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Development of Equipment and Protocols to Test Laboratory or Field Applied Chip Seals on Compacted Asphalt Concrete

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Abstract: This paper's primary objective was to present developmental efforts and experimental data for the Chip Seal Abrasion Test (*CSAT*). The *CSAT* focuses on aggregate retention by testing a chip seal placed onto compacted asphalt concrete by applying abrasive forces through a rubber hose. Time to 100% mass loss is the primary test output. Review of literature provides evidence that a protocol with all the *CSAT's* features is largely non-existent. Work was divided into four components: 1) develop laboratory equipment and protocols to place a chip seal onto asphalt concrete; 2) develop laboratory equipment and protocols to evaluate aggregate loss of chip seals placed onto asphalt concrete; 3) monitor chip sealed pavements and collect cores for testing; 4) compare laboratory produced and field applied chip seals when using the same materials. Component 3 evaluated two Mississippi chip seal projects; one used Size 7 limestone and the other used Size 89 limestone. Replication of field behavior with laboratory produced specimens was only successful for Size 7 aggregates after very short durations in service. Laboratory applied Size 7 chip seals, on average, had 97% of the time to 100% mass loss in the *CSAT* test as did field applied chip seals. Laboratory applied Size 89 aggregates did not represent field applied chip seals taken after very short durations in service. Laboratory applied Size 89 chip seals, on average, had 46% of the time to 100% mass loss in the *CSAT* test as did field applied chip seals.

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Introduction

In recent years, pavement preservation activities such as chip seals have been given considerable attention, and their potential economic advantages and overall usefulness to Departments of Transportation (DOT's) has been well documented. Rejuvenation of the existing asphalt surface, crack control, skid resistance, and aggregate retention are key performance factors for chip seals. Several test methods exist to evaluate aggregate retention (see Howard et al. [1-2] for a literature review). Despite the large number of available aggregate retention methods, equipment and protocols capable of fabricating and/or evaluating aggregate retention of chip seals placed on compacted asphalt concrete remains largely absent from literature or practice.

Available aggregate retention test methods have many desirable attributes, but they also have limitations. Example limitations frequently encountered include not testing project gradations, inability to test as placed chip seals, and inability to assess the effects of time dependent embedment on aggregate retention. Additional aggregate retention test protocols that can address one or more of the aforementioned items would be useful. As described in the next paragraph, aggregate retention test methods are likely be even more important in future years than they have been in past years.

The current state of highway infrastructure is generally understood to be a cause of concern. It appears that pavement preservation and rehabilitation activities with modest finances will continue to be a central component of DOT activities. For example, the Mississippi Department of Transportation (MDOT) in 2012 had approximately half of their pavements in fair condition (PCR of 72 to 81), 30% in good condition (PCR of 82 to 88), and 10% in poor condition (PCR of 63 to 71). Chip seals are one method to delay Pavement Condition Rating (PCR) decreases.

Objectives and Scope

This paper's primary objective is to present developmental efforts and experimental data for the Chip Seal Abrasion Test (*CSAT*). The *CSAT* focuses on aggregate retention by testing a chip seal placed onto compacted asphalt concrete. Note the MDOT State Study 211 report [3] used the acronym LTP to refer to the same equipment configuration. To accomplish the paper's objective, there were 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 aggregate loss of chip seals placed onto asphalt concrete; 3) monitor chip sealed pavements and collect cores for testing; 4) compare laboratory produced and field applied chip seals when using the same materials.

The desired outcome of these efforts was to improve the ability to characterize an actual chip seal placed on the surface of an actual asphalt pavement. A similar but related desired outcome was to be able to produce a representative chip seal on compacted asphalt concrete in the laboratory. Current protocols generally omit one or

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more components of an actual chip seal (e.g. test only part of the gradation, chip seal not applied to compacted asphalt concrete, etc.).

Literature Review

A literature review was conducted to identify testing that either investigated long term performance, or had attributes of potential relevance to long term aggregate retention. The limited information found is summarized below. As noted in the introduction of this paper, aggregate retention methods capable of evaluating actual chip seals placed on compacted asphalt pavement are a limitation at present.

The accelerated chip seal simulation device (*HSKSC*) simulates traffic loads on a chip seal placed on a 60 cm thick unbound granular base where performance is determined by surface texture and skid-resistance [4]. The *HSKSC* applies a 5.9 kN single wheel load moving at 1 m/sec.

The Mini Fretting Test (*MFT*) predicts chip seal performance by loading with a planetary mixer and cylindrical piece of rubber (modification of ASTM D3910). The *MFT* is capable of comparing emulsions while predicting short term chip seal aggregate loss according to Khalid [5]. The *MFT* is considered a short term performance test since it is conducted where little to no aggregate embedment has taken place.

Islam and Hossian [6] produced 4 cm thick slabs with a kneading compactor and applied a chip seal after placing tape around the slab to prevent emulsion leakage. Emulsion was manually applied with a brush and smoothed with a thin steel plate. Aggregates were applied to avoid overlapping, and 15 passes of a 37.2 kg concrete cylinder was used to seat the aggregates. The chip sealed slabs were tested in the Hamburg wheel-tracking device in 35^{o}C water.

The Model Mobile Loading Simulator (*MMLS3*) is a 3rd scale wheel load simulator through which chip seals can be evaluated [7-8]. *MMLS3* testing occurs after curing at predetermined temperatures where a 3.57 kN wheel load is applied to a modified version of ASTM D7000 sweep test specimens. There are two different traffic loading cycles: simulation of initial field loading; and evaluation of retention performance characteristics of surface treatments under traffic. Aggregate loss is change in aggregate mass divided by original mass.

Martin and Sharp [9] used an Accelerated Loading Facility (ALF) to test full-scale seal treatments. 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 transverse wander pattern was used to simulate in-service trafficking. Deterioration was characterized by rutting, roughness, and falling weight deflectometer (FWD) measurements.

Materials Tested

Limestone aggregates were sampled from MDOT chip seal projects that are described in the next section; properties are shown in Table 1. One CRS-2P (SBR) emulsion formulation and source was used for *Hwy 44* and *Hwy 366*, and this emulsion was utilized through most of this paper. Two additional seal treatment emulsions (one CRS-2P and one engineered emulsion) were also tested, but the information was used in a manner that emulsion properties were not pertinent. The CRS-2P (SBR) project emulsion had the following average properties: 50^{o}C Saybolt viscosity of 258 seconds, 70% residue, 0.05% Sieve, a pH of 2.19, 70% demulsibility, 121 dmm penetration at 25^{o}C, a 150 cm ductility at 25^{o}C, a 54% elastic recovery at 10^{o}C, and a grading temperature interval of 94.5^{o}C (62.4-32.1^{o}C). Emulsion test methods included AASHTO T49, T51, T59, T72, T200, T301, T313, T315. Cationic emulsions were used throughout since they are more commercially used than anionic emulsions in much of the southeastern United States. Emulsion selections were influenced by dialogue with manufacturers as described by Howard et al. [1].

Table 1. Properties of Chip Seal Aggregates.

Property	Highway 366	Highway 44
Abbreviation	*Hwy 366*	*Hwy 44*
Size Designation	89	7
% Passing 4.75 mm Sieve	30	7
% Passing 0.075 mm Sieve	0.3	0.2
Water Absorption	1.7	0.4
Flakiness Index (%)	28	24
Coefficient of Uniformity (C_u)	3.0	1.8
Average Least Dimension (ALD), cm	0.46	0.64

A plant produced surface mix was sampled from an MDOT project on highway 49 (*Hwy 49*), and was compacted to 7±1% T331 air voids, sliced in half, and the sliced face was treated as the pavement surface in this paper for purposes discussed in later sections. Surface lifts were sampled from three MDOT highways: highway 44 (*Hwy 44*) near Hattiesburg, highway 45 (*Hwy 45*) in Crawford, and highway 366 (*Hwy 366*) near Baldwyn. Three different materials were obtained from *Hwy 366*, resulting in six total surfaces on which to produce chip seals. Several additional aggregate, emulsion, and pavement surface properties (and corresponding procedures) were reported by Howard et al. [3].

Field Test Sections

Previously mentioned *Hwy 44* (63,650 m^2 sealed) and *Hwy 366* (91,700 m^2 sealed) were the two full scale field test sections evaluated. Annual Average Daily Traffic (AADT) estimates for *Hwy 44* and *Hwy 366* were 1800 and 750, respectively. Prior to sealing, MDOT pavement management data had *Hwy 44* with a PCR of 74 (fair), a 2 mm rut depth, and an IRI of 1.8 mm/m. *Hwy 366* had a PCR of 67 to 71 (poor), a 3 to 6 mm rut depth, and an IRI of 2.4 mm/m.

Chip seal aggregate application rate estimates were calculated using MDOT Special Provision 907-410.03.6.1 to be approximately 9 kg/m^2 for *Hwy 44* and 8 to 9 kg/m^2 for *Hwy 366*. When presented by volume, aggregate application rates were 9.48 to 9.82 (10^{-3}) m^3/m^2 (0.28 to 0.29 ft^3/yd^2) for *Hwy 44* and 9.48 to 10.50 (10^{-3}) m^3/m^2 (0.28 to 0.31 ft^3/yd^2) for *Hwy 366*. Emulsion application rates were 1.72 to 1.77 L/m^2 for *Hwy 44* and 1.13 to 1.31 L/m^2 for *Hwy 366*. Visual condition surveys revealed *Hwy 44* and *Hwy 366* were in good condition just after chip seal placement and in reasonable to decent condition two years after placement. A considerable amount of additional information on the test sections is reported by Howard et al. [3].

Cores were obtained from each pavement: 1) prior to sealing for later use in laboratory specimen fabrication (1 day prior for *Hwy 44* and 4 days prior for *Hwy 366*); 2) just after sealing for an unaged assessment of the as-built seal (6 days after for *Hwy 44* and 10 days after for *Hwy 366*); and approximately two years after sealing for an aged assessment of the as-built seal (729 days after for *Hwy 44* and 736 days after for *Hwy 366*). Three test sections ≈60 m long were established per highway where no significant distresses such as potholes or patches were present and cores were taken in a prescribed pattern from these sections. Approximately 160 total cores (treated and untreated combined) were taken that produced useable data.

Specimen Preparation and Test Methods

A flowchart of the experimental program is provided in Fig. 1. Several details omitted from this paper for brevity are provided by Howard et al. [3]. An example is scaled drawings of all equipment developed. The information presented in this paper is aimed toward an understanding of the *CSAT* equipment, protocols, and potential usefulness.

Sweep Testing and Distress Surveys

Distress surveys were collected by MDOT using automated profilers. Data collected in this manner includes: Pavement Condition Rating (PCR), rut depths, International Roughness Index (IRI), and Annual Average Daily Traffic (AADT). Sweep testing was performed according to the *Sweep-M* protocol described by Howard et al. [1] and Alvarado and Howard [10].

CSAT Equipment and Protocols

Generally speaking, use of *CSAT* equipment involves specimen fabrication, embedment, conditioning, and testing. Fig. 2(a) shows all fabrication components that were designed by Mississippi State University (MSU) and fabricated by a local machine shop. One production cycle (< 7.5 minutes) can produce four 15 cm diameter specimens or one ≈30 cm square slab (slabs can be cored or used for other purposes that are outside the scope of this paper).

CSAT Fabrication

Fabrication consists of emulsion application, aggregate application, and aggregate seating. Pre-batched aggregate conforming to the full project gradation is placed into each quadrant of the *Aggregate Divider* in a manner to avoid segregation (Fig. 2(b)), the divider is removed, and the *Aggregate Restrainer* is placed (Fig. 2(c)). Specimens are taped around the sides to facilitate emulsion application, which occurs on a scale where the desired emulsion application rate is evenly spread (based on visual examination) with a plastic spoon (Fig. 2(d) and 2(e)).

The *Specimen Panhandle* is then used for placement into the *Specimen Box* (Fig. 2(f)). The emulsion applied specimens are next slid into the bottom compartment of the *Spreader Base* (Fig. 2(g)). Rapid removal of the *Aggregate Spreader Sheet* (Fig. 2(h)) places aggregate onto the emulsion applied specimens, and afterwards specimens are removed for seating (Fig. 2(i)). Three passes each 90^{o} apart with a D7000 sweep test compactor with a 13 mm thick rubber pad affixed to its face were used for seating (Fig. 2(j)). Fabricated cores are removed from the *Specimen Box* as shown in Fig. 2(k). Slabs are fabricated similar to cores, except the *Specimen Box* is not used; Fig. 2(l) is a fabricated slab.

A key component of specimen fabrication is the *Aggregate Restrainer*. Anchor bolts that weigh 15 grams each use their free-floating self-weight to restrain aggregates. The bolts assume the general shape of the aggregate profile and prevent lateral aggregate movement while the *Aggregate Spreader Sheet* is removed. The *Aggregate Restrainer* was successfully tested by Howard et al. [3] with colored aggregates to verify aggregates dropped vertically without appreciable lateral movement. Ultimately, to effectively retain Size 89 gradations, around 800 anchor bolts were needed; only around 400 were needed for Size 7 gradations.

CSAT Embedment and Conditioning

Eleven embedment protocols were incorporated. Six of them (those of most relevance) used the Linear Asphalt Compactor (LAC) [11], as shown in Fig. 3. Forty-six steel plates 1.3-1.4 cm thick were placed side by side to produce kneading compactive effort and an approximate static pressure of 0.17 kg/cm^2 (Fig. 3(c)). A temperature-time curve (Fig. 3(f)) was measured within the LAC cavity via a bead thermocouple inserted through a small drilled hole (Fig. 3(e)) while the Fig. 3(d) heating element was in place. The Fig. 3(f) curve began with the system at room temperature and after

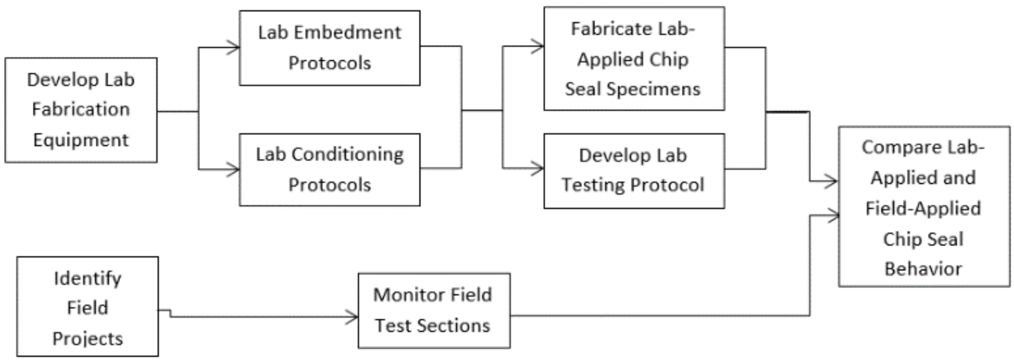


Fig. 1. Experimental Flowchart.

Fig. 2. CSAT Equipment and Specimen Fabrication.

approximately 6 hours, temperatures were 30 to 35°C. Some embedment protocols began at room temperature, while others were pre-heated overnight.

The LAC was used for embedment since it is conceptually similar to traffic kneading action during summertime temperatures. Embedment within the LAC would be more efficient if fixtures were fabricated that fit into the specimen carriage to provide lateral confinement and more precise height control. Several specimens were damaged during embedment that were visually identified and discarded.

For purposes of this paper, embedment efforts have been divided into three categories. First are five embedment protocols that produced only modestly useful data that often relied only on temperature and static pressure. Second is one embedment protocol that began at room temperature where specimens were in the Fig. 3(d) environment for 3 days before 6 roller passes occurred at a hydraulic system pressure of 1551 kPa. There are five embedment protocols where specimens were placed in a 35^{o}C oven overnight while the LAC was heated to 30 to 35^{o}C. Specimens were then placed into the LAC carriage and left to sit under the plates for 2.5 hours with the Fig. 3(d) heating element in place to allow equilibrium temperatures of 30 to 35^{o}C to be achieved. A rubber pad (Fig. 3(g)) was in between the steel plates and the specimens. Specimens were then embedded at a specified hydraulic system pressure and number of passes (five combinations were used and values are reported with test results). Fig. 3(h) shows an LAC pass. A five minute pause occurred between each group of 25 passes with the hydraulic system pressure removed but the surcharge plates still in place.

Eleven conditioning protocols were used that generally relied upon ovens, though water baths were used occasionally. Of these eleven protocols, two were of primary interest herein. They were: 7 days in a 35^{o}C oven, and 3 days in a 64^{o}C oven. Specimens were conditioned after being embedded.

CSAT Testing

Fig. 4 describes pertinent aspects of the CSAT test protocol's final version. There were several intermediate protocol iterations that are described by Howard et al. [3]. Fig. 4(a) shows an overall view of testing and the Hobart N50 planetary mixer used to apply abrasive forces to prepared specimens (mixer speed 1 is used, which is an agitator speed of 136 RPM). Fig. 4(b) shows the ASTM D3910 rubber abrasion hose used to apply forces to chip seals. The Adapter Base (Fig. 4(c) and 4(d)) was developed at MSU to hold specimens securely on the mixer mounting base during abrasion (Adapter Base is clamped to the mixer base plate). A dial bolt is on the side of the Adapter Base to tighten and secure the specimen during testing.

To determine the amount of time needed to achieve the desired test temperature, a mark was placed on top of a specimen and its temperature was monitored versus time with an infrared temperature device (Fig. 4(e) and 4(f)). The final pre-heating protocol was to heat a specimen for 2.5 hours while in the Adapter Base in an oven set to the desired temperature. The time from opening the oven doors to commencing abrasive forces (T1) should generally be 60 seconds or less. Fig. 4(g) shows a local view where a specimen has begun to be abraded with the abrasion head which is free-floating, capable of vertical movement, and rotating on top of the specimen's surface to dislodge aggregates. The specimen is secure, level, and has 10 mm or more of clearance above the Adapter Base. Specimens were abraded until 100% mass loss, or T2, (i.e. surface condition where all aggregates had become dislodged from their original position regardless of the aggregate's location thereafter as determined by visual evaluation). Time to 100% mass loss ($T_{100\%}$) is the CSAT output, which is T2 minus T1 (time is continuously recorded beginning when the oven doors are opened).

For example, if the pre-heating oven doors were opened at time 0, and CSAT 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 read 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. In cases where 100% mass loss was not reached in 900 seconds, the test was terminated early (defined T_{max}). Fig. 4(h) is an example of a specimen at 100% mass loss that also shows the abrasion hose at the conclusion of testing. A typical number of testes performed in a traditional work day period was 6 with two Adapter Bases (output could be increased with additional Adapter Bases).

Test Results

Sweep-M Test Results

Sweep testing was performed at 1, 2, and 4 hours. Mass losses were 51, 45, and 26% for *Hwy 44*, and 42, 32, and 14% for *Hwy 366*. Moisture losses were 27, 39, and 48% for *Hwy 44*, and 31, 41, and 53% for *Hwy 366*. The *Hwy 366* limestone (Size 89) had lower mass loss and higher moisture loss than the *Hwy 44* limestone (Size 7) when tested with the project emulsion. 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 the emulsion than the *Hwy 44* limestone. Note that *Sweep-M* testing generally produced twice the mass loss of D7000 [1].

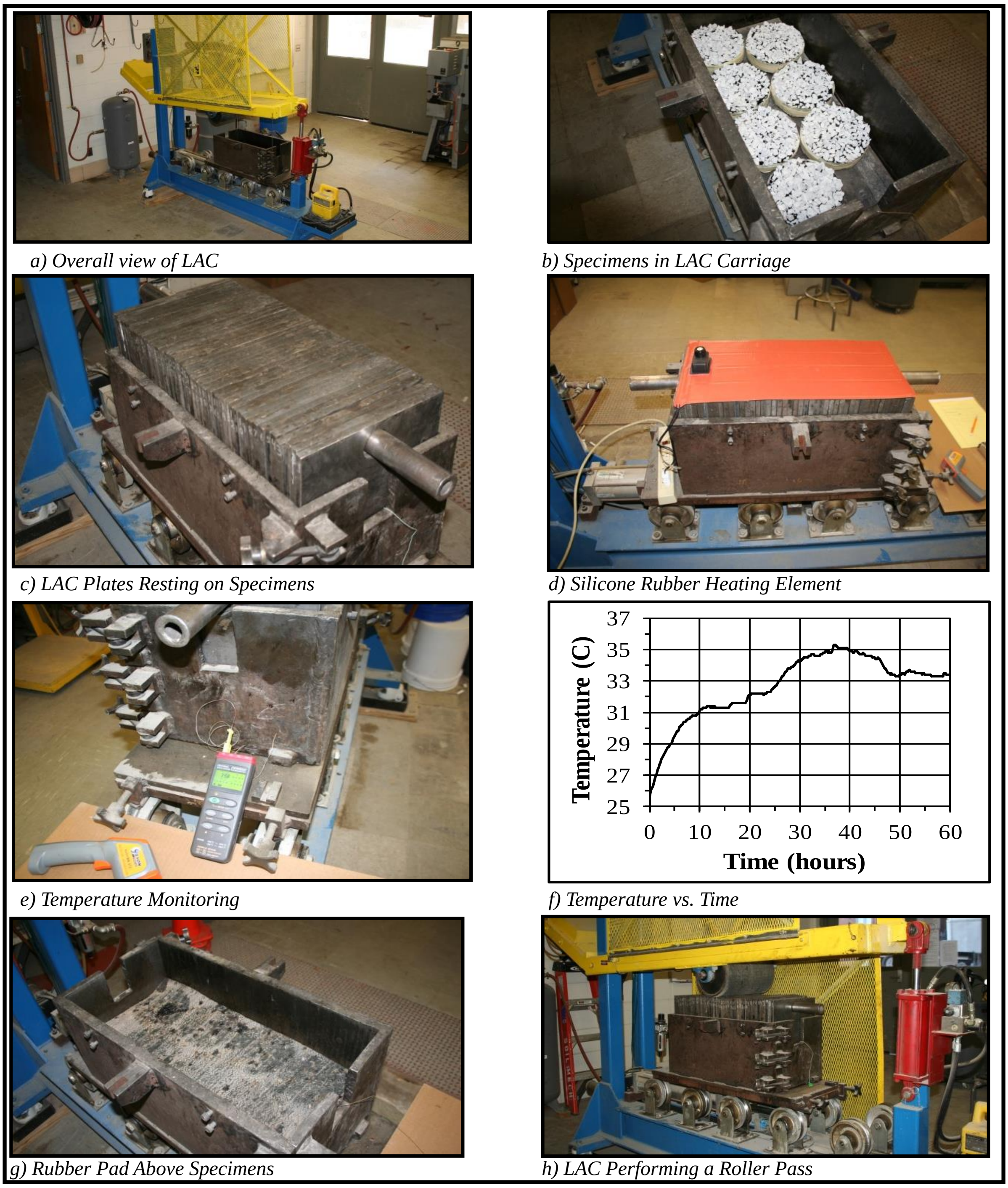
CSAT Results for Field Applied Chip Seals

Results of the 126 field cores successfully tested are shown in Table 2. These specimens were not embedded or conditioned beyond what occurred in the field. Each pavement and age was subjected to four *CSAT* test temperatures to determine a broad behavioral assessment.

Data from each of the three test sections was combined per pavement to provide an overall behavioral evaluation. For *Hwy 44*, this was reasonable since the existing surface was placed in the same year and was fairly consistent in terms of distresses prior to sealing. Consistent chip seal application rates were also used throughout the project. For *Hwy 366*, combining all three test sections into one data set was not an ideal approach in that different pavement surfaces and emulsion application rates were used (details provided earlier in the paper and Howard et al. [3]). While handling of *Hwy 366* was not ideal, it does give a general idea of field behaviors for comparison of laboratory and field produced specimens and is suitable for this paper.

$T_{100\%}$ increased from the specimens field aged 6 or 10 days to 729 or 736 days. There was a fair amount of variability between test results. In a few cases, one small area not dislodging resulted in noticeably higher $T_{100\%}$ values.

Average Size 7 aggregate $T_{100\%}$ 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^{o}C testing for a 6 day age had the



a) Overall view of LAC
b) Specimens in LAC Carriage
c) LAC Plates Resting on Specimens
d) Silicone Rubber Heating Element
e) Temperature Monitoring
f) Temperature vs. Time
g) Rubber Pad Above Specimens
h) LAC Performing a Roller Pass

Fig. 3. Embedment with the Linear Asphalt Compactor.

lowest COV of the four temperatures, but at a 729 day age 70^{o}C had the highest COV of the four temperatures. At a 52^{o}C level, COV values were 40 to 55%, which was the most desirable overall variability.

Average $T_{100\%}$ values for Size 89 aggregate were higher than Size 7 aggregates in all cases. These results should, however, be interpreted in light of sweep test findings presented earlier where *Hwy 366* aggregates appeared more compatible with the project CRS-2P emulsion for similar aggregate sizes. Average Size 89 $T_{100\%}$ 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 for Size 89 aggregates other than they were very high.

CSAT Results for Laboratory Applied Chip Seals

Laboratory efforts by Howard et al. [3] occurred in three phases. Only the most important points from phases 1 and 2 are provided herein as phase 3 produced the majority of the project's useful data by building upon information learned in phases 1 and 2. Regardless of phase, all pavements were treated the same for emulsion

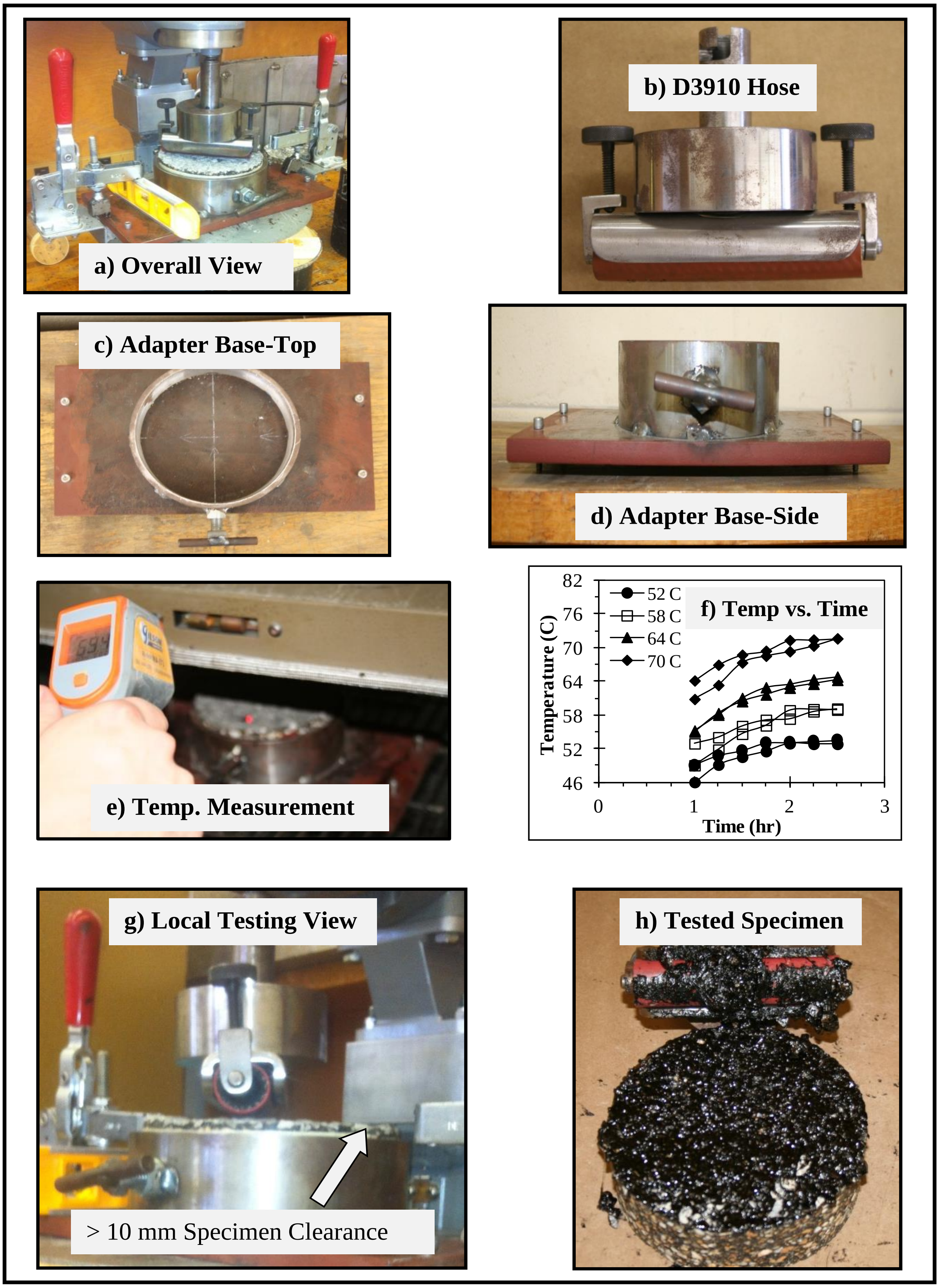


Fig. 4. CSAT Test Protocols.

application rates; i.e. texture was not considered by changing application rates. Not accounting for pavement texture is a limitation of this research. Key points from phases 1 and 2 are summarized in bulleted form and are based on testing on the order of 100 specimens.

- Aggregate application rates around 11 kg/m^2 worked better than higher application rates
- The sliced face of a gyratory compacted specimen was

Table 2. Summary of *CSAT* Results for Field Applied Chip Seals.

Pavement	Aging Time (days)	Test Temp (^oC)	n[b]	$T_{100\%}$ (Seconds) Average	Min	Max	St dev	COV (%)
Hwy 44[c]	6	52	8	77	20	148	43	55
Size 7		58	8	46	23	78	19	41
		64	9	21	12	35	7	34
		70	3	15	12	19	4	24
Hwy 44[c]	729	52	9	451	222	688	182	40
Size 7		58	9	362	45	880	275	76
		64	9	350	23	900	324	93
		70	9	236	20	900	296	126
Hwy 366[d]	10	52	9	409	88	900	329	80
Size 89		58	9	166	64	406	126	76
		64	9	69	35	211	54	79
		70	5	33	18	50	15	45
Hwy 366[d]	736	52	3	900[a]	900	900	0	0
Size 89		58	9	844	397	900	168	20
		64	9	610	57	900	327	54
		70	9	451	80	900	369	82

[a] Note that some of the *Hwy 366* specimens with $T_{100\%}$ values of 900 seconds abraded the D3910 hose.
[b] n = number of tests, COV = coefficient of variation (standard deviation divided by mean) as a percentage.
[c] *Hwy 44* used emulsion application rates of 1.72 to 1.77 L/m^2 (0.38 to 0.39 gsy).
[d] *Hwy 366* used emulsion application rates of 1.13 to 1.31 L/m^2 (0.25 to 0.29 gsy).

preferred over the non-sliced face (i.e. the top or the bottom) since emulsion application on the non-sliced face resulted in excessive emulsion loss along the sides of and into specimens due to lower density

- Pausing testing for intermediate observations was unproductive
- The D3910 abrasion hose was more aggressive and since it better facilitated aggregate loss it was deemed more suitable than the D7000 brush
- Laboratory test temperatures should be 50^{o}C or higher with using the D3910 abrasion hose as lower temperatures can damage the hose as opposed to dislodging aggregates
- Absent embedment, aggregates began to dislodge immediately
- Without kneading action to embed aggregates, $T_{100\%}$ values were 25 seconds or less with an average of 15 seconds (32 specimens were tested with different properties)

Phase 3 used consistent material types and application rates. The *Hwy 44* and *Hwy 366* CRS-2P (SBR) emulsion formulation used on these projects was also used in all phase 3 laboratory testing. Emulsion application rates were 1.81 L/m^2 for Size 7 and 1.36 L/m^2 for Size 89. Both aggregate sizes were applied at 11 kg/m^3. All testing occurred at 52^{o}C after 2.5 hours of pre-heating in the *Adapter Base*. A total of 120 laboratory prepared specimens were successfully tested in phase 3, and results are provided in Table 3.

Size 7 aggregates were more effectively characterized relative to the *Hwy 44* field project, and as a result more of the laboratory efforts focused on Size 7. Fig. 5 provides photos of laboratory and field applied Size 7 aggregates. Visually, embedment effects were very noticeable and provided qualitative support that the *CSAT* protocol is promising for representing field applied chip seals. Note that specimens were laboratory applied unless stated otherwise.

As seen in Table 3, Size 7 $T_{100\%}$ values increased from no embedment or conditioning to 200 roller passes at a 2413 kPa hydraulic system pressure with one exception. Two of the specimens embedded with 100 roller passes at a 2413 kPa pressure had very high $T_{100\%}$ values (214 and 252 seconds), which led to a very high average $T_{100\%}$ value when all data was included. Investigation into these values did not determine a reason for their unusually high value. Overall, these two values were not considered in any meaningful extent considering 28 replicates of 200 roller passes at 2413 kPa (a more aggressive protocol) had a maximum $T_{100\%}$ value of 145.

The key finding for Size 7 aggregates was that 200 roller passes at a 2413 kPa hydraulic system pressure coupled with 3 days oven conditioning at 64^{o}C applied to laboratory fabricated specimens produced chip seals that represented field applied chip seals taken from *Hwy 44* six days after construction. Table 3 $T_{100\%}$ values for *Hwy 44* only were similar to those in Table 2; both are summarized below. Note that specimens produced on either *Hwy 45* or *Hwy 49* specimens also had test results that were reasonable (average values were within 25% of each other) relative to *Hwy 44*, which was also encouraging.

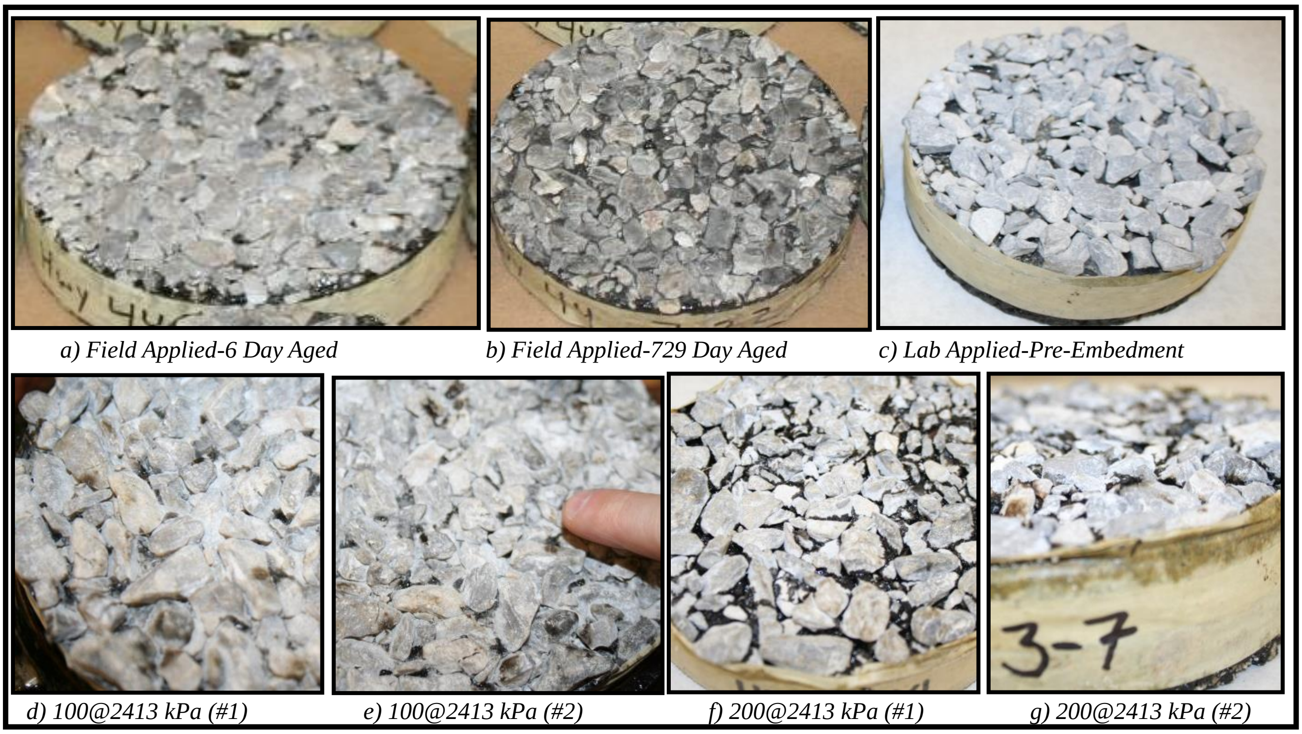
- Table 2 (Field Applied): average = 77, range = 20 to 148, COV = 55%
- Table 3 (Laboratory Applied): average = 75, range = 29 to 131, COV = 42%

No embedment produced similar average $T_{100\%}$ values for Size 7 and Size 89 aggregates (13 seconds for Size 89 and 10 seconds for Size 7). This same trend held for 6 passes at 1551 kPa 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 sweep data presented earlier indicating Size 89 aggregates were perhaps more compatible with the emulsion used are considered. Embedment with 200 roller passes and 2413 kPa produced considerably higher

Table 3. Summary of *CSAT* Results for Laboratory Applied Chip Seals.

Project	Pavement[b]	Embedment[c]	Conditioning[e]	n	$T_{100\%}$ (seconds) Avg.	Min	Max	St dev	COV
Hwy 44	All	None	None	14	10	5	14	2	22
Size 7	All	6 @ 1551 kPa[d]	7 days at 35°C	26	16	11	23	3	21
	All	25@ 1551 kPa	3 days at 64°C	5	17	14	23	4	22
	All	100@ 1551 kPa	3 days at 64°C	6	32	26	49	9	27
	All	25@ 2413 kPa	3 days at 64°C	3	36	26	48	11	31
	All	100@ 2413 kPa	3 days at 64°C	5	119[a]	29	252	106	89
	All	200@ 2413 kPa	3 days at 64°C	28	68	26	145	32	47
Hwy 44	*Hwy 45, 49*	6 @ 1551 kPa[d]	7 days at 35°C	18	16	11	23	3	22
Size 7	*Hwy 44*	6 @ 1551 kPa[d]	7 days at 35°C	8	17	13	22	3	17
	Hwy 45, 49	200@ 2413 kPa	3 days at 64°C	13	60	26	145	32	53
	Hwy 44	200@ 2413 kPa	3 days at 64°C	15	75	29	131	32	42
Hwy 366	All	None	None	4	13	10	16	3	21
Size 89	All	6 @ 1551 kPa[d]	7 days at 35°C	12	20	14	25	4	17
	All	200@ 2413 kPa	3 days at 64°C	17	188	29	634	198	105

[a] There were two distinct groups of data (three readings with average of 43 seconds, and two readings with average of 233 seconds).
[b] Some of the specimens shown were produced from cores, while others were produced as slabs and cored to produce circular test specimens.
[c] Embedment data is interpreted as number of passes @ LAC hydraulic system pressure.
[d] Embedment of 6 passes at 1551 kPa hydraulic system pressure is protocol where process began at room temperature. The remaining five protocols were described earlier as the third embedment category.
[e] Conditioning occurred in a forced draft oven.



a) Field Applied-6 Day Aged *b) Field Applied-729 Day Aged* *c) Lab Applied-Pre-Embedment*
d) 100@2413 kPa (#1) *e) 100@2413 kPa (#2)* *f) 200@2413 kPa (#1)* *g) 200@2413 kPa (#2)*

Fig. 5. Photos of Size 7 Field and Laboratory Applied Chip Seals.

average $T_{100\%}$ values for Size 89 (188 seconds) relative to Size 7 (68 seconds) when all data in each category was considered.

Embedment with 200 roller passes and 2413 kPa hydraulic system pressure coupled with conditioning for 3 days at 64°C was not successful in replicating Table 2 field applied chip seal $T_{100\%}$ values on Size 89 specimens taken 10 days after construction. On average, laboratory applied Size 89 specimens had 46% of the $T_{100\%}$ value of field applied specimens. More investigation would be needed for quantification of this behavior. Possible causes could be fabrication, embedment, or a combination. A comparative summary of field and laboratory applied Size 89 specimens is provided below.

- Table 2 (Field Applied): average = 409, range = 88 to 900, COV = 80%

- Table 3 (Laboratory Applied): average = 188, range = 29 to 634, COV = 105%

Summary, Conclusions, and Recommendations

This paper's primary objective was to present developmental efforts and experimental data for the Chip Seal Abrasion Test (*CSAT*). The *CSAT* focuses on aggregate retention by testing a chip seal placed onto compacted asphalt concrete. Literature review presented earlier in this paper provides evidence that a protocol with all the features of the *CSAT* is largely non-existent.

To accomplish the paper's objective, four components were identified. In brief form they were: 1) develop equipment to fabricate chip seals on asphalt concrete; 2) develop equipment to test chip seals applied to asphalt concrete; 3) monitor field test sections; and 4) compare laboratory and field specimen behavior for purposes of attempting to replicate field behavior in the laboratory. The desired outcome of these efforts was to improve the ability to characterize an actual chip seal placed on the surface of an actual asphalt pavement. A similar but related desired outcome was to be able to produce a representative chip seal on compacted asphalt concrete in the laboratory.

The primary objective was met, though replication of field behavior with laboratory produced specimens was only successful for Size 7 aggregates after very short durations in service. Laboratory applied Size 7 chip seals, on average, had 97% of the time to 100% mass loss ($T_{100\%}$) in the *CSAT* test as did field applied chip seals. Laboratory applied Size 89 aggregates did not represent field applied chip seals taken after very short durations in service. Laboratory applied Size 89 chip seals, on average, had 46% of the time to 100% mass loss ($T_{100\%}$) in the *CSAT* test as did field applied chip seals.

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. An embedment and conditioning protocol more aggressive than anything attempted in this paper appears to be necessary to represent chip seals that have been in service for a few years. While the efforts presented in this paper stopped short of longer term field behavior prediction, they did provide a foundation for future efforts (especially considering equipment and protocols of this nature are not commonplace for chip seals).

The ability to fabricate chip seals in the laboratory in a consistent manner could also be valuable for other applications in addition to those presented herein. For example, in the fall of 2013 MDOT placed a Size 89 scrub seal and overlaid the seal with a 25 mm thick 9.5 mm nominal maximum aggregate size asphalt concrete overlay. Note that scrub seals are similar to chip seals in the areas of pertinence to this paper. This combined treatment approach would be an example where having the ability to place chip or scrub seals on compacted asphalt slabs in the laboratory could be useful. Once a chip seal has been placed, a kneading compactor such as the LAC could be used to compact asphalt concrete over the chip or scrub seal for examination and subsequent testing.

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