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MANUAL FOR EMULSION-BASED CHIP SEALS FOR PAVEMENT PRESERVATION

FINAL REPORT

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Abstract

This report documents a study contracted to develop a manual of practices recommended for designing and constructing chip seals placed on hot mix asphalt pavements. The manual identifies factors that influence chip seal design, construction and performance and provides guidelines that enables practitioners to improve the opportunity for success when building these systems. Many practices in chip seal technology have been subjective for many years and considered 'art' by some. Therefore, this study focused on elements of chip seal technology that were subjective or not practiced in the United States. The manual replaces the subjective or qualitative judgments previously used during chip seal design and construction with field and laboratory testing. Some of the findings of this study include a means of determining when to broom or allow traffic on fresh chip seals, a quantitative method for measuring chip embedment, a simple method for measuring viscosity of emulsions during construction, an improved method to recover emulsion residues, and a recommendation for emulsion and residue properties related to environmental conditions.

CHAPTER 1 - Introduction

1.1 Background

Emulsion-based chip seals are the most commonly used type of chip seal in the United States for preserving asphalt pavements. The purpose of these preservation treatments is to seal fine cracks in the underlying pavement surface and prevent water intrusion into the base and subgrade. Chip seals are not expected to provide additional structural capacity to the pavement. Benefits are obtained by reducing pavement deterioration before significant distress is exhibited. A large body of research is available on chip-seal design practices (NCHRP Synthesis 342: Chip Seal Best Practices 2005) and was further investigated in this report. However, chip-seal design in the United States has not been developed significantly beyond early work (McLeod 1960, 1969; Epps 1981).

In spite of their apparent benefits, the use of chip seals for pavement preservation in the United States has been hampered by the lack of nationally accepted guidance on their design and construction and appropriate specifications and testing procedures for constituent materials. Therefore, research was needed to develop a manual that identifies factors that influence chip seal design, construction and performance and provides guidelines that enables practitioners to improve the opportunity for success when building these systems.

1.2 Project Objectives and Scope

This research was conducted to develop a manual describing the best methods to use for designing and constructing chip seals placed on hot mix asphalt pavements. A significant body of knowledge existed about chip seal design and construction before this research, much of which is contained in this manual. However, other practices in chip seal technology have been subjective for many years and considered ‘art’ by some. Therefore, the research conducted in this study focused on elements of chip seal technology that were subjective or not practiced in the United States. This research, presented in this report, includes a manual that replaces the subjective or qualitative judgments previously used during chip seal design and construction with field and laboratory testing, and thus can be used to improve the opportunity for success when building chip seals.

1.3 Organization of the Report

This report has five chapters. Chapter 1 is the introduction and describes the purpose of the research and the scope of the work. Chapter 2 describes the state of the practice of chip seal design and construction. Chapter 3 describes the results and analysis of a series of laboratory and field tests. Chapter 4 discusses the application of research findings. The final chapter presents the study conclusions and recommendations. The report also includes the recommended

"Manual for Emulsion-Based Chip Seals for Pavement Preservation" as Attachment 1 and a set of recommended test methods as Attachment 2. Further elaborations on the research are provided in Appendices A through J.

CHAPTER 2 - Research Methodology

2.1 Introduction

Research conducted in this project focused on aspects of chip seal technology that have been qualitative in the past or were based on material properties that did not necessarily relate to chip seal performance. Quantitative methods were developed to help replace past subjective practices and allow improved prediction of chip seal behavior in the field. The following issues were addressed with the research:

- Chip adhesion to emulsion and residue
- Time required before sweeping and uncontrolled traffic
- Emulsion consistency in the field
- Surface texture measurement
- Residue recovery and properties

Each of these issues were addressed in the research through laboratory and field experiments.

2.1.1 Chip Seal Definition

Chip seals considered in this research are based on emulsified asphalt binders and natural mineral aggregate chips. The chip seal is constructed by spraying the asphalt emulsion onto the existing asphalt pavement, dropping the aggregate chips into the asphalt emulsion, and embedding the chips in the emulsion using pneumatic-tired rollers. The purpose of the chip seal is to preserve an existing asphalt pavement by sealing the surface before cracking occurs or after minor cracks have emerged and also to provide additional surface friction.

2.2 Chip Adhesion to Emulsion and Residue

The required adhesive and cohesive strength of the emulsion residue used as the binder in a chip seal is directly related to when the chip seal can be opened to traffic after construction. This strength is usually judged subjectively during construction by experienced personnel who decide based on how easily chips can be dislodged from the emulsion. This experience is often gained by trial and error, sometimes leading to vehicle damage when residues that have not gained sufficient strength release chips under traffic loads (Gransberg, 2005; Shuler, 1998). Several tests such as Vialit (Vialit Plate Shock Test), frosted marble (Howard, et al, 2009) and the Sweep Test (Cornet, 1999; Barnat, 2001; ASTM D7000) attempt to quantify this adhesive behavior and identify when chip seals are ready to accept uncontrolled traffic. However, these tests have shown high variability and therefore, have not been widely adopted. One method (Lynch, 2007) uses a hand broom to sweep the chips. When the amount of chips dislodged during this procedure is less than 10 percent, the chip seal is judged ready for traffic. This test is attractive since it uses actual construction materials and with practice could be a means to evaluate adhesion. The sweep test described by ASTM D7000, Standard Test Method for Sweep Test of Bituminous Surface Treatment Samples, appeared to be a reasonable approach to simulating the forces which dislodge aggregate chips from chip seals. This procedure is relatively effective at evaluating differences in adhesive abilities of different emulsions with a single aggregate. This test utilizes a template for specific aggregate gradations to establish the emulsion application rate. While a single emulsion application rate is suitable for relative comparison between emulsions, when aggregate sizes differ the embedment percentage changes which affects chip retention. In addition, the test describes a procedure of 'hand casting' the aggregates onto the emulsion prior to testing. Attempts to repeatedly place precise amounts of aggregate on test samples during this research proved difficult to replicate. Therefore, the test apparatus was modified so the exact amount of chips was placed on the test pad each time. To determine if the modified test procedure would be useful to evaluate the adhesive ability of different emulsions and different aggregate chips under varying moisture conditions a controlled laboratory experiment was conducted.

2.2.1 Experiment Design

Because of variability associated with the manner with which aggregate chips are prepared for testing according to ASTM D7000, a modification to the procedure was made to precisely control how chips are placed on the test pad prior to sweeping. To determine if the modified procedure was an improvement over the ASTM procedure an experiment was conducted to measure the ability of the modified sweep test to discriminate between four independent variables believed to affect early chip seal performance. These variables were emulsion type, aggregate source, emulsion cure level, and aggregate chip moisture content.

2.2.1.1 Independent Variables

Independent variables in this experiment are the following:

Aggregates:	Basalt, Granite, Limestone, Alluvial
Emulsions:	RS-2, RS-2P, CRS-2, CRS-2P, HFRS-2P
Emulsion Cure:	40%, 80%
Aggregate Moisture:	Dry, Saturated Surface Dry (SSD)

A full-factorial, randomized experiment was designed for each emulsion according to the model shown below (Anderson 1993):

$$Y_{ikl} = \mu + A_i + W_k + M_l + AW_{ik} + AM_{il} + WM_{kl} + AWM_{ikl} + \varepsilon_{ikl}$$

Where,

Y_{ikl} = Chip Loss, %
μ = mean loss, %
A_i = effect of aggregate i on mean loss
W_k = effect of water removed k on mean loss
M_l = effect of aggregate moisture l on mean loss
AW_{ik}, etc.= effect of interactions on mean loss

ε_{ikl} = random error for the ith aggregate, kth water removed, and lth replicate

This experiment design was chosen because results can be easily evaluated using conventional analysis of variance techniques (ANOVA). The experiment was repeated for each emulsion to eliminate potential variability that could be associated with differences in emulsion behavior due to aging.

2.2.2 Materials

A variety of emulsions were selected to represent the range available for construction. These included conventional and polymer modified anionic (RS-2 and RS-2P), high float (HFRS-2P) and cationic types (CRS-2 and CRS-2P). Production of these emulsions using a laboratory emulsion mill, in close proximity to the research laboratory was desirable since emulsions have limited shelf life. These factors helped to reduce variability of the emulsion materials. Properties of the emulsions are shown in Table 1.

Table 1. Emulsion Properties

Emulsion Tests	**RS-2P**	**RS-2**	**CRS-2**	**CRS-2P**	**HFRS-2P**
Viscosity, SFS 122F	108	96	78	119	132
Storage Stability, 1 day, %	0.1	0.1	0.2	0.1	0.2
Sieve Test, %	0.0	0.0	0.0	0.0	0.0
Demulsibility, 35 ml	65	72	76	76	42
Residue, by evaporation, %	65.1	68.0	67.9	67.7	65.3
Residue Tests					
Penetration, 77F, 100g, 5s	115	112	125	121	115
Ductility, 77F, 5cm/min	100+	100+	55	65	60
Float, 140F, s	na	na	na	na	1290

A variety of aggregates was used to determine if the modified sweep test could discriminate between different mineralogy, shape, and texture. These were a limestone (LSTN) aggregate from Colorado Springs, CO, granite (GRNT) from Pueblo, CO, basalt (BSLT) from Golden, CO and an alluvial source (ALLV) from Silverthorne, CO. The properties of these materials are presented in Table 2.

2.2.3 Sweep Test Procedure

The test procedure is described in detail in Appendix B and presented in Attachment 2. Differences between the procedure conducted in the research and that described by ASTM D7000 include the following:

Table 2. Aggregate Properties

Sieve No.	Sieve Size, mm	Passing, % LSTN	GRNT	BSLT	ALLV
1/2"	12.5	100	100	100	100
3/8"	9.5	100	99	100	100
5/16"	8.0	100	50	79	73
1/4"	6.3	48	9	30	33
4	4.75	1	1	1	2
8	2.36	1	1	1	2
16	1.18	1	1	1	2
30	0.60	1	1	1	2
50	0.30	1	1	1	2
100	0.15	1	1	1	2
200	0.075	1	1	1	2

Bulk Specific Gravity	2.615	2.612	2.773	2.566
Loose Unit Weight, lbs/cf	78.3	84	92.2	86.1
Los Angeles Abrasion Loss, %	26.3	27.8	20.1	22
Flakiness Index	33.8	5.8	13.1	10.5

- 40 percent initial embedment of the aggregate chips
- 40 and 80 percent emulsion moisture loss, and
- consistent, uniform application of the aggregates to the test pad

In this procedure asphalt emulsion is applied to a 15 pound per square yard roofing felt substrate in a circle by means of a steel template, with 11-inch diameter cut-out. Emulsified asphalt is screeded level with the template by means of a strike-off rod shown in Figure 1. Aggregate is then placed mechanically using a dropping apparatus as shown in Figure 2. The aggregate is then set in place, one stone thick, by means of a compactor as shown in Figure 3. The specimen is then placed in a 160F oven to allow the emulsified asphalt to cure to 40% moisture loss or 80% moisture loss after which the specimen is removed from the oven. It is then cooled, and any loose particles are removed. The specimen is then swept under the action of a weighted brush which is spun by a planetary motion mixer for one minute as shown in Figure 4. The specimen is then removed from the machine, brushed by hand to remove all particles that were mechanically dislodged from the specimen surface and the mass loss is determined; expressed as percent loss of the original aggregate mass.

Figure 1. Emulsion Strike-Off Apparatus

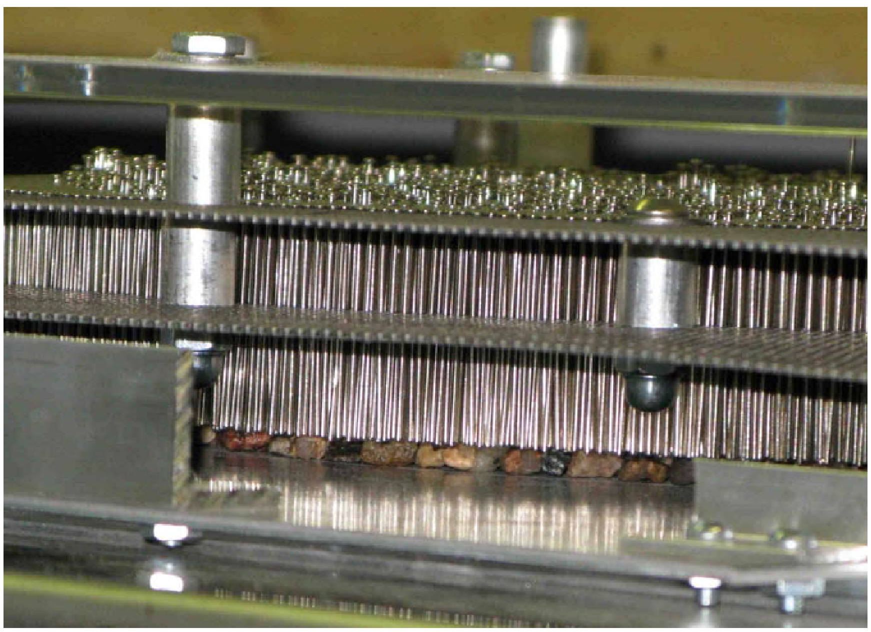

Figure 2. Dropping Apparatus Placing Aggregate on Test Pad

Figure 3. Compactor Setting Aggregates on Test Pad

Figure 4. Modified Sweep Test Mixer

2.3 Time Required Before Brooming or Traffic

Determining when the first brooming can be accomplished to remove excess chips or when to open a fresh chip seal to traffic is one of the most subjective decisions that must be made. Releasing traffic too soon can lead to vehicle damage due to flying aggregate particles. Releasing traffic too late can lead to delays and congestion. And, if light brooming results in damage to the chip seal the chip seal is often left unbroomed until binder strength increases. However, allowing traffic on the fresh, unswept chip seal can lead to flying chips and potential damage.

The modified sweep test which measures the relative adhesive strength of emulsions and emulsion residues in the laboratory was used to evaluate materials from full-scale chip seals. The objective of this experiment was to determine if the moisture content of the chip seal in the field affects the ability of the chip seal to withstand brooming and traffic stresses.

2.3.1 Full-Scale Field Tests

Three full-scale chip seal projects were included in this research. Test pavements were located on County Road 11 near Frederick, Colorado, approximately 30 miles north of Denver, Colorado; the Main Entrance Road in Arches National Park, Utah, approximately 15 miles north of Moab, Utah; and US101 near Forks, Washington, on the western edge of Olympic National Park.

2.3.2 Moisture Tests

Moisture in a chip seal comes from two sources: the chips and the asphalt emulsion, and on some projects additional moisture may be present in the roadway. If the amount of moisture in the chips and the emulsion is known at the time the chip seal is constructed, the amount of moisture that evaporates after emulsion and chip application can be measured. The objective of this part of the research was to measure the moisture loss in the three chip seal projects and develop a relationship to chip adhesion.

The amount of moisture remaining in each chip seal was measured and compared with the relative strength of the residue on a scale of 1 (no strength) to 10 (ready for traffic), judged by pulling three chips out of the fresh seal and qualitatively judging dislodgement potential. This qualitative evaluation was conducted after rolling. Moisture remaining in the emulsion was determined by placing plywood pads covered with aluminum foil measuring 24 by 24 inches in front of the asphalt distributor prior to spraying with emulsion. The pads were weighed before and after spraying and chipping and the loss in weight was determined periodically during the day until approximately 95 percent of the water had evaporated. Figure 5 shows the setup used to measure the tare weight of the apparatus prior to spraying and chipping.

Figure 5. Moisture Test Pads Prior to Spraying/Chipping

The tared pad was placed in front of the asphalt distributor and chip spreader before chip seal operations began. After the emulsion and chips were applied to the pavement and tared pad the pad was removed from the pavement and re-weighed. As moisture evaporated from the pad the weight was recorded and the strength of the emulsion residue was evaluated using the 1 to 10 scale. The resulting relationship between emulsion strength and moisture loss was developed.

2.4 Emulsion Consistency in the Field

The consistency of the emulsion is an important factor that influences performance of the chip seal. An emulsion with viscosity too low may not have the ability to hold chips in place or could flow off the pavement. An emulsion with viscosity too high could be difficult to spray evenly or have the wetting ability needed to coat chips. Emulsions are often tested at the point of manufacture and a certificate of compliance issued by the manufacturer indicating compliance to state, local, ASTM or AASHTO specifications. However, because changes to physical properties of emulsions used for chip seals can occur during transportation, a means of measuring the consistency of the emulsion at the construction site is desirable. Some highway agencies have portable laboratories capable of conducting viscosity tests in the field (Santi, 2009). However, most agencies do not have laboratories or trained personnel to conduct such tests. Therefore, a simple method of verifying the ability of the emulsion to be used as a chip seal binder was identified in this research.

2.4.1 Full-Scale Field Tests

Two simple methods for measuring the consistency of asphalt emulsions in the field were evaluated. One method based on a procedure developed by Wyoming DOT (Morgenstern 2008), requires a Wagner Part# 0153165 funnel, wind protection, 16 ounce plastic cups, thermometer, and a stop watch. The other method was a falling cylinder viscometer which was found to be cumbersome to operate and time consuming to clean and not appropriate for use in the field.

The first tests were conducted at the Arches site using the Wagner funnel with a 4 mm orifice. However, the emulsion required over 90 seconds to empty the funnel. This resulted in large differences between test results because the emulsion viscosity increased as the temperature decreased, increasing the time to empty the Wagner cup. Therefore, the orifice was drilled out to increase the diameter until the cup emptied in approximately 60 seconds or less. This process was repeated for the Frederick, CO and Forks field tests.

The test proved simple to conduct, low cost, and required a simple apparatus. Although this test would require more development to be used for determining specification compliance in the field, the test will help a field inspector rapidly determine the suitability of an emulsion upon delivery to the construction site.

2.5 Pavement Texture Testing

Adjusting the emulsion spray rate to compensate for differences in pavement surface texture is one of the most subjective adjustments made during chip seal construction. Except for the sand patch test used in South Africa and Australia/New Zealand (Austroads 2006, South Africa 2007), adjustments in the U. S. are made using judgment based on past experience. The objective of this experiment was to provide a more quantitative method for evaluating pavement texture and adjustment of emulsion application rate.

Macrotexture is the texture type that is relevant to chip seals. Macrotexture is surface roughness that is caused by the mixture properties of an asphalt concrete surface or by the finishing/texturing method of a portland cement concrete surface (Hall et al., 2006).

Previous work has indicated that either the sand patch test (ASTM E 965) or the circular texture meter (CT meter) profile (ASTM E 2157) can be used to effectively evaluate pavement macrotexture (Abe et al., 2001; Hall et al., 2006; Hanson et al., 2004). Both of these measurements are easily performed in the field, but traffic control is needed during these measurements. The sand patch test has been used for texture measurement because it requires inexpensive equipment that is easy to obtain, and it provides acceptable measurements (Austroads 2006, South Africa 2007). However, conducting the test is slow and exposes personnel to traffic and results are influenced by wind and moisture.

The CT meter evaluation of surface macrotexture can be made more quickly than sand patch testing and therefore exposes the technician to less traffic and accident risk. Also, the CT meter measurements do not depend upon operator skill. Figure 6 shows the interior of the CT Meter which faces the pavement when taking measurements.

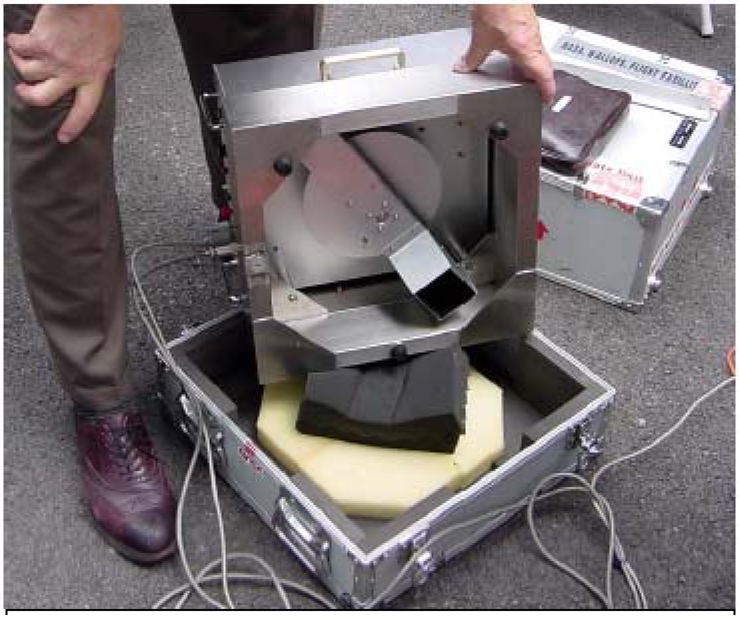

Figure 6. CT Meter

2.5.1 Laboratory Texture Testing

One part of this research involved testing three slabs of varying surface texture. These test slabs provided a range of textures for evaluating three texture measurement techniques. The slabs were fabricated to simulate three surfaces ranging from very rough, simulating a highly raveled and pocked surface to very smooth, simulating a very flushed surface.

The slabs were cast over asphalt pavements using a very low viscosity self-consolidating concrete. The self-consolidating concrete was used to make the texture specimens because of the concrete ability to flow into the smallest voids in the surface of the asphalt pavements. This created texture test specimens that mimicked the texture of the three pavement surfaces. Texture of the three slabs was measured using sand patch, CT Meter, and the Aggregate Imaging System (AIMS).

2.5.1.1 Sand Patch Test

The sand patch test (ASTM E 965) is a volumetric technique for determining the average depth of pavement surface macrotexture. A known volume of small particles (either sieved sand or small glass beads) is poured onto the pavement surface and spread evenly into a circle using a spreading tool. Four diameters of the circle are measured and an average profile depth is calculated from the known material volume and the averaged circle area. This depth is reported as the mean texture depth (MTD). The method provides an average depth value and is insensitive to pavement microtexture characteristics.

The CT meter test method (ASTM E 2157) is used to measure and analyze pavement macrotexture profiles with a laser displacement sensor. The laser sensor is mounted on an arm which follows a circular track of 284 mm (11.2 in.) diameter. Depth profiles are measured at a sample spacing of 0.87 mm, and the data are "segmented into eight 111.5 mm (4.39 inch) arcs of

128 samples each" (ASTM E 2157) A mean profile depth (MPD) is calculated for each segment and an average MPD is then calculated for the entire circular profile.

2.5.1.2 AIMS

The aggregate imaging system (AIMS) was created to quantitatively describe the characteristics of aggregates (Masad, 2005) The system consists of a camera mounted above a table with several lighting arrangements. Using AIMS, coarse aggregate is characterized by particle shape, angularity, and texture. Samples of coarse aggregate are placed on the AIMS table under the camera and lighted from above, below, or both; and camera images are used to quantify the aggregate characteristics. Analyzing macrotexture of coarse aggregates can be compared to measuring macrotexture of a pavement surface.

Using AIMS, microtexture or macrotexture of coarse aggregate surfaces can be quantified using wavelet analysis of a greyscale digital photo. Camera focal length is adjusted depending on whether macro or microtexture is of interest. Using AIMS, depth measurements were generated every 1 mm for four scanlines of 100 mm length each, 20 mm apart, and in two perpendicular directions, for a total of eight scanlines per test slab. The total of eight scanlines at 100 mm length each was chosen to be similar to the eight segments of the CT meter profile. The two sets of four scanlines each were taken in perpendicular directions to account for directional differences in pavement texture. This arrangement could be used to compare directional differences in texture, that is by texture in the direction of traffic versus texture perpendicular to the direction of traffic. Profiles were generated for the scanlines and analyzed in a procedure similar to the CT meter analysis (ASTM E 1845-01). A mean profile depth, MPD, was calculated from the AIMS data for each of the three test slabs.

2.6 Residue Recovery Methods and Properties

The Performance Grading (PG) asphalt binder grading system (Asphalt Institute, SP-1) is widely used as the specification for grading and selecting asphalt binders. The PG specification was developed for use in hot mix asphalt concrete (HMAC) pavement layers. However, the PG system is not applicable to classifying and choosing binders for use in pavement chip seals. Chip seals differ from full depth HMAC layers in construction methods, structural functions, behavioral responses, distress types, and effects of environmental exposure. Threfore, the binder grading system, Surface Performance Grading (SPG), was first suggested to classify emulsion residues or hot-applied binders for use in chip seals (Epps et al., 2001; Barcena et al., 2002). This grading system utilizes the same test methods as the PG system, but applies limits on test parameters that are consistent with the mechanics of chip seals rather than hot mix asphalt.

An emulsion residue specification requires a standardized emulsion residue recovery method that produces a material representative of the emulsion residue in situ. Currently, emulsion residues are recovered by distillation (ASTM D 6997) that exposes the material to high temperatures and may destroy or change any polymer networks present in modified emulsion residues.

This section describes the experiment utilized to compare emulsion residue recovery methods, characterize the emulsion residues by both the PG and SPG grading systems, and some additional tests, and recommends an emulsion residue recovery method and emulsion residue specification.

2.6.1 The Surface Performance-Graded (SPG) Specification

The tests used in the SPG grading system are conducted with standard PG testing equipment and the analyses are performance-based and consistent with chip seal design, construction, behavior, in-service performance, and associated distresses (Epps et al., 2001; Barcena et al., 2002). Field validation of the initial SPG system was completed in Texas (Walubita et al., 2005; Walubita et al., 2004) and resulted in the proposed three SPG grades shown in Table 3.

2.6.2 Residue Recovery Experiment

The standard PG system (Asphalt Institute, SP-1) and the modified SPG system (Epps et al., 2001; Barcena et al., 2002; Walubita et al., 2005; Walubita et al., 2004) were both used to grade all base binders and corresponding recovered emulsion residues in this experiment.

2.6.2.1 Materials

Eight emulsions were included in this research. Five of which, identified as emulsions 1-5, were laboratory prepared. The other three emulsions were obtained from the full scale test pavements in Utah Arches National Park; Frederick, Colorado, CR11; and Forks, Washington, US101. Table 4 lists the types of emulsions and, when known, the PG grades of the base binders as reported by the supplier.

2.6.2.2 Emulsion Residue Recovery Methods

Hot Oven (with Nitrogen blanket) and Stirred Can (with Nitrogen purge) Emulsion Residue Recovery methods (SCERR) were used to extract the water from the emulsions and to supply de-watered residue for the material properties testing. A third residue recovery method known as Warm Oven or Low Temperature Evaporative Technique (Kadrmas, 2008; Hanz et al., 2009) was also compared with the Hot Oven and Stirred Can techniques (Prapaitrakul et al., 2009).

2.6.2.3 Laboratory Tests

Rheology Tests

Binder characterization tests utilized the same equipment and some of the same tests as specified in the PG system (Asphalt Institute, SP-1), but with different limiting criteria and test conditions as shown in Table 4.

All of the binders in this experiment were aged using the pressure aging vessel (PAV), as described in the PG grading system (Asphalt Institute, SP-1). Rolling thin film oven (RTFO) aging was not used because emulsion binders are not exposed to this type of heating in chip seal construction.

Table 3. Criteria for SPG Grades for Emulsion Residues (Walubita et al., 2005; Walubita et al., 2004)

	Surface Performance Grade*											
	SPG 58				**SPG 61**				**SPG 64**			
	-10	**-16**	**-22**	**-28**	**-10**	**-16**	**-22**	**-28**	**-10**	**-16**	**-22**	**-28**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<58				<61				<64			
Minimum Surface Pavement Design Temperature, °C	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28
Original Binder												
Viscosity ASTM D 4402 Maximum: 0.15 Pa.s; Minimum: 0.10 Pa.s Test Temperature, °C	≤205				≤205				≤205			
Dynamic Shear, AASHTO TP5 $\frac{G^*}{Sin\,\delta}$, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	58				61				64			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1)												
PAV Aging Temperature, °C	90				100				100			
Creep Stiffness, AASHTO TP1 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8s, °C	-10	-16	-22	-28	-10	-16	-22	-28	-10	-16	-22	-28

Note: The above table presents only three SPG grades as an example, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3 and 6 ^{o}C increments.

**SPG 58-10 indicates a material suitable for construction in an environment from 58C to -10C.*

Table 4. Binders and PG and SPG grades.

Emulsion	AASHTO Emulsion Type	Expected Base Grade	Batch #	Recovery Method	PG Grade from Tests	Continuous PG Grade	SPG Grade from Tests	Continuous SPG Grade
1	RS-2P	PG 64-28	1	Base Asphalt	PG 64-34	67.8 - 34.2	SPG 70 -24	71.7 - 24.0
			6	Stirred Can with N	PG 64-34	69.3 - 34.1	SPG 73 -18	73.0 - 21.3
			11	Hot Oven-N Blnkt	PG 64-34	69.5 - 34.1	SPG 73 -18	73.4 - 21.1
2	CRS-2	na	2	Base Asphalt	PG 58-28	60.2 - 30.7	SPG 61 -18	63.1 - 19.4
			7	Stirred Can with N	PG 58-28	62.9 - 31.0	SPG 64 -18	66.4 - 19.2
			12	Hot Oven-N Blnkt	PG 58-28	61.9 - 32.1	SPG 64 -18	64.5 - 20.7
3	RS-2	PG 64-22	3	Base Asphalt	PG 64-22	66.9 - 27.1	SPG 67 -12	69.7 - 14.7
			8	Stirred Can with N	PG 64-22	68.2 - 26.8	SPG 70 -12	71.4 - 15.9
			13	Hot Oven-N Blnkt	PG 64-22	68.5 - 26.5	SPG 70 -12	71.7 - 15.1
4	CRS-2P	PG 64-28	4	Base Asphalt	PG 64-28	67.6 - 32.9	SPG 70 -18	70.8 - 22.2
			9	Stirred Can with N	PG 64-28	68.6 - 33.2	SPG 70 -18	72.3 - 22.9
			14	Hot Oven-N Blnkt	PG 64-28	69.2 -33.7	SPG 70 -18	72.9 - 23.4
5	HFRS-2P	PG 70-28	5	Base Asphalt	PG 58-28	62.3 - 30.4	SPG 64 -18	65.7 - 18.7
			10	Stirred Can with N	PG 58-28	63.4 - 31.6	SPG 67 -18	67.0 - 20.1
			15	Hot Oven-N Blnkt	PG 58-28	63.3 - 31.8	SPG 64 -18	66.9 - 20.0
6 - UT	LMCRS-2	na	16	Stirred Can with N	PG 70-22	74.7 -26.4	SPG 76 -12	78.7 - 15.3
			17	Hot Oven-N Blnkt	PG 76-22	76.7 - 26.3	SPG 79 -12	80.9 - 15.7
7 - CO	HFRS-2P	na	18	Stirred Can with N	PG 70-28	72.0 - 32.0	SPG 76 -18	76.6 - 21.1
			19	Hot Oven-N Blnkt	PG 70-28	72.7 - 31.6	SPG 76 -18	77.0 - 20.3
8 - WA	CRS-2P	PG 64-22	20	Hot Oven-N Blnkt	PG 64-28	64.1 - 28.0	SPG 67 -18	67.6 - 18
			21	Stirred Can with N	PG 64-22	64.0 - 27.9	SPG 67 -12	67.1 - 17.1

Unaged binder was tested at the high temperatures, which is the critical condition for early strength development in chip seals.

PAV aged binder was used in the Bending Beam Rheometer (BBR) to simulate long-term in-service aging that may cause failure at cold temperatures for chip seals. PAV aging simulates approximately the first hot and cold seasons of a chip seal which is when most chip seal failures occur (Epps et al., 2001; Barcena et al., 2002).

Strain Sweep Tests

Strain sweep tests using a dynamic shear rheometer have been correlated to the chip seal sweep test, ASTM D-7000 (ASTM International, 2009) (Kucharek, 2007). Therefore, strain sweep information collected in this research supplements the SPG system for evaluating strain tolerance and resistance to raveling of emulsion residues during curing and at early ages.

The strain sweeps were conducted using a dynamic shear rheometer (DSR) at 25˚ C with 8 mm plates and 2 mm gap on both unaged and PAV aged material to show the change in the complex modulus (G*) with increasing strain. Test results are affected by how the test is performed and by the parameters input into the DSR. The DSR is continually oscillating during strain sweep testing. Input to the DSR requested strains of 1 to 50 percent, and the strain sweeps were initiated at 1 percent. A ten minute period was allowed after mounting the sample and before testing started for thermal equilibrium to occur. An angular loading frequency of 10 radians/second and a linear loading sequence with time was applied. A delay time of 1 second after the load (strain) was incremented but before the measurements were taken was chosen, and 20 to 30 strain measurements were taken during each test. The test time for each strain sweep was approximately 1 to 2 minutes (after thermal equilibrium).

Chemical Tests

Gel permeation chromatography (GPC) was performed on each recovered residue to determine if all of the water had been removed during the residue recovery process. Presence or absence of a peak at a time of 35 to 37.5 minutes on the GPC chromatogram indicates the presence or absence of water in the residue.

Fourier transform infrared (FT-IR) spectroscopy was performed on the residues from the five laboratory emulsions to obtain an indication of whether the recovery methods caused oxidation of the materials. The infrared spectra were plotted, and then the area under the wavenumber band from 1820 to 1650 cm^{-1} was integrated to determine the carbonyl area which is carbonyl used to represent the extent of oxidation in the materials (Epps et al., 2001; Prapraitrakul et al., 2009; Woo et al., 2006).

2.7 Estimating Chip Embedment Depth During Construction

Embedment depth is usually determined during construction by pulling several chips out of the binder and visually estimating the amount of the chip embedment in the binder. Because it is generally difficult to accurately assess chip embedment using this procedure two methods based on the sand patch test were developed to provide a quantitative measure of embedment depth: the ‘Constant Volume Method’ and the ‘Constant Diameter Method’.

Both methods were developed using the limestone (LSTN) and granite (GRNT) aggregates from the laboratory sweep test experiment. These aggregates were used because they represent a range of flakiness from a high of approximately 34 percent for the limestone to a low of 6 percent for the granite.

2.7.1 Constant Volume Method

The objective of this experiment was to determine if the diameter of a constant volume of glass beads spread in a circular shape onto the surface of a new chip seal could be used to estimate the embedment of chips in the binder.

The aggregate chips (LSTN and GRNT) were oriented on their widest faces so that the average particle heights were their average least dimensions. Embedment percentage was determined for each specimen based on the aggregate average least dimension, weight to volume relationships of the materials and the diameter of the glass bead circle from equation 1.

The texture depth (T) is the average distance the aggregate chip is exposed above the surface of the asphalt or (ALD – Embedment Depth) as shown in Figure 7.

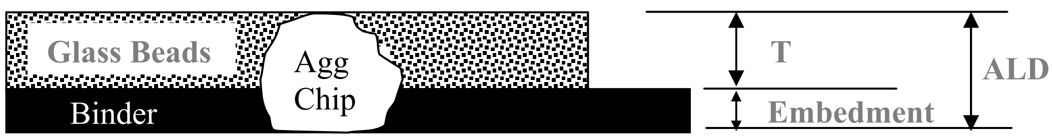

Figure 7. Embedment Depth by Constant Volume Model

$$T = \frac{\text{Volume of Beads Between the Binder Surface and the top of the chip}}{\text{Area of Glass Bead Circle (A)}}$$

Volume of Beads Between Binder Surface and and top of the chip, $V_{bb} = W_{bb} / \gamma_b$

Where,

W_{bb} = weight of beads between binder surface and top of chip

γ_b = unit weight of beads

so,

$$T = W_{bb} / \gamma_b * A$$

Since,

Embedment, % = 100 * (ALD – T)/ALD

$$\text{Embedment, \%} = 100 * \{ALD - [W_{bb} /(\gamma_b * A)]\}/ALD \qquad (1)$$

This relationship assumes the volume of glass beads is spread over the chip seal up to the peak of each particle such that the glass beads follow the profile of the particle peaks. Therefore, the average height of the glass beads on the chip seal is equivalent to the void height that would be seen between equal-height particles of a chip seal that is built with exactly one-sized aggregate.

Equation 1 can be used to calculate the percent embedment of a chip seal for a known volume of glass beads spread in a circle of a measured diameter. This procedure was used for limestone and granite aggregates and the results were compared with the actual embedment depths to determine if the procedure yields appropriate results.

2.7.2 Constant Diameter Method

This method uses a constant diameter mold and measures the amount of glass beads necessary to fill the mold above the chip seal. Constant diameter chip seal specimens were covered with glass beads until the peaks of the largest chips were completely submerged in glass beads. A mold was used to confine the glass beads to a constant diameter. By subtracting the volume of beads above the average particle height from the total volume of glass beads used, the volume of beads below the average particle height can be determined. Figure 8 represents the apparatus used in this experiment.

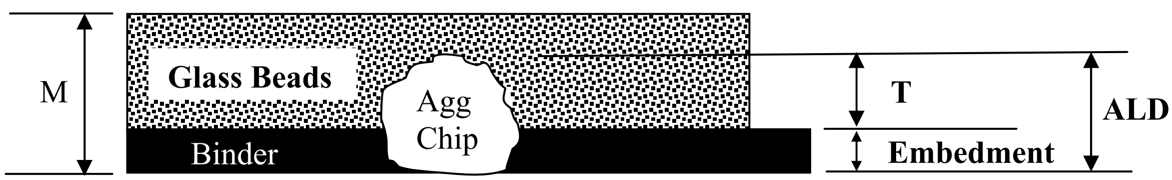

Figure 8. Embedment Depth by Constant Diameter Model

To determine embedment percent, the chip seal specimen is placed in the mold, the mold is filled with glass beads to the top of the mold. The total mass of beads which fills the space above the specimen is determined and its volume is calculated using its density. Knowing the average height of the chip seal aggregate, the volume of glass beads between the top of the mold and the top of the average particle is calculated from the following:

$$\text{Volume of Beads Above Chips to Top of Mold, } V_{ba}\text{, mm}^3 = (M - ALD) * A$$

Where:

M = mold height, mm,
ALD = average particle height, mm,
A = mold cross-sectional area, mm^2.

The volume of beads between the chips is determined by subtracting V_{ba} from the total volume of beads to fill the mold. This value is used to determine the distance the chips extend above the binder.

$$\text{Volume of Beads Between the Chips, } V_{bb}\text{, mm}^3 = V_{bt} - V_{ba}$$

Where:

V_{bt} = total volume of beads to fill the mold, $cm^3 = (W_{bt} / \gamma_b) - V_{ba}$

W_{bt} = weight of beads to fill mold, gm

γ_b = unit weight of beads, gm/cm^3

Percent embedment is calculated as follows:

$$\text{Embedment Depth, \%} = [ALD - (V_{bb} / A)]/ALD \quad (2)$$

CHAPTER 3 – Results and Analysis

This chapter describes the results of the laboratory and field studies conducted during this project that were used to develop the Manual for Emulsion-Based Chip Seals for Pavement Preservation provided as Attachment 1. Details of the laboratory and field testing are provided in the Appendices.

3.1 Sweep Test

Chip loss measured after the sweep test is shown in Figures 9 through 12 for each of the dry, SSD, 40 percent and 80 percent moisture loss test conditions. Results of analysis of variance (ANOVA) shown in Table 5 and the Newman-Keuls (Anderson and McLean 1993) multiple comparison test in Table 6 indicate statistically significant differences between the 40 percent and 80 percent moisture loss test specimens for all five emulsions. Chip loss with dry aggregates averaged approximately 70 and 15 percent at 40 and 80 percent moisture loss, respectively. Chip loss for SSD aggregates averaged approximately 65 and 10 percent moisture loss, also respectively.

The sweep test indicates a statistically significant difference in chip loss between aggregates that were dry when embedded in the emulsion and those that were in the SSD condition when embedded. Newman-Keuls multiple range comparison from Table 6 indicates that dry aggregate has significantly higher loss than SSD aggregates except when the CRS-2 emulsion is the binder used because damp aggregates allow the emulsion to wick into the aggregate pores and provide improved adhesion and cohesion properties.

There are statistically significant differences in chip loss between the emulsions. The RS-2P showed aggregate loss similar to the other emulsions at 40 percent moisture loss with either dry or SSD chips but higher chip loss at 80 percent moisture loss with either dry or SSD chips. The CRS-2P performed similarly to the other emulsions under all conditions except at 80 percent moisture loss with SSD chips, where it showed less aggregate loss than the other binders except the HFRS-2P.

The particle charge on the emulsion appears to have little effect on chip loss at 40 percent moisture loss as shown in Figures 10 and 11. That is, the anionic RS-2 adheres equally well to the limestone as the granite and basalt, and the cationic CRS-2 adheres equally well to all of the aggregates. Some difference may be significant with respect to the polymer modified RS-2P where adhesion appears much better on the limestone. However, in general, the anionic emulsions do not appear to have a greater affinity to limestone and the cationic do not appear to have a greater affinity to the granite nor basalt. Table 6 shows an opposite trend for the CRS-2P, which adhered better to the limestone (25 percent loss) than the granite (38 percent loss) at $\alpha = 0.05$. Also, the basalt had the least chip loss and the alluvial had the most loss regardless of the emulsion. This indicates that factors other than surface chemistry affect adhesion.

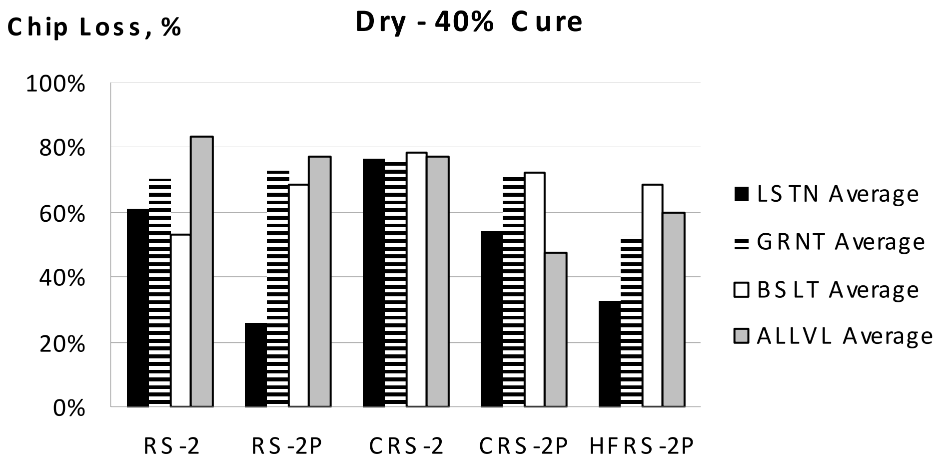

Figure 9. Sweep Test Results for Dry Chips at 40% Cure

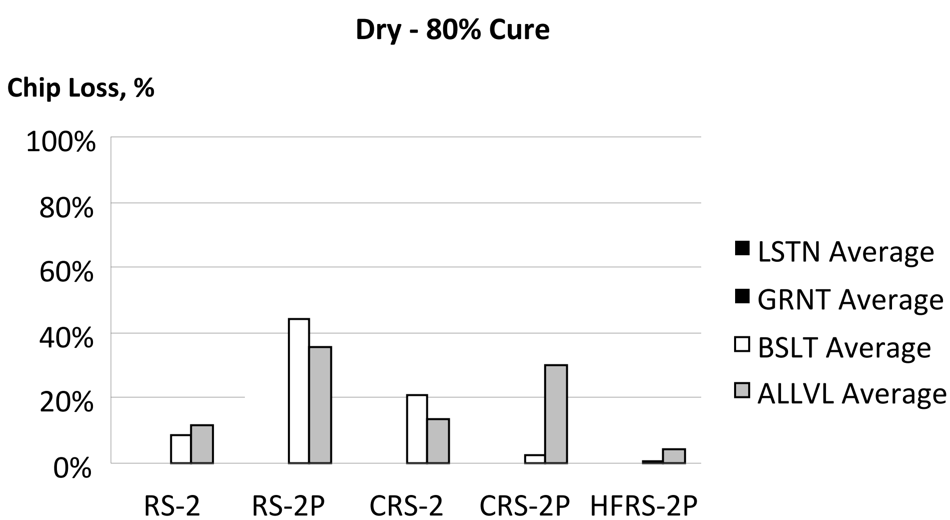

Figure 10. Sweep Test Results for Dry Chips at 80% Cure

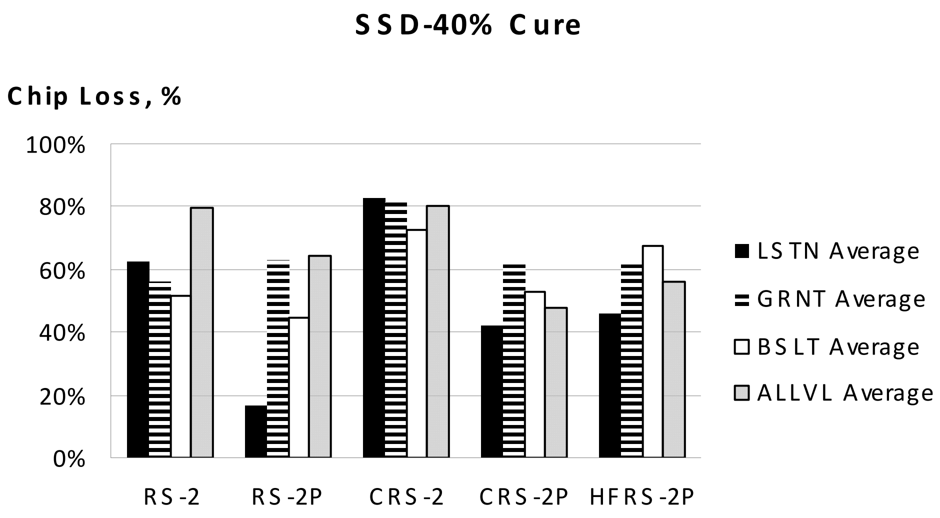

Figure 11. Sweep Test Results for SSD Chips at 40% Cure

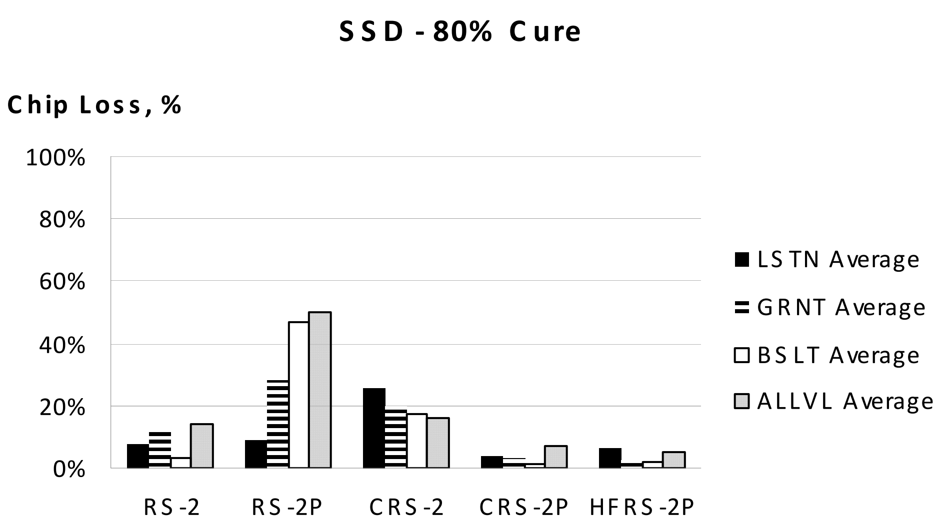

Figure 12. Sweep Test Results for SSD Chips at 80% Cure

Table 5. Results of ANOVA for Laboratory Sweep Tests

	Alpha Level for Significant Differences				
Variable Tested	RS-2	RS-2P	CRS-2	CRS-2P	HFRS-2P
aggregate	<0.0001*	<0.0001*	0.3887	0.0049*	<0.0001*
moisture	0.0169*	0.0220*	0.1597	0.0003*	0.0335*
cure	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
agg x ** moist	0.2468	0.3618	0.0994	0.7574	0.5873
agg x cure	0.0001*	0.0020*	0.3927	0.0005*	0.0032*
moist x cure	0.5425	0.0136*	1.0000	0.9546	0.6490
agg x moist x cure	0.1064	0.2088	0.8805	0.0114*	0.2366

* Statistical significance at $\alpha = 0.05$ or less

** x indicates the interaction effect of the variables shown on the mean chip loss

Table 6. Results of Student Newman-Keuls Multiple Comparison Test for Aggregate

Aggregate	Emulsion				
	RS-2	RS-2P	CRS-2	CRS-2P	HFRS-2P
ALL	A*(47)**	A(57)	A(50)	A (38)	A (44)
GRN	B(39)	A(51)	A(49)	A/B (33)	A/B (37)
LS	B(36)	A(51)	A(47)	A/B (32)	B (28)
BST	C(29)	B(18)	A(47)	B (25)	B (25)

* Letters indicate statistical significance in mean chip seal loss at alpha = 0.05. For example, there is a statistically significant difference in population mean chip loss between the alluvial (ALL) and the granite (GRN) for the RS-2 (47% vs 39% chip loss), but there is *not* a statistically significant difference in population mean chip loss between the alluvial (ALL) and the granite (GRN) for the RS-2P (57% vs 51%), the CRS-2 (50% vs 49%), the CRS-2P (38% vs 33%) or the HFRS-2P (44% vs 37%).

** Numbers in parentheses are the average percent chip loss after the sweep test

3.2 Field Moisture Tests

The results of this experiment indicate that chip adhesion reaches the point where significant force is required to dislodge the chip at approximately 75 to 85 percent moisture loss. At that time sweeping can commence and traffic can be allowed to travel on the new surface. Figures 13, 14 and 15 show the relationship between chip seal binder strength and moisture loss for each test pavement. The chip seal binder strength was judged subjectively by pulling three chips out of the emulsion and rating the relative strength with respect to how difficult the chips were to pull out of the emulsion residue on a scale of 1 (no strength) to 10 (ready for traffic. This qualitative rating was made after rolling.

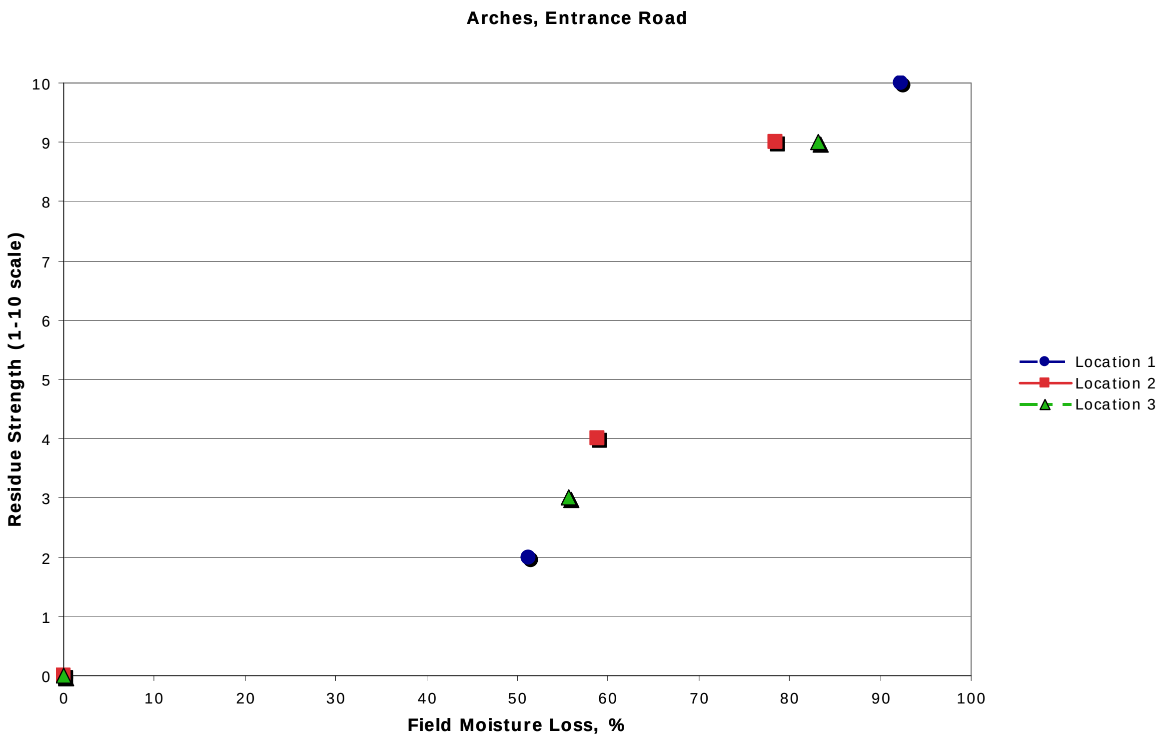

Figure 13. Residue Strength vs Emulsion Moisture at Arches NP, UT

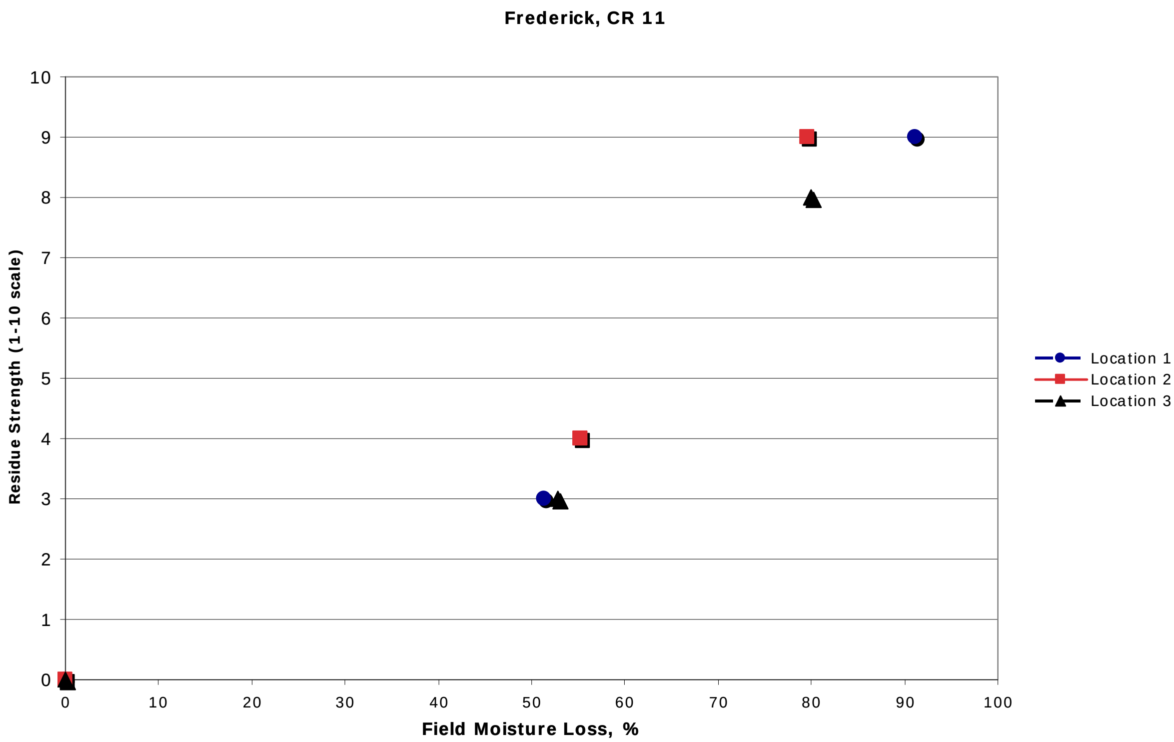

Figure 14. Residue Strength vs Emulsion Moisture for CR 11, Frederick, CO

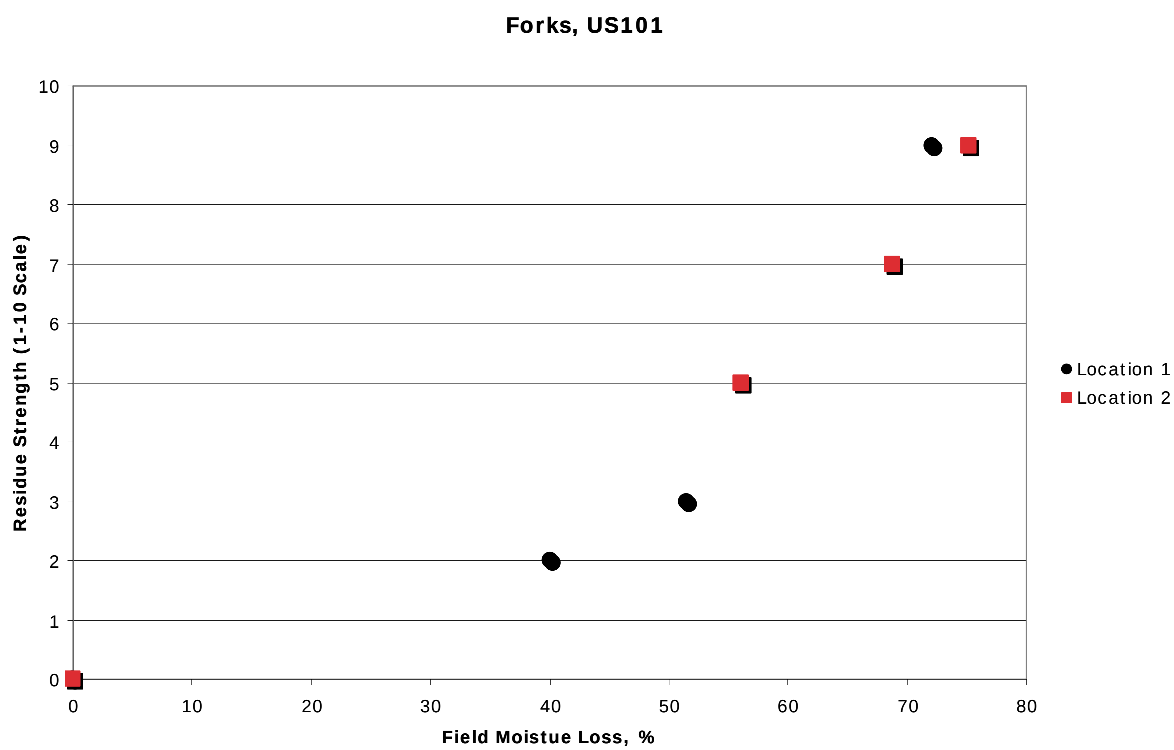

Figure 15. Residue Strength vs Emulsion Moisture at US101, Forks, WA

3.2 Laboratory Sweep Test for Field Materials

The sweep test was conducted for aggregates and emulsions obtained from the three field test pavements. Aggregates were tested using two moisture contents and a range of moisture loss percentages. Results are presented in Table 7 and the relationship between moisture loss and chip loss is shown in Figure 16. At approximately 85 percent moisture loss, residue strength increased to the point where chips could not be dislodged during the test. This suggests that a relationship exists between the laboratory sweep test and actual residue strength in the field as a function of moisture content of the chip seal system.

The results show little difference between the dry and SSD aggregate conditions with respect to chip loss. The regression equation for both moisture conditions were similar, also location had little effect. However, there appears to be a strong relationship between chip seal moisture loss and chip loss. Therefore, the moisture content of the chip seal system (i.e., the moisture of the emulsion and the moisture of the chips) could be used to determine when the chip seal has developed enough adhesive strength to resist the stresses of sweeping and uncontrolled traffic.

Table 7. Chip Loss for Test Pavement Materials

Site	Aggregate Moisture	Chip Seal Moisture Loss, %	Avg. Sweep Test Chip Loss, %
Arches	Dry	41.0	32.3
Arches	Dry	84.0	0.05
Frederick	Dry	45.9	39.3
Frederick	Dry	81.6	0.00
Forks	Dry	40.6	68.2
Forks	Dry	75.7	0.05
Arches	SSD	38.9	63.3
Arches	SSD	80.3	0.21
Frederick	SSD	41.6	40.6
Frederick	SSD	81.6	0.04
Forks	SSD	42.9	47.6
Forks	SSD	71.3	0.41

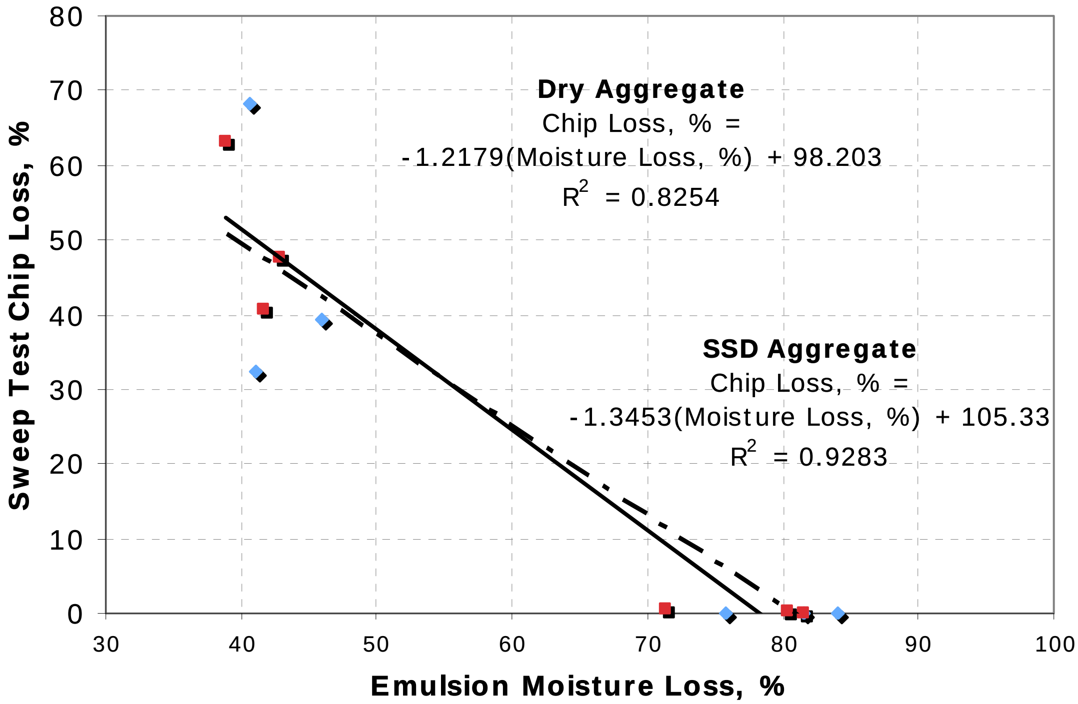

Figure 16. Sweep Test Chip Loss for Field Test Site Aggregates and Emulsions

3.3 Emulsion Consistency in the Field

Results of the tests at Arches National Park, CR11-Frederick, and US101-Forks are shown in Figures 17 and 18 for the 6 and 7.5 mm orifices, respectively. Arches testing did not include the 7.5 mm orifice.

The emulsion consistency at all three field test sites was considered acceptable for constructing chip seals, i.e. it remained on the pavement surface and did not flow off but was not so viscous as to prevent wetting of the aggregate chips. Based on this observation Wagner cup flow times of 20 to 70 seconds at emulsion temperatures of 85 to 150F for a 6 mm orifice or 10 to 60 seconds at emulsion temperatures of 85 to 140F for the 7.5 mm orifice may be appropriate for use as a guide for evaluating emulsion flow.

A correlation between Wagner Cup flow time and Saybolt viscosity was developed by Wyoming DOT (Morgenstern 2008) and is presented in Figure 19 for a CRS-2P. Similar curves could be developed at different temperatures.

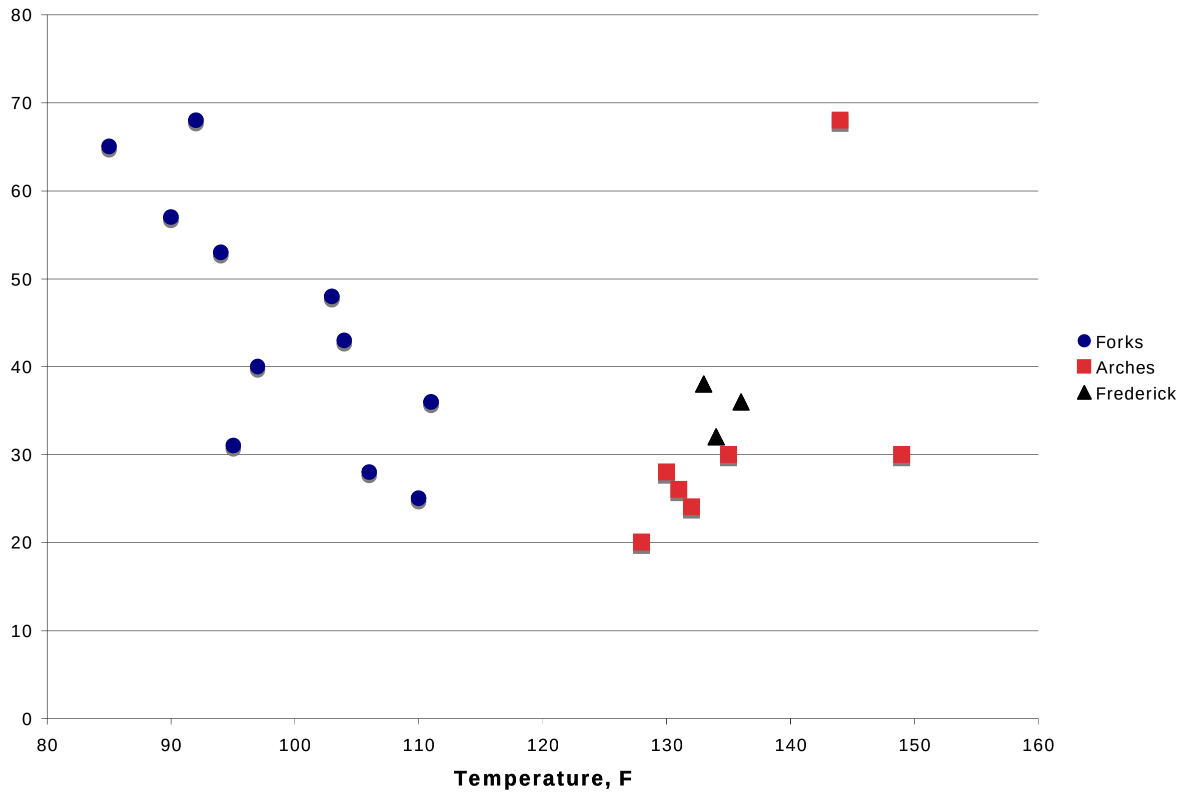

Figure 17. Field Flow Times for 6mm Orifice Wagner Cup

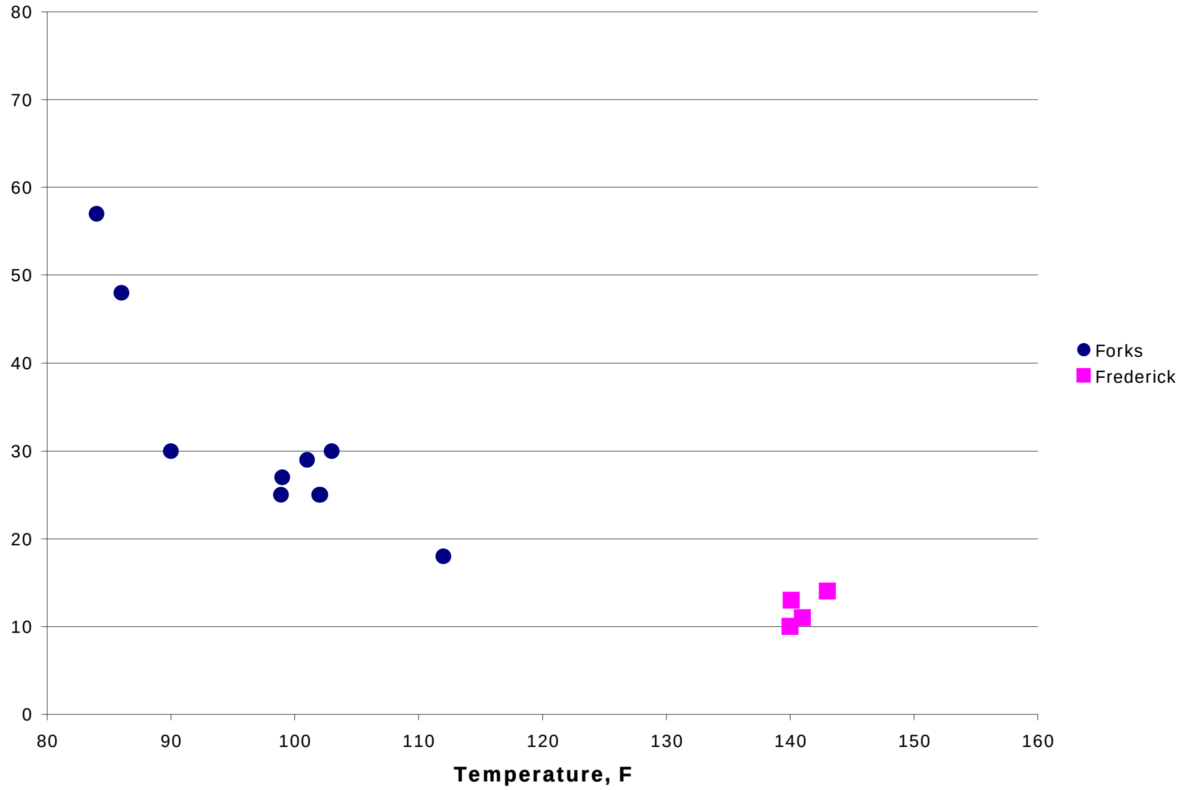

Figure 18. Field Flow Times for 7.5mm Orifice Wagner Cup

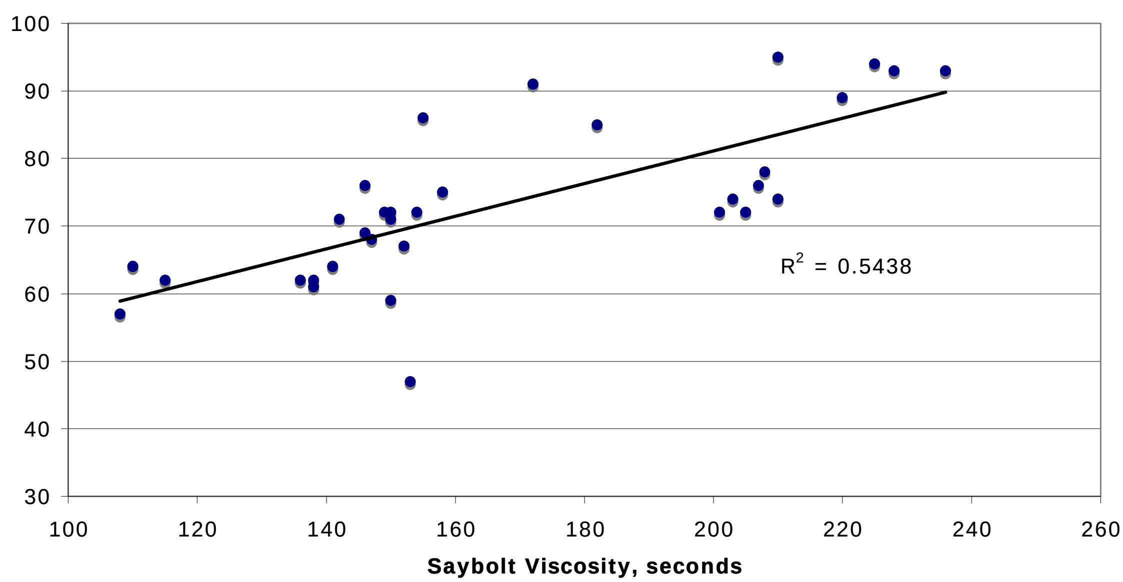

Figure 19. Saybolt Viscosity vs Wagner Cup Flow Time (Morgenstern 2008)

3.4 Pavement Texture Measurement

Texture of three concrete texture slabs was measured in the laboratory using the sand patch test, the CT Meter and the AIMS apparatus. Texture measurements were also made on the test pavements at Arches-Utah; Frederick, Colorado; and Forks, Washington. Multiple measurements of within-wheel path and between-wheel path textures were made on each project; an average texture depth at each measurement location was calculated.

3.4.2 Laboratory Texture Measurements

Results of texture measurements for the laboratory texture slabs using the sand patch, CT Meter and AIMS test methods are shown in Figure 20. Both the CT Meter and AIMS test methods correlate fairly well to the sand patch test. Further testing using the CT Meter and sand patch were made at each of the three field test sites.

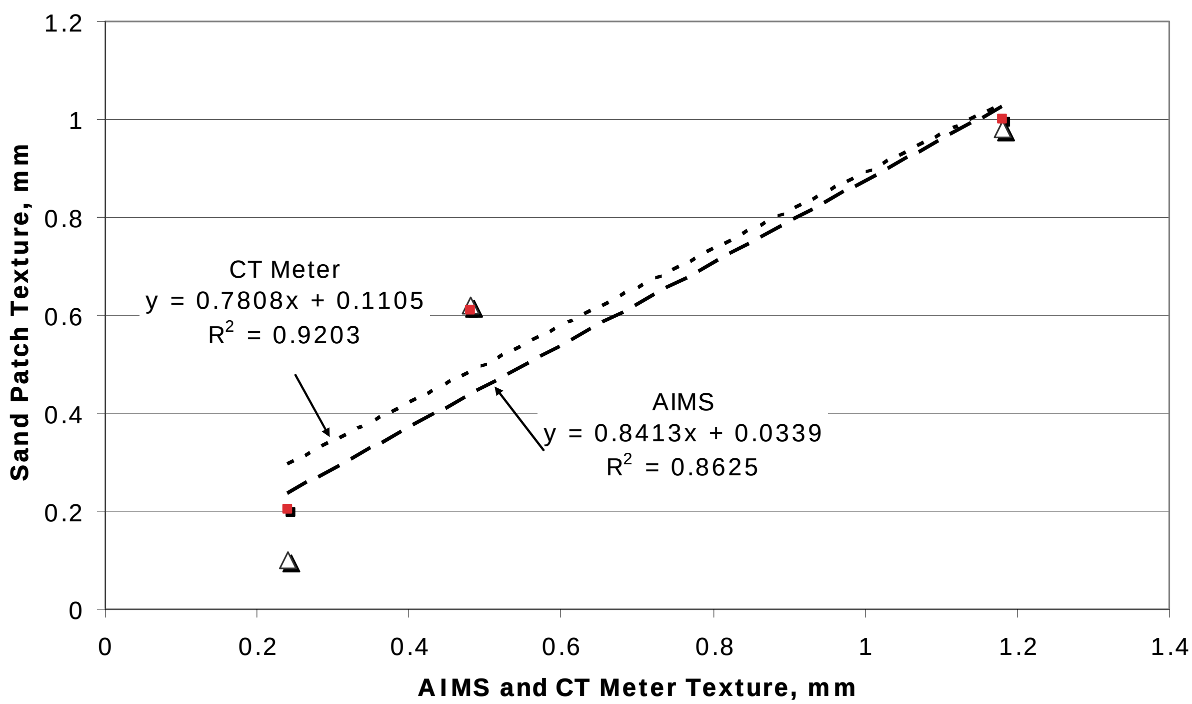

Figure 20. Laboratory Test Slab Texture by Sand Patch and AIMS

3.4.1 Field Texture Measurements

Texture measurements for the three field test sites and the three laboratory test slabs are shown in Figure 21. Texture ranges from 0.1 mm for one of the test slabs to nearly 3 mm at the

Arches site. Linear regression using all data resulted in an R^2 of 0.96 with slope of 0.96 and intercept of 0.14 indicating nearly a one to one relationship between sand patch and CT meter texture measurements when laboratory and field data are combined.

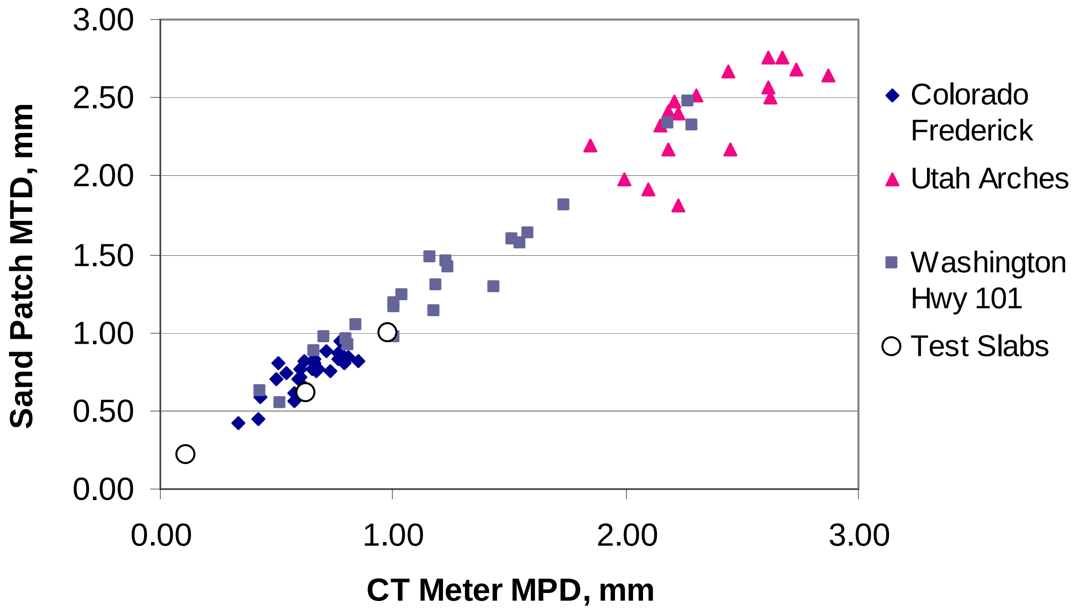

Figure 21. CT Meter Versus Sand Patch Texture

3.5 Residue Recovery Methods and Properties

Rheological Properties

At the high temperatures, the base binders in every case exhibited lower G*/sin δ than did the recovered residues possibly due to stiffening and aging of the residues during either the emulsification process or the residue recovery process. The BBR test results indicated that the base binders and the recovered emulsion residues had similar cold temperature properties, probably due to deterioration of the polymer additive structure over time and with aging (Woo et al., 2006). All of the materials met the PG (G*sin δ) criterion at the SP-1 specified intermediate temperatures.

PG and SPG Grading

Both PG and SPG grades were determined for all of the base binders and recovered residues, and the results are shown in Table 4. Interpolation was used to determine the continuous grades. In general, the PG and SPG grades were consistent for the base binder and the residues from both recovery methods. However, examination of the continuous grades indicated that the base binder grades were slightly different from the grades of the recovered residues. The SPG system resulted in a higher continuous grade at both the high and the low temperature ends than the continuous grade with the PG system. The average difference in the high and low temperature continuous grades (SPG minus PG) were +3.6º C and +11.3º C, respectively.

Chemical Properties

The GPC chromatograms for all of the residues from both of the recovery processes indicated that water was absent from the recovered emulsion residues and had therefore been completely removed from the emulsions during the recovery procedures.

The carbonyl areas calculated from FT-IR spectra for the five laboratory emulsions indicated that the recovered binders were all slightly more oxidized than the base binders. This oxidation could have occurred during emulsification or during the residue recovery process.

Statistical Analyses Summary

The rheological data collected with the DSR and the BBR were analyzed statistically to determine if there were statistical differences between the emulsions and between the recovery methods. Analysis of Variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison techniques with a level of confidence of α =0.05 were used in all of the analyses.

When comparing the DSR data by recovery method, the analysis results statistically grouped the recovery methods of stirred can and hot oven together, and the base binder ("no recovery") was grouped separately for the emulsions with base binders available (1-5). Both recovered residues were stiffer, with larger values of G*, than the base binders, but not stiff enough to change the high-temperature PG grade for emulsions 1-5 as shown in Table 8. With smaller temperature increments, the high-temperature SPG grade did change to a larger value for four of emulsions 1-5.

Analysis of the BBR measurements showed that the recovery procedure (with base binders included as "no recovery") did not affect the response variables S or m-value of the recovered residues. This result seems to indicate that after PAV aging, the polymers and additives no longer have an effect on stiffness properties.

The spectroscopic data were also analyzed statistically using Analysis of Variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison techniques for a level of confidence of α =0.05. Statistical analyses of carbonyl areas did not differentiate the recovery methods. The base binders and the recovered residues were statistically different, but the two recovery methods were similar to each other in terms of oxidative effects.

Strain Sweep Results

Strain sweeps were conducted on unaged and PAV aged materials. The unaged material represented the binder residue after the chip seal was constructed and the binder had cured with complete water removal. The PAV aged material represented the binder residue after the chip seal would have been in place for approximately one summer (high temperature) and one winter (low temperature). The majority of chip seal failures occur during either the first summer or the first winter (Epps et al., 2001).

Review of the plots of G* versus % strain indicate that the magnitudes of the G* and strain values and the shapes and rates of change of the curves can be used to compare materials and characterize strain tolerance. For comparison, the strain sweep data from the stirred can recovery residues for aged and unaged materials are shown in Figure 22.

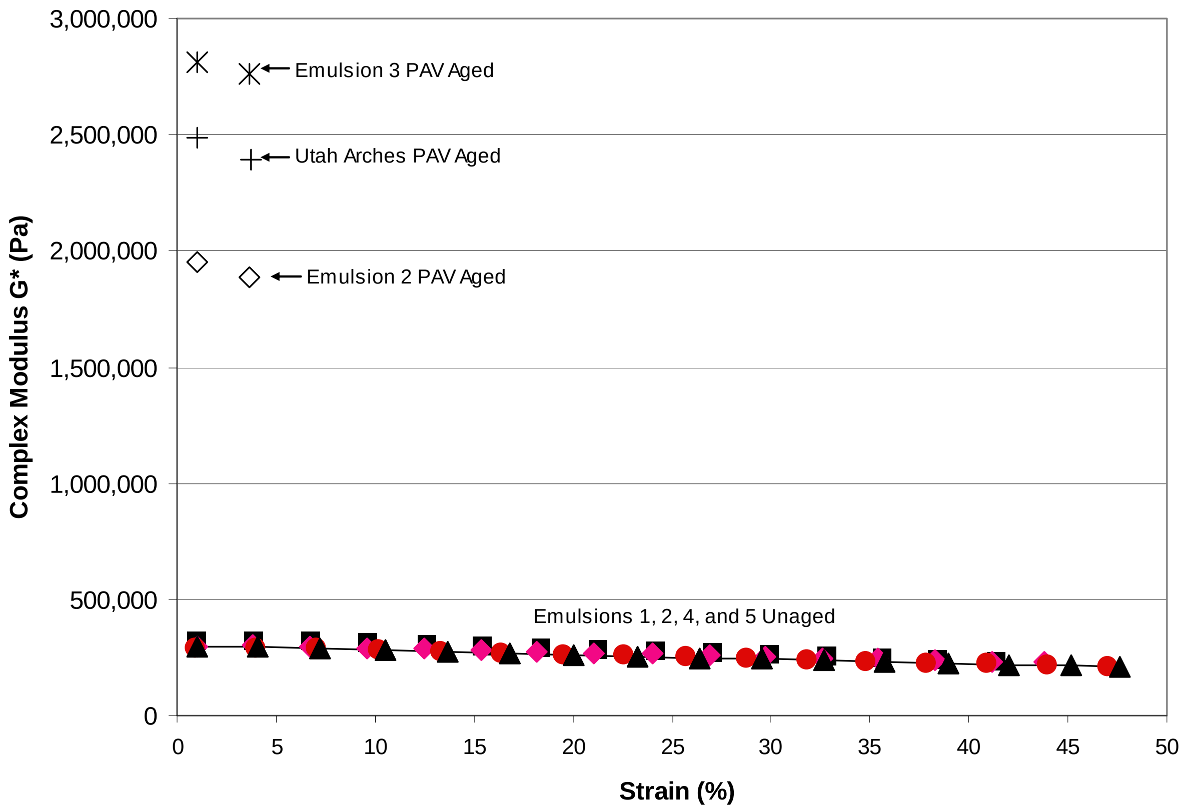

Figure 22. G* versus Shear Strain from Stirred Can Recovery Method

Materials with high strain tolerance exhibit slow deterioration of G* with increasing strain level, indicating that the material maintains stiffness and holds together under repeated and increasing loads. Emulsions 1, 2, 4, and 5 in the unaged state exhibited this behavior and were visibly more adhesive and elastic when handling in the laboratory. After PAV aging some materials exhibit less strain tolerance and develop a steep decrease in G* with increasing strain. Emulsions 2, 3 and Utah Arches are examples of this type of behavior. These materials were very stiff and broke off of the test plates in a brittle manner after the strain sweep testing was completed.

An asphalt binder must develop enough stiffness (G*) to be able to carry vehicle loads before the chip sealed pavement is broomed or opened to traffic. The amount of moisture remaining in the chip seal has been shown to relate to binder strength development. This moisture level could be correlated with G* from strain sweep testing to determine a minimum G* for traffic bearing capacity.

Researchers have conducted testing on binders during curing and have recommended the following criteria for determining strain tolerance and failure of the emulsion residue during curing (Hanz et al., 2009):

a) 10% reduction in G*, or $0.10G_i$* characterizes strain tolerance and indicates that the material is behaving nonlinearly and is accumulating damage;
b) 50% reduction in G* or $0.50G_i$* defines failure of the material.

Hanz (Hanz et al., 2009) found that stiffer emulsion residues after PAV aging are difficult to induce 50% G_i* and even 90% G_i* in strain sweep testing. Most of the unaged and only a few of the PAV aged materials reached 80% G_i*, as shown in Table 8 and none reached 50% G_i*. It is possible that intermediate reductions in G_i* could be used to characterize behavior of the fully cured residues when 50% or 90% G_i* cannot be attained.

Table 8. Strain Sweep Test Results

Emul-sion	Recovery	UNAGED G_i* (Pa, at 1% γ)	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*	AGED G_i* (Pa, at 1% γ)	% γ at $0.98G_i$*	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*
1	base	241,120	21.23	34.74	n/a	987,120	4.95	10.88	12.67*	n/a
1	stirred can	326,460	19.20	31.22	n/a	883,620	5.01	11.86	14.15*	n/a
1	hot oven	337,500	19.79	32.67	60.06*	844,030	5.53	11.46	14.82*	n/a
2	base	248,290	25.72	6.18	84.03*	1,448,300	3.93	7.31	8.62*	n/a
2	stirred can	298,170	22.17	38.31	n/a	1,948,300	2.77	5.29	6.40*	n/a
2	hot oven	318,660	21.32	36.98	63.37*	1,385,600	4.33	7.68	9.01*	n/a
3	base	747,630	14.84	16.71	n/a	3,329,800	2.31	n/a	n/a	n/a
3	stirred can	825,740	13.26	15.13	n/a	2,811,300	3.62	n/a	n/a	n/a
3	hot oven	813,970	13.64	15.35	n/a	3,163,400	2.14	n/a	n/a	n/a
4	base	219,060	25.41	44.14	n/a	954,040	5.24	10.92	13.11*	n/a
4	stirred can	289,860	20.77	34.51	n/a	905,480	5.58	11.27	13.82*	n/a
4	hot oven	257,750	24.35	34.26	n/a	778,100	4.84	11.11	16.10*	n/a
5	base	266,850	22.03	38.45	n/a	1,260,200	4.92	8.81*	9.91*	n/a
5	stirred can	297,360	17.79	31.46	67.95*	765,620	5.18	10.76	16.35*	n/a
5	hot oven	286,680	17.27	30.57	70.53*	801,740	3.96	10.38	15.54	n/a
6 – UT	stirred can	1,182,300	9.18	10.56*	n/a	2,486,600	2.45	4.46	n/a	n/a
6 – UT	hot oven	1,203,200	9.21*	10.37*	n/a	2,886,400	3.33	3.84*	n/a	n/a
7 - CO	stirred can	440,260	18.16	28.36	45.86*	1,235,400	3.36	8.41	10.11	n/a
7 - CO	hot oven	444,800	17.92	28.20	45.42*	1,198,900	3.06	7.51	10.36	n/a
* Max DSR stress was reached; n/a = test didn't run that far										

Besides differing in the rate at which G* decreased with increasing strain, the materials differed in their original stiffness, G_i*, and the rate of change of G_i* between the unaged and the PAV aged states as shown in Table 8. The stiffest material in the unaged state was Emulsion Residue 6, a latex modified rapid-setting emulsion. The stiffest material in the aged state was the Emulsion 3 residue, a rapid-setting unmodified emulsion. G* increased the most from the unaged to the aged state for the Emulsion 3 residue. It was followed by the Emulsion 2 residue, also a rapid-setting unmodified emulsion, and then by the Emulsion 6 residue. Residues for polymer modified Emulsions 1, 4, 5, and 7 increased in G* and exhibited aged behavior after the PAV aging, but not by as much as residues for Emulsions 2, 3, and 6. Also, for Emulsions 1, 4, and 5 the base binder increased in G* considerably more than the recovered residue did, possibly indicating that either the emulsification process or the residue recovery process reduced the susceptibility of these materials to the PAV aging process.

Based on the results of the strain sweep testing, emulsions 1, 2, 4, 5, and 7 would be expected to resist raveling due to their high strain tolerances. Emulsions 3 and 6, which had very stiff unaged residues, would be expected to resist flushing and also might be able to be opened to traffic earlier. However, these emulsions became more brittle with aging and could therefore exhibit raveling with age.

A comparison between the emulsion residues used at the three field tests and those recommended by the SPG criteria are shown in Table 9. In all three cases the materials used were higher temperature grades than the SPG recommended criteria, and in the case of Washington and Utah, lower temperature grades, as well.

Table 9. Recommended SPG Temperature Ranges (C)

Field Site	SPG Recommendation	Actual Material Used
Forks, WA	52-12	67-15
Arches NP, Utah	61-12	79-15
Frederick, CO	58-24	76-18

The proposed emulsion residue criteria shown in Table 10 are based on those originally proposed in previous research shown in Table 3, including equivalent testing and performance thresholds for parameters measured in the dynamic shear rheometer and bending beam rheometer for unaged high temperature and aged low temperature properties, respectively. Additional testing and performance thresholds were added based on strain sweep testing conducted as part of NCHRP 14-17 and other research (Hanz 2010) and the significantly different performance of Emulsion 3 and the Utah Arches emulsion. The thresholds provided for the DSR and BBR parameters are based on validation with Texas field test sections adjusted for climates in Utah and Colorado.

Table 10. Proposed Emulsion Residue Criteria

*This table presents only three SPG grades as an example, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3 and 6 °C increments for the high temperature and low temperature grades, respectively.	**Performance Grade**											
	SPG 61				**SPG 64**				**SPG 70**			
	-12	**-18**	**-24**	**-30**	**-12**	**-18**	**-24**	**-30**	**-12**	**-18**	**-24**	**-30**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<61				<64				<70			
Minimum Surface Pavement Design Temperature, °C	>-12	>-18	>-24	>-30	>-12	>-18	>-24	>-30	>-12	>-18	>-24	>-30
Original Binder												
Dynamic Shear, AASHTO TP5 $\frac{G^*}{Sin\,\delta}$, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	61				64				70			
Shear Strain Sweep % strain @ 0.8G_i*, Minimum: 25 Test Temperature @10 rad/s linear loading from 1-50% strain, 1 sec delay time with measurement of 20-30 increments, °C	25				25				25			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1)												
PAV Aging Temperature, °C	100				100				100			
Creep Stiffness, AASHTO TP1 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8s, °C	-12	-18	-24	-30	-12	-18	-24	-30	-12	-18	-24	-30
Shear Strain Sweep G_i*, Maximum: 2.5 MPa Test Temperature @ 10 rad/s linear loading at 1% strain and 1 sec delay time, °C	25				25				25			

3.6 Estimating Embedment in the Field

Embedment depth is usually determined during construction by pulling several chips out of the binder and visually estimating the amount of embedment. This practice is problematic even if chips have a very low flakiness index because it is difficult to assess quantitatively with any precision. Therefore, two methods based on the sand patch test were developed to estimate embedment depth: The constant volume method and the constant diameter method.

3.6.1 Constant Volume Method

Glass beads were spread out in a circle on top of chips embedded to 20 and 80 percent of the chip average least dimension. The diameter of the circle was compared with the theoretical diameter that should result based on weight to volume characteristics of the materials presented in Section 2.7.1. Results of this experiment are shown in Figure 23.

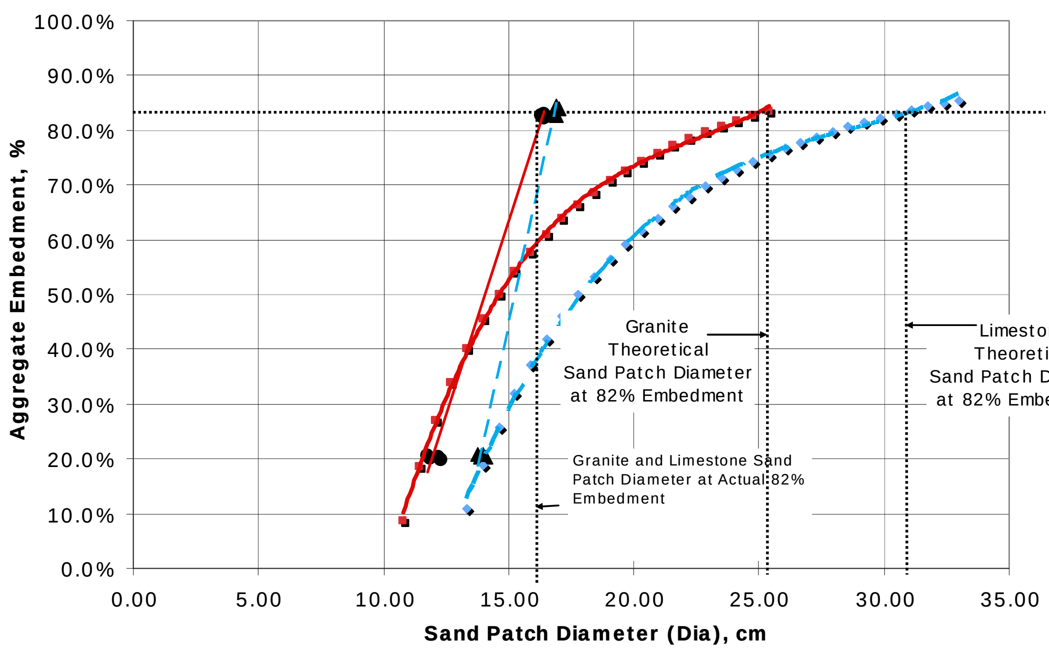

Figure 23. Comparison of Calculated to Measured Embedment Depth

At 20 percent embedment, the measured diameters are reasonably close to the theoretical diameters. However, at 82 percent embedment, the measured diameters are significantly less than the calculated values.

At 20 percent embedment, voids are deep, requiring many beads, and the procedure of spreading the beads from particle peak to peak contributes less to error than it does at higher embedment percentages when the amount of beads between the aggregate voids is relatively less. At 80 percent embedment many particles were fully covered by asphalt making it impossible to spread the glass beads between these aggregates.

Test results indicate that this procedure to be useful when chip seal particle embedments are closer to 50 percent or not submerged and chips have low flakiness index.

3.6.2 Constant Diameter Method

This method of estimating embedment depth used a mold of constant diameter in which glass beads were poured on top of the aggregate chips and the volume measured. Using weight to volume relationships for the materials the volume of glass beads required to fill the mold was calculated as a function of the aggregate embedment depth. A comparison between the calculated volume of glass beads required to fill the mold and the actual volume measured for the limestone and granite aggregates embedded to 20 and 82 percent are shown in Figure 24.

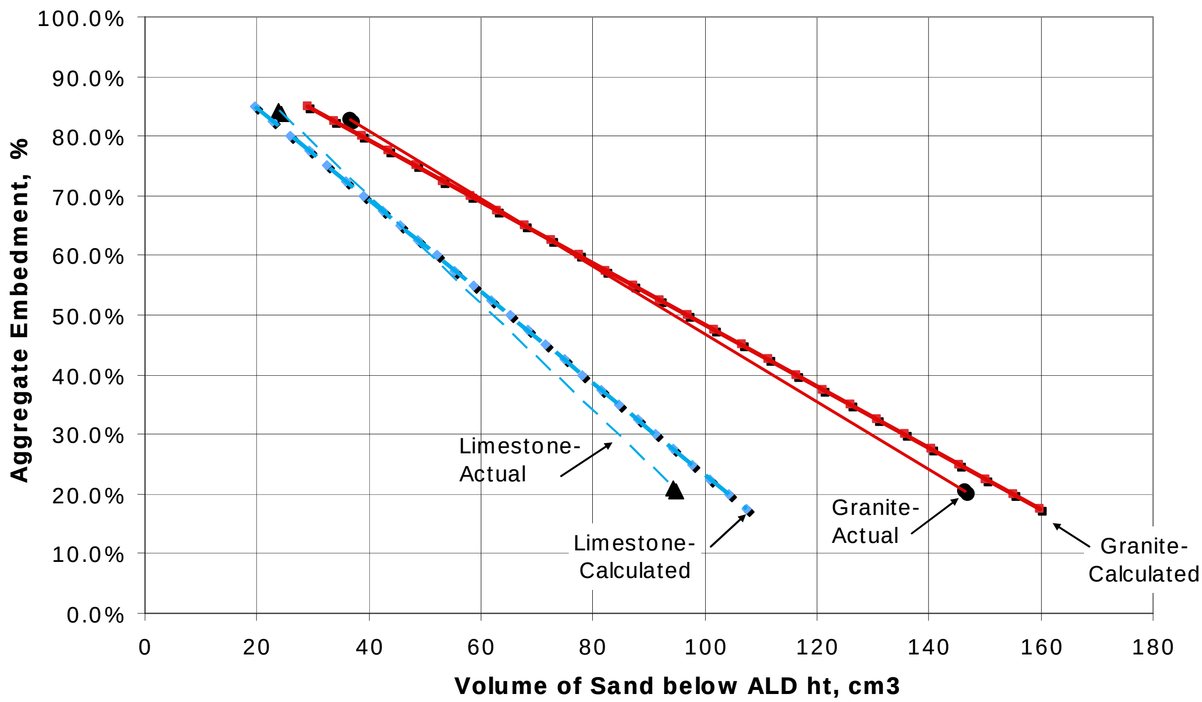

Figure 24. Embedment Depth From Constant Diameter Method

At 20 percent embedment, measured values deviate 10 percent from the theoretical values. At 82 percent embedment, the deviation is less at 5 percent from theoretical. Deviations were similar for the limestone and the granite at both levels of embedment.

CHAPTER 4 - Practical Application of the Research

Five new products were identified in this research to improve the design and construction of chip seals. This chapter describes these products and their application.

4.1 Modified Sweep Test and Critical Moisture Contents

This test provides a method to determine the timing for chip seal brooming and opening to uncontrolled traffic. The test determines the moisture content of the chip seal which corresponds to adhesion needed to retain chips under traffic loads. The moisture content of the chip seal can be monitored during construction to determine when the desired moisture content is reached. This moisture content ranged from about 15 to 25 percent of the total chip seal moisture. A description of the test method is provided in Attachment 2.

Results of the modified sweep test indicated that an aggregate in the saturated surface dry condition provides better adhesion than dry aggregates. This finding suggests that chip seal aggregates be moistened prior to construction.

4.2 Field Consistency Test

A Wagner cup viscometer was used in this research to measure the consistency of emulsions.

By conducting the test at a variety of temperatures in the laboratory, a temperature versus flow time relationship can be produced. Flow in the field could then be measured and compared with laboratory results to determine actual viscosity at the field temperature. The test method is described in Attachment 2.

4.3 Pavement Texture

A direct correlation between the sand patch test and the CT Meter indicates that pavement texture measurements can be made with the CT Meter and used as a substitute for the sand patch test results in the design process. This texture measurement can then be used to adjust emulsion spray rates during construction. Recommended adjustments are provided in Attachment 1.

4.4 Residue Recovery and Desirable Properties

The stirred can emulsion residue recovery (SCERR) method is recommended for obtaining emulsion residues for use in tests proposed for measuring physical properties. Proposed emulsion residue criteria are listed in Table 10.

The test is provided in Attachment 2.

4.5 Measuring Aggregate Embedment in the Field

Two methods for measuring aggregate embedment in the field have been developed. The constant volume method is a simple method, using a constant volume of glass beads spread on the pavement surface in a circle. By measuring the diameter of the circle, the embedment of the aggregate can be estimated. However, this procedure becomes less accurate at embedment over 50 percent. An alternative procedure, the constant diameter method, can be used to estimate embedment up to 80 percent. These test methods are provided in Attachment 2.

CHAPTER 5 - Conclusions and Recommendations

5.1 Conclusions

This report documents laboratory testing and field evaluation of several new procedures suitable for use by highway agencies, consultants, contractors and others involved in the design and construction of chip seals. These new procedures were developed to add objective measurement capability to some of the largely subjective judgments made during chip seal design and construction.

A new laboratory test that simulates the sweeping action of rotary brooms during chip seal construction was developed. This test simulates the shear forces applied by brooms and uncontrolled traffic to fresh chip seals, and can be used to predict the time required before brooms or uncontrolled traffic can be allowed on the surface of the chip seal. The test indicated the following:

- The moisture content at which 90 percent of the aggregate chips are retained during the sweep test is the "critical moisture content" corresponding to very high residue adhesive strength at which traffic could be allowed onto the chip seal sections.
- Significantly higher chip loss was measured for sweep test specimens fabricated with dry aggregates than with saturated surface dry aggregates.
- No significant differences in chip loss was measured either at 40 or 80 percent moisture loss between cationic and anionic emulsions used with either calcareous or siliceous aggregates.

The Wagner cup viscometer for measuring the consistency of paints was successfully adapted to measuring viscosity of emulsions. The test is inexpensive, field portable, repeatable, simple to operate, and can be correlated to laboratory tests.

An adjustment to the emulsion spray quantity should be made to account for pavement surface texture. This process is often done subjectively or measured using the sand patch test in other countries. Although the sand patch test can measure texture effectively CT Meter, and AIMS apparatus were found to be faster and provide very similar results.

Extensive testing was done to evaluate new methods of emulsion residue recovery. The methods included hot oven (with Nitrogen blanket), stirred can (with Nitrogen purge) and warm oven. Residues recovered using these methods were tested using the Superpave PG test methods and chemical analysis to determine which recovery technique mimicked the base asphalts closest and resulted in the least amount of water remaining in the samples. These tests indicated that the stirred can emulsion residue recovery (SCERR) method is rapid and provides a good simulation of the base asphalt material properties. Also, recovered emulsion residues were shown to be different from their base binders at high temperatures before PAV aging, but similar to the base binders at cold temperatures after PAV aging.

The residues obtained from the emulsions used in the three field test sites were characterized using the Superpave PG binder tests. The result of this work is a performance-based criteria for chip seal residues. Initially, this surface performance graded (SPG) criteria was calibrated using field test sections in Texas. However, results of this research indicated that adjustments to the original criteria should be made to accommodate other climates. Therefore, characterization of residues should be done by evaluating the complex shear modulus, G*, over a range of shear strains to evaluate strain resistance. These results could be used to predict when emulsion based chip seals will develop enough stiffness to be opened to traffic and resistance to raveling, both in newly constructed chip seals and after weathering and aging.

5.2 Recommendations

The findings of this project were based on a significant amount of field and laboratory measurement. However, additional studies would help improve these findings and the recommendations. Such studies may include the following:

1. Further sweep testing with other sources of aggregate and emulsion to verify the validity of test as a means of measuring chip adhesion.
2. Evaluation of grayscale photography and image analysis for quantifying macrotexture of pavement surfaces (Pidwerbesky et al., 2009) may provide a viable and relatively inexpensive alternative to the sand patch test and the CT meter measurements.
3. Monitoring the performance of the three test sites constructed as part of this research to provide additional validation for setting thresholds in the proposed SPG specification.

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