EVALUATION OF LIGHTWEIGHT AGGREGATES IN CHIP SEAL

by

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Abstract

Pavement preservation by adopting low-cost maintenance techniques is increasing among transportation agencies day by day. Chip seal, also known as seal coat, is widely used as a low-cost, thin surface treatment in preventive maintenance of asphalt pavements in many states, including Kansas. Loosening of aggregate particles from chip-sealed pavement and associated windshield damage to vehicles is a common problem. Thus the Kansas Department of Transportation (KDOT) uses lightweight aggregates as cover materials for chip seals. Although this has decreased windshield damage problems extensive chip loss on seal-coated pavements in the state has been reported. In this study, lightweight aggregates along with polymer-modified asphalt emulsion were used to determine proper aggregate and emulsion application rates to minimize chip loss in chip seals. Again, lightweight aggregates were studied in the laboratory to determine the effect of moisture content and electrical charge on chip loss. Evaluation of chip seal was performed by statistical analysis based on rutting potential, chip embedment, and retention. Results show that aggregate retention and embedment depth depend on aggregate-emulsion interaction, whereas rutting depends on the type of aggregate. Proper selection of aggregate and asphalt emulsion is important to maximize aggregate retention in chip seal. Chip loss also results from a lack of compatibility between the aggregate and asphalt emulsion. Results indicate that retention of aggregate depends on the prevailing charges of aggregate and emulsion particles. Moisture condition of the aggregate does not have any effect on chip loss. A new sweep test machine has been developed to assess chip loss, and it was found to be better than the sweep test currently recommended by the American Society for Testing and Materials (ASTM).

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Dedication

To my parents and teachers

CHAPTER 1 - INTRODUCTION

1.1 Introduction

Roads and highways play a key role in transportation systems of any country. The U.S. highway system consists of about four million miles of public roads (AASHTO 2010). Pavement conditions deteriorate because of traffic and weathering actions. According to TRIP (2010), about 32% of major roads in this country are in a condition which requires maintenance. This report also mentions deteriorated pavements increasing vehicle operation costs significantly, requiring an additional $67 billion per year. AASHTO (2010) reports a total of $166 billion is needed to maintain roadways and bridges per year, whereas the American Reinvestment and Recovery Act (ARRA 2009) provided only $26.8 billion. In this budget shortfall, pavement preservation can play a vital role. Pavement preservation is defined as “a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations” (FHWA 2010). Actions used for pavement preservation include routine maintenance, preventive maintenance (PM), and corrective maintenance (Uzarowski and Bashir 2007). Transportation agencies use chip seal, slurry seal, fog seal, etc. as PM treatment, and chip seal is the most cost effective among these (Chen and Daleiden 2005).

1.2 Treatments of Asphalt Pavement Preservation

Factors responsible for pavement deterioration include traffic loading, weathering, aging, moisture, etc. According to AASHTO (2010) and TRIP (2009), if pavements are not treated in time, deterioration rates increase and pavements become candidates for heavy rehabilitation or reconstruction. They also mention timely application of maintenance treatments reduces overall life-cycle costs. Hicks et al. (2000) reported pavement treatments are cost effective when applied on pavements in good condition. Preventive maintenance (PM), i.e. chip seal, slurry seal, etc. is applied to structurally sound pavements.

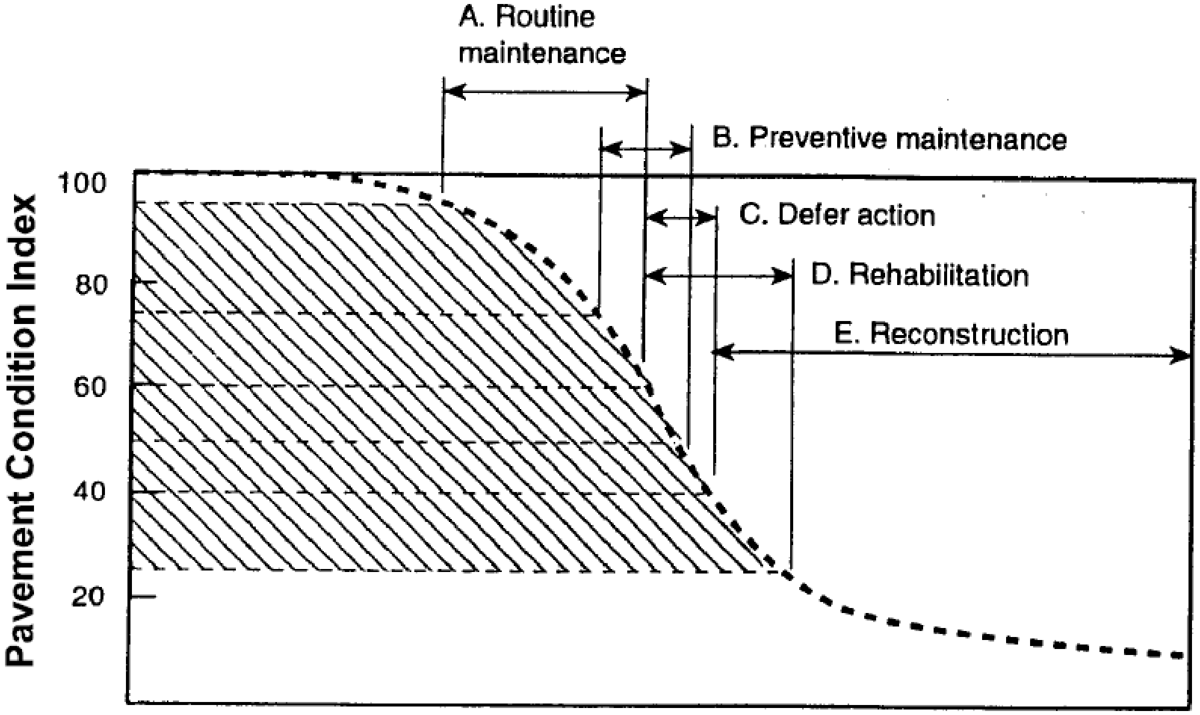


Figure 1.1 Pavement Condition and Required Treatments (Hicks et al. 2000)

Pavement condition changes with time and requires different types of treatments as shown in Figure 1.1. To ensure higher service life and retard pavement deterioration, routine maintenance, preventive maintenance, and minor rehabilitation are applied. If pavement is badly cracked, major rehabilitation is performed.

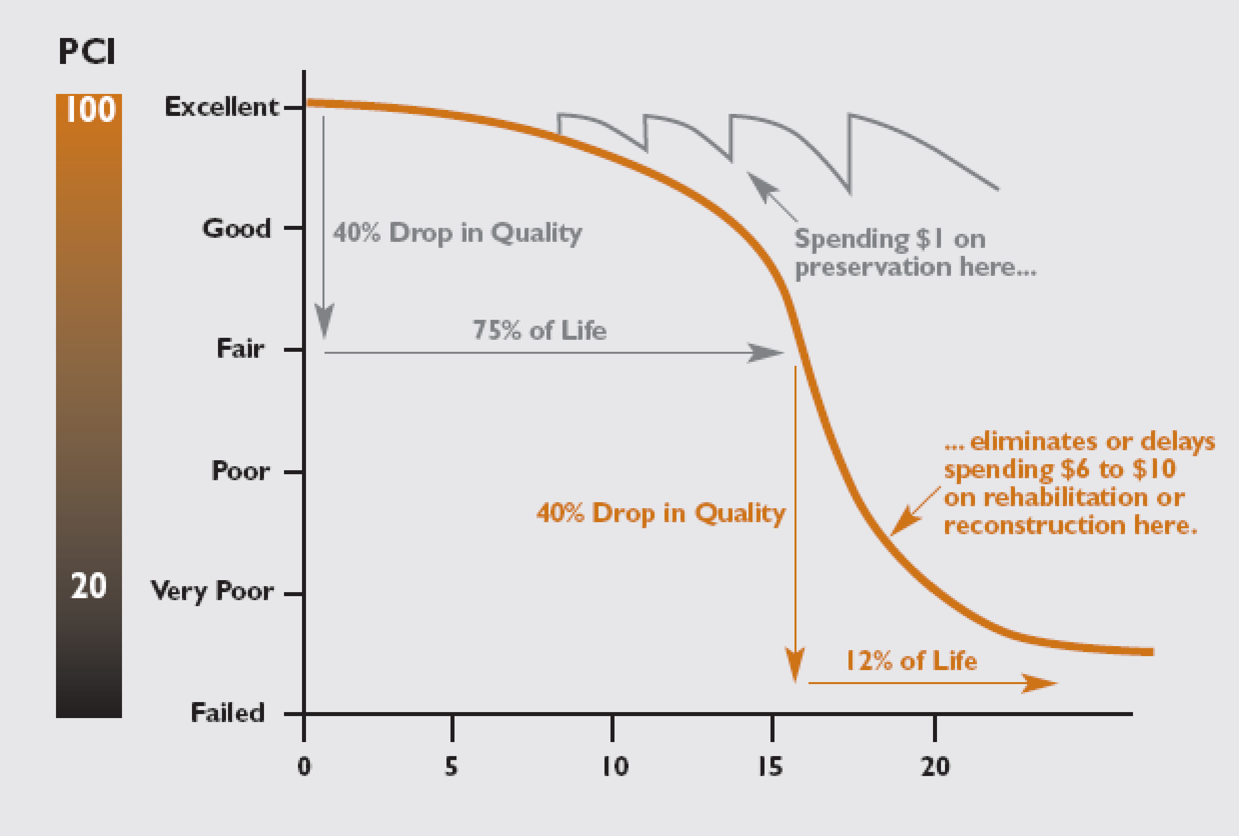


Figure 1.2 Preventive Maintenance Concepts (Galehouse et al. 2006)

Figure 1.2 shows timely application of preventive maintenance reduces costs. If pavement is treated in good condition at $1 per yd^2, it defers pavement deterioration. Delayed application however, can increase costs from $6 to $10.

Asphalt pavement preservation activities are divided into three major categories (Uzarowski and Bashir 2007) and are shown in the tree diagram shown in Figure 1.3.

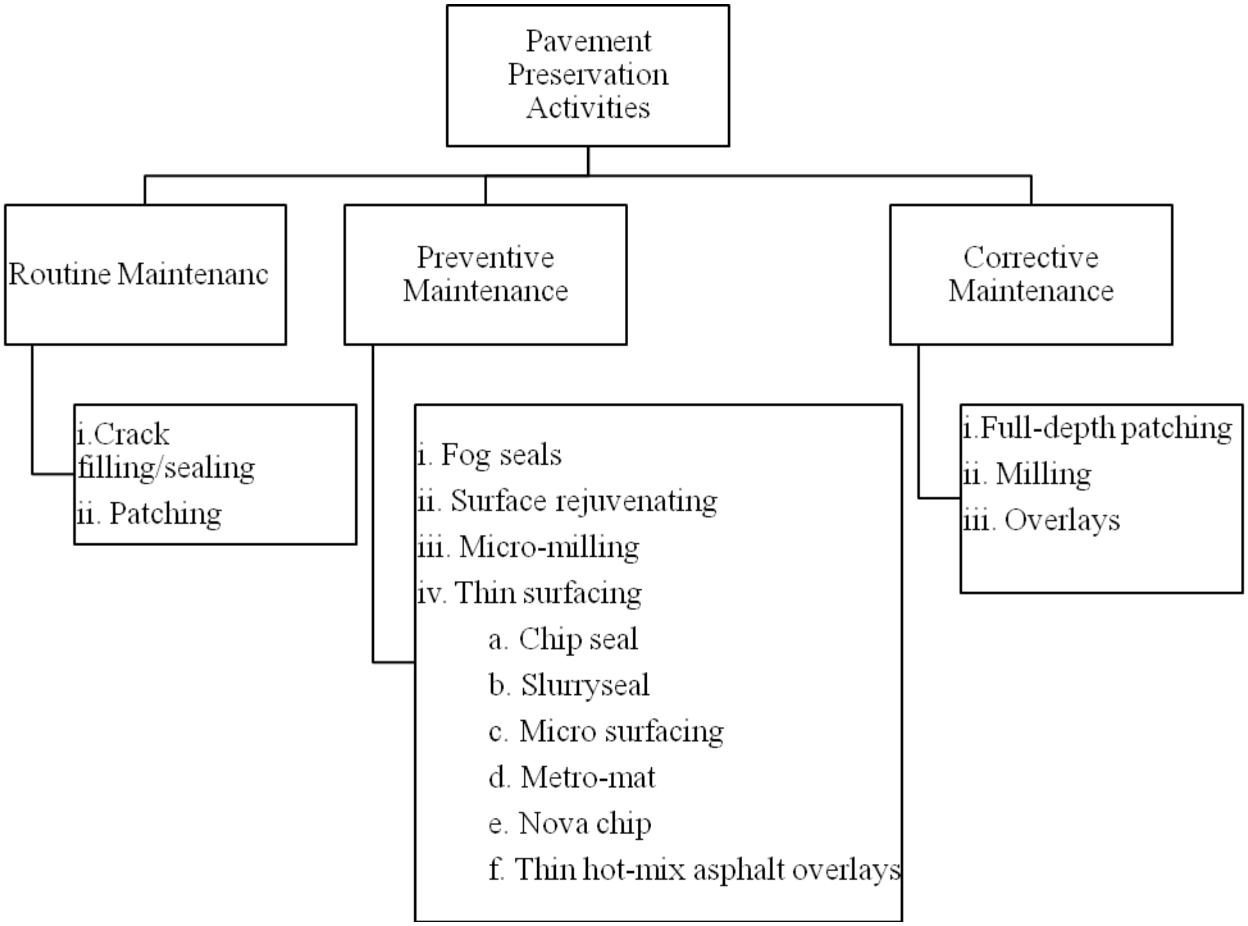


Figure 1.3 Pavement Preservation Activities (Uzarowski and Bashir 2007)

Transportation agencies in the United States use chip seal to preserve flexible pavements (Gransberg and James 2005). The expected service life of a chip seal is five to seven years (Chen et al. 2003, Jackson et al. 1990).

1.3 Problem Statement

The Kansas Department of Transportation (KDOT) puts great effort into preserving pavements by applying preventive maintenance techniques. Preservation actions for flexible pavements include many methods, and chip seal is one of them. These treatments are applied based on previous experience and contractors' recommendations. Current chip seal design methods were developed for regular aggregates. KDOT mostly uses lightweight aggregates. Loosening of aggregate particles from chip-sealed pavement is a common problem in Kansas. Lightweight aggregates have been blamed for this. Thus, evaluation of lightweight aggregates in chip seal is necessary.

1.4 Study Objectives

Objectives of this study are as follows:

a) To find aggregate and emulsion application rates for proper lightweight aggregate embedment so that aggregate loss in service can be minimized;
b) To assess aggregate-binder compatibility as a function of moisture content and electrical charge of aggregate particles;
c) To evaluate rutting potential of aggregates in chip seal; and
d) To develop a modified sweep test setup to better assess aggregate-asphalt emulsion compatibility.

1.5 Organization of Thesis

This thesis is divided into four chapters. Chapter 1 is an introduction to the study. It describes the concept of pavement preservation, benefits of preventive maintenance, the problem statement, and objectives of the study. Chapter 2 is a literature review of the entire chip seal process. It includes chip seal aggregates, asphalt binder, review of existing chip seal design methods, and construction of chip seal. Chapter 3 discusses chip seal simulation and analysis of the results. It includes tests on aggregate and asphalt emulsion, chip seal design, laboratory test methods, and statistical analysis of results. Chapter 4 describes conclusions of this study and presents recommendations for further study.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

Chip seal is a thin surface treatment of flexible pavement. The treatment involves spraying of binder, i.e. asphalt emulsion, followed by application of aggregates. It bridges minor cracks and does not allow water into existing pavement on which chip seal is applied (Gransberg and James 2005). Many states use chip seal as a preventive maintenance technique. Liu et al. (2010) noted “A total of 4,156 chip seal treatments were performed on 3,552 segments of 280 highways in Kansas from 1992 to 2006.” Chen et al. (2003) studied fourteen sites in Texas with preventative maintenance treatments, noticing that chip seal performance is highly satisfactory compared to the other techniques, i.e. thin overlay and slurry seal. Costs of these treatments were also compared in this study. Chip seal’s cost is lower than that of an overlay as shown in Table 2.1.

Table 2.1 Costs of Preventive Maintenance Treatments (Chen et al. 2003)

Treatment	Cost per lane-mile
2-inch overlay	$20,000-$35,000
Slurry seal	$7,000-$10,000
Chip seal	$7,000-$10,000
Crack seal	$700-$1,000

Although chip seal has been used for the last 90 years, a survey conducted by the National Highway Cooperative Research Program (NCHRP Synthesis 342) shows that most states in the U.S. use an empirical approach to design chip seal (Gransberg and James 2005). Chip seal is now applied on both low-traffic and high-traffic roads.

2.1.1 Types of Chip Seal

Chip seals are classified depending on “construction sequences, number of courses applied, and variations in nominal aggregate sizes” (Gransberg and James 2005).

a. Single chip seal
b. Double chip seal
c. Racked-in seal
d. Cape seal
e. Inverted seal
f. Sandwich seal
g. Geotextile-reinforced seal

a. Single Chip Seal

The concept of chip seal was developed based on single chip seal. A single chip seal involves applying a single layer of aggregates after applying bituminous binder, i.e. asphalt emulsion. Single chip seal is widely used for flexible pavement where no other situations exist that require a special kind of seal (Gransberg and James 2005). Figure 2.1 is a typical diagram of single chip seal.

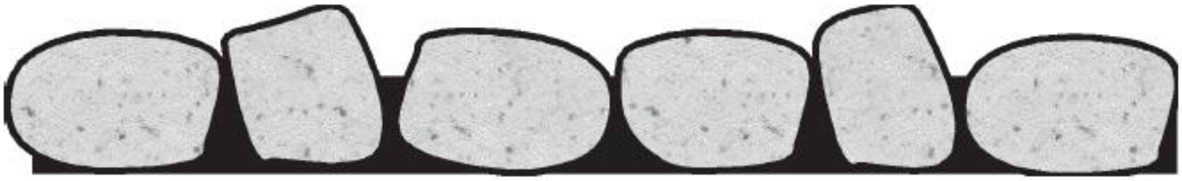


Figure 2.1 Single Chip Seal (Wood et al. 2006)

b. Double Chip Seal

According to Gransberg and James (2005), a double chip seal consists of two layers of bituminous binder and aggregate application, where aggregates of the top layer are “about half the nominal size” of the bottom layer. Double chip seals provide enhanced performance to prevent water entrainment into pavement. As smaller particles are used in the second seal, traffic noises are also reduced. A double chip seal is stronger than a single chip seal and is typically used in roads with high-traffic volume (Gransberg and James 2005). Figure 2.2 shows a double chip seal.

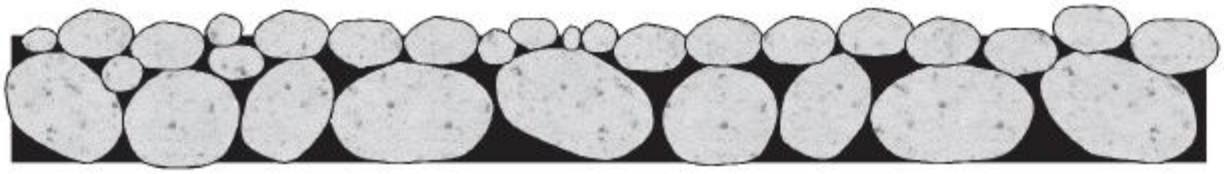


Figure 2.2 Double Chip Seal (Wood et al. 2006)

c. Racked-In Seal

A racked-in seal is a special kind of chip seal typically applied in the areas of high turning movements. A layer of choke stone is applied after a single chip seal to prevent the loss of aggregates. Choke stones are about half the size of the aggregates used in the first application. This seal allows bituminous binder to cure fully by interlocking between the aggregates (Grasnberg and James 2005). Figure 2.3 shows a typical diagram of a racked-in seal.

Figure 2.3 Racked-In Seal (Wood et al. 2006)

d. Cape Seal

Cape seal was invented in South Africa, and is named after Cape Town. It is a combination of a single seal and a slurry seal. Cape seal provides a “stable matrix” as the second application, i.e. slurry seal helps to dislodge the larger aggregate particles. Although South Africa uses larger than ¾-inch aggregate for the first seal, smaller-sized aggregates are used in North America for cape seal (Gransberg and James 2005). Advantages that cape seals provide include “a smooth, dense surface, one having good skid resistance and a relatively long service life” (Solaimanian and Kennedy 1998). Figure 2.4 shows a typical cape seal system.

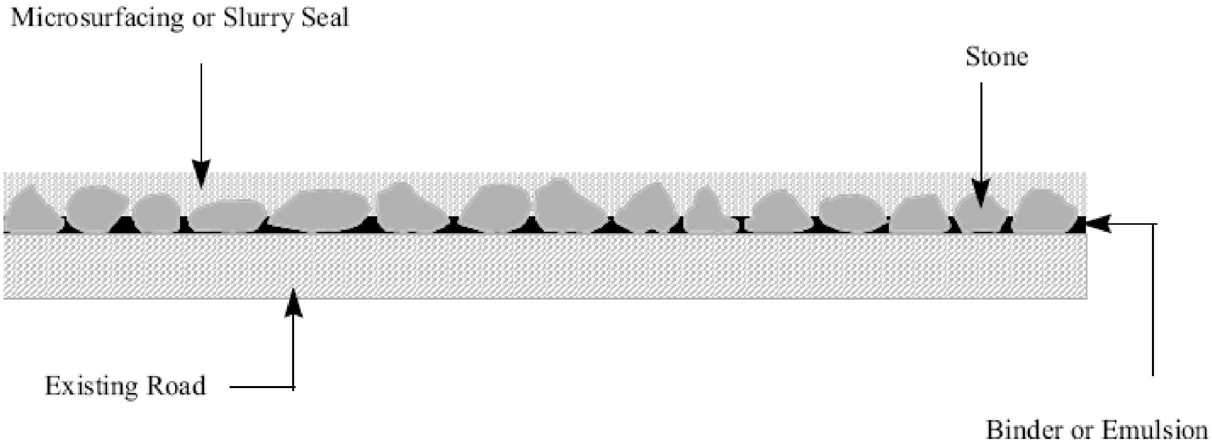


Figure 2.4 Cape Seal (Solaimanian and Kennedy 1998)

e. Inverted Seal

Inverted seal is a kind of double chip seal where smaller particles are applied for the first seal without any application of bituminous binder. When pavement shows bleeding, inverted seal is applied to correct this problem. Not only are inverted seals used in Australia for remedying bleeding in high-traffic roads, but it also reinstates “uniformity to surfaces with variation in transverse surface texture” (Gransberg and James 2005). Figure 2.5 shows a typical inverted seal system.

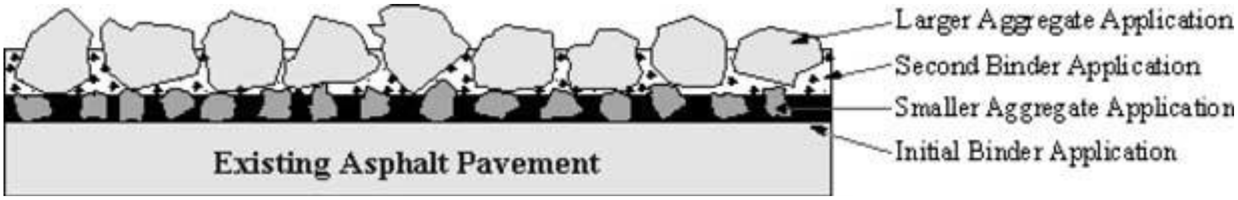


Figure 2.5 Inverted Seal (Gransberg and James 2005)

f. Sandwich Seal

Although two layers of aggregates are applied in sandwich seals, only a single spray of asphalt binder is used in between them. These seals are used to correct "surface texture on raveled surfaces" (Gransberg and James 2005). Figure 2.6 shows a typical sandwich seal system.

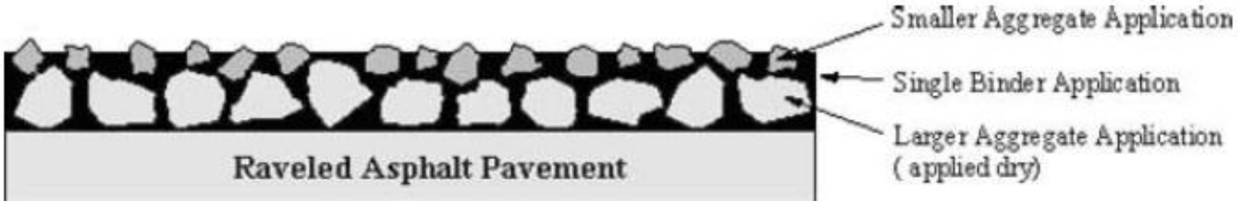


Figure 2.6 Sandwich Seal (Gransberg and James 2005)

g. Geotextile-Reinforced Seal

Conventional chip seals are not suitable for cracked road surfaces, which require high-cost rehabilitation or reconstruction. Geotextile-reinforced seals are applied in these cases. A geotextile fabric is placed on pavement surfaces with a light application of asphalt binder, and a single seal is applied on it. This kind of seal is successful to prevent reflective cracking. Geotextile-reinforced seals act as a "stress-absorbing membranes interlayer (SAMI) system" (Gransberg and James 2005). Figure 2.7 shows a typical geotextile-reinforced seal system.

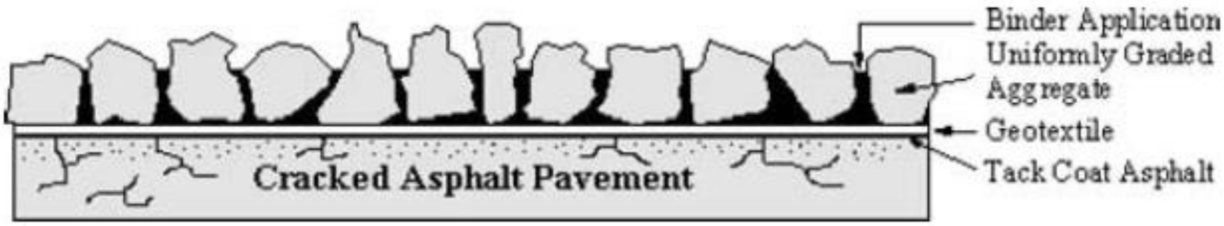


Figure 2.7 Geotextile-Reinforced Seal (Gransberg and James 2005)

2.1.2 Benefits of Chip Seal

If chip seals are constructed properly on flexible pavements, they provide the following benefits (Gransberg and James 2005, Seal Coat and Surface Treatment Manual 2004, Caltrans Divison of Maintenance 2003):

- prevents water from entering into the underlying pavement
- increases skid-resistant
- corrects dry or raveled pavement
- bridges minor cracks (<¼ in.) of existing pavement
- prevents deterioration of distressed-showing pavement
- defends pavement surfaces from degradation resulting from oil or chemical agents
- produces chosen texture
- provides an aesthetic, smooth, and uniform pavement surface
- offers good durability
- offer ease of construction

Aggregates and bituminous binder have different roles in chip seals. Bituminous binder acts as a binding agent among aggregate, and prevents water intrusion into the pavement base. Aggregates used in chip seals work against abrasion caused by vehicles, and provide surface texture and skid-resistant surfaces (Gransberg and James 2005, Seal Coat and Surface Treatment Manual 2004).

In spite of these benefits, chip seals do not (Senadheera et. al 2006, Gransberg and James 2005) —

- increase strength of existing pavement
- correct major cracks and weathered pavements
- explain reasons behind failure of a project
- offer an alternative to reconstruction

2.1.3 Project Selection for Chip Seal

Effectiveness of chip seals depends on structural strength of the pavement. Selection of projects for chip seals is governed by pavement strength and the level of distresses. Application of chip seal should be performed before significant pavement deterioration (Gransberg and James 2005).

2.2 Chip Seal Materials Selection

Chip seal materials selection includes deciding on the aggregate and asphalt binder type to be used. Normal or lightweight aggregates are used as cover material. Nowadays, application of asphalt emulsions as binder is more prevalent in chip seal construction.

2.2.1 Selection of Aggregate

According to Gransberg and James (2005), selection of chip seal aggregate is very important as it works against the wearing action of wheels. It governs selection of chip seal and binder types, and construction procedures. Performance of chip seals largely depends on particle cleanliness, durability, and wearing resistance. Selected aggregates should be such that they are able to give a skid-resistant surface, as well as transfer vehicle load to the underlying pavement layers. Although North America compromises on local aggregates by considering shipment costs, other countries, i.e. Australia and New Zealand, are more rigid about the quality of aggregates. They perform a cost analysis while selecting aggregates for chip seals. Aggregate and asphalt binder compatibility is also an important issue as both carry electrical charges on their surfaces (Gransberg and James 2005).

Factors affecting performance of chip seals, and which are considered during selection of aggregates, include (Gransberg and James 2005) —

a. aggregate size and gradation
b. aggregate shape
c. dust-content
d. aggregate abrasion resistance
e. aggregate type

a. Aggregate Size and Gradation

Size of aggregate is important in chip seal design because it is a function of asphalt binder application rate (Gransberg and James 2005). Single-size aggregates perform best in chip seal by providing less variation in binder application (Wood et al. 2006; Gransberg and James 2005). Although larger particles provide a stable matrix, insufficient embedment of aggregate in the asphalt binder may cause windshield damage as well as increase in traffic noise. One-sized aggregates are not always practically available. Although graded aggregates are used for chip seals, aggregates "very close to one size" are used in chip seal to achieve uniform embedment

(Gransberg and James 2005). Figure 2.8 and Figure 2.9 show chip seal with single-sized aggregate and graded aggregates, respectively. Table 2.2 shows KDOT's gradation requirements of cover aggregates.

Figure 2.8 Chip Seal Constructed with Single-Size Aggregates (Wood et al. 2006)

Figure 2.9 Chip Seal Constructed with Graded Aggregate (Wood et al. 2006)

Table 2.2 Gradation Requirements for Aggregates for Cover Material (KDOT 2004)

Type	Composition	Percent Retained-Square Mesh Sieves					
		3/4”	½”	3/8”	No. 4	No. 8	No. 50
CM-A	Sand-Gravel		0	0-20	30-100	85-100	
CM-B	Sand-Gravel		0	0-25		35-100	90-100
CM-C	Crushed Stone	0	0-12	40-100	95-100		
CM-D	Crushed Sandstone	0	0-5	15-35	70-100	95-100	
CM-G	Sand-Gravel or Crushed Sandstone		0	0-15	45-100	95-100	
CM-H	Crushed Stone	0	0-5		40-100	90-100	
CM-J	Sand-Gravel	0	1-20			30-100	90-100
CM-K	Crushed Limestone	0	0-5	15-35	70-100	95-100	
CM-L	Lightweight Aggregate	0	0-5	0-15	70-100	90-100	

b. Aggregate Shape

Aggregates shape affects performance of chip seals, and a cubical shape is preferred. Due to the action of traffic, aggregates turn onto their flattest side. Chip seals show flushing or bleeding if flat aggregates are predominately used for chip seal construction. When low rates of asphalt binder are used in chip seal with flat or elongated aggregates, these rates become insufficient for other particles, resulting in loss of aggregates (Gransberg and James 2005, Wood et al. 2006, Seal Coat and Surface Treatment Manual 2004). Figure 2.10 shows chip seal with flat aggregates.

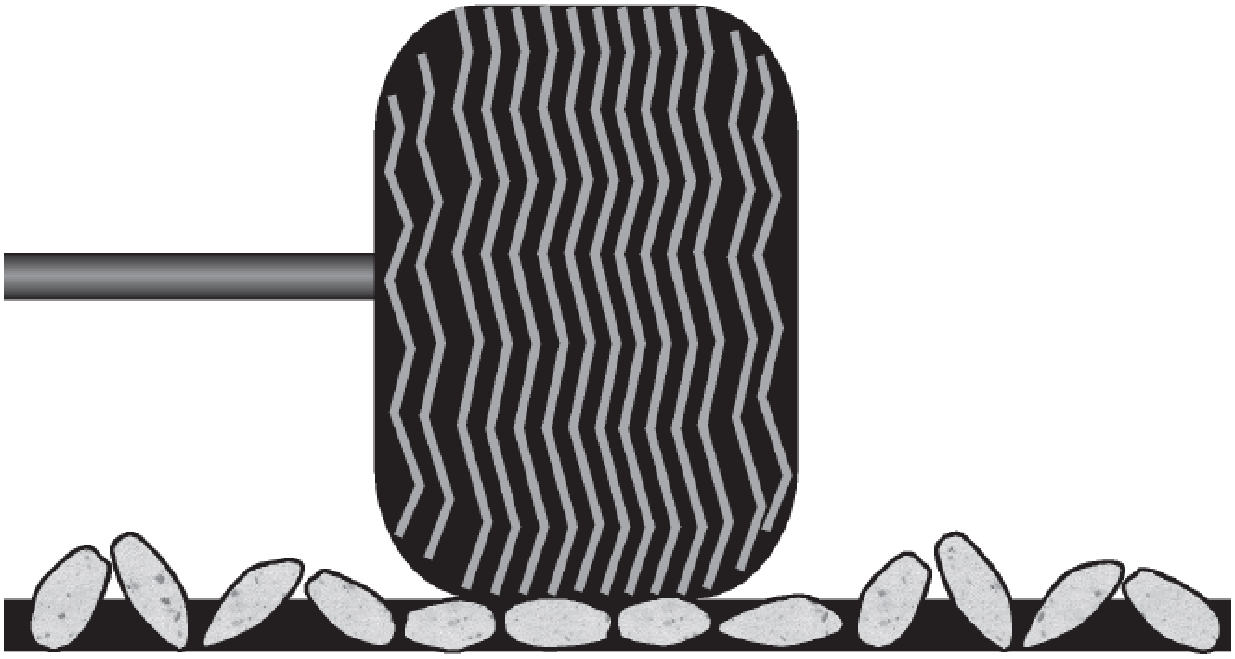


Figure 2.10 Chip Seal with Flat Aggregates (Wood et al. 2006)

Traffic action does not re-orient cubical aggregates. The possibility of uniform embedment of aggregate particles into asphalt binder is high with cubical aggregate, and also reduces occurrences of bleeding (Wood et al. 2006, Gransberg and James 2005). The Flakiness Index is determined by "testing a small sample of the aggregate particles for their ability to fit through a slotted plate.” Low values of the Flakiness Index represent cubical shape (Wood et al. 2006; Seal Coat and Surface Treatment Manual 2004). Angular aggregates face an adverse situation in highly “stopping or turning traffic” areas, whereas rounded aggregates are more susceptible to dislodgment (Gransberg and James 2005). Figure 2.11 shows chip seal with cubical aggregates.

Figure 2.11 Chip Seal with Cubical Aggregates (Wood et al. 2006)

c. Dust Content

Particles passing through a US No. 200 sieve are considered dust. Loss of aggregates from chip-sealed pavements increases if cover aggregates contain a significant amount of dust. In fact, dust acts as a barrier around the aggregate particles, hindering adhesion with the asphalt binder. Different roadway agencies have their own specifications for dust content in the aggregates, but most allow a maximum 2% dust as tabulated in Table 2.3 (Gransberg and James

2005; Wood et al. 2006). Figure 2.12 and Figure 2.13 show chip seals constructed with dusty aggregates.

Table 2.3 Maximum Dust Content (Lee 2007)

State	Maximum Percentage Passing No. 200
Alabama	1
Florida	3.75
Indiana	2
Kansas	2
Maryland	1
North Carolina	1.5
North Dakota	4
Ohio	3
Pennsylvania	2
South Carolina	0
South Dakota	2
Tennessee	1

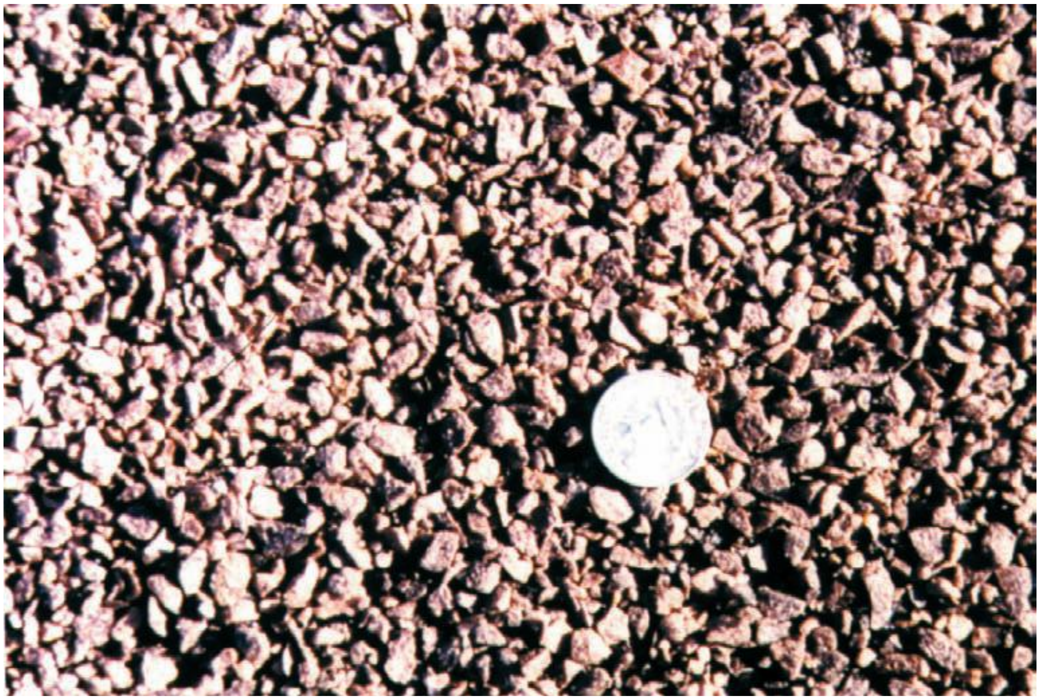


Figure 2.12 Chip Seal Constructed with High-Dust-Content Aggregates before Sweeping (Wood et al. 2006)

Figure 2.13 Chip Seal Constructed with Highl-Dust-Content Aggregates after Sweeping (Wood et al. 2006)

By washing or precoating, the problem associated with dusty aggregates can be resolved. Here, precoating is defined as a light application of “a film of paving-grade asphalt or a specially formulated precoating bitumen to the aggregate” (Gransberg and James 2005). The Pennsylvania Department of Transportation used precoated aggregates; they seal pavements with precoated aggregates for pavements “carrying more than 1,500 average daily traffic” (Kandhal and Motter 1991).

d. Aggregate Abrasion Resistance

Abrasion resistance of aggregates is measured by the Los Angeles Abrasion test (ASTM C131-06, AASTHO T96, KTMR-25). Aggregates used for chip seals should be strong and durable so they can perform well against the wearing action of wheels. Aggregates with high abrasion values are not strong enough to withstand wear caused by vehicles, and more dust is produced which can cause vehicle damage as well (Seal Coat and Surface Treatment Manual 2004). Table 2.4 shows KDOT's abrasion resistance requirements.

Table 2.4 Maximum Abrasion Losses of Cover Aggregates (Reproduced from KDOT 2004)

Aggregate Type	Maximum Abrasion Loss Allowed (Percent)
Sand-gravel, gravel, or limestone	40
Sandstone	45
Lightweight	30

e. Aggregate Type

Both natural and synthetic (artificially produced, i.e. expanded shale, clay, and slate) aggregates are used as cover materials for chip seals, though transportation agencies choose aggregates depending "on the availability and cost …within proximity to the project" (Gransberg and James 2005). New Zealand uses igneous or sedimentary rocks as production sources of chip seal aggregates, but aggregates produced from metamorphic rock show satisfactory performance in other countries (Transit New Zealand et al. 2005, Gransberg and James 2005). Table 2.5 tabulates different aggregates used for chip seal (Gransberg and James 2005). Natural gravels are predominant in North America, followed closely by limestone aggregates.

Table 2.5 Natural Aggregate Used for Chip Seals (Gransberg and James 2005)

Type	North America (%)	Australia, New Zealand, United Kingdom, South Africa (%)
Limestone	37	13
Quartzite	13	38
Granite	35	38
Trap Rock	13	25
Sandstone	10	25
Natural Gravels	58	25
Greywacke, Basalt	4	88

Lightweight aggregates are particles with "an apparent specific gravity considerably below that for normal sand and gravel" (Expanded Shale, Clay, and Slate Institute 1971). Table 2.6 shows bulk-density requirements of lightweight aggregates (ACI Committee 213). Lightweight aggregates are successful as cover materials in chip seal. Application of lightweight aggregates is more prevalent in Australia, New Zealand, United Kingdom, and South Africa compared to the United States (Gransberg and James 2005).

Table 2.6 Bulk-Density Requirements of ASTM C 330 and C 331 for Dry, Loose, and Lightweight Aggregates (ACI Committee 213)

Aggregate size and group (ASTM C 330 and C 331)	Maximum density, lb/ft3 (kg/m3)
Fine aggregate	70 (1120)
Coarse aggregate	55 (880)
Combined fine and coarse aggregate	65 (1040)

Although lightweight aggregates are costly, they offer good skid resistance and reduce aggregate dislodgement (Gransberg and James 2005). Benefits of lightweight aggregates can be summarized in the following ways (Gransberg and James 2005, Martin 2003, Expanded Shale, Clay, and Slate Institute 1971):

- superior skid-resistance
- better aggregate retention
- reduction or elimination of windshield damage
- superior bonding with asphalt emulsion
- low content of dusts
- low transportation cost

Drawbacks of lightweight aggregates are as follows (Gransberg and James 2005):

- costlier than normal-weight aggregates
- high water absorption

Lightweight aggregates can be obtained from natural sources, i.e. pumice, scoria, and volcanic cinders, but are produced mainly by industrial processes using shale, clay, and slate. Industrial by-products (slag, fly ash) are also used as raw materials for lightweight production (Bush et al. 2006). Lightweight aggregates produced from calcined bauxite offer superior skid resistance (Transit New Zealand et al. 2005).

According to Chen et al. (2008), the following two requirements are needed in the rotary kiln during industrial production of lightweight aggregates. Moreover, these conditions are required to expand the particles:

a. Sufficient “glassed-phase formation,” which helps to retain bloating gases; this “glassed-phase” occurs at a very high temperature (about 2,000ºF).

b. Gas-forming materials expand aggregate particles when the “glassed-phase” forms.

Different gasses are produced in the kiln during industrial lightweight aggregate production, which expands aggregate particles. Sulfur-dioxide (SO_2) is produced at a relative low temperature (750ºF). Clay minerals contain water, and dehydroxylation occurs at about 1,110ºF.

Carbon-dioxide (CO_2) is produced at about 1,300ºF from "carbon-based compounds" and at about 1,560ºF from carbonates (CO_3^{-2}). Iron compounds generate oxygen gas (O_2) at a very high temperature (2,000ºF) (Owens 2005).

According to Chandra and Berntsson (2002), although two production methods (rotary-kiln and sintering) are available, the rotary-kiln method is widely used for lightweight aggregate production. In the rotary-kiln method, a 100 to 200-foot-long kiln with a five-degree inclination, similar to a Portland cement production kiln, is used. Raw materials (shale, clay, and slate) are supplied through the elevated end, and aggregates are cooled down at the lower end after passing through the hot kiln (Chandra and Berntsson 2002). Figure 2.14 shows typical diagram of lightweight aggregate production process by rotary-kiln method.

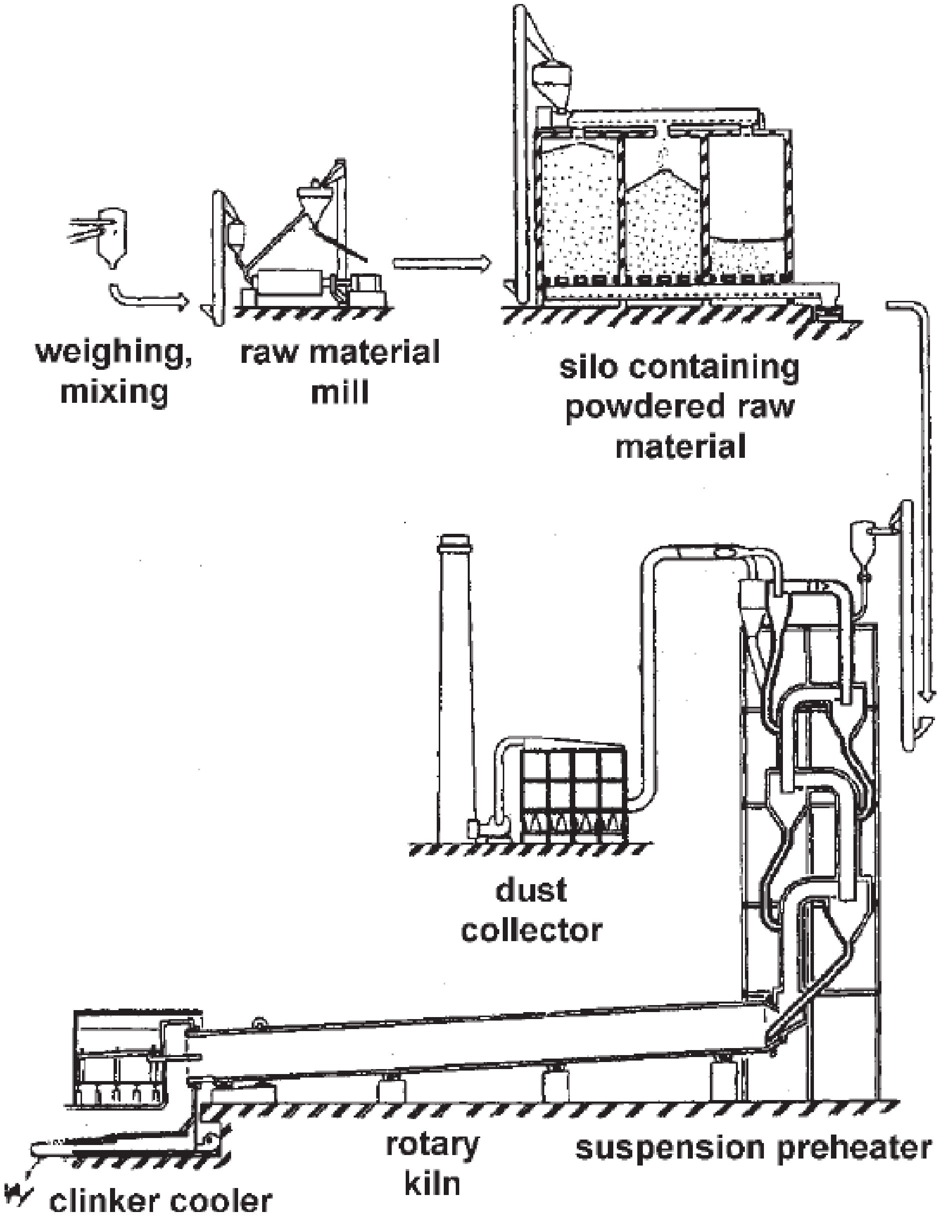


Figure 2.14 Typical Diagram of Lightweight Aggregate Production by Rotary-Kiln Method (Reproduced from Chandra and Berntsson 2002)

2.2.1 Selection of Asphalt Binder

Factors that govern the selection of asphalt binder include aggregate particles, existing pavement temperature, and weather conditions at the chip seal project sites. Selected asphalt binder should be such that it will not cause bleeding, as well as offer good adhesion to aggregate particles. Its viscosity should allow uniform application (Gransberg and James 2005; Seal Coat and Surface Treatment Manual 2004). Mainly asphalt cement and asphalt emulsions are used in chip seal construction all over the world, though application of asphalt emulsion is more prevalent in the United States. Figure 2.15 shows usages of different binders used for chip seal in North America (reproduced from Gransberg and James 2005).

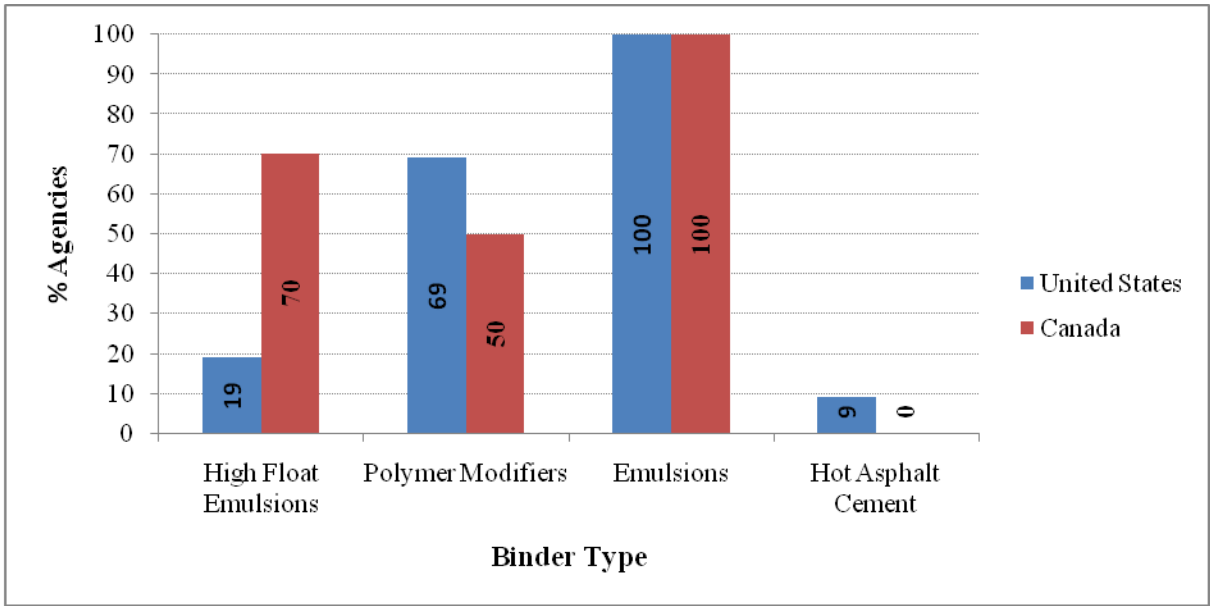


Figure 2.15 Asphalt Binder Used in Chip Seal in North America (Reproduced from Gransberg and James 2005)

Basically, asphalt emulsion is produced by an industrial process through mixing asphalt cement, water, and a specified emulsifying agent, which imparts charges to asphalt particles. Thus, asphalt particles in emulsion contain electrical charges, i.e. positive or negative depending on the emulsifying agent used in the production process (Gransberg and James 2005, James 2006).

Other than these three basic components, few other materials are also used in asphalt emulsion production, depending on requirements of the project. These components include calcium and sodium chlorides, adhesive agents, solvents, and latex (James 2006). A typical recipe of asphalt emulsion is shown in Figure 2.16 (James 2006):

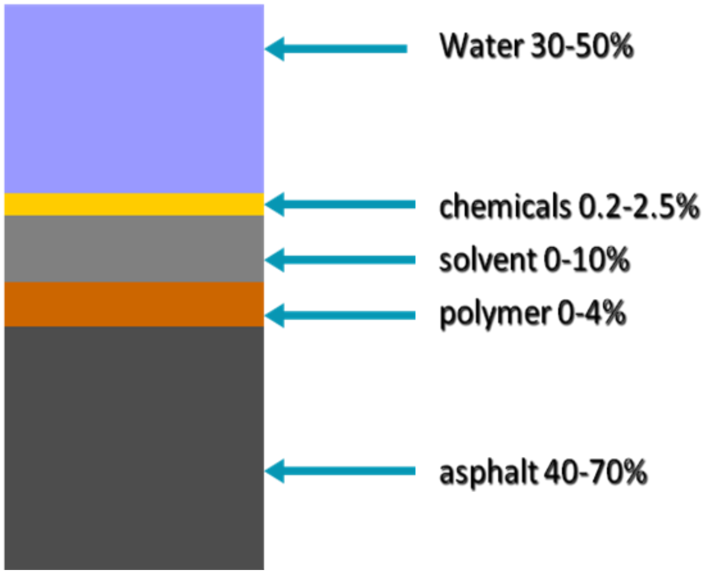


Figure 2.16 Typical Composition of Asphalt Emulsion (Reproduced from James 2006)

Benefits offered by asphalt emulsion can be summarized as follows (James 2006, Gransberg and James 2006):

- can be applied at relatively low temperature (about 140°F)
- saves energy and has a lower negative environmental impact
- saves asphalt from oxidation
- offers ease of handling during construction
- particle charge ensures better bonding with aggregates
- reduces dislodgement of aggregates
- reduces bleeding and increases durability when polymer-modified emulsion is used

Table 2.7 shows the different types of emulsions used in the United States (Gransberg and James 2005). Kansas appears to be one of only two states that use CRS-1HP.

Table 2.7 Types of Asphalt Emulsion Used by Transportation Agencies in North America (Gransberg and James 2005)

Binder Type	U.S. Locations	Non-U.S. Locations
CRS-1	Nevada	None
CRS-1HP	Kansas, Nevada	None
CRS-2	Connecticut, Iowa, Maryland, Michigan, Montana, Nevada, New York, North Carolina, Oklahoma, Utah, Virginia, Washington, Wisconsin	Ontario
CRS-2H	Arizona, California, Texas	None
CRS-2P	Arizona, Arkansas, Alaska, Idaho, Iowa, Louisiana, Michigan, Minnesota, Mississippi, Montana, Nebraska, North Carolina, New York, North Dakota, Oklahoma, Texas, Washington, Wisconsin, Wyoming	New Zealand, Nova Scotia
HFRS	Alaska, Colorado, New York, Wisconsin	British Columbia, Manitoba, Ontario, Saskatchewan, Quebec, Yukon
HFRS-2P	Colorado, New York, North Dakota, Oregon, Texas, Wisconsin, Wyoming	Saskatchewan, Quebec

According to James (2006), ammonium compounds are used as emulsifying agents to produce cationic emulsion where nitrogen ions are gathered on the surface of asphalt particles. Thus, positive charges form on the surface of asphalt particles. He also indicates anionic emulsions impart a negative charge on the asphalt particles. Figure 2.17 shows positive ions of emulsifying argents surround the asphalt particles, while negative ions diffuse into water (James 2006).

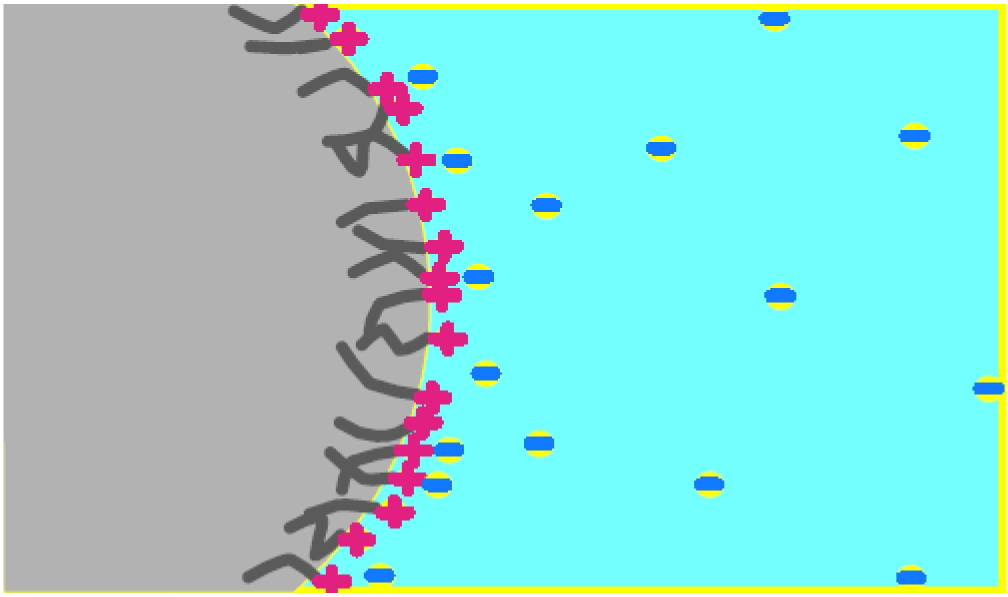


Figure 2.17 Formations of Positive Charges on Asphalt Particles (James 2006)

Breaking and curing stages associated with asphalt emulsion are very important. According to Gransberg and James (2005), separation of water from asphalt emulsion after application is known as "breaking." They also mentioned at the end of this stage, the emulsion's color turns to black. Several factors affect the breaking of emulsion, including emulsion composition, aggregate type, and temperature at the time of chip seal application (Transit New Zealand et al. 2005). The process of strength gaining to form a stable matrix with aggregates is known as "curing" (Transit New Zealand et al. 2005).

2.3 Chip Seal Design Methods

Hanson first developed the chip seal design method in 1935, introducing the concept of partial filling of voids in aggregates (Transit New Zealand et al. 2005). Later, other methods were developed based on Hanson's method. These include McLeod, Kearby, and modified

Kearby methods. Another method developed by Transit New Zealand is known as the New Zealand chip seal method (Transit New Zealand et al. 2005).

Voids occur among loose aggregates when they are laid down in single layer. Hanson (1935) addressed partially filling these voids when they are applied for chip seal. He noted voids among the cover aggregate vary from 30% to 50% throughout the service life of the chip seal. Hanson’s concept is shown in Figure 2.18.

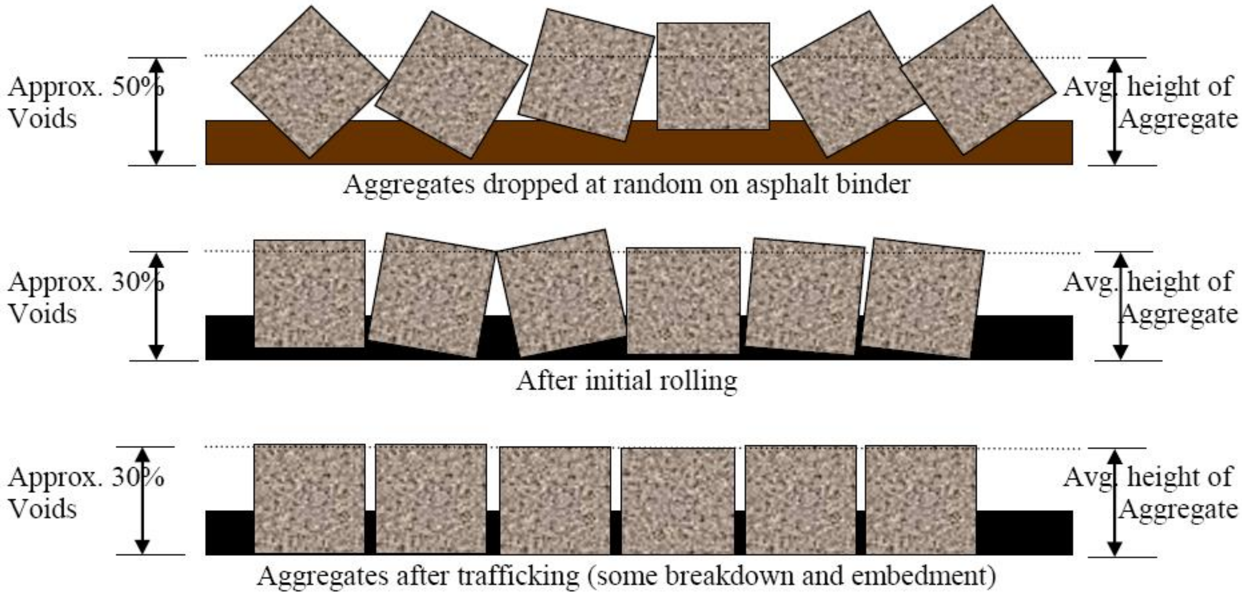


Figure 2.18 Concept of Voids among Aggregate in Chip Seal (Reproduced from Lee 2007)

McLeod (1969) developed a chip seal design method which is applicable to both single and multiple layers of chip sealing. His method is based on two basic principles including aggregate and asphalt application rates. Aggregate application should be such that there will be a single layer of aggregate. Application rate depends on gradation, shape, and specific gravity. The most important issue he addressed is the asphalt application rate. He stressed a 70% filling of voids among aggregates. Asphalt application rate depends on a few factors including aggregate "gradation, absorption and shape, traffic volume, existing pavement condition, and residual asphalt content of the binder" (Seal Coat and Surface Treatment Manual 2004).

According to Gransberg and James (2005), the first chip seal design method in the United States was developed by Kearby (1953). He introduced a nomograph to determine the required asphalt quantity. A number of design factors including thickness, aggregate embedment, and percentage of voids are required to determine appropriate binder rate from the nomograph (Kearby 1953). He emphasized using single-sized aggregates for chip seals.

Epps et al. (1974) modified the Kearby method as they found it does not estimate the quantity of asphalt normally applied for chip seals with lightweight aggregates. They introduced a curve in the nomograph for lightweight aggregates with more than 30% coating of aggregate. Epps et al. (1980) introduced two factors, traffic volume and pavement condition, to determine asphalt rate. A board test is used in the modified Kearby method to determine aggregate application rate. In this method, a ½-yd^2 board is covered by single-layer aggregates, and the amount of aggregate is determined.

According to the Seal Coat and Surface Treatment Manual (2004), the following equations and procedures are used in the modified Kearby method to determine aggregate and asphalt application rates for chip seals:

The quantity of aggregates for chip seals is determined by Equation 1,

$$S = \frac{27W}{Q} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where S = designed aggregate application rate (yd^2/yd^3); W = dry loose unit weight of aggregates measured from the unit weight test, (lbs/ft^3); and Q = amount of aggregates required to cover the board (lbs/yd^2).

According to this manual, asphalt application rate (for asphalt cement) is determined by Equation 2,

$$A = 5.61E(1 - \frac{W}{62.4G})T + V \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where A = designed asphalt application rate, gal/yd^2 at 60°F; E = aggregate embedment depth determined using Equation 3; G = dry bulk specific gravity of the aggregate; T = traffic correction factor; and V = existing pavement surface condition factor.

$$E = ed \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where d = average height of the chip seal, inch, obtained by Equation 4; and e = percentage of aggregate embedment.

$$d = 1.33\frac{Q}{W} \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where Q = amount of aggregate required to cover the board (lbs/yd^2); and W = dry-loose unit weight of aggregate measured from unit weight test, (lbs/ft^3).

Equation 2 is used to determine asphalt application quantity, but this rate is applicable for asphalt cement. Adjustment is incorporated in the modified Kearby method when asphalt emulsion is selected as the binder for chip seal. This adjustment is done using Equation 5,

$$A_{recommended} = A + K(A_{theoretical} - A) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where $A_{recommended}$ = recommended asphalt emulsion application rate; A = designed asphalt application rate using Equation 2; and K = an adjustment factor depending on the chip seal construction season; $A_{theoretical}$ = A/R); R = percentage of residual asphalt content in asphalt emulsion.

Most chip seal design methods consider filling of 60-70% voids in aggregates, and the 2004 Seal Coat Design Algorithm assumes no aggregate loss will occur from chip-sealed pavement during the first winter season (Transit New Zealand et al. 2005). Houghton and Hallet (1987) mentioned the loss of aggregates in the winter season depends on voids in the aggregate. They showed aggregate stripping occurs while voids are less than 35%. This key point is used to determine asphalt application rate, which is sufficient enough to provide more than 35% voids in the winter season but no flushing in summer. This algorithm also includes the texture-adjustment factor. There are other adjustment factors, depending on the chip seal construction project, including soft substrate, absorptive surface, chip shape, and steep grades (Transit New Zealand et al. 2005).

The chip seal design procedure used by KDOT involves determination of aggregate and asphalt application rates. Cover material application rate is based on median particle size (M.P.S) of aggregates. Binder quantity depends chip size, traffic volume, and existing pavement conditions (KDOT 2004).

2.4 Construction of Chip Seal

Chip seal construction includes the use of equipments (Gransberg and James 2005) — aggregate particles spreader, asphalt sprayer, pneumatic-tired roller, dump truck, and rotary broom.

Some precautions need to be followed before chip sealing. These include weather conditions and surface preparation. Asphalt emulsions used for chip seal require a high pavement temperature with low humidity (Gransberg and James 2005). Kansas performs chip seal applications from June to September (KDOT 2004). Surface preparation for chip sealing is very important. Patching, crack filling, leveling pavement surfaces, and sweeping to remove debris are also required for successful application of chip seal (Gransberg and James 2005).

Chip seal performance depends on accurate application of asphalt binder. Thus, calibration and inspection of asphalt distributor are necessary (Gransberg and James 2005). Normally, asphalt emulsions are applied at about 140ºF. Aggregates are applied immediately after asphalt spraying. As mentioned earlier, chip seal success depends on proper embedment of aggregates into the asphalt emulsion applied; delayed application of aggregates hamper the goal. If the applied aggregate amount is more than required, loose aggregates will be dislodged (Gransberg and James 2005). Rolling should be done as soon as possible after aggregate spreading, using pneumatic-tire rollers. Performance and durability of chip seal depend on proper aggregate embedment by rolling (Gransberg and James 2005).

Excess aggregates need to be swept after the rolling operation. Traffic control is also required after chip seal application. According to the KDOT (2004) Construction Manual, newly sealed road need to be closed to regular traffic for four hours in the case of asphalt emulsions being used as binder. This time is reduced to one and one-half hours for polymer-modified asphalt emulsion. Distin (2008) noted that in South Africa, traffic is allowed a minimum of two hours before the outside temperature falls below 77°F.

2.5 Performance Measurement of Chip Seal

According to Gransberg and James (2005), both quantitative and qualitative approaches are used for performance measurement of a chip seal. They recommended both engineering-based and visual inspections be performed. Measurement of skid resistance and texture depth are engineering-based procedures. They also mentioned skid resistance as the frictional force developed between wheel and aggregate particles. Skid resistance is measured by the ASTM E274 test. Texture measurement is performed by the sand patch method, covered by ASTM E965. According to that report, qualitative measurement is performed by visual inspection.

2.6 Summary

Chip seal, a preventive maintenance treatment, is widely used because of low construction cost. It extends service life by providing skid resistance as well as stopping water intrusion into the pavement. Both normal-weight (gravel, sand stone, etc) and lightweight (expanded shale, clay, slate, etc.) aggregates are used for chip seals. Precoated normal-weight aggregates are typically used in many countries (especially South Africa) for chip seal construction. Lightweight aggregates minimize wind shield damage problems as well as provide superior skid resistance. Asphalt emulsion is the most common binder used for chip seal construction. It offers better bonding, along with saving energy. The main focus of designing chip seal concentrates on estimating aggregate and asphalt binder quantities. Highway agencies use empirical experience, the modified Kearby method, the Mcleod method, and other methods in chip seal design. Each step of chip seal construction is important to achieve the best-performing chip seal. Rolling is also very important. Loose aggregates from improper rolling may damage vehicles. Chip seal performance is measured by texture depth, as well as by presence of flushing or bleeding. Optimum aggregates and asphalt application, along with careful construction processes result in a better chip seal.

CHAPTER 3 - CHIP SEAL CONSTRUCTION SIMULATION, RESULTS AND ANALYSIS

3.1 Lightweight Aggregates

In this research project, four lightweight aggregate sources were evaluated. Lightweight aggregates from Kansas, Missouri, Oklahoma, and Colorado were studied.

3.1.1 Aggregates Used

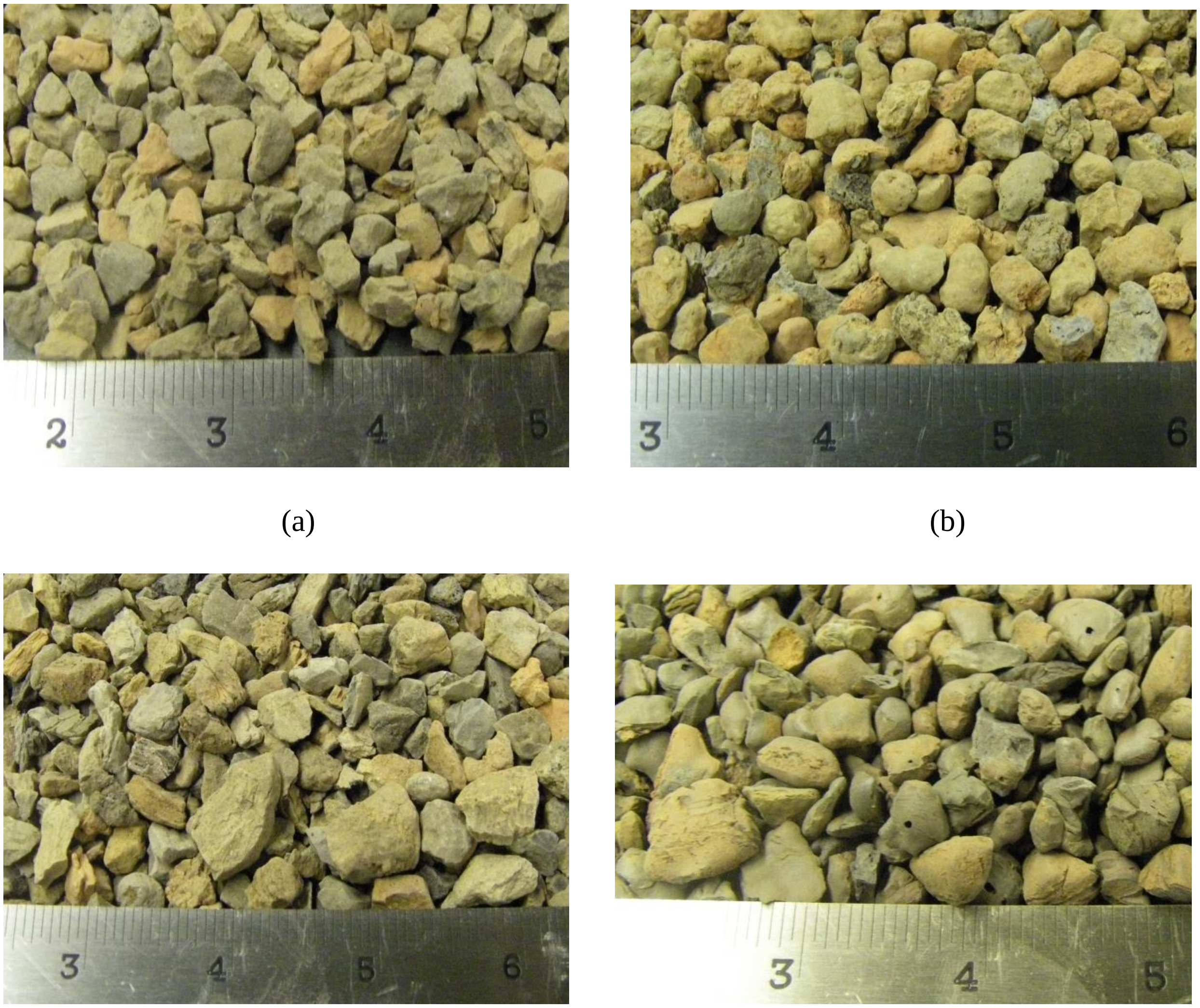
Four types of lightweight aggregates were evaluated: expanded shale and clay from Colorado (Agg-1T), expanded clay from Oklahoma (Agg-2C), expanded slate from Kansas (Agg-3M) and expanded shale from Missouri (Agg-4N). Figure 3.1 shows aggregates used in this study.

3.1.2 Aggregate Properties

Several aggregate properties have been evaluated in the laboratory, and these are listed in the following sections.

3.1.2.1 Gradation of Lightweight Aggregates

Sieve analyses were performed on all aggregates in accordance with Kansas Test Method KT-2. Table 3.1 shows summary of sieve analysis whereas Table 3.2 presents the percentage of aggregate passing through each sieve. Figure 3.2 shows gradation curves of individual samples, and curves have been drawn on the 0.45 power chart. The median particle size (M.P.S) of each sample has been reported in Table 3.1. The median size is the aggregate particle size at 50% passing in the gradation curve. Agg-1T, Agg-2C, and Agg-3M meet lower specification limits of KDOT for materials retained on ½-in. and 3/8-in. sieves. The uniformity coefficient (Cu) is the ratio of the aggregate particle size corresponding to 60% and 30% finer by weight. These values are obtained from the particle size distribution curve. The Cu value indicates the uniformity of particles. The closer this number is to one, the more uniformly the aggregate is graded. The Cu's of the tested aggregates are 1.46, 1.47, 2.12, and 2.12 for the Agg-1T, Agg-2C, Agg-3M, and Agg-4N, respectively. Therefore, Agg-1T and Agg-2C have more uniform aggregate particle sizes than Agg-3M and Agg-4N.



(a) (b)

(c) (d)

Figure 3.1 Aggregate Types: (a) Agg-1T, (b) Agg-2C, (c) Agg-3M, and (d) Agg-4N

Table 3.1 Summary of Sieve Analysis

Sieve Size	Percent passing			
	Agg-1T	Agg-2C	Agg-3M	Agg-4N
3/4 in.	100	100	100	100
½ in.	100	100	100	100
3/8 in.	100	98	96.9	91.8
#4	7.9	4.6	18.8	16.6
#8	2.4	1.2	1.6	3.6
#16	1.6	1.1	0.9	2.4
#30	1.0	1.0	0.7	1.9
#50	0.7	1.0	0.6	1.6
#100	0.5	0.8	0.4	1.4
#200	0.4	0.6	0.3	0.3
Median Size, in	0.255 in. (6.5 mm)	0.263 in. (6.7 mm)	0.244 in. (6.2 mm)	0.255 in. (6.5 mm)

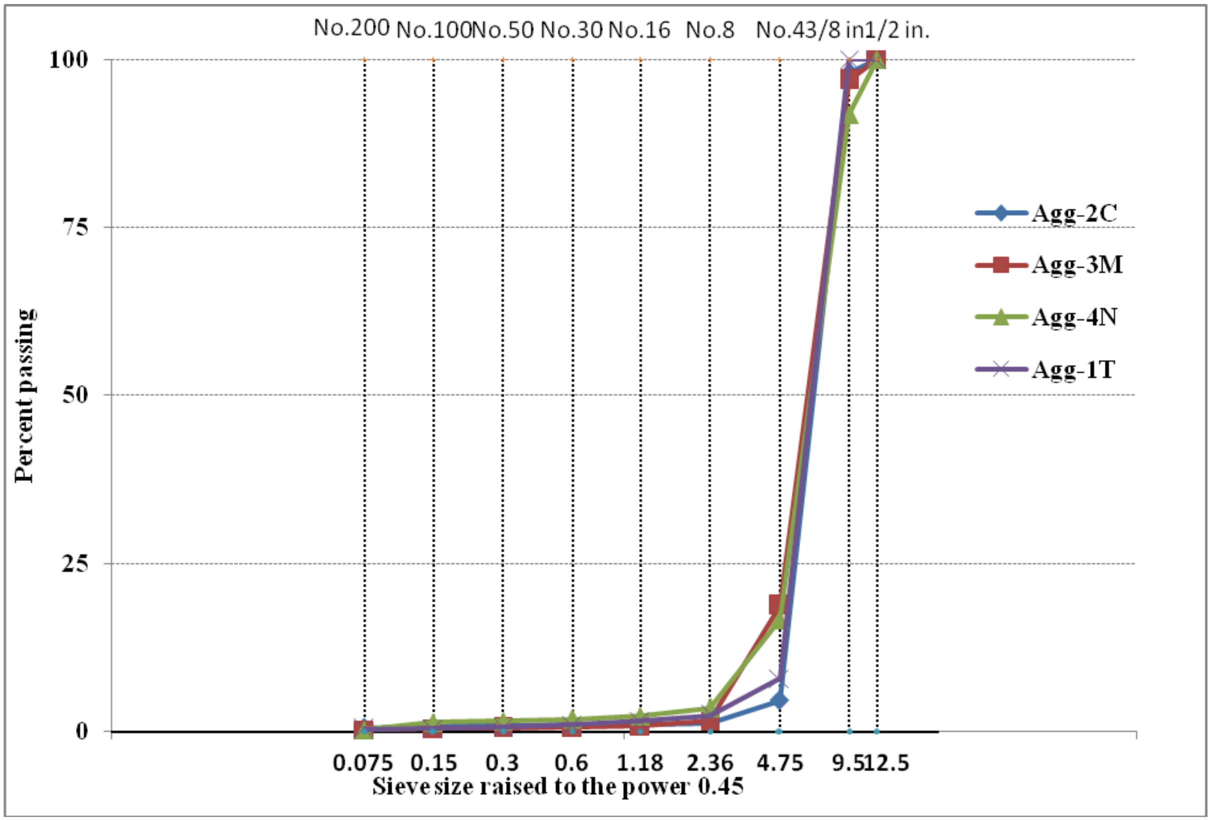


Figure 3.2 Aggregate Particle-Size Gradations

Table 3.2 KDOT Aggregate Gradation Requirements

Sieve size	Percent Retained				
	Agg-1T	Agg-2C	Agg-3M	Agg-4N	KDOT
¾ in.	0	0	0	0	0
½ in.	0	0	0	0	0-5
3/8 in.	0	2	3.1	8.2	0-15
No. 4	92.1	95.4	81.2	83.4	70-100
No. 8	97.6	98.8	98.4	96.4	90-100
No.200	99.6	99.4	99.7	99.7	98 (minimum)

3.1.2.2 Bulk Specific Gravity

Bulk specific-gravity tests were performed on all aggregates. The aggregates were divided into two different sizes: the size that 1) is retained on the No. 4 sieve, and 2) passes the No. 4 sieve and is retained on the No. 100 sieve. These tests were conducted following Kansas Test Method KT-6, and the results are shown in Table 3.3. Agg-3M and Agg-4N have relatively lower specific gravities than the other aggregates. Figure 3.3 shows rolling of pycnometer to remove air bubbles.

Table 3.3 Bulk Specific Gravity of Aggregates

Aggregate Type	Bulk specific gravity			
	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Retained on No. 4 sieve	1.53	1.51	1.23	1.17
Passing No.4 and retained on No. 100 sieve	1.57	1.53	1.25	1.21
Average bulk specific gravity	1.55	1.52	1.24	1.19

Figure 3.3 Bulk Specific Gravity of Fine Aggregate Determination

3.1.2.3 Loose Unit Weight of Aggregate

The loose unit weight (M) was determined by the Kansas Test Method KT-5 that is used to determine voids in loose aggregates. Design requirements for quantities of aggregates to be applied per square yard for chip seal are based on the bulk specific gravity and percent voids of the aggregates, exists in loose condition. Figure 3.4 shows leveling of cylindrical measure by tamping rod. The Equation (3.1) is used to calculate percent of voids, and the results are shown in Table 3.4.

$$\% \text{ Void} = \frac{100\left[(S \times W) - M\right]}{S \times W} \cdots\cdots\cdots\cdots\cdots\cdots (3.1)$$

Where

W = density of water,

S = bulk specific gravity, and

M = loose unit weight, kg/m^3.

Figure 3.4 Unit Weight Measurements of Aggregates

Table 3.4 Loose Unit Weight and Percent Voids

Aggregate Type	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Total Bulk Specific Gravity, S	1.55	1.52	1.24	1.19
Loose Unit Weight (lb/yd^3), M	1357	1423	1153	1139
%Voids in the Loose Aggregate	0.48	0.44	0.45	0.43

3.1.2.4 Aggregate Absorption

As lightweight aggregates are highly porous, the absorption capacity of lightweight aggregates is higher than that of normal weight aggregates. Normally, absorption of lightweight aggregate is in the range of 5 to 25%. Absorption and moisture content tests were performed according to Kansas Test Method KT-6. Table 3.5 shows the absorption of aggregates used in this study.

Table 3.5 Absorption and Moisture Content of Aggregates

Aggregate Type	Agg-1T	Agg-2C	Agg-3M	Agg-4N
% Absorption	13.47	16.69	19.57	10.94
Moisture content, %	1.35	1.64	2.47	0.14

3.1.2.5 Toughness

The aggregate must be able to resist abrasion and degradation. Toughness is measured by the Los Angeles abrasion test (KTMR-25). The Los Angeles abrasion loss values have been given in Table 3.6.

Table 3.6 Los Angeles Abrasion Test Results

Type of Aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N	KDOT limit
Los Angeles abrasion loss, %	19	23	25	28	Max. 30

3.1.2.6 Aggregate Charge

Aggregate surface charge is also very important in chip seal when emulsified asphalt is used as a binder. Normally, cationic or anionic emulsion is used for chip seal. According to Hooleran (1999), surface charge is controlled by the type and mineralogy of aggregates.

In laboratory, particles are ground to make suspension with water. After application of an electric field, velocity of particles charges is measured. The Zeta potential, measured on particulate samples of each aggregate at their natural pH conditions, is given in Table 3.7, along with their pH values. Although the pH values are similar, the Zeta potentials of the aggregates in this study are different. Agg-3M has a positive Zeta potential. The sign of Zeta potential indicates the type of charge on the surface of aggregate and intensity of surface charge increases with absolute value of the Zeta potential (Agilent Technologies 2008).

Table 3.7 Zeta Potential and pH Value of Aggregates

Type of Aggregate	pH value	Zeta potential (mV)
Agg-1T	8.2	-0.9
Agg-2C	9.8	-2.6
Agg-3M	8.9	1.3
Agg-4N	8.6	-2.5

3.2 Asphalt Emulsion

Asphalt emulsion consists of asphalt binder and water that evaporates as the binder cures. Therefore, in designing the chip seal, the residual asphalt content of the binder is used. CRS-1HP and CRS-2P emulsions used in this project have 69% and 71.4% residual asphalt content, respectively, according to test results provided by the KDOT Materials and Tests Unit. Other properties of both asphalt emulsions have been listed in Table 3.8.

Table 3.8 Asphalt Emulsion Properties

Properties	CRS-1HP	CRS-2P
Specific Gravity 60°/60°F.	1.0094	1.01
Saybolt Furol Viscosity at 122°F., sec.	68.7	83.6
Residue from Distillation percent	69.0	71.4
Oil Distillate, percent by volume	1.5	1.0
Particle Charge	Positive	Positive
Characteristics of Distillation Residue:		
Penetration 77°F., 100 grams, 5 sec.	113	115
Ductility at 77°F., cm.	80+	80+
Elastic Recovery @ 50°F,20 cm. elongation, percent	63	60
Polymer Content, %	3.5	3.5

3.3 Simulation of Chip Seal Construction

3.3.1 Specimen Fabrication

Chip seals were applied on 11.75-inch x 10.25-inch x 1.62-inch slabs made with a 3/8-inch nominal maximum aggregate size Superpave mix (know as SM-9.5A). The loose mix was first heated to 320°F, and then was compacted in a kneading compactor to achieve 4±1 % air voids. Figure 3.5 shows PMW compactor machine used to make slabs. Theoretical maximum specific gravity (G_{mm}) of the loose mixture was determined according to Kansas Test Method KT-39 and was 2.433. Mass of each sample was found with this G_{mm} for 4% air voids.

Theoretical Maximum specific gravity, G_{mm} = 2.433

Expected air voids = 4%

Mass of each sample = $\dfrac{(1-0.04)\times 2.433\times 12.75\times 10.25\times 1.625\times 1000}{12^3\times 3.28^3}$

= 8.135 kg = 8,135 gm = 17.83 lbs

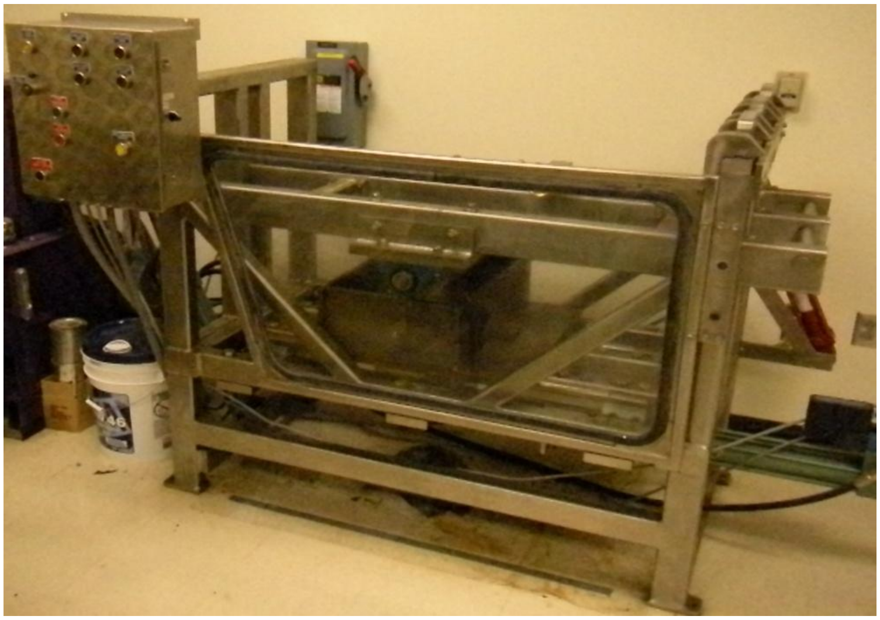


Figure 3.5 PMW Compactor Machine

Bulk specific gravity (G_{mb}) of slabs was also determined randomly to check the percent of air voids. This test was conducted according to Kansas Test Method KT-15, and test results are given in Table 3.9.

Table 3.9 Bulk Specific Gravity of Compacted Mix (Following KT-15 Procedure III)

Specimen ID	1	2	3	4
Dry mass in air, gm, (A)	8145.2	8156.7	8128.7	8151.2
Mass in water, gm, (C)	4642.9	4663.6	4647.1	4650.6
SSD mass in air, gm, (B)	8154.5	8167.0	8139.6	8175.1
G_{mb} = A/(B-C)	2.319	2.328	2.327	2.313
G_{mm}	2.433	2.433	2.433	2.433
Air content, %	4.7	4.3	4.3	4.9

3.3.2 Design of Chip Seal

Chip seal design includes determination of aggregate and asphalt binder quantities required for application. Excess or less aggregate and asphalt binder application may cause premature failure of chip seal. Therefore, determination of optimum aggregate and emulsion rates is critical for designing a long-lasting chip seal.

3.3.2.1 Quantity of Aggregates

Two approaches were followed to determine the optimum quantity of aggregates; one was the current KDOT construction manual procedure and the other was the modified Kearby method (Seal Coat and Surface Treatment Manual 2004). The KDOT design approach uses the median particle size (MPS) of the aggregates from the results of sieve analysis. The median particle size (MPS) is the particle size corresponding to 50% passing by weight. The amount of aggregate was calculated by the following formula:

Amount of aggregate = MPS * Area of the slab * Unit weight of aggregate

= 0.244*10.25*12.75*684.2/ (12^3*3.28^3)

= 0.3578 kg = 357.8 gm = 0.789 lb

Here, the rate is 0.87 lb/ft^2.

Aggregate quantity for each slab was based on the median particle size and is given in Table 3.10.

Table 3.10 Quantity of Aggregate for Chip Seals

Type of aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Quantity of aggregate, lbs	0.970	1.050	0.789	0.817
Rate, lb/yd^2	9.62	10.41	7.82	8.08

In the modified Kearby method, the board test, as shown in Figure 3.6, is used to determine the amount of aggregate. This test was conducted by placing one layer of aggregate on an 11.75-inch x 10.25-inch slab, and determining the amount of aggregate needed to cover the slab. Thus the aggregate application rates were obtained. The results of the board test are tabulated in Table 3.11.

Figure 3.6 Board Test

Table 3.11 Board Test Results

Type of aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Trial 1, lbs	0.967	1.037	0.856	0.805
Trial 2, lbs	0.990	1.059	0.817	0.768
Trial 3, lbs	0.960	1.065	0.841	0.793
Average, lbs	0.972	1.054	0.838	0.789

Although both tests produced identical results, the maximum amount of aggregate was used as the design rate for chip seal specimen construction. The second aggregate rate had 5% higher aggregate quantity. Table 3.12 shows aggregate application rates.

Table 3.12 Aggregate Application Rate

Type of aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Rate 1, lbs	0.972	1.054	0.838	0.817
Rate 2, lbs	1.021	1.104	0.882	0.860

3.3.2.2 Quantity of Asphalt Emulsion

Both KDOT and modified Kearby methods were used to determine emulsion application rates. The KDOT approach uses the median particle size (MPS) of the aggregate from the sieve analysis results, traffic count, residual asphalt content, and roadway surface conditions. KDOT design inputs for emulsion application rates are given in Table 3.13.

Table 3.13 KDOT Chip Seal Design Inputs

Type of aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Median particle size, inch	0.255	0.263	0.244	0.255
Traffic count, vehicles/day	1260	1260	1260	1260
Traffic factor	0.88	0.88	0.88	0.88
Pavement condition adjustment, gal/yd^2	0.00	0.00	0.00	0.00
Asphalt residue, %	69.8	69.8	69.8	69.8

Table 3.14 shows the emulsion application rates determined by the KDOT method.

Table 3.14 KDOT Emulsion Application Rate

Type of aggregate	Agg-1T	Agg-2C	Agg.-3M	Agg.-4N
Rate, gal/yd^2	0.32	0.33	0.31	0.32
Quantity for one sample, gm	122.2	125.9	118.3	122.2

With this emulsion rate, 70% embedment of aggregate was not obtained. Lightweight aggregate is more porous than normal-weight aggregate, and this was not considered in this method. Several trials were done to obtain the optimum emulsion amount to achieve 70% embedment of aggregates.

The modified Kearby method incorporates the dry-bulk specific gravity of the aggregate, average aggregate depth, percent embedment of aggregate, traffic volume, existing pavement surface condition, residual asphalt content, and construction site seasonal factor. The design factors and estimated emulsion application rates are shown in Table 3.15.

Table 3.15 Design Inputs and Emulsion Rates of Modified Kearby Method

Type of aggregate	Agg-1T	Agg-2C	Agg-3M	Agg-4N
Bulk specific gravity of the aggregate, G	1.55	1.52	1.24	1.19
Dry loose unit weight, W, lbs/yd^3	1357	1423	1153	1139
Traffic correction factor, T	1.00	1.00	1.00	1.00
Correction for surface condition, V	-0.03	-0.03	-0.03	-0.03
Aggregate quantity, Q, lbs/yd^2	9.62	10.41	8.31	8.08
Embedment, e, %	70	70	70	70
Emulsion rate, gal/yd^2	0.42	0.46	0.41	0.43
Emulsion, lbs/sample	0.416	0.450	0.407	0.422

Existing chip seal design methods use 50% to 70% embedment of aggregate particles to design the chip seal (Gransberg and James 2005). In this study, emulsion application rates were determined based on 70% embedment of aggregates. It was found from trials that 0.58 gal/yd^2 of emulsion gives about 70% embedment. The embedment depth was measured by the modified sand circle method that will be described later. Residual asphalt contents of the emulsion were 69% and 71.4 %t for CRS-1HP and CRS-2P, respectively. The specific gravity was 1.009 and 1.01, respectively.

It is noticeable the two procedures can differ substantially on the emulsion quantity estimates, but agree well for aggregate quantity. In this study, 32 aggregate-emulsion combinations were studied based on their type and quantity. Two replicates were done for each combination. The chip seal design matrix used in the study can be summarized as follows:

Table 3.16 Chip Seal Design Matrix

Aggregate Type	Aggregate Application Rate, gm	Emulsion Type	Emulsion Application Rate, gm
Agg-1T	441.0	CRS-1HP, CRS-2P	220.0, 230.0
	463.0	CRS-1HP, CRS-2P	220.0, 230.0
Agg-2C	478.0	CRS-1HP, CRS-2P	220.0, 230.0
	501.0	CRS-1HP, CRS-2P	220.0, 230.0
Agg-3M	380.0	CRS-1HP, CRS-2P	220.0, 230.0
	400.0	CRS-1HP, CRS-2P	220.0, 230.0
Agg-4N	370.7	CRS-1HP, CRS-2P	220.0, 230.0
	389.7	CRS-1HP, CRS-2P	220.0, 230.0

3.3.4 Chip Seal Application

The complete chip seal application procedure followed in the laboratory to simulate chip seal construction involved the following steps:

1. The compacted slab was heated to 70°F. A thick tape was used around the slab to make a dam so that emulsion would not spill out of the slab surface. Later, the slab was placed in a wooden frame.
2. Emulsion was measured and heated to 150°F, and was manually applied over the slab surface with a roller brush.
3. A thin steel plate was used to make the surface even and smooth.
4. Aggregates were then applied carefully to avoid overlapping.
5. An 82-lb concrete cylinder was used to compact the aggregates.
6. After three hours, each sample was swept to remove loose aggregate and reported as initial loss.

3.4 Test Methods

In this study, chip seal performance was measured by aggregate retention (sweep test), aggregate embedment depth, and rutting test.

3.4.1 Embedment Test

In chip seal construction, the objective of rolling is to attain proper aggregate embedment to resist dislodgment under traffic loading and to attain maximum bonding (Gransberg and James 2005). Therefore, the rolling operation must follow as closely behind the aggregate spreader as possible to avoid failure. In order to estimate the embedment of the aggregates, the sand circle method is often used. The method measures exposure depth of the aggregates in the chip seal based on a volumetric technique. A modified sand circle set up has been used to measure actual embedment depth of the aggregates into the emulsion film. This method is described in detail in the following section.

3.4.1.1 Modified Sand Circle Method

A modified sand circle method, based on the Australian test method T 240: Texture Depth of Coarse Textured Road Surfaces (Road and Traffic Authority-Australia 2004), was developed for measuring texture depth of chip seal. After pouring the sand on the pavement surface, a circle is formed. Formation of a complete circular shape is tough as the diameter is not uniform. Thus, a ring at the center of the rectangular steel plate (Figure 3.7(a)) was used to keep the sand within the circle. Calculation of the loose unit mass of sand and the sand circle test procedure are described below.

Calculation of Loose Unit Mass of Sand

The loose unit of mass of sand was first measured, and this sand was used for the modified sand circle test later. A calibrating container was weighed (M_1), and after filling with sand, it was weighed (M_2) again. Internal volume (V) of the container was determined from the quantity of water necessary to fill the container. Loose unit mass of the sand was determined as follows:

$$\text{Loose unit mass, } W = \frac{M_2 - M_1}{V} \text{ lb/ft}^3$$

1. This procedure was repeated three times and the mean loose unit mass computed.

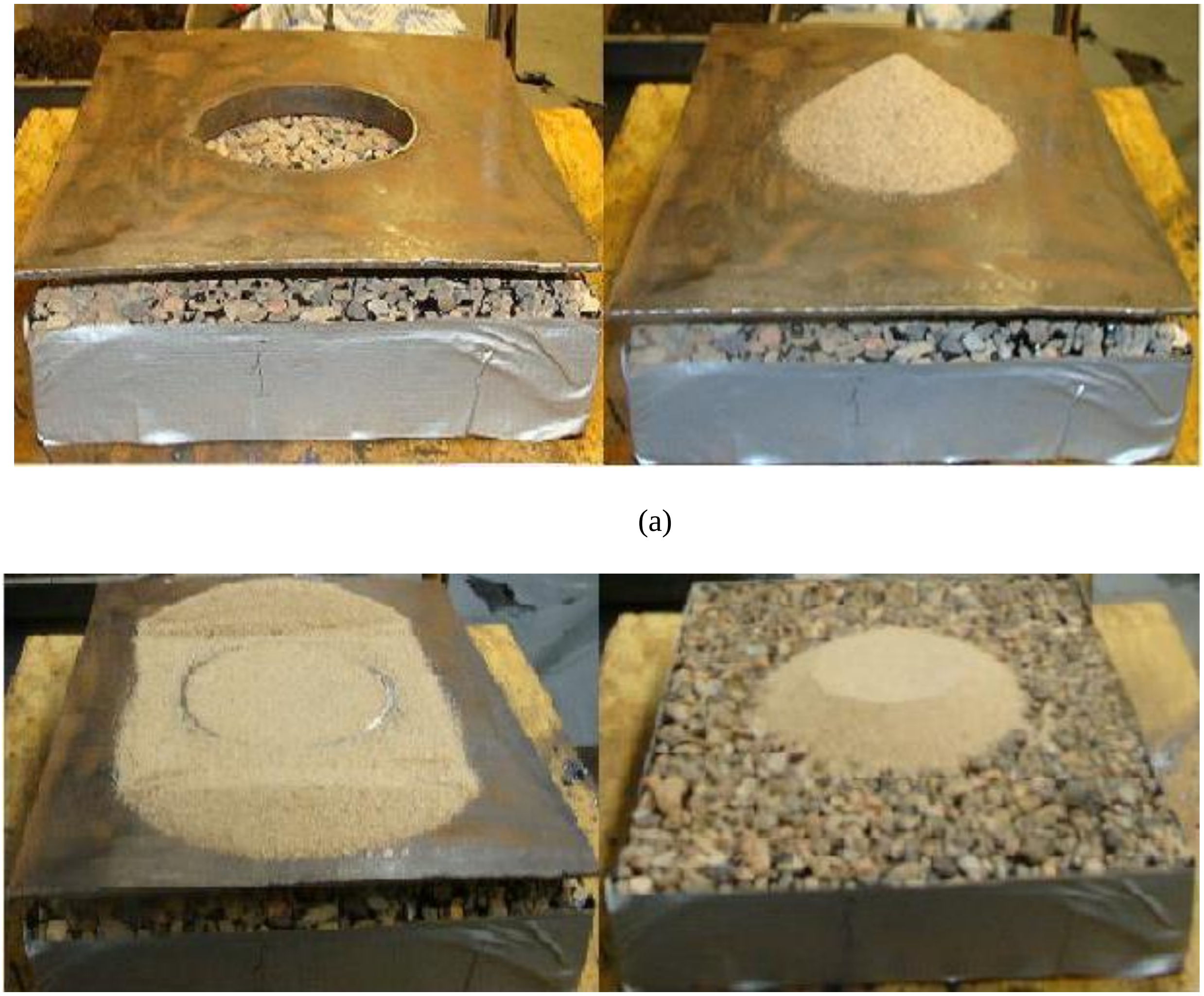
Modified Sand Circle Test Procedure

1. Measure sand required to fill the ring to the nearest 0.0002 lb (W_1).

2. Put a ring with rectangular plate on the specimen.
3. Pour the sand into the ring in an even stream, keeping the pouring spout approximately 1-inch above the surface of the sand to form a central cone. Slightly overfill the container and carefully level the surface by a sharp plate.
4. Remove the steel plate and determine the mass of the sand left on the sample to the nearest 0.0002 lb (W_2).
5. Determine mass of sand required to fill the voids of sample by subtracting W_1 from W_2.
6. Calculate average embedment depth as follows:

Average sand depth = $\frac{1272M}{Wd^2}$

where W = loose unit mass of the sand (lb/ft^3), d = ring diameter (inch); and M = mass of the sand (W_2-W_1) (lb).



(a)

(b)

Figure 3.7 Steps of Modified Sand Circle Test: (a) Ring on Chip Seal Sample and Sand Poured in Ring, and (b) Smoothing Surface of Ring and Amount of Sand Required for Filling Texture Depth and Ring

Percent embedment was calculated based on median particle size (MPS) of the aggregate. The following formula was used to determine percent embedment.

$$\%\ \text{Embedment} = \frac{\text{MPS} - \text{Average Sand Depth}}{\text{MPS}} \times 100$$

3.4.2 Hamburg Wheel-Tracking Device Test

The Hamburg wheel tracking device is used to assess the sustainability of pavement at the worst condition. The steel wheel passes on pavement samples submerged under hot water (generally held at 122°F). The steel wheels weigh 158 lbs. This test method measures rut depth and the number of wheel passes to a pre-specified rut depth. Rut depth or number of wheel passes whichever comes first are considered as failure criteria of pavement sample.

Two slabs with chip seals with the same aggregate and emulsion rates were tested in this device simultaneously. Chip seal samples used for embedment measurements were later used for rut tests in this device. A 0.787-inch rut depth is generally used as failure criteria for compacted hot-mix asphalt. This study is concerned with the effectiveness of chip seal. Thus median particle size (MPS) was taken as the maximum rut depth. This maximum rut depth, or maximum 20,000 wheel passes, whichever occurred first, was taken as the failure criteria. Water temperature during testing was 95º F, since any temperature greater than this would result in flow of asphalt in the emulsion. Figure 3.8 shows Hamburg Wheel-Tracker set up and tested sample.

(a) **(b)**

Figure 3.8 Rut Test Phases in Hamburg Wheel-Tracker Machine: (a) Conditioning of Chip Seal Samples for Rut Test, and (b) Chip Seal Samples after Rut Test

3.4.3 ASTM Sweep Test

Aggregate retention performance can be evaluated using various test methods, including the aggregate retention test (ART) (Tex-216-F), AustRoad Pull-Out Test (RTA T-238), the Vialet test, the Pennsylvania aggregate retention test (PART), and the sweep test (ASTM D7000) (Gransberg and James 2005). However, each of these methods applies a different form of mechanical energy to assess the aggregate-asphalt bond instead of applying a mechanical force that simulates traffic wheels. In this study, the sweep test (ASTM D 7000-04) was used to assess aggregate retention characteristics due to the simple nature of the test. Figure 3.9 shows ASTM D 7000 sweep test set up. Aggregates were placed in an oven and dried to a constant mass. The dried aggregates were then sieved to obtain a test sample that had 100% passing the 3/8-inch sieve and less than 1% passing the No. 4 sieve. The amount of aggregate used for each specimen was determined from the following equation.

$$\mathrm{Y} = \frac{A(202.1X - 14.7)}{100} + \frac{B(146.4X - 4.7)}{100}$$

where A = % of aggregate from 3/8 to 1/4 inch, B = % of aggregate from 1/4 to 0.187 inch, X = bulk specific gravity, and Y = amount of aggregate needed for the sweep test, lbs.

Figure 3.9 ASTM Sweep Test

In ASTM D 7000-04 test, the following equation is used to determine total mass loss:

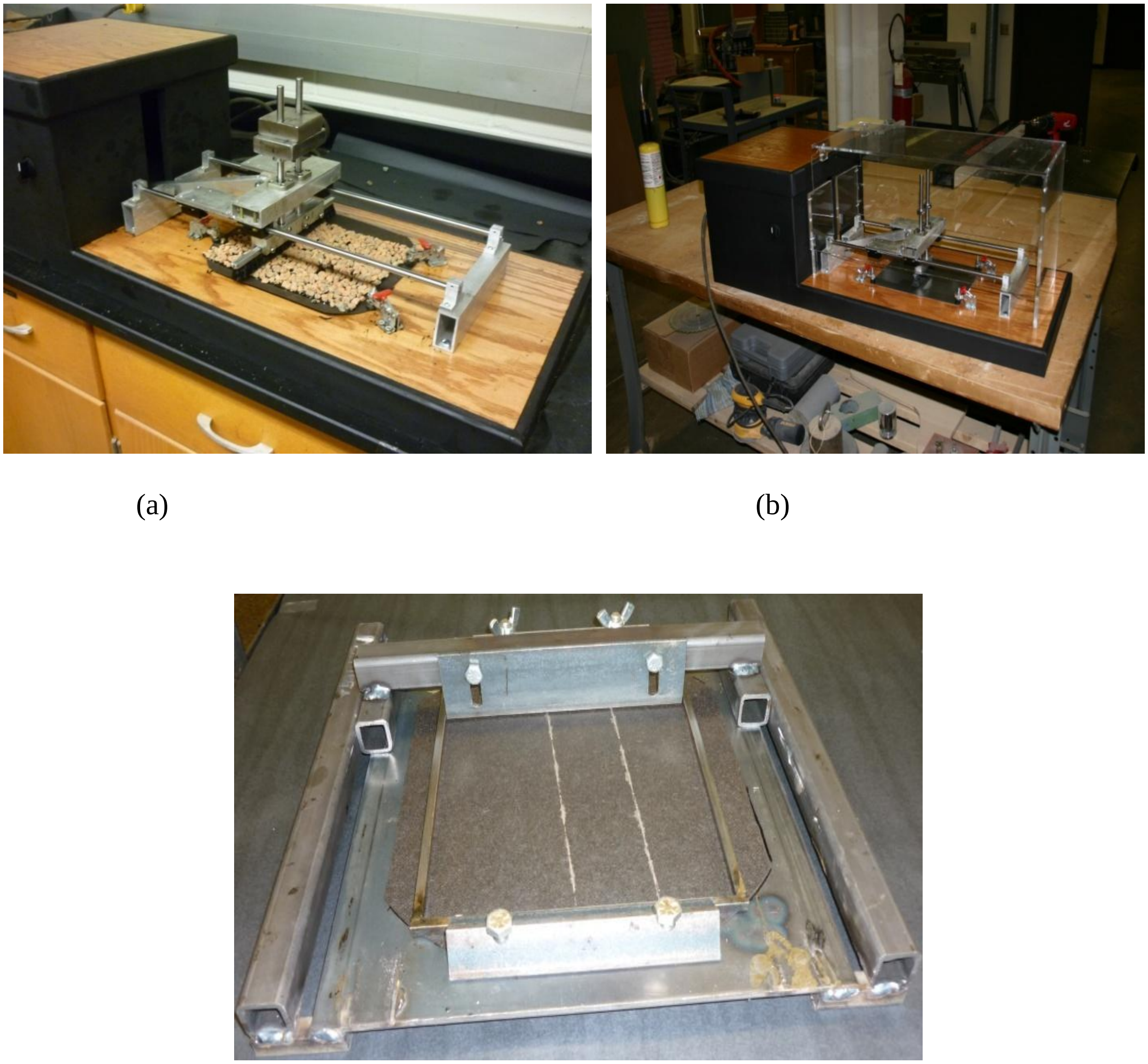
$$\% \text{ Mass loss} = \frac{A-B}{A-C} \times 100 \times 1.33$$

where A = initial weight of the sample, B = final weight of the sample, and C = weight of the felt disk.

3.4.4 Modified Sweep Test

In ASTM D 7000-04 sweep test, the 5-inch-long rotating brush does not cover the whole test sample. Also, as aggregates are applied by hand, there are inherent variabilities. Uniform emulsion application is also challenging. Thus keeping all these issues in mind, a new setup for simulating the sweep test has been developed for better emulsion application and subsequently a better sweep test. The setup is shown in Figure 3.10. In the modified test, a rectangular sample with 9.25-inch length and 7.5-inch width is used. A 7.5- inch-wide brush moves back and forth over the whole sample length. To accomplish the 9.25-inch linear stroke, a custom flywheel was made out of 6061 aluminum mounted on an AC gear motor with a speed of 100 rpm. The carriage assembly, where the brush is mounted, moves on four linear bearings sliding on 18-inch-long precision ground shafts with a 6061 aluminum connecting rod transferring the motion from the flywheel to the sliding carriage assembly. Thus the brush is able to freely ride up and down over the surface of the test specimen.

For the brush to float freely above the sample, surface linear bearings were used once again. A brush holder was machined out of 6061 aluminum with two 8-inch-long precision shafts mounted vertically that ride in two linear bearings inside the carriage assembly. This gives the brush movement laterally with the carriage and also the ability to float freely over the sample as it moves across. Shaft collar clamps were placed on each shaft to allow for different sized weights to be placed on the brush, as per the requirements for the test. Two motors each with a torque output of 7-inch-lb at 100 rpm have been coupled to power the brush properly for the entire test. The sample is clamped down during a test with four toggle clamps, one at each corner for secure mounting that does not impede the test functionality. A Plexiglas shield is used during the test for safety and is easily removable for sample changing and service of the machine.



(a) (b)

(c)

Figure 3.10 Modified Sweep Test Machine: (a) Brush Moving Over the Sample, (b) Overall View of Machine Showing Complete Assembly, and (c) Setup for Emulsion Application

Test Procedure

A 9.25-inch x 7.5-inch rectangular asphalt felt disc is used in this modified test. After fixing the asphalt application setup (Figure 3.10 (c)) with the help of end clamps, asphalt emulsion is applied while a strike-off thin plate is moved over the sample to provide uniform asphalt thickness. A fixed quantity of asphalt emulsion (0.136±0.01 lb, application rate of 2.62 lbs/yd^2, same as in ASTM D7000-04) is poured on the top of the felt disk. The ASTM D7000-04 sample preparation procedure was followed for the rest of the process.

3.5 RESULTS AND STATISTICAL ANALYSIS

Analysis of variance (ANOVA) is generally used to analyze to identify independent variables that are related to the dependent variable. To find factors affecting embedment depth, aggregate retention, rut depth, and number of wheel passes and to compare the population means of these factors, ANOVA was used. This analysis was done by the SAS (Statistical Analysis System) software. In ANOVA, a model is formed involving dependent variable with independent variables. Independent variables that have an effect on dependent variables are determined by ANOVA at a specified confidence level. Least square mean (LS mean) is used for multiple comparison. According to SAS/STAT User’s Guide (2009), LS mean determines marginal means of sample. It has mentioned that differences among means are better estimated if more balanced (equal number of replication) observations is available. Separate analyses were done in this study for aggregate loss, aggregate embedment depth, and number of wheel passes in the Hamburg wheel tracker. A 95% confidence level (CL) was used in the analysis.

3.5.1 Sweep Test Results Analysis

In this section, results from the sweep test are presented to discuss the effect of aggregate and emulsion on aggregate retention. Table 3.17 and Table 3.18 tabulate the statistical analysis outputs, whereas Figure 3.11 shows the least square mean values of mass loss, and error bars show standard deviations. Four aggregate types (Agg-1T, Agg-2C, Agg-3M & Agg-4N) and two emulsion types (CRS-1HP & CRS-2P) are the independent variables to estimate the percent aggregate loss. Eight replications were made for each aggregate-emulsion combination.

The ANOVA model for this experiment is

$$Y_{ijk}= \mu + A_i + E_j + AE_{ij}+ \varepsilon_{ijk}$$

where Y_{ijk} = chip loss (%), μ = mean loss (%), A_i = effect of aggregate i, E_j = effect of emulsion j, AE_{ij} = effect of interaction, and e_{ijk} = random error for the ith aggregate, jth emulsion, and kth replicate.

Table 3.17 SAS Output of ASTM Sweep Test (Dry Aggregate)

Dependent Variable: Aggregate Loss

R-Square: 0.89325

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	1389.562	198.508	32.52	<.0001
Error	56	341.803	6.103		
Source	DF	Type I SS	Mean Square	F Value	Pr > F
agg	3	681.698	227.232	37.23	<.0001
emsln	1	39.564	39.564	6.48	0.0137
agg*emsln	3	668.299	222.766	36.50	<.0001

ANOVA results in Table 3.17 indicate that significant interaction between aggregate and emulsion exists at the 95% confidence level. Thus selection of aggregate and binder is dependent on each other. When Agg-4N is used with CRS-1HP emulsion, loss of aggregate particles is the lowest (Figure 3.11). The reason could be the presence of low moisture in Agg-4N, because moisture encourages stripping of aggregate particles. The aggregate surface charge might be another factor, because Agg-4N has a higher negative surface charge. The highest aggregate loss is obtained when Agg-1T is used with CRS-1HP emulsion. Interaction of all aggregate types with emulsions can be observed from Figure 3.11. It is evident that all aggregates except Agg-4N show better aggregate retention with the CRS-2P emulsion.

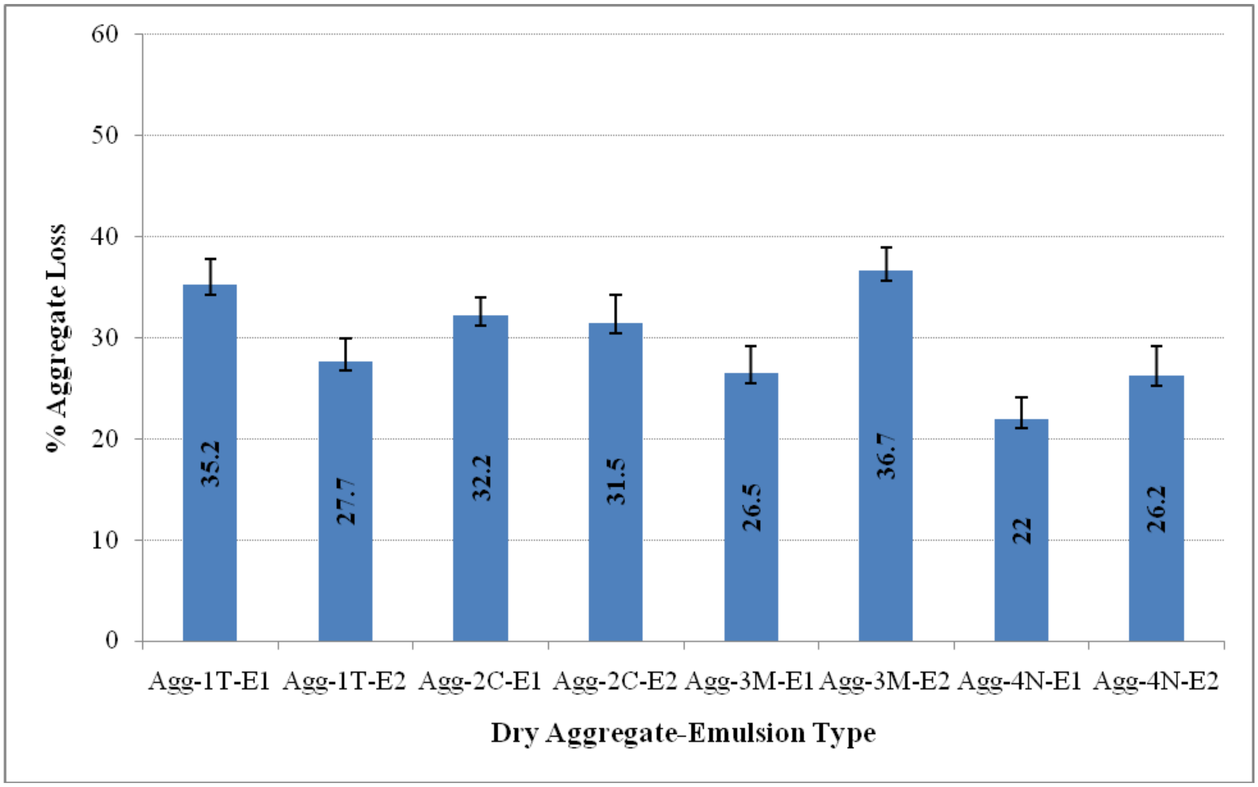


Figure 3.11 Sweep Test Results under Dry Aggregate Condition

In this section, results from the sweep test are presented to discuss the effects of aggregate moisture content, surface charge, and interaction with emulsion on mass loss or in other words, aggregate retention. Figures 3.11 and 3.12 show the mean values of aggregate or chip loss for dry and SSD aggregates, respectively. When dry Agg-4N was used with the CRS-1HP emulsion, the chip loss was the lowest. In case of SSD aggregates, Agg-4N, Agg-2C, and Agg-1T showed almost similar chip loss. Agg-3M in SSD condition showed the maximum chip loss. The reason might be the surface charge of aggregate particles. As this aggregate has a positive surface charge, and cationic emulsion was used, no electrostatic forces formed.

There is only a small difference in chip loss considering moisture conditions of the aggregate particles as seen in Table 3.19. When dry aggregate were used, dust in the aggregate particles impeded the binder coating of the aggregates. This might be the reason behind the minimum aggregate loss of Agg-4N, which contained only 0.3 percent dust. When SSD aggregates were used, several factors were in play including (a) no dust on the surface of the aggregates, (b) pores completely filled with water, and (c) surface charge of the aggregate particles. As there were charges on the particle surface and no dust, a better bonding environment existed. However, excess water in the aggregate particles slows down the curing process and that may lead to more aggregate loss.

Table 3.18 SAS Output of ASTM Sweep Test (SSD Aggregate)

Dependent Variable: Aggregate Loss

R-Square: 0.86025

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	818.705	116.957	12.13	<.0001
Error	56	540.075	9.644196		
Source	DF	Type I SS	Mean Square	F Value	Pr > F
agg	3	372.896	124.298	12.89	<.0001
emsln	1	79.210	79.210	8.21	0.0058
agg*emsln	3	366.598	122.199	12.67	<.0001

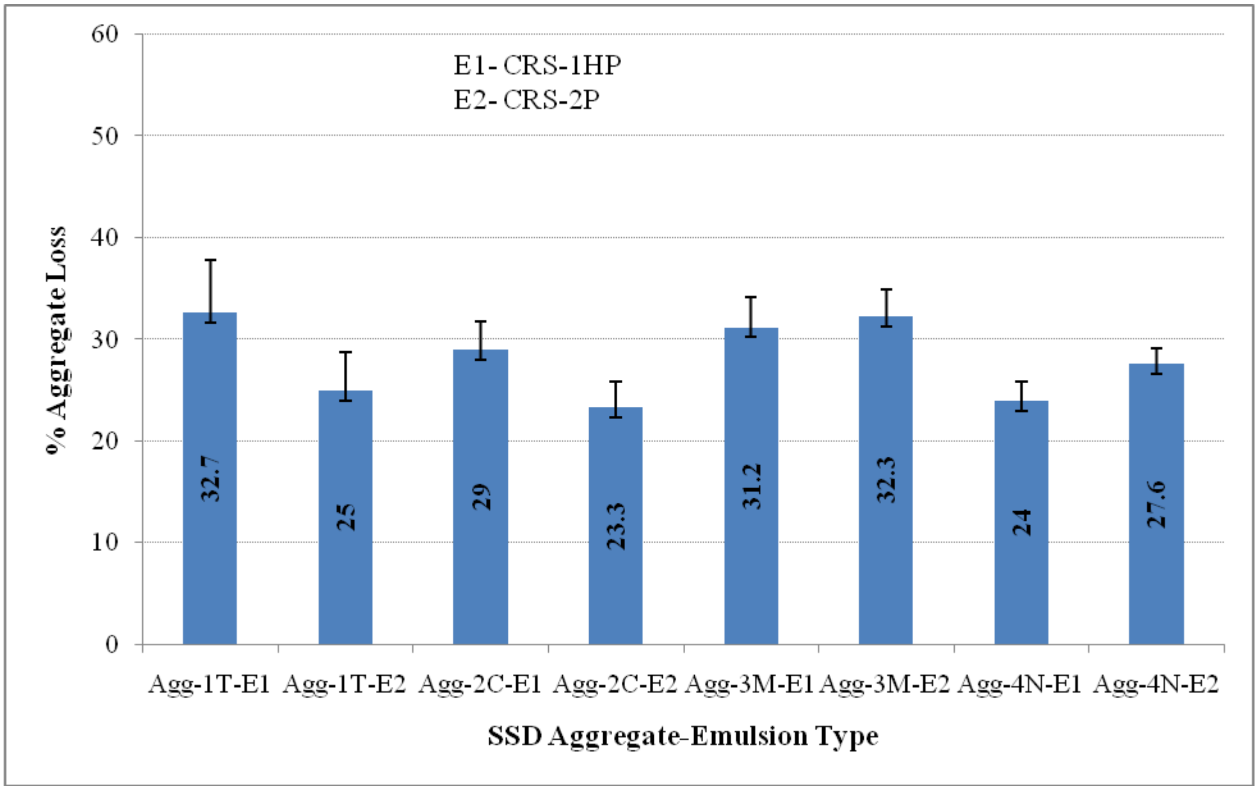


Figure 3.12 Sweep Test Results under SSD Aggregate Condition

Table 3.19 Summary of Chip Loss in ASTM and Modified Sweep Tests

Aggregate Type	Emulsion Type	ASTM Sweep Test				Modified Sweep Test			
		Mean Mass Loss (%)	Standard Deviation	Coefficient of Variance (%)	Replication, N	Mean Mass Loss (%)	Standard Deviation	Coefficient of Variance (%)	Replication, N
Agg-1T	CRS-1HP	35.20	2.65	7.54	8	36.72	1.47	4.01	8
Agg-1T	CRS-2P	27.74	2.26	8.16	8	41.56	1.68	4.04	8
Agg-2C	CRS-1HP	32.15	1.77	5.51	8	29.35	1.28	4.35	8
Agg-2C	CRS-2P	31.54	2.79	8.86	8	50.03	1.51	3.03	8
Agg-3M	CRS-1HP	26.48	2.70	10.21	8	55.03	1.98	3.59	8
Agg-3M	CRS-2P	36.65	2.30	6.27	8	46.42	1.79	3.86	8
Agg-4N	CRS-1HP	22.00	2.13	9.70	8	36.95	1.90	5.13	8
Agg-4N	CRS-2P	26.19	2.93	11.19	8	51.04	1.60	3.14	8

Comparison of Sweep Test and Modified Sweep Tests

Modified sweep tests were done for all four aggregates and two emulsion types. Since the ASTM D7000 sweep tests did not show any significant differences in mass loss between dry and SSD conditions, modified sweep tests were done only for dry aggregates. The ANOVA analysis of modified sweep test results (Table 3.20) was also conducted. Again, asphalt emulsion and aggregate interaction is significant. Figure 3.13 shows the aggregate loss results from this test.

Table 3.20 SAS Output of Modified Sweep Test

Dependent Variable: loss

R-Square: 0.95950

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	4270.182	610.026	219.92	<.0001
Error	56	155.333	2.773		
Source	DF	Type I SS	Mean Square	F Value	Pr > F
agg	3	1375.761	458.587	165.33	<.0001
emsln	1	961.077	961.077	346.48	<.0001
agg*emsln	3	1933.343	644.447	232.33	<.0001

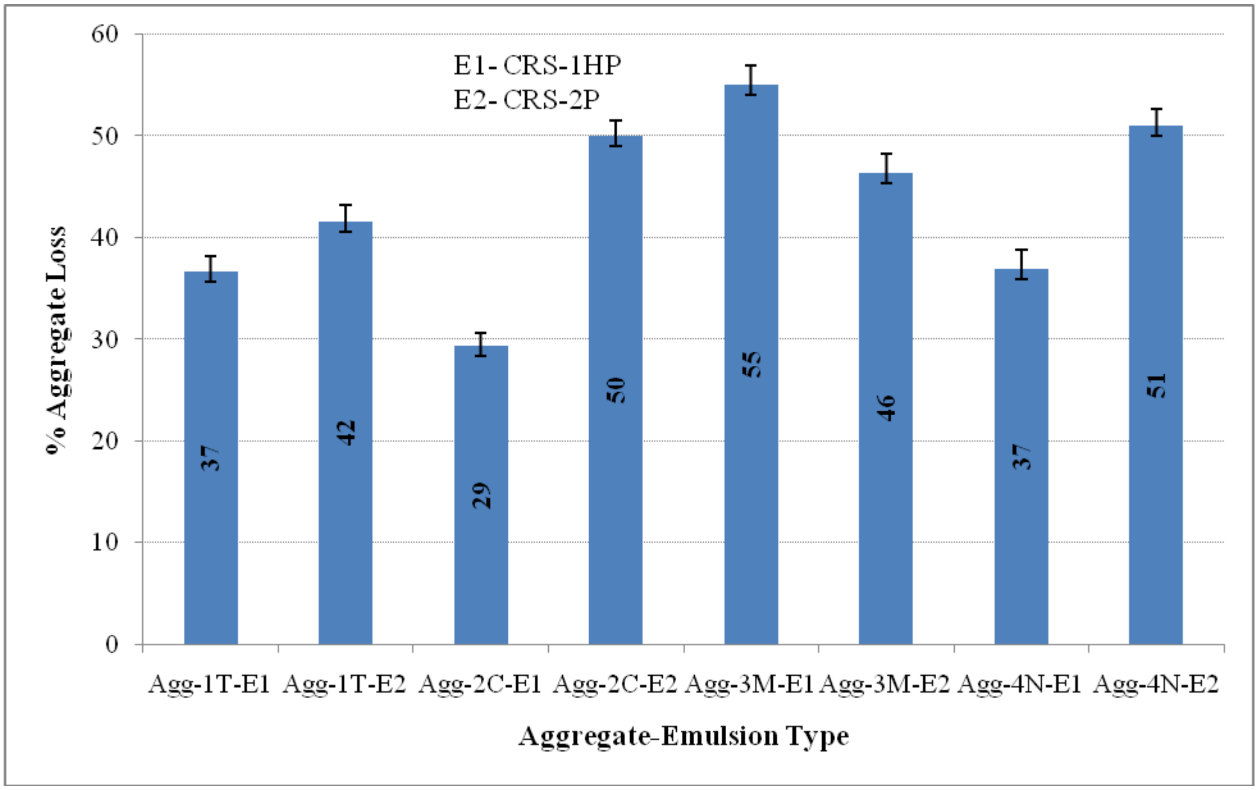


Figure 3.13 Modified Sweep Test Result under Dry Aggregate Condition

Results of the modified sweep test were compared with the standard ASTM sweep test results. The R-square values of the standard ASTM sweep test and modified sweep test were 0.8932 and 0.9595, respectively. Thus, the modified sweep test can describe variability better than the ASTM sweep test. It is to be noted the mass or aggregate loss determined by the Modified Sweep test is always greater than that of the ASTM Sweep test for all aggregate-emulsion combinations except Agg-2C-E1 (Agg-2C and CRS-1HP emulsion). As mentioned earlier, the brush in the ASTM sweep test does not rotate over the whole sample. Since the aggregates are applied manually, uniformity cannot be maintained. Therefore, the test will result in more or less mass loss if the brush rotates over that part with more or less aggregate, respectively. In the proposed modified sweep test, the brush covers the entire sample. On top of that, emulsion application is also more uniform. In most cases, mass loss determined by the modified sweep test is more than 50 percent higher than that from the ASTM sweep test. However, the trend is the same as indicated by Agg-3M that shows the maximum aggregate loss in both tests**.**

3.5.2 Embedment Measurement Analysis

The analysis of variance (ANOVA) was performed to find the significant factors that affect embedment depth and in turn, retention of aggregates. SAS (Statistical Analysis System) software was used for this purpose. The ANOVA model for this experiment is

$Y_{ijk} = \mu + A_i + E_j + AE_{ij} + \varepsilon_{ijk}$

where Y_{ijk} = Embedment of aggregate (%), μ = mean embedment (%), A_i = effect of aggregate i, E_j = effect of emulsion j, AE_{ij} = effect of interaction, and e_{ijk} = random error for the ith aggregate, jth emulsion, and kth replicate.

Table 3.21 SAS Embedment Analysis

Dependent Variable: Embedment

R-Square: 0.86545

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	1240.039844	40.001285	3.56	0.0003
Error	32	359.065000	11.220781		
Source	DF	Type I SS	Mean Square	F Value	Pr > F
agg	7	184.0810938	26.2972991	2.34	0.0474
emlsn	3	167.4942188	55.8314063	4.98	0.0060
agg*emlsn	21	888.4645312	42.3078348	3.77	0.0004

The ANOVA results, tabulated in Table 3.21, show interaction between aggregate and emulsion is significant at the 95% confidence level. Therefore, embedment is dependent on the aggregate-emulsion compatibility. Figure 3.14 presents percent embedment depths of aggregates measured by the modified sand circle method. In this figure, C, M, N, and T stand for Agg-2C, Agg-3M, Agg-4N, and Agg-1T, respectively, whereas “1” and “2” denote two different aggregate rates. Again, E1 and E2 indicate CRS-1HP and CRS-2P emulsion, respectively. R1 and R2 refer to two different emulsion application rates. From Figure 3.14, it can be seen that the aggregate embedment depth is in the range of 63% to 78%. It was found that with a few exceptions, when a higher emulsion application rate was used, embedment depth increased. Lower embedment was noticed for Agg-4N because there were a few big particles, and effective compaction was not achieved. Agg-3M showed the most uniform embedment with both CRS-1HP and CRS-2P emulsion when a higher application rate of this aggregate was used.

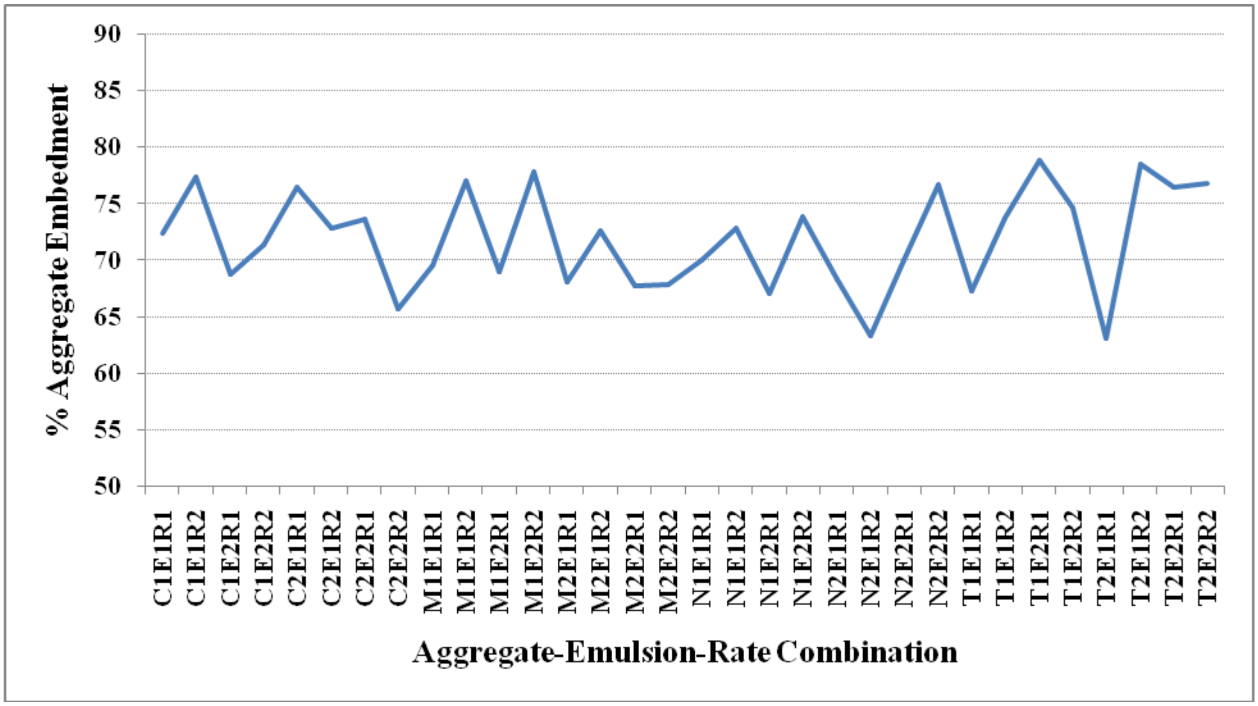


Figure 3.14 Embedment of Aggregate

In this experiment, 32 aggregate-emulsion combinations, based on their type and quantity, were used. Hypothesis test results showed that five combinations performed significantly different from others, and these combinations show greater depth of embedment. Table 3.22 identifies these combinations.

Table 3.22 Aggregate Embedment

Aggregate Type	Aggregate Rate	Emulsion Type	Emulsion Rate	% Embedment
Agg-2C	Rate 1	CRS-1HP	Rate 2	77.4
Agg-3M	Rate 1	CRS-1HP	Rate 2	77.0
Agg-3M	Rate 1	CRS-2P	Rate 2	77.8
Agg-1T	Rate 1	CRS-2P	Rate 1	78.9
Agg-1T	Rate 2	CRS-1HP	Rate 2	78.5

3.5.3 Rut Test Results Analysis

In this section, embedment of aggregate results from the modified sand circle method and rut test results have been studied using two-way ANOVA.

Independent variables in this analysis are shown below:

Aggregates Type: Agg-1T, Agg-2C, Agg-3M & Agg-4N

Aggregate Spread Rate: Two rates for each type of aggregate

Emulsion: CRS-1HP & CRS-2P

Emulsion Spread Rate: 220 gm & 230 gm

The ANOVA model for this experiment is

$$Y_{ijk} = \mu + A_i + E_j + (AE)_{ij} + \varepsilon_{ijk}$$

where Y_{ijk} = number of wheel passes or percentage of embedment, μ = mean wheel passing or percentage of embedment, A_i = effect of aggregate with specific rate i, E_j = effect of emulsion with specific rate j, $(AE)_{ij}$ = effect of aggregate and emulsion interaction, and e_{ijk} = random error. The results are shown in Table 3.23. Interaction between aggregate and emulsion for rutting is not significant at the 5% significance level. Even the effect of emulsion is not significant. Therefore, only the main effect of aggregate has been considered.

Table 3.23 Rut Test SAS Output

```
Dependent Variable: Wheel Passes
R-Square: 0.82158
                       Sum of
Source      DF    Squares         Mean Square    F Value    Pr > F
Model       31    1248049817      40259672       3.12       0.0010
Error       32    412507038       12890845
Source      DF    Type I SS       Mean Square    F Value    Pr > F
agg         7     820827223.4     117261031.9    9.10       <.0001
emlsn       3     38654080.7      12884693.6     1.00       0.4057
agg*emlsn   21    388568512.8     18503262.5     1.44       0.1741
```

Figure 3.15 shows that both rates of Agg-1T and rate 2 of Agg-3M meet the criteria set for the rutting test. It is evident that rutting depends on the aggregate abrasion resistance. Aggregate interlocking might be another factor because both Agg-1T and Agg-3M have rough surfaces and offer good interlocking, whereas Agg-2C and Agg-4N are almost rounded. Agg-1T shows the lowest abrasion loss (19%) among all aggregates used in this study. Although all four aggregates meet KDOT requirements for maximum abrasion loss (30 %), Agg-1T loss is below this limit. Considering both aggregate retention and rutting tests, it can be concluded that Agg-1T behavior is most contradictory i.e., it shows better performance in rutting tests but does worse in the sweep test.

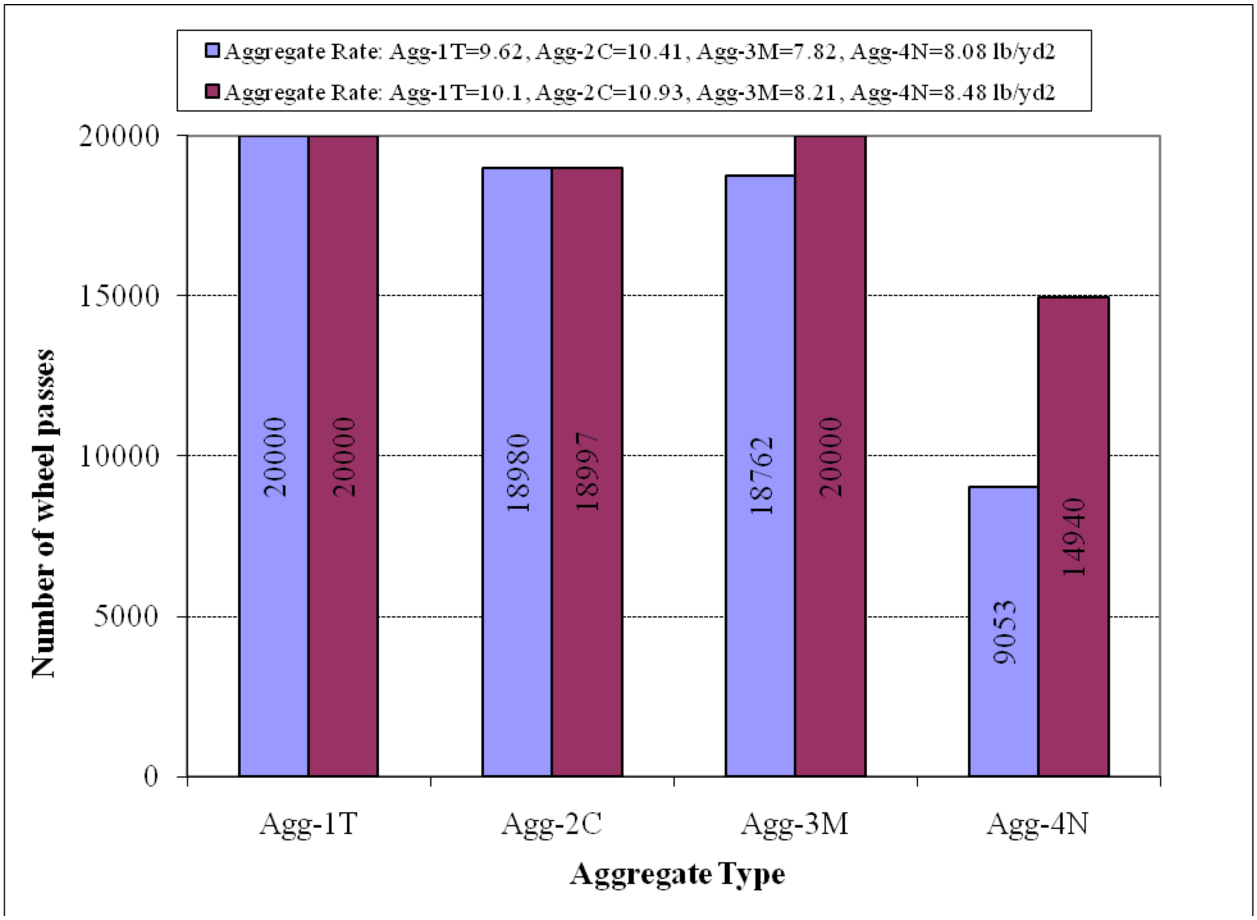


Figure 3.15 Variation of Number of Wheel Passes for Different Aggregates and Rates

CHAPTER 4 - CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This research presents a study of chip seal with lightweight aggregate and asphalt emulsion. Aggregate retention, aggregate embedment depth, and rutting were evaluated. A modified sweep test setup was developed to evaluate aggregate-emulsion compatibility. Use of appropriate combinations of asphalt and aggregate can result in better chip seal and thereby, turn into significant savings in pavement life-cycle costs. This study showed that surface chemistry of aggregate plays a significant role in the adhesion of asphalt emulsion. The following conclusions can be drawn from this study:

a) Selection of binder should be based on aggregate-emulsion compatibility to reduce loss of aggregate particles, which is a major concern for chip seal.

b) Optimum binder requirements greatly differ from the rate estimated in the current KDOT construction manual.

c) Binder quantity estimated from the modified Kearby method may be used as the theoretical rate and would require adjustment in the field.

d) Expanded shale and slate from Colorado performs better in rutting tests but not in sweep tests. The opposite is true for the expanded shale from Missouri. Moisture content encourages stripping, and hardness provides rutting resistance.

e) Sixty to 70% embedment of aggregates can be obtained using currently designed aggregate and emulsion rates.

f) Aggregate surface charge plays a significant role in retention of chip seal.

g) Aggregate and asphalt emulsion with opposite electric charges show less aggregate loss in the ASTM sweep test.

h) Although statistically no significant difference was found, all aggregate-emulsion combinations show higher aggregate loss when saturated surface dry (SSD) aggregates were tested.

i) The modified sweep test developed in this study results in a more uniform asphalt emulsion application. Although the proposed test shows higher aggregate loss than the ASTM sweep test, test results explain the variability better than outputs from the standard ASTM sweep test.

4.2 Recommendations

a) Further studies need to be conducted with field experiments to determine actual behavior of chip seal with the aggregate-emulsion combination and rates used in this study.

b) Sweep test aggregate spreading needs to be automated, and this will reduce variability of mass loss.

c) Tests for macrotexture require quantifying road conditions. This result can then be used as input for the chip seal design, and this may determine the correct rate of asphalt binder.

d) Inclusion of existing pavement’s texture depth in chip seal design required to be studied to better estimate asphalt binder application rate.

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Appendix A - ASTM Sweep Test Data

Table A.1 ASTM Sweep Test Data (Dry Aggregate)

	Sample No	Felt Disk Wt. C (gm)	Amount of Aggregate (gm)	Mass of Sample, gm	Applied Emulsion wt. (gm)	Initial Specimen wt. A (gm)	Final Specimen wt. B (gm)	% Mass Loss
Agg-1T & CRS-1HP	1	51	261	392.8	80.8	356.9	276	35.17
	2	50.3	261	391.9	80.6	359.3	277.5	35.21
	3	50.8	261	397.4	85.6	362.4	271.1	38.97
	4	50.5	261	395.8	84.3	349.3	269.9	35.34
	5	50.6	261	390.4	78.8	360.2	270.5	38.53
	6	50.5	261	398.8	87.3	355.4	278.6	33.50
	7	51	261	393.8	81.8	352.8	275.4	34.11
	8	50.7	261	394.1	82.4	357	286.2	30.74
Agg-1T & CRS-2P	1	50.5	261	397.4	85.9	372.1	302.5	28.78
	2	50.6	261	392	80.4	362.9	300.4	26.62
	3	50.9	261	396.8	84.9	370.4	310.7	24.85
	4	51.1	261	398.2	86.1	376.8	312.2	26.38
	5	51.2	261	392.2	80	368.6	299.7	28.87
	6	50.6	261	398.6	87	370.1	292.5	32.30
	7	50.7	261	393.3	81.6	375.1	308.1	27.47
	8	51	261	396.8	84.8	360.6	298.5	26.68
Agg-2C & CRS-1HP	1	50.5	267	392.2	74.7	357.5	286.9	30.59
	2	50.7	267	388.2	70.5	360.3	281.7	33.77
	3	50.6	267	390.1	72.5	362.3	279.7	35.24
	4	50.6	267	389.2	71.6	358.8	283.2	32.62
	5	50.7	267	393.1	75.4	361.5	287.7	31.58
	6	50.7	267	387.8	70.1	359.2	287.2	31.04
	7	50.5	267	388.5	71	358.1	289.1	29.83
	8	50.8	267	388.9	71.1	360.1	284.4	32.55
Agg-2C & CRS-2P	1	50.9	267	392.8	74.9	374.3	295.2	32.53
	2	51.2	267	399.9	81.7	366.7	294.5	30.44
	3	51.2	267	398.4	80.2	370.4	300.2	29.25
	4	51.4	267	396.6	78.2	368.6	305.3	26.54
	5	51.5	267	393.1	74.6	371.4	290.4	33.68
	6	51.4	267	394.3	75.9	374.1	289.1	35.03
	7	51.2	267	397.3	79.1	375.1	299.6	31.00
	8	51.4	267	398.5	80.1	369.2	288.4	33.81

	Sample No	Felt Disk Wt. C (gm)	Amount of Aggregate (gm)	Mass of Sample, gm	Applied Emulsion wt. (gm)	Initial Specimen wt. A (gm)	Final Specimen wt. B (gm)	% Mass Loss
Agg-3M & CRS-1HP	1	50.2	217	356.4	89.2	319.8	267.1	26.00
	2	50.4	217	357.1	89.7	321.3	266.5	26.90
	3	50.7	217	357.8	90.1	325.6	260.1	31.69
	4	51	217	360.3	92.3	322.1	269.6	25.76
	5	50.9	217	355.1	87.2	320.4	275.2	22.31
	6	50.8	217	359.6	91.8	318.2	262.7	27.60
	7	51	217	360.7	92.7	317.9	268.8	24.47
	8	50.8	217	356.1	88.3	320	265.2	27.07
Agg-3M & CRS-2P	1	51.3	217	355.2	86.9	325.8	251.8	35.85
	2	51.3	217	354.3	86	325.7	248.4	37.47
	3	51.4	217	356.8	88.4	332.9	257.4	35.67
	4	50.7	217	358.3	90.6	338.2	269.5	31.78
	5	51.1	217	355.7	87.6	330.8	250.5	38.18
	6	51	217	360.3	92.3	331.4	253.7	36.85
	7	50.9	217	359.5	91.6	320.4	242.7	38.35
	8	50.9	217	357.9	90	333.9	250.8	39.05
Agg-4N & CRS-1HP	1	50.4	201	339.3	87.9	308.4	264.8	22.48
	2	50.9	201	342.6	90.7	315.8	272.8	21.59
	3	50.6	201	340.7	89.1	310.2	267.3	21.98
	4	50.4	201	341.1	89.7	312.7	276.8	18.20
	5	50.4	201	345.4	94	310.8	268.3	21.71
	6	50.8	201	342.7	90.9	308.7	259.5	25.37
	7	50.3	201	338.9	87.6	304.8	258.9	23.99
	8	50.5	201	336.5	85	311.3	270.7	20.70
Agg-4N & CRS-2P	1	51.3	201	328	75.7	301.3	247.1	28.83
	2	51.3	201	336.9	84.6	314.6	267.8	23.64
	3	51	201	330.9	78.9	312.3	258.1	27.59
	4	51.1	201	331.6	79.5	309.7	260.3	25.41
	5	50.7	201	335.5	83.8	310.7	252.5	29.77
	6	50.4	201	329.4	78	309.3	254.6	28.10
	7	51.3	201	328.2	75.9	306.6	258.4	25.11
	8	50.6	201	336.1	84.5	308.4	267.6	21.05

Table A.2 ASTM Sweep Test Data (Saturated Surface Dry Aggregate)

	Sample No	Felt Disk Wt., C (gm)	Mass of Sample, (gm)	Initial Specimen Wt. A,(gm)	Final Specimen Wt. B, (gm)	% Mass Loss
Agg-1T & CRS-1HP	1	50.4	428.8	377.5	289.4	35.82
	2	50.8	431.7	383.8	285.7	39.18
	3	50.7	432.8	395	301.4	36.16
	4	50.2	432.5	386.5	286.7	39.47
	5	51.9	430.7	399.9	326.3	28.13
	6	51.4	429.6	388.8	313.4	29.72
	7	51	431.7	405.3	324.2	30.44
	8	51.2	431.9	398.7	330.8	25.99
	9	51.3	430.6	395	321.8	28.33
Agg-1T & CRS-2P	1	51.3	430.6	396	321.9	28.59
	2	50.7	432.2	394.2	326.3	26.29
	3	49.8	427	395.1	334.9	23.19
	4	49.9	431.6	394.9	344.5	19.43
	5	51	430.3	396.1	331.9	24.74
	6	50.7	430.6	399.1	316.7	31.46
	7	50.5	430.7	398.8	335.4	24.21
	8	50.7	427.7	394.6	338.1	21.85
Agg-2C & CRS-1HP	1	50.7	441.9	392.5	332.2	23.46
	2	50.3	438.2	393.8	326.4	26.10
	3	50.2	442.5	400.2	321.2	30.02
	4	50.2	445	398.3	323.5	28.58
	5	50.7	439.4	392.3	313.1	30.84
	6	50.3	435.2	397.6	316	31.25
	7	50.3	442.4	393	315.8	29.96
	8	50.2	443.3	394.1	313.5	31.17
Agg-2C & CRS-2P	1	51.2	433.6	403	335.4	25.56
	2	51.4	436.3	384.5	313.9	28.19
	3	50.8	444.4	407.7	342.5	24.30
	4	51.2	441.8	412.2	352.9	21.85
	5	50.9	438.1	415.6	356	21.74
	6	50.7	433	411.7	351.1	22.33
	7	51.3	451.4	407.3	352.3	20.55
	8	50.8	446.6	410.9	349.6	22.64
M & CRS	1	50.3	383.1	341.2	266.7	34.06

	Sample No	Felt Disk Wt., C (gm)	Mass of Sample, (gm)	Initial Specimen Wt. A,(gm)	Final Specimen Wt. B, (gm)	% Mass Loss
	2	49.9	385.9	343.9	266.6	34.97
	3	50.3	390.2	345.1	272.1	32.93
	4	50.3	385.4	342	275.9	30.14
	5	50.2	381.4	336.4	264.6	33.37
	6	50.3	384.5	340.9	279.1	28.28
	7	50.3	383.8	346.8	283.6	28.35
	8	50.1	381.5	349.5	287.9	27.36
Agg-3M & CRS-2P	1	50.9	385.1	354.3	279.9	32.61
	2	51.2	383	349.8	283.8	29.40
	3	51	390.3	359	277.2	35.32
	4	51.2	389.2	355	280.4	32.66
	5	51.1	383.7	353.7	276.3	34.02
	6	51.1	386.2	352	271.2	35.71
	7	50.8	385.7	356.7	289.1	29.39
	8	50.9	383.2	350.8	283.5	29.85
Agg-4N & CRS-1HP	1	50	349.4	317.3	267.4	24.83
	2	50.6	334.8	312.2	271.6	20.64
	3	50.5	354.8	320.1	268.5	25.46
	4	50.4	356.6	320.3	274.9	22.37
	5	50.6	363.6	330.6	275.9	25.98
	6	50.5	364.2	332.3	279.8	24.78
	7	50.6	368.1	338	283.9	25.04
	8	50.1	362.5	328.6	280.2	23.11
Agg-4N & CRS-2P	1	49.9	355.2	328.3	275.5	25.22
	2	49.7	355.4	325.8	267.7	27.99
	3	49.6	362.3	330.5	272.2	27.60
	4	49.9	354.2	324.8	268.5	27.24
	5	50.8	356.1	329.6	274.8	26.14
	6	50.5	362.7	333.5	271.8	29.00
	7	49.6	359.9	336.4	276.7	27.69
	8	49.6	356.2	326.9	263.8	30.26

Appendix B - Modified Sweep Test Data

Table B.1 Modified Sweep Test Data

	Sample No	Felt Disk Wt. C (gm)	Aggregate Wt. (gm)	Mass of sample, gm	Emulsion Wt. (gm)	Initial Specimen Wt. A (gm)	Final Specimen Wt. B (gm)	% Mass Loss
Agg-1T & CRS-1HP	1	44.2	200	302.7	58.5	290.3	219.3	38.37
	2	44.2	200	312.4	68.2	288.6	223.9	35.21
	3	44.5	200	309.4	64.9	284.1	215.1	38.30
	4	44.6	200	307.3	62.7	292.5	228.9	34.12
	5	44.4	200	311.4	67	280.7	215.5	36.70
	6	44.3	200	305.7	61.4	291.4	222.6	37.03
	7	44.1	200	309.5	65.4	275.9	212.4	36.43
	8	44.6	200	310.1	65.5	293.5	223.2	37.56
Agg-1T & CRS-2P	1	44.6	200	307.4	62.8	298.6	222.1	40.06
	2	44.6	200	310.2	65.6	290.1	210.4	43.18
	3	44.3	200	303.5	59.2	287.3	207.2	43.84
	4	44.2	200	304.7	60.5	280.4	205.3	42.29
	5	44.1	200	312.2	68.1	295.6	218	41.04
	6	44.5	200	310.6	66.1	292.1	218.5	39.53
	7	44.5	200	308.3	63.8	288.7	210.1	42.81
	8	44.4	200	305.8	61.4	285.9	213.7	39.76
Agg-2C & CRS-1HP	1	44.6	236	345.8	65.2	320.5	258.9	29.69
	2	44.7	236	348.2	67.5	322.3	257.7	30.95
	3	44.5	236	346.7	66.2	327.6	263.7	30.02
	4	44.6	236	344.8	64.2	318.2	261.5	27.56
	5	44.6	236	346.1	65.5	315.4	255.6	29.37
	6	44.3	236	348.3	68	321.6	258.3	30.36
	7	44.5	236	347.3	66.8	312.1	257.1	27.34
	8	44.6	236	345.5	64.9	319.3	258.4	29.49
Agg-2C & CRS-2P	1	44.3	236	341.7	61.4	332.7	228.5	48.05
	2	44.2	236	346.4	66.2	330.5	222.3	50.26
	3	44.2	236	344.8	64.6	325.7	217.2	51.26
	4	44.2	236	340.2	60	320.3	210.9	52.70
	5	44.5	236	348.5	68	330.4	223.3	49.82
	6	44.6	236	342.7	62.1	331.6	226.1	48.89
	7	44.6	236	343.8	63.2	328.5	220.6	50.55

	Sample No	Felt Disk Wt. C (gm)	Aggregate Wt. (gm)	Mass of sample, gm	Emulsion Wt. (gm)	Initial Specimen Wt. A (gm)	Final Specimen Wt. B (gm)	% Mass Loss
	8	44.3	236	343.2	62.9	333.1	227.4	48.68
Agg-3M & CRS-1HP	1	44.5	155	264.8	65.3	230	150.6	56.93
	2	44.6	155	261.9	62.3	221.7	148.4	55.05
	3	44.4	155	269.9	70.5	230.5	156.3	53.03
	4	44.3	155	263.4	64.1	225.7	145.6	58.73
	5	44.6	155	266.5	66.9	241.3	161.2	54.16
	6	44.6	155	263.1	63.5	233.5	154.7	55.48
	7	44.5	155	258.2	58.7	220.6	149.8	53.47
	8	44.2	155	257.5	58.3	236.7	159.4	53.41
Agg-3M & CRS-2P	1	44.6	155	262.7	63.1	218.9	160.3	44.71
	2	44.6	155	258.6	59	225.6	163	46.00
	3	44.3	155	269.1	69.8	230.5	163.7	47.71
	4	44.5	155	255.1	55.6	238.8	166.7	49.35
	5	44.6	155	259.4	59.8	225.1	160.3	47.75
	6	44.4	155	261.8	62.4	240.3	173.9	45.08
	7	44.5	155	266.8	67.3	228.2	163.7	46.70
	8	44.5	155	261.5	62	233.4	170.8	44.08
Agg-4N & CRS-1HP	1	44.6	155	265.1	65.5	240.2	186.7	36.38
	2	44.2	155	262.6	63.4	233.7	182.8	35.72
	3	44.5	155	264.6	65.1	230.6	175.7	39.24
	4	44.4	155	266.3	66.9	245.5	190.8	36.18
	5	44.6	155	267.4	67.8	244.4	186.3	38.68
	6	44.6	155	263.7	64.1	237.8	180.5	39.45
	7	44.3	155	266.1	66.8	232.7	183.9	34.45
	8	44.5	155	264.5	65	242.6	189.7	35.52
AAgg-4N & CRS-2P	1	44.2	155	261.9	62.7	245.3	169.7	50.00
	2	44.4	155	265.8	66.4	250.7	168.8	52.80
	3	44.4	155	257.1	57.7	240.7	165.1	51.22
	4	44.6	155	260.5	60.9	241.9	167.3	50.29
	5	44.3	155	263.9	64.6	250.3	172.5	50.23
	6	44.4	155	262.7	63.3	242.6	162.6	53.68
	7	44.6	155	266.6	67	241.4	165.4	51.36
	8	44.1	155	260.5	61.4	237.4	166.6	48.71

Appendix C - Rut Test Data

Table C.1 Rut Test Data

	Aggregate Amount, gm	Emulsion Amount, gm	Height of Chip Seal, mm	Mass of Sand to Fill Void & Ring,gm,W2	Mass of Sand to Fill Voids,W2-W1, gm	Embedment Depth, mm	% Embedment	Rut Depth(mm)	Wheel Passing	Water Temperature, °C
Agg-2C & CRS-1HP	478	220	6.7	317.1	32.1	4.83	72.0	6.715	12090	35
	478	220	6.7	316.1	31.1	4.88	72.9	3.975	20000	35
	501	220	6.7	311.3	26.3	5.16	77.1	6.297	20000	35
	501	220	6.7	312.7	27.7	5.08	75.9	2.782	20000	35
	478	230	6.7	315	30	4.95	73.9	3.452	20000	35
	478	230	6.7	307	22	5.42	80.8	4.406	20000	35
	501	230	6.7	316.8	31.8	4.84	72.3	6.858	12282	35
	501	230	6.7	315.4	30.4	4.93	73.5	2.463	20000	35
Agg-2C & CRS-2P	478	220	6.7	317	32	4.83	72.1	6.718	19850	35
	478	220	6.7	324.7	39.7	4.38	65.4	6.565	20000	35
	501	220	6.7	311.9	26.9	5.13	76.6	4.724	20000	35
	501	220	6.7	318.5	33.5	4.74	70.8	2.379	20000	35
	478	230	6.7	320.3	35.3	4.64	69.2	6.718	19900	35
	478	230	6.7	315.4	30.4	4.93	73.5	3.028	20000	35
	501	230	6.7	322.3	37.3	4.52	67.5	6.565	19700	35
	501	230	6.7	326.6	41.6	4.27	63.8	1.839	20000	35
Agg-3M & CRS-1HP	380	220	6.4	315	30	4.65	72.6	2.654	20000	35
	380	220	6.4	321.6	36.6	4.26	66.6	6.305	20000	35
	400	220	6.4	326.5	41.5	3.98	62.2	3.632	20000	35
	400	220	6.4	313.5	28.5	4.74	74.0	5.334	20000	35
	380	230	6.4	311.2	26.2	4.87	76.1	4.564	20000	35
	380	230	6.4	309.2	24.2	4.99	77.9	6.552	13446	35
	400	230	6.4	317.1	32.1	4.53	70.7	4.991	20000	35
	400	230	6.4	313	28	4.77	74.5	5.572	20000	35

	Aggregate Amount, gm	Emulsion Amount, gm	Height of Chip Seal, mm	Mass of Sand to Fill Void & Ring,gm,W2	Mass of Sand to Fill Voids,W2-W1, gm	Embedment Depth, mm	% Embedment	Rut Depth(mm)	Wheel Passing	Water Temperature, °C
Agg-3M & CRS-2P	380	220	6.4	317.5	32.5	4.50	70.4	5.804	20000	35
	380	220	6.4	320.6	35.6	4.32	67.5	5.982	20000	35
	400	220	6.4	321.5	36.5	4.27	66.7	5.372	20000	35
	400	220	6.4	319.3	34.3	4.40	68.7	5.232	20000	35
	380	230	6.4	307.5	22.5	5.09	79.5	4.453	20000	35
	380	230	6.4	311.2	26.2	4.87	76.1	6.591	16650	35
	400	230	6.4	317.2	32.2	4.52	70.6	3.048	20000	35
	400	230	6.4	323.3	38.3	4.16	65.1	5.600	20000	35
Agg-4N & CRS-1HP	370.7	220	6.5	315.4	30.4	4.73	72.7	6.796	1618	35
	370.7	220	6.5	321.4	36.4	4.38	67.3	6.502	10458	35
	389.7	220	6.5	319.7	34.7	4.47	68.8	6.629	17000	35
	389.7	220	6.5	320.8	35.8	4.41	67.9	5.753	20000	35
	370.7	231	6.5	318	33	4.57	70.4	6.551	2848	35
	370.7	231	6.5	312.6	27.6	4.89	75.2	5.654	19650	35
	389.7	231	6.5	328.2	43.2	3.98	61.2	5.562	20000	35
	389.7	231	6.5	323.4	38.4	4.26	65.5	4.260	20000	35
Agg-4N & CRS-2P	370.7	220	6.5	325.1	40.1	4.16	64.0	6.515	544	35
	370.7	220	6.5	318.2	33.2	4.56	70.2	6.502	6110	35
	389.7	220	6.5	322.2	37.2	4.33	66.6	6.594	5124	35
	389.7	220	6.5	314.6	29.6	4.77	73.4			35
	370.7	230	6.5	316.8	31.8	4.64	71.4	6.572	11550	35
	370.7	230	6.5	311.3	26.3	4.96	76.4	6.464	19650	35
	389.7	230	6.5	313.3	28.3	4.85	74.6	6.407	7400	35
	389.7	230	6.5	308.5	23.5	5.13	78.9	5.334	20000	35
Agg-1T & CRS-1HP	441	220	6.5	323.1	38.1	4.28	65.8	3.556	20000	35
	441	220	6.5	319.9	34.9	4.46	68.7	3.149	20000	35
	463	220	6.5	327	42	4.05	62.3	0.014	20000	35
	463	220	6.5	325.2	40.2	4.15	63.9	3.937	20000	35
	441	230	6.5	314.3	29.3	4.79	73.7	3.289	20000	35
	441	230	6.5	314.1	29.1	4.80	73.9	4.667	20000	35
	463	230	6.5	306.4	21.4	5.25	80.8	2.616	20000	35

	Aggregate Amount, gm	Emulsion Amount, gm	Height of Chip Seal, mm	Mass of Sand to Fill Void & Ring,gm,W2	Mass of Sand to Fill Voids,W2-W1, gm	Embedment Depth, mm	% Embedment	Rut Depth(mm)	Wheel Passing	Water Temperature, °C
	463	230	6.5	311.5	26.5	4.95	76.2	5.588	20000	35
Agg-1T & CRS-2P	441	220	6.5	310.6	25.6	5.01	77.0	2.413	20000	35
	441	220	6.5	306.5	21.5	5.25	80.7	4.264	20000	35
	463	220	6.5	307.3	22.3	5.20	80.0	2.616	20000	35
	463	220	6.5	315.1	30.1	4.74	73.0	5.957	20000	35
	441	230	6.5	314.2	29.2	4.80	73.8	3.353	20000	35
	441	230	6.5	305.6	20.6	5.30	81.5	5.258	20000	35
	463	230	6.5	312.7	27.7	4.88	75.1	1.549	20000	35
	463	230	6.5	308.9	23.9	5.10	78.5	4.572	20000	35