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

Musharraf Zaman, Ph.D., P.E.
Dominique Pittenger, Ph.D.
Douglas Gransberg, Ph.D., P.E.
Sesh Commuri, Ph.D.
School of Civil Engineering and Environmental Science
College of Engineering
The University of Oklahoma
Norman, Oklahoma

Rifat Bulut, Ph.D.
School of Civil and Environmental Engineering
Oklahoma State University
Stillwater, Oklahoma

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Oklahoma Department of Transportation

Implementation of Research for Transportation Excellence
spr@odot.org
Materials and Research Division
Research & Implementation

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FINAL REPORT ~ FHWA-OK-14-01
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Submitted to:
John R. Bowman, P.E.
Director, Capital Programs
Oklahoma Department of Transportation

Submitted by:
Musharraf Zaman, Ph.D., P.E.
Dominique Pittenger, Ph.D.
Douglas Gransberg, Ph.D., P.E.
Rifat Bulut, Ph.D.
Sesh Commuri, Ph.D.
College of Engineering
The University of Oklahoma

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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. 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 provides 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 quantifies how well the newly developed performance-based uniformity coefficient (PUC) correlates 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* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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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 evaluation of 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 evaluation of the aggregate-binder compatibility. Moreover, the chip seal construction practices followed by ODOT Maintenance Divisions has been documented and effective practices have 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) correlates 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 major benefits of the research are: (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 effective construction practice. This can eliminate or reduce premature failures due to incompatible binder-aggregate combinations. It can 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 include 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 can be organized for the purpose of Oklahoma implementation of 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 can be made immediately available in a form that permits rapid implementation.

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 Oklahoma Transportation Center (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 sphericity 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 study evaluates the shape and texture-related index properties, as well as durability, of commonly used cover aggregates in chip seal programs in Oklahoma, and provides a methodology for inclusion as a metric in future chip seal specifications.

2. It quantifies how well the newly developed performance-based uniformity coefficient (PUC) correlates with chip seal performance in Oklahoma, and if it should be incorporated into state chip seal specifications.
3. It generates 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 research include: (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 compatible in each ODOT division; (iii) the influence of fog seal on chip seal performance; and (iv) documentation of construction practices in each maintenance division and identification of effective 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 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 include 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.

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 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. Chip seal application is illustrated in Figure 2.1.

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, 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. The nomograph is shown in Figure 2.2.

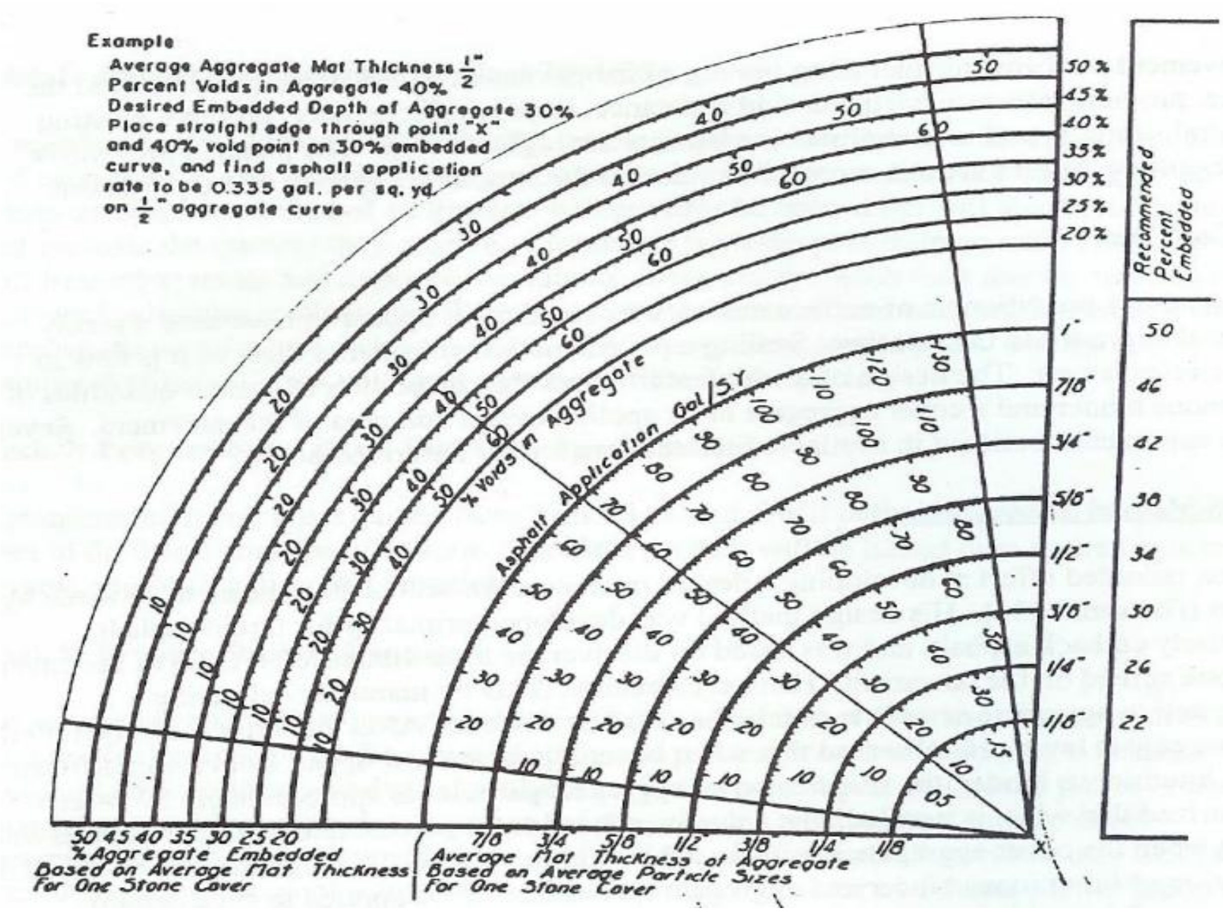

Figure 2.2 Kearby Nomograph [1]

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].

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

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. 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 and Table 2.3 show the asphalt application rate correction factors corresponding to traffic level and existing surface condition, respectively.

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. 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 is a schematic of the McLeod failure criteria [2].

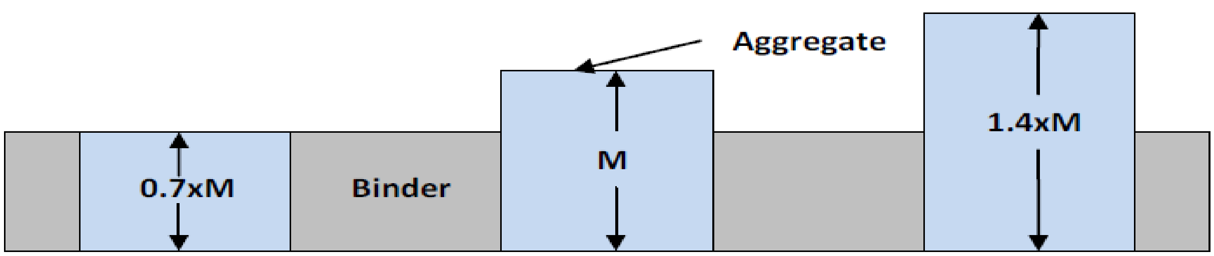

Figure 2.3 Schematic of McLeod’s Failure Criteria [2]

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.

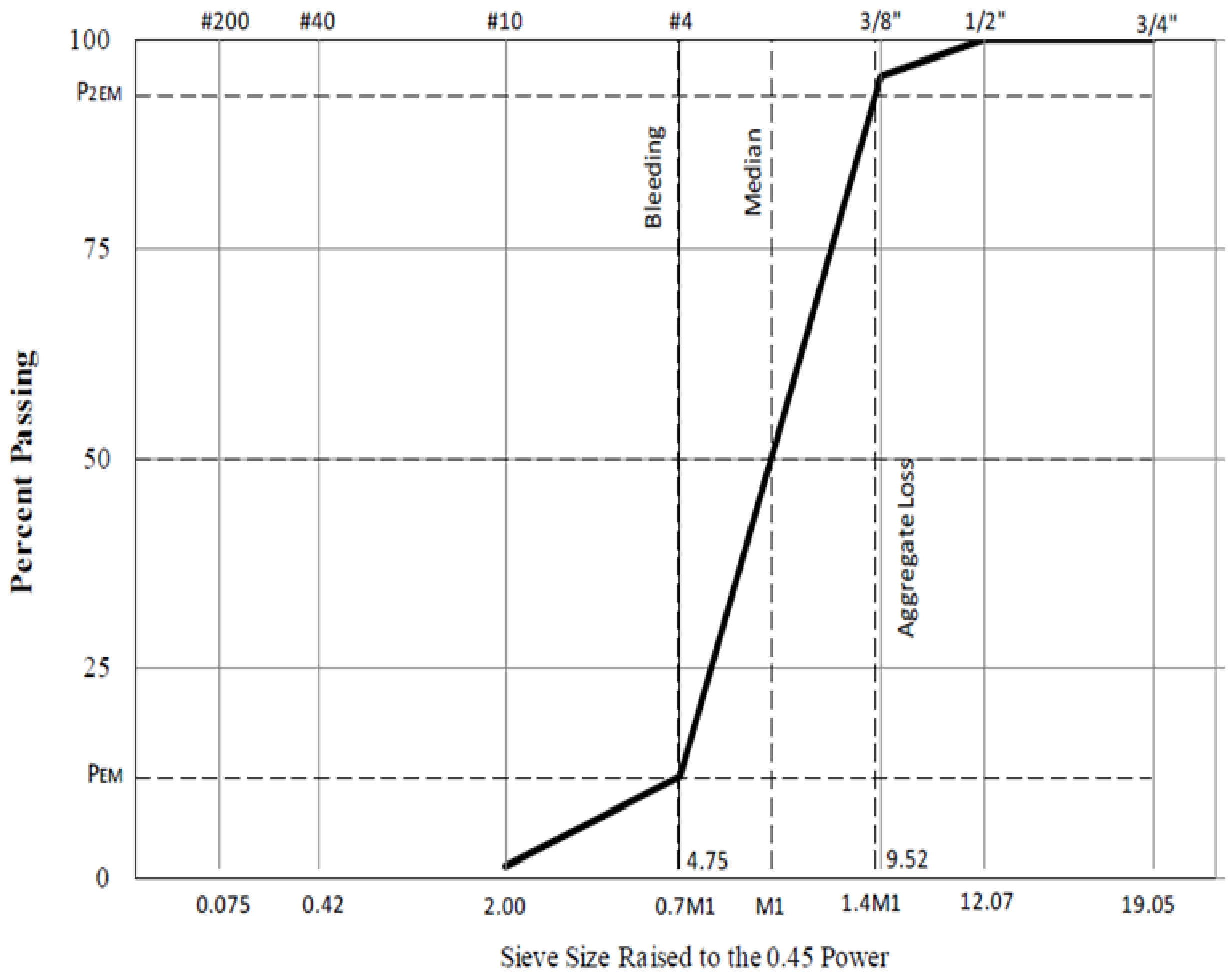

Figure 2.4 Gradation Range to Maximize Performance (after [10])

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. The system contains a camera unit, which has an optem zoom 160 video microscope.

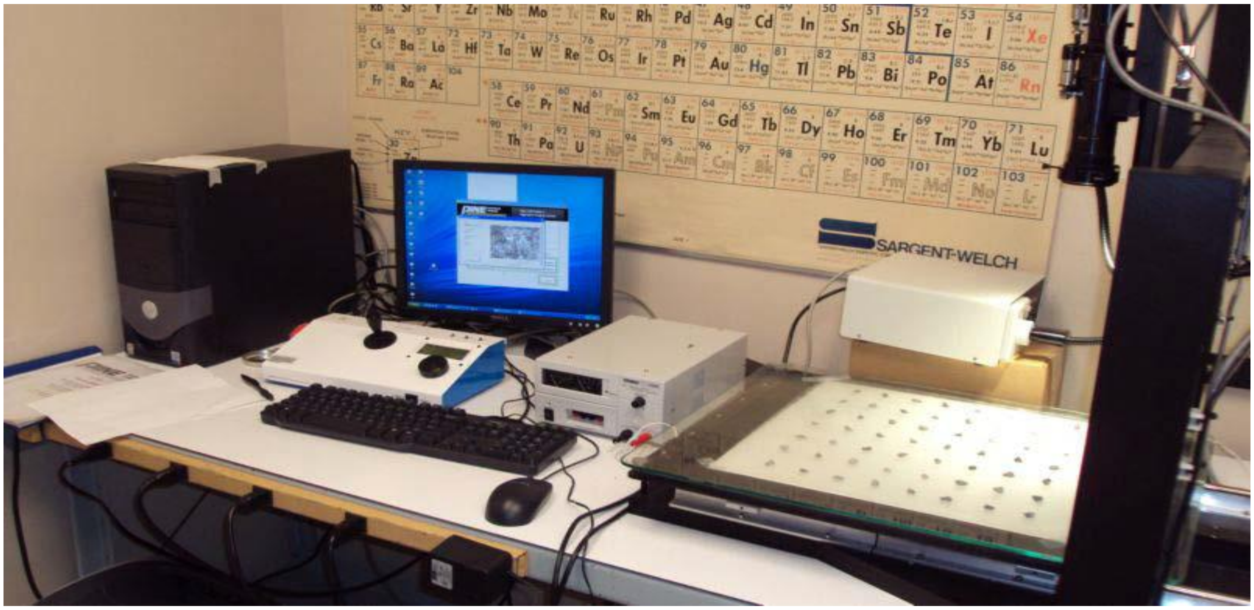

Figure 3.1 Aggregate Imaging System in OU Lab

Figure 3.1 shows the AIMS in the OU laboratory. 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.

$$Sphericity = \left(\frac{d_s * d_l}{d_L^2}\right)^{\frac{1}{3}} \qquad \text{Equation 6}$$

$$Shape\ Factor = \frac{d_s}{\left(d_L * d_l\right)^{\frac{1}{2}}} \qquad \text{Equation 7}$$

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 RӨ is the radius of the particle at an angle of Ө; and ΔӨ 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.

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

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. Senadheera 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.

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

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.

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

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 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.

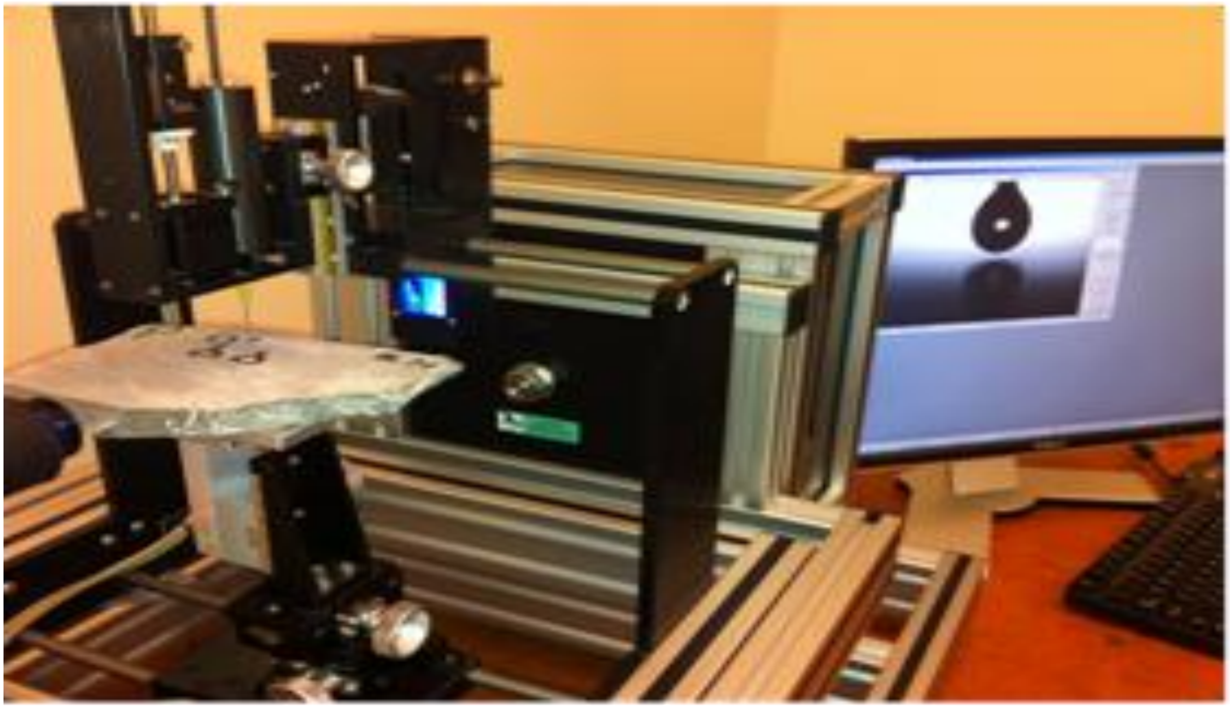

Figure 3.2 Sessile Drop Device

The Sessile Drop (SD) device is shown in Figure 3.2. The SFE can also be used to quantify bond strength (cohesion, adhesion, energy ratio).

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].

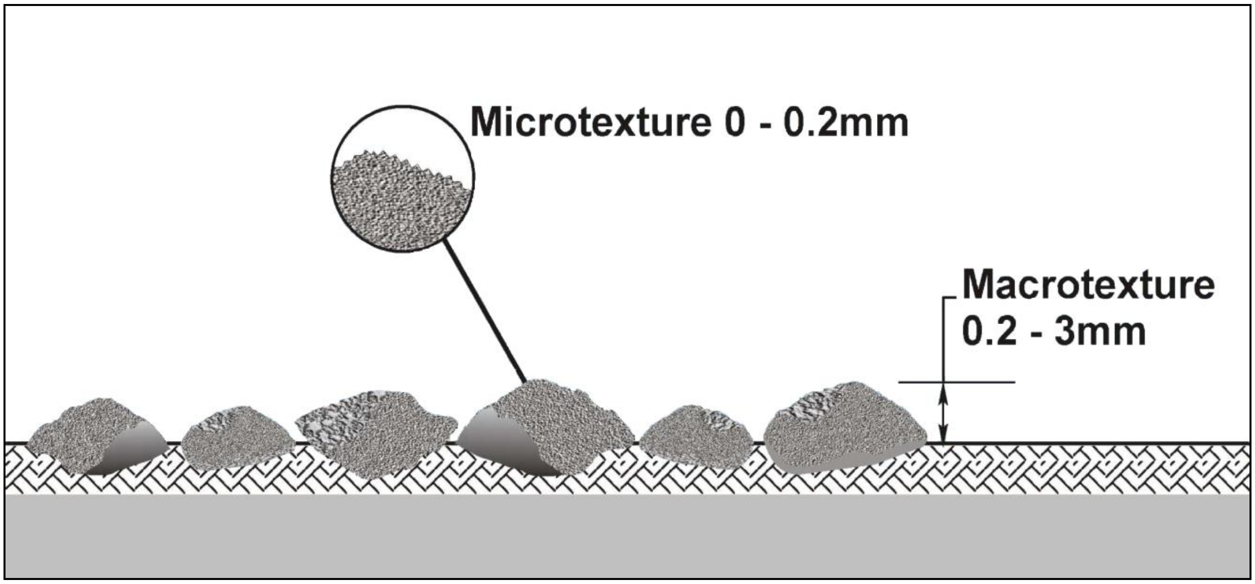

Figure 3.3 Pavement Surface Microtexture and Macrotexture [42]

Microtexture and macrotexture are illustrated in Figure 3.3. 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. 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.

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

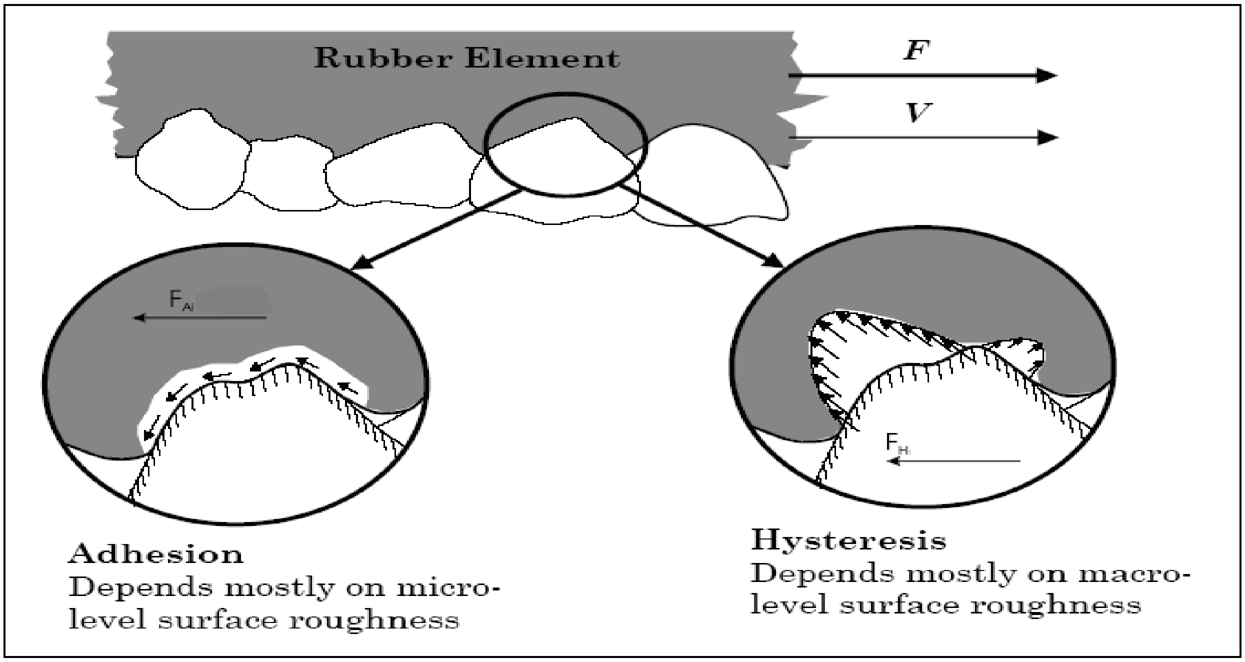

Figure 3.4 Pavement Friction Model [43]

Figure 3.4 shows these forces. 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".

Error! Reference source not found. shows the TNZ T/3 test being conducted in the ield. 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].

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.

Figure 3.5 ODOT Skid Truck

40 mph is the standard for towing the ODOT skid tester, pictured in Figure 3.5. 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].

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 provide the basis for 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 compatible in each ODOT division. Additionally, the research provides documentation of construction practices in each maintenance division and identification of effective 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, aggregate was obtained from Dolese Davis in Year 2 of the research when it was identified as being the aggregate source for the test sections based upon cost and gradation availability.

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 low traffic volumes.

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 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.

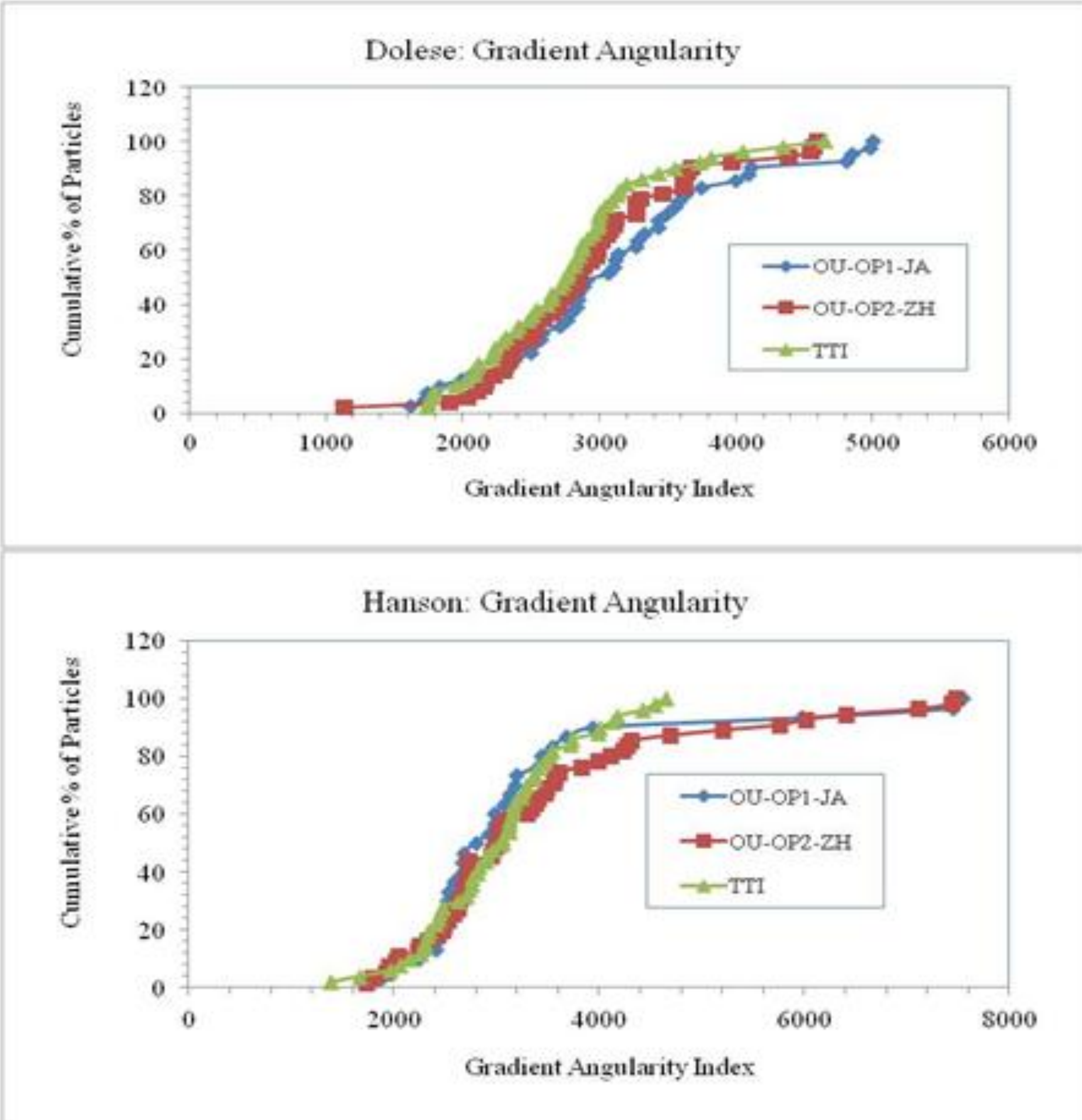

Figure 4.2 Validation of AIMS1 Gradient Angularity: Dolese (top) Hanson (bottom)

The comparability is also illustrated in 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].

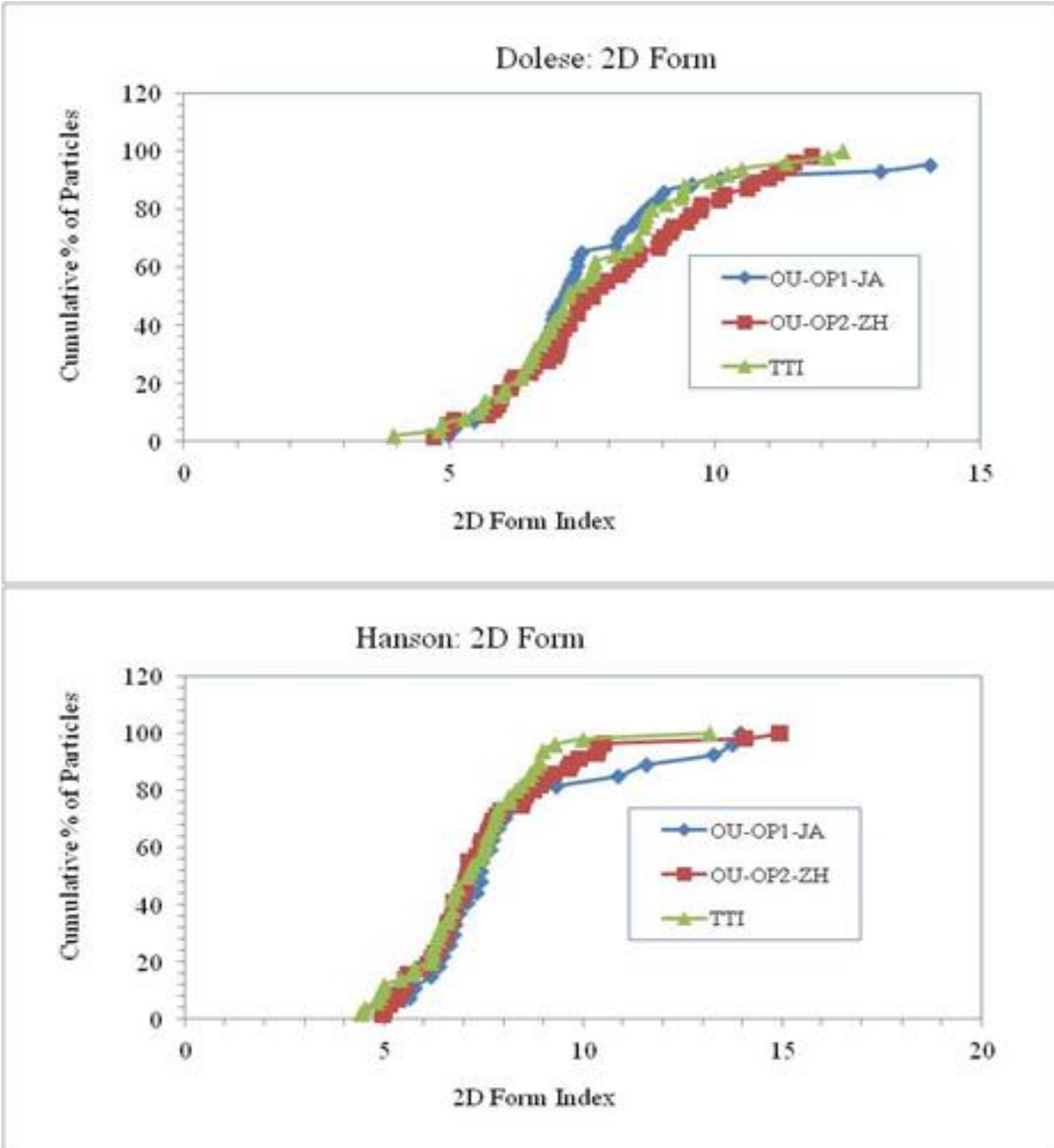

Figure 4.3 Validation of AIMS1 2D Form: Dolese (top), Hanson (bottom)

However, a statistically significant difference in the measured texture indices was observed between AIMS1 and AIMS2. 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.

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.

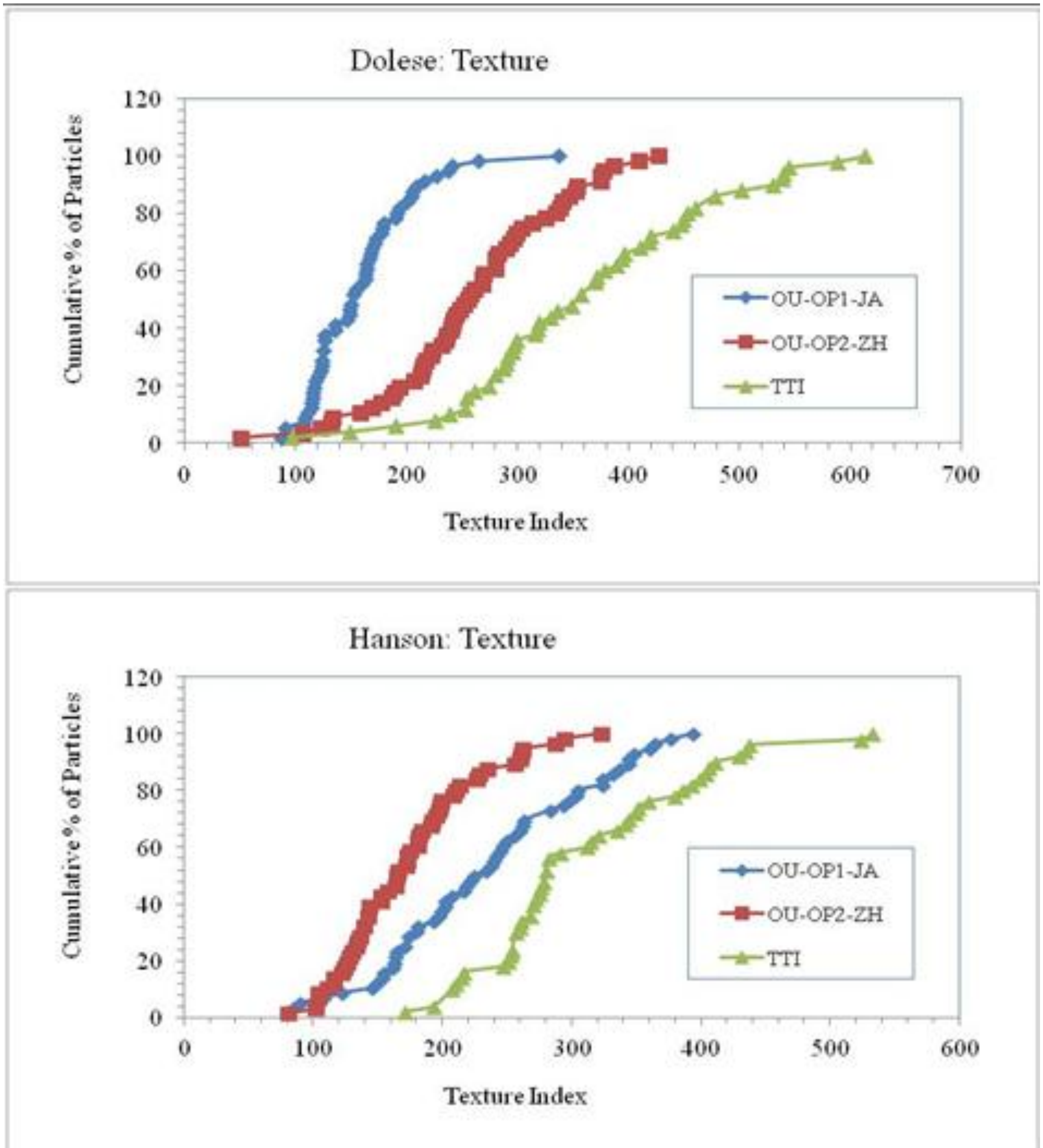

Figure 4.4 Validation of AIMS1 Texture: Dolese (top), Hanson (bottom)

Figure 4.4 illustrates the variance in texture indices.

4.2 DETERMINING OKLAHOMA AGGREGATE-BINDER COMPATIBILITY

Currently, there is no standard sample preparation or testing procedures for measuring contact angles of aggregates/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) was used to determine gradations for *single size* (SS) chip seal test section design. Chip seal test sections were constructed for the purpose of evaluating the PUC concept using surface texture performance indicators.

4.3.1 PUC-Based 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.

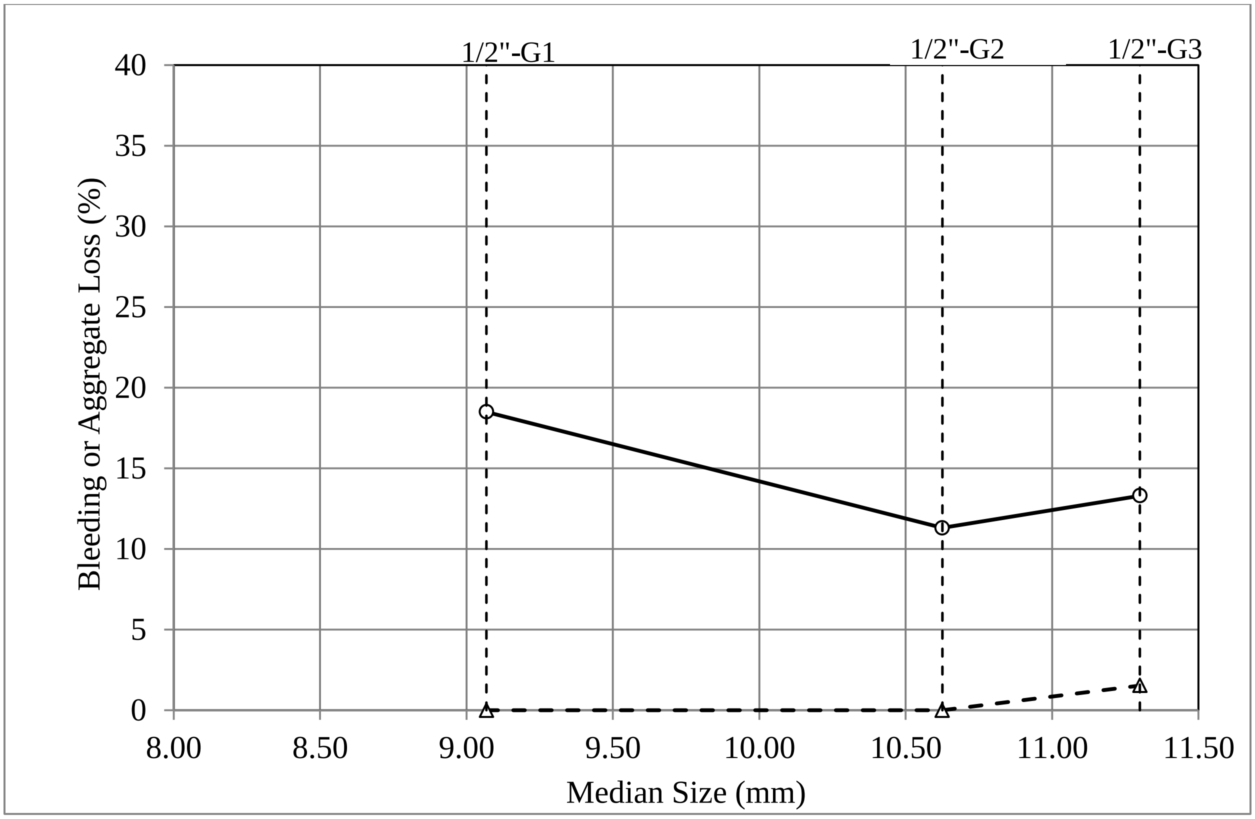

Figure 4.6 Bleeding and Aggregate Loss Values for Three ½” Gradations

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			
	TS 1 & 1s #2 (3/8")		TS 2 & 2s (1/2")		TS 3 & 3s 3C (5/8")		TS 4 & 4s #2-G2 (3/8"SS)		TS 5 & 5s ½"- 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 4.7 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.

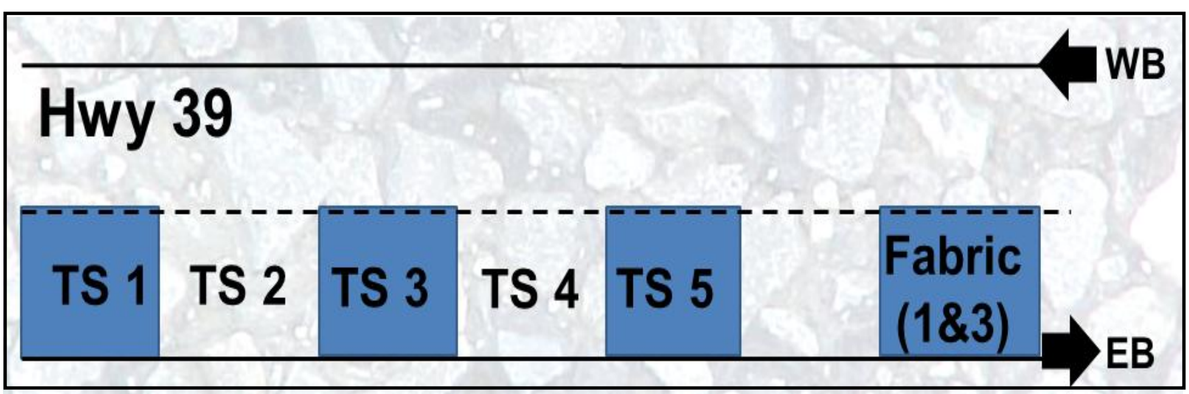

Figure 4.7 Chip Seal Test Section Layout

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 4.8. 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 4.9 and Figure 4.10. 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.

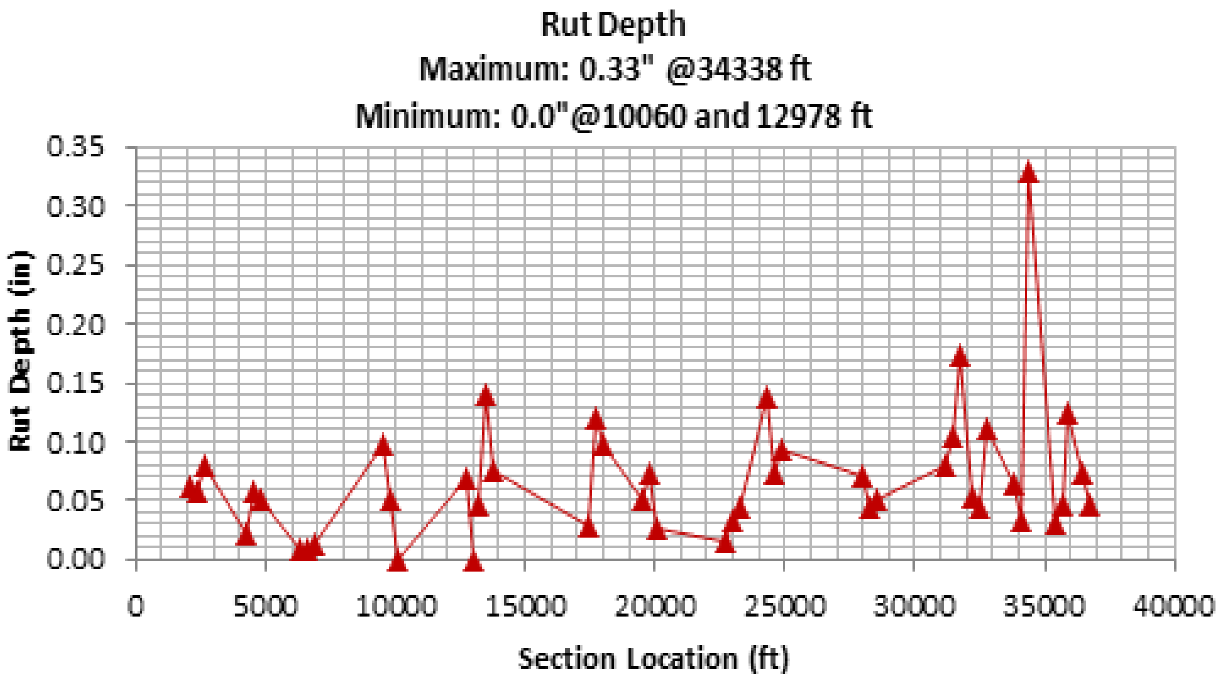

Figure 4.9 Dipstick Device (Rutting) Output

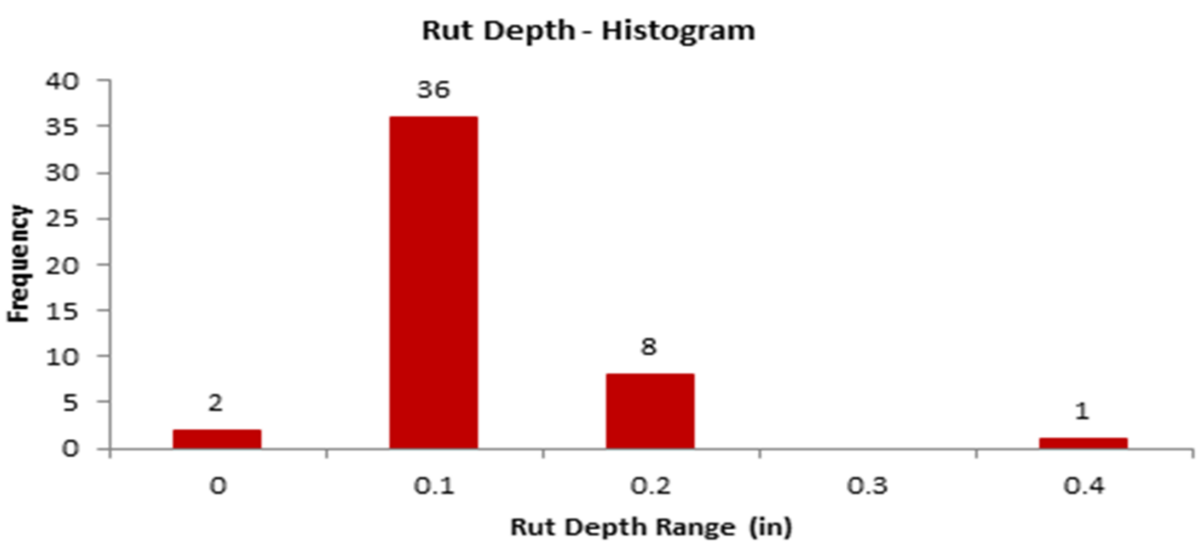

Figure 4.10 Dipstick Device Output Histogram

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 4.11 shows the similar pre- and post-construction results.

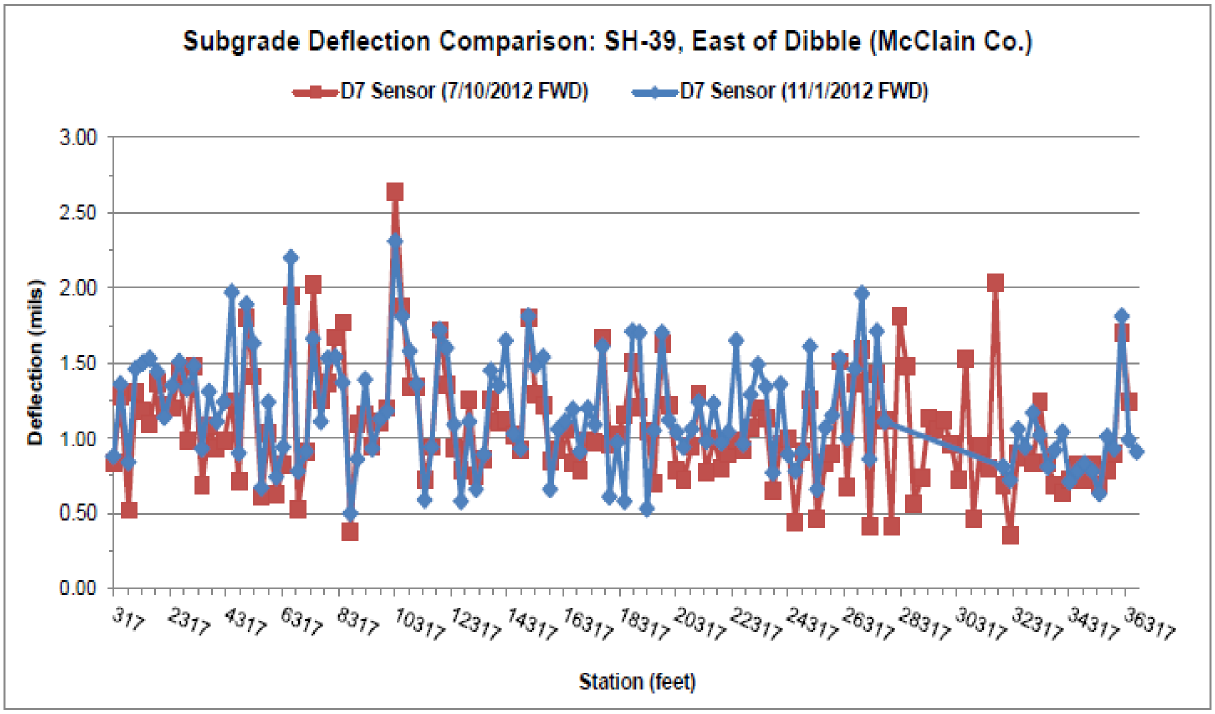

Figure 4.11 FWD Results, Pre- and Post-Construction (Chip Seal)

4.3.3 Surface Texture Measurement

An attempt has been made to obtain microtexture and macrotexture measurements on a monthly basis during the testing period of October 2012 – September 2013. The chip seal test sections all have the same level of 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 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 purpose of obtaining surface texture measurements on this project was to facilitate the creation of deterioration models to compare the performance of PUC-based and non-PUC-based chip seal test sections. However, linear regression could not be appropriately applied to the field trial microtexture and macrotexture data due to insufficient data. Therefore, the researchers are unable to approximate the deterioration rate and extrapolate the remaining service life of each treatment, which has been found to yield high R^2 values when applied to chip seal [56].

Insufficiency in microtexture (skid number) data points was due to the lack of availability of the ODOT Skid Tester. The tester was in the shop for maintenance for two of the twelve testing period months. The tester was later rear-ended (non-project related) and was unavailable for an additional five months. Because of this, only 5 data points were obtained for each of the test sections, which is not enough to adequately support neither statistical significance nor deterioration models. Therefore, limited analysis could be completed. The failure point considered for microtexture was a skid number less than 25.

A logarithmic equation has been shown to model chip seal deterioration, on the basis of macrotexture, over the service life well [56]. The deterioration at this point in the service life of the study test sections is not well modeled by the logarithmic equation since the data has not started to “level off”, due to variables such traffic levels and weathering, etc. Applying the logarithmic equation on the current data results in a premature “leveling off” of the deterioration rate and subsequently yields unreasonably long service life estimates (i.e. 20+ years).

Therefore, New Zealand’s P/17, *Notes for the Specification of Bituminous Reseals* [45], which is a performance specification, was used to evaluate test section performance on the basis of macrotexture. The philosophy behind the P/17 specification is that the texture depth after twelve months of service is the most accurate indication of the performance of the chip seal for its remaining life. The New Zealand specification also contends, “the design life of a chip seal is reached when the texture depth drops below 0.9 mm (0.035 inches) on road surface areas supporting speeds greater than70 km/h (43 mph)” [45]. The deterioration models developed in New Zealand have directed the P/17 Specification to require a minimum texture depth one year after the chip seal is completed, as calculated by using Equation 14.

$$Td_{1=} 0.07\, ALD\ \log Y_d + 0.9 \qquad \text{Equation 14}$$

Where: Td_1 = texture depth in one year (mm)
Y_d = design life in years
ALD = average least dimension of the aggregate (mm)

Chip seal macrotexture performance will be assessed using Equation 14 and design life values of 4, 5 and 6 years, consistent with ODOT survey and literature [4].

The newly constructed chip seal sections on Highway 39 were first tested in October 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 4.12. Fog seal is a pavement preservation treatment option [57,58] that is essentially “a light spray application of dilute asphalt emulsion” [59].

Figure 4.12 Fog Seal Application to Chip Seal Test Sections

Aggregate loss is a failure criterion associated with chip seal [2] that may 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 conducted 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].

5.0 LABORATORY TEST RESULTS AND ANALYSIS

This section reports current results and provides analysis for laboratory testing, including chip seal aggregate characterization and aggregate-binder compatibility.

5.1 AGGREGATE CHARACTERIZATION RESULTS AND ANALYSIS

The aggregate samples collected from the various quarries identified in Phase I of the research were characterized using sieve analysis, the Los Angeles abrasion test, the Micro-Deval abrasion test and AIMS1. Additionally, the test section aggregate obtained from Dolese Davis in Phase II of the research was characterized using sieve analysis and AIMS1. This section provides the results and analysis regarding aggregate characterization. These results allow comparison between aggregate sources. Additionally, they provide insight into chip seal test section performance.

5.1.1 LA Abrasion and Micro Deval Results

LA Abrasion and Micro-Deval tests were conducted on the five aggregate sources identified in Phase 1 of the research. These tests provide insight into the impact resistance and abrasion resistance of aggregate. Ideally, chip seal aggregate that is more resistant to abrasion is less likely to be adversely impacted by handling between the quarry and the road project. Aggregates results are shown in Table 5.1.

Table 5.1 LA Abrasion and Micro-Deval Results

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

ODOT specifies a percent loss of less than or equal to 40% on LA Abrasion. Therefore, the values are within specification. While ODOT does not specify Micro Deval for chip seal cover aggregate, it does use a standard of less than or equal to 25% allowable percentage loss for other applications (such as Superpave). The corresponding LA abrasion test specification in these applications is either less than or equal to 30% or 40% depending on the aggregate’s use.

It should be noted that previous studies have shown that no correlation exists between LA Abrasion and Micro-Deval test results, which is also supported by this study. 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. While this stands true for Micro Deval, the LA Abrasion returned a different result. The Micro Deval results show that the Dolese limestone was similarly resistant to abrasion as the rhyolite. The relative ranking between the sources reveals that the Hanson Davis aggregate was the most impact resistant sample and the Kemp Stone aggregate sample was the least. It also shows that the Martin Marietta sample was the most resistant to abrasion while the Kemp Stone sample was the least.

5.1.2 AIMS Results

Research by McLeod [2] showed that aggregate shape was a key factor in chip seal performance. Since the technology to efficiently measure and characterize particle shape did not exist, McLeod developed failure criteria based on the ratio of aggregate retained weights to the median particle size (the 50% passing sieve size). Lee and Kim [10] built on McLeod’s concepts and proposed a metric called the Performance-Based Uniformity Coefficient (PUC). Their work was based on the premise that the “perfect” particle shape was a cube. As the stone shape becomes more elongated, the chance that it will not be properly embedded (defined as less than 50% by Lee and Kim) increases. Additionally, if the percent of particles less than the median particle size is greater than those that are greater than the median particle size, the potential for flushing or bleeding increases [10]. The AIMS technology now provides the ability to quantify particle shape that McLeod did not have in 1962 and hence, this research builds on the work done by Lee and Kim by adding the AIMS output to the suite of chip seal performance indicators.

5.1.2.1 AIMS1 Results - Quarries

The AIMS properties for the 3/8” aggregate from each of the six quarries are compared in this section to determine (1) relative differences between sources and (2) if any correlations exist between laboratory tests. See Appendix C for all analyses.

High angularity in aggregate can enhance chip seal performance. It increases surface area, which promotes adhesion between the binder and the aggregate. Additionally, the previous OkTC study [6] found that skid number is related to aggregate gradient angularity. In AIMS analysis, it was found that increasing aggregate gradient angularity tracked with increasing skid number [6]. Table 5.2 shows the descriptive statistics for the AIMS1 gradient angularity output for the aggregate sources.

Table 5.2 AIMS1 Gradient Angularity: Descriptive Statistics for 6 Quarries

AIMS1 Output: Gradient Angularity, 3/8” Aggregate					
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1374)**	**Min. Value**	**Max. Value**
Hanson - Davis	56	3370	1492	364	8472
Dolese - Cooperton	52	2992	900	1133	6545
Dolese - Hartshorne	85	3623	1613	1851	9400
Martin Marietta – Mill Creek	99	3571	1588	795	9926
Kemp Stone - Pryor	111	3040	1019	1458	7750
Dolese – Davis	51	3332	1434	838	7930

The gradient angularity data obtained from Sample 1 testing (N = 56, approx.) is graphically depicted in Figure 5.1 and numerically expressed in Table 5.3. Most of the indices for the tested particles from the aggregated results fall within the range of 1800 to 5000, with the bulk of the particles considered to be sub-rounded as classified by AIMS.

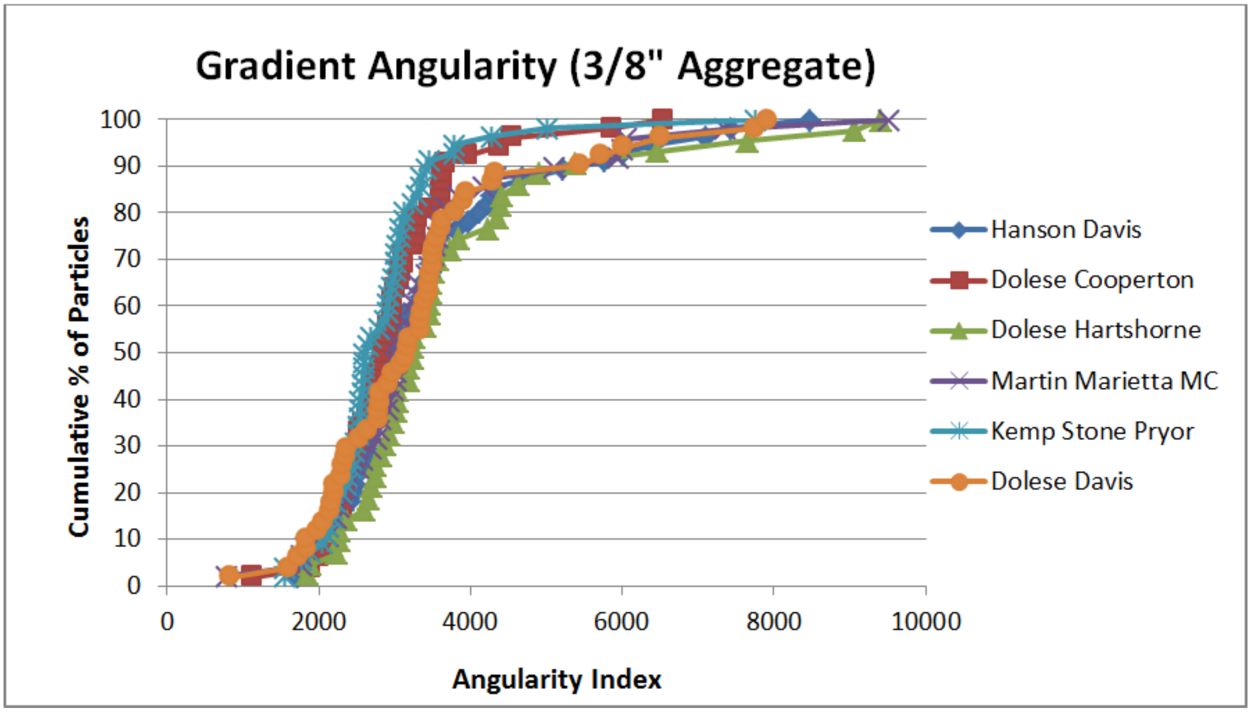

Figure 5.1 AIMS1 Output for Gradient Angularity (3/8" Aggregate, Sample 1)

The analysis of variance showed that there was a statistically significant difference ($p = 0.011$) between the Kemp Stone (more rounded) and Dolese Hartshorne (more angular) material based upon a 95% confidence interval (Tukey's Method). Table 5.3 shows that 25% of the Dolese Hartshorne material was considered sub-angular and angular, versus 5% for Kemp Stone.

Table 5.3 AIMS1 Gradient Angularity Classification for 6 Quarries (Sample 1)

Quarry	**Rounded** (< 2100)	**Sub-Rounded** (2100-4000)	**Sub-Angular** (4000-5400)	**Angular** (> 5400)
	% in Range			
Hanson - Davis	12	66	11	11
Dolese - Cooperton	11	81	6	2
Dolese - Hartshorne	5	70	21	4

Quarry	**Rounded** (< 2100)	**Sub-Rounded** (2100-4000)	**Sub-Angular** (4000-5400)	**Angular** (> 5400)
Martin Marietta – Mill Creek	10	74	6	10
Kemp Stone - Pryor	11	84	3	2
Dolese – Davis	14	70	6	10

Based upon these results, Dolese Hartshorne material may provide better adhesion with the binder and better skid resistance than the Kemp Stone aggregate.

Micro Deval results have been shown to correlate with AIMS results. In this case, the Dolese Hartshorne material has the greater resistance to impact and abrasion and also has the highest percentage of sub-angular/angular particles. Therefore, the material from this source may experience less degradation between the pit and the road than the Kemp Stone material.

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. 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. It is also fundamental to the PUC concept because it reduces bleeding and flushing. 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. Table 5.4 provides the descriptive statistics for sphericity data resulting from AIMS testing of the samples from the various aggregate sources.

Table 5.4 AIMS1 Sphericity I: Descriptive Statistics for 6 Quarries

AIMS1 Output: Sphericity I, 3/8" Aggregate					
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1011)**	**Min. Value**	**Max. Value**
Hanson - Davis	49	0.5398	0.0838	0.3720	0.7580
Dolese - Cooperton	52	0.6383	0.0968	0.3390	0.8680
Dolese - Hartshorne	94	0.6875	0.1128	0.2890	0.8850
Martin Marietta – Mill Creek	105	0.7228	0.1046	0.3030	0.9680
Kemp Stone - Pryor	105	0.6688	0.0974	0.3960	0.8860
Dolese – Davis	50	0.6484	0.0979	0.4090	0.8330

The sphericity data obtained from Sample 1 testing (N = 56, approx.) is graphically depicted in Figure 5.2 and numerically expressed in the table that follows. A higher value is desirable, as particles tend to be more cubicle (the ideal cover aggregate shape) as the value approaches 1. The indices range from 0.30 to 0.89.

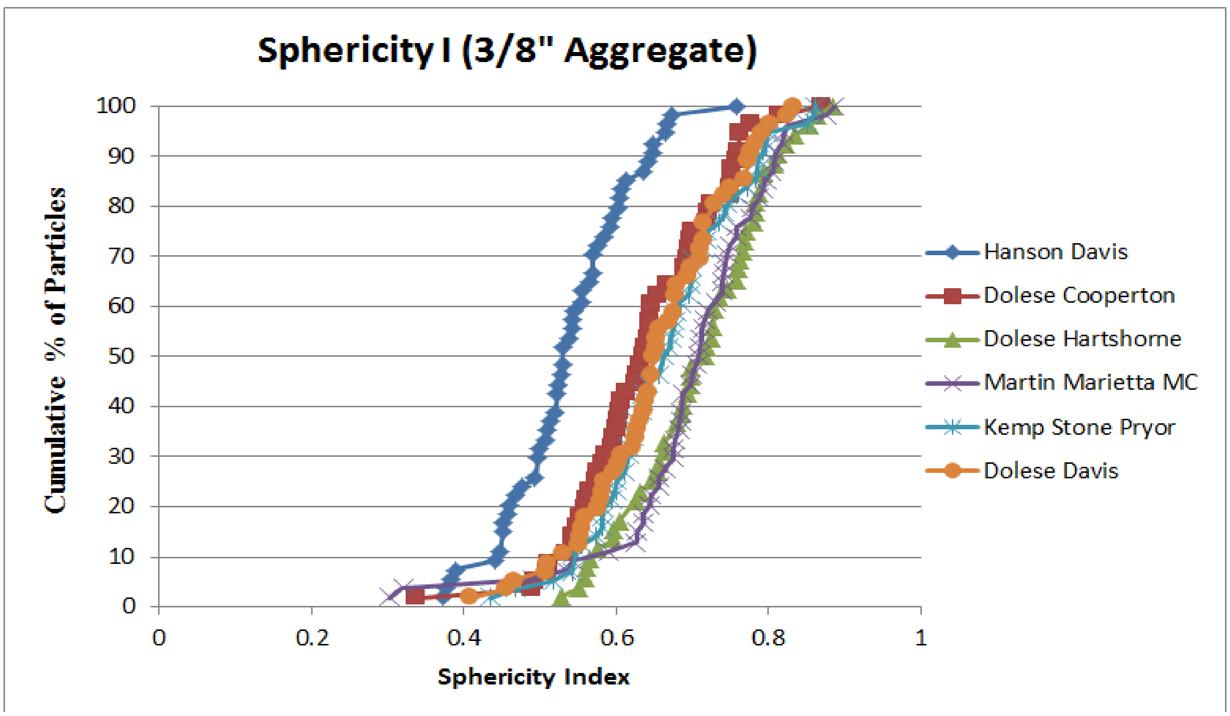

Figure 5.2 AIMS1 Output for Sphericity I (3/8" Aggregate, Sample 1)

The analysis of variance showed that there was a statistically significant difference (p = 0.000) between the Hanson Davis material (less cubicle) and the other five quarries based upon a 95% confidence interval (Tukey's Method). Table 5.5 shows that 78% of the Hanson material was considered to be flat/elongated, versus one-third or less of material for all of the other quarries.

Table 5.5 AIMS1 Sphericity I Classification for 6 Quarries (Sample 1)

Quarry	**Flat/ Elongated** (< 0.6)	**Low Sphericity** (0.6 - 0.7)	**Moderate Sphericity** (0.7 – 0.8)	**High Sphericity** (> 0.8)
	% in Range			
Hanson - Davis	78	21	1	0
Dolese - Cooperton	34	40	23	3
Dolese - Hartshorne	15	33	46	6
Martin Marietta – Mill Creek	11	34	42	13
Kemp Stone - Pryor	23	43	29	5
Dolese – Davis	27	41	28	4

These results indicate that the limestone material exhibits a lower flat-elongated ratio (is more cubicle in shape) than the Hanson rhyolite material, which may enhance embedment. It also contributes to its impact resistance. Although the Hanson material has a lower Micro Deval value, the shape of the limestone particles may contribute for its lower impact resistance and be less prone to breakage under traffic. 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.

There is also a statistically significant difference between the Martin Marietta Mill Creek material (more cubical) and the rest of the quarries, with the exception of Dolese Hartshorne. This is also consistent with the Micro Deval results that show Martin Marietta material has the greatest resistance to abrasion.

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. The descriptive statistics are provided in Table 5.6.

Table 5.6 AIMS1 Texture: Descriptive Statistics for 6 Quarries

AIMS1 Output: Texture, 3/8" Aggregate					
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 75.8)**	**Min. Value**	**Max. Value**
Hanson - Davis	51	176.8	54.8	81	323
Dolese - Cooperton	56	260.0	78.9	51	428
Dolese - Hartshorne	105	237.4	71.8	87	414
Martin Marietta – Mill Creek	108	233.5	99.3	90	557
Kemp Stone - Pryor	101	126.9	54.3	45	289
Dolese – Davis	52	165.9	77.3	42	367

The texture data obtained from Sample 1 testing (N = 56, approx.) is graphically depicted in Figure 5.3. The AIMS classifies texture in a range that has a low end of "polished faces" (index < 165) and a high end of "high roughness" (index > 460). Therefore, a higher value is desirable. The indices of the tested material range from 42 to 557.

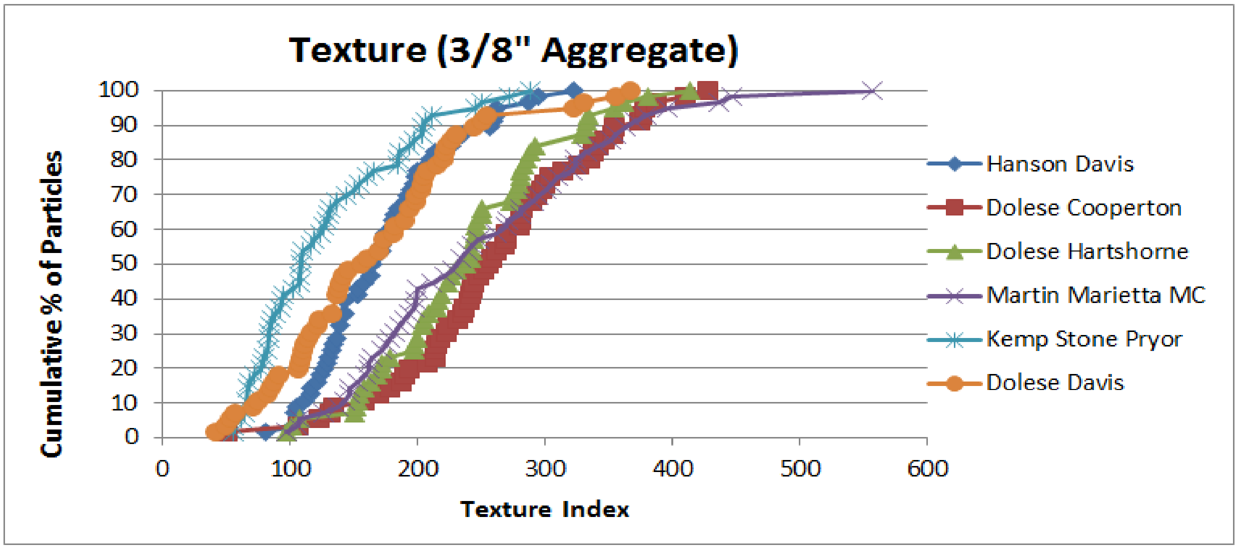

Figure 5.3 AIMS1 Output for Texture (3/8" Aggregate, Sample 1)

The analysis of variance showed that there was a statistically significant difference ($p = 0.000$) between material sources with regard to texture. Based on these results, the Martin Marietta and Dolese (Cooperton and Hartshorne) materials exhibited greater roughness (texture) than the Hanson, Dolese Davis and Kemp Stone materials based upon a 95% confidence interval (Tukey's Method). This indicates that the Martin Marietta and Dolese materials may offer increased surface friction and adhesion.

5.1.2.2 AIMS1 Results – Test Section Source (Dolese Davis)

This section presents AIMS results for the test section aggregate from Dolese Davis obtained from the chip spreader during construction of each test section. Comparisons of the various size fractions (1/2", 3/8", 1/4" and No. 4) were made to determine any trends that exist between AIMS properties and field performance. See Appendix C for all analyses.

In a previous OkTC study [6], a potential correlation was found between the gradient angularity measured by AIMS1 and the skid number as measured with the locked wheel skid test. Additionally, there was a promising relationship between the Performance-based Uniformity Coefficient (PUC) and the sphericity index measured by AIMS1. This section presents results that support these findings.

The analysis in this section focuses on the comparison of the aggregate size fractions found in the ½" test sections (TS 2 and TS 5) to determine if there were correlations between the AIMS1 results and the field test results. The gradations used in this study show that four size fractions characterize most of the aggregate in the gradations: 1/2", 3/8", 1/4" and No. 4. The table also shows that the 1/2" SS gradation can contain up to 85% material that is retained on the 3/8" sieve, versus 40% in the traditional gradation. The sieve analysis showed that the actual TS 5 gradation (1/2" SS) contained approximately 70% of 3/8" and larger material, versus half that value (39%) in TS 2. The remainder of the traditional gradation is made up mostly of 1/4" and No. 4 material. Results were analyzed and then evaluated in the context of test section performance results (Section 6 of this report).

Skid resistance is an important pavement characteristic purely from a safety standpoint. The previous study [6] found that microtexture (skid number) is related to aggregate gradient angularity. The analysis of variance conducted in this study revealed that there is no statistically significant difference ($p = 0.927$, CI = 95%) between the four size fractions on the basis of gradient angularity. The AIMS1 output for gradient angularity is shown in Figure 5.4. Extending the previous study's findings that increasing gradient angularity tracks with increasing skid number, one would expect that no difference in gradient angularity would track with no difference in skid number. Section 6.1 shows this to be the case. Although the skid number sample size was too small to determine significance, the values appear to be similar over time (as described in Section 6). This is consistent with the findings in the previous study that AIMS1 gradient angularity output trends with skid numbers.

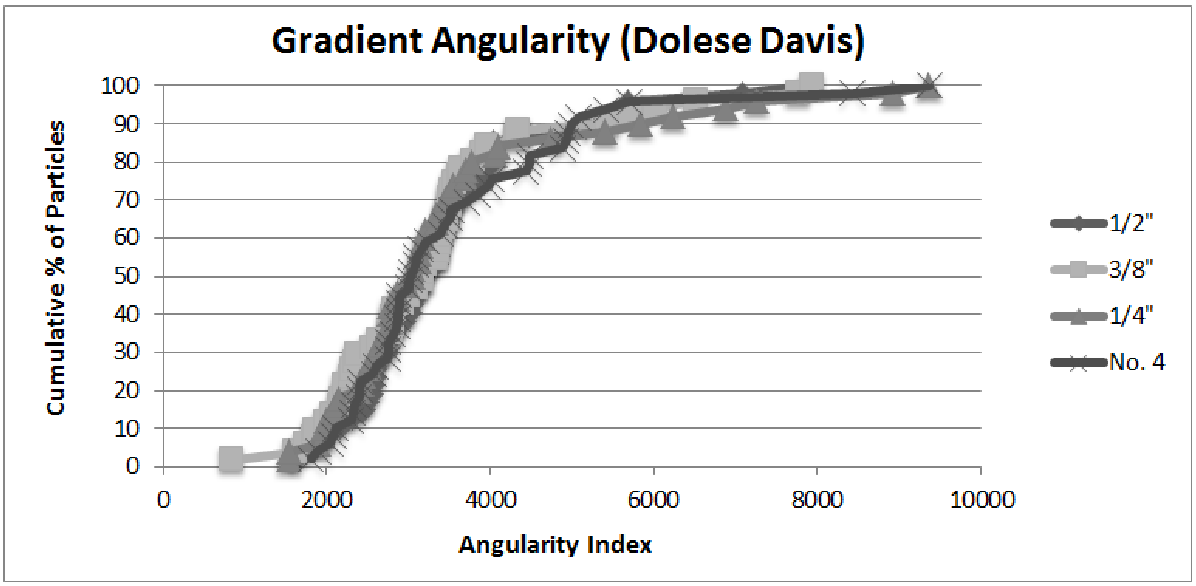

Figure 5.4 AIMS 1 Output: Gradient Angularity for Test Section Aggregate

Texture was analyzed and a statistically significant difference exists between the 1/2" aggregate compared to the smaller aggregate (1/4" and No. 4). However, the test section gradations contain less than 5% of the 1/2" aggregate, so it should be expected to have minimal to no impact on performance. There was no statistically significant difference between the 3/8" and the 1/4" and No. 4 size fractions on the basis of texture, which further supports the similar skid number results and gradient angularity output.

Figure 5.5 shows the texture output for the various size fractions.

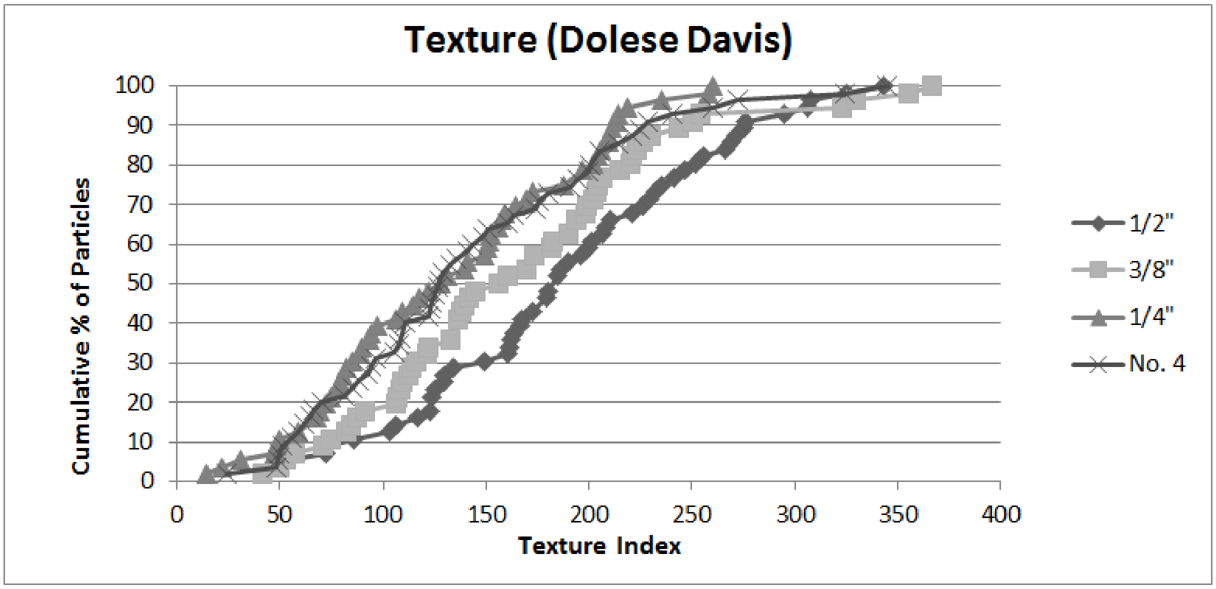

Figure 5.5 AIMS 1 Output: Texture for Test Section Aggregate

The PUC is a promising metric for measuring chip seal susceptibility to failure due to flushing/bleeding. The previous study [6] found trends between the PUC and the AIMS1 sphericity index results. Figure 5.6 shows the AIMS1 output for sphericity obtained in this study.

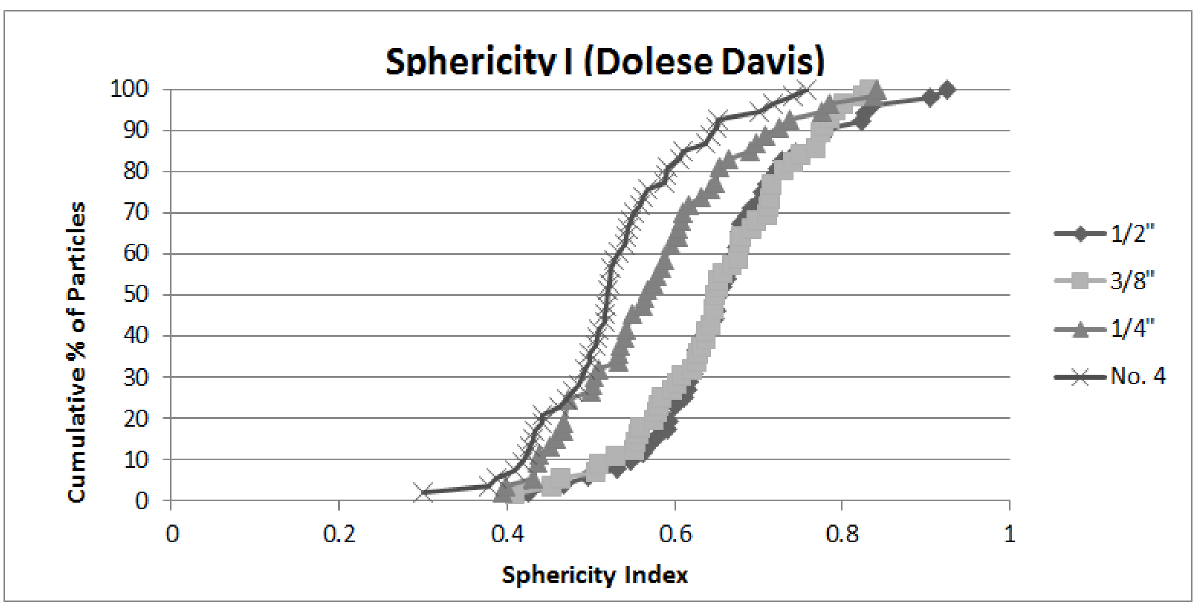

Figure 5.6 AIMS 1 Output: Sphericity for Test Section Aggregate

The analysis of variance for this study showed that there was a statistically significant difference between sphericity characteristics of size fractions (p = 0.00, CI = 95%). The Tukey's Test revealed that the 1/2" and 3/8" aggregate were statistically the same, but that there was a statistically significant difference between them and the 1/4" and No.4 aggregate. Essentially, the 1/2" and 3/8" aggregate samples provide greater sphericity values (more cubical shape) than the other two size fractions.

In terms of chip seal performance, the higher sphericity values should translate to greater embedment potential and greater aggregate retention, reducing the potential for failure based upon flushing/bleeding. Ultimately, the chip seal containing the larger aggregate at greater quantities that exhibits higher sphericity indices would theoretically allow better protection of the bituminous seal from traffic wear. This study's findings were consistent with the previous study's conclusions based upon the relationship between PUC and sphericity [6]. As described in Section 6.1, the single size (SS) test sections based upon PUC generally outperformed the traditional gradation sections over the 1 year period on the basis of macrotexture ("drainability", aggregate retention). This could be because the SS test sections contain nearly twice as much 1/2" and 3/8" aggregate as the test sections built with traditional gradations.

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. Complete Sessile Drop results for the five aggregates are listed in Appendix B.

Sessile Drop results for Dolese-Cooperton (probe liquid: water) are shown for illustrative purposes in graphical and numerical form in Figure 5.7 and Table 5.7, respectively.

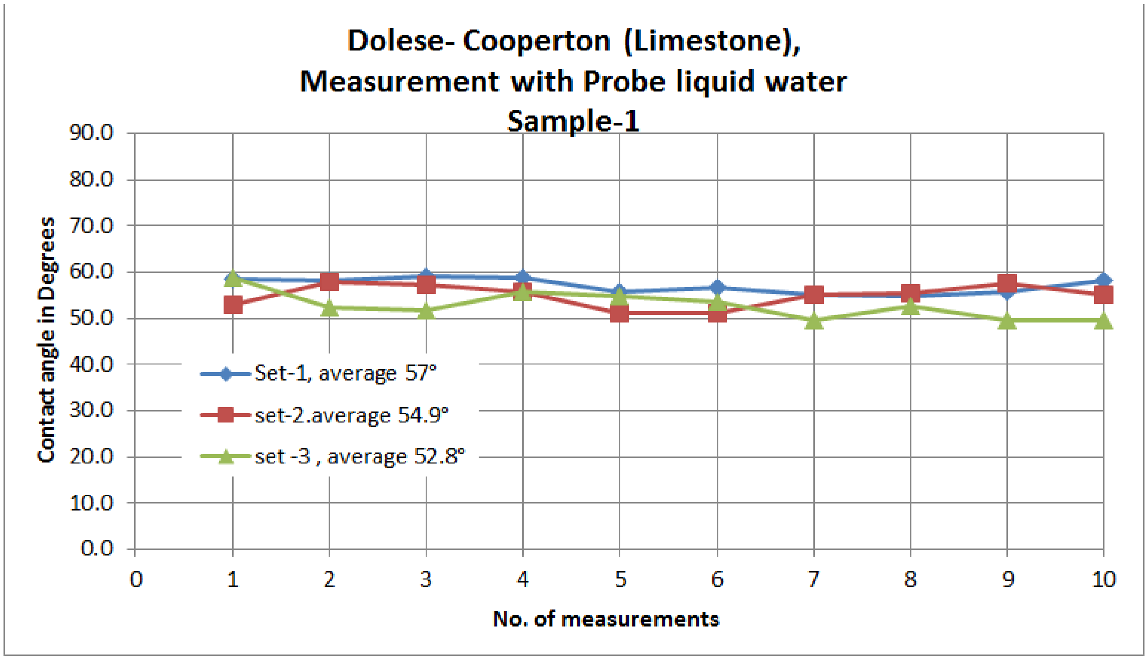

Figure 5.7 Sessile Drop Results Graph for Dolese Cooperton

Table 5.7 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 5.8.

Table 5.8 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
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

Subsequently, the free energy of adhesion was calculated and the results are listed in Table 5.9.

Table 5.9 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. 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 5.8 shows some typical DCA specimens prepared from an asphalt binder sample.

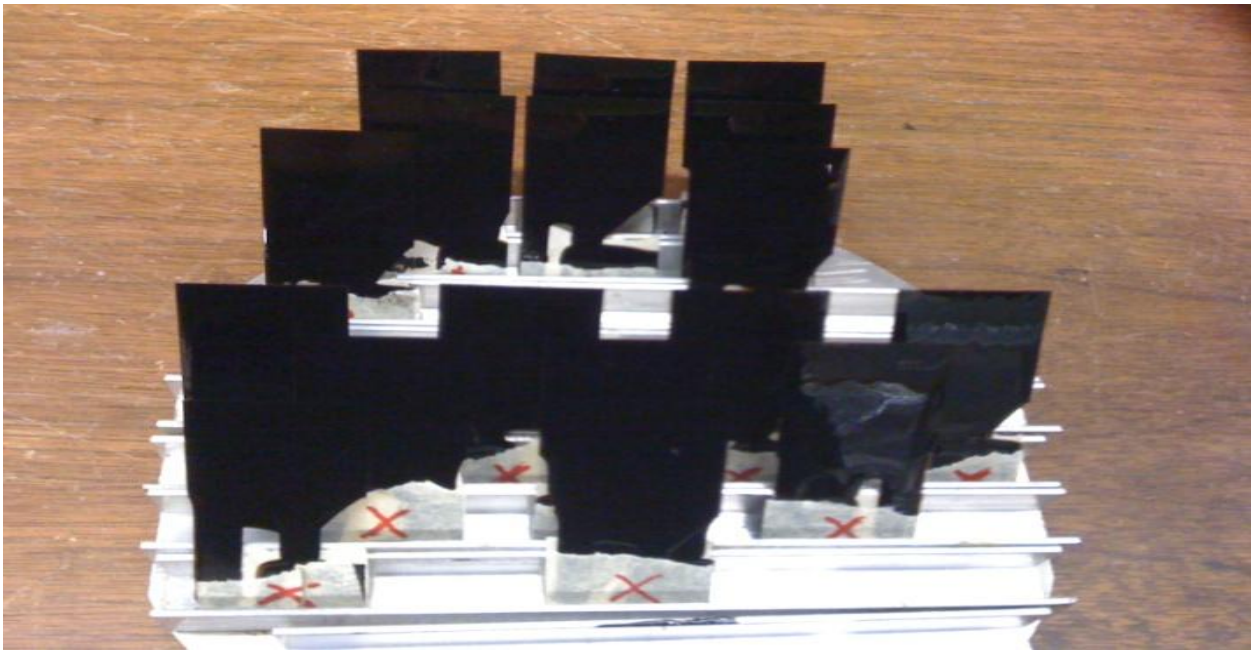

Figure 5.8 Typical DCA Specimens Prepared from Asphalt Binder

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 prepared and contained significant number of bubbles around their surface, 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.

Specimens were prepared as shown in Figure 5.9.

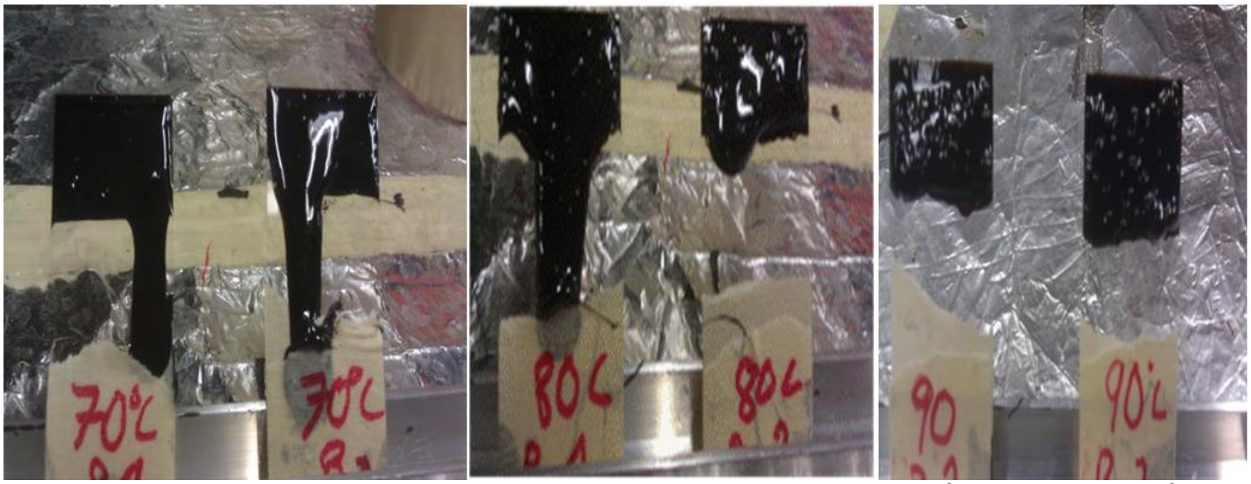

Figure 5.9 Emulsion Coated Glass Cover Specimens: (Left) 70^{0}C; (Middle) 80^{0}C; (Right) 90^{0}C

The Cahn Dynamic Contact Angle (DCA) analyzer (Figure 5.10) 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.

Figure 5.10 The Cahn Dynamic Contact Angle (DCA) Analyzer

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 5.11, in which the vertical bar represents one standard deviation (error bar) for the given set of specimens.

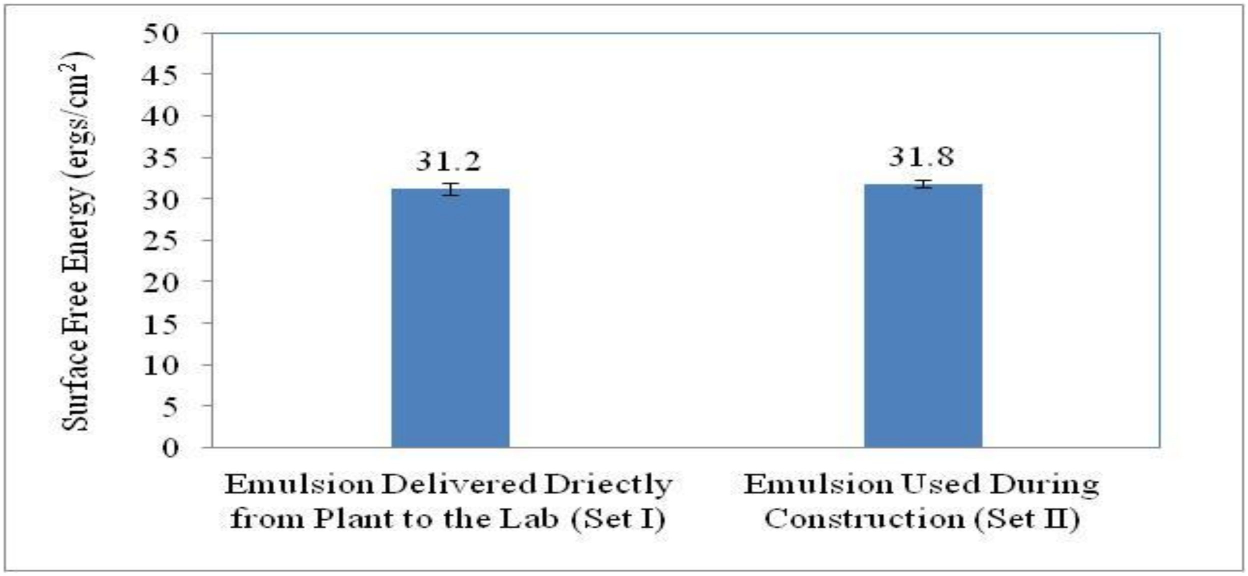

Figure 5.11 Total SFE (ergs/cm2) of Tested Emulsion

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 5.11 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 5.10. All ratios are greater than 0.8, indicating that each aggregate source is compatible with each emulsion source, as listed.

Table 5.10 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 5.10, 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 5.10 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 5.11.

Table 5.11 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 5.12 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 5.12 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 5.12 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 was to determine relative differences in performance between the chip seal test sections. Specifically, the objective was 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 were monitored for performance. Macro- and microtexture values obtained at one year of service have been deemed appropriate to evaluate chip seal performance [45,64]. Macrotexture measurements were obtained from the chip seal test sections in month 12. However, the ODOT skid tester was involved in a rear-end collision and was unavailable to provide more than 5 months of microtexture data. All of the chip seal test sections were performing satisfactorily on the basis of macro and microtexture at the time of their respective final measurements. Chip seal construction practices were observed and compared with effective practices. The chip seal test sections have not exhibited short term failure, which 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 Month 1 (November 2012) 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 off the aggregate by traffic. This is may be the case for Test Section 4s, with its 1% increase in skid value over the 7 month period in which the 5 data points were obtained (Table 6.1). Microtexture should be expected to, at some point, begin to decrease with deterioration soon after the fog seal has been worn off by traffic. This deterioration is demonstrated in the microtexture values obtained in May 2013 (Table 6.1). 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 in the fog seal and the emulsion seal test sections, as noted in Table 6.1.

Table 6.1 Microtexture (Skid Number) Values at Month 1 and Month 7 (Final)

Test Section	Chip Seal Description	12-Nov	13-May	% Change
1	ODOT 3/8"	47.1	34.6	-26.5
1s	ODOT 3/8", fog seal	37.5	32.3	-13.8
2	ODOT 1/2"	48.7	No data	-22.7*
2s	ODOT 1/2", fog seal	39.0	34.5	-11.6
3	ODOT 5/8"	46.4	36.6	-21.1
3s	ODOT 5/8", fog seal	37.0	36.2	-2.3
4	3/8" Single Size	43.7	34.3	-21.5
4s	3/8" Single Size, fog seal	34.6	34.9	1.0
5	1/2" Single Size	45.6	36.0	-21.1
5s	1/2" Single Size, fog seal	37.6	33.8	-10.0
1f**	ODOT 3/8", fabric	44.2	30.0	-32.0
1sf**	ODOT 3/8", fog seal and fabric	34.1	28.8	-15.5
3sf**	ODOT 5/8", fog seal and fabric	36.7	33.2	-9.5
3f**	ODOT 5/8", fabric	42.9	32.8	-23.5
*No May data due to missing marker; April-13 data (37.3) used to calculate % Change				
**Test Sections that mistakenly received emulsion instead of fog seal				

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 7 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 appears to be no significant difference in skid values for all of the test sections as of May 2013, which is when final measurements were taken. It should be noted that all test section skid values in Table 6.1 were still above the failure criterion of 25.

It was expected that differences in the test sections would be observed after one year of service (September 2013). However, the ODOT Skid Tester was involved in a rear-end collision (non-project related) and subsequent measurements were not obtained. Additionally, the skid tester was in the shop for maintenance in December 2012 and

January 2013, so measurements were not obtained in those months. Therefore, deterioration models could not be created nor significance determined for differences due to insufficient data.

Figure 6.1 shows the measurements that were obtained (smooth tire) in remaining months. The value at time zero is the baseline measurement obtained before chip seal application.

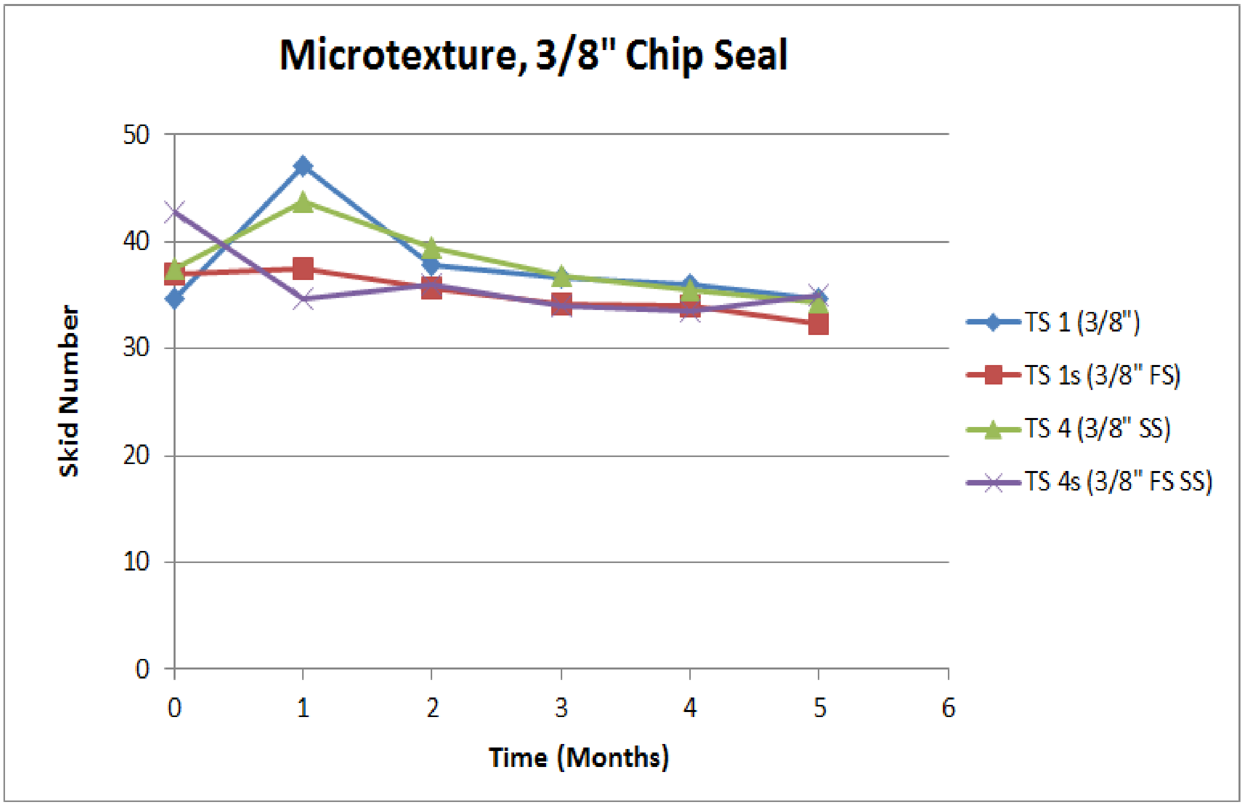

Figure 6.1 Microtexture Values for 3/8" Test Sections

There appears to be no difference in skid performance of the 3/8” chip seal test sections, regardless of gradation or fog seal. This also appears to be the case for the 1/2” chip seal sections (next figure).

These results, shown in Figure 6.2, are consistent with previous findings and with the AIMS results obtained in the laboratory, as discussed in the previous section of this report (Section 5.1.2.2).

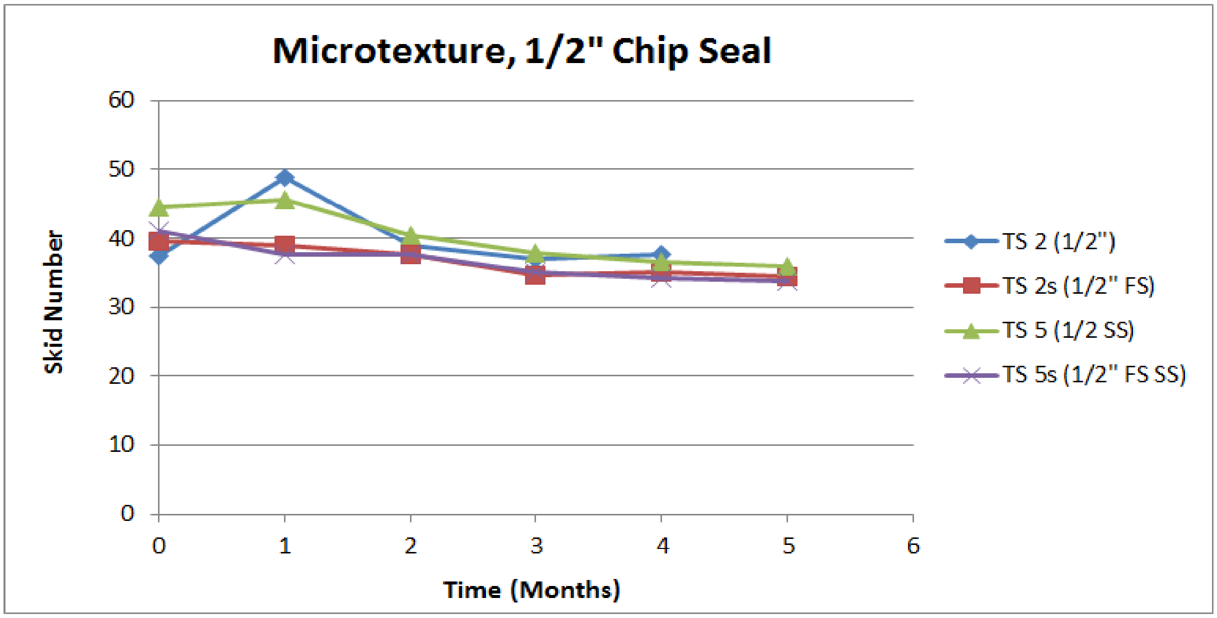

Figure 6.2 Microtexture Values for 1/2" Test Sections

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 were monitored for performance based upon macrotexture.

Table 6.2 Macrotexture Values at Month 1 (Initial) and Month 12 (Final)

Test Section	Chip Seal Description	12-Nov	13-Oct	% Change
		MTD (mm)		
1	ODOT 3/8"	2.99	2.46	-17.7
1s	ODOT 3/8", fog seal	3.07	2.60	-15.1
2	ODOT 1/2"	5.54	3.18	-42.6
2s	ODOT 1/2", fog seal	3.35	2.63	-21.3
3	ODOT 5/8"	4.66	3.48	-25.4
3s	ODOT 5/8", fog seal	4.71	3.18	-32.4
4	3/8" Single Size	3.35	2.58	-23.1
4s	3/8" Single Size, fog seal	3.39	2.50	-26.1

Test Section	Chip Seal Description	12-Nov	13-Oct	% Change
5	1/2" Single Size	4.21	2.98	-29.3
5s	1/2" Single Size, fog seal	4.53	3.39	-25.1
1f	ODOT 3/8", fabric	3.03	2.44	-19.6
1sf	ODOT 3/8", fog seal and fabric	2.60	2.08	-20.0
3sf	ODOT 5/8", fog seal and fabric	3.87	2.86	-26.2
3f	ODOT 5/8", fabric	3.92	3.09	-21.3

Figure 6.3 shows all of the 3/8" chip seal sections macrotexture data points obtained in the field. The first data point represents baseline (pre-construction) measurement. At this point in the service life, there is no statistical significant difference ($p>0.05$) between the performance of the 3/8" test sections with traditional ODOT gradation and PUC-based gradations (denoted "SS" for single size in the graph). However, the single size section (TS 4) has yielded higher macrotexture values over the testing period than the other test sections. Regardless of fog seal or single-size gradation, all are performing well above the 0.9mm failure criterion.

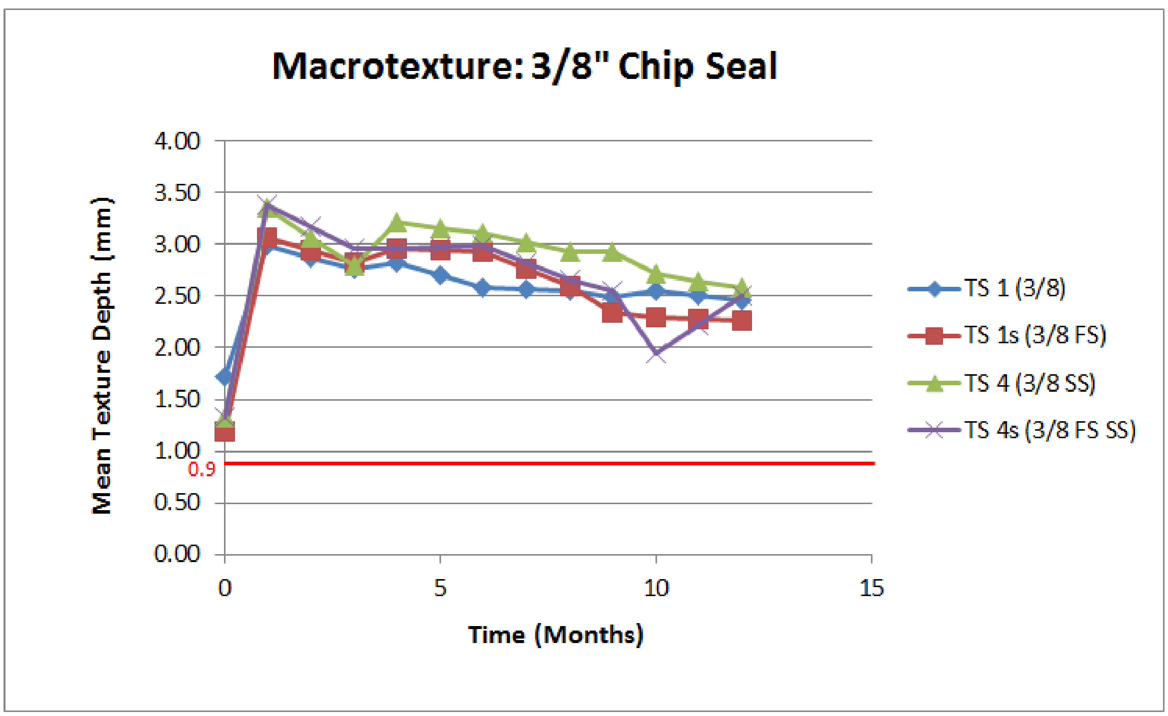

Figure 6.3 Macrotexture Values for 3/8" Test Sections

The macrotexture values for the 1/2” Chip Seal Test Sections show that the PUC-based sections have outperformed (albeit slightly) the non-PUC-based sections, as depicted in Figure 6.4. All sections are still performing well above the 0.9mm failure criterion. However, at this point in the service life, a statistically significant difference exists between the PUC-graded test section with fog seal versus the traditional gradation section with fog seal ($p<0.05$). These results are consistent with previous findings and with the AIMS results obtained in the laboratory, as discussed in the previous section of this report (Section 5.1.2.2).

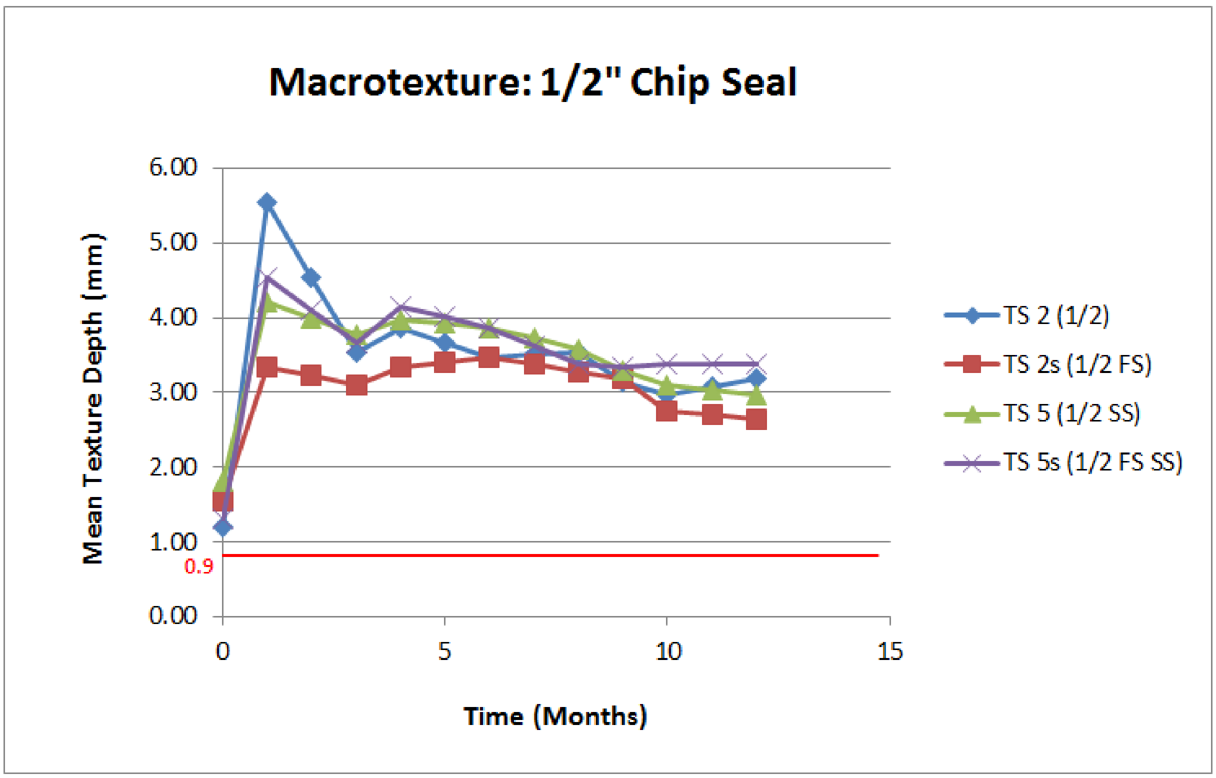

Figure 6.4 Macrotexture Values for 1/2" Test Sections

Unfortunately, Dolese did not supply the PUC-based 5/8” gradation. The macrotexture values show that the PUC-based gradations for 1/2” chip seal have been generally greater than the ODOT gradations on the basis of macrotexture. Also, the 1/2” chip seal sections have performed better than the 3/8” sections at this point in the service life. If the trend that the SS sections with larger aggregate are outperforming their counterparts is valid (in the context of AIMS and macrotexture), then it may be hypothesized that a PUC-based 5/8" chip seal would outperform the ODOT 5/8" section.

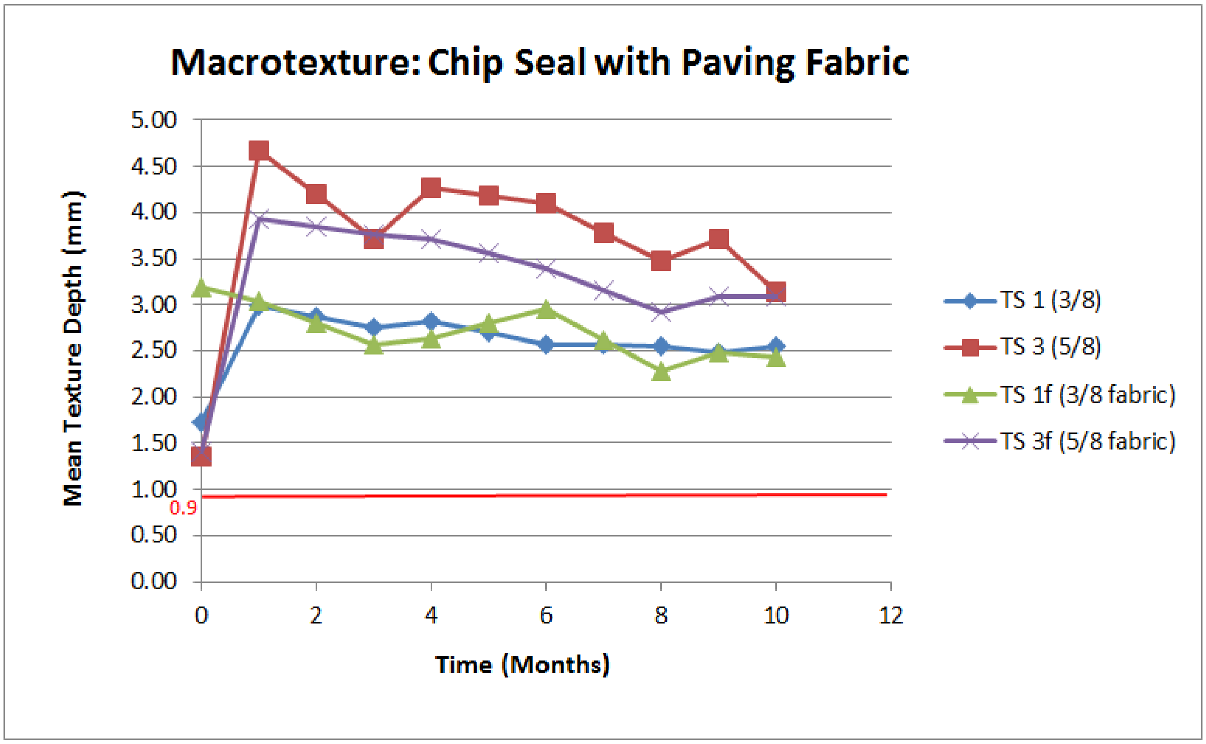

Figure 6.5 Macrotexture Values for Test Sections with and without Fabric

Figure 6.5 shows that the test sections with geosynthetic fabric are not outperforming their respective sections at this point in the service life. However, it should be noted that fabric sections are performing well (have not reached macro and microtexture failure criterion) and that the fabric sections were placed in an area where the pavement exhibited more distresses (i.e. cracking, rutting) than in other test sections, as per the ODOT condition survey and substrate characterization measurements. Additionally, the 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.

In general, chip seal deterioration occurs more rapidly at the beginning of the service life, then “levels off” in following years [56]. Therefore, a logarithmic equation has been shown to model chip seal deterioration over the service life well [56]. However, the deterioration at this point in the service life of the study test sections is not well modeled by the logarithmic equation since the data has not started to “level off”, due to variables such traffic levels and weathering, etc. Applying the logarithmic equation on the current data results in a premature “leveling off” of the deterioration rate and subsequently yields unreasonably long service life estimates (i.e. 20+ years). Therefore, development of deterioration models based upon linear regression is not appropriate at this point in the test section service life.

However, the use of the TNZ performance specification can provide some insight into expected performance of the chip seal test sections on the basis of macrotexture [45]. The TNZ T/3 sand circle test was chosen for this particular study (Table 6.2) because it can be directly compared with the Australian and New Zealand research upon which the project builds. Table 6.3 shows the minimum macrotexture values required for the test sections as observed at 12 months of service. The TNZ failure criterion is 0.9mm. Referencing Table 6.2, all test sections are yielding values above the failure criterion of 0.9mm, as well as the P/17 12- month criterion at all possible design lives, as noted in Table 6.3. Therefore, according to the performance specification, all of the test sections should be expected to reach a service life of greater than 6 years on the basis of macrotexture.

Table 6.3 TNZ P/17 Performance Specification Comparison

Treatment	**P/17 12-month Minimum Macrotexture at Given Design Life**		
	4-year	5-year	6-year
3/8" Chip Seal	1.17	1.29	1.37
1/2" Chip Seal	1.32	1.52	1.60
5/8" Chip Seal	1.43	1.68	1.85

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 this section's tables.

Common chip seal equipment includes an emulsion distributor, aggregate spreader, rollers, dump trucks and sweeping equipment. Figure 6.6 shows part of the chip seal crew that installed the test sections. It shows the distributor 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]. Additionally, all of the ODOT Divisions indicated similar practices with regard to equipment and methods for chip seal construction in their regions.

Common chip seal equipment includes an emulsion distributor, aggregate spreader, rollers, dump trucks and sweeping equipment. Figure 6.6 shows part of the chip seal crew that installed the test sections.

Figure 6.6 Chip Seal Construction: Distributor, Chip Spreader and Dump Truck

It shows the distributor 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 6.4. Additionally, all of the ODOT Divisions indicated similar practices with regard to equipment and methods for chip seal construction in their regions.

Table 6.4 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	✓

Best Practice	Purpose	Observed
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 6.5. 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. Division 1 (Muskogee) 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 6.5 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	✓

Best Practice	Purpose	Observed
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 6.5 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 6.7 shows the rolling operation for test section construction that included two pneumatic rollers.

Figure 6.7 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 6.8, as deliver their loads of aggregate to the spreader.

Figure 6.8 Dump Trucks in Staggered Pattern

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 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.

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 6.9, to keep traffic off of the newly chip sealed surface, as well as to protect and warn the traveling public.

Figure 6.9 Traffic Control Signage and Pilot Car for Test Section Installation

7.0 CONCLUSIONS

The following 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) resulting in single size gradations appears to enhance chip seal performance in Oklahoma. However, authoritative conclusions cannot be drawn based upon the limited data obtained within the research time frame. Specifically, the research was limited by the rate of deterioration exhibited in the first year of the chip seal service lives. However, the results indicate that the ½" single size (PUC) gradation is outperforming the traditional ODOT ½" gradation.
4. All of the chip seal test sections are performing satisfactorily on the basis of microtexture (skid resistance) after seven months of service and on the basis of macrotexture (aggregate retention) after twelve months of service.
5. Based upon the Transit New Zealand Performance Specification (P/17), all test sections should exceed 6 years of service life on the basis of macrotexture ("drainability" and aggregate retention).
6. AIMS1 testing results are consistent with previous findings that show a correlation exists between AIMS properties (sphericity) and Micro Deval results: aggregate that exhibits greater sphericity (cubical shape) may exhibit greater resistance to degredation due to impact and abrasion.
7. AIMS testing has shown that there are statistically significant differences between aggregate sources in Oklahoma that may impact chip seal performance.
8. AIMS1 and AIMS2 (new generation AIMS) provide comparable shape results; however, a statistically significant difference exists between texture results.
9. Testing has provided further support for potential links between AIMS results and field performance.

10. There was no difference in AIMS1 gradient angularity and texture output for the aggregate obtained during construction of the various test sections. This is consistent with the similar skid numbers exhibited by all test sections.
11. There was a difference in AIMS sphericity output for the aggregate obtained during construction of the various test sections. The larger size fractions provided higher sphericity indices. This is consistent with the greater macrotexture performance of the single size chip seals, which contain approximately twice as much of the larger aggregate than the traditional chip seals.
12. Fog seal and geosynthetic fabric has not improved chip seal performance in the short term.
13. 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.

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APPENDIX A - Outline Specification for Single Size Chip Seal

The following outline specification is a product of this research. It should be noted that performance data resulting from this study, upon which the specification recommendations are based, was limited to the first year of the service life of the chip seal test sections. The specification may enhance Oklahoma Department of Transportation (ODOT) chip seal design and performance through introducing new criteria for the selection of cover aggregate and binder. These criteria are based upon the recent technological advances in the characterization of aggregate shape and texture as well as aggregate-binder compatibility. Specifically, the specification includes metrics for aggregate index properties obtained from the Aggregate Imaging System (AIMS) and performance-based uniformity coefficients (PUC). It also uses the surface free energy (compatibility ratio) approach in evaluation of the aggregate-binder compatibility. Lastly, effective chip seal construction practices are incorporated.

SINGLE SIZE CHIP SEAL

1. DESCRIPTION

This work consists of constructing a single surface, single size treatment of aggregates and bituminous materials.

2. MATERIALS

Provide materials in accordance with the following sections:

Cover Aggregates (Materials Section):

C. Gradation

Provide cover aggregates with gradations in accordance with the following:

	1/2"-G1 (SS)		5/8"-G1 (SS)	
Sieve #	LL	UL	LL	UL
1 in				
7/8 in				
3/4 in			100	
5/8 in	100		95	100
1/2 in	95	100	15	45
3/8 in	15	40	0	5
1 /4 in				
No. 4	0	5		
No. 8	0	2	0	1
No. 200				

Gradation to have a performance uniformity coefficient (PUC) less than 0.2.

Gradation to meet the following limits for aggregate imaging on the basis of sphericity:

Flat/Elongated (< 0.6)	**Low Sphericity** (0.6 - 0.7)	**Moderate Sphericity** (0.7 – 0.8)	**High Sphericity** (> 0.8)
% in Range			
27	41	28	4

Bituminous Binder (See Materials Section):

The bituminous binder and aggregate should yield a minimum compatibility ratio (based on *surface free energy* (SFE)) of 0.8 to 1.0 for compatibility.

3. EQUIPMENT

4. CONSTRUCTION METHODS

Rolling

Roll the entire surface at a rate of 3500 SY/hour as a standard benchmark.

X. PERFORMANCE*

Use a performance specification* to evaluate chip seal performance on the basis of macrotexture. The design life of a chip seal is reached when the texture depth drops below 0.9 mm (0.035 inches) on road surface areas supporting speeds greater than70 km/h (43 mph)" [45]. After twelve months of service, obtain the in-field texture depth and compare it to the minimum texture depth at 1 year, as calculated by using Equation 14.

$$Td_{1=} 0.07\, ALD\ \log Y_d + 0.9 \qquad \text{Equation 14}$$

Where: Td_1 = texture depth in one year (mm)

Y_d = design life in years

ALD = average least dimension of the aggregate (mm)

*Based on New Zealand's P/17, *Notes for the Specification of Bituminous Reseals* [45]

APPENDIX B - 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

APPENDIX C – AIMS1 Results

This sections provides descriptive statistics, One-Way ANOVA and Tukey's Test Results (CI = 95%) for the four size fractions (1/2", 3/8", 1/4" and No. 4) for the six quarries listed in the report. Each table provides the p-value for the ANOVA (p-values < 0.05 indicate that groups are significantly different). Additionally, the Tukey's Method grouping information is provided (means that do not share a Tukey's grouping letter are significantly different): the pairwise comparison based upon the pooled standard deviation.

1/2" Aggregate

AIMS1 Gradient Angularity: Descriptive Statistics for 6 Quarries, ½" Aggregate

AIMS1 Output: Gradient Angularity, 1/2" Aggregate							
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1342)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	53	3616	1243	2175	8651	A
Dolese - Cooperton	33	3135	932	1650	5647	AB
Dolese - Hartshorne	88	3619	1598	1654	9351	A
Martin Marietta – Mill Creek	102	3637	1488	1688	8980	A
Kemp Stone - Pryor	112	2749	1133	653	9907	B
Dolese – Davis	47	3430	1286	1582	7872	A
p-value = 0.000						

AIMS1 Sphericity I: Descriptive Statistics for 6 Quarries, ½" Aggregate

AIMS1 Output: Sphericity I, 1/2" Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 0.1058)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	50	0.7345	0.0876	0.398	0.879	AB
Dolese - Cooperton	33	0.7245	0.1334	0.336	0.913	ABC
Dolese - Hartshorne	90	0.7048	0.1404	0.299	0.960	BC
Martin Marietta – Mill Creek	98	0.7693	0.0963	0.307	0.959	A
Kemp Stone - Pryor	105	0.6986	0.0765	0.444	0.869	BC
Dolese – Davis	48	0.6635	0.0998	0.426	0.925	C
p-value = 0.000						

AIMS1 Sphericity II: Descriptive Statistics for 6 Quarries, ½" Aggregate

AIMS1 Output: Sphericity II, 1/2" Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 0.1306)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	53	0.7567	0.1269	0.3842	0.9938	AB
Dolese - Cooperton	34	0.7138	0.1612	0.3053	0.9525	B
Dolese - Hartshorne	97	0.7450	0.1382	0.3694	1.0000	AB
Martin Marietta – Mill Creek	106	0.7911	0.1055	0.4472	0.9808	A
Kemp Stone - Pryor	111	0.7557	0.1013	0.5515	0.9963	AB
Dolese – Davis	52	0.5914	0.1878	0.1306	0.9764	C
p-value = 0.000						

AIMS1 2D Form: Descriptive Statistics for 6 Quarries, ½" Aggregate

AIMS1 Output: 2D Form, 1/2" Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 2.567)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	55	7.726	2.206	4.57	17.47	A
Dolese - Cooperton	32	7.660	3.129	1.00	18.33	AB
Dolese - Hartshorne	91	8.336	3.376	4.22	19.98	A
Martin Marietta – Mill Creek	97	7.616	2.073	4.59	14.36	A
Kemp Stone - Pryor	103	6.441	1.351	3.74	9.66	B
Dolese – Davis	53	8.794	3.421	4.41	19.26	A
p-value = 0.000						

AIMS1 Texture: Descriptive Statistics for 6 Quarries, ½" Aggregate

AIMS1 Output: Texture, 1/2" Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 81.3)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	56	193.7	69.4	48.0	364.0	C
Dolese - Cooperton	49	293.2	99.3	52.0	501.5	A
Dolese - Hartshorne	53	230.4	77.8	76.5	433.5	BC
Martin Marietta – Mill Creek	53	244.1	104.7	50.0	518.0	B
Kemp Stone - Pryor	51	138.2	52.3	69.0	289.0	D
Dolese – Davis	53	188.5	74.0	42.0	343.5	C
p-value = 0.000						

3/8" Aggregate

AIMS1 Gradient Angularity: Descriptive Statistics for 6 Quarries - 3/8" Aggregate

AIMS1 Output: Gradient Angularity, 3/8" Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1374)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	56	3370	1492	364	8472	AB
Dolese - Cooperton	52	2992	900	1133	6545	AB
Dolese - Hartshorne	85	3623	1613	1851	9400	A
Martin Marietta – Mill Creek	99	3571	1588	795	9926	AB
Kemp Stone - Pryor	111	3040	1019	1458	7750	B
Dolese – Davis	51	3332	1434	838	7930	AB
p = 0.011						

AIMS1 Sphericity I: Descriptive Statistics for 6 Quarries – 3/8" Aggregate

AIMS1 Output: Sphericity I, 3/8" Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1011)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	49	0.5398	0.0838	0.3720	0.7580	C
Dolese - Cooperton	52	0.6383	0.0968	0.3390	0.8680	B
Dolese - Hartshorne	94	0.6875	0.1128	0.2890	0.8850	AB
Martin Marietta – Mill Creek	105	0.7228	0.1046	0.3030	0.9680	A
Kemp Stone - Pryor	105	0.6688	0.0974	0.3960	0.8860	B
Dolese – Davis	50	0.6484	0.0979	0.4090	0.8330	B
p = 0.000						

AIMS1 Sphericity II: Descriptive Statistics for 6 Quarries – 3/8" Aggregate

AIMS1 Output: Sphericity II, 3/8" Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1339)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	54	0.7513	0.1172	0.4794	0.9804	AB
Dolese - Cooperton	56	0.6794	0.1221	0.4192	0.8931	B
Dolese - Hartshorne	101	0.7358	0.1441	0.2857	0.9839	AB
Martin Marietta – Mill Creek	110	0.7698	0.1185	0.3738	0.9920	A
Kemp Stone - Pryor	112	0.7454	0.1222	0.3463	0.9629	A
Dolese – Davis	56	0.5863	0.1833	0.2005	0.9656	C
p = 0.000						

AIMS1 2D Form: Descriptive Statistics for 6 Quarries – 3/8" Aggregate

AIMS1 Output: 2D Form, 3/8" Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 2.281)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	51	7.579	2.042	4.97	14.91	AB
Dolese - Cooperton	53	8.232	2.379	4.67	18.12	AB
Dolese - Hartshorne	87	8.396	2.760	4.34	18.28	A
Martin Marietta – Mill Creek	99	7.579	2.264	4.14	16.39	AB
Kemp Stone - Pryor	107	7.298	1.715	3.78	13.28	B
Dolese – Davis	51	8.053	2.560	4.31	15.19	AB
p = 0.011						

AIMS1 Texture: Descriptive Statistics for 6 Quarries – 3/8" Aggregate

AIMS1 Output: Texture, 3/8" Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 75.8)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	51	176.8	54.8	81	323	B
Dolese - Cooperton	56	260.0	78.9	51	428	A
Dolese - Hartshorne	105	237.4	71.8	87	414	A
Martin Marietta – Mill Creek	108	233.5	99.3	90	557	A
Kemp Stone - Pryor	101	126.9	54.3	45	289	C
Dolese – Davis	52	165.9	77.3	42	367	B
p = 0.000						

1/4” Aggregate

AIMS1 Gradient Angularity: Descriptive Statistics for 6 Quarries - 1/4” Aggregate

AIMS1 Output: Gradient Angularity, 1/4” Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1456)**	**Min. Value**	**Max. Value**	**Tukey’s Grouping**
Hanson - Davis	83	3847	1728	1320	9820	A
Dolese - Cooperton	76	3537	1512	1373	9156	AB
Dolese - Hartshorne	103	3398	1246	1925	9665	AB
Martin Marietta – Mill Creek	93	3611	1635	1590	9907	A
Kemp Stone - Pryor	110	2922	1027	1126	9331	B
Dolese – Davis	50	3471	1708	1532	9353	AB
p = 0.001						

AIMS1 Sphericity I: Descriptive Statistics for 6 Quarries – 1/4” Aggregate

AIMS1 Output: Sphericity I, 1/4” Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1047)**	**Min. Value**	**Max. Value**	**Tukey’s Grouping**
Hanson - Davis	85	0.6587	0.1171	0.346	0.865	A
Dolese - Cooperton	92	0.5666	0.1044	0.335	0.926	C
Dolese - Hartshorne	105	0.6199	0.1066	0.338	0.922	AB
Martin Marietta – Mill Creek	97	0.6569	0.0966	0.375	0.955	A
Kemp Stone - Pryor	103	0.6127	0.0967	0.404	0.823	B
Dolese – Davis	47	0.5823	0.1106	0.395	0.841	BC
p = 0.000						

AIMS1 Sphericity II: Descriptive Statistics for 6 Quarries – 1/4” Aggregate

AIMS1 Output: Sphericity II, 1/4” Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1374)**	**Min. Value**	**Max. Value**	**Tukey’s Grouping**
Hanson - Davis	93	0.7208	0.1384	0.3411	0.9945	A
Dolese - Cooperton	95	0.6309	0.1554	0.2442	0.9502	B
Dolese - Hartshorne	109	0.6929	0.1448	0.3467	0.9789	A
Martin Marietta – Mill Creek	102	0.6764	0.1139	0.4260	0.9373	AB
Kemp Stone - Pryor	111	0.7137	0.1104	0.4854	0.9630	A
Dolese – Davis	53	0.4746	0.1734	0.1081	0.8612	C
p = 0.000						

AIMS1 2D Form: Descriptive Statistics for 6 Quarries – 1/4” Aggregate

AIMS1 Output: 2D Form, 1/4” Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 2.655)**	**Min. Value**	**Max. Value**	**Tukey’s Grouping**
Hanson - Davis	87	8.768	2.692	5.27	19.54	A
Dolese - Cooperton	85	9.464	2.794	1.00	18.53	A
Dolese - Hartshorne	104	8.702	2.773	5.02	17.65	A
Martin Marietta – Mill Creek	95	8.871	2.942	5.17	18.98	A
Kemp Stone - Pryor	109	7.609	1.956	3.89	15.63	B
Dolese – Davis	52	8.591	2.840	4.79	15.93	AB
p = 0.000						

AIMS1 Texture: Descriptive Statistics for 6 Quarries – 1/4” Aggregate

AIMS1 Output: Texture, 1/4” Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 67.59)**	**Min. Value**	**Max. Value**	**Tukey’s Grouping**
Hanson - Davis	107	162.85	50.58	37.0	280.5	BC
Dolese - Cooperton	101	249.06	84.45	55.0	586.5	A
Dolese - Hartshorne	110	182.89	65.22	50.5	329.0	B
Martin Marietta – Mill Creek	106	178.01	77.37	51.0	364.0	B
Kemp Stone - Pryor	100	125.16	51.37	56.0	270.0	D
Dolese – Davis	53	141.08	72.11	24.0	345.0	CD
p = 0.000						

No. 4 Aggregate

AIMS1 Gradient Angularity: Descriptive Statistics for 6 Quarries – No.4 Aggregate

AIMS1 Output: Gradient Angularity, No.4 Aggregate						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1369)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	88	3873	1707	1805	9968	A
Dolese - Cooperton	85	3887	1386	2116	9749	A
Dolese - Hartshorne	107	3532	1504	1622	9429	A
Martin Marietta – Mill Creek	97	3763	1268	1877	9547	A
Kemp Stone - Pryor	111	2953	846	1294	5912	B
Dolese – Davis	49	3528	1498	1805	9363	AB
p = 0.000						

AIMS1 Sphericity I: Descriptive Statistics for 6 Quarries – No.4 Aggregate

AIMS1 Output: Sphericity I, No.4 Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1042)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	88	0.6076	0.0948	0.391	0.811	A
Dolese - Cooperton	88	0.5404	0.1198	0.303	0.897	B
Dolese - Hartshorne	102	0.5969	0.0961	0.401	0.817	A
Martin Marietta – Mill Creek	102	0.6178	0.1101	0.285	0.886	A
Kemp Stone - Pryor	105	0.5842	0.1038	0.320	0.834	A
Dolese – Davis	50	0.5297	0.0947	0.300	0.758	B
p = 0.000						

AIMS1 Sphericity II: Descriptive Statistics for 6 Quarries – No.4 Aggregate

AIMS1 Output: Sphericity II, No.4 Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 0.1491)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	94	0.6837	0.1248	0.4289	0.9645	A
Dolese - Cooperton	92	0.6045	0.1809	0.1932	0.9840	C
Dolese - Hartshorne	110	0.6898	0.1294	0.3384	0.9887	A
Martin Marietta – Mill Creek	104	0.6130	0.1416	0.2717	0.9519	BC
Kemp Stone - Pryor	109	0.6699	0.1436	0.3287	0.9945	AB
Dolese – Davis	53	0.4105	0.1870	0.2677	0.8489	D
p = 0.000						

AIMS1 2D Form: Descriptive Statistics for 6 Quarries – No.4 Aggregate

AIMS1 Output: 2D Form, No.4 Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 2.503)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	90	9.414	2.658	5.90	18.41	AB
Dolese - Cooperton	86	10.082	2.761	5.39	18.63	A
Dolese - Hartshorne	106	8.456	2.187	4.94	17.59	BC
Martin Marietta – Mill Creek	99	9.329	2.777	5.19	18.62	AB
Kemp Stone - Pryor	109	8.085	1.845	5.28	17.63	C
Dolese – Davis	48	9.773	3.027	5.65	18.63	A
p = 0.000						

AIMS1 Texture: Descriptive Statistics for 6 Quarries – No.4 Aggregate

AIMS1 Output: Texture, No.4 Aggregate						
Quarry	**Sample Size**	**Mean**	**Standard Deviation (Pooled: 63.78)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
Hanson - Davis	103	159.04	50.73	41.5	333.5	B
Dolese - Cooperton	101	212.78	79.33	49.5	448.5	A
Dolese - Hartshorne	105	155.73	47.19	45.0	252.0	B
Martin Marietta – Mill Creek	107	155.99	79.07	33.0	427.5	B
Kemp Stone - Pryor	103	118.63	49.14	33.0	272.0	C
Dolese – Davis	53	141.08	72.11	24.0	345.0	BC
p = 0.000						

Dolese Davis Aggregate

AIMS1 Gradient Angularity: Descriptive Statistics for Dolese Davis

AIMS1 Output: Gradient Angularity, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 1492)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	47	3430	1286	1582	7872	A
3/8" Aggregate	51	3332	1434	838	7930	A
1/4" Aggregate	50	3471	1708	1532	9353	A
No. 4 Aggregate	49	3528	1498	1805	9363	A
p = 0.927						

AIMS1 Radius Angularity: Descriptive Statistics for Dolese Davis

AIMS1 Output: Radius Angularity, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 3.785)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	56	11.311	3.720	5.024	19.768	AB
3/8" Aggregate	52	10.305	3.652	4.182	17.931	B
1/4" Aggregate	50	11.733	4.402	4.675	19.643	AB
No. 4 Aggregate	51	12.442	3.306	6.646	19.378	A
p = 0.037						

AIMS1 Sphericity I: Descriptive Statistics for Dolese Davis

AIMS1 Output: Sphericity I, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 0.1008)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	48	0.6635	0.0998	0.426	0.925	A
3/8" Aggregate	50	0.6484	0.0979	0.409	0.833	A
1/4" Aggregate	47	0.5823	0.1106	0.935	0.841	B
No. 4 Aggregate	50	0.5297	0.0947	0.300	0.758	B
p = 0.000						

AIMS1 Sphericity II: Descriptive Statistics for Dolese Davis

AIMS1 Output: Sphericity II, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 0.1829)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	52	0.5914	0.1878	0.1306	0.9764	A
3/8" Aggregate	56	0.5863	0.1833	0.2005	0.9656	A
1/4" Aggregate	53	0.4746	0.1734	0.1081	0.8612	B
No. 4 Aggregate	53	0.4105	0.1870	0.1442	0.8489	B
p = 0.000						

AIMS1 2D Form: Descriptive Statistics for Dolese Davis

AIMS1 Output: 2D Form, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 2.982)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	53	8.794	3.421	4.41	19.26	AB
3/8" Aggregate	51	8.053	2.560	4.31	15.19	B
1/4" Aggregate	52	8.591	2.840	4.79	15.93	AB
No. 4 Aggregate	48	9.773	3.027	5.65	18.63	A
p = 0.038						

AIMS1 Texture: Descriptive Statistics for Dolese Davis

AIMS1 Output: Texture, 4 Size Fractions						
Quarry	**Sample Size (N)**	**Mean**	**Standard Deviation (Pooled: 71.8)**	**Min. Value**	**Max. Value**	**Tukey's Grouping**
1/2" Aggregate	53	188.5	74.0	42.0	343.5	A
3/8" Aggregate	52	165.9	77.3	41.5	366.5	AB
1/4" Aggregate	54	132.3	63.4	14.0	260.5	B
No. 4 Aggregate	53	141.1	72.1	24.0	345.0	B
p = 0.000						