregates on the surface (Figure 6.8b).

Key findings from phase 1 were: use sliced faces of SGC specimens for chip seal preparation, lower aggregate application rates to below 12 kg/m^3, use the D3910 abrasion head, measure time to 100% mass loss as the LTP test output, and incorporate test temperatures on the order of 50 C or higher. It was also observed that improved temperature control, incorporating embedment protocols, and continuing to evaluate conditioning protocols would be needed for phases 2 and 3.

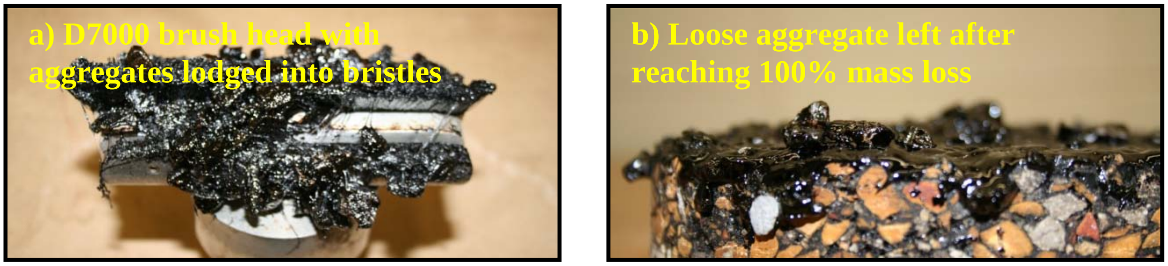


Figure 6.8. LTP Phase 1 Test Results Highlighting Aggregate Dislodging at 50 C

Table 6.4. Phase 1 LTP Test Results

		$T_{100\%}$ (seconds)		
Pavement	**Conditioning**	**Test Temp.**	**ASTM D7000 Abrasion Head**	**ASTM D3910 Abrasion Head**
Hwy 49-S1	C-6	35 C	900	288
SGC			900	308
Sliced Face		50 C	165	137
			184	224
	C-9	35 C	900	900
			900	900
		50 C	446	344
			416	355
	C-10	35 C	900	357
			900	314
		50 C	392	160
			331	110
Hwy 45-S1	C-6	35 C	594	249
			559	705
		50 C	212	168
			275	181
	C-9	35 C	834	202
			869	173
		50 C	120	63
			149	69
	C-10	35 C	578	179
			776	132
		50 C	300	107
			201	88

Note: T_{max} was 900 seconds (15 minutes)

6.4.2 Phase 2 LTP Results for Laboratory Applied Chip Seals

Fifty specimens were fabricated, embedded, conditioned, tested, and their results quantified. Several additional specimens were fabricated and used for informational purposes, often related to embedment and conditioning, but were either not tested or their results were not used for anything more than subjective assessment. The following subsections provide specific results by aggregate size.

6.4.2.1 Size 7 Phase 2 Results

Table 6.5 summarizes phase 2 LTP results performed on Size 7 aggregates; 48 specimens were tested. Visually, emulsion was very sticky or tacky during testing for most phase 2 specimens tested as seen in Figure 6.9. Aggregates began to dislodge from their original position from abrasion almost immediately, which is an indicator of inadequate embedment. Table 6.5 $T_{100\%}$ values are much lower than Tables 6.2 or 6.3.

Individual $T_{100\%}$ results represented in Table 6.5 ranged from 7 to 25 seconds for E-1 to E-4, and from 12 to 38 seconds for E-5 to E-6. When all 32 specimens that experienced E-1 to E-4 were combined, their average $T_{100\%}$ value was 15 seconds, with a standard deviation of 4.3. When all 16 specimens that experienced E-5 to E-6 were combined, their average $T_{100\%}$ value was 21 seconds, with a standard deviation of 7.5. Aggregate embedment seemed to improve slightly by performing 6 LAC passes (i.e. E-5 and E-6 protocols), but this improvement did not result in adequate embedment to represent field applied chip seals. The observations from phase 2, however, did shift emphasis from other embedment approaches to increased numbers of LAC passes coupled with increased hydraulic cylinder system pressures. Phase 2 observations also led to less emphasis on conditioning and using a straightforward conditioning approach.

Table 6.5. Phase 2 LTP Test Results

Pavement	Specimen Type	Embedment	Conditioning	n	Avg. $T_{100\%}$ (sec)
Hwy 49-S1	SGC	None	None, C-2	3	14
Hwy 49-S1	SGC	E-1	C-2	3	11
Hwy 49-S1	SGC	E-2	C-2, C-3	6	14
Hwy 49-S1	SGC	E-3	C-2, C-7	4	16
Hwy 49-S1	SGC	E-4	None, C-2, C-7, C-8	16	16
Hwy 49-S1	SGC	E-5	C-4	6	27
Hwy 45-S1	Slab	E-5	C-4	4	22
Hwy 45-S1	Core	E-6	C-4	6	17

--All specimens used Size 7, Emulsion A, 1.81 L/m^2, and were tested at 52 C.
--All but 4 specimens used 11 kg/m^2, and these used either 10 or 12 kg/m^2.

Figure 6.9. Phase 2 Emulsion Tackiness Example

6.4.2.2 Size 89 Phase 2 Results

Around 12 specimens were fabricated with Size 89 aggregate on *Hwy 45-S1* with 1.13 to 1.81 L/m^2 of emulsion and 11 to 12 kg/m^3 of aggregate. Visually, these specimens did not approximate field cores after hand brushing (Figure 6.10), and all but two were discarded and not tested. The two specimens tested were embedded with E-4, were tested at 52 C, and had a time to 100% seal loss of 14 seconds. It was observed that smaller aggregates were under larger aggregates, even after embedment (note these specimens were exposed to embedment methods that did not include LAC roller passes) These issues were largely resolved when the modified bolt configuration was used in the *Aggregate Restrainer* (Figure 4.6f) and when rolling embedment was used in the LAC (i.e. E-6 to E-11 described in Table 4.2). Phase 3 utilized the modified bolt configuration and rolling embedment.

a) Specimen Pre-Hand Brushing

b) Specimen Post-Hand Brushing

Figure 6.10. Initial Difficulties with Fabrication of Size 89 Specimens

6.4.3 Phase 3 LTP Results for Laboratory Applied Chip Seals

Phase 3 used consistent material types and application rates. Emulsion C was used throughout, with 1.81 L/m^2 used for Size 7 and 1.36 L/m^2 used for Size 89. Aggregate application rates were 11 kg/m^3 for both aggregate sizes. All testing occurred at 52 C after 2.5 hours of pre-heating in the *Adapter Base*.

A total of 138 specimens were evaluated in phase 3; one slab generally produced two cores that were each counted as one specimen. Of these 138 specimens, 18 were damaged in the LAC during embedment (Chapter 4 provides discussion on embedment damage) leaving 120 LTP measurements. Of these 138 specimens, 42 were untreated cores taken from Hwy 44 and Hwy 366 (5 of these 42 specimens were damaged in the LAC during embedment leaving 37 LTP data points that provided direct comparison with Tables 6.2 and 6.3 since all materials used were the same).

6.4.3.1 Size 7 Phase 3 Results

Figure 6.11 provides representative Size 7 specimen photos post fabrication. Figure 6.12 provides representative photos of Size 7 specimens post embedment with the two most aggressive protocols used. Visually, embedment effects were very noticeable.

Figure 6.11. Representative Laboratory Fabricated Size 7 Specimens Pre-Embedment

a) E-7 Specimen 1 *b) E-7 Specimen 2* *c) E-11 Specimen 1* *d) E-11 Specimen 2*

Figure 6.12. Example Photos Showing Size 7 Aggregate Embedment

Table 6.6 provides all phase 3 Size 7 results. Table 6.6 data is inconsistent in terms of replication for a few reasons. One reason was the research team was exploring a variety of combinations of LAC hydraulic cylinder system pressure and roller passes. Embedment approaches showing more promise to replicate Table 6.2 values were given more consideration. Also, the E-6 and C-4 combination was, to some extent, a transition between phase 2 and phase 3. Another reason was specimens being damaged in the LAC during embedment. A third reason was availability of materials (existing pavements in particular).

To provide a more tangible data set for interpretation, the data presented in Table 6.6 was combined by embedment type and sorted according to the aggressiveness of the embedment and conditioning protocol (refer to Tables 4.2 and 4.3 for detailed embedment and conditioning information). Combined and sorted data is provided in Table 6.7. As seen, $T_{100\%}$ values increased from no embedment or conditioning to E-11 embedment and C-11 conditioning, with one exception. Two of the specimens embedded with E-7 had very high $T_{100\%}$ values (214 and 252 seconds), which led to a very high average $T_{100\%}$ value for E-7 when all data was included. Investigation into these values did not determine a reason for their unusually high value; it is known that these values are not recording errors as they were noticed by the operator during conduction of the test. Overall, these two values were not considered in any meaningful extent considering 28 replicates of E-11 (a more aggressive protocol) had a maximum $T_{100\%}$ value of 145.

The key finding from phase 3 for Size 7 aggregates was that E-11 embedment coupled with C-11 conditioning that was applied to laboratory fabricated specimens produced chip seals that represented field applied chip seals taken from *Hwy 44* 6 days after construction. Table 6.7 $T_{100\%}$ values for *Hwy 44* only were similar to those in Table 6.2; both are summarized below. Note that specimens produced on either *Hwy 45* or *Hwy 49* specimens also had test results that were reasonable relative to *Hwy 44*, which was also encouraging. Attempts to replicate specimens that had aged approximately 2 years was beyond the scope of this effort.

- Table 6.2 (Field Applied): average = 77, range = 20 to 148, COV = 55%
- Table 6.7 (Laboratory Applied): average = 75, range = 29 to 131, COV = 42%

Table 6.6. Phase 3 Size 7 Laboratory LTP Test Results

					$T_{100\%}$ (seconds)				
Pavement	**Type**	**Embedment**	**Conditioning**	**n**	**Average**	**Min**	**Max**	**Stdev**	**COV (%)**
Hwy 45-S1	Core	None	None	7	10	5	13	3	26
Hwy 49-S1	SGC	None	None	7	10	8	14	2	19
Hwy 45-S1	Slab	E-6	C-4	4	14	13	16	2	11
Hwy 45-S1	Core	E-6	C-4	7	16	11	23	4	27
Hwy 49-S1	SGC	E-6	C-4	7	16	12	22	4	22
Hwy 44-S1	Core	E-6	C-4	3	18	14	22	4	23
Hwy 44-S2	Core	E-6	C-4	3	15	13	18	3	16
Hwy 44-S3	Core	E-6	C-4	2	18	17	18	---	---
Hwy 49-S1	SGC	E-7	C-11	5	119	29	252	106	89
Hwy 45-S1	Core	E-8	C-11	2	30	26	34	---	---
Hwy 49-S1	SGC	E-8	C-11	1	48	---	---	---	---
Hwy 45-S1	Core	E-9	C-11	2	27	26	27	---	---
Hwy 49-S1	SGC	E-9	C-11	4	35	28	49	10	27
Hwy 45-S1	Core	E-10	C-11	1	23	---	---	---	---
Hwy 49-S1	SGC	E-10	C-11	4	16	14	18	2	12
Hwy 45-S1	Slab	E-11	C-11	8	48	26	65	14	28
Hwy 45-S1	Core	E-11	C-11	2	58	30	86	---	---
Hwy 49-S1	SGC	E-11	C-11	3	94	50	145	48	51
Hwy 44-S1	Core	E-11	C-11	6	63	29	113	32	51
Hwy 44-S2	Core	E-11	C-11	7	81	38	131	33	41
Hwy 44-S3	Core	E-11	C-11	2	91	72	109	---	---

--All specimens were prepared with 11 kg/m^3 of aggregate and 1.81 L/m^2 of Emulsion C; tested at 52 C.
--Statistical values were only reported for cases with 3 or more replicated (i.e. for n =3 or greater).

Table 6.7. Phase 3 Combined and Sorted Size 7 Laboratory LTP Test Results

					$T_{100\%}$ (seconds)				
Pavement	**Type**	**Embedment**	**Conditioning**	**n**	**Average**	**Min**	**Max**	**Stdev**	**COV (%)**
All	All	None	None	14	10	5	14	2	22
All	All	E-6	C-4	26	16	11	23	3	21
All	All	E-10	C-11	5	17	14	23	4	22
All	All	E-9	C-11	6	32	26	49	9	27
All	All	E-8	C-11	3	36	26	48	11	31
All	All	E-7	C-11	5	119[a]	29	252	106	89
All	All	E-11	C-11	28	68	26	145	32	47
Hwy 45, 49	All	E-6	C-4	18	16	11	23	3	22
Hwy 44	All	E-6	C-4	8	17	13	22	3	17
Hwy 45, 49	All	E-11	C-11	13	60	26	145	32	53
Hwy 44	All	E-11	C-11	15	75	29	131	32	42

--All data used to generate Table 6.7 was taken from Table 6.6.
a: There were two distinct groups of data (three readings with average of 43 seconds, and two readings with average of 233 seconds.

6.4.3.2 Size 89 Phase 3 Results

Table 6.8 provides all phase 3 Size 89 test results. Table 6.8 is inconsistent for the same reasons presented for Table 6.6. Noticeably less testing was performed on Size 89 than Size 7. Table 6.9 provides combined and sorted data taken from Table 6.8 in the same manner as for Size 7 (Tables 6.6 and 6.7).

When compared to Size 7 data in Table 6.7, no embedment produced similar average $T_{100\%}$ values (13 seconds for Size 89 and 10 seconds for Size 7). This same trend held for E-6 embedment (20 seconds for Size 89 and 16 seconds for Size 7). In both of these cases, Size 89 average $T_{100\%}$ values were higher than Size 7, but not by meaningful amounts, especially when the Table 6.1 sweep data is considered. E-11 embedment produced considerably higher average $T_{100\%}$ values for Size 89 (188 seconds) relative to Size 7 (68 seconds).

E-11 embedment coupled with C-11 conditioning was not successful in replicating Table 6.3 field applied chip seal $T_{100\%}$ values on specimens taken 10 days after construction. On average, laboratory applied specimens had 46% of the $T_{100\%}$ value of field applied specimens. More investigation would be needed for quantification of this behavior.

- Table 6.3 (Field Applied): average = 409, range = 88 to 900, COV = 80%
- Table 6.9 (Laboratory Applied): average = 188, range = 29 to 634, COV = 105%

Table 6.8. Phase 3 Size 89 Laboratory LTP Test Results

					$T_{100\%}$ (seconds)				
Pavement	**Type**	**Embedment**	**Conditioning**	**n**	**Average**	**Min**	**Max**	**Stdev**	**COV (%)**
Hwy 45-S1	Core	None	None	2	15	13	16	---	---
Hwy 49-S1	SGC	None	None	2	11	10	11	---	---
Hwy 45-S1	Slab	E-6	C-4	4	21	20	23	2	7
Hwy 45-S1	Core	E-6	C-4	2	22	19	25	---	---
Hwy 49-S1	SGC	E-6	C-4	2	16	14	17	---	---
Hwy 366-S1	Core	E-6	C-4	4	20	15	25	4	20
Hwy 45-S1	Core	E-11	C-11	3	106	63	178	63	59
Hwy 49-S1	SGC	E-11	C-11	4	225	47	501	195	87
Hwy 366-S1	Core	E-11	C-11	4	195	29	634	294	150
Hwy 366-S2	Core	E-11	C-11	6	200	51	609	209	105

--All specimens were prepared with 11 kg/m3 of aggregate and 1.36 L/m2 of Emulsion C, and testing occurred at 52 C.
--Statistical values were only reported for cases with 3 or more replicated (i.e. for n =3 or greater).

Table 6.9. Phase 3 Combined and Sorted Size 89 Laboratory LTP Test Results

					$T_{100\%}$ (seconds)				
Pavement	**Type**	**Embedment**	**Conditioning**	**n**	**Average**	**Min**	**Max**	**Stdev**	**COV (%)**
All	All	None	None	4	13	10	16	3	21
All	All	E-6	C-4	12	20	14	25	4	17
All	All	E-11	C-11	17	188	29	634	198	105

CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This report's primary objective was to initiate development of a long term performance (LTP) test protocol for chip seals focused on aggregate retention. The primary objective was met, though the effort stopped short of long term performance prediction of in service chip seals. The primary conclusion from this report was that fabricating chip seals in the laboratory that represent those placed in the field was feasible to some extent. A bulleted list of specific conclusions is provided after the next paragraph.

Chip seals fabricated using the equipment developed in this research with Size 7 aggregates embedded with protocol E-11 and conditioned with protocol C-11 did represent field applied chip seals taken from *Hwy 44* 6 days after construction. Laboratory applied Size 7 chip seals, on average, had 97% of the time to 100% mass loss ($T_{100\%}$) in the LTP test as did field applied chip seals. Chip seals fabricated using the equipment developed in this research with Size 89 aggregates embedded with protocol E-11 and conditioned with protocol C-11 did not represent field applied chip seals taken from *Hwy 366* 10 days after construction. Laboratory applied Size 89 chip seals, on average, had 46% of the time to 100% mass loss ($T_{100\%}$) in the LTP test as did field applied chip seals.

- Chip seals can be produced in the laboratory on top of compacted asphalt cores, slabs, or laboratory produced gyratory specimens using the equipment designed and fabricated for this report.
- Chip seals produced in the laboratory or cored from field projects can be successfully tested for abrasion resistance (i.e. aggregate retention) using the protocols developed for this report. Key test parameters include use of the D3910 abrasion hose and test temperatures of 52 to 70 C.
- Eleven embedment and eleven conditioning protocols were evaluated, and from those evaluations it was concluded that E-11 and C-11 (Tables 4.2 and 4.3) have the most applicability to represent field applied chip seals. An embedment and conditioning protocol more aggressive than E-11 and C-11 appears to be needed to represent chip seals that have been in service for a few years.
- Testing cores taken from field applied chip seals indicated $T_{100\%}$ increased from a few days of field aging to approximately two years of field aging.
- There was a fair amount of variability in field applied and laboratory produced chip seal $T_{100\%}$ results.

7.2 Recommendations

If the LTP protocols and concepts described in this report are to be used on a more widespread scale, embedment protocols need refined. If the Linear Asphalt Compactor (LAC) is to be used for embedment, fixtures need to be fabricated that fit the LAC that provide lateral confinement and allow for more precise height control. Additional research is needed to develop embedment and conditioning protocols that can predict behavior of a chip seal after a period of service of a few years. Testing a variety of chip seal materials and projects over time using existing LTP protocols could provide insight into field behaviors.

CHAPTER 8 – REFERENCES

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