OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

DEVELOP DRAFT CHIP SEAL COVER AGGREGATE SPECIFICATION BASED ON AIMS ANGULARITY, SHAPE AND TEXTURE TEST RESULTS

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16. ABSTRACT

The objective of the study is to improve Oklahoma Department of Transportation (ODOT) chip seal design and performance through introducing new criteria for the selection of cover aggregate and binder. These criteria will be based upon the recent technological advances in the characterization of aggregate shape and texture as well as aggregate-binder compatibility. The study evaluates the shape and texture-related index properties, as well as durability, of commonly used cover aggregates in chip seal programs in Oklahoma. Additionally, it will provide a methodology for inclusion of these characteristics as a metric in future chip seal specifications. The study includes both laboratory testing and construction and performance evaluation of chip seal test sections. The study is ongoing and is quantifying how well the newly developed performance-based uniformity coefficient (PUC) correlate with chip seal performance in Oklahoma, and if it should be incorporated into state chip seal specifications. It has generated aggregate-binder compatibility data, based on the surface free energy (compatibility ratio) approach, for commonly used aggregates and asphalt emulsion binders in Oklahoma. Moreover, the chip seal construction practice followed by different ODOT Maintenance Divisions was documented and the best practice identified. This repository of information will be a useful resource for ODOT maintenance divisions.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

Develop Draft Chip Seal Cover Aggregate Specification Based on AIMS Angularity, Shape and Texture Test Results

Final Report

OTCREOS11.1-65

June 30, 2013

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EXECUTIVE SUMMARY

The study seeks to improve Oklahoma Department of Transportation (ODOT) chip seal design and performance through introducing new criteria for the selection of cover aggregate and binder. These criteria will be based upon the recent technological advances in the characterization of aggregate shape and texture as well as aggregate-binder compatibility. Specifically, the study includes evaluating aggregate index properties obtained from the Aggregate Imaging System (AIMS) and performance-based uniformity coefficients (PUC) in tweaking ODOT chip seal cover aggregate specifications. It also uses the surface free energy (compatibility ratio) approach in evaluating the aggregate-binder compatibility. Moreover, the chip seal construction practice followed by ODOT Maintenance Divisions has been documented and the best practice has been identified. The study includes both laboratory testing and construction and performance evaluation of chip seal test sections. Division THREE (Ada) has been actively involved in the construction of the chip seal test sections as well as performance monitoring.

This study has three objectives. The first objective is to evaluate the shape and texture-related index properties, as well as durability, of commonly used cover aggregates in chip seal programs in Oklahoma, and provide a methodology for inclusion of these characteristics as a metric in future chip seal specifications. The second objective is to quantify how well the newly developed performance-based uniformity coefficient (PUC) correlate with chip seal performance in Oklahoma, and if it should be incorporated into state chip seal specifications. The last objective is to generate aggregate-binder compatibility data, based on the surface free energy (compatibility ratio) approach, for commonly used aggregates and asphalt emulsion binders in Oklahoma, which will be a useful resource for ODOT maintenance divisions.

The expected major benefits of the research will be: (i) a more precise specification of the required characteristics of chip seal cover aggregate; (ii) the identification of combinations of chip seal binder and aggregate that are incompatible in each ODOT division; (iii) influence of fog seal on chip seal performance; (iv) documentation of construction practices in each maintenance division and identification of best construction practice. This should eliminate or reduce premature failures due to incompatible binder-aggregate combinations. It should also accrue benefits by increasing chip seal average service life by quantifying the aggregate characteristics that promote proper adhesion as determined by field performance evaluation and laboratory aggregate analysis. Achieving these benefits will provide a further benefit of releasing scarce maintenance funds to be used as programmed by reducing the amount of unplanned reactive maintenance that occurs on a state-wide basis. This comes from increasing the probability of chip seal success by eliminating those factors that can be controlled in the design process.

The research team has implemented a program of real-time feedback to ODOT divisions as developments have been made. This was done through presentations and workshops for rapid implementation. Dr. Kim who introduced the PUC-based gradation concept in North Carolina conducted a workshop at ODOT in May 2013 and delivered a presentation at the University of Oklahoma as a technology transfer event for this project. The major products of this project will be recommendations for revising ODOT chip seal cover aggregate specifications and fine-tuning division-specific chip seal design procedures. Once the research findings are reviewed and approved by ODOT, a seminar will be organized on Oklahoma implementing the revised specification and its ramification on current division maintenance practices. The target audience is ODOT maintenance engineers; however, it will be made available to all interested ODOT employees. The seminar could also be used as an outreach opportunity by inviting pavement managers from cities and counties as well. Thus, the results of the research will be made immediately available in a form that permits rapid implementation. The project is ongoing through November 2013. It is on schedule, on budget, and will complete as planned.

1.0 INTRODUCTION

Chip seals are widely used for preventive maintenance of pavements. While there has been extensive research on the various parts of the surface treatment, there is little research on how to combine the various materials and methods. Hence, chip sealing continues to be considered an art rather than a rationally engineered composite system. While some systematic methodology exists for design and installation of chip seals, the methods are quite dated [1,2]. In most cases, the Oklahoma Department of Transportation (ODOT) maintenance engineers use empirical design based on trial and error. However, additional technical information is needed that defines aggregate gradation and selection based on performance characteristics and binder compatibility. This could permit ODOT engineers to specify appropriate chip seal gradations and enhance chip seal specifications and design methods.

1.1 BACKGROUND

Chip seals are one of the major pavement preservation tools used to extend the service lives of asphalt pavements across the nation [3]. Based on the relatively low costs of chip seals, they are used regularly by most ODOT maintenance divisions as a pavement preservation technique. A traditional chip seal consists of a single layer of asphalt emulsion binder (henceforth called "*binder*") covered with a single layer of aggregate, as illustrated in Figure 1.1. As a result of its simplicity, the quality of its two components (cover aggregate and binder) becomes critical.

Figure 1.1 Chip Seal Schematic [3]

The primary purpose of a chip seal is to seal a pavement against water intrusion. Additionally, chip sealing plays an important safety role by providing enhanced macrotexture, which increases drainage, and enhanced microtexture, which provides surface friction [3,4].

A recent OkTC study by the research team (OTCREOS7.1-16, “Quantifying the Costs and Benefits of Pavement Retexturing as a Pavement Preservation Tool,” [4]) demonstrated that chips seals will fail in two unrelated timeframes. The first is a short-term failure caused by the loss of cover aggregate within the first year of service. This type of failure is normally related to incompatibility of the aggregate and the binder, excessive fines in the aggregate, or some weather event or deficiency in the construction process such as inadequate rolling or placing the chip seal late in the season where ambient air temperatures are below specified minimums [3,4,5]. The second type of failure is a long-term failure, which occurs after the first year of service but before the end of the expected service life [4]. The OkTC study demonstrated that this type of failure, which manifests as aggregate loss or bleeding, will be either due to a loss of surface macrotexture or a loss of skid resistance. In both failure modes, the quality of the cover aggregate is an important issue.

In a recent ODOT SPR project (FHWA-OK-10-PS01), the research team identified that the test method using the aggregate imaging system (AIMS) holds potential to measure cover aggregate angularity, which is a predictor of adhesion between the binder and the aggregate [6]. The project also discovered a potential correlation between the gradient angularity measured by AIMS [7-9] and the skid number as measured with the locked wheel skid test. Moreover, the project found promising relationships between the *performance-based uniformity coefficient* (PUC), a North Carolina DOT chip seal metric [10], and the radial angularity, sphericity, and texture index measured by AIMS. Thus, these issues will be investigated for ODOT to determine the potential for early chip seal failure which result in costly corrective maintenance.

Compatibility between aggregates and binders is important to ensure that adequate adhesion is achieved [3]. Most of the research in this field has focused on material science aspects of either the asphalt binders or the aggregates, but little has been written about combinations of binder and aggregate. A Texas DOT (TxDOT) study found that electrostatic incompatibility of aggregates and binders (i.e. using an anionic binder with an aggregate that is also anionic) was a major cause of early failure in emulsion chip seals [11]. Additionally, the study found that lack of adequate angularity and hardness caused Texas chip seals to fail to achieve their design lives. The results were used to revise TxDOT chip seal specifications [11] and develop a manual for statewide implementation [12].

Successful chip seal application is also extremely dependent on the methods employed in the field during construction. Much of the previous materials research relies on assumption that the material will be properly installed in the field [13]. Additionally, the research that has looked at actual project performance is focused on the forensic evaluation of failures. Thus, ODOT and its paving contractors have a body of reference knowledge that details what should not be done when installing chip seals with very little guidance on the subject of what should be done to successfully apply an emulsion chip seal. This fact was confirmed at the national level in an NCHRP study of chip seal best practices [3]. This project seeks to extend the previous research and add to the body-of-knowledge in this area specifically for Oklahoma climate, traffic conditions, and locally available materials. Thus, *the focus will be on how to replicate success* with Oklahoma materials, means, and methods *rather than how to avoid failure*.

1.2 OBJECTIVES

This study has three objectives:

1. The proposed study will evaluate the shape and texture-related index properties, as well as durability, of commonly used cover aggregates in chip seal programs in Oklahoma, and provide a methodology for inclusion as a metric in future chip seal specifications.

2. It will quantify how well the newly developed performance-based uniformity coefficient (PUC) correlate with chip seal performance in Oklahoma, and if it should be incorporated into state chip seal specifications.
3. It will generate aggregate-binder compatibility data, based on the surface free energy (compatibility ratio) approach, for commonly used aggregates and asphalt emulsion binders in Oklahoma, which will be a useful resource for ODOT maintenance divisions.

The major benefits of the proposed research will be: (i) a more precise specification of the required characteristics of chip seal cover aggregate; (ii) the identification of combinations of chip seal binder and aggregate that are incompatible in each ODOT division; (iii) influence of fog seal on chip seal performance; (iv) documentation of construction practices in each maintenance division and identification of best construction practice. This should eliminate or reduce premature failures due to incompatible binder/aggregate combinations. It should also accrue benefits by increasing chip seal average service life by quantifying the aggregate characteristics that promote proper adhesion as determined by field performance evaluation and laboratory aggregate analysis. Achieving these benefits will provide a further benefit of releasing scarce maintenance funds to be used as programmed by reducing the amount of unplanned reactive maintenance that occurs on a state-wide basis. This comes from increasing the probability of chip seal success by eliminating those factors that can be controlled in the design process.

1.3 SCOPE

The project is on schedule, on budget, and will complete in November 2013 as planned. The following tasks constitute the scope of this study:

1. Literature Review
2. Selection of Cover Aggregate and Binder Sources and Collection of Samples
3. Laboratory Testing of Aggregates
4. Laboratory Evaluation of Aggregate-Binder Compatibility
5. Evaluation of Performance-Based Uniformity Coefficient (PUC)

6. Field Testing for Performance Evaluation of Chip Seals
7. Construction of New Chip Seal Test Sections
8. Constructability Review of ODOT Division Chip Seal Practices
9. Draft Cover Aggregate Specifications

1.4 TECHNOLOGY TRANSFER

The research team has implemented a program of real-time feedback to ODOT divisions as developments have been made. This was done through presentations and workshops for rapid implementation. Dr. Kim [10] who introduced the PUC-based gradation concept in North Carolina conducted a workshop at ODOT in May 2013 and delivered a presentation at the University of Oklahoma as a tech transfer for this project. The major products of this project will be recommendations for revising ODOT chip seal cover aggregate specifications and fine-tuning division-specific chip seal design procedures. Once the research findings are reviewed and approved by ODOT, a seminar will be organized on Oklahoma implementing the revised specification and its ramification on current division maintenance practices. The target audience is ODOT maintenance engineers; however, it will be made available to all interested ODOT employees. The seminar could also be used as an outreach opportunity by inviting pavement managers from cities and counties as well. Thus, the results of the research will be made immediately available in a form that permits rapid implementation.

1.5 REPORT ORGANIZATION

The body of the report is organized in three major sections, following the three primary areas in which the project is organized. Those sections are as follows:

- The history and science of chip seal design and performance: covers the information necessary to understand the laboratory and field test results.
- Laboratory and field test methodology and protocols: describes the procedures used in the research.
- Laboratory and field test results: provides results and analysis of the laboratory research to date.

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2.0 CHIP SEAL DESIGN

Chip seals are applied to existing asphalt pavements to seal surface cracks against air and water intrusion. They furnish other benefits such as enhancing skid values (microtexture) to reduce wet weather crashes, providing a uniform looking surface and improving the visibility of traffic lane striping. Chip seals contribute no structural capacity to the pavement since they are effectively one rock thick. However, chip seals do enhance pavement performance through the extension of pavement service life, qualifying them as a pavement preservation or preventive maintenance application [16].

Chip seal applications, illustrated in Figure 2.1, are appropriate for low- to mid- volume roads to mitigate weathering and raveling for pavements with no significant structural distress, only minor surface distresses. Chip seals cannot be used to improve the pavement ride quality [3]. They should not be applied to correct badly cracked or weathered pavement surfaces where a rehabilitation or overlay activity is needed. In some cases, chip seals may be used on such poor surfaces as a stopgap measure until the corrective action can be taken. Flushed or bleeding surfaces should be considered carefully before chip sealing because flushing is generally reflected through the new seal if the aggregate and binder rates are not designed accordingly [3]. One of the major difficulties in chip seal design is the non-uniformity of the pavement [3]. Most chip seal candidate sections will have preexisting patching, flushing and raveling observed at different locations of the pavement. All of these conditions require binder application rate to be varied as the surface conditions change. This is typically performed by an experienced field crew changing the rates as needed in the field [3].

Aggregates used in chip seal are expected to transfer the load to the underlying surface as well as protect the new seal from traffic abrasion [3]. Selection of chip seal cover aggregates is directly related to the local availability of aggregates. Whatever the selected aggregate is, caution should be exercised with the aggregate size distribution. Gradation of the aggregate is should be as uniform as possible [3]. The rule of thumb for a single-size chip seal cover aggregate gradation correlates roughly to 85% by weight passing the desired sieve size. Single size cover stone is thought to furnish a better interlocking of particles and better aggregate retention on the surface.

Figure 2.1 Chip Seal Installation

Also, the embedment depth will be more uniform across the road's surface. The shape of cover aggregate is also crucial to obtain a good interlocking pattern of aggregates. Angular aggregate shapes such as cubical or pyramidal surfaces have demonstrated satisfactory service [3]. Rounded, elongated and flat gravels should be avoided. Flakiness index defined as the ratio of smallest size of aggregate to the average aggregate size can indicate the suitability of the aggregate. In practice such undesired particle shapes are avoided by specifying a maximum percentage of aggregates having a 0.6 flakiness index [15].

2.1 HISTORY OF CHIP SEAL DESIGN

The early practitioners of surface treatments like chip seals appear to have used a purely empirical approach to their design. Sealing a pavement was considered then, as it is now in many circles, an art. Chip seal design involves the calculation of correct amounts of a bituminous binder and a cover aggregate to be applied over a unit area of the pavement. The two major components of the chip seal design process are the types and amounts of binder and aggregate.

2.1.1 Hanson Method (New Zealand)

The first recorded effort for developing a chip seal design procedure appears to be made by Hanson [17]. His design method was developed primarily for liquid asphalt, specifically cutback asphalt, and was based on the average least dimension (ALD) of the cover aggregate. Hanson calculated ALD by manually calipering a representative aggregate sample to obtain the smallest value for ALD that represents the rolled cover aggregate layer. He observed that when cover aggregate is dropped from a chip spreader on to a bituminous binder, the voids between aggregate particles is approximately 50 percent. He theorized that when it is rolled, this value is reduced to 30 percent and it further reduces to 20 percent when the cover aggregate is compacted by traffic. Hanson's design method involved the calculation of bituminous binder and aggregate spread rates to be applied to fill a certain percentage of the voids between aggregate particles. Hanson specified the percentage of the void space to be filled by residual binder to be between 60 and 75 percent depending on the type of aggregate and traffic level.

2.1.2 Kearby Method (Texas)

One of the first efforts to design chip seal material application rates in the United States was made by Jerome P. Kearby, then Senior Resident Engineer at the Texas Highway Department [1]. He developed a method to determine the amounts and types of asphalt and aggregate rates for one-course surface treatments and chip seals. He developed the nomograph, shown in Figure 2.2, which provided an asphalt cement application rate in gallons per square yard for the input data of average mat thickness, percent aggregate embedded and percent voids in aggregate. The percent voids in aggregate correspond to the percent voids in a bulk loose volume of aggregate and not to the aggregate spread on a pavement. If liquid asphalt were to be used, he recommended that the rate of bituminous material application should be increased such that the residual asphalt content is equal to the asphalt content given by the design nomograph. In order to determine the aggregate spread rate for aggregates containing flat and elongated particles, Kearby recommended the laboratory board test. In this test, the aggregate is manually spread over a one square-yard area and then weighed to determine the weight per unit area design spread rate.

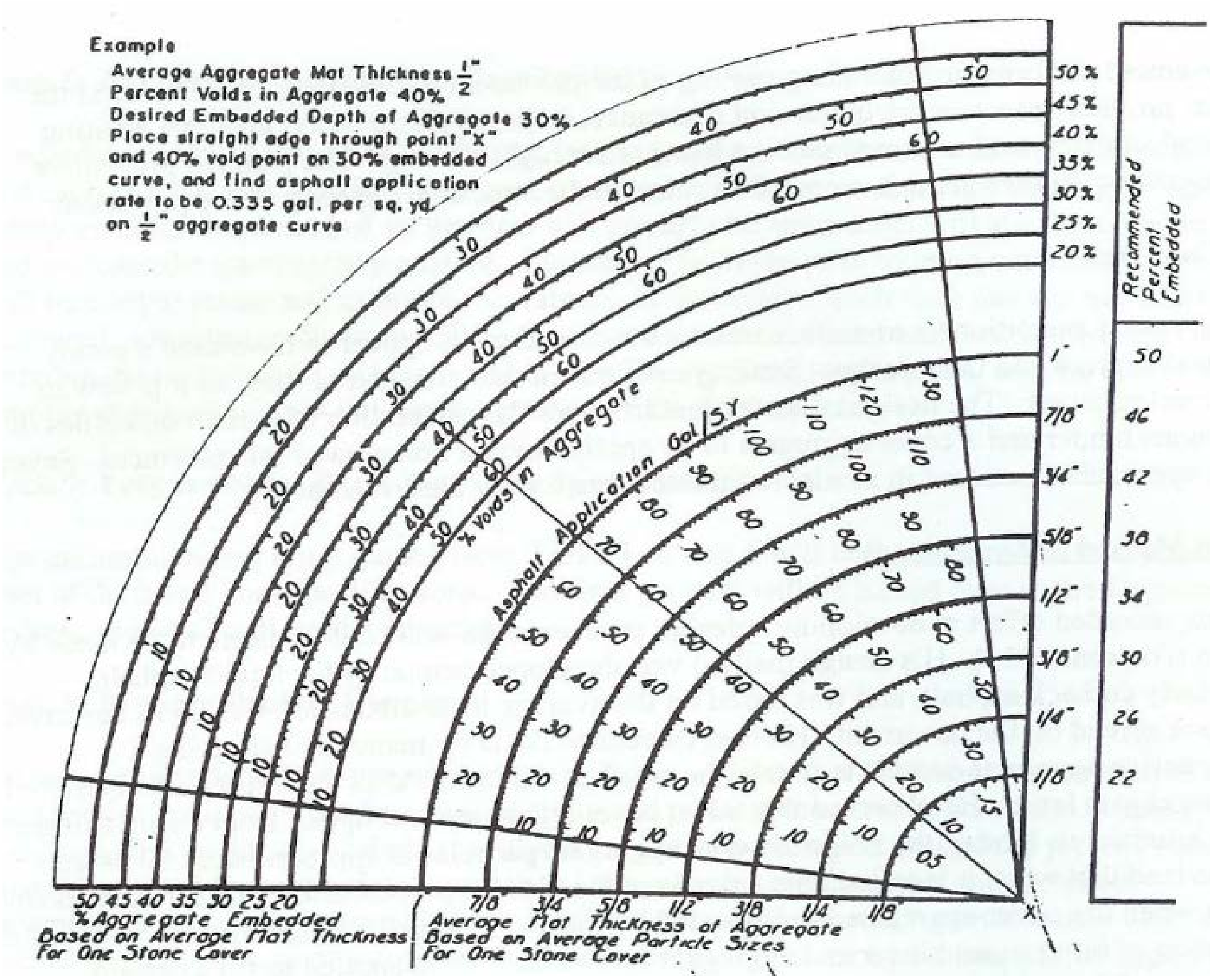

Figure 2.2 Kearby Nomograph [1]

In addition to the nomograph, Kearby recommended the use of a uniformly graded aggregate by outlining eight grades of aggregate based on gradation and associated average spread ratios. Each gradation was based on three sieve sizes. He also recommended that combined flat and elongated particle content should not exceed ten percent of any aggregate gradation requirement. Flat particles were defined as those with a thickness less than half the average width of particle, and elongated particles were defined as those with length greater than twice the other minimum dimension.

Kearby stated that "computations alone cannot produce satisfactory results and that certain existing field conditions require visual inspection and the use of judgment in the choice of quantities of asphalt and aggregate." He suggested that when surface treatments are applied over existing hard-paved surfaces or tightly bonded hard base courses, the percentage of embedment should be increased for hard aggregates and reduced for soft aggregates. He also mentioned that some allowance should be made for traffic. It was suggested that for highways with high counts of heavy traffic, the percent embedment should be reduced along with using larger-sized aggregates. For those with low traffic volumes, the embedment should be increased with the use of medium-sized aggregates. However, Kearby did not recommend any specific numerical corrections.

Kearby also elaborated on the following construction aspects of surface treatments and chip seals based on his experience at the Texas Highway Department [1]:

- Chip seals had been used satisfactorily on both heavy-traffic primary highways and low-traffic farm roads, with the degree of success largely depending on the structural strength of the pavement rather than the surface treatment itself.
- Thickness of the surface treatment range from ¼ in. to 1 in. with the higher thickness being preferred. However, lighter treatments have, in general, proven satisfactory when the pavement has adequate structural capacity and drainage.
- In general, most specification requirements for aggregate gradation are very broad, resulting in considerable variations in particle shape and size as well as percent voids taken together.
- It is better to err on the side of a slight deficiency of asphalt to avoid a fat, slick surface.
- Considerable excess of aggregate is often more detrimental than a slight shortage.

- Aggregate particles passing the #10 sieve acts as filler, thereby raising the level of asphalt appreciably and cannot be counted on as cover material for the riding surface.
- Suitable conditions for applying surface treatments are controlled by factors such as ambient, aggregate, and surface temperatures as well as general weather and surface conditions.
- Rolling with both flat wheel and pneumatic rollers is virtually essential.

During the same period, two researchers from the Texas Highway Department [18] published a paper on their aggregate retention studies on chip seals. They conducted tests to determine the aggregate retention under a variety of conditions including source of asphalt cement, penetration grade of asphalt, number of roller passes, binder type (AC vs. cutback), aggregate gradation and binder application temperature. All their tests were conducted under the same conditions with only the test parameter being variable. The authors concluded that aggregate retention was not significantly different in asphalt cements picked from five different sources commonly used by the Texas Highway Department at the time. A commentary made in the early 1950's by the authors on the subject of asphalt quality strikes a familiar theme commonly used by practitioners even today.

"There has long been a perhaps natural but unjustified tendency to attribute a large variety of job failures to the *quality* or source of the asphalt without adequate investigation of the other factors involved. Ironically, this was as true back in the days of almost universal use of Trinidad natural asphalt ... now often referred to as standards of *quality* in demonstrating the inferiority of some *modern* product, as it is today" [18]. This study also highlighted the interrelationship between the binder type, binder grade and the temperature of the pavement during the asphalt shot and during rolling. In one set of laboratory experiments, the aggregate loss from an OA-230 penetration grade asphalt cement (close to an AC-2.5) reduced from 44 percent to 11 percent when the number of roller passes increased from one to three. In the same study, the effect of aggregate gradation on the performance of chip seals was investigated. An OA-135 asphalt cement (close to an AC-5) applied at a rate of 0.32 gallons per square yard was used under different aggregate treatments and the corresponding aggregate loss values are reproduced in Table 2.1. These results highlight the authors' contention that increased #10-sized aggregate content pose aggregate retention problems in chip seals. In addition, these researchers showed that a smaller portion of aggregate smaller than ¼ in. size will result in better performance of the chip seal.

Table 2.1 Effect of Aggregate Gradation/Aggregate Treatment on Retention [18]

Test Condition for Aggregate	Aggregate Loss as a % of Original
12.6% passing #10 sieve	72.0
6.7% passing #10 sieve	57.4
0% passing #10 sieve	30.5
12.6% passing #10 sieve & rock pre-heated to 250ºF	17.7
12.6% passing #10 sieve & rock precoated with MC-1	33.6

In 1953, more research findings on aggregate retention were published by Benson and Galloway of Texas Engineering Experiment Station [18]. The intent of this research was to study the effects of field factors that usually affect the surface treatments as an extension of the Kearby design method. A comprehensive laboratory test program was conducted to study a number of factors including the material application rates, aggregate gradation, moisture and dust in the aggregate as well as the elapsed time between the application of binder and aggregate for different binder types. Some of the notable conclusions made by Benson and Galloway are listed below [18].

- A ten percent upward correction to aggregate quantity is needed, calculated from the Board Test recommended by Kearby, to account for spreading inaccuracy.
- For average mat thickness less than 0.5 in., a higher percentage embedment is needed to hold the smaller aggregate particles together. As a result, the authors proposed an alteration to the curve proposed by Kearby.
- When asphalt cement is used as the binder, aggregate should be spread as soon as possible after the asphalt is sprayed.
- Harder asphalt cements hold cover stone more tightly, but initial retention is more difficult to obtain

- Cover stone with a limited variation in grading will give the highest retention.
- Wet aggregates give poor retention with asphalt cement.
- Dust in aggregate results in poor retention. However, wetting the dry aggregate before application and by allowing it to dry before rolling reduced the negative effect from dust.
- Aggregate retention increased with increased quantity of asphalt.
- When a 24-hour curing period was allowed, the retention of wet stone by RS-2 emulsion was slightly greater than that for dry stone.
- The retention of wet dusty stone was slightly less than for dry stone.

During the 1940's and 1950's, research work indicated that sufficient curing time is needed for chip seals constructed using liquid asphalt. The recommendation from researchers was that at least 24 hours of curing is required before opening the road for traffic. J. R. Harris [19] of the Texas Highway Department proposed, based on his experience, that precoated aggregate should be used to increase the performance of the chip seal as well as to expedite the construction process. Harris' contention was that precoated aggregates considerably shorten the required curing time by eliminating the problems associated with aggregate dust and moisture, and that traffic can be allowed to use the roadway within one hour after a chip seal is placed with precoated aggregate. Also, the report said that this would allow using chip seals on high traffic roadways where shorter lane closure times due to the use of precoated aggregates would make the traffic control problem a lot more manageable.

2.1.3 Modified Kearby Method (Texas)

In 1974, Epps et al. proposed a further change to the design curve developed by Kearby for use in chip seals using synthetic aggregates [20]. Due to high porosity in synthetic aggregates, a curve showing approximately 30 percent more embedment than the Benson-Galloway curve was proposed. The rationale for this increase was that high friction lightweight aggregate may overturn and subsequently ravel under the action of traffic.

In a separate research effort, Epps et al. [20] continued the work done in Texas by Kearby [1] and Galloway and Harper [21] by undertaking a research program to conduct a field validation of Kearby's design method. Actual pre-construction and post-construction data of 80 different projects were gathered and analyzed for this purpose. It was observed that Kearby design method predicted smaller asphalt rates than what was actually used in Texas practice and the study proposed two changes to the design procedures. The first one was a correction to the asphalt application rates based on level of traffic and existing pavement condition. The second change was the justification of the shift of the original design curve proposed by the Kearby and Benson-Galloway methods, as appropriate for lightweight aggregates.

Equation 1 was used to calculate the asphalt application rate (in gallons per square yard), which included two correction factors determined for traffic level and existing surface condition [20].

$$A = 5.61\frac{E}{d}\left(1 - \frac{W}{62.6G}\right)T + V \qquad \text{Equation 1}$$

Where *W* and *G* are the dry unit-weight and dry bulk specific gravity of the aggregate, respectively, and *d* is the mat thickness that can be measured in the laboratory. Also, *E* is the depth of embedment and *T* and *V* are traffic correction factor and surface correction factor, respectively, for the asphalt application rate (*A*).

The proposed correction factors were projected from the actual mat thickness-embedment combinations that were proven to work well in the field. Table 2.2 and Table 2.3 show the asphalt application rate correction factors corresponding to traffic level and existing surface condition, respectively. Epps et al. [15] also suggested that the asphalt rate should be varied both longitudinally and transversely as reflected by the pavement surface condition. Since then, practitioners and researchers have labeled this design approach the "Modified Kearby Method."

Table 2.2 Asphalt Application Rate Correction Factor for Traffic [15]

	Traffic Level – Vehicles Per Day Per Lane				
	Over 1000	500 to 1000	250 to 500	100 to 250	Under 100
Traffic Factor (*T*)	1.00	1.05	1.10	1.15	1.20

Table 2.3 Asphalt Application Rate Existing Surface Correction Factors [15]

Description of Existing Surface	**Asphalt Application Rate Correction (Gallons per Square Yard)**
Flushed asphalt surface	- 0.06
Smooth, nonporous surface	- 0.03
Slightly porous, slightly oxidized surface	0.00
Slightly pocked, porous, oxidized surface	+ 0.03
Badly pocked, porous, oxidized surface	+ 0.06

2.2 CURRENT DEVELOPMENTS IN CHIP SEAL DESIGN

A significant US development in chip seal research was proposed by Lee and Kim [10] resulting from a project funded by the North Carolina DOT. Essentially, the research extended the study conducted in 1962 by Norman McLeod that developed failure criteria for chip seals based upon bleeding/flushing and aggregate loss distresses [2]. Lee and Kim showed that improved chip seal performance can be achieved using the *performance-based uniformity coefficient* (PUC) concept to select cover aggregate gradation. In this ODOT study, the researchers have altered the commonly used chip seal aggregate gradations consistent with the PUC methodology to determine if any correlation exists between PUC-gradations and field performance of chip seal projects in Oklahoma.

Aggregate gradation is one of the major factors affecting chip seal performance [2,10]. McLeod postulated that “the largest size for a chip seal aggregate should be no more than twice the smallest size” [2]. Thus, the ideal chip seal aggregate gradation would contain only particles of a single size. Figure 2.3 is a schematic of the McLeod failure criteria [2]. According to McLeod, the correct binder application rate should be such that each cover aggregate embeds in the binder to a certain percentage of the chip seal depth [2]. For a pavement subjected to moderate traffic (1,000 to 2,000 ADT), the optimal binder should fill about 70% of the voids between the chip seal aggregate particles to achieve good performance [10]. The aggregate particle that is the same size as the embedment depth (0.7xM) represents failure due to flushing/bleeding. Whereas, the particle that is 1.4 times the median aggregate size (1.4xM) represents failure due to aggregate loss because of inadequate embedment. “M” is the median particle size which represents the desired single size aggregate that is expected to mitigate both flushing/bleeding and aggregate loss. However, obtaining single-size aggregate is not economically feasible. Therefore, Lee and Kim [10] advocate allowing a pragmatic tolerance and posit that cover aggregate should fall within the *range* shown in Figure 2.3 (0.7xM < desired aggregate gradation < 1.4xM) to maximize chip seal performance. They also suggested that the tolerance be developed in a way that enhances chip seal performance based on the principles of pavement preservation, which state that a higher initial cost can be justified by a reduced life cycle cost [10,16].

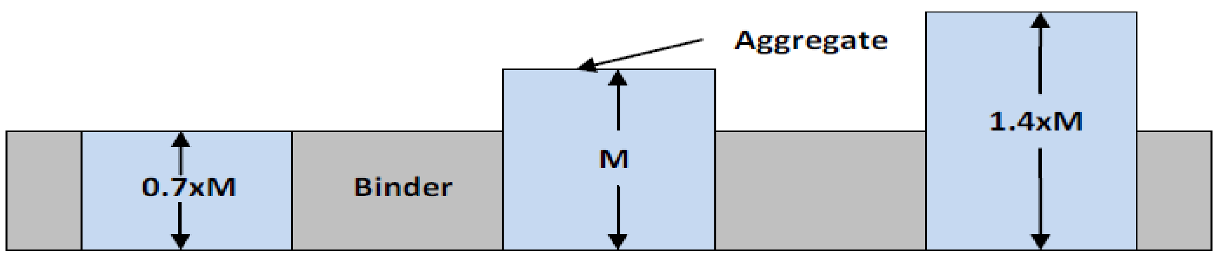

Figure 2.3 Schematic of McLeod’s Failure Criteria [2]

Lee and Kim [10] proposed a coefficient of uniformity, called the *performance-based uniformity coefficient* (PUC). They describe the process used to compute the PUC for a given chip seal aggregate sample. The PUC can be used in a chip seal aggregate specification to quantify the allowable tolerance for particle sizes outside the bounds fixed by the McLeod failure criteria for bleeding and aggregate loss. According to Kim and Lee, the closer the PUC is to zero, the more uniformly graded the aggregate and the better the chip seal performance.

PUC is calculated as shown in Equation 2 [10].

$$PUC = \frac{P_{EM}}{P_{2EM}} \qquad \text{Equation 2}$$

Where: P_{EM} is indicative of bleeding potential and equals percent passing at a given embedment depth and P_{2EM} is indicative of aggregate loss and equals percent passing at twice the given embedment depth, as illustrated in Figure 2.4.

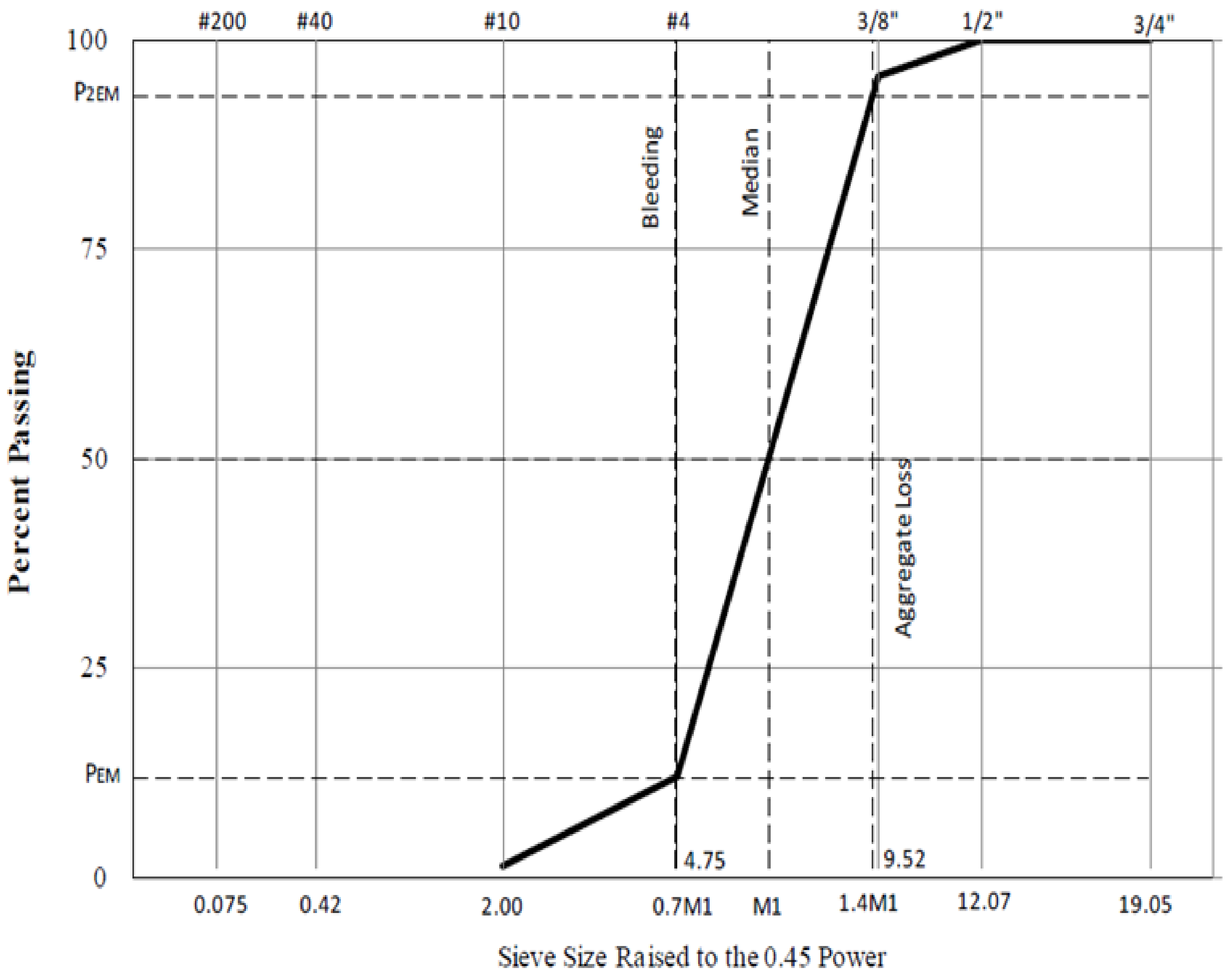

Figure 2.4 Gradation Range to Maximize Performance (after [10])

3.0 CHIP SEAL PERFORMANCE

Aggregate characteristics, such as durability, shape, texture and binder compatibility, will affect chip seal performance [2,10]. Therefore, various laboratory and field tests are conducted to ensure proper chip seal design. Typical laboratory testing includes aggregate durability and abrasion resistance tests. Recently, the aggregate imaging system (AIMS) has been used to determine aggregate shape and texture properties. Additionally, aggregate-binder compatibility tests are conducted. Aggregate is responsible for surface friction in the field. Therefore, field testing includes measurement of microtexture and macrotexture. Thus, these test methodologies will be implemented in this ODOT study to characterize cover aggregates and chip seals used in Oklahoma.

3.1 LABORATORY TESTS FOR COVER AGGREGATE

Laboratory tests are used to characterize cover aggregate for the purposing of enhancing chip seal performance. Los Angeles Abrasion and Micro-Deval tests assess aggregate durability and resistance to abrasion. AIMS determines aggregate shape and texture. Sessile Drop and Universal Sorption Device evaluate aggregate-binder compatibility. Analyzing the data from the laboratory tests can provide insight about the potential for early chip seal failures.

3.1.1 Los Angeles Abrasion & Micro-Deval Tests

NCHRP Synthesis 342 found that one of the major causes of chip seal failure related to aggregate was excessive fines [3]. The fine content in chip seal aggregate is typically measured at the aggregate quarry. Each time the aggregate is moved, the gradation changes and the fines content increases. Therefore, the gradation may change significantly between the quarry and the aggregates' final destination on the road. The amount of degradation is a function of the aggregate's abrasion and impact resistance. The Los Angeles (LA) Abrasion test and the Micro-Deval test provide information about aggregate abrasion and impact resistance. It is worth noting that ODOT only specifies the LA Abrasion, not Micro-Deval, for cover aggregates.

The LA Abrasion and Impact Test (AASHTO T 96) is the most widely used method for measuring aggregate resistance for abrasion and aggregate toughness [22]. It simulates degradation during transport, mixing, and compaction and measures aggregate resistance to the degradation. The methodology involves obtaining 5000 ± 5 g of an aggregate blend, which is placed into a steel cylinder drum with six to twelve 46.8 mm steel spheres, depending on the gradation used for the blend. The aggregates and steel spheres are then rotated in the drum at 30 to 33 rpm until the total rotations reach 500. The weight loss is measured as material passing the #12 sieve, and the percent weight loss is calculated using Equation 3.

$$Percent\ Loss = \frac{Weight\ Before - Weight\ After}{Weight\ Before} \qquad \text{Equation 3}$$

The Micro-Deval test was developed in the 1870s in France to evaluate road aggregate, and it was initially adopted by ASTM in 1908 [23]. The Micro-Deval test is standardized in AASHTO T 327 "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus". The Micro-Deval test simulates aggregate resistance to abrasion and weathering. Unlike the dry conditions used in LA Abrasion method, an aggregate blend sample weighing 1500 ± 5 g is soaked in 2000 ± 50 mL of water for a minimum of one hour. The sample is then placed in a steel cylinder with 5000 ± 5 g of steel ball bearings, much smaller in size than the spheres used in the LA Abrasion test. This mixture of water, aggregate, and ball bearings are rotated for 105 minutes at 100 ± 5 rpm. After the abrasion process, the aggregates are washed, and the weight loss is measured as material passing the #16 sieve. It can also be calculated using Equation 3 to determine the percent weight loss.

Research has shown that there is no correlation between Micro-Deval and the LA abrasion test. According to AASHTO T 96, the LA Abrasion test is a measure of aggregate degradation due to abrasion, impact, and grinding. However, other studies indicate that LA Abrasion primarily measures an aggregate's resistance to mechanical breakdown rather than abrasion due to wear [24,25]. The wet conditions in the Micro-Deval test are thought to better simulate the field condition of aggregates and resistance to abrasion than the dry state of the LA Abrasion test [24]. Two National Center for Asphalt Technology (NCAT) studies reported that Micro-Deval did not correlate with other abrasion tests, including the LA abrasion test [22,26].

3.1.2 Aggregate Imaging System (AIMS)

The importance of cover aggregate shape and texture has been recognized even by the early pioneers of chip seal designs [2,15,20]. Technological advances in imaging tools now make it possible to accurately quantify aggregate shape and texture. One of the most appropriate technologies in this regard is the Aggregate Imaging System (AIMS), available at the OU Binders Laboratory, shown in Figure 3.1. The Aggregate Imaging System (AIMS) captures aggregate characteristics in terms of shape, angularity, and surface texture through image processing and analysis techniques. Currently, there are no approved AASHTO test methods for conducting AIMS testing; only provisional standards [27].

The shape and texture of the chip seal aggregate furnishes two important physical characteristics related to chip seal performance. First, the angularity and sphericity of each particle impact the quality of the bond formed between the aggregate and the binder. A very angular stone has more surface area over which to develop the bond than a smooth stone. The sphericity relates to the ease with which the stone can be seated during construction. During rolling, the individual particles are reoriented to their least dimension and embedded in the binder [18]. If proper embedment is achieved, the probability of premature loss of aggregate is minimized. In addition to orientation of the embedded chip being important, cubical aggregate shapes are preferred because traffic does not have a significant effect on the final orientation of aggregate [28]. Cubical materials tend to lock together and provide better long-term retention and stability.

AIMS equipment consists of a computer automated unit which includes an aggregate measurement tray with marked grid points at specified distances along x and y axes (Figure 3.1). The system contains a camera unit, which has an optem zoom 160 video microscope.

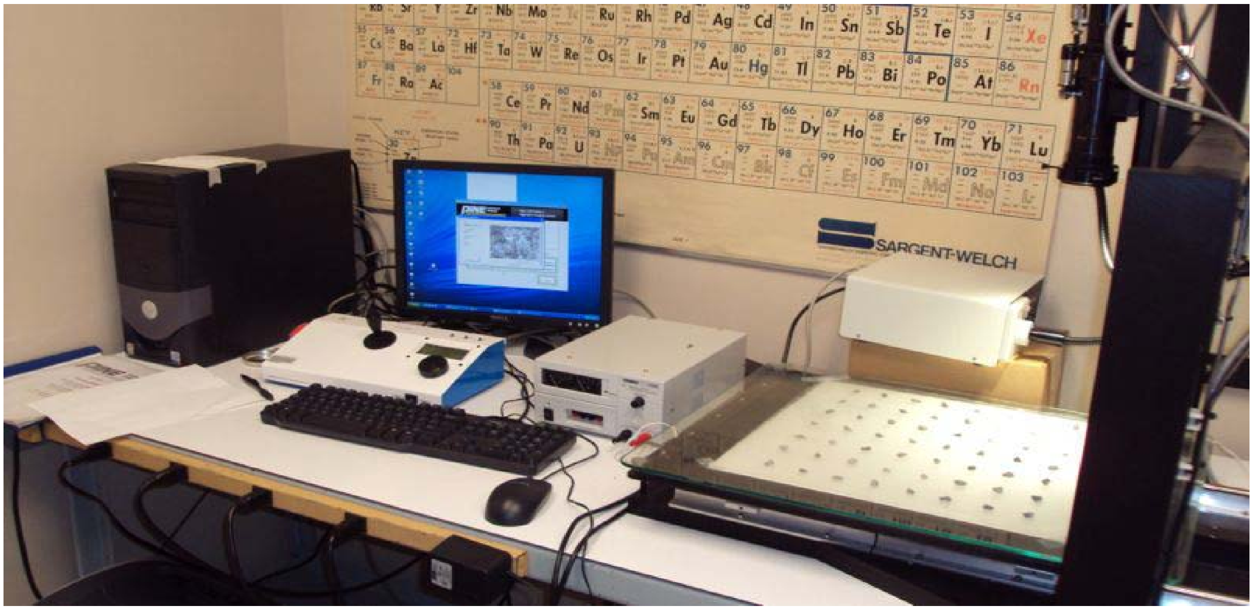

Figure 3.1 Aggregate Imaging System in OU Lab

The system is also equipped with bottom and top lightning to capture images in black and white format as well as gray format. The camera moves along specified grid locations in x, y, and z directions. The travel distance in the x and y directions are 37.5 cm and 10 cm in the z direction. The x, y and z-axes movement is controlled by a closed loop direct current (DC) servo and highly repeatable focus is achieved by GTS-1500. The user has a real-time image window for selecting the type of analysis and size of aggregates to be analyzed. The first step in measurement is the calibration of the instrument for the type of analysis to be performed. A coarse aggregate sample (56 particles) is then placed on the specified grid points, or fine aggregate sample is spread uniformly on the entire tray.

The AIMS software analyzes the aggregate images and produces characteristic measurements [8,29]. Aggregate angularity is described by measuring the irregularity of a particle surface using the radius and gradient methods (angularity index). Shape is described by 2D form and 3D form (sphericity). Aggregate texture is quantified using wavelet analysis method (texture index) [29]. The test is limited to aggregates whose size ranges from 37.5 mm to 150 mm [8].

3.1.2.1 Radius Method (Angularity)

The analysis of angularity by the radius method was developed by Masad et al. [9] using black and white images. In the radius method, the angularity index is measured as the difference between the particle radii in a given direction to that of an equivalent ellipse, as shown in Equation 4.

$$Angularity\ Index\ (Radius) = \sum_{\theta=0}^{n} \frac{|R_{\theta} - R_{EE\theta}|}{R_{EE\theta}}$$

Equation 4

Where R_{Θ} is the radius of the particle at an angle of Θ; and $R_{EE\Theta}$ is the radius of the equivalent ellipse at an angle of Θ [9].

3.1.2.2 Gradient Method (Angularity)

The gradient method is based on the principle that at sharp corners of the image the direction of the gradient vector changes rapidly, whereas it changes slowly along the outline of rounded particles. The angularity is calculated based on the values of angle of orientation of the edge points (Θ) and the magnitude of difference of these values (ΔΘ). The sum of angularity values for all the boundary points are accumulated around the edge to get the angularity index. The angularity is mathematically represented in Equation 5.

$$Angularity\ Index\ (Gradient) = \sum_{\theta=0}^{n-3} |\theta_i - \theta_{i+3}|$$

Equation 5

Where *n is* the total number of points on the edge of the particle with the subscript *i* denoting the *ith* point on the edge of the particle [7].

3.1.2.3 Sphericity

Sphericity quantifies the aggregate’s form using the three dimensions of the particle, which are the longest dimension (d_L), the intermediate dimension (d_I), and the shortest dimension (d_s) and are used in Equations 6 and 7 for sphericity and shape factor. A sphericity index of 1.0 denotes that a particle is a perfect sphere or cube while sphericity decreases as a particle becomes more flat and/or elongated.

$$Sphericity = \left(\frac{d_S * d_I}{d_L^2}\right)^{\frac{1}{3}} \quad \text{Equation 6}$$

$$Shape\ Factor = \frac{d_S}{(d_L * d_I)^{\frac{1}{2}}} \quad \text{Equation 7}$$

3.1.2.4 Form

Form analysis using the form index was proposed by Masad et al. [9], and is used to quantify the form in two dimensions. The form index uses incremental change in the particle radius and is expressed by Equation 8:

$$Form\ Index = \sum_{\theta=0}^{\theta=360-\Delta\theta} \frac{|R_{\theta+\Delta\theta} - R_\theta|}{R_\theta}$$

Equation 8

Where RΘ is the radius of the particle at an angle of Θ; and ΔΘ is the incremental difference in the angle.

3.1.2.5 Texture Analysis

The AIMS also has the capability to analyze the surface texture of aggregate, which is initiated by taking a grayscale image of the surface of the aggregate particle. The Wavelet method, described in detail in NCHRP Report 4-30, is the used to determine surface texture [7]. The wavelet analysis uses short, high-frequency basis functions and long, low-frequency basis functions to isolate fine and coarse variations in texture. The texture contents in all directions are given equal weight and the texture index is computed as the simple sum of squares of the detail coefficients at that particular resolution.

The texture index is given by Equation 9.

$$Texture\ Index\ (Wavelet) = \sum_{i=1}^{3}\sum_{j-1}^{N} D_{ij}\ (x,y)^2$$

Equation 9

Where N is the total number of coefficients in a detailed image of texture, i takes values 1, 2, or 3 for the three detailed images of texture, j is the wavelet coefficient index and (x, y) is the location of the coefficients in the transformed domain [7].

3.1.3 Sessile Drop and Universal Sorption Device

Compatibility between aggregates and binders is critical to ensure that adequate adhesion is achieved [30,31]. A TxDOT study found that electrostatic incompatibility of aggregates and binders (i.e. using an anionic binder with an aggregate that is also anionic) was a major cause of early failure in emulsion chip seals [11]. Emulsions routinely come in either anionic or cationic forms. For a compatible aggregate-binder system, the binder and aggregate must have opposite charges. Otherwise, the residual binder will not form a strong bond with the aggregate. Sinadheera et al. [30] developed a performance-based test method for aggregate-binder compatibility. This method essentially requires the preparation of a chip seal specimen on hot aluminum plate and subjecting the specimen to debonding failure using a Modified Proctor Hammer [30]. The “Coating Ability and Water Resistance” method, specified in ASTM D244 22-29, provides a framework for evaluation of aggregate-binder compatibility. However, none of these methods are based on mechanistic performance.

The theory of surface energy can be used to characterize aggregate-binder compatibility [32]. Specifically, the strength of the interface bonding can be quantified fundamentally by comparing the wet adhesive bond strength with the dry adhesive bond strength between the binder and aggregate. Three components comprise a material’s total surface free energy: the Lifshitz-van der Waals (LW) component, the Lewis acid component and the Lewis base component [32]. The total work of adhesion (W_{AS}) can be determined by incorporating these values, which can be determined indirectly using contact angles (e.g., Sessile Drop), vapor adsorption isotherm (e.g., Universal Sorption Device), or heat of immersion measurements [32,33,34,35], into Equation 10.

$$W_{AS,dry} = 2\sqrt{\gamma_A^{LW}\gamma_S^{LW}} + 2\sqrt{\gamma_A^{-}\gamma_S^{+}} + 2\sqrt{\gamma_A^{+}\gamma_S^{-}} \qquad \text{Equation 10}$$

Where γ represents total SFE of each material, γ^{LW} is the LW component, γ^{+} is the Lewis acid component, and γ^{-} is the Lewis base component, and A and S denote binder and aggregate, respectively.

Equation 11 is used to calculate total work of adhesion in wet condition.

$$W_{AS,wet} = \gamma_{AW} + \gamma_{SW} - \gamma_{AS} \qquad \text{Equation 11}$$

Where the subscripts *AW, SW*, and *AS* refer to the interfacial energy between asphalt binder and water, aggregate and water, and asphalt binder and aggregate, respectively [32].

The Sessile Drop (SD) device, shown in Figure 3.2, measures the contact angles of both aggregate and binder directly. The contact angles are measured with liquids of known surface free energy (SFE), which in turn can be used determine the SFE components. The SFE components of a binder and aggregate system can then be used to estimate *compatibility ratio* (CR) [36,37]. The CR of a binder-aggregate system is the ratio of the free energy of adhesion under dry conditions ($W_{AS,\ dry}$) to the free energy of adhesion in the presence of moisture ($W_{AS,\ wet}$). Higher CR values (greater than 0.8) denote better bonding [32]. A CR value less than 0.5 indicates poor compatibility. The SFE can also be used to quantify bond strength (cohesion, adhesion, energy ratio).

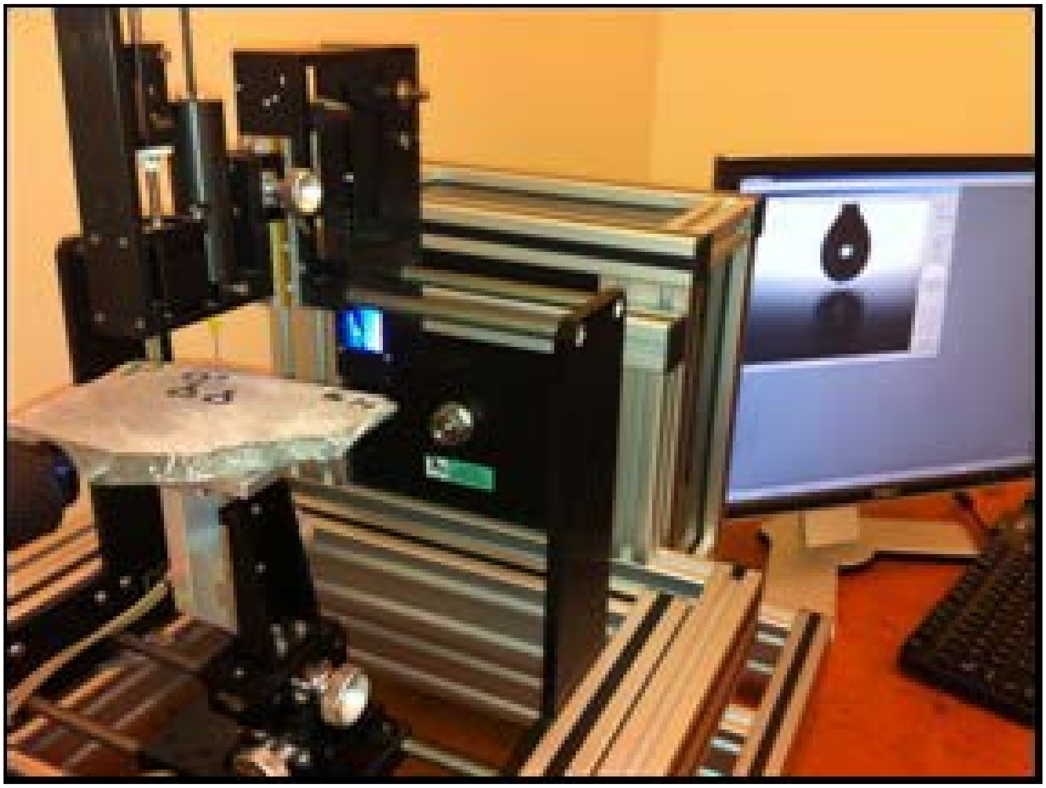

Figure 3.2 Sessile Drop Device

3.2 FIELD TESTS FOR COVER AGGREGATE IN CHIP SEAL

Two common field measurements used to assess chip seal performance are *microtexture* and *macrotexture,* which are surface texture characteristics [3,38]. Essentially, microtexture is the quantitative measure of aggregate surface friction properties that contribute to skid resistance, while macrotexture is the quantitative measure of aggregate physical properties (size, shape and spacing) that contribute to drainability, whereby enhancing surface friction and skid resistance [13]. Micro and macrotexture deteriorate over time due to traffic and environmental conditions. Pavement managers can evaluate chip seal performance (service life) by monitoring the deterioration rate until the surface reaches a certain threshold value that signals remedial action is required.

3.2.1 Managing Pavement Surface Texture

Roadway crashes are complex events that are the result of one or more contributing factors relating to three main categories: driver-related causes, vehicle-related causes, and highway condition-related causes [39]. Pavement engineers must manage pavement surface texture (microtexture and macrotexture) to reduce the highway condition-related causes throughout the pavement life cycle. During design and construction phases, the engineer has control over the geometry of the road, both in horizontal and vertical alignments, the speed of travel, the signage of the roadway system and the material properties of the surface course. The maintenance engineer is responsible for managing the characteristics of the pavement surface as it deteriorates over time. Pavement preservation and maintenance treatments, such as chip seal, are installed to preserve the road's structural capacity and to ensure that the surface frictional characteristics are sufficient.

Deterioration of surface texture is the result of mechanical wear and polishing action rolling or braking and/or accumulation of contaminants [40]. In Australia and New Zealand, extensive work has been done to manage deterioration through remediation of mean texture depth (MTD), or macrotexture, to control crash rates. In North America extensive work has been done to manage skid number, or microtexture, to control crash rates. Generally, US agencies believe that if an engineer could control wet weather related crashes then all crashes would be reduced. Therefore, most studies regarding crash rates and surface characteristics, whether macrotexture or microtexture, primarily focus on the reduction of wet weather crashes [41]. Microtexture and macrotexture are illustrated in Figure 3.3.

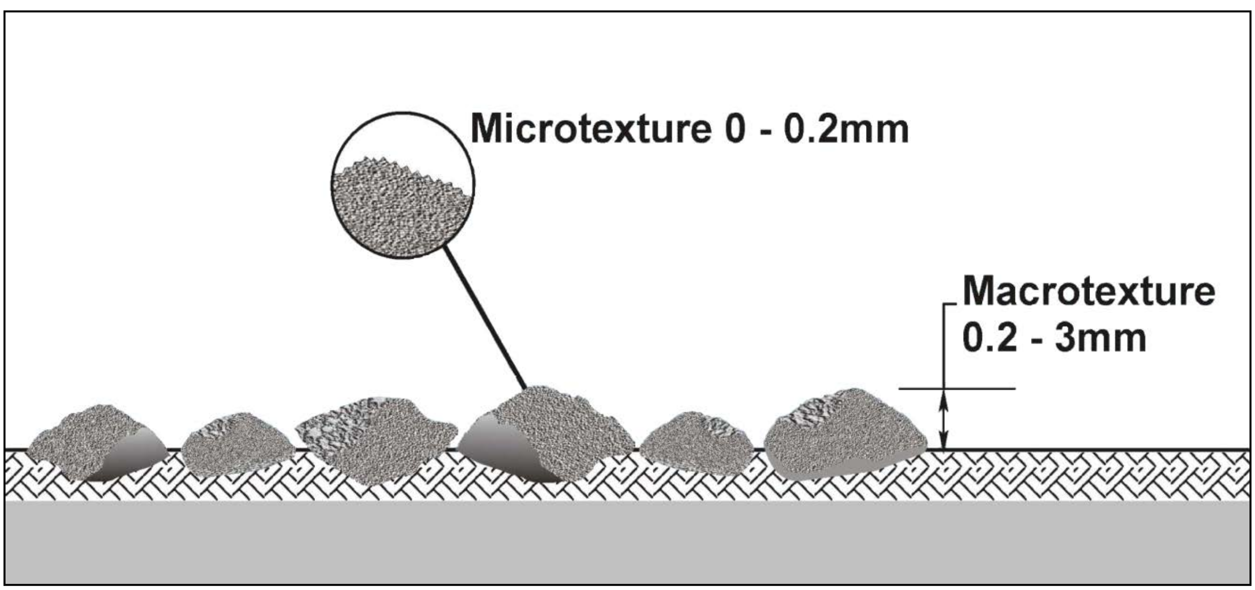

Figure 3.3 Pavement Surface Microtexture and Macrotexture [42]

The skid resistance of a highway pavement is the result of a “complex interplay between two principal frictional force components—adhesion and hysteresis” (Hall 2006). There are other components such as tire shear, but they are not nearly as significant as the adhesion and hysteresis force components. Figure 3.4 shows these forces. The force of friction (F) can be modeled as the sum of the friction forces due to adhesion (F_A) and hysteresis (F_H) as shown in Equation 12.

$$F = F_A + F_H \qquad \text{Equation 12}$$

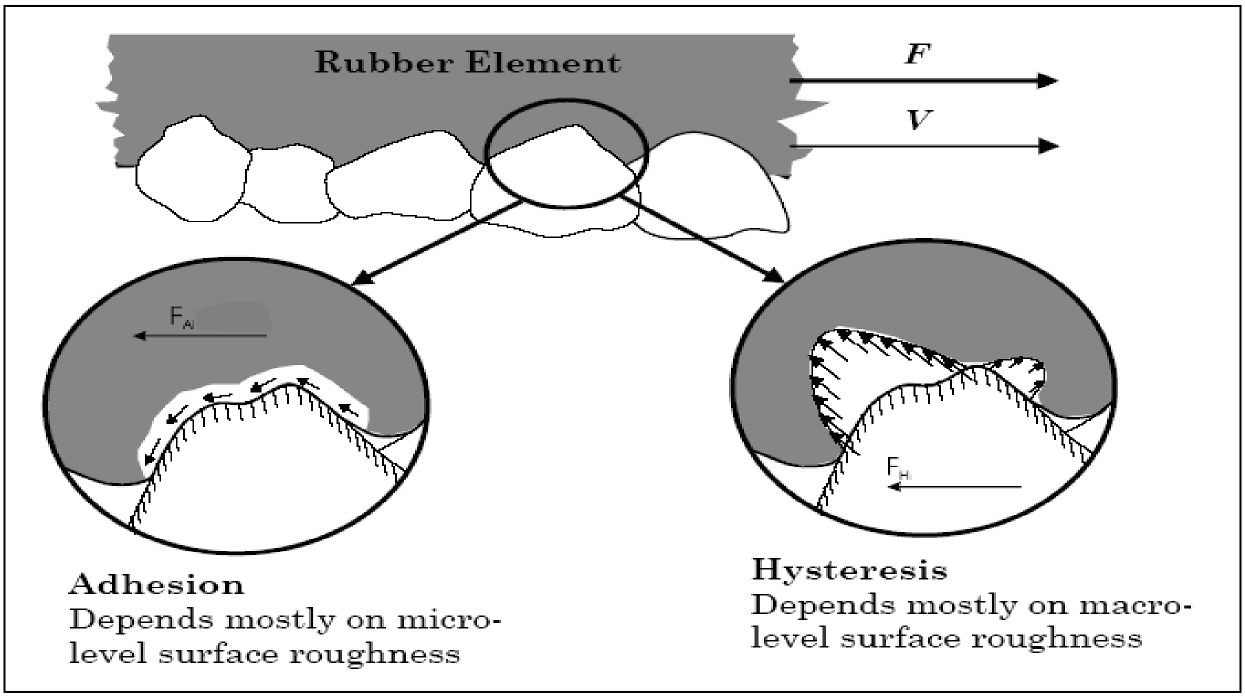

Figure 3.4 Pavement Friction Model [43]

Relating Figure 3.3 to Figure 3.4, the frictional force of adhesion is “proportional to the real area of adhesion between the tire and surface asperities” [43], which makes it a function of pavement microtexture. The hysteresis force is “generated within the deflecting and visco-elastic tire tread material, and is a function of speed” making it mainly related to pavement macrotexture [43]. Thus, if an engineer wants to improve skid resistance through increasing the inherent friction of the physical properties of the pavement, then the engineer should seek to improve *both* surface microtexture and macrotexture.

3.2.2 Measuring Surface Texture

Macrotexture and microtexture are primary performance indicators for chip seal [3,38]. The deterioration of these surface texture characteristics can be measured and analyzed to determine remaining service life [4].

3.2.2.1 Macrotexture Measurement

Macrotexture is an indicator of aggregate loss in chip seals. The New Zealand Transport Agency (NZTA) uses chip seal extensively throughout its network to ensure adequate macrotexture for surface drainage. NZTA considers macrotexture measurement to be one of the key performance indicators (KPI) of surface treatments [44]. If the average macrotexture of a road surface drops below 0.9mm (0.04 in) on roads with posted speed limits greater than 70 km/hr (43.5 mph), then the NZTA requires remedial action to restore surface texture. Based on this failure criterion, NZTA maintenance engineers have developed trigger points based on local conditions that allow the programming of pavement preservation treatments, like chip seal, before the macrotexture loss becomes critical [42].

Macrotexture can be assessed by measuring mean texture depth (MTD) with the New Zealand Sand Circle testing procedure (TNZ T/3), which provides information about surface "drainability". Figure 3.5 shows the TNZ T/3 test being conducted in the field. The TNZ T/3 testing procedure feeds the TNZ P/17 performance specification which can then be used as a metric to judge the success or failure of the surface treatments in their first 12 months based on a field-proven standard [45]. A recently completed pavement surface texture research project in Texas proved the validity of both the test procedure and the performance specification for use in the US [46].


Figure 3.5 TNZ T/3 Sand Circle Testing in Progress [4]

The sand circle test is a volumetric test, performed by placing a known volume of sand, in this case 45 mL, which is then spread by revolving a straight edge in a circle until the sand is level with the tops of the surface aggregate and can no longer be moved around [45]. Once the known volume has been spread in a circle on the surface of the roadway and can no longer be moved, two measurements are taken to determine the average diameter of the circle. These values are then averaged and inserted into Equation 13.

$$Mean\ Texture\ Depth\ (mm) = \frac{57{,}300}{Diameter\ (mm^2)} \qquad \text{Equation 13}$$

The surface texture is inversely proportional to the diameter of the circle produced on the surface. This testing protocol is relatively simple but has limitations: it is susceptible to operator inconsistency, environmental issues with rain and wind, and roadway imperfections, such as abnormal aggregate heights on the surface of the road. A wind shield is used to shelter the circle from winds and prevent loss of test sand during the test. However, The TNZ T/3 sand circle test provides better reliability than the ASTM sand patch test, as demonstrated in previous studies [46,47]. Additionally, studies have shown no statistically significant difference exists between the results of the TNZ T/3 sand circle test and other tests, like circular track meter and RoboTex, which measure macrotexture [4].

3.2.2.2 Microtexture Measurements

Microtexture (skid number) can be an indicator of flushing or bleeding in chip seals, as well as aggregate loss. Various methods can be used to measure skid number, but the common method is to use an ASTM E 274 skid tester equipped with either with a smooth tire or a ribbed tire. The testing apparatus is towed behind a vehicle at the desired speed. 40 mph is the standard for towing the ODOT skid tester, pictured in Figure 3.6. Water is then applied in front of the tire just before the tire’s brakes force the tire to lock up. The resultant force is then measured and converted into a skid number value [48].

Figure 3.6 ODOT Skid Truck

4.0 RESEARCH METHODOLOGY AND PROTOCOLS

The research methodology and protocols were established for the purpose of achieving the study objectives. The objectives include characterizing commonly used chip seal aggregate, determining aggregate-binder compatibility and evaluating the performance-based uniformity coefficient (PUC) and any correlation it may have with chip seal performance in Oklahoma. The results will assist the researchers in determining if a more precise ODOT specification of the required characteristics of chip seal cover aggregate is warranted. Results will also identify combinations of chip seal binder and aggregate that are incompatible in each ODOT division. Additionally, the research provides documentation of construction practices in each maintenance division and identification of best construction practices. Lastly, the influence of fog seal and geosynthetic fabric on chip seal performance is investigated.

4.1 CHARACTERIZING OKLAHOMA CHIP SEAL AGGREGATE

A Project Panel was formed that consisted of members from the chip seal community, including members of ODOT, aggregate and binder suppliers to assist the research team in the selection of commonly used cover aggregates and binders to be characterized. Among other factors, type, demographic distribution and suppliers were considered in the materials selection, and the actual number of sources was guided by the input of the Project Panel. Bulk aggregate and binder samples were collected in cooperation with the Project Panel members and the suppliers. The aggregate samples were obtained from the following quarries (locations illustrated in Figure 4.1):

1. Dolese Cooperton (limestone),
2. Hanson Davis (rhyolite),
3. Martin Marietta Mill Creek (granite),
4. Dolese Hartshorne (limestone) and
5. Kemp Stone Pryor (limestone).

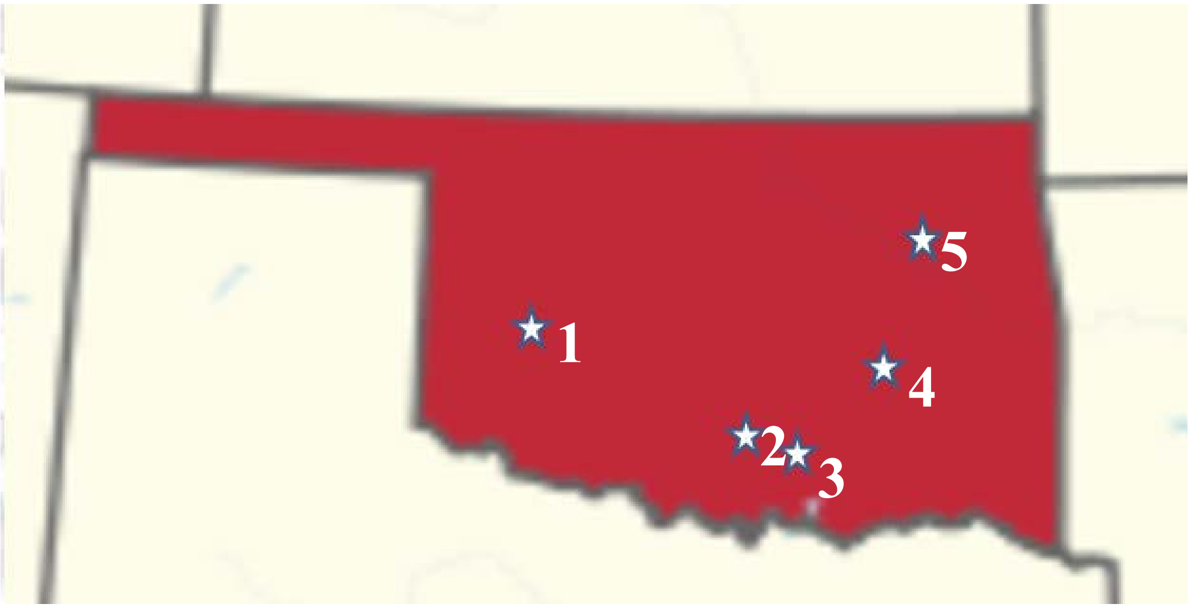

Figure 4.1 Study Aggregate Sources – (1) Dolese-Cooperton, (2) Hanson-Davis, (3) Martin Marietta-Mill Creek, (4) Dolese-Hartshorne and (5) Kemp Stone-Pryor

Additionally, emulsion (CRS-2S) samples were gathered from ERGON Lawton and Coastal Missouri. CRS-2 is the most common chip seal binder used in the US, including Oklahoma [3], and was identified by the Project Panel for inclusion in this study. "CRS" designates the material as being a *cationic rapid set* emulsified asphalt; the "2" in "2S" refers to a specified viscosity and the "S" denotes the source as being a *s*oft base asphalt. CRS-2S is non-polymer modified, so it is best used on roads with less traffic.

Aggregate characterization tests were conducted at the Broce Laboratory and Binders Laboratory located at The University of Oklahoma. The aggregate samples were first characterized using a sieve analysis. The durability of selected cover aggregates was evaluated using Los Angeles Abrasion (AASHTO T 96) and Micro-Deval (AASHTO T 327) tests. Shape and texture-related index properties were assessed using AIMS (AASHTO TP81-10).

Recently, some issues have been raised concerning the influence of ambient light on the texture index [49]. Reference aggregates selected from a national level round robin study available at the Texas Transportation Institute (TTI), were used to ensure consistency of AIMS results. TTI owns a new generation AIMS (hereafter referred to as AIMS2). The research team compared results for selected aggregates obtained from the OU AIMS (hereafter referred to as AIMS1) with those from the AIMS2. Dr. Dallas Little with TTI conducted the AIMS2 testing. Results were comparable when comparing natural aggregate.

The research team also sent aggregate samples identified for this study to TTI for comparison. A selective size (passing ½ in (12.5mm) and retained on 3/8 inch (9.5 mm)) of aggregate from two sources, Dolese Cooperton and Hanson Davis, were tested. The surface properties (angularity, 2D form, and texture) were compared with those obtained from the AIMS2. Furthermore, the same samples were tested by two independent operators at OU (OU-OP1-JA and OU-OP1-ZH) by using the AIMS1 device to ensure repeatability.

The AIMS1 results were validated by the AIMS 2 and multiple operators for angularity and form, as evidenced by the comparability illustrated in Figure 4.2 and Figure 4.3. A previous study on AIMS1 also reported similar findings: "AIMS has been found to have excellent repeatability and reproducibility for all measured parameters when compared with many other test methods" [50].

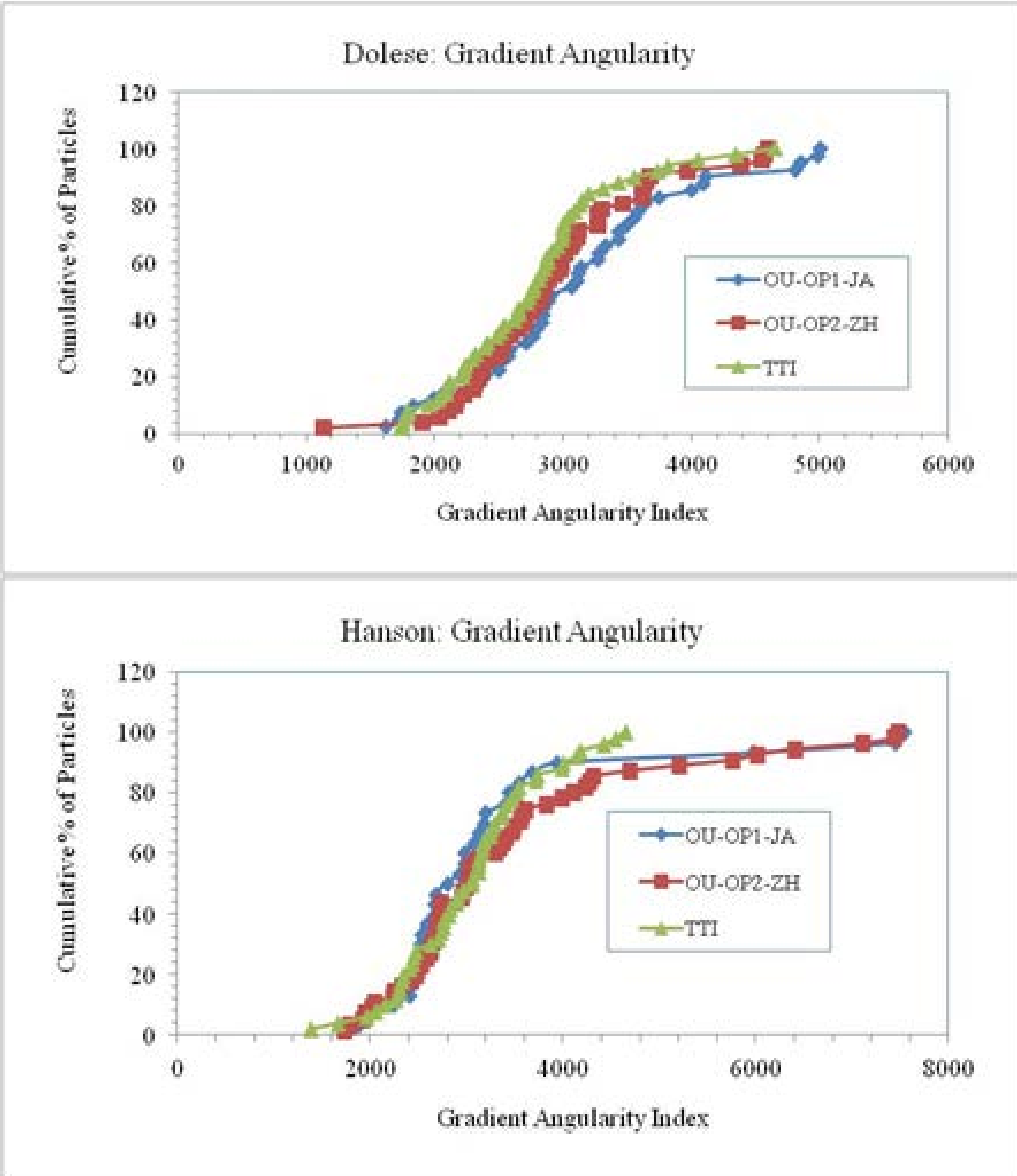

Figure 4.2 Validation of AIMS1 Gradient Angularity: Dolese (top) Hanson (bottom)

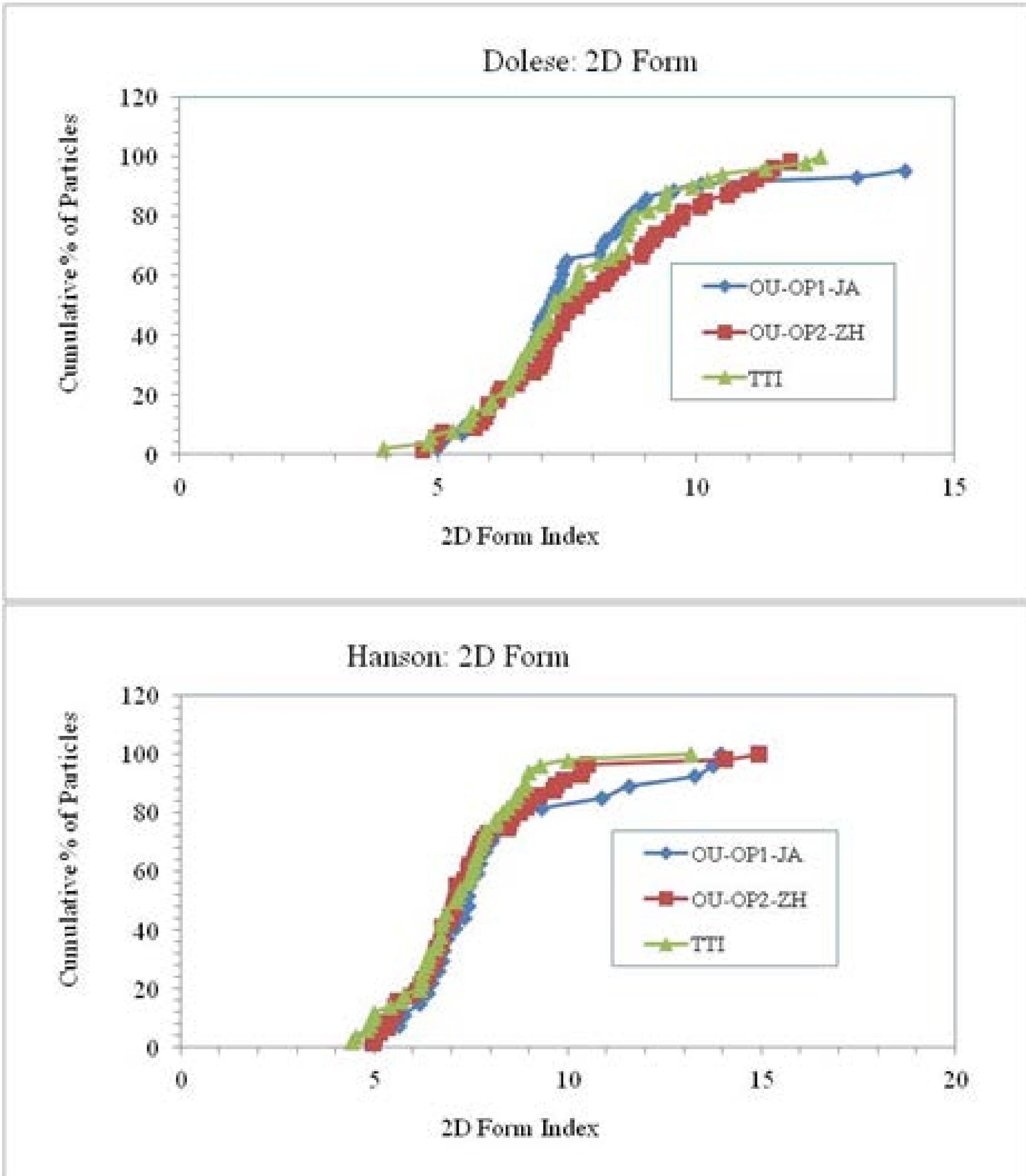

Figure 4.3 Validation of AIMS1 2D Form: Dolese (top), Hanson (bottom)

However, significant difference in the measured texture indices was observed between AIMS1 and AIMS2, as shown in Figure 4.4. A recent study by Texas Transportation Institute researchers [51] reported similar findings, "AIMS1 to AIMS2 2D-Form, Angularity, and Dimensional ratios required no adjustments. The AIMS2 texture value required adjustment to match the AIMS1 texture.” This is partly due to the fact that the texture measurement process is highly dependent on ambient light intensity. The backlight of the tray must be kept in OFF mode and the rim (top) light should be kept in the ON mode while capturing images for texture analysis to reduce variability. However, it should be noted that AIMS1 and AIMS2 texture index values may differ. The trend noted in this study is that the texture index obtained from AIMS2 is higher than that obtained from AIMS1.

Light intensity may be an issue with AIMS results, especially with synthetic aggregates or light-colored natural aggregates. It can be noted that Pine Instrument Company, the AIMS manufacturer, recommends the light intensity range of images be from 165 to 175 cd. While capturing images for texture analysis for this study, light intensity will be maintained at the recommended level for all 56 particles and any images outside of the recommended range will be discarded.

Figure 4.4 also shows that the texture indices vary between two operators using the same AIMS1 device. This is partly due to the fact that the layouts (orientations) of specimens on the testing tray were random and the texture index of one face of a particle can be different from that of the opposite or another face. Therefore, for this study, the same set of aggregates with random payout will be tested at least three times and the average of the measured indices will be reported.

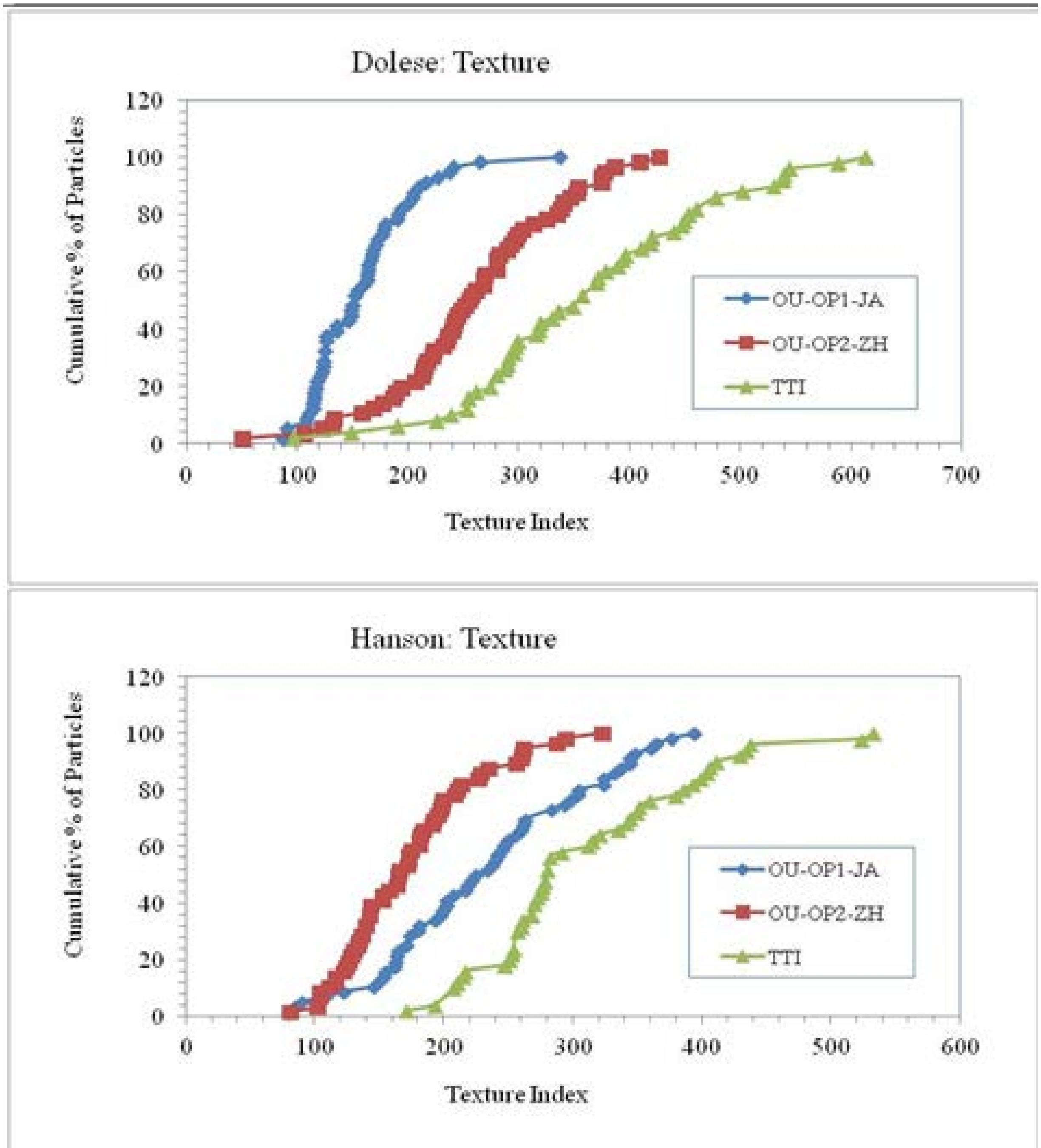

Figure 4.4 Validation of AIMS1 Texture: Dolese (top), Hanson (bottom)

4.2 DETERMINING OKLAHOMA AGGREGATE-BINDER COMPATIBILITY

Currently, there is no standard sample preparation or testing procedures for measuring contact angles of aggregates and aggregates coated with binders with Sessile Drop for the purpose of determining aggregate-binder compatibility. However, under an OkTC project (OTCREOS10.1-06), the research team has successfully developed guidelines that provide meaningful and reproducible results that are consistent with the results from other devices (e.g., Wilhelmy Plate (WP), Universal Sorption Device (USD)). Details of the test procedures are given by Bulut et al. [33].

The Sessile Drop (SD) device available at Oklahoma State University was used to characterize the aggregate-binder compatibility of materials identified by the Project Panel. Three samples of each of the five aggregate sources were obtained from the quarries. Although aggregate samples came from the same source, differences in texture and color were noted in some of the samples. The exception was Dolese material from the Hartshorne Quarry, which visually appeared similar. Therefore, the number of samples tested for each source was based upon exhibited differences and is listed in parentheses as follows:

- Dolese – Cooperton (3),
- Hanson – Davis (2),
- Martin Marietta - Mill Creek (3),
- Dolese – Hartshorne (1), and
- Kemp Stone – (2).

The samples which were cut with thicknesses varying from 1 cm to 2 cm using a Hill Quist mechanical hacksaw. Then the samples were polished consecutively using 220 (66-μm), 320 (34.3-μm) and 400 (22.1-μm) silicon carbide grits on a polishing device which rotates mechanically for approximately 15 min each. Then the samples were polished using 600 (14.5-μm) and 1000 (9.2-μm) silicon carbide grits followed with 5 micron alumina oxide powder on a glass plate for about 20 min each. After samples were polished, they were cleaned with hexane or octane, then with a mixture of soap and warm water, and finally rinsed with water. Octane is used on Sample 1 and Sample 2 of Miller-Creek Granite, Sample 2 of Pryor Stone Limestone and Sample 2 of Hanson Davis Rhyolite because hexane was not available when taking measurements on those samples. Octane and hexane are two chemicals with same characteristics and can be used for cleaning process on aggregates without any adverse effects to their chemical structure, as suggested by Dr. Wilber Gregory of Environmental Engineering in

Oklahoma State University. The samples were kept in an oven at a temperature of 110°C for 12 hours for drying. Then, samples were kept in a desiccator for 12 hours for cooling to the testing temperature. The numbers of sets of measurements as given in the tables in the Results section were taken in consecutive days maintaining the 12 hours of oven and 12 hours of cooling process. One of the prepared samples is shown in Figure 4.5.

Figure 4.5 Prepared sample from Dolese Cooperton (limestone)

Both WP and USD are available at OU and were used selectively for Sessile Drop results validation purposes. Universal Sorption Device (USD) is a gravimetric sorption device designed for water and organic vapor sorption studies of materials. This technique works based on the development of a vapor sorption isotherm, i.e. the amount of vapor adsorbed, or desorbed, on the solid surface at a fixed temperature and partial pressure. The range of relative pressure (RP) can be designed from 0.02 to 0.98 and temperatures from 5 to 60°C. At each relative humidity (RH) or pressure step, the system controls the RH or RP and monitors sample weight until it reaches equilibrium conditions. Sample weight, temperature, and RH or RP are recorded in a data file at user defined intervals. Identical conditions of temperature and humidity for a sample and a reference are achieved by using a symmetrical two-chamber aluminum block. To achieve research quality data, the critical components of the system, microbalance, aluminum block, and humidifier sections are thermostatically separate. Sample weight changes are recorded using a microbalance. The SFE components of selected aggregate(s) in this study were determined using a USD and applying the methodology discussed by Bhasin and Little [32]. The probe vapors of known SFE components, namely water, n-hexane, and methyl propyl ketone (MPK) were used to determine adsorption isotherms. Thereafter, based on the adsorption isotherms, SFE components of each tested aggregate were determined. To prepare aggregate samples for testing, aggregates were crushed from rock samples. The portion passing No.4 and retained on No. 8 sieves was selected and washed several times with distilled water to obtain a dust-free and clean aggregate surface. Then the aggregate was oven dried at 120°C for 12 hours and allowed to cool to room temperature in a desiccator sealed with silica gel. About 20 grams of aggregate was used to conduct one USD test. The test was repeated three times using each probe vapor to ensure consistency of the results.

Although asphalt cement SFE determination is found in literature, no specific testing protocol exists for determining the surface free energy values of emulsion. Therefore, the research team developed these methodologies for determining emulsion SFE so that compatibility ratios could be calculated and aggregate-binder compatibility could be determined. Specifically, the Good-van Oss-Chaudhury (GVOC) approach was followed by using liquid probes, shown in Table 4.1, to facilitate determination of the surface free energy (SFE) components of the CRS-2S asphalt emulsion. The GVOC approach or acid-base theory has been widely used in various disciplines for the calculation of SFE components of polymers, colloids, asphalt binders, and aggregates [32,34,35,52-55].

Table 4.1 Surface energy components of liquid probes [54]

Liquid Probe	γ^{Total}	γ^{LW}	γ^{AB}	γ^{-}	γ^{+}
	(ergs/cm^2 or mJ/m^2)				
Water	72.80	21.80	51.00	25.50	25.50
Di-iodomethane	50.80	50.80	0.00	0.00	0.00
Ethylene Glycol	48.00	29.00	19.00	1.92	47.00
Glycerol	64.00	34.00	30.00	57.40	3.92
Formamide	56.00	39.00	19.00	39.60	2.28

The methodology for testing asphalt binder specimens has been modified for testing the CRS-2S asphalt emulsion for contact angle measurements using the SD method. The following testing protocol was followed:

- In order to obtain a homogeneous mixture of the emulsion sample, the asphalt emulsion container was shaken vigorously.
- The asphalt emulsion sample was then poured into a small canister.
- A plain microscopic glass slide with 76 mm x 25 mm x 1 mm dimensions was dipped into the asphalt emulsion for a few seconds and then held out of the canister for another few seconds to allow excessive liquid to drop off the glass. This process was repeated two times, when necessary, to obtain a flat and smooth surface area of the asphalt emulsion on the glass surface. This resulted in a glass slide with a film thickness about 1 mm of asphalt emulsion with a smooth surface being obtained.
- Since the viscosity of the CRS-2S asphalt emulsion is not high enough for the probe liquid drops to form finite contact angles, the asphalt emulsion covered glass slides were kept either in a desiccator or exposed to open-air at the room temperature for varying hours (2, 4, 6, 8, and 24 hours) for sample conditioning, curing and drying before performing the direct contact angle measurements.

- For this study, 42 asphalt emulsion glass slide specimens were prepared. Half of the specimens were kept in a desiccator and the other half were kept in the open air until they gained enough viscosity for contact angle measurements.

The contact angle measurements were also performed on asphalt emulsion specimens with different film thicknesses of about 2 mm (double layered) and 3 mm (triple layered) glass slide specimens. These specimens were prepared following the same protocol for single layered (about 1 mm film thickness) asphalt emulsion samples described in the preceding section.

- Once the single layered specimen is obtained, it is kept at the room temperature for 30 minutes in order to gain some viscosity from drying.
- The sample is then dipped into the canister filled with asphalt emulsion one more time.
- Hence another layer of asphalt emulsion is added on the surface of the glass slide.
- After waiting 30 more minutes, the above process was repeated if the triple layered asphalt emulsion specimen was needed.

The testing protocol for contact angle measurements using the SD device on asphalt emulsion samples is identical to the testing protocol for asphalt binders and it is given below. The contact angle measurements were conducted on single layered (about 1 mm film thickness) asphalt emulsion specimens after 2, 4, 6, 8, and 24 hours of setting, curing, and drying. After taking six consecutive contact angle readings on each slide with one probe liquid, the slide was disposed. For each time interval, three specimens were tested with three different probe liquids namely; water, di-iodomethane (methylene iodide), and ethylene glycol. The measurements on the double and triple layered specimens were obtained after a 2-hour waiting period. A brief explanation of the testing protocol is given below:

- The SD device is calibrated before each testing set according to standard protocol.

- The syringe that contains the probe liquid was refilled before the test. When a different probe liquid was used, the syringe was either replaced or cleaned thoroughly.
- Once the device was calibrated and the samples were at the testing temperature (at room temperature), the specimen was placed under the needle attached to the syringe in the automated pump system of the SD device.
- About 5 μL of probe liquid was dispensed on the specimen from the needle using the FTA software in the SD device system.
- While the liquid was still in the form of a pendant drop, the platform that holds the specimen was elevated slowly until the specimen touches the drop.
- The drop detaches from the needle and forms the sessile drop on the flat surface of the specimen.
- The high resolution camera constantly captures the images of the liquid-solid interface and sends it to the software for processing. The number of the images per second and test duration, if needed, can be adjusted from the software. In this study, three images per second were used. The time period for a single test was about 15 seconds.

Finally, the software processes each image and determines the average contact angles. The testing protocols for contact angle measurements on the single, double, and triple layered asphalt emulsion specimens are identical.

4.3 EVALUATING PUC APPLICABILITY

Performance-based uniformity coefficient (PUC) gradations were determined for *single size* chip seal test section design. Chip seal test sections were constructed for the purpose of evaluating the PUC concept using surface texture performance testing.

4.3.1 PUC Gradation and Test Section Development

Several (at least three) gradations were selected within the gradation range of the specification (e.g., CA #3) with the same median "M" value for each gradation. Each "P_{EM}" and "P_{2EM}" of the selected gradations was obtained from the respective percent passing that correspond to 0.7M (bleeding line) and 1.4M (aggregate loss line). Figure 4.6 shows a graph of ½" gradation possibilities generated for this study based upon the PUC concept. The figure indicates that the G2 gradation is expected to minimize both bleeding and aggregate loss. A similar plot for the aggregates selected for this study and the gradations in current ODOT specifications will show where changes in the current specifications are needed most. Also, these results will be helpful to ODOT maintenance engineers in tweaking cover aggregate gradations for future chip seal projects to enhance chip seal performance.

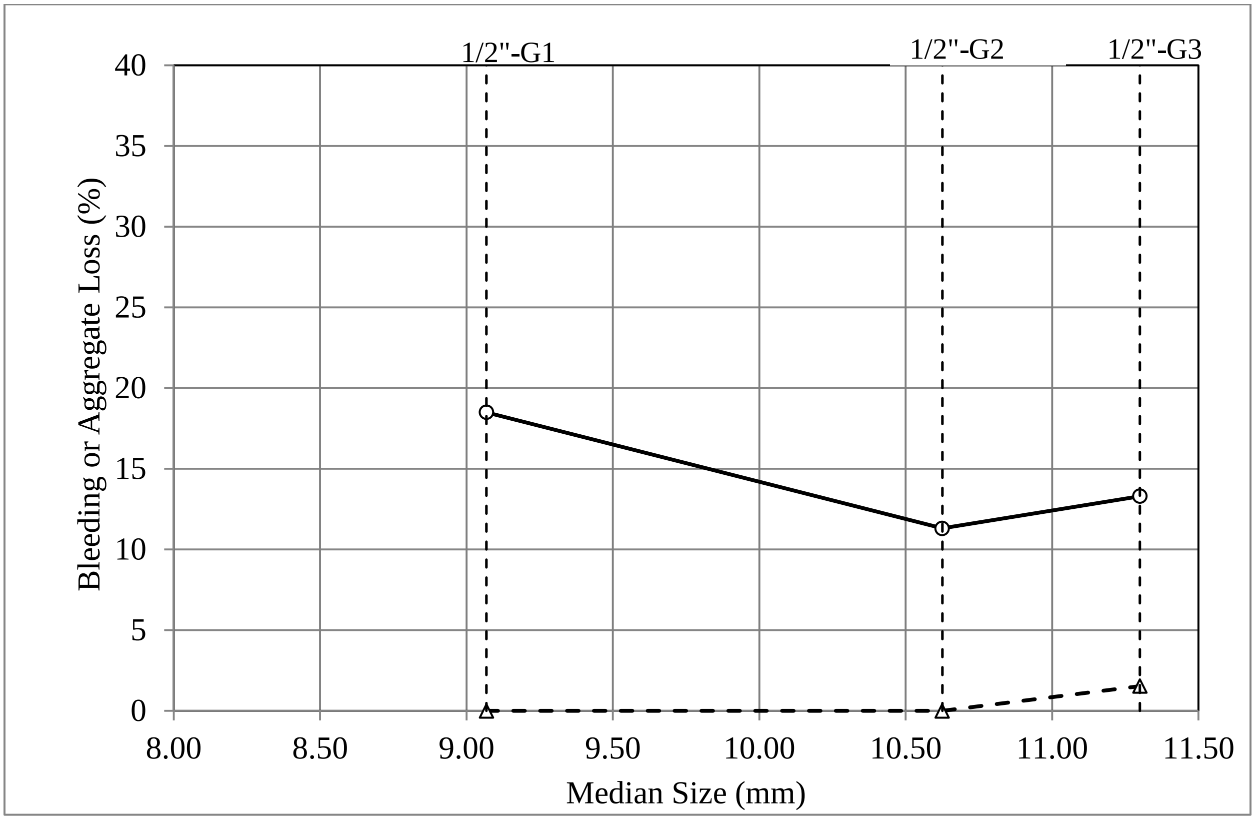

Figure 4.6 Bleeding and Aggregate Loss Values for Three ½" Gradations

Table 4.2 shows the PUC values based upon the bleeding and aggregate loss values for gradations in Figure 4.6. The lowest PUC is desirable. Therefore, Gradation 2 (G2: PUC=0.11) is the gradation that is expected to make the greatest contribution to chip seal performance and is the gradation for Test Section 5.

Table 4.2 PUC Values for ½" Gradations

Aggregate Type	Median Size (mm)	Bleeding (%)	Aggregate Loss (%)	PUC
1/2"-G1	9.07	18.5	0	0.185
1/2"-G2	10.63	11.32	0	0.11
1/2"-G3	11.30	13.31	1.54	0.14

The same process was conducted for the 3/8" gradation as well. Unfortunately, the aggregate supplier that supplied the PUC-based gradations did not produce the PUC-based 5/8" gradation. The test sections with PUC-based gradations are shown in columns 4 and 5 in Table 4.3.

Table 4.3 Test Section Gradations

	Common ODOT Gradations						Single Size Gradations			
	1		2		3		4		5	
	TS 1 & 1s		TS 2 & 2s		TS 3 & 3s		TS 4 & 4s		TS 5 & 5s	
	#2 (3/8")		(1/2 ")		3C (5/8 ")		#2-G2 (3/8" SS)		1/2"-G2 (SS)	
Sieve #	LL	UL	LL	UL	LL	LL	UL	UL	LL	UL
1 in										
7/8 in										
3/4 in										
5/8 in			100		100				100	
1/2 in	100		95	100	70	100	100		95	100
3/8 in	90	100	60	80	20	55	95	100	15	40
1 /4 in							15	35		
No. 4	0	25	0	5	0	15	0	5	0	5
No. 8	0	5	0	2	0	5	0	2	0	2
No. 200	0	2			0	2				

4.3.2 Test Section Construction

In cooperation with ODOT Division 3, fourteen new chip seal test sections were constructed on a 7-mile segment of Highway 39 (2300 ADT) west of Purcell, Oklahoma, that was scheduled to receive a maintenance chip seal. Test section performance comparison requires uniform test sections. Therefore, the project eliminated as many ancillary factors as possible. The sections were placed in the eastbound lane of travel with care to avoid major turning motions at intersections and driveways. To ensure uniformity, the sections were also designed as full lane-width sections to not inadvertently create an uneven driving surface.

Figure 4.8 shows the layout of the field test sections. Each test section (gradation section) is 1 mile in length, of which ½ mile includes fog seal (SS-1). The exceptions are found in the fabric sections, which contain two different gradations in ½ mile sections and of each, ¼ mile sections were to receive fog seal, but CRS-2S was mistakenly applied to the surface of the chip seal. The test section numbers correlate with the gradation numbers found in Table 4.3. Specifically, the fabric sections contain gradations 1 and 3 (ODOT 3/8-inch and 5/8-inch NMAS, respectively).

Test section designations denote inclusion or exclusion of fog seal and fabric. For example, "TS 1" designates a 3/8" NMAS Chip Seal (gradation 1). "TS 1s" designates the same chip seal, but with fog seal ("s"). "TS 1f" designates the same chip seal without fog seal, but with geosynthetic fabric ("f"). Finally, "TS 1sf" would designate a gradation 1 chip seal with both fog seal and fabric. Permanent markers were installed to demarcate test sections with these designations.

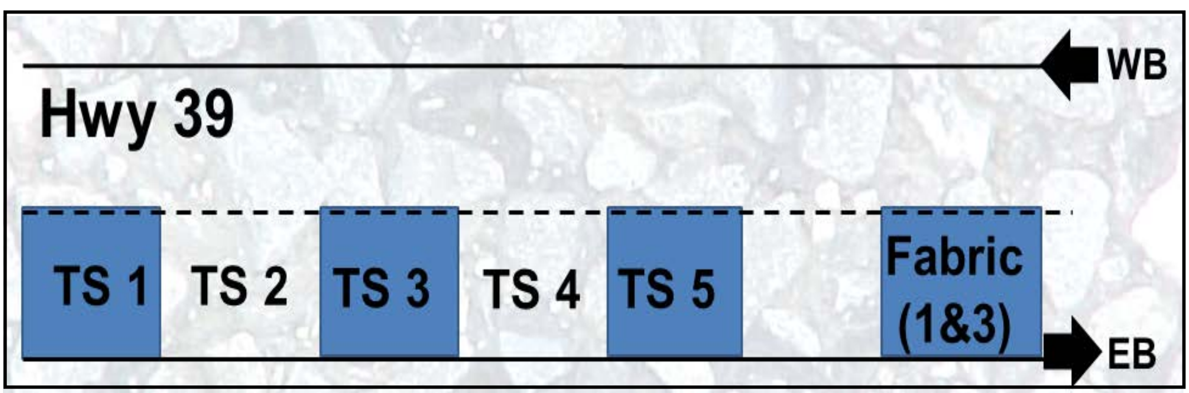

Figure 4.7 Chip Seal Test Section Layout

The aggregate source for the test sections was Dolese-Davis. Researchers verified by sieve analysis that the proposed single size gradations based upon PUC evaluation corresponded to actual test section gradations. The researchers also verified that the initial evaluation of PUC was still applicable. The emulsion (CRS-2S) source was ERGON-Lawton. Shot rates were consistent with supplier recommendations and are noted in Table 4.4.Two of the test sections constructed included TenCate paving fabric (MPV-500) installation over PG 64-22 OK (Source: Vance Bros. in Oklahoma City). ODOT Division 3 installed the chip seal in September 2012. Fog seal was applied two weeks after construction as weather permitted.

Table 4.4 Chip Seal Test Section Shot Rates

Test Section	Aggregate Shot Rate (lb/SY)	Emulsion Shot Rate (gal/SY)
1 & 1s (Gradation 1)	22.5	0.275
2 & 2s (Gradation 2)	26.5	0.319
3 & 3s (Gradation 3)	28	0.420
4 & 4s (Gradation 4)	26	0.329
5 & 5s (Gradation 5)	28	0.429

Vance Bros. contributed binder and paving fabric installation, as shown in Figure 4.9. TenCate contributed paving fabric and had two representatives on site.

Figure 4.8 Geosynthetic (paving) fabric being installed in test sections

Prior to construction, baseline pavement measurements were obtained for the purpose of characterizing the existing substrate. Measurements included microtexture (skid), macrotexture (sand circles), falling weight deflectometer (FWD) and rutting measurements (Dipstick Device). A road that exhibits structural distress will eventually result in cracks being reflected through the new chip seal, therefore FWD testing was conducted to determine the structural condition of the pavement. Additionally, rutting causes the emulsion to flood the wheel paths and creates an uneven distribution of binder across the lane. The extra binder left in the wheel paths will contribute to early flushing and be measurable by a loss of skid numbers. This is a lesson learned from the OkTC project. The literature shows that international chip seal design procedures use average rut depth as an input variable in selecting the gradation and top size of the cover aggregate. The general rule is that the deeper the rut, the larger the average least dimension of the cover aggregate. OTCREOS7.1-16 did not make these measurements and one of the chip seal test sections failed prematurely [4]. Since it was the test section that had the smallest top size aggregate, the failure may have been due to the ruts being deeper than the dimension of the stone. Adding this to the field test protocol permitted the research team to make an informed recommendation as to whether or not ODOT should include average rut depth in its chip seal design procedure.

Consistent with pavement preservation requirements, the condition of the existing Highway 39 pavement section make it an ideal candidate for pavement preservation treatment application, like chip seal. Baseline measurements using all four tests were taken at the same locations (as close as possible) so that future performance measurements (via sand circles) could be compared with baseline condition. The testing revealed that the substrate is structurally sound, with only surface issues, like cracking and some isolated, but minimal, rutting. The Dipstick Device output (rut depth plot and histogram) for the 47 locations is shown in Figure 4.10 and Figure 4.11. The rut depth for the majority of the test sections is within the range of 0.0-0.1”, except for one location at 34,338 ft (in the fabric test section) which has 0.33” rut. Overall, the substrate seems to have no significant rut depth.

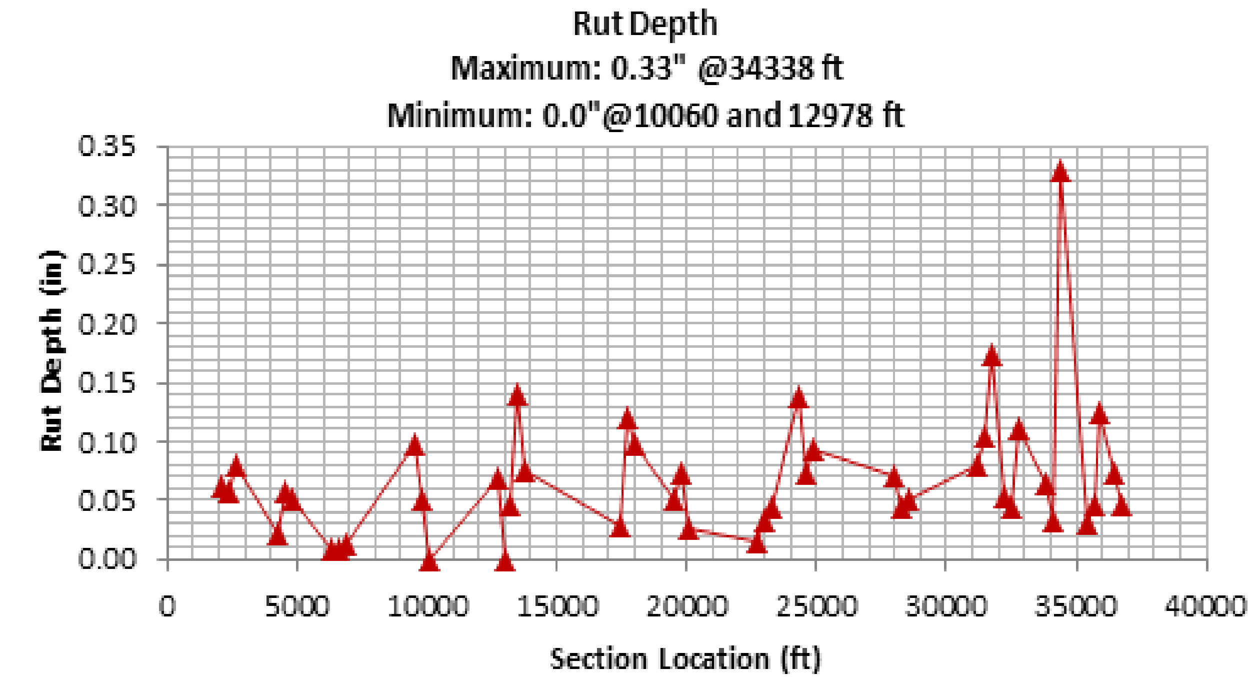

Figure 4.9 Dipstick Device (Rutting) Output

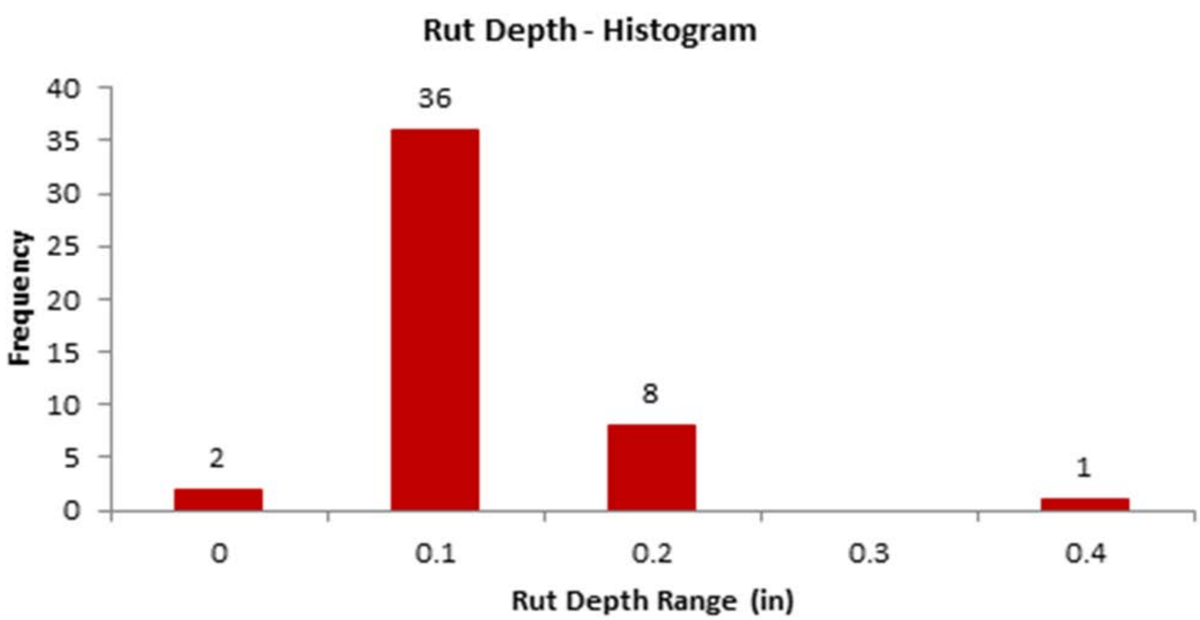

Figure 4.10 Dipstick Device Output Histogram

The baseline Falling Weight Deflectometer (FWD) measurements were taken approximately every 250 feet throughout the test section locations. Post-construction

FWD measurements were obtained and show that the chip seal made no considerable contribution to the structural capacity of the pavement, as expected and further supporting its classification as a pavement preservation treatment. Figure 4.12 shows the similar pre- and post-construction results.

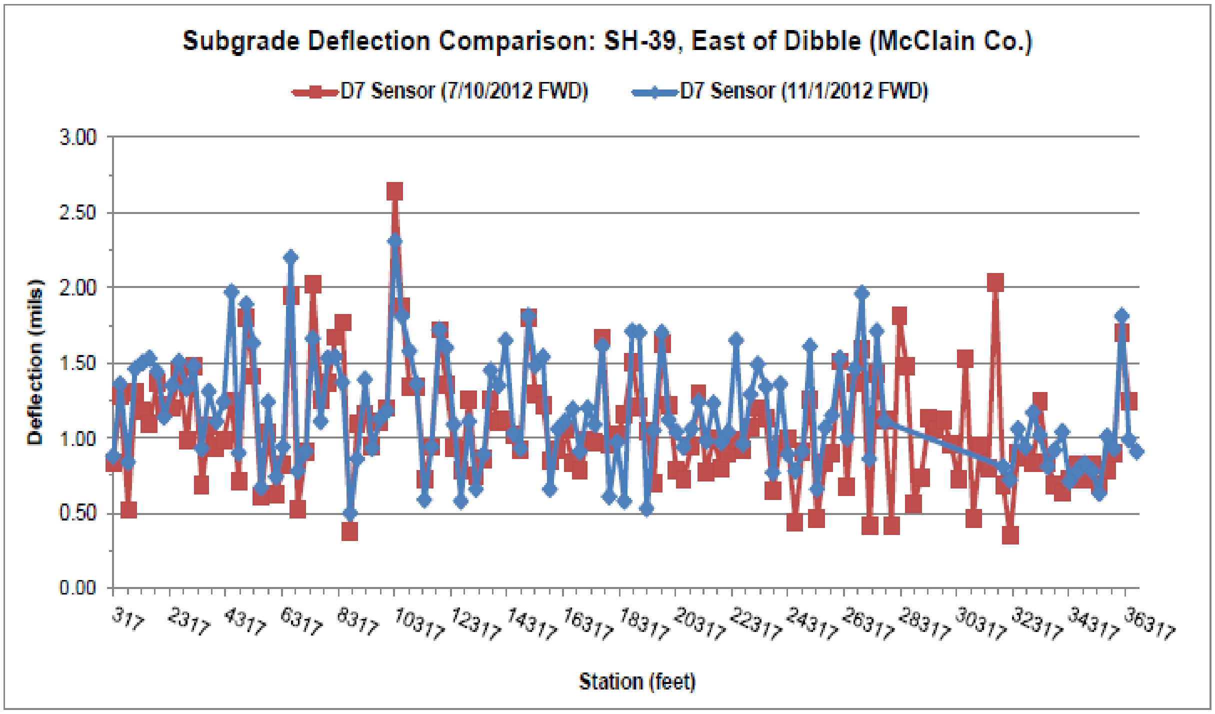

Figure 4.11 FWD Results, Pre- and Post-Construction (Chip Seal)

4.3.3 Surface Texture Measurement

Microtexture and macrotexture measurements have been obtained on a monthly basis and are ongoing. The chip seal test sections all have the same traffic, same environmental conditions, and were installed by the same construction crew with the same equipment. This furnishes a direct comparison that involves only the variables of interest in this project.

The purpose of obtaining surface texture measurements on this project is to facilitate the creation of deterioration models to compare the performance of PUC-based and non-PUC-based chip seal test sections. Linear regression will be applied to the field trial microtexture and macrotexture data to approximate the deterioration rate and extrapolate the remaining service life of each treatment, which was found to yield high

R^2 values when applied to chip seal [56]. These will then be compared to failure criteria found in the literature. Service life will be determined by identifying the time it took each treatment to deteriorate to each failure criterion. The failure criterion for macrotexture is 0.9mm, which is consistent with TNZ P/12 performance specification [45]. The failure point considered for microtexture is a skid number less than 25. The resulting approximate service life for each alternative will be compared literature review results.

There are two tests being performed on each test section monthly to facilitate performance evaluation:

1. Microtexture (ASTM E274)
2. Macrotexture (TNZ3 Sand Circle).

To reduce variability in monthly measurements, the research team identified the locations of the baseline measurements and marked them with PK nails and landmarks so that sand circle testing occurs as close to the same locations as possible. Photos were also taken for future locating reference.

The newly constructed chip seal sections on Highway 39 were first tested in November 2012 after one month of service. For macrotexture measurement, three sand circles were taken on the outside wheel path and averaged together to eliminate any irregularities caused due to slight variations in the test location. Macrotexture on all sections increased from the baseline measurements, as expected because chip seal increases macrotexture. The baseline measurement was conducted on asphalt pavement, which only exhibits microtexture.

Seventy existing-substrate microtexture measurements were taken with: a ribbed tire (mean skid number = 45.8, sd = 3.15) and a smooth tire (mean skid number = 39.1, sd = 4.68), showing that the existing asphalt pavement exhibited adequate skid resistance. Post-construction measurements were taken to obtain a ribbed tire measurement (mean skid number = 41.5, sd = 4.95) and a smooth tire measurement (mean skid number = 41.8, sd = 5.16) showing that the chip seal did not significantly alter skid resistance. Microtexture was measured on the outside wheel path by the ODOT skid truck. Five ribbed tire measurements and five smooth tire measurements have been obtained for every test section each month when possible. The five skid numbers resulting from the respective tests were averaged to eliminate any irregularities due to slight variations in the test location and provide data for a given test section.

As part of OTCREOS7.1-16, four chip seal test sections were constructed on Highway 77 in Norman [4]. The performance of these chip seals was being monitored using field observations and testing as part of Phase II of OTCREOS9.1-21, which has completed [56]. With ODOT assistance, field testing and performance monitoring of these test sections was to continue on a quarterly basis for two years so that the results could be correlated with chip seal performance. However, test results have not been provided by ODOT so no analysis can be completed.

4.4 DOCUMENTING OKLAHOMA CHIP SEAL CONSTRUCTION PRACTICES

ODOT Division 3 indicated that a careful documentation of the chip seal construction procedures would add value to this research. Therefore, a constructability review of the chip seal test section construction practices was conducted. Additionally, other ODOT Divisions participated by sharing common chip seal construction practices used in their regions. NCHRP Synthesis 342: Chip Seal Best Practices was reviewed [3] and a checklist was created, augmented with the 2009 ODOT specifications, to assist researchers in conducting the constructability review.

The review has identified those construction factors that impact chip seal performance but cannot be specified by other means. Information was collected regarding the chip sealing equipment to determine its state of maintenance, equipment-related factors such as roller tire pressures before, during and after construction, and the number of times the aggregate is handled between the pit and the road. The exact steps taken by the chip seal crews to prepare the substrate, install the chip seal, roll the section, broom, and timing of various events in the construction process was noted. Moreover, the review evaluated the traffic control methods used and the age of the seal when traffic control is removed. The purpose of this type of analysis was to find those construction factors that support good chip seal performance and identify the means and methods that allow ODOT to replicate success.

4.5 INVESTIGATING FOG SEAL AND GEOSYNTHETIC FABRIC CONTRIBUTION

Fog seal (slow setting emulsion: SS-1) was obtained from Vance Bros. in Oklahoma City and applied to half of each chip seal test section two weeks after construction, as shown in Figure 4.13. Fog seal is a pavement preservation treatment option [57,58] that is essentially “a light spray application of dilute asphalt emulsion” [59]. Aggregate loss is a failure criterion associated with chip seal [2] that can be mitigated by applying fog seal to the chip seal surface, whereby maintaining macrotexture [38. Although performance information is limited, fog seals have been found to enhance short-term pavement performance [58], but have not been shown to enhance skid resistance or slow surface deterioration over the long term and more research is needed [58,60,61,62]. Therefore, this research is conducting surface texture testing to determine the efficacy of fog seal on the chip seal test sections.

The fabric section mistakenly received CRS-2S emulsion instead of fog seal. Some agencies use CRS instead of SS-1 on the surface of chip seal to retain aggregate. However, this adds another variable in the test sections that will have to be considered when comparing fabric sections to non-fabric sections.

On the day of test section construction, geotextile fabric was installed in two of the test sections. MPV-500 paving fabric was installed over PG 64-22 OK on the existing pavement, then rolled with a pneumatic-tire roller before the chip seal was installed. Paving fabric under chip seal can mitigate reflective cracking and water penetration to protect the underlying pavement and extend its service life, yielding a lower life cycle cost than a traditional chip seal [63]. The use of paving fabric in chip seal systems is a common and effective practice in New Zealand and Australia; however there are mixed results reported in US applications [3].

Figure 4.12 Fog Seal Application to Chip Seal Test Sections

5.0 LABORATORY TEST RESULTS AND ANALYSIS

This study is ongoing under ODOT project [2239]. However, the scope of the project is mostly complete. This section reports current results and provides analysis for laboratory testing, including aggregate characterization and aggregate-binder compatibility.

5.1 AGGREGATE CHARACTERIZATION RESULTS AND ANALYSIS

Aggregate samples for the five gradations were collected from the quarries and also from the stockpiles on Highway 39. A sieve analysis was conducted and all of the samples were in gradation. Samples of the five gradations were also taken from the chip spreader at the beginning of each test section. A sieve analysis will be conducted on these samples. The samples from each area (quarry, stockpiles and chip spreader) will also be AIMS tested to document any changes in aggregate characteristics due to handling.

Preliminary results from LA Abrasion and Micro-Deval tests for the five aggregate sources are shown in Table 5.1. It should be noted that previous studies have shown that no correlation exists between LA Abrasion and Micro-Deval test results, which was also found by this study.

Table 5.1 Preliminary LA Abrasion and Micro-Deval Results

Quarry	Aggregate Type	LA Abrasion	Micro-Deval
Dolese-Cooperton	limestone	18%	10.1%
Hanson-Davis	rhyolite	11%	7.6%
Martin Marietta-Mill Creek	granite	19%	0.3%
Dolese-Hartshorne	limestone	13%	10.7%
Kemp Stone-Pryor	limestone	21%	22.8%

The rhyolite from Hanson and the granite from Martin Marietta were expected to be more resistant to impact and abrasion than the limestone from the other three sources. However, Micro Deval and LA Abrasion results are mixed. The Micro Deval results show that the limestone was similarly resistant to impact as the rhyolite. The AIMS results based upon Sphericity II in the next section indicate that the Dolese Cooperton limestone material exhibited a lower flat-elongated ratio than did the Hanson rhyolite material, which contributes to its impact resistance. Therefore, the shape of the limestone particles may compensate for its lower impact resistance. This finding may support chip seal design practices, as most divisions prefer to use limestone cover aggregate in chip seals because it is thought to mitigate windshield damage from dislodged aggregate.

Two of the five aggregate source samples have been analyzed by AIMS1. The descriptive statistics for each material is listed in Table 5.2 for each of the AIMS1 parameters. A statistically significant difference exists between the materials on the basis of sphericity and texture ($p<0.05$), but no difference exists on the basis of angularity and 2D form ($p>0.05$). It is important to note that the values are based on 3/8" size fraction only. The results may differ for the aggregate blends noted in the chip seal gradations in Table 4.3. The AIMS1 testing for the blends is ongoing and results will be reported in the ODOT report.

Table 5.2 Descriptive Statistics for AIMS1 Output for 2 Aggregate Samples

AIMS Property	Hanson – Davis (3/8")			Dolese – Cooperton (3/8")			p-value (CI=95%)
	Sample Size	Mean	Std. dev.	Sample Size	Mean	Std. dev.	
Gradient Angularity	55	3424	1448	52	2992	900	0.065
Sphericity I	49	0.54	0.084	52	0.64	0.097	0.000
Sphericity II	54	0.3022	0.1316	56	0.5938	0.1779	0.000
2D Form	51	7.579	2.042	53	8.232	2.379	0.136
Texture	51	176.8	54.78	56	260.0	78.9	0.000

Rounded particles are more susceptible to slide laterally on hot summer days under heavy traffic, which increase the rutting potential of the chip seal. The gradient angularity indices can provide insight about the roundedness of particles. Figure 5.1

shows gradient angularity indices output for the Hanson Davis 3/8” aggregate. The indices for all of the tested Hanson particles in the sample range from 1800 to 8500. However, the majority (about 68%) of the particles are sub-rounded, indicated by an angularity index of particles in the range of 2100 to 4000. About 12% of the particles are rounded, indicated by an angularity index of less than 2100. Figure 5.1 also shows gradient angularity indices for the Dolese Cooperton 3/8” aggregate. The sample exhibited a tighter indices range of 1100 to 6500. Although it had fewer rounded particles (approximately 5%) than the Hanson material, 90% of the particles were contained within the rounded and sub-rounded ranges. No statistically significant difference exists between the gradient angularity indices for the two materials, meaning both 3/8” material should contribute the same level of rutting resistance based on this AIMS parameter.

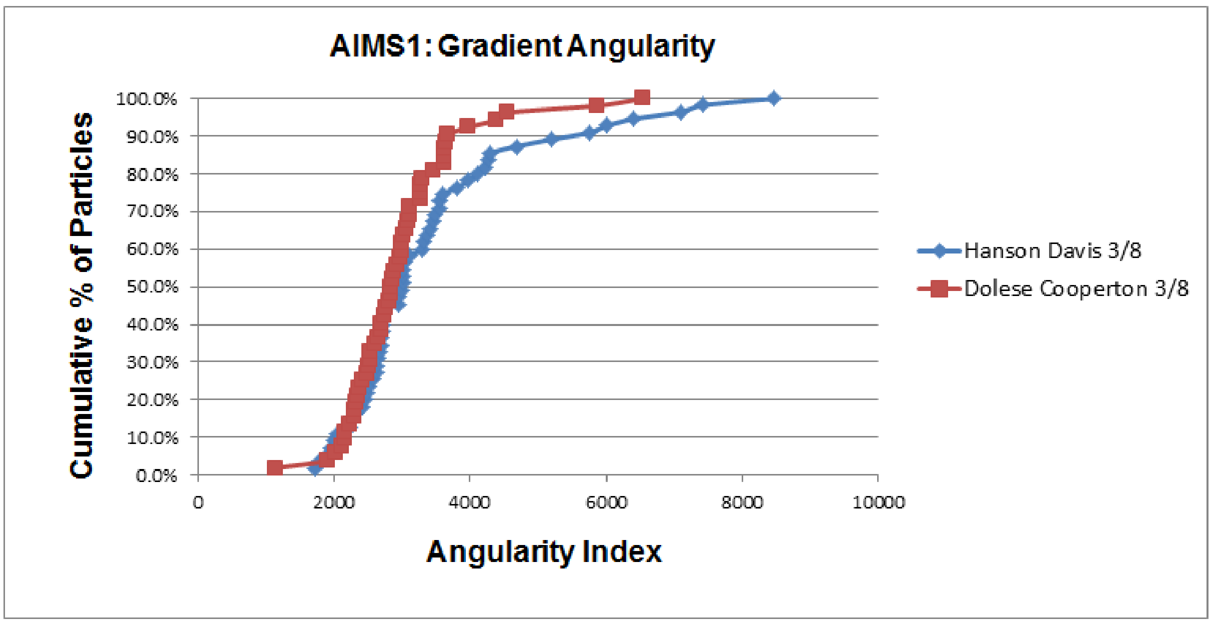

Figure 5.1 AIMS1 Output for Gradient Angularity

Figure 5.2 and Figure 5.3 show AIMS1 output for Sphericity I & II, respectively, for 3/8” Hanson Davis aggregate. Although the Sphericity I indices range from 0.38 to 0.68, the majority (80%) of the tested particles have flat/elongated to low sphericity, compared to only 40% of the 3/8” Dolese Cooperton material, as shown in Figure 5.2. The same trend is apparent in Figure 5.3. A statistically significant difference exists between the two materials based upon sphericity. Sphericity is a relative measure of aggregate shape with the greatest value denoting a cubical particle, the desired cover aggregate shape. Since the purpose of the cover aggregate is to protect the bituminous seal from traffic wear, a high sphericity index is desirable. This is based on the need for a consistent size particle to ensure that the majority of the cover aggregate particles have a least dimension greater than the embedment depth, which is also fundamental to the PUC concept to reduce bleeding and flushing.

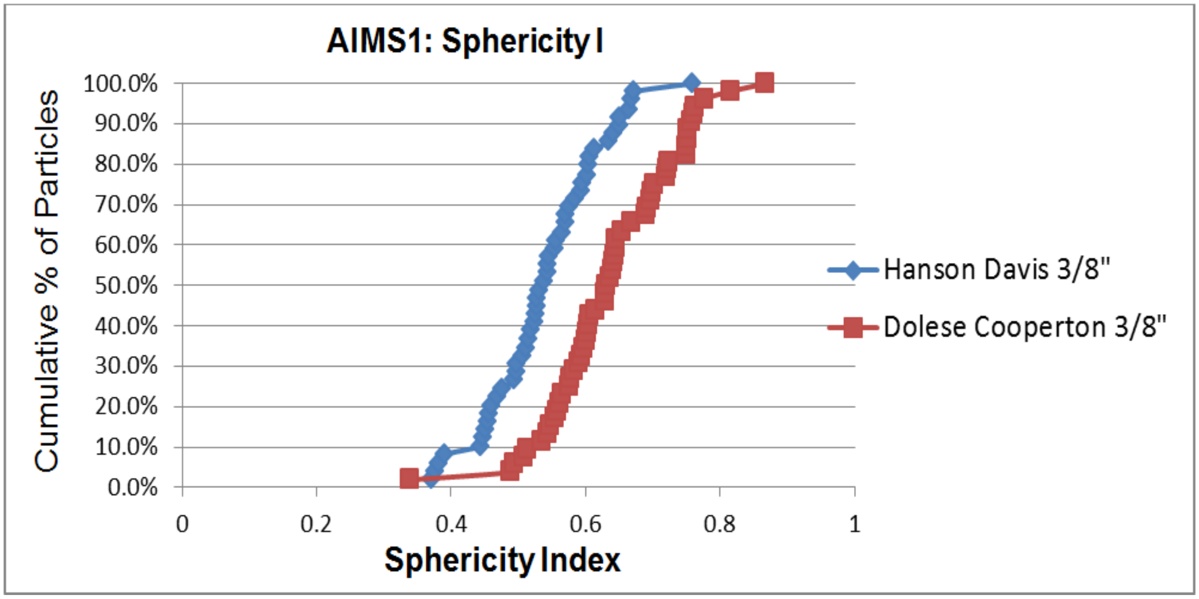

Figure 5.2 AIMS1 Output for Sphericity I

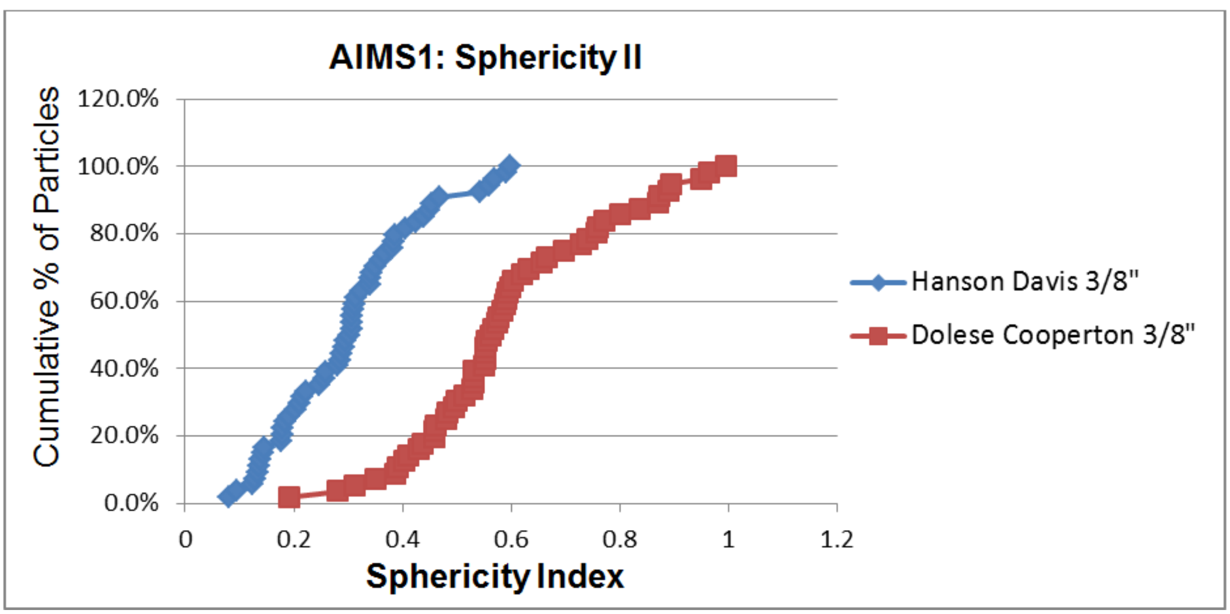

Figure 5.3 AIMS1 Output for Sphericity II

The distribution of particles in Figure 5.3 indicates that there are a significant number of particles above the 5:1 elongation ratio for both materials. However, the Superpave requirement is to have no more than 10% particles below 5:1 elongation ratio. Approximately 40% of the Hanson material falls below the 5:1 ratio compared to approximately 4% of the Dolese material. Therefore, the Dolese Cooperton material, although limestone, may be less prone to breakage under traffic than the Hanson material.

Research continues as to the validity of AIMS1 and AIMS2 output and correlation. AIMS1 texture indices were shown to be lower (polish values higher) than AIMS2 texture indices based upon preliminary results of this study, as explained in Section 4.1. Aggregates that have higher polished face values are not as desirable for use in chip seal; therefore, the AIMS1 results will not appear as favorable as AIMS2 with regard to texture. Care should be exercised when interpreting the AIMS1 data in this section. The researchers are considering only relative differences in texture for the purpose of comparing given aggregates, which suits the purpose of this research.

Figure 5.4 shows the texture output for the 3/8” Hanson Davis material. Texture indices range from 100 to 300. The results indicate that approximately half of the faces of tested particles are mostly polished, while the other half are smooth. Approximately only 5% of the sample exhibits low roughness. The texture output for the 3/8” Dolese Cooperton material is also shown in Figure 5.4. A statistically significant difference exists in data for the aggregate sources indicating that the Dolese Cooperton 3/8” may provide an increased level of surface friction and adhesion.

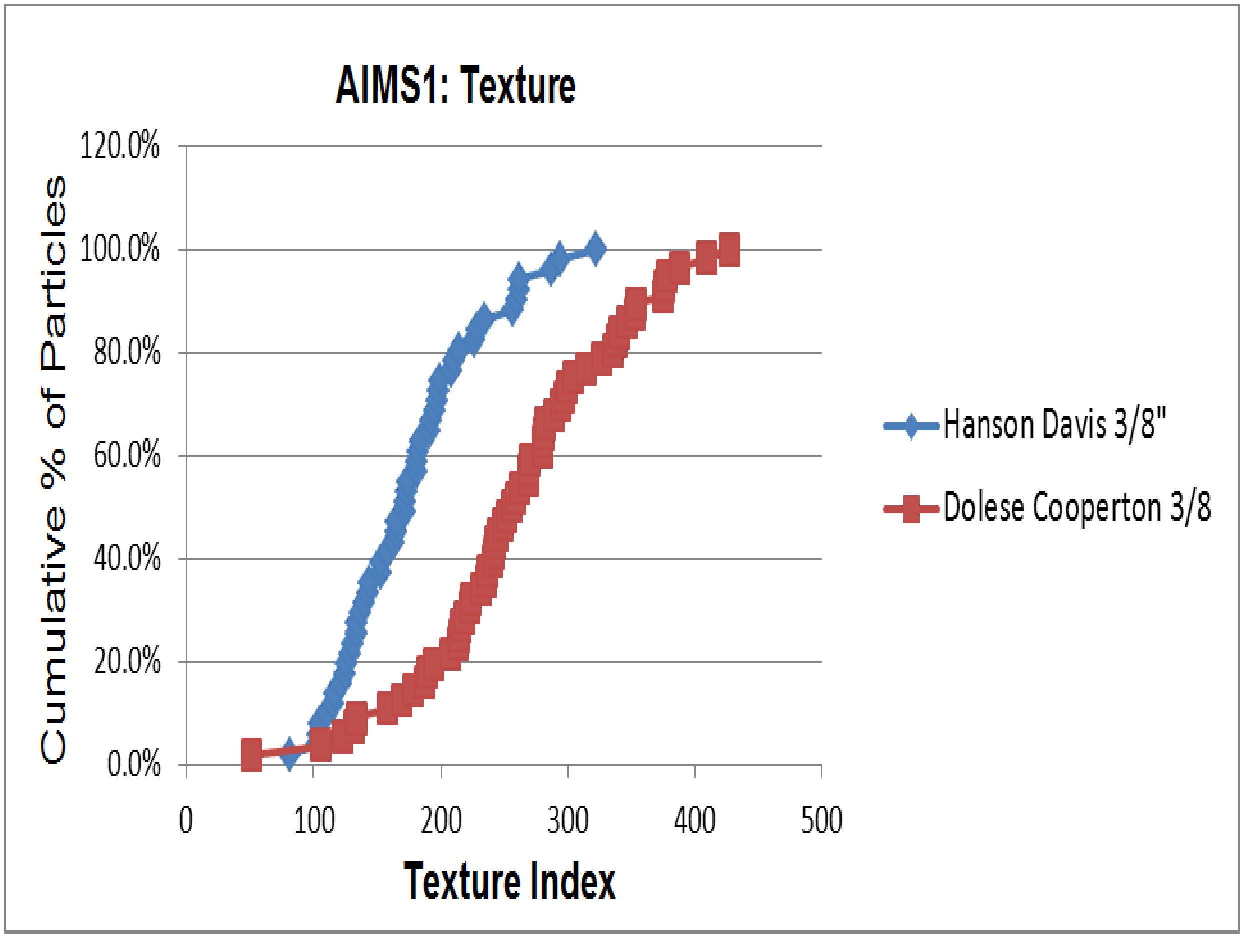

Figure 5.4 AIMS1 Output for Texture

Results for the 3/8" aggregates from Hanson Davis and Dolese Cooperton are summarized in Table 5.3. Results of shape and texture for each aggregate source and size fraction will be obtained and combined into a weighted average based upon gradation. Conclusions will be drawn to determine Oklahoma aggregate-source characteristics that affect chip seal performance. Additionally, test section aggregate obtained at three locations (quarry, stockpile and road) will be tested to determine any effect of handling.

Table 5.3 AIMS1 Results for Two 3/8" Aggregate Sources

AIMS Property	Hanson – Davis (3/8")		Dolese – Cooperton (3/8")	
Shape	Range	% in Range	Range	% in Range
Gradient Angularity	1800 - 8500	100	1100 - 6500	100
Rounded (< 2100)		12		5
Sub-Rounded (2100 - 4000)		68		85
Sub-Angular (4000 - 5400)		10		6
Angular (> 5400)		10		4
Sphericity I	0.38 – 0.68		0.34 – 0.88	
Flat/Elongated (< 0.6)		80		30
Low Sphericity (0.6 – 0.7)		19		40
Moderate Sph. (0.7 – 0.8)		1		26
High Sphericity (> 0.8)		0		4
Sphericity II				
Above 5:1 elongation ratio		60		96
Below 5:1 elongation ratio		40		4
Texture				
Texture	100 - 300		75 - 325	
Polished Faces (< 165)		55		15
Smooth Faces (165 – 275)		40		45
Low Roughness (275 – 350)		5		30
Mod. Roughness (350 - 460)		0		10
High Roughness (> 460)		0		0

In a previous OkTC study, aggregate angularity was shown to be a predictor of adhesion between the binder and the aggregate [6]. There was also a potential correlation between the gradient angularity measured by AIMS1 and the skid number as measured with the locked wheel skid test. Moreover, there was a promising relationship between the Performance-based Uniformity Coefficient (PUC) and the radial angularity, sphericity, and texture index measured by AIMS1. Micro Deval results have also been shown to correlate with AIMS results. These correlations will continue to be investigated as this study continues.

5.2 AGGREGATE-BINDER COMPATIBILITY

Testing for aggregate-binder compatibility has been completed. Contact angles of aggregates were evaluated using the aggregates collected for the research. Contact angle measurements with liquids of known surface energy (water, ethylene glycol and di-iodomethane (DIM)) were used to quantify the SFE components of the aggregate. Sessile Drop results for Dolese-Cooperton (probe liquid: water) are shown for illustrative purposes in graphical and numerical form in Figure 5.5 and Table 5.4, respectively. Complete Sessile Drop results for the five aggregates are listed in Appendix A.

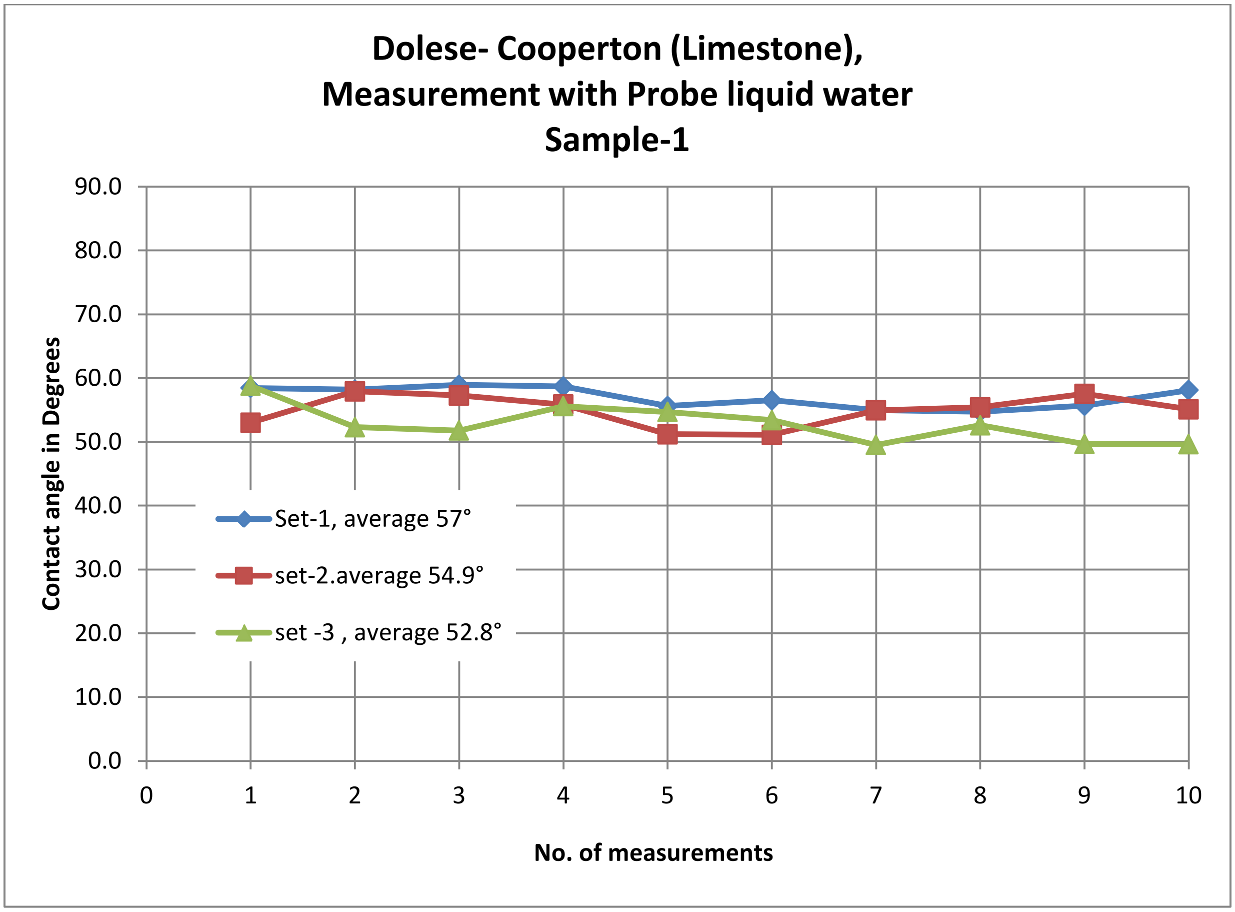

Figure 5.5 Sessile Drop Results Graph for Dolese Cooperton

Table 5.4 Sessile Drop Results for Dolese Cooperton

Test No.	set – 1 (Day-1)	set – 2 (Day-2)	set – 3 (Day-3)
		(In Degrees)	
1	58.5	53.0	58.8
2	58.2	57.9	52.3
3	58.9	57.3	51.8
4	58.7	55.8	55.6
5	55.6	51.2	54.7
6	56.5	51.1	53.4
7	55.0	54.9	49.5
8	54.7	55.4	52.6
9	55.7	57.5	49.7
10	58.1	55.1	49.6
Average	**57.0**	**54.9**	**52.8**
Std. deviation	**1.7**	**2.5**	**3.0**
Overall average		**54.9**	

Sessile Drop testing (and subsequent data collection) has been completed for all of the aggregate and emulsion sources. Surface free energy values for each are listed in Table 5.5. Subsequently, the free energy of adhesion was calculated and the results are listed in Table 5.6.

Table 5.5 SFE Components of Study Aggregates and Emulsion

Materials	SFE Components (ergs/cm^2) from Sessile Drop				
	γ^{Total}	γ^{LW}	γ^{AB}	γ^{-}	γ^{+}
ERGON CRS-2S	37.65	29.85	7.80	77.29	0.24
Coastal CRS-2S	38.54	29.01	9.53	71.63	0.32
Dolese Cooperton 1	48.17	44.30	3.86	22.97	0.16
Dolese Cooperton 2	41.61	37.58	4.03	31.51	0.13
Dolese Cooperton 3	41.24	38.73	2.52	16.95	0.09
Hanson Davis 1	45.57	39.91	5.66	26.26	0.31
Hanson Davis 2	43.74	37.03	6.71	18.53	0.61
Martin Marietta Mill Creek 1	43.73	35.84	7.89	36.98	0.42
Martin Marietta Mill Creek 2	40.33	34.74	5.60	25.62	0.31
Martin Marietta Mill Creek 3	42.13	38.69	3.44	39.42	0.07
Dolese Hartshorne	44.78	38.16	6.62	14.02	0.78
Kemp Stone Pryor 1	45.33	37.48	7.85	21.05	0.73

Materials	SFE Components (ergs/cm^2) from Sessile Drop				
	γ^{Total}	γ^{LW}	γ^{AB}	γ^{-}	γ^{+}
Kemp Stone Pryor 2	49.36	42.16	7.20	14.34	0.90
Kemp Stone Pryor Average	47.35	39.82	7.53	17.70	0.82
Davis Dolese 1	39.04	37.57	1.47	20.68	0.03
Davis Dolese 2	35.39	32.77	2.62	14.21	0.12
Davis Dolese 3	38.13	36.34	1.79	20.15	0.04
Davis Dolese Average	37.52	35.56	1.96	18.35	0.06

Table 5.6 Free Energy of Adhesion Values for Aggregate and Emulsion Sources

Materials	Free Energy of Adhesion			
	ERGON CRS-2S		Coastal CRS-2S	
	Wet Case	Dry Case	Wet Case	Dry Case
Dolese Cooperton 1	29.30	84.48	26.59	83.89
Dolese Cooperton 2	37.91	78.85	34.97	78.49
Dolese Cooperton 3	24.57	77.33	21.83	76.77
Hanson Davis 1	31.69	83.86	28.98	83.27
Hanson Davis 2	22.90	84.46	20.43	83.64
Martin Marietta Mill Creek 1	40.25	82.79	37.41	82.34
Martin Marietta Mill Creek 2	31.79	79.17	29.02	78.64
Martin Marietta Mill Creek 3	44.55	78.79	41.47	78.59
Dolese Hartshorne	16.88	86.71	14.58	85.73
Pryor Stone Pryor 1	24.88	86.43	22.42	85.60
Pryor Stone Pryor 2	16.28	91.36	14.06	90.29
Davis Dolese 1	29.60	74.50	26.70	74.10
Davis Dolese 2	21.85	72.35	19.12	71.79
Davis Dolese 3	29.02	73.80	26.13	73.40

Additional testing was completed in an effort to determine the SFE of emulsion, since no protocol currently exists in literature. The initial objective of the supplemental SFE analysis was to estimate SFE through dynamic contact angle (DCA) measurements, which requires thin and smooth glass plates (Fisher Scientific) specimens (50 mm X 24 X No. 1.5) coated with emulsion. Figure 5.6 shows some typical DCA specimens prepared from an asphalt binder sample. In the specimen preparation process, asphalt binder is heated at 150^{o}C for about two hours and then hot glass plates are dipped into the liquid asphalt to prepare smooth specimens. These specimens are tested by measuring SFE components of asphalt binder samples by using three probe liquids (water, ethylene glycol and formamide) as recommend by Texas Transportation Institute researchers. The measured SFE components are then used to estimate the total SFE of the asphalt binder systems.

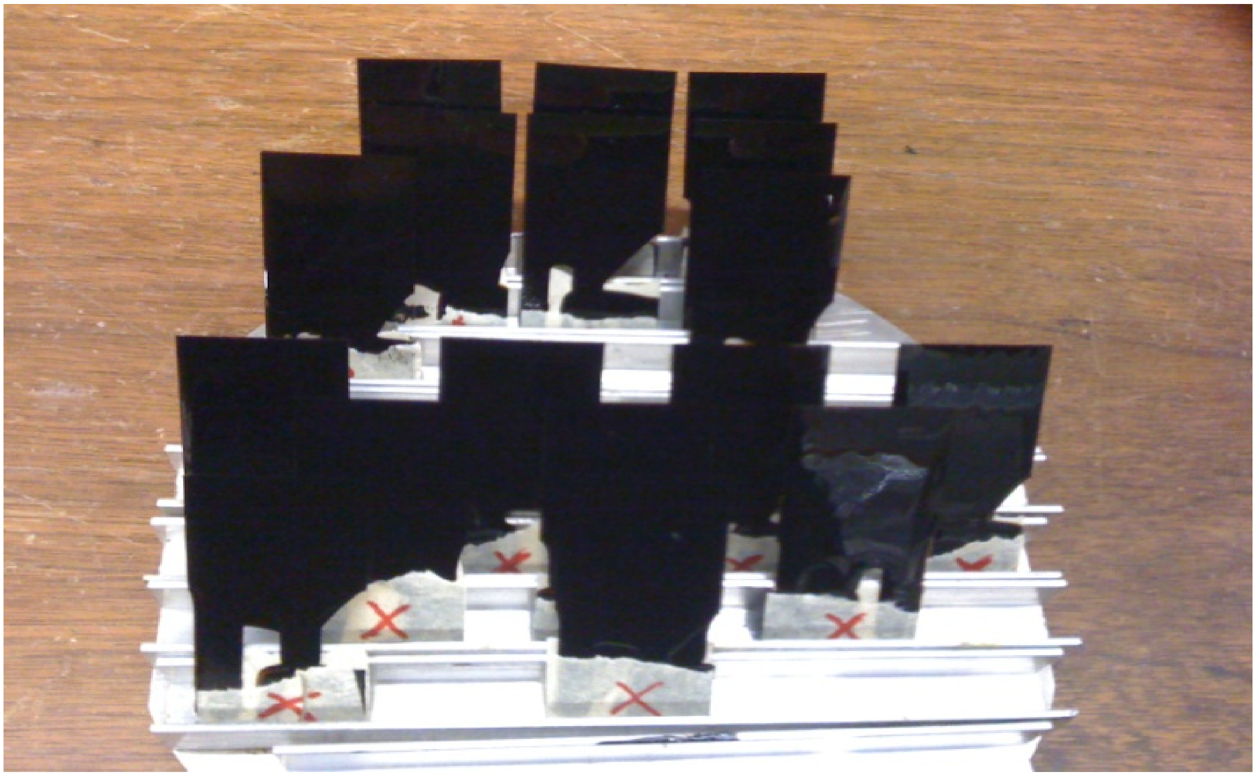

Figure 5.6 Typical DCA Specimens Prepared from Asphalt Binder

Since emulsions contain significant portion of water, which is expected to evaporate at high temperature, the research team did not pursue the same protocol used for asphalt binders. Even though emulsions are liquid at room temperature, they are not soft enough to prepare DCA specimens. Thus, reduced temperature (less than 100^{o}C) was applied gently to prepare low consistency emulsion (liquid). To this end, the emulsion sample was heated for one hour at three selected temperatures: 70^{o}C, 80^{o}C and 90^{o}C. Specimens were then prepared, as shown in Figure 5.7. Specimens contained significant number of bubbles around their surfaces (Figure 5.7), making them non-uniform, which is not desirable for DCA measurements. Thus, the research team explored a different approach to measure the total SFE as explained in the next section.

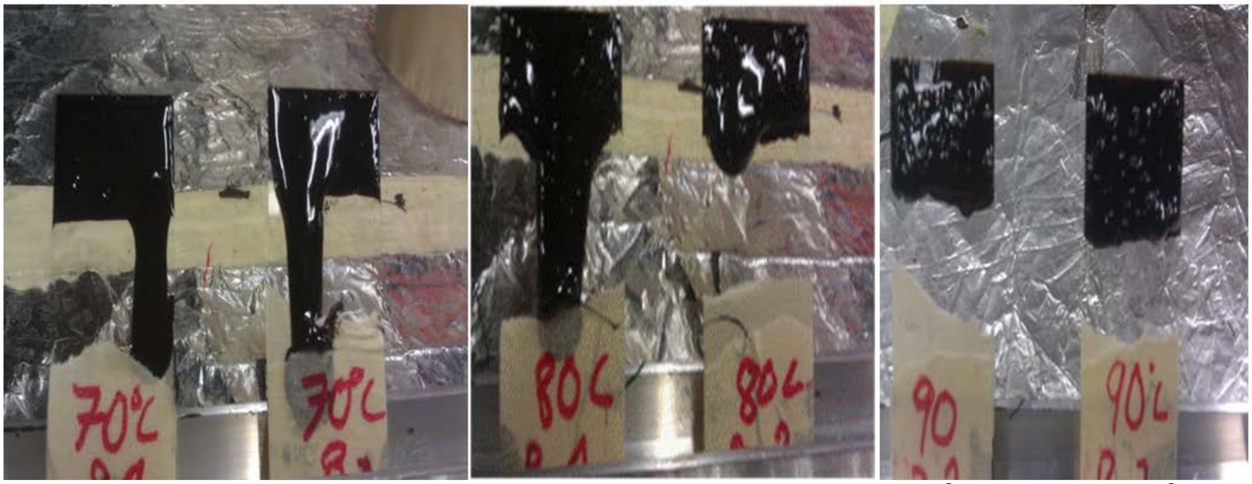
Figure 5.7 Emulsion Coated Glass Cover Specimens: (Left) 70^{0}C; (Middle) 80^{0}C; (Right) 90^{0}C

The Cahn Dynamic Contact Angle (DCA) analyzer (Figure 5.8) was used to measure the surface tension (ST) of emulsion samples, consisting of a highly sensitive balance, a moving stage mechanism and a control station. The ST measurements were then used to estimate the total SFE values of the tested emulsion samples. A window based software program, WinDCA, was used to control the DCA system, collect data and perform data analysis. In this application, a Wilhelmy plate, made of glass was used to measure ST of emulsion. At the beginning of each set of test, the validation of the device was performed by measuring ST of deionized water at room temperature (25^{o}C), which was about 72 dynes/cm.

The tested emulsion was a cationic emulsion produced by Ergon at Lawton, OK ((Product: CRS-2[5]; Tank No. 20; Date Sampled: 5/18/12; Batch Run: LA051112004; Person Sampled: SR). The emulsion was sampled at two conditions: (1) sample obtained directly from the refinery, or plant (Set I), and (2) sample collected from construction test site (Set II). Emulsion samples were collected at the construction site at the beginning and middle point of the day of construction. Total SFE values of the tested emulsion are shown in Figure 5.9, in which the vertical bar represents one standard deviation (error bar) for the given set of specimens.

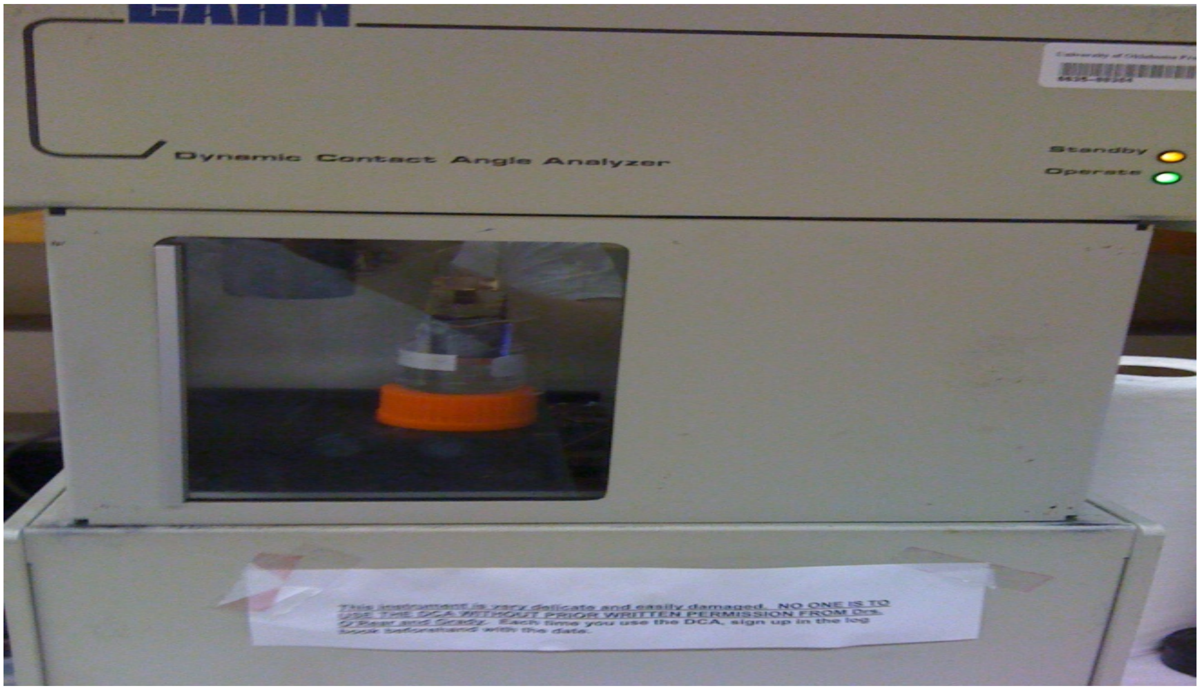

Figure 5.8 The Cahn Dynamic Contact Angle (DCA) Analyzer

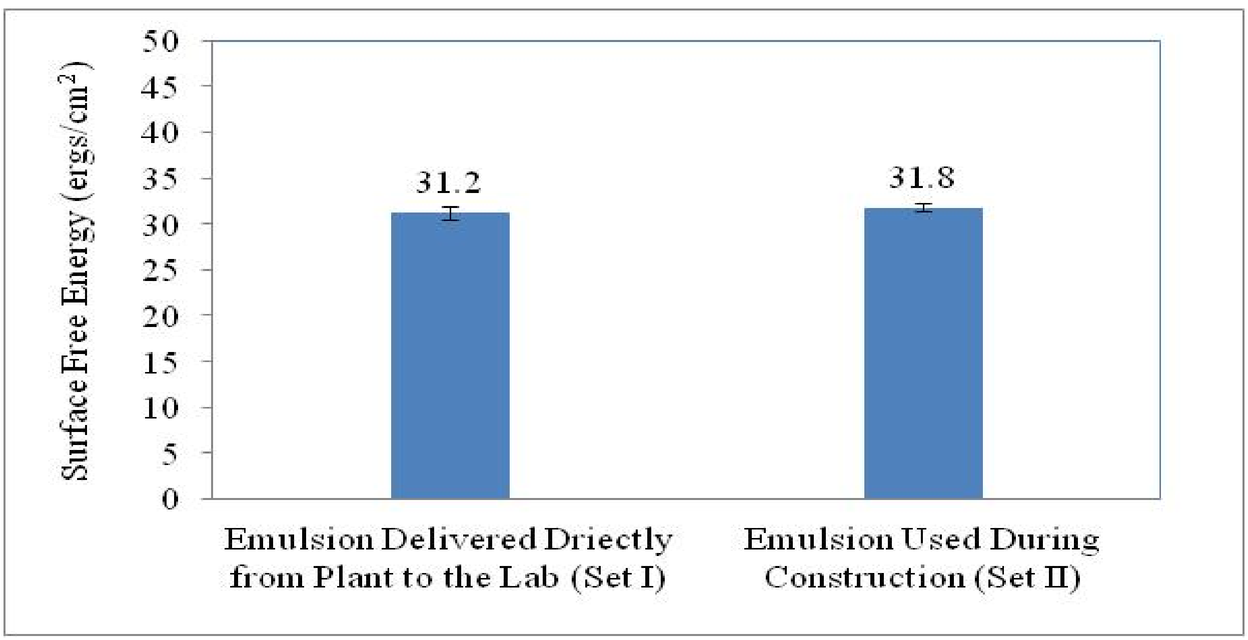

Figure 5.9 Total SFE (ergs/cm2) of Tested Emulsion

Four replicate specimens were tested for each emulsion sample to ensure repeatability. Thus, a total of eight specimens were tested and good repeatability was observed. Figure 5.9 shows that the SFE values of Set I and Set II samples were found to be 31.2 ergs/cm^2 and 31.8 ergs/cm^2, respectively. This indicates that the SFE values of the emulsion sample collected from the construction site and the emulsion sample shipped to the testing lab are almost identical. Therefore, no changes in SFE values occurred between emulsion source and project destination.

Using the SFE components of tested emulsions and aggregates obtained from the Sessile Drop method as presented previously, the CR values were calculated. The CR of different aggregate emulsion systems are listed in Table 5.7. All ratios are greater than 0.8, indicating that each aggregate source is compatible with each emulsion source, as listed.

Table 5.7 Compatibility Ratios for Aggregate-Binder Compatibility

Material	**Compatibility Ratio (CR)**	
	ERGON (Lawton)	Coastal (MO)
Martin Marietta Mill Creek	2.08	2.23
Dolese Cooperton	2.60	2.84
Davis Dolese	2.74	3.04
Hanson Davis	3.08	3.37
Kemp Stone Pryor	4.29	4.78
Dolese Hartshorne	5.14	5.88

After the test section aggregate was procured from Dolese Davis, it was also evaluated for compatibility. As noted in Table 5.7, it also has good compatibility with the listed emulsion sources. This is also supported by test section performance, discussed in the next section, which has not exhibited early failure as would be expected if the materials had poor compatibility. Therefore, when each of the cover aggregates are paired with the emulsions listed in Table 5.7 for chip seal application, the pavement engineer can expect the system to have good resistance to moisture damage excepting any other variables.

Validation of these results is required to assure data quality due to the difficulty associated with preparing high quality DCA and SD samples using emulsion, for which no protocol exists. The challenge lies in obtaining a consistent and smooth surface for the plates coated with emulsion. Hence a typical set of SFE results from DCA testing conducted on PG 64-22 asphalt binder was used to calculate CR values for the different tested aggregates. PG 64-22 asphalt binder was selected to represent the base asphalt binder used for emulsion production. The SFE components of the PG 64-22 asphalt binder are presented in Table 5.8.

Table 5.8 SFE Components of Typical PG 64-22 Asphalt Binder

Materials	SFE Components (ergs/cm^2) from Sessile Drop				
	γ^{Total}	γ^{LW}	γ^{AB}	γ^{-}	γ^{+}
Typical PG 64-22	11.57	9.44	2.13	0.93	1.22

Table 5.9 presents the free energies of adhesion in dry and wet conditions and CR values calculated for each aggregate with the Typical PG 64-22 asphalt binder.

Table 5.9 Compatibility Values for Aggregates with PG 64-22 Asphalt Binder

Materials	SFE Components (ergs/cm^2) from Sessile Drop					Free Energy of Adhesion (ergs/cm^2)		CR value
	γ^{Total}	γ^{LW}	γ^{AB}	γ^{-}	γ^{+}	Wet Case	Dry Case	
Dolese Cooperton 1	48.17	44.30	3.86	22.97	0.16	33.68	52.24	1.55
Dolese Cooperton 2	41.61	37.58	4.03	31.51	0.13	29.18	50.74	1.74
Dolese Cooperton 3	41.24	38.73	2.52	16.95	0.09	41.19	47.90	1.16
Hanson Davis 1	45.57	39.91	5.66	26.26	0.31	30.85	51.19	1.66
Hanson Davis 2	43.74	37.03	6.71	18.53	0.61	36.22	48.39	1.34
MM Mill Creek 1	43.73	35.84	7.89	36.98	0.42	23.59	51.45	2.18
MM Mill Creek 2	40.33	34.74	5.60	25.62	0.31	32.68	48.45	1.48
MM Mill Creek 3	42.13	38.69	3.44	39.42	0.07	24.43	52.58	2.15
Dolese Hartshorne	44.78	38.16	6.62	14.02	0.78	39.52	47.92	1.21
Kemp Stone Pryor 1	45.33	37.48	7.85	21.05	0.73	33.27	53.14	1.60
Kemp Stone Pryor 2	49.36	42.16	7.20	14.34	0.90	37.65	53.35	1.42
Davis Dolese 1	39.04	37.57	1.47	20.68	0.03	39.13	48.76	1.25
Davis Dolese 2	35.39	32.77	2.62	14.21	0.12	45.13	45.54	1.01
Davis Dolese 3	38.13	36.34	1.79	20.15	0.04	39.69	48.23	1.22

It is evident that the CR values for all of the aggregate-binder combinations listed in Table 5.9 are greater than 0.8. This may be interpreted as a possible indication of acceptable performance against debonding from the binder as a result of moisture induced damage. The same trend is also observed in the aggregate and emulsion SFE data that were used for CR calculation. Therefore, the aggregate-emulsion compatibility results are validated.

6.0 FIELD TEST RESULTS AND ANALYSIS

The ultimate goal of the project field testing is to determine relative differences in performance between the chip seal test sections. Specifically, the objective is to evaluate test sections that have PUC gradations and compare them to test sections that were built with traditional gradations. Additionally, sections with and without fog seals and geosynthetic fabric are being monitored for performance. Macro- and microtexture values obtained at one year of service have been deemed appropriate to evaluate chip seal performance [45,64]. However, some insight can be gained by examining research data to date that has been obtained from chip seal test sections over the last 7 months. All of the chip seal test sections are performing satisfactorily on the basis of macro and microtexture at the time of this writing. Additionally, chip seal construction practices were observed and compared with effective practices. The fact that the chip seal test sections have not exhibited short term failure is an indication of proper construction practices and aggregate-binder compatibility, among other factors.

6.1 MICROTEXTURE AND MACROTEXTURE RESULTS AND ANALYSIS

Post-construction microtexture measurements were taken in November that show all of the sections that received fog seal (or emulsion, mistakenly) exhibited a lower skid number compared to respective sections with no fog seal, as expected. For example, Table 6.1 shows that Test Section 1 has a higher skid value (47.1) than Test Section 1s (37.5), which is the fog sealed section. This is due to the initial “slickness” that the fog seal/emulsion causes. It is common for skid numbers to increase as the fog seal is worn by traffic. This is thought to be the case for Test Section 4s, with its 1% increase in skid value over the last 7 months (Table 6.1), although the change could just be within the margin of error for the test method. However, microtexture will at some point begin to decrease with deterioration soon after the fog seal has been worn by traffic. Emulsion (CRS-2S) was placed on the fabric sections (1/2 mile) instead of SS-1, mistakenly (Vance Bros. loaded the ODOT distributor with the wrong material). There appears to be no significant difference between skid numbers (microtexture) in the fog seal and the emulsion seal test sections, as noted in Table 6.1.

Table 6.1 Microtexture Values at Month 1 and Month 6

Test Section	Chip Seal Description	12-Nov	13-Apr	% Change
1	ODOT 3/8"	47.1	36.0	-24%
1s	ODOT 3/8", fog seal	37.5	32.5	-13%
2	ODOT 1/2"	48.7	34.0	-30%
2s	ODOT 1/2", fog seal	39.0	29.4	-25%
3	ODOT 5/8"	46.4	37.7	-19%
3s	ODOT 5/8", fog seal	37.0	35.0	-6%
4	3/8" Single Size	43.7	37.5	-14%
4s	3/8" Single Size, fog seal	34.6	35.0	1%
5	1/2" Single Size	45.6	36.5	-20%
5s	1/2" Single Size, fog seal	37.6	33.2	-12%
1f	ODOT 3/8", fabric	44.2	36.5	-17%
1sf	ODOT 3/8", fog seal and fabric	34.1	34.2	0%
3sf	ODOT 5/8", fog seal and fabric	36.7	33.5	-9%
3f	ODOT 5/8", fabric	42.9	34.5	-19%

Additionally, another trend that can be observed in Table 6.1 is that the sections that received fog seal or emulsion seal had a smaller percent change, or rate of deterioration, during the 6 month period. It is not believed that fog seal slows microtexture deterioration, but that the initial “slickness” obscures the true rate of surface friction deterioration of the chip seal. However, there currently appears to be no significant difference in skid values for all of the test sections at the time of this writing. It is expected that differences in the test sections will be observed after one year of service (September 2013). It should be noted that all test section skid values in Table 6.1 are still above the failure criterion of 25.

Macrotexture, which contributes to surface friction by providing “drainability”, is a good measure of aggregate retention. All test sections are currently performing well above the failure criterion of 0.9mm, as shown in Table 6.2. The fog seal and emulsion seal appear to make no appreciable difference in mean texture depth (MTD) values (i.e. aggregate retention), as supported by literature [58,60,61,62,64]. However, the test sections will continue to be monitored for performance based upon macrotexture.

Table 6.2 Macrotexture Values at Month 1 and Month 6

Test Section	Chip Seal Description	12-Nov	13-Apr	% Change
		MTD (mm)		
1	ODOT 3/8"	2.99	2.58	-14%
1s	ODOT 3/8", fog seal	3.07	2.92	-5%
2	ODOT 1/2"	5.54	3.48	-37%
2s	ODOT 1/2", fog seal	3.35	3.48	4%
3	ODOT 5/8"	4.66	4.09	-12%
3s	ODOT 5/8", fog seal	4.71	3.92	-17%
4	3/8" Single Size	3.35	3.11	-7%
4s	3/8" Single Size, fog seal	3.39	2.99	0%
5	1/2" Single Size	4.21	3.87	-8%
5s	1/2" Single Size, fog seal	4.53	3.87	-15%
1f	ODOT 3/8", fabric	3.03	2.70	-11%
1sf	ODOT 3/8", fog seal and fabric	2.60	2.15	-17%
3sf	ODOT 5/8", fog seal and fabric	3.87	3.26	-16%
3f	ODOT 5/8", fabric	3.92	3.39	-14%

Although there are not yet enough data points to create deterioration models based on linear regression, Figure 6.1 shows that the PUC-based test sections (denoted “SS” for single size in the graph) are preliminarily outperforming the ODOT 3/8” chip seal (TS 1). Both of the fog seal sections (PUC-based and non-PUC-based) appear to exhibit the same level of performance. The first data point represents baseline measurement.

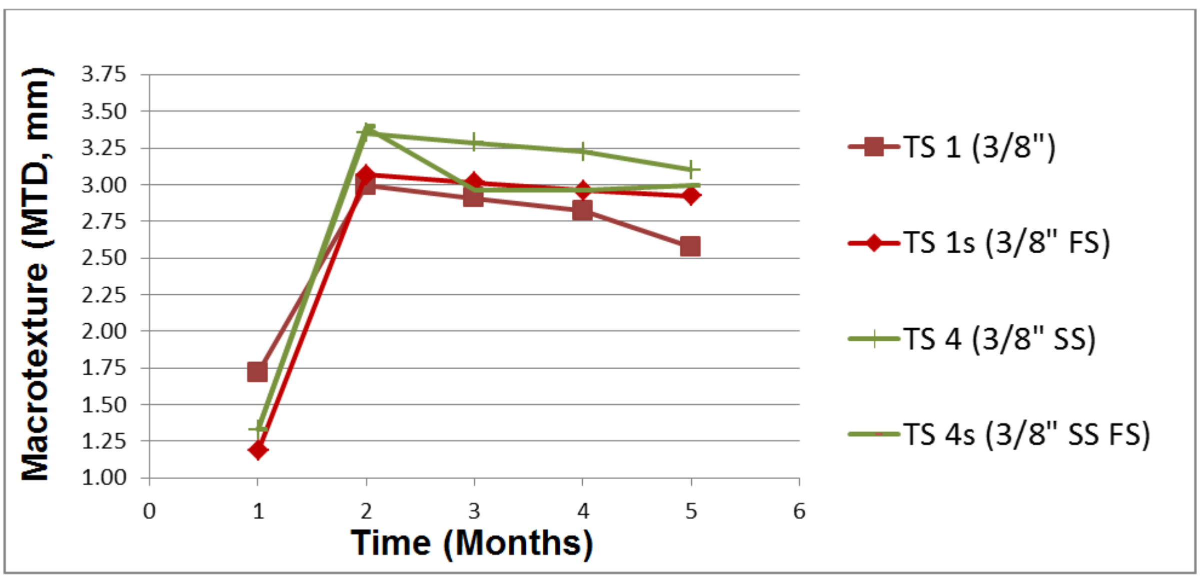

Figure 6.1 Macrotexture Values for 3/8" Test Sections

The preliminary macrotexture values for the ½” Chip Seal Test Sections also show the PUC-based sections are outperforming (albeit slightly) the non-PUC-based sections, as depicted in Figure 6.2. Statistical analysis will be conducted on the data when a sufficient amount of data exists to determine if any difference in performance exists.

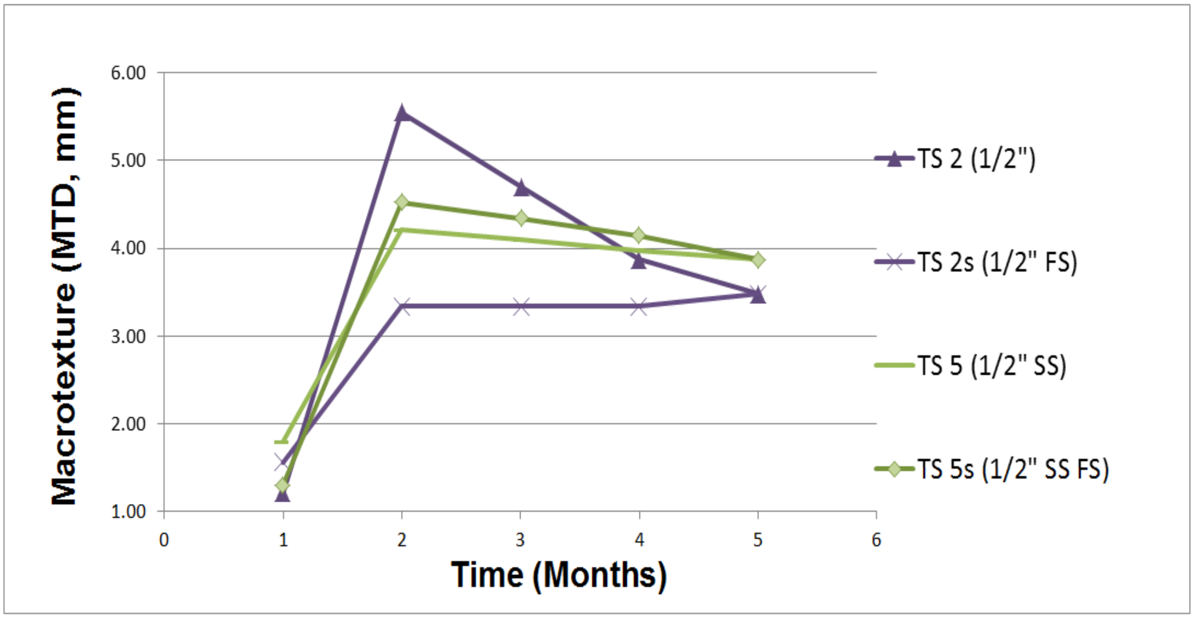

Figure 6.2 Macrotexture Values for 1/2" Test Sections

Unfortunately, Dolese did not supply the PUC-based 5/8” gradation. From Table 6.2, Figure 6.1 and Figure 6.2, preliminary observation shows that the PUC based gradations are outperforming the ODOT gradations on the basis of macrotexture. In general, the 1/2” chip seal sections appear to be performing better than the 3/8” sections. The ODOT 5/8” chip seal sections are performing same as or slightly better than the PUC-based 3/8” and 1/2" sections. However, if the trend that the PUC sections are outperforming their counterparts is valid, then it may be hypothesized that a PUC-based 5/8” chip seal would outperform the ODOT 5/8” section.

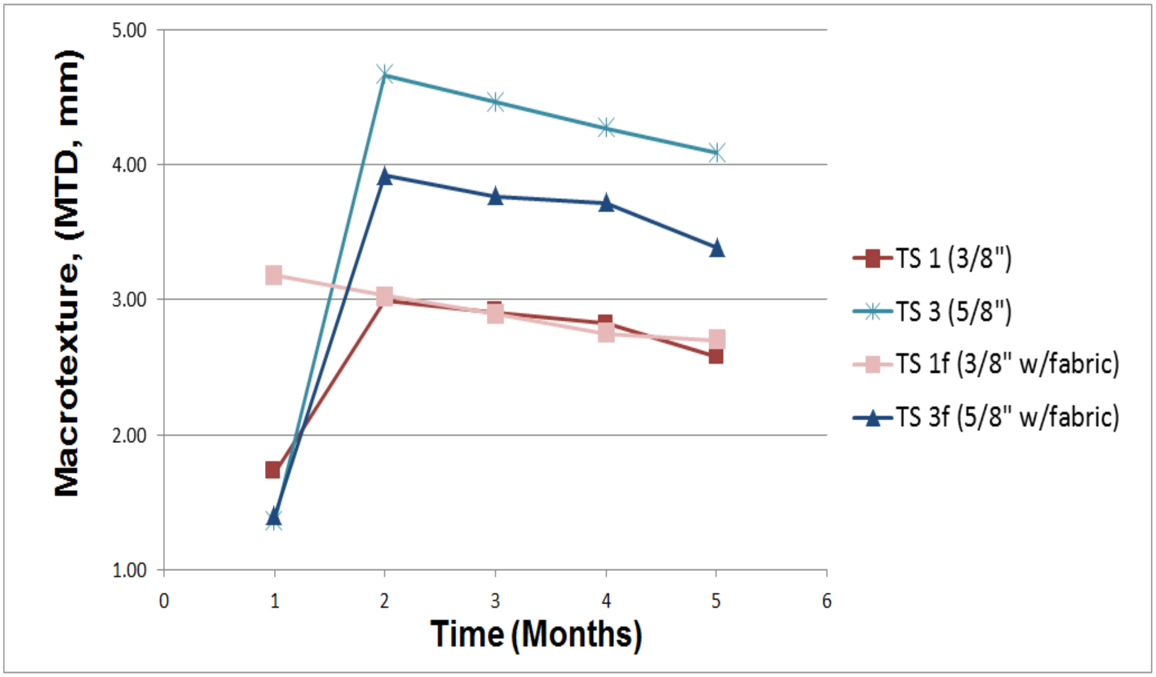

Figure 6.3 Macrotexture Values for Test Sections with and without Fabric

Figure 6.3 shows that the test sections with geosynthetic fabric are not outperforming their respective sections at this point in the study. However, it should be noted that fabric sections are performing well (have not reached macro and microtexture failure criterion). Additionally, value from the use of geosynthetic fabric stems from its contribution to chip seal service life extension. Therefore, conclusions cannot be drawn based on this preliminary data as to the efficacy of geotextile fabric use in chip seal systems. Ideally, the chip seal sections would be tested to failure and forensic life cycle cost analyses could reveal the value of fabric use. Future measurements of micro- and macrotexture, as well as condition inspection should continue over the life of the chip seals to gain a more accurate depiction of performance. Performance of these sections will continue to be monitored for the duration of the study.

6.2 CONSTRUCTION PRACTICES REVIEW

Short-term failure in chip seal is defined as failure within the first year of service, mainly caused by the loss of cover aggregate. This type of failure is normally related to incompatibility of the aggregate and the binder, excessive fines in the aggregate, or some weather event or deficiency in the construction process such as inadequate rolling or placing the chip seal late in the season where ambient air temperatures are below specified minimums [3,4,5]. In fact, construction quality can have the greatest impact on chip seal success [3]. Therefore, ODOT chip seal construction practices were reviewed. Additionally, the other five ODOT divisions that use chip seal in their maintenance programs provided information about their construction practices. The practices were then compared to the best construction practices listed in *NCHRP Synthesis 342: Chip Seal Best Practices,* listed in Table 6.3 and Table 6.4 [3].

Common chip seal equipment includes an emulsion distributor, aggregate spreader, rollers, dump trucks and sweeping equipment. Figure 6.4 shows part of the chip seal crew that installed the test sections. The distributor is installing the CRS-2S emulsion in front of the chip spreader, which is spreading the cover aggregate, called "chips" on the emulsion. Also partially pictured is one of the dump trucks responsible for keeping the chip spreader continuously supplied with cover aggregate. In general, the practices observed in the field were consistent with chip seal best practices [3] as noted in Table 6.3 and Table 6.4. Additionally, all of the ODOT Divisions indicated similar practices with regard to equipment and methods for chip seal construction in their regions.

Figure 6.4 Chip Seal Construction: Distributor, Chip Spreader and Dump Truck

Table 6.3 Chip Seal Best Practices: Equipment (After [3])

Best Practice	Purpose	Observed
Computerized Distributor with Variable Nozzles	To ensure consistent and accurate emulsion application	✓
Synchronized Equipment Production Rates	To allow adequate time for rolling operation before emulsion cures	✓
Properly Calibrated Equipment	To ensure accurate distribution of material	✓
Verification of Application Rates (Aggregate and Binder)	To ensure application rates are appropriate for field conditions	✓
Self-Propelled, Computerized Chip Spreader with Adjustable Discharge Gate/Roller	To ensure uniform spread of cover aggregate	✓
Sufficient # of Dump Trucks	To ensure sufficient supply to spreader for continuous operation	✓
Sufficient #, Speed, Pattern of Rollers	To ensure proper embedment and orientation of aggregate into binder	✓
Proper Roller Weight, # and size of tires, inflation pressure	To ensure proper weight and pressure to embed and orient aggregate into binder	✓
Properly sized static steel-wheeled roller, if used	To ensure cover aggregate is not crushed	**N/A**
Use of Sweeping Equipment	To remove debris from pavement surface immediately prior to chip seal installation and to remove loose aggregate after chip seal installation	✓

Chip seal best practices for construction involve proper conditions, materials, means and methods, as listed in Table 6.4. All of the Divisions reported similar weather condition requirements and construction practices. There was one main exception. Timing for opening the newly chip-sealed surface back over to traffic did vary between the Divisions. During test section construction, a 30-minute average was observed between the time that the roller was finished and the time that the road was open to traffic. The responses from the Divisions ranged from “immediately” to four hours after rolling operations cease. The Division that requires a four-hour period stated the reason was to allow adequate emulsion cure time, a practice that is consistent with best practices [3]. It is recommended that all Divisions ensure that the emulsion has adequately cured before turning the section over to traffic. Although this may cause temporary inconvenience to the traveling public, the benefits can be realized in enhanced aggregate retention and extended chip seal service life.

Table 6.4 Chip Seal Best Practices: Construction (After [3])

Best Practice	Purpose	Observed
Apply chip seal in warmest, driest weather	To reduce chance of short-term chip seal failure	✓
Apply chip seal when: ambient air temp between 50ºF - 100ºF surface temp between 70ºF - 140ºF	To ensure proper aggregate-binder adhesion and chip seal-pavement surface adhesion	Ambient air temp range was 72ºF at start, 86ºF at finish; surface temp was 82ºF, then 112ºF
Prepare existing substrate months in advance (patching – 6 months, crack seal – 3 months)	To ensure adequate time for repairs to cure before placing chip seal	✓
Sweep existing substrate prior to chip seal construction	To ensure proper bond between chip seal and pavement	✓
Hand-rake in aggregate in deficient areas behind spreader	To ensure proper aggregate coverage	✓
Apply aggregate immediately after emulsion	To ensure proper time for rolling operations	✓
Have experienced personnel adjust application rates as warranted by field conditions	To ensure proper application rates	✓
Apply a small amount of excess aggregate in areas with high turning and stopping activity	To protect binder from traffic damage	Not Observed
Proper roller operations (3,000 – 5,000 SY per hour of coverage before emulsion break)	To ensure proper roller coverage for aggregate embedment	Approx 3,500 SY/hour until one of the rollers stopped working
Sweep only after emulsion breaks	To ensure aggregate retention	✓
Open to traffic only after emulsion breaks	To ensure aggregate retention	Average 30 minutes behind roller
Have experienced personnel ensure QC/QA in field	To ensure proper materials, means and methods	✓
Evaluate aggregate-binder compatibility	To ensure proper adhesion for aggregate retention	Based upon experience; validated by this research
Test binder at the distributor and aggregate at stockpiles	To ensure material quality has not degraded during handling	Completed for this research project

Recommendations from previous studies include using precoated aggregates to shorten cure time, allowing at least 24 hours of cure time and/or ensuring at least 85% moisture evaporation before opening the road for traffic to ensure maximum aggregate retention [19,66].

There were a limited number of chip seal emulsion and aggregate sources identified by the project panel. “A limited number of suppliers is a distinct advantage when the constructability is evaluated” [65] because it allows ODOT to more easily isolate the source of material with quality issues as well as simplify the process of initiating corrective action [11]. Ensuring aggregate-binder compatibility is listed in Table 6.4 as an important best practice, and this research has shown that the limited pool of material suppliers have compatible materials to support ODOT chip seal programs.

Proper rolling techniques are critical in allowing the chip seal achieve its design life [3]. Pneumatic (rubber-tire) rollers are almost universally used and are responsible for proper cover aggregate embedment and orientation in the emulsion, so that mechanical interlock between the individual pieces of aggregate can be achieved [3]. The rollers should follow closely behind the chip spreader and maintain specified speeds and roller patterns. Figure 6.5 shows the rolling operation for test section construction that included two pneumatic rollers.

Figure 6.5 Chip Seal Rolling Operation

All of the ODOT Divisions indicated that they enlist the dump trucks to aid in the embedment process by staggering their positions relative to each other, as shown in Figure 6.6, as deliver their loads of aggregate to the spreader. One of the rollers blew a hydraulic hose after rolling test sections 1, 1s, 2 and 2s. Therefore, the rest of the test sections only had one roller, which is not considered best practice due to the fact that the rolling process is the slowest part of the chip seal installation and may not keep pace with the operation before the emulsion cures. However, from the current performance results (Table 6.1 and Table 6.2), it appears that any detrimental effect of having only one roller on the test sections was compensated by the dump truck rolling contribution.

Figure 6.6 Dump Trucks in Staggered Pattern

Proper traffic control methods are also important for ensuring adequate emulsion cure time. The ODOT Divisions use pilot cars and flaggers, as well as warning signs such as “Loose Gravel”, as illustrated in Figure 6.7, to keep traffic off of the newly chip sealed surface, as well as to protect and warn the traveling public.

Figure 6.7 Traffic Control Signage and Pilot Car for Test Section Installation

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7.0 CONCLUSIONS

The following preliminary conclusions can be drawn from the preceding analyses:

1. Protocol for determining SFE of emulsion using contact angles has been developed.
2. The compatibility ratios indicate that the aggregate and emulsion materials from the listed sources are compatible and will not be the cause of short term failure in Oklahoma chip seals.
3. The newly developed performance-based uniformity coefficient (PUC) appears to correlate well with chip seal performance in Oklahoma; however, continued performance testing may support a conclusive statement.
4. All of the chip seal test sections are performing satisfactorily after eight months of service.
5. AIMS testing has shown that there are differences between aggregate sources that may impact chip seal performance. AIMS testing continues.
6. AIMS1 and AIMS2 (new generation AIMS) provide comparable shape results; however, a statistically significant difference exists between texture results.
7. Fog seal and geosynthetic fabric has not improved chip seal performance in the short term. Performance will continue to be monitored.
8. ODOT chip seal construction practices are consistent with best practices as noted in *NCHRP 342: Synthesis Chip Seal Best Practices*. However, time between rolling operation and opening to traffic was an hour or less for all but one ODOT Division. Actual emulsion cure times was not measured as part of this research effort, but literature supports keeping the chip seal section closed until the emulsion has cured to ensure adequate aggregate retention.

The final task of the research involves drafting cover aggregate specifications, which will occur at the conclusion of the project. Findings from all of the tasks presented in this report will be analyzed carefully, discussed with the Project Panel and other stake holders, and assembled into draft cover aggregate specifications as warranted. The draft cover aggregate specifications will include more mechanistic factors such as aggregate shape and texture indices (i.e., radius angularity, gradient angularity, sphericity, form), PUC-based gradation, as well as aggregate-binder compatibility metric (i.e., interfacial bond strength, compatibility ratio, energy ratio). This will be an important deliverable for this project. Specific emphasis will be placed on collecting chip seal specifications from sources outside of ODOT for purposes of comparison.

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APPENDIX A Sessile Drop Results

Contact Angles (Probe Liquid: Water)					
Aggregate	1st	2nd	3rd	Average	Std. Dev.
Dolese Cooperton 1	57	54.9	52.8	54.90	2.10
Dolese Cooperton 2	51.1	52	52.9	52.00	0.90
Dolese Cooperton 3	67.1	63.5	66.4	65.67	1.91
Hanson Davis 1	51.7	53.5	54.5	53.23	1.42
Hanson Davis 2	61.7	61.5	59.5	60.90	1.22
Martin Marietta Mill Creek 1	47.98	46.15	41.95	45.36	3.09
Martin Marietta Mill Creek 2	55.57	59.19	58.08	57.61	1.85
Martin Marietta Mill Creek 3	45.3	45	44.5	44.93	0.40
Dolese Hartshorne	62	65.1	65.6	64.23	1.95
Kemp Stone Pryor 1	58.2	55.26	58.25	57.24	1.71
Kemp Stone Pryor 2	61.3	60.04	60.56	60.63	0.63

Contact Angles (Probe Liquid: DIM)					
Aggregate	1st	2nd	3rd	Ave	Std. Dev.
Dolese Cooperton 1	29.2	29.7	30.3	29.80	0.55
Dolese Cooperton 2	43.5	44	44.3	43.93	0.40
Dolese Cooperton 3	40.8	41.7	42.7	41.73	0.95
Hanson Davis 1	38.9	37.4	39.5	39.40	1.08
Hanson Davis 2	45.9	44.4	44.6	44.97	0.81
Martin Marietta Mill Creek 1	45.7	47.4	48.42	47.17	1.37
Martin Marietta Mill Creek 2	48.08	49.72	49.69	49.16	0.94
Martin Marietta Mill Creek 3	42	42.6	40.8	41.80	0.92
Dolese Hartshorne	40.2	43.9	44.4	42.83	2.29
Kemp Stone Pryor 1	43.15	43.58	45.6	44.11	1.31
Kemp Stone Pryor 2	31.92	35.27	36.95	34.71	2.56

Contact Angles (Probe Liquid: Ethylene Glycol)					
Aggregate	1st	2nd	3rd	Ave	Std. Dev.
Dolese Cooperton 1	28.4	28.2	26.65	27.70	0.96
Dolese Cooperton 2	34.9	37.9	37.2	36.67	1.57
Dolese Cooperton 3	41.3	46.4	43.8	43.83	2.55
Hanson Davis 1	30.4	30.5	27.9	29.40	1.47
Hanson Davis 2	32.3	34.3	33.1	33.23	1.01
Martin Marietta Mill Creek 1	30.34	28.32	26.53	28.40	1.91
Martin Marietta Mill Creek 2	39.17	40.55	38.51	39.41	1.04
Martin Marietta Mill Creek 3	32.3	34.3	33.1	33.23	1.01
Dolese Hartshorne	35.3	29.3	29.2	31.27	3.49
Kemp Stone Pryor 1	28.88	27.78	27.31	27.99	0.81
Kemp Stone Pryor 2	18.2	17.58	20.36	18.71	1.46