Report No. CDOT-2013-7
Final Report

PERFORMANCE OF CHIP SEALS USING LOCAL AND MINIMALLY PROCESSED AGGREGATES FOR PRESERVATION OF LOW TRAFFIC VOLUME ROADWAYS

Scott Shuler

July 2013

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

Technical Report Documentation Page

1. Report No. CDOT-2013-7	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PERFORMANCE OF CHIP SEALS USING LOCAL AND MINIMALLY PROCESSED AGGREGATES FOR PRESERVATION OF LOW TRAFFIC VOLUME ROADWAYS		5. Report Date July 2013
		6. Performing Organization Code
7. Author(s) Scott Shuler		8. Performing Organization Report No. CDOT-2013-7
9. Performing Organization Name and Address Colorado State University Ft. Collins, CO 80523-1584		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Colorado Department of Transportation - Research 4201 E. Arkansas Ave. Denver, CO 80222		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code 12.72

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract
This report documents the performance of two low traffic volume experimental chip seals constructed using locally available, minimally processed sand and gravel aggregates after four winters of service. The projects were constructed by CDOT maintenance personnel during the summer of 2009 using two sources of aggregate. These aggregates consisted of locally available products representing 1) materials routinely utilized and 2) materials that were marginal with respect to aggregate gradation and crushing requirements. An objective of this work was to evaluate the feasibility and cost/benefit of using aggregates in chip seals of lower quality than normally used with respect to gradation on low volume roadways. Because the cost of transporting high quality aggregates from front range sand and gravel and quarry locations to the eastern regions of Colorado is high and much of the pavement preservation activities in eastern Colorado are on low volume roadways, utilizing locally available aggregates would provide economic benefits if acceptable performance were demonstrated.

After four winters and three summers service both experimental chip seals are performing well. Condition surveys of each pavement were conducted after each winter and summer to document pavement condition. Results indicate that pavement distress is in the form of longitudinal and transverse cracking and localized flushing due to non-uniform asphalt emulsion application during construction. Based on results from the last condition survey, both test pavements should perform acceptably for the next several years assuming no significant change in traffic levels. No significant differences were measured in performance for any of the evaluation sections.

Implementation
It appears that locally available, minimally processed aggregates can be successfully applied as chip seal aggregate on low volume roadways.

17. Keywords low volume roadways, experimental chip seals, marginal aggregate chip seals, pavement preservation	18. Distribution Statement This document is available on CDOT's website http://www.coloradodot.info/programs/research/pdfs

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	96	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

Thanks to study panel members Gary DeWitt, CDOT Region 4 Materials; Masoud Ghaeli, CDOT R-6 Materials; Rex Goodrich, CDOT R-3 Materials; Roy Guevara, CDOT Materials and Geotechnical Branch; Donna Harmelink, FHWA Colorado Division; Neal Retzer, CDOT Materials and Geotechnical Branch; Gary Strome, CDOT R-4 Materials; and Roberto de Dios CDOT-DTD Research for coordinating the research and helping to establish the full scale test sections. Also, thanks are due to Byron Rogers and his crew of Region 4 Maintenance for constructing the test sections and helping to coordinate and construct the application of the different aggregates in the locations identified by the research team.

Thank you all.

EXECUTIVE SUMMARY

Many highways in Colorado are in locations with limited sources of high quality aggregates. Therefore, high quality aggregates must be transported to these locations when pavement construction or preservation activities are needed. This transportation increases the cost of pavement construction and preservation in these areas of the state. In the case of the chip seal aggregates utilized in this research, the cost difference represented an increase of 65 percent for the materials. This cost increase often mean that timely pavement preservation activities are postponed. This postponement leads to deterioration of the infrastructure and, ultimately, increased costs. In addition, many of the pavements requiring preservation are low volume facilities. These low volume roads may not require the very high quality aggregates necessary on higher traffic volume facilities. Therefore, if more economical local aggregates could be demonstrated to perform acceptably, pavement preservation could be accomplished within budget at appropriate intervals.

Chip seals are used extensively by CDOT for extending pavement life. Chip seals utilizing locally available and minimally processed aggregates should be a more economical pavement preservation treatment than chip seals constructed with higher quality, more expensive aggregates. Although chip seals constructed on high traffic roadways require high quality, crushed and approximately single-sized aggregates, low traffic roadways may not demand such materials to perform acceptably. Therefore, an experiment was designed to demonstrate the performance of chip seals constructed using two different aggregates on two low volume state highways. The control aggregate was the material routinely used for chip seal construction and the second aggregate was a material that was of lower quality with respect to gradation and fractured faces.

Construction of the test sections was conducted by CDOT maintenance forces in 2009. Condition surveys were performed to determine pre-chip seal condition and then periodically for the next three years to track performance.

Two five hundred foot long evaluation sections were located within each test pavement for each aggregate resulting in two thousand lane-feet of test area for each roadway.

Results of the experiment after three years of service indicate no significant difference in performance between the aggregates. Distress in both pavements is limited to a return of transverse and longitudinal cracks, but with low percentages of chip loss. Some limited areas of the pavements also contain longitudinal flushing streaks where distributor nozzles may not have been adjusted correctly and higher quantities of asphalt were applied.

Implementation

Based on this research, recommendations are provided regarding chip seal materials, design, and construction methods to be used for low traffic volume pavements. It appears that locally available, minimally processed aggregates can be successfully applied as chip seal aggregate on low volume roadways.

TABLE OF CONTENTS

INTRODUCTION

Many highways in Colorado are in locations without high quality aggregates. Therefore, high quality aggregates must be transported to these locations when pavement construction or preservation activities are needed. This transportation increases the cost of pavement construction and preservation in these parts of the state. Increased costs often mean that timely pavement preservation activities are postponed. This postponement leads to deterioration of the infrastructure and, ultimately, increased costs. In addition, many of the pavements requiring preservation are low volume facilities. These low volume roads may not require the very high quality aggregates necessary on higher traffic volume facilities. Therefore, if more economical local aggregates could be demonstrated to perform acceptably, pavement preservation could be accomplished at appropriate intervals and within budget. Both short and long term savings would result.

Chip seals are used extensively by CDOT for extending pavement life. Chip seals utilizing locally available and minimally processed aggregates may be a more economical pavement preservation treatment than chip seals constructed with higher quality, more expensive aggregates. Although chip seals constructed on high traffic roadways require high quality, crushed and approximately single-sized aggregates, low traffic roadways may not demand such materials to perform acceptably. Therefore, an experiment was designed to demonstrate the performance of chip seals constructed using two different aggregates on two low volume state highways. The control aggregate was the material routinely used for chip seal construction and the second aggregate was a material that did not meet specifications for gradation or fracture.

Objectives

1. Construct chip seal test and control sections using locally available and minimally processed aggregates and document the performance of these pavements for three consecutive years.
2. Develop and/or adopt monitoring and documentation procedures for evaluating the performance of the test sections.

3. Develop or adopt a design procedure, aggregate specifications, and construction guidelines for chip seals constructed with local, minimally processed aggregates on low traffic volume roadways.

LITERATURE REVIEW

There is a significant amount of information available on chip seal design, construction and performance. From two design methods by Hanson in New Zealand (Hanson, 1934-1935) and Kearby (Kearby, 1953) in Texas, most methods used today can be traced (McLeod, 1960, 1969; Potter and Church, 1976; Marais, 1981; Epps, 1981). These methods are essentially based on the concept that aggregate in a chip seal should be as one-sized as possible and that embedment of the aggregate in the asphalt binder should occupy a specific percentage of the aggregate dimension. How the aggregate dimension is determined and how the volume of asphalt binder is calculated vary between methods but usually require measuring the gradation of the aggregate in order to obtain the average least dimension (ALD) in the case of the Hanson method or the unit weight, specific gravity and spread quantity in the case of Kearby. The shape of the aggregate is considered important and is measured using the Flakiness Index in the case of the Hanson method and the percent embedment is varied as a function of traffic for both methods. However, although both of these methods are rational procedures, based on sound engineering principles, they have been shown to produce different results when applied to the same aggregates and emulsions on the same pavement (Shuler, 1998). An evaluation of the most evolved version of both design methods is proposed in the Research Plan to determine which design process should be recommended at the conclusion of this research.

Once the chip seal has been designed, how it performs during construction and in early life under traffic is the greatest concern. Loss of chips during construction leads to construction delays and loss of chips during early trafficking may lead to vehicular damage. Therefore, reducing this potential has been a focus of research. Benson (Benson and Gallaway, 1953) evaluated the effects of various factors on the retention of cover stone on chip seals. Among other factors this study evaluated the effects of cover stone and asphalt quantity, aggregate gradation, time between asphalt and aggregate application, and dust and moisture content of chips on retention of cover stone. The type of binder used in the chip seal can have an effect on performance. Studies have been conducted to measure binder viscosity as function of chip size, precoated or not, damp or dry (Kari, 1962; Major, 1965; Kandhal, 1991) and make recommendations regarding the optimum consistency for desired performance. In addition, the performance of the chip seal after long term trafficking can be affected by the properties of the cover stone and the substrate pavement. A process of evaluating the ability of the substrate pavement to resist chip penetration is practiced in the UK and Africa (Hitch, 1981; Colwill, et al., 1995). Predicting early chip retention has been done using laboratory abrasion tests, impact tests, and traffic simulators (Kari, 1965; Shuler, 1990; Stroup-Gardiner, 1990; Davis, 1991).

The performance of chip seals has been reported by many (Jackson, 1990; Sebaaly, 1995; Temple, 2003; Chen, 2003; Jahren, 2004; Gransberg, 2005).

Selecting Appropriate Pavement to Chip Seal

There is a need to identify when it is "best" to apply chip seals. Treatment performance is greatly dependent on the condition of the pavement at the time of treatment application, and different types of treatments are likely only to be effective when placed at certain times in a pavement's life. When placed at the right time, a chip seal becomes a cost-effective means of attaining the desired life and performance of the pavement. Chip seals applied too soon add little benefit and applied too late are ineffective. Although this general rule is self-evident, there is little available on specifics in the literature except ranges of time as shown in the table below for various seal coat methods.

Table 1. Summary of the Performance of Selected Preventive Maintenance Treatments for Asphalt Concrete Pavements. (Geoffroy, 1996).

TREATMENT		Pavement Age at Time of First Application (yrs)	Frequency of Application (yrs)	Observed Increase in Pavement Life (yrs)
Single Application Chip Seal	Min	<2	2-4	2-4
	Mode	7-8	5-6	5-6
	Max	15-20	9-10	7-8
Slurry Seal	Min	4-5	2-4	2-4
	Mode	5-6,7-8,9-10	5-6	5-6
	Max	9-10	7-8	7-8
Micro-Surfacing	Min	5-6	5-6	2-4
	Mode	9-10	5-6	5-6
	Max	10-15	9-10	7-8
Thin HMA Overlay	Min	5-6	2-4	>2
	Mode	9-10	9-10	7-8
	Max	15+	11-12	9-10

Further analysis by Geoffroy provides some indication of performance and cost for single application chip seals as shown in the table below.

Table 2. Single Application Chip Seal Performance and Cost Data. (Goeffroy, 1996).

STATE	Pavement Age at Time of First Application (yrs)	Frequency of Application (yrs)	Observed Increase in Pavement Life (yrs)	Cost per Lane Mile (dollars)
AL	7-8	7-8	2-4	5,000-6,999
AZ	7-8	7-8	2-4	7,000-9,999
IN	7-8	5-6	5-6	2,000-3,999
MD	9-10	5-6	5-6	4,000-4,999
NY	7-8	2-4	2-4	7,000-9,999
NC	7-8	5-6	5-6	5,000-6,999
PA	5-6	5-6	5-6	4,000-4,999
TN	>10	Varies	2-4	10,000-14,999

There are few studies that have successfully determined how to identify the optimal time to apply chip seals; although a number of completed studies have examined this issue and other research continues to study it (NCHRP Report 523, 2004).

One method for identifying timing is based on an analysis of benefit and costs. Timing that maximizes benefit while minimizing costs is the most effective timing scenario. To make the actual values of the benefits/costs (B/C) ratios more meaningful, the concept of an Effectiveness Index (EI) has been introduced (NCHRP Report 523, 2004). The EI normalizes all individually computed B/C ratios to a 0 to 100 scale by comparing all B/C ratios with the maximum individual B/C ratio (i.e., the ratio associated with the optimal timing scenario). The maximum individual B/C ratio is assigned an EI of 100, and all other B/C ratios are represented as a fraction of the maximum EI.

The EI is computed for each timing scenario using the following equation:

$$EI_i = \left[\frac{(B/C)_i}{(B/C)_{max}}\right] \times 100$$

where:

EI_i = EI associated with the *i*th timing scenario (dimensionless),

$(B/C)_i$ = B/C ratio associated with the *i*th timing scenario,

$(B/C)_{max}$ = Maximum of all of the B/C ratios associated with the different timing scenarios, and

i = Index associated with the current timing scenario (NCHRP Report 523, 2004).

Of course, identifying the benefit can be difficult to quantify, and without this, the above analysis has less utility.

Chip seals are applied to provide increased friction or to seal the surface of asphalt pavements to prevent moisture intrusion. Assuming moisture intrusion is be controlled the following decision tree has been proposed to determine when to use chip seals or other sealing methods. These authors suggest that for traffic over 5000 ADT, chip seals should not be used.

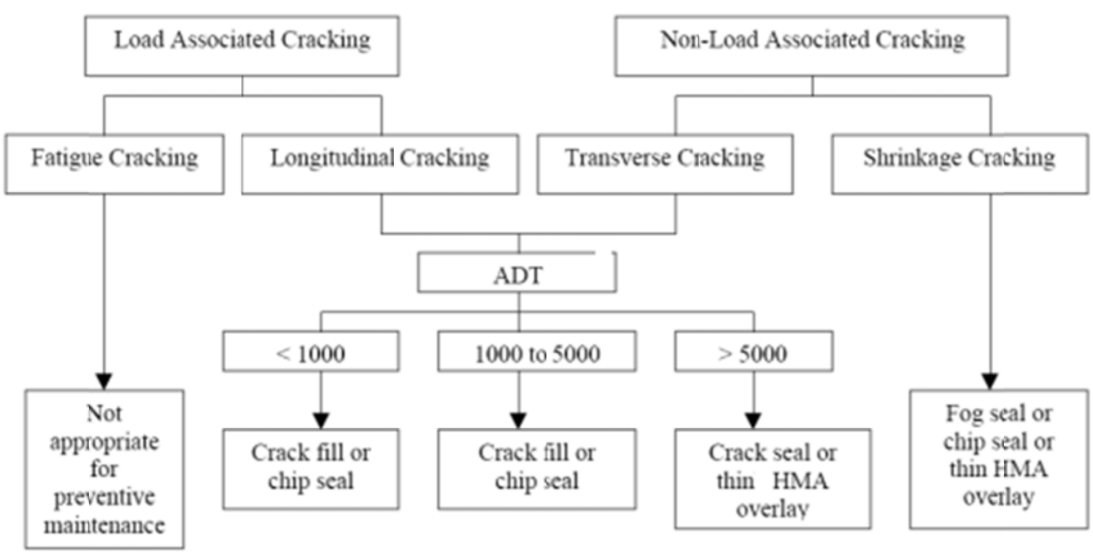


Figure 1. (Zimmerman, & Peshkin, 2003).

Al-Mansour and Sinha (1994) used regression analysis to determine a functional relationship between the immediate gain in PSI (pavement serviceability index) and the PSI at the time of application of a chip seal. The authors note that the immediate gain in PSI represents the change in PSI estimated within one year of undertaking a chip seal activity. The equation describing the relationship is:

$$\Delta PSI = 0.3325*(PSI - 1.433)$$

where:

ΔPSI = gain in pavement serviceability owing to chip seal activity, and

PSI = PSI at time of chip seal application.

Al-Mansour & Sinha (1994), developed a model for the cost (in $ per lane-mile) of performing a chip seal. The cost model is based on the pavement condition at the time the chip seal is performed. The logarithmic equation shown below is based on 34 observations and has a correlation coefficient (R^2) of 0.3079:

$$\text{Log } SC = 3.6101 + (-0.1034 * PSI)$$

where:

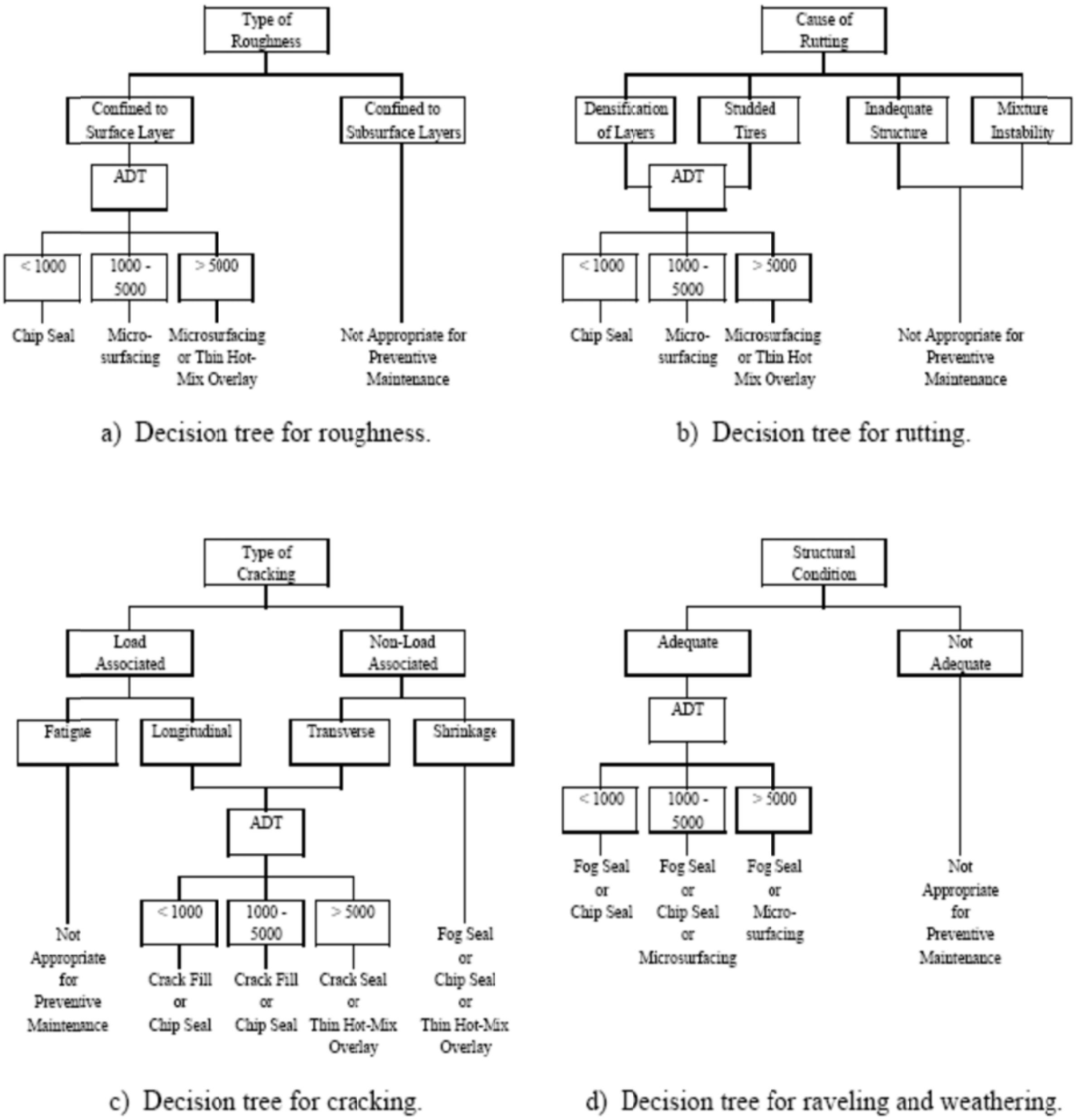
SC = cost of performing chip seal ($ per lane-mile), and

PSI = pavement serviceability index at time of chip seal.

A life cycle cost analysis was also performed in this study. The results showed that for optimal cost savings when considering total costs (agency costs and vehicle operating costs), chip seal applications should be applied before the PSI value drops below 3.0.

Abdullah, Sinha, & Kuczek found that chip or sand seals only provided adequate performance on low volume roads if applied at advanced stages in the pavement life.

Hicks, et al., provide the following decision tree for selection of various treatments depending on pavement condition. Again, note that chip seals are recommended only when traffic levels are below 5000 ADT.



a) Decision tree for roughness.

b) Decision tree for rutting.

c) Decision tree for cracking.

d) Decision tree for raveling and weathering.

Figure 2. Decision Tree for Selecting Preventive Maintenance Techniques (Hicks, et al., 2000)

A similar decision tree is offered by these authors depending on distress level as shown below:

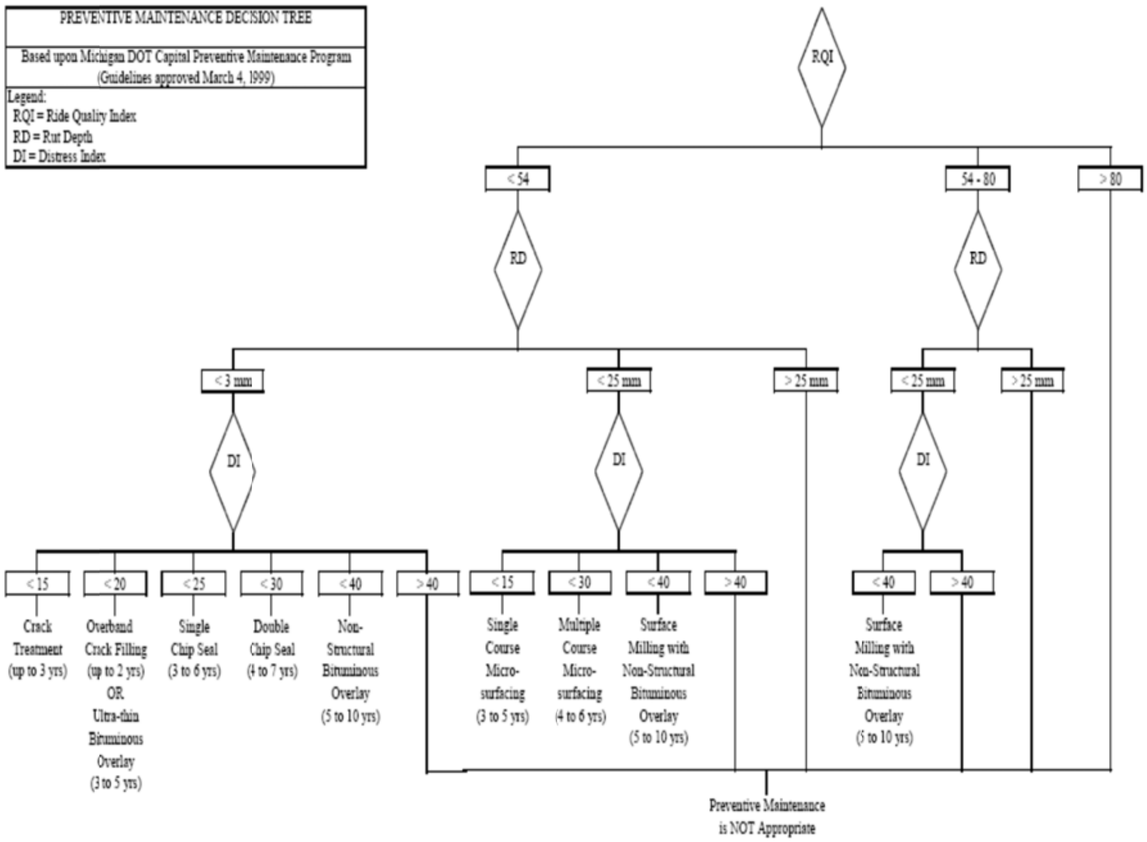


Figure 3. Distress Level Preventive Maintenance Decision Tree (Hicks, Seeds, & Peshkin, 2000)

The main criteria addressed by the varying chip seal types are:

- Conventional chip seals are used on structurally sound pavements with minimal cracking.
- Polymer-Modified Emulsion (PME) chip seals are used to correct raveling and pavement oxidation.
- Rubberized chip seals cure quickly, restore skid resistance on worn surfaces and resist reflection cracking.
- Special binders such as asphalt rubber and polymer modified asphalt may be used to address specific distress modes.
- Distresses such as cracking, flushing, and base failures cannot be addressed with conventional or hot applied chip seals.
- Deformation, rutting and shoving cannot be addressed with chip seals of any kind.

Table 3 lists appropriate binder/chip seal combinations for addressing various distress mechanisms. Generally, chip seals are not used on roads with AADT > 40,000.

Table 3. Binder/Chip Seal Combinations for Addressing Specific Distress Mechanisms (Caltrans Maintenance Technical Advisory Guide, 2003)

Binder/ Chip Seal Combination	Raveling	Aged Pavements	Bleeding/Flushing	Load Associated Cracks	Water Proofing	Climate Associated Cracks	Heavy Traffic Volumes	Stone Retention	Improve Skid Resistance
PME/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PME/Double	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PME/Sand	Yes	Yes	No	No	Yes	No	No (light)	Yes	No
PBA/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PBA/Double	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PBA/Sand	Yes	Yes	No	No	Yes	No	No	Yes	No
AR/SAM	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Rejuvenating Emulsion	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes

Once a pavement has been selected for a chip seal the following well known requirements are needed to optimize performance:

- Evaluate surface texture;
- Evaluate traffic conditions: volume, speed, percentage of trucks, etc;
- Evaluate climatic and seasonal characteristics;
- Evaluate and select type of chip seal;
- Evaluate aggregate selection;
- Determine binder application rate; and
- Determine how many hours per day are available for construction operations.

(from NCHRP Synthesis 342, 2005).

Rational Construction Practice

Binder Application

The residual binder application rate is one of the most important factors affecting chip seal performance. Enough binder must be present to hold the aggregate in place, but not so much that the binder fills, or is forced by traffic action to cover the aggregate. The proper amount of binder ensures the desired surface texture is maintained. Binder application rates can be determined based on the average least dimension of the aggregate, as well as other aggregate properties such as shape, density, absorption and grading. The optimum binder content also depends on how much binder flows into existing voids in the pavement, and how much binder is already present at or near the pavement surface (Caltrans Division of Maintenance, 2003).

It is most important that the distributor be properly adjusted and operated to uniformly apply the proper amount of asphalt. The bar and its nozzles must be properly set to obtain a uniform application. The nozzle size, spacing, and angle in relation to the bar determine the height of the bar (Washington State Department of Transportation, 2003).

If the binder is applied too heavily, flushing of the asphalt in the wheel paths will result. If applied too thin, excessive chip loss will result. Most distributors used today have computerized controls which can regulate the pressure of the material to compensate for the speed of the vehicle. This results in a constant application rate, regardless of travel speed. Two distributors are normally used on a seal coat project. This allows one to continue to work while the other is being refilled by the tanker (Janisch & Gaillard,1998).

Distributor speed for the desired asphalt rate can be calculated from following equation. Spray bar output is dependent on the type of the binder sprayer used. W is the width of the shot and is used interchangeably with x value in this calculation as x = W (Gransberg, et.al., 2004):

$$S_f = \frac{9G_t}{WR}$$

where:

S_f = distributor speed (ft/min),

G_t = spray bar output (gal/min),

W = sprayed width (ft),

R = rate of binder application (gal/ sy), and

9 = conversion factor from sy to sf.

In this analysis, the production rates of the chip spreader and asphalt distributor are taken to be equal as observed in practice (Gransberg et al., 1999). Therefore, the combined production rate of the system is expressed as the distributor production rate. If the stipulated minimum rolling time requirement was being strictly enforced on a TxDOT chip seal project, the rollers were observed to be lagging behind the asphalt distributor and aggregate spreader. If the equipment spread moved up to the next shot before the rollers had completed their linger time, the rollers tried to catch up, and failed to provide the minimum rolling time called for in the contract. The computations below prove that rollers cannot keep up with the distributor under the mentioned assumptions. This example shows it is extremely important that a sufficient numbers of rollers be available to provide a rolling production rate that matches or exceeds the production of the distributor (Gransberg, et al., 2004).

An accurate and uniform rate of application of bituminous binder is an important element in undertaking effective sprayed seal work. New procedures have now been introduced in Australia that set national standards for sprayer calibration and central administration of calibration test certificates. Figure 3 describes a procedure for the calibration and certification of bitumen sprayers in Australia. (Austroads work tips, 2002)

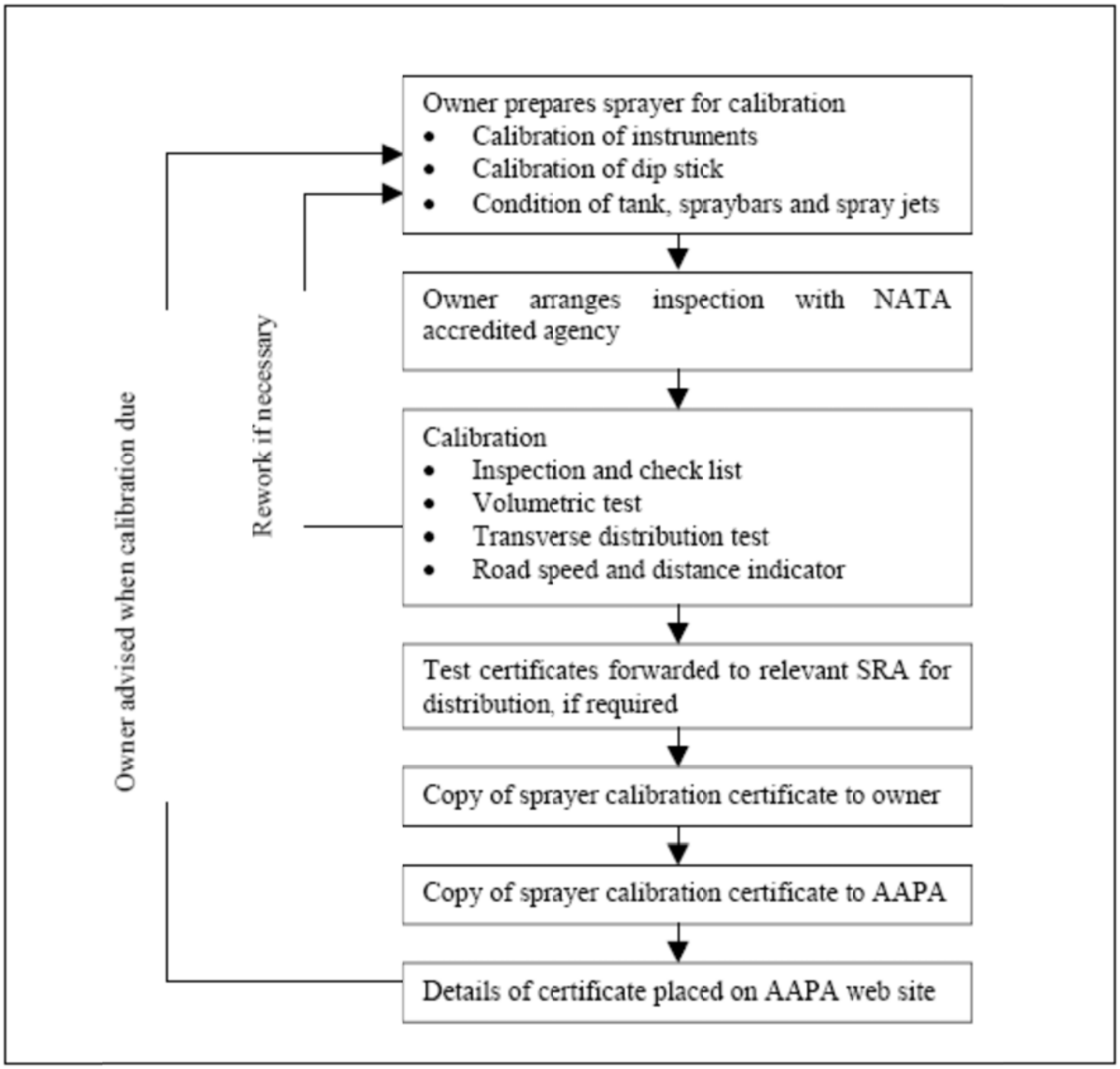


Figure 3. Calibration and Certification of Distributors in Australia

One study (Shuler, 1998) described the calibration of the nozzles inserted into contractor distributors. This study was based on the practice in the Brownwood District of the Texas DOT that provided specially machined, calibrated nozzles to contractors before chip seal operations could proceed.

One interesting study suggests that binder application rates should be increased by 10–15 per cent for fast or downhill traffic conditions and decreased by 10 per cent for slow or, uphill conditions (Hitch, 1981).

One method for estimating the binder content is as follows (Caltrans Division of Maintenance, 2003):

$$B = [0.40(H) \times T \times V + S + A + P] / R$$

where:

B = Binder Content (l/m2),

H = average least dimension (ALD) (m),

T = Traffic Factor,

V = Voids in Loose Aggregate (%),

S = Surface Condition Factor (l/m2),

A = Aggregate Absorption (l/m2),

P = Surface Hardness Correction for Soft Pavement (L/m2), and

R = Percent Binder in the Emulsion (%).

For projects in areas maintained by snowplows, the binder content is calculated using both the median particle size and the average least dimension (ALD). The average of these two results is used as the starting application rate in these areas (Caltrans Division of Maintenance, 2003)

Asphalt distributors must be calibrated and adjusted prior to chip seal operations to obtain a successful chip seal. Figures 4 and 5 show the influence of angle for nozzle discharge and the influence of spray bar height.

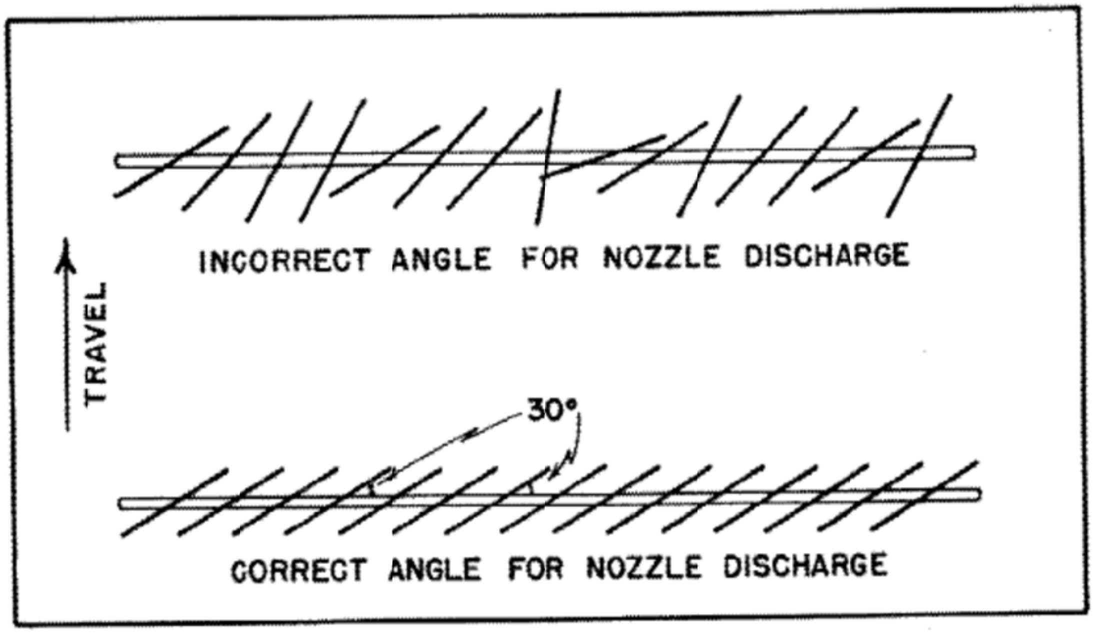


Figure 4. Influence of Angle for Nozzle Discharge (McLeod, 1960)

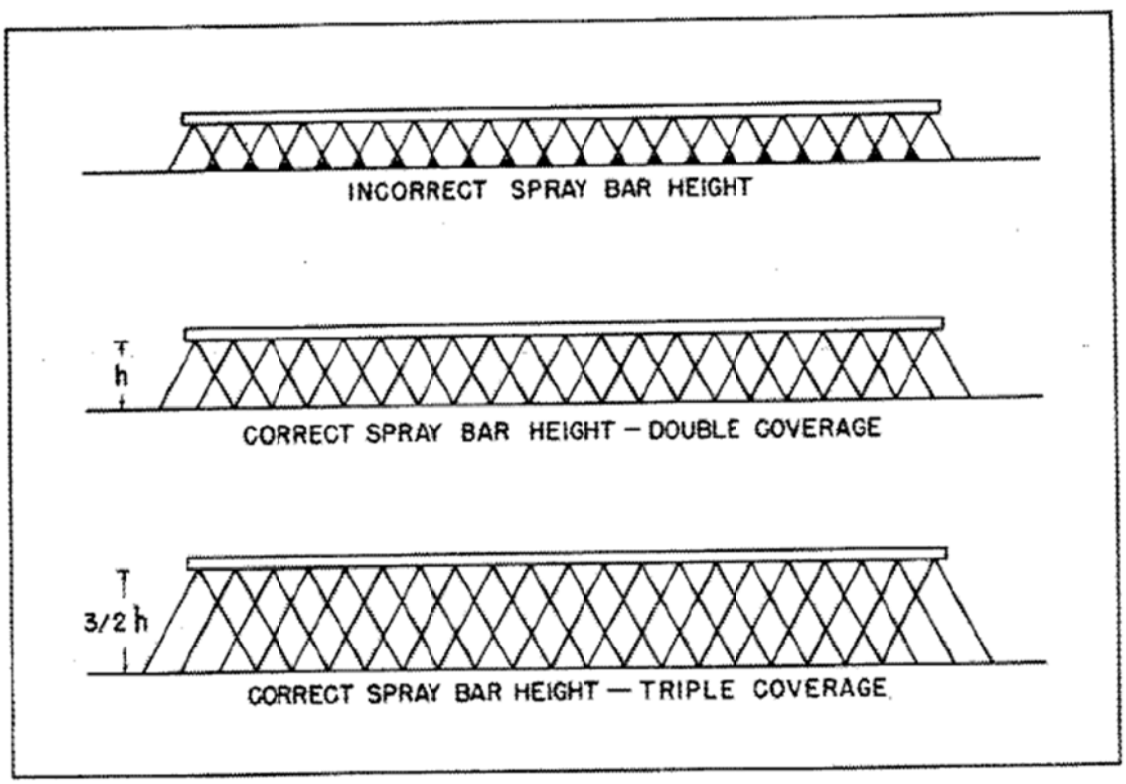


Figure 5. Influence of Spray Bar Height(McLeod, 1960)

Every bituminous distributor should be calibrated periodically. For highway departments whose specifications specifically require this calibration, the items calibrated or checked include the following:

- Distributor tank
- Pump
- Spray bar and spraying system
- Transverse distribution of binder applied by the spray bar
- Hydraulic pressure in the spray bar
- Road speed indicator
- Opening and closing of the spray bar
- Thermometer
- Field test for uniformity of bitumen application

The following are examples of the requirements of tolerances that have been specified for some of these items (McLeod, 1960):

- Pump output under all conditions shall not vary from the mean by more than ±5%.
- Hydraulic pressure in the spray bar when spraying shall not vary from any given predetermined pressure by more than ±5%.

Air Temperature

The success of a seal coating operation is highly dependent on the weather conditions while spraying the binder and the placing the aggregate. Asphalt emulsions break slowly in cold or damp conditions. An air temperature of 55^{o}F (10^{o}C) in the shade and rising is often used as guideline for seal coating (Croteau, et al., 2005).

Effects of weather can have a marked effect on the quality of a seal coat. These variations can be cool temperatures, hot temperatures, rain, wind, and variations can be cool temperatures, hot temperatures, rain, wind, and humidity (Washington State Department of Transportation, 2003).

Griffith, et al., 2000 quotes that initially, it was speculated that asphalt cement chip seals could be applied over a wider range of temperatures than emulsified asphalt seals. However, cool temperatures and pavement temperatures (under 13°C (55°F)) may impact embedment and bonding.

On the actual day when chip seals are constructed the weather should be clear and warm. In general, pavement surface temperatures should be 10°C (55°F) and rising, and the humidity should be 50% or lower (Caltrans Division of Maintenance, 2003).

Sealing in hot weather at air temperatures above 90^{o}F may create construction problems with emulsion chip seals. At these elevated temperatures, the asphalt is less viscous and does not develop full strength until cooler. Traffic control, pilot vehicles and a dry choke stone application also help protect new chip seals in hot weather (Washington State Department of Transportation, 2003).

Cool air or pavement temperatures (under 55-60^{o}F) can affect the binding characteristics of the asphalt by making it less tacky (sticky) and/or increasing its viscosity. This can result in a poorer bond between the existing pavement, the asphalt, and the rock. Further, it can reduce the embedment of the rock into the asphalt. In either case, it can result in extensive rock loss. A moderate increase of the asphalt application rate in cooler conditions improves rock retention, but increases the possibility of flushing or bleeding when the weather warms (Washington State Department of Transportation, 2003).

Seal coating must be postponed, if there is rain or the threat of rain. If it rains several steps may help save the seal: 1) close the road to traffic (impractical), 2) reduce the speed of traffic, or 3) apply additional cover stone (Washington State Department of Transportation, 2003). Any rainfall immediately before, during or after the construction of the chip seal will contribute to failure of the treatment. Thus, placement of chip seals should be avoided during such conditions (Caltrans Division of Maintenance, 2003).

Sealing during high winds should be discouraged. High winds can distort the spray pattern from the distributor and prevent a uniform asphalt application. High winds can blow dust onto the road surface to be sealed or onto fresh emulsion before the cover rock can be applied. Wind may cause the emulsion spray to be diverted and compromise uniformity of application rate. However, a gentle breeze will assist in accelerating cure times (Caltrans Division of Maintenance, 2003).

The set time for asphalt emulsions is increased when humidity is high. Late spring to early fall are the seasons most likely to have weather that is favorable for chip seal construction. Generally, there are also more daylight hours during this time of the year. Although daytime temperatures may be warm, cool overnight temperatures, typical during the spring and the fall and in mountainous areas, will increase the cure time for asphalt emulsions (Washington State Department of Transportation, 2003). Some recommendations for application temperatures for asphalt emulsions are shown below:

Table 4. Recommendations for Application Temperatures for Asphalt Emulsions (Washington DOT, 2003)

Emulsion Type	Distributor, min F	Distributor, max F
CSS-1, CSS-1h	70	140
CRS-1, CRS-2, RS-1, RS-2	125	185

It may be desirable to maintain the temperature somewhat below the maximum recommendation to reduce the danger of breaking the emulsions too soon (Washington State Department of Transportation, 2003).

Aggregate Spreading

An aggregate spreader is used to place a uniform application of cover aggregate onto the freshly applied asphalt emulsion. Aggregate spreaders are either self-propelled or attached to the dump truck tail gate. Some self-propelled aggregate spreaders have the capability of placing the aggregate onto the roadway at variable widths. The self-propelled spreader pulls the supply trucks. The aggregate is placed into a receiving hopper and it is conveyed towards the front of the machine to a system that drops the aggregate from a constant height onto the roadway (Croteau, et al., 2005).

The chip spreader must be able to apply a uniform, even layer of aggregate across the width of the pavement to be chipped. A study by Griffith, et al., 2000, mentions a chip spreader equipped with computerized controls that adjust the opening and closing of the gates based on the speed of the spreader (Griffith, et al., 2000).

Some specifications indicate the application of aggregate should follow the binder application by no more than 90 seconds in order to obtain the best aggregate retention. A good visual check is that the spreader should be no more than 100 feet (30 meters) behind the distributor truck (Caltrans Division of Maintenance, 2003). However, these recommendations may not always be true depending on weather and materials conditions. One method to determine when to apply chips is to cast a handful of chips onto the fresh emulsion surface. When the chips do not roll over on impact, but stick to the surface, the chip spreader should apply the chips.

Calculation of the design aggregate application rate is based on determining the amount of aggregate needed to create an even, single coat of chips on the pavement surface. The amount of cover aggregate required can be determined using the following equation (Caltrans Division of Maintenance, 2003):

$$C = (1 - 0.4V) \times H \times G \times E$$

where:

C = Cover Aggregate (kg/m^2),

V = Voids in Loose Aggregate (%),

H = ALD (mm) ,

G = Bulk Specific Gravity, and

E = Wastage Factor (%).

Another method, called the Board Method, uses a one square yard piece of plywood with 1 x 2 lumber nailed to the perimeter. The chips planned for use in the chip seal are spread onto the board one stone thick until no more chips can be squeezed onto the board. The board is weighed, and the amount of aggregate is calculated in pounds per square yard (Epps, et al. ,1981).

Gates on the aggregate spreader should be adjusted to apply a uniform application of aggregate. However, the gates in line with the wheel paths may be opened slightly more to give a heavier cover in these areas. This is the area of the greatest initial wheel loading. A slightly heavier aggregate cover prevents pick up on the wheels of the chip spreader and aggregate trucks. If there is an auger roller in the aggregate hopper it should not be bent or out of round. This can cause corrugations (Washington State Department of Transportation, 2003).

When constructing a seal coat, the cover aggregate should be applied so it is only one-layer thick. Applying too much aggregate not only increases the chance of windshield damage to passing vehicles but can also dislodge properly embedded stones. The exception to this is in areas where extensive stopping and turning movements take place, such as intersections and turn lanes. Using a slight excess of aggregate, about 5 or 10 percent, can help reduce the scuffing caused by vehicle tires turning on the fresh, uncured, seal coat. (Janisch & Gaillard1998).

Hitch, 1981, and others (Shuler, 1998) mention a procedure used to measure the rate of spread where light metal trays approximately 10 mm deep and $0.1m^2$ in area were used to check rates of spread. Three trays were placed for each 200m run of the distributor and the weight of binder deposited on each was recorded. The rate of spread, taken as the mean of three trays, assisted in the calibration of the machine and verified the rate of binder actually sprayed. The unsealed squares beneath the trays were repaired by hand in the earlier trials but subsequently they were mowed to remain thus providing a comparison between the original and the resealed surface. Unsealed squares were always repaired during work on new bases. The poor condition of some of the distributors sometimes prevented the required rates of spread from being obtained consistently.

To achieve maximum sustained production, the production rates of the chip spreader and the rollers must be greater than or equal to the sustained production rate of the distributor. The distributor controls the overall production because no other piece of equipment can begin to produce its function until the distributor has applied the binder to the surface. Therefore, to ensure a high standard of quality control, all other equipment systems must be able to keep up with the production of the distributor (Gransberg, et al., 2004). Observations in the field confirm that the distributor sets the pace for the rest of the equipment spread (Gransberg, et al., 1999).

Rolling

Rollers embed the aggregate into the asphalt binder and orient the chips on their flat side. It is important to have enough rollers to complete the rolling quickly. The chips need to be embedded into the emulsion before it 'breaks' or sets. Normally, a minimum of three rollers will be required. The first two, drive side-by-side rolling the outer edges. The third roller then follows closely behind, rolling the center of the lane. It is very important for the rollers to travel slowly, no more than 5 miles per hour (8 km/hr), so the chips are correctly embedded into the binder. (Janisch & Gaillard1998). Rolling can be standardized on the basis of certain number of roller passes, or a rolling time in hours, for each 250 gallons of binder sprayed (Potter & Church, 1976).

Pneumatic rollers are preferred for rolling chip seals because they tend not to fracture the rock and will roll into depressions or wheel ruts. Rolling of a seal coat is done to orient the rock. Rollers should be operated at speeds under 5 miles per hour so the rock is set, not displaced. The number of rollers required for a seal coat project depends on the spread of the operations. It takes two to four passes of the roller to set the rock. These rollers should have tire pressures of 45 psi or more (Washington State Department of Transportation, 2003)

Figure 6 shows the required number of rollers versus specified rolling linger time (1.0 yd^2/h 50.84 m^2/h) in a study by Gransberg, et al., 2004.

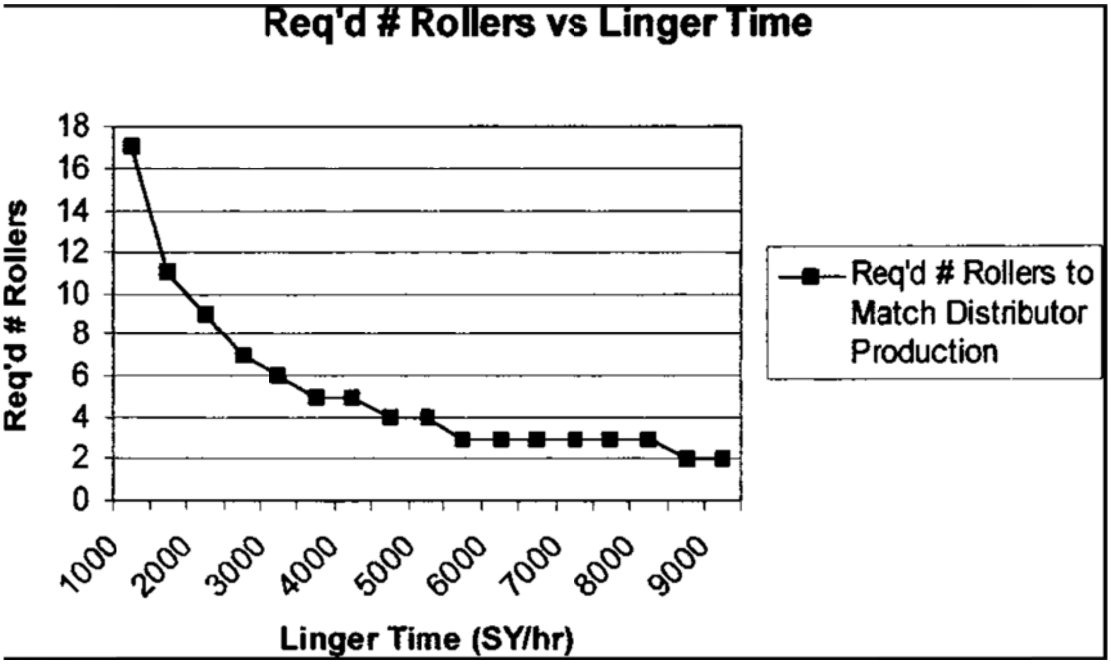


Figure 6. Linger Time Versus Number of Rollers required (Gransberg, et al., 2004)

Well-timed rolling is even more critical in cooler temperatures and shaded areas. In shade, it is very important to quickly roll the panel to embed the chips into the binder and to orient them on their flat side before the asphalt cools too much. Also, during cooler weather it is essential that the rolling occur without delay (Griffith, et al., 2000).

A Wisconsin DOT study found that rolling as soon as possible after application of the binder increased embedment, as expected. This is because as the binder cools, the viscosity increases, which subsequently increases the amount of rolling energy required to achieve the same embedment. However, rolling too soon can cause pickup on the tires of rollers, damaging the chip seal surface. Two studies conducted in Texas and Minnesota found that aggregate loss typically occurs outside and between the wheel paths where roller coverage is less when using three rollers on a twelve foot lane width. The use of four rollers provides a uniform coverage and twice as much rolling between the wheel paths as three rollers according to Gransberg (Gransberg, et al., 2004)

Rollers with ballast are very useful in assuring sufficient contact pressure. The ballasted weight should be 4 to 6 tons (4500 to 5400 kg) with a corresponding tire pressure of 90 psi (600 kPa).

Tires must have a smooth tread, should not vary more than 7 psi (50 kPa) in pressure, and should not wobble during operation. Rollers should follow aggregate spreading by no more than 500 ft (150 m) and should not be operated at more than 6 mph (10 kph). The rolling pattern will depend on the number of rollers used. A minimum of two rollers should be used to cover the full width of the chip spreader. When two rollers are used, three passes are sufficient; one forward, one in reverse, and the final pass extending into the next section according to California (Caltrans Division of Maintenance October 2003).

Sweeping

Sweeping the chip seal is recommended before, after, and sometimes during the chip seal operation. After the chip seal has been constructed, excess aggregate must be broomed off to minimize whip-off by traffic. Sweeping is done using rotary brooms with nylon or steel bristles or with vacuum mobile pickup brooms. The broom should not be worn, and should not be operated in such a manner that removes embedded aggregate. Mobile pickup brooms are usually capable of picking up aggregate and storing it. Sometimes so-called “kick brooms” are used. These brooms move the aggregate into a windrow so that is can be collected, but they often generate dust and may sweep aggregate into gutters. Sweeping can generally be done within 2 to 4 hours after sealing. Hot applied chip seals can be swept within 30 minutes while conventional chip seals can be swept in 2 to 4 hours. A flush coat shall be applied after brooming to eliminate further rock loss and improve durability prior to opening the pavement to uncontrolled traffic (Caltrans Division of Maintenance October 2003).

It is desirable to broom during the cool period of the day. If the rock is being dislodged, the brooming should be delayed until the asphalt has cured further or the weather is cooler. The gutter broom on a pick-up sweeper should not be used because it may exert too much force and damage the chip seal (Washington State Department of Transportation, 2003).

Recent research (Shuler 2011, Howard 2011) indicates that moisture content in the chip seal is directly related to chip adhesion. This work suggests that a moisture content of approximately 15 percent is the limit below which the seal should resist dislodgement of chips due to brooms and traffic.

Traffic Control

The aggregate layer in a freshly placed chip seal is often fragile for several hours after the completion of rolling and sweeping. Therefore, high speed vehicular traffic may dislodge aggregates during the first few hours after the placement of the seal coat. Therefore, reduced speeds are needed to avoid flying chips and, have been shown, to aid in the embedment of the chips in the new seal (Shuler, 1998). Speed enforcement will be necessary to ensure that traffic adheres to the speed limitations (Croteau, et al., 2005).

After chipping, pilot cars should be used for between 2 and 24 hours to ensure that traffic speed is limited to less than 20 mph (30 kph) (Caltrans Division of Maintenance, 2003). The primary purpose of the pilot car is to control the speed of the traffic through the project. In addition, the pilot car can move traffic back and forth across the roads to prevent traveling in the same wheel paths. This traffic will supply some secondary pneumatic tired rolling and helps embed the aggregate further (Washington State Department of Transportation, 2003, Gransberg, 2005).

Wet Weather Adhesion Problems

Most aggregates prefer to be coated with water rather than with asphalt. However, this trend may be reversed in two ways: 1) by making the chip surface less attractive to water than to asphalt by precoating the chip with asphalt, or 2) by making the asphalt “wetter” than water by treating the asphalt with an antistripping additive. Although both of these processes have been reported (Major, 1965) use with emulsions may not be appropriate since precoating aggregates with asphalt may interfere with the emulsion setting process. However, some evaluation may be warranted if antistripping additives could be added to the base asphalt prior to emulsification.

General Construction Guidelines

In a study done by Jackson (1990) statewide uniformity of construction inspection procedures and focus on the following basic guidelines of chip sealing have been suggested (Jackson, 1990):

- Use of clean single sized aggregates: the existing ½” to ¼”. Washington State Department of Transportation (WSDOT)aggregate specification works well.

- Chip seal yields should be tightly controlled to minimize waste and windshield damage: the field review indicated chip rates of 35-60 lb/sq yd were used where 25-30 lb/sq yd was more than adequate in all cases for ½" ¼" chips.
- Asphalt emulsion rates should be such that the chips embed about 50-70 percent into the asphalt film: for ½" to ¼" chips this rate is about 0.45 gal/sq yd were used, in the past, with almost all of the lower application rates losing chips.
- A choke stone course of ¼"-0 helps to complete the aggregate matrix and lock down single-sized chips when applied immediately after the initial rolling. The field review indicated that chocker stone was used sporadically with mixed results, most likely caused by high-chip rates s and inconsistent chocker stone application procedure.
- When emulsions are used, rolling that embeds chips or lays them on their flat side must occur immediately but in no case longer than the time it takes the emulsion to set. The standard specifications governing rolling should indicate the time limit.
- Brooming should be accomplished as soon as possible after the emulsion has set up. Brooming can usually be accomplished the morning after the shot. The existing specification called for final brooming after 5 days.
- When embedment is low and there are signs of chip loss after brooming or exposure to traffic, a fog seal of CSS-one asphalt emulsion can be used to increase embedment and eliminate or reduce winter chip loss.

The following steps can be taken to mitigate raveling according to Jackson (1990):
Use of preseals: A preseal is a light application of emulsion (0.15-0.20 gal/ sq yd) followed by a light application ¼"or smaller chips (8 to 15 lb/sq yd). When construction prior to placement of the seal coat over pavements that are dry, crack open, or have had recent hot mix patches, the preseal provides a more uniform and less porous surface. This also results in a more consistent final product. The preseal provides a cost-effective crack seal when the existing pavement has excessive alligator cracking.

Effect of Traffic on Performance

Traffic plays a very important role in the performance of a chip seal. Therefore, it is necessary to predict or measure the traffic volume as accurately as possible. Observations of the performance of single chip seals indicate that the usual equivalency factors used in structural pavement design for converting cars to equivalent single wheel loads do not apply in the case of chip seals. In fact, cars are of little consequence in structural pavement design but they play an important part in the performance of chip seals, as do trucks. If particular information becomes available of an exceptional increase or decrease in the present traffic count, it should be taken into consideration in the design calculation. (Benson & Gallaway, 1953).

Benson & Gallaway, 1953 studied and analyzed retention of chip seals for two types of aggregates and four types of asphalt materials, all of which have given satisfactory field performance. Following conclusions are warranted from the study: The proper quantity of a given aggregate for a one course surface treatment is the quantity required to cover a square yard one stone thick plus an allowance of 10 percent for spreading inaccuracy.

The experimental work reported here shows that the Kearby Method is a good procedure for determining the asphalt quantity for a one course surface treatment. It is recommended, however, that the broken line in the above figure be used for percentage of embedment for the smaller sizes. Field quantities must also be adjusted for the expected absorption of the surface.

When asphalt cements are used as binders for surface treatments, it is important that the stone be placed as soon as possible after the asphalt is applied. The harder asphalt cements hold the cover stone more tightly, but initial retention is more difficult to obtain.

The grading of the aggregate has an important bearing on the amount of stone retained for a given maximum size. Cover stone with a limited variation in grading will give highest retention for a given quantity applied.

The retention of stone rolled in a wet condition is very poor. If however, the stone is allowed to dry before rolling, reasonably good retention results.

Dust in the aggregates is an important cause of poor aggregate retention and in particular the dry dusty condition is bad. Wetting dusty aggregates before application and allowing drying before rolling reduces the effect of dust.

The retention was found to be slightly lower for RS-2 emulsion and RC-2 cutback on a gallon for gallon basis, than for OA-230 asphalt cement for the aggregates and conditions used in this experiment work. The differences do not appear to be significant.

For a given quantity of aggregates applied, the retention increases with increase in quantity of asphlatic material for the all asphlatic material used and for the application rates studied. The retention of wet stone by RS-2 emulsion was slightly greater than that for dry stone. The retention of wet dusty stone was slightly less than dry stone. The above applies where a 24 hour curing period under summer atmospheric conditions was provided.

Temperature is an important factor in the adhesion of stone to asphalt cements in surface treatments. Limited studies indicated that heating the stone to 150-200^{o}F would increase retention for a given of stone and asphalt applied (Benson & Gallaway, 1953).

Hanson found that for a surface treatment that has carried considerable traffic, the cover aggregate reaches its densest condition with about 20% voids. If enough asphalt binder has been applied to more than fill this 20 per cent of void spaces, the excess binder accumulates on the surface and causes flushing or bleeding. If too little binder is used, the cover stone is torn by traffic because there is not enough binder to cement the aggregate firmly into place. Considerable analysis of surface treatment samples, Hanson concluded that the optimum bituminous binder content for a surface treatment or seal coat is just enough to fill approximately two-thirds of the 20% of void space between the aggregate particles (McLeod, 1960). However, these studies were done before the advent of polymer modified asphalts. These asphalts have significantly higher consistency than unmodified asphalts and have been shown to not necessarily flush in the wheelpaths when application rates rise (Shuler, 1998).

Aggregate Specifications

The best chip seal performance is obtained when aggregate has the following characteristics (Caltrans Division of Maintenance, 2003):

- Single-sized
- Clean
- Free of clay
- Cubical (limited flat particles)
- Crushed faces
- Compatible with the selected binder type.
- Aggregates must be damp for emulsion use.

The aggregate should be carefully analyzed to determine its unit weight, specific gravity, percent of voids, and screen analysis. From the screen analysis the average particle size and effective mat thickness of the aggregate is determined by multiplying each individual screen size by its individual percentage and then obtaining the sum of the products. (Kearby, 1953).

Aggregate Cleanliness

Dusty and dirty aggregate ultimately lead to problems with aggregate retention. Asphalt binders have difficulty bonding to dirty or dusty aggregate, causing the aggregate to be dislodged on opening to traffic (McLeod 1969; Gransberg & James, 2005). It is recommended that the aggregate be sprayed with water several days before the start of the project (Maintenance Chip Seal Manual 2000, Gransberg & James, 2005). Washing chip seal aggregate with clean, potable water before application may assist in removing fine particles that will prevent adhesion with the binder. In addition, damp chips will assist the binder in wetting the rock, thus increasing embedment (Maintenance Chip Seal Manual, 2000, Gransberg & James, 2005). In addition to washing with water, petroleum materials are sometimes used to clean the aggregate before application. Petroleum-based materials such as diesel fuel are commonly used to wash aggregate in Australia and New Zealand (Sprayed Sealing Guide 2004; Gransberg & James, 2005).

Dust on the aggregate surface is one of the major causes of aggregate retention problems. Dust is defined as the percentage of fine material that passes the No. 200 sieve. To improve the quality of the material, the percentage of fines passing the No. 200 sieve should be specified as a maximum of 1% at the time of manufacture (Janisch & Gaillard, 1998).

The cover aggregate for a seal coat should not have a dust coat. Better results are obtained if the rock is damp when it is applied. The aggregate should be dampened in the stock pile (Washington State Department of Transportation, 2003).

Precoated Aggregates

Precoated aggregate is typically used when asphalt cements are the chip seal binder. When emulsion binders are used, the aggregate is usually not precoated because the precoating inhibits the breaking of the emulsion (Seal Coat, 2003). A recent survey indicated that most U.S. and Canadian agencies do not precoat chip seal aggregates (Gransberg & James, 2005).

An effective way to ensure aggregate cleanliness and to eliminate dust, however, is to precoat the aggregate with either an emulsified asphalt or an asphalt cement. Precoating involves running the aggregate through an asphalt plant and lightly coating the chips with asphalt. The target concentration of asphalt should be no greater than 1% by weight. Precoating also helps achieve a better bond between the asphalt cement sprayed on the roadway and the chips when they are applied to the roadway surface (Sprayed Sealing Guide, 2004). Additionally, a chip seal with precoated aggregate provides a darker pavement surface and contrasts better with striping (Griffith, et al., 2000, Gransberg and James, 2005, Kandhal and Motter 1991). However, there may be a disadvantage to precoating aggregates when using emulsified asphalts as mentioned earlier because a barrier to setting may occur (Vagher, 2004).

Aggregate Shape

Flakiness: The flakiness of the aggregate particle is evaluated by determining the percentage of flat particles within the aggregate. The preferred shape of the cover aggregate is cubical rather than flaky. Flaky particles tend to lie on their flat side in the wheel paths and tend to lie randomly in the less trafficked areas. An excessive amount of flaky particles in a chip seal system may cause the system to bleed in the wheel paths and to be more susceptible to snow plow damage and aggregate dislodgment in the less trafficked areas. The flakiness characteristic of the aggregate is most often determined using the Flakiness Index. (Croteau, et al., 2005, Texas Test Method Tex-224F).

The Flakiness Index by the Texas procedure is used to determine the percentage of particles in a coarse aggregate material that have a thickness (smallest dimension) of less than 60 percent of the average aggregate size. The least dimension of an aggregate is defined as the minimum opening of a slot through which the aggregate can be passed. There are five slots in the plate for five different size fractions of the aggregate. If the chips can fit through the slotted plate they are considered to be flat. If not, they are considered to be cubical. The lower the Flakiness Index, the more cubical the material is. The weight of material passing all of the slots is then divided by the total weight of the sample to give the percent flat particles, by weight, or Flakiness Index. The five slots in the plate are for the following:

- Slot 1: Material passing the 1 in. sieve (25 mm) but retained on the 3/4 in. sieve (19 mm).
- Slot 2: Material passing the 3/4 in. sieve (19 mm) but retained on the 1/2 in. sieve (9.5 mm).
- Slot 3: Material passing the 1/2 in. sieve (9.5 mm) but retained on the 3/8 in. sieve (6.3 mm).
- Slot 4: Material passing the 3/8 in. sieve (9.5 mm) but retained on the 1/4 in. sieve (6.3 mm).
- Slot 5: Material passing the 1/4 in. sieve (6.3 mm) but retained on the No. 4 sieve (4.75 mm).

The tolerance limits for the flakiness of the aggregate are based on traffic but generally should be less than 30 (Croteau, et al., 2005).

Aggregate shape is typically characterized by angularity. As the orientation of the embedded chip is important, cubical aggregate shapes are preferred because traffic does not have a significant effect on the final orientation of aggregate (Janisch and Galliard, 1998).

Australian practice requires that 75% of the aggregate have at least two fractured faces (Sprayed Sealing Guide, 2004). Rounded aggregates, as indicated by low percent fracture, are susceptible to displacement by traffic because they provide the least interfacial area between the aggregate and binder. The roundness of the aggregate will determine how resistant the chip seal will be to turning and stopping movements. (Gransberg & James, 2005).

Gradation

Uniformly graded aggregates usually develop better interlocking qualities and provide lateral support to adjacent particles, thereby preventing displacement from traction and friction of high speed traffic. (Kearby, 1953). The gradation of the aggregate is assessed to determine the average least dimension of an aggregate. The average least dimension of an aggregate is influenced by the mean size of an aggregate. An aggregate is considered coarse if its gradation is positioned in the lower part of the gradation band and fine if it is positioned in the upper part. Accordingly, the mean size of the aggregate varies from course to fine gradations within the same gradation band. The optimal binder spray rate for a single chip seal system may vary as much as ten percent between a coarse aggregate and a fine aggregate even when both chips comply with the same single-size gradation band. The impact of the aggregate gradation on the binder rate is less for the secondary layers of multi-layer chip seal systems (Croteau, et al., 2005).

Table 5 shows the recommended grading of aggregates for chip seals by Kearby from 1953.

Table 5. Recommended Grading of Aggregates for Chip Seals (Kearby,1953).

RECOMMENDED GRADING OF AGGREGATES FOR ASPHALT SURFACE TREATMENTS			
Grade I	Retained on 1⅛″	Screen	0%
	Retained on 1″	Screen	40–60%
	Retained on ⅞″	Screen	95–100%
Grade II	Retained on 1″	Screen	0%
	Retained on ⅞″	Screen	40–60%
	Retained on ¾″	Screen	95–100%
Grade III	Retained on ⅞″	Screen	0%
	Retained on ¾″	Screen	40–60%
	Retained on ⅝″	Screen	95–100%
Grade IV	Retained on ¾″	Screen	0%
	Retained on ⅝″	Screen	40–60%
	Retained on ½″	Screen	95–100%
Grade V	Retained on ⅝″	Screen	0%
	Retained on ½″	Screen	40–60%
	Retained on ⅜″	Screen	95–100%
Grade VI	Retained on ½″	Screen	0%
	Retained on ⅜″	Screen	40–60%
	Retained on ¼″	Screen	95–100%
Grade VII	Retained on ⅜″	Screen	0%
	Retained on ¼″	Screen	40–60%
	Retained on #10	Mesh	95–100%
Grade VIII	Retained on ¼″	Screen	0%
	Retained on #10	Mesh	40–60%
	Retained on #20	Mesh	95–100%

Table 6 lists typical chip seal gradations taken from various state DOT manuals in the United States.

Table 6. Examples of Chip Seal Gradations in the U. S (Gransberg & James, 2005)

	State and Gradations							
Sieve Size	Alaska E Chip	Arizona Low Traffic	Arizona High Traffic	Minnesota Aggregate	Minnesota Choke Stone	Montana Grade 4A	South Dakota Type 1A	South Dakota Type 1B
1/2 in.	100	100	100	100	100	—	100	100
3/8 in.	90–100	100	70–90	90–100	100	100	40–70	100
1/4 in.	—	70–90	0–10	40–70	100	—	—	—
No. 4	10–30	1–10	—	0–15	85–100	0–30	0–15	10–90
No. 8	0–8	0–5	0–5	0–5	10–40	0–15	0–5	0–30
No. 40	—	—	—	—	0–5	—	—	0–4
No. 200	0–1	0–1	0–1	0–1	0–1	0–2	0–1	—

Uniform appearance and the best nonskid characteristics are obtained with an aggregate with few fines. The removal of the fines fraction (usually ¼" or smaller) from the chips results in a uniformly graded surface (Washington State Department of Transportation, 2003).

A one-sized aggregate gradation produces a uniform pavement surface. However, without the finer rock matrix, the one-sized rock has a tendency to roll under traffic. A choke stone applied after the rolling, but before the seal is opened to traffic, can prevent this rock displacement (Washington State Department of Transportation, 2003).

Aggregate should be free of excess material passing the No. 200) sieve. Usually, less than 1% is considered acceptable (Croteau, et al., 2005, Benson and Gallaway, 1953, Wegman, 1991, Janisch & Galliard 1998). These clean chip seal aggregates are defined as one-size aggregate if nearly all the aggregate particles are contained between two consecutive sieves that obey the general rule of $d \geq 0.6D$ where "d" represents the size of the smaller sieve, while "D" represents the size of the larger sieve. The common sizes of the chips, expressed in d/D, are 2/4 mm, 2/6 mm, 4/6 mm, 6/10 mm and 10/14 mm in Europe. Coarser chips (14/20 mm) are also used as the primary layer of triple chip seals. The graded-aggregate may be dense graded or gap graded. They are usually unwashed and the dust content may range between 1 to 8 percent. The nominal maximum size of the aggregate or the D value ranges from 10 mm to 16 mm. Coarser graded-aggregate such as 20 mm are occasionally used as the first layer of multi-layer systems (Croteau, et al., 2005).

The small percentage of oversize particles of aggregate permitted by some specifications are usually the flying stones that we hear so much about as being hazardous and damaging to traffic. The excess percentage of undersize particles of aggregates permitted by some specifications are often times so fie as to bolt the asphalt film and prevent the larger aggregates from becoming embedded in the asphalt. In many cases, specification allow gap-graded aggregates which are undesirable and also allow aggregates graded uniformly from fine to course, with maximum density and minimum voids desirable for certain asphalt mixes but very undesirable for penetration-asphalt surface treatments (Kearby, 1953).

Aggregate size, typically referred to as nominal maximum size, is the smallest sieve through which all of the aggregate passes. The average of the smallest dimension of the aggregate is referred to as the Average Least Dimension (ALD) (Hanson, 1934/35). The nominal size of aggregate is selected based on traffic, surface condition, and type of chip seal. Larger aggregate particle sizes are generally more durable and less sensitive to variations in binder application rate (Gransberg, et al., 1998).

The Average Least Dimension, or ALD, is determined from the Median Particle Size and the Flakiness Index. It is a reduction of the Median Particle Size after accounting for flat particles. It represents the expected seal coat thickness in the wheel paths where traffic forces the flat chips to lie on their flattest side (Janisch & Gaillard, 1998).

The average least dimension (ALD) can be determined using the following equation (Asphalt Institute):

$$H = [M / 1.139285 + (0.011506)*FI]$$

where:

H = Average Least Dimension, or (ALD),

M = Median Particle Size, and

FI = Flakiness Index.

A larger sized aggregate requires more asphalt to hold the aggregate in place. This will result in a thicker binder layer, enhancing the quality of the chip seal. However, if not properly embedded and swept, larger aggregate can cause more damage to vehicles immediately after application. Its coarser texture also results in a chip seal with higher noise emissions. The specified gradation should be such that the texture of the chip seal is consistent. Tight gradation bands, which ensure a uniformly graded aggregate, with minimal fines and dust, are necessary for a high-quality chip seal. In fact, a study of chip seals on high traffic pavements exceeding 7500 vehicles per day per lane recommended a job mix formula be developed as in hot mix asphalt construction to control construction gradations (Shuler, 1998).

The specification should limit the amount of flat and elongated particles in the aggregate and define what shall be considered flat and elongated particles. Flat and elongated particles combined should not exceed 10 percent of any aggregate gradation requirement (Kearby, 1953).

A uniformly graded aggregate provides a more consistent embedment that results in improved aggregate retention, surface friction, and drainage capabilities of the seal (McHattie 2001).

Loose Unit Weight

The loose unit weight of an aggregate is used to determine the voids in the loose aggregate. If the voids in the loose aggregate are known after rolling, the amount of binder can be calculated to fill the voids. The loose unit weight of an aggregate depends on its gradation, shape, texture and specific gravity (Epps, et al., 1981, Croteau, et al., 2005).

ASTM C29 can be used to measure the loose unit weight. This approximates the voids in the loose aggregate when it is dropped onto the pavement. It is assumed that once rolled a cubical aggregate will contain voids of approximately 30% and finally to 20% after trafficking. Figure 6 shows the average least dimension (ALD), the effects of flakiness and changes in voids based on compaction (Caltrans Division of Maintenance, 2003).

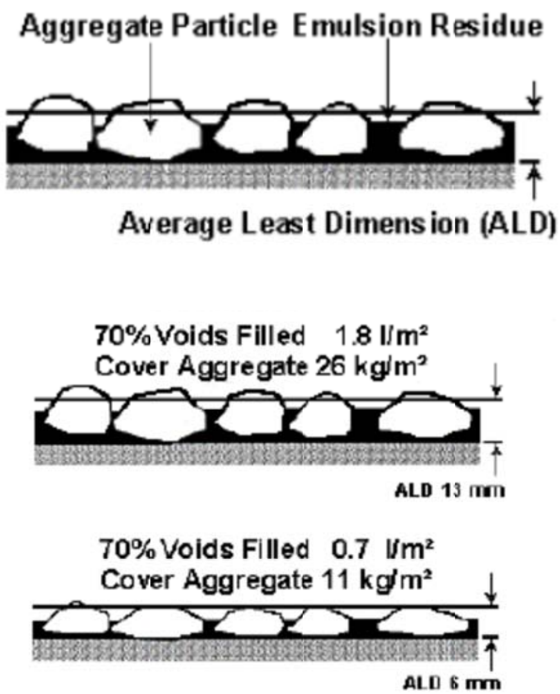


Figure 6. (Caltrans Division of Maintenance, 2003)

The average least dimension represents the average of the thickness of all individual particles when the particles lie with their least dimension upwards. The aggregate flakiness and gradation are evaluated to determine the average least dimension of the aggregate. The voids in the loose aggregate provide an indication of the space available to fit the binder in between the aggregate particles. The aggregate loose unit weight along with the aggregate specific gravity is used to determine the voids in the loose aggregate (Croteau, et al, 2005).

The voids in loose aggregate may be calculated using the familiar equation:

$$V = 1 - W / (G * 62.4)$$

where:

V = Voids in the Aggregate,

W = Loose Unit Weight of the Aggregate, and

G = Bulk Specific Gravity of the Aggregate.

Potter & Church developed the relationship shown in Figure 7 showing the reduction in voids with decreasing layer depth.

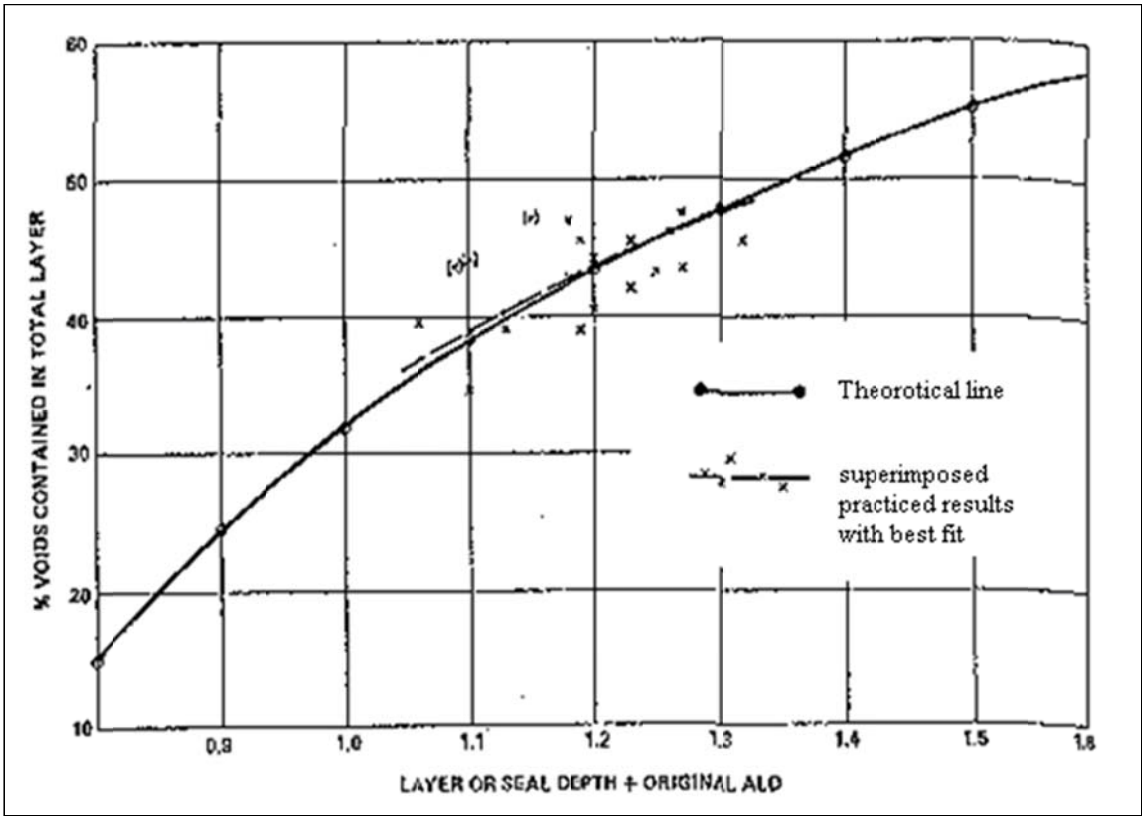


Figure 7. Reduction in voids with decreasing layer depth (Potter & Church, 1976).

Angularity

Angularity of the aggregate is not a factor considered in determining the binder spray rate, however, it is an important factor to take into account. Tightly packed chip seal aggregates are more difficult to achieve with round particles than with angular, crushed particles. Therefore, round aggregates tend to be more prone to dislodgement due to rolling of the aggregate (Croteau, et al., 2005).

Lightweight Aggregate

The advantages in the use of lightweight chips are reduced windshield damage compared with standard chips, and lower haul costs because they weigh less than standard chip weight (Outcalt, 2001).

Figure 8 is a graph showing aggregate loss compared with asphalt application rate from a study done by Gallaway, & Harper, 1966.

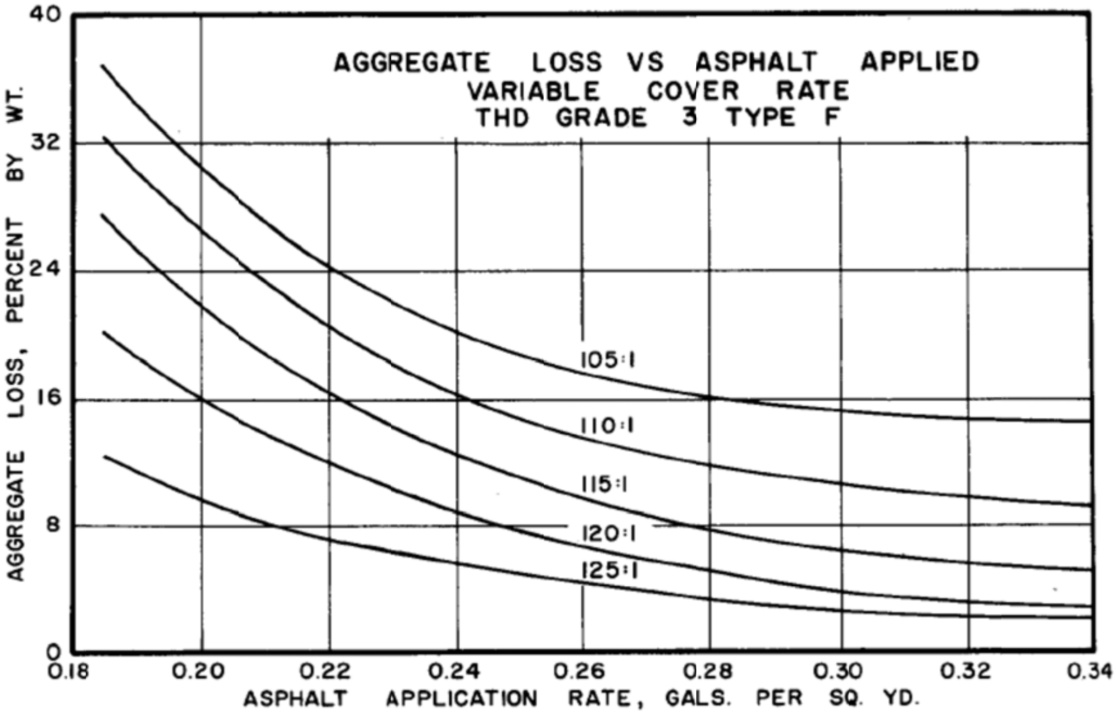


Figure 8. (Gallaway, & Harper, 1966).

Gallaway, & Harper, 1966 found that lightweight aggregates had a strong affinity for all asphalts used in the project. Lightweight aggregates reduced windshield damage because specific gravity is approximately 25 percent that of natural stone aggregate. However, lightweight aggregates are generally more expensive than natural aggregate and may have high water absorption. Gallaway, & Harper, 1966 suggests that consideration should be given to setting a minimum as well as a maximum unit weight for lightweight aggregates used in seals and surface treatments. This minimum could be set figure or it could be provisionally based on service records and or laboratory data from an abrasion test and rapid freeze-thaw results. The definite advantages of clean uniform graded materials were emphasized in the study. It is suggested that consideration should be given to adopting the Louisiana modification of the L.A. abrasion test with washing of the plus No 5 material after test being provisional (Analysis for wear should be made by use of the No. 5 sieve rather than the No 4). The use of synthetic aggregates in paving systems of all types should be encouraged where these material meet service requirement General specifications should be prepared which would place the various synthetic aggregates in use categories. However, the advantages of using lightweight aggregates may disappear as traffic levels increase. A pavement constructed in Tulsa, OK using lightweight aggregate in one of the test sections completely disintegrated after one day (Shuler, 1991) although Los Angeles Abrasion results indicated the aggregate had a loss of 28 percent, well within specification limits. The discrepancy apparently was due to the cushioning effect of the aggregates in the Los Angeles drum as the test proceeds, producing a misleading test result.

Aggregate–Binder Compatibility

Adhesion between the aggregate and binder is governed by a number of variables. The adhesion between aggregate and binder is a function of mechanical, chemical, and in the past, it was believed electrostatic properties (Yazgan and Senadheera 2003). Possible mechanical- and chemical-related factors include aggregate dust, moisture content, and binder temperature. Different types of aggregate were thought to be better suited to certain binders as a result of electrostatic charges (Sprayed Sealing Guide, 2004). However, new evidence indicates this may only be true before the emulsion has set and that after the binder becomes a residue, no effect exists (Shuler, 2011).

In addition, porosity and the presence of water on the surface of the aggregate affect binder–aggregate compatibility. Aggregate, which is quite porous, will actually lead to excessive absorption of the binder. Loss of aggregate shortly after construction is indicative of poor adhesion between the binders and aggregate. Before construction, it is essential to conduct laboratory testing to determine the adhesion capability between the aggregate and the binder. An antistrip test, such as ASTM D1664 (AASHTO T182), will assist in determining the compatibility between the aggregate and binder. This test may also highlight the need for an antistrip additive (Asphalt Seal Coats, 2003).

Aggregate Absorption

The amount of binder applied to the roadway not only needs to compensate for absorption into the existing pavement but also into the cover aggregate itself. Sedimentary aggregates such as limestone can have ten times the absorption of igneous aggregate such as granite or trap rock. Failure to recognize this fact and correct for it can lead to excessive chips loss due to lack of embedment (Janisch & Gaillard, 1998).

Important aggregate characteristics include absorption and shape. Corrections for absorption are based on experience and the characteristics of the local aggregates. Chip shape effects are variable: rounded chips leave greater voids and do not interlock and are not recommended. This type of chip also requires additional binder. Non-uniform sized aggregates produce uneven surfaces (Caltrans Division of Maintenance, 2003).

Aggregate Toughness and Soundness

Resistance to abrasion, degradation, and polishing will ensure that the selected aggregate remains functional for the expected life span of the chip seal. It is desirable to use aggregates with resistance to polishing, as indicated through tests such as the British Wheel test (AASHTO T279, ASTM D3319). The results of this test indicate the polished stone value of the aggregate, and the Australians recommend a polished stone value in the range of 44 to 48 (Sprayed Sealing Guide 2004). Resistance to degradation and abrasion is also an important characteristic of suitable aggregate. Survey results indicate that testing for those characteristics is quite common and usually measured by the Los Angeles abrasion test (AASHTO T96, ASTM C131). Resistance to weathering and freeze-thaw degradation is generally measured by either magnesium sulfate loss or sodium sulfate loss (AASHTO T104, ASTM C88) (Gransberg & James, 2005).

Aggregate Type

Igneous, metamorphic, sedimentary, and manufactured aggregates have all been successfully used for chip sealing (Sprayed Sealing Guide 2004). Limestone, granite, and natural gravels are most widely used in North America. Also, one comprehensive report studied the suitability of lightweight aggregate as cover stone for chip seals (Gallaway and Harper 1966).

Lightweight aggregate has proved to be a successful cover aggregate for chip seals on low volume roads but on high traffic over 7500 vehicles per day per lane it may be problematic (Shuler, 1991). A more recent study showed that lightweight synthetic aggregate furnished a superior ability to retain its skid resistance (Gransberg and Zaman 2002). Such a phenomenon was highlighted by Australian and United Kingdom responses that stressed the use of calcined bauxite, a synthetic aggregate, in high-stress areas where chip polishing is an issue (Gransberg & James, 2005).

Aggregate Moisture

Excess moisture on the cover aggregate has an effect similar to a coating of dust. The moisture film prevents or delays the wetting and development of good adhesion between aggregate and binder. In humid, or damp cool weather, evaporation of the moisture on the aggregate occurs slowly, but it dries out quickly on warm dry days. During this drying period, uncontrolled high speed traffic may displace the cover stone. If rain falls soon after construction, while the adhesion between binder and damp cover stone is still poorly developed, traffic may cause very serious or even complete loss of cover aggregate. A combination of both dust and moisture on the cover stone, increases the delay in the development of good adhesion between aggregate and binder, and multiplies the possibility of loss of cover aggregate under traffic, if cool rainy or hot humid weather follows immediately after construction. Every reasonable effort should be made to have the cover aggregate only damp before it is applied to the emulsion (McLeod, 1960).

Material Selection

As previously stated, one-sized aggregates are preferred for producing successful chip seals. However, Jahren, (2004) found that graded cover aggregates for chip seals have performed well, producing tight, quiet surfaces. These tight surfaces also seem to be beneficial to reduce snowplow damage. This research indicates that if application rates can be controlled sufficiently to prevent bleeding problems that the various size pieces of aggregate can be bound well enough to prevent aggregate loss problems. Smaller sizes (e.g., 0.25”) of chip seal aggregate perform well in the short term. They provide a tighter surface texture (improving noise) and require less weight of aggregate to provide adequate coverage. Also, less binder is required to bind the aggregate to the surface, further reducing costs. Generally, the literature suggests that chip seals constructed with smaller cover aggregate sizes will wear more quickly than larger sizes, especially under heavier traffic (Jahren, 2004).

Janisch and Gaillard, 1998 state that the selection of chip seal materials is project dependent, and the engineer in charge of design must fully understand not only the pavement and traffic conditions in which the chip seal will operate but also the climatic conditions under which the chip seal will be applied. It appears that the widespread use of emulsion binder chip seals results from the notion that emulsions are less sensitive to environmental conditions during construction. Additionally, emulsions are constructed at a lower binder temperature so they are less hazardous to the construction workers.

The selection of the binder is dependent on the type of aggregate that is economically available for the chip seal. Australia and New Zealand pay higher aggregate costs to ensure the quality of chip seals is achieved. The aggregate should be checked to ensure that electrostatic compatibility is met with the type of binder specified.

Several best practices can be obtained from these other countries (Janisch and Gaillard, 1998):

1. Conduct electrostatic testing of chip seal aggregate source before chip design to ensure that the binder selected for the project is compatible with the potential sources of aggregate.
2. Specify a uniformly graded, high-quality aggregate.
3. Consider using lightweight synthetic aggregate in areas where post-construction vehicle damage is a major concern and traffic volumes are low.
4. Use life-cycle cost analysis to determine the benefit of importing either synthetic aggregate or high-quality natural aggregates to areas where availability of high quality aggregate is limited.
5. Use polymer-modified binders to enhance chip seal performance.

Aggregate Spread Rate

Hanson proposed that the spread rate of stone was directly related to the ALD of stone or 20% of the ALD volume. He also stated that the voids in any loose volume of stone are equivalent to 50% of the total volume occupied by the stone. Both these volumes were taken to be independent of the size and shape of the stone. Marais has shown that the voids in a single layer of stone are related to ALD of the stone. He has also shown that the voids in a loose volume of stone are to some extent, dependent on the shape of the stone as defined by the flakiness index. As can be seen the flakiness index does have an effect on the void volume of stone (single-sized). The more flaky stone (higher flakiness index) has a greater volume of voids in the loose bulk condition. When it is assumed that the average compacted depth of stone layer is equal to the ALD, the following is obtained:

$$SR_t = \frac{1000}{ALD}\,\frac{100-V1}{100-V2}$$

where:

SR_t = spread rate of stone (theoretical) (m^2/m^3),

ALD = Average least dimension of stone (mm),

V1= void volume in loose bulk expressed as percentage of total volume occupied by stones, and

V2 = void volume in a single layer of stone expressed as a percentage of ALD volume.

The above relationship shows that the rate of spread of stone (no allowance for excess stone) is inversely proportional to the ALD of the stone and the voids in the single layer of stone, and directly proportional to the voids in a loose volume of stone (Benson & Gallaway, 1953). Whip-off should range from 2% for large cover stone to 10%when the cover aggregate is small. With reasonably careful application of stone chips therefore, the loss of one size cover aggregate from a seal coat or surface treatment due to traffic whip-off should not exceed 10%. In addition to whip-off by traffic, experience in Australia has shown that an average wastage loss of about 5% occurs during handling and transportation between the quarry or other source of cover aggregate and its actual application on the road surface (McLeod, 1960).

Rate of Application of Binder

The optimum quantity of asphalt is determined on the basis that a certain percentage of embedment of the stone is necessary in order to hold the stone adequately and at the same time not produce a sticky surface. The percentage of embedment is stated by Kearby to be a function of the average thickness of the one stone layer which is designed as the average mat thickness. Kearby's recommendation for percentages of embedment is shown by the solid line in Figure 9.

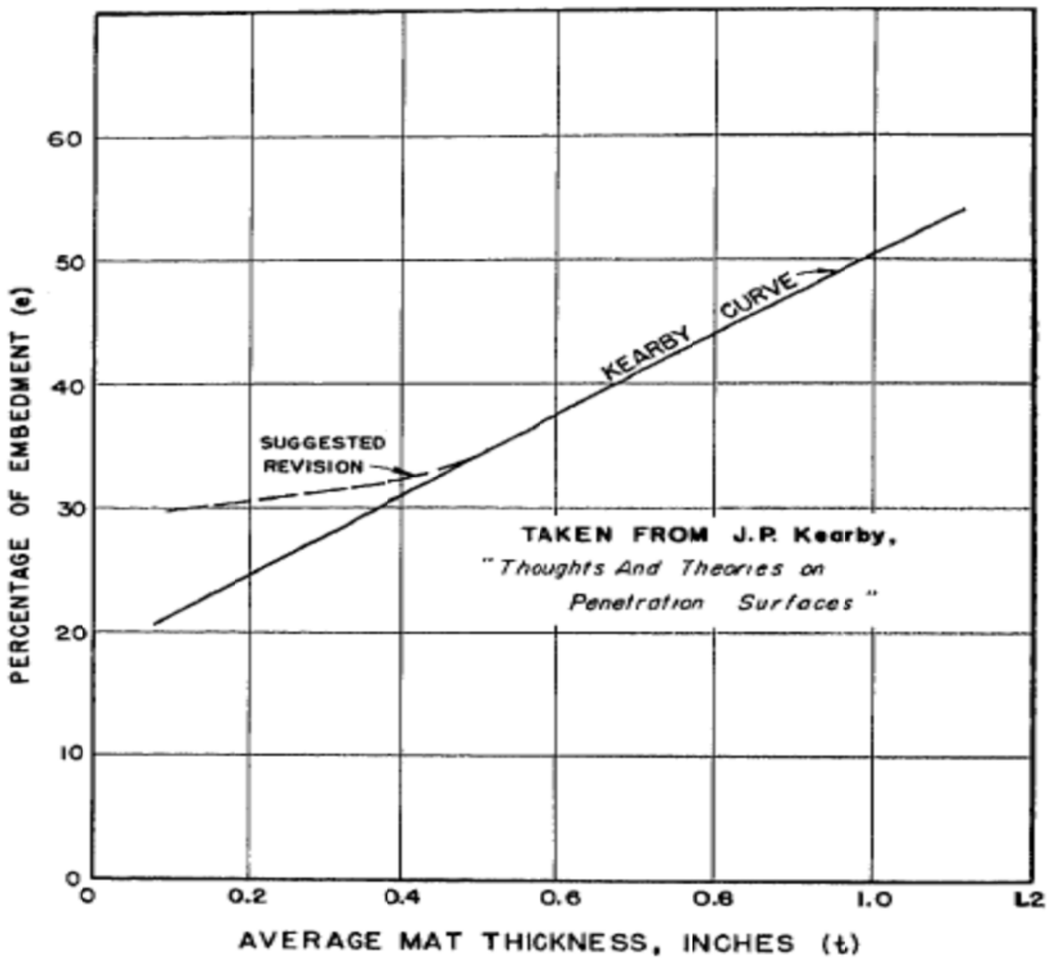


Figure 9. Embedment as a Function of Average Mat Thickness (Kearby, 1953)

Benson and Gallaway suggested a revised Kearby relationship shown in Figure 9 by not allowing less than 30% embedment as the mat thickness approached 0.1 inches (Benson & Gallaway, 1953). The method of calculation of the optimum asphalt quantity from the percentage of embedment is relatively simple. The specific gravity, the dry loose unit weight of the aggregate, and the optimum quantity to cover one square yard one stone thick must be known (Benson & Gallaway, 1953):

Q = optimum quantity of stone, lbs,

w = dry loose unit weight of stone, lbs per cu ft., and

g = specific gravity of the stone.

Average mat thickness t = 1.33Qw

Percentage embedment from Figure 9 = e

Asphalt depth d = $\frac{et}{100}$

Gallons of asphalt per sq yd = 7.48 (9d/12) (1-w/62.4 g)

$= 5.61\ d\ (1- \frac{w}{62.4g})$

Wide differences in ALD values for two one-size cover aggregates of the same nominal size results in equally wide differences in the quantities of asphalt binder that should be applied for one of these cover aggregates as compared with the other (McLeod, 1960). The Vialit Test (CalTrans, 2003) for aggregate retention in chip seals is an indicator of aggregate retention for chip seals. Asphalt emulsion or hot asphalt cement is applied to standard size stainless-steel pans. Exactly one hundred graded aggregates are embedded in the binder. The material is allowed to cure under specified conditions. Following this cure, the trays are conditioned at -22° C for 30 minutes. Then a 500 g ball is dropped 3 times from a distance of 50 cm onto the inverted trays. The results are recorded as percent aggregate retention (Caltrans, 2003).

Binder Properties

Proprietary modified binders, made by addition of polymers or other means, are available. There is no standard specification for these binders at present, but a suite of discriminatory tests is under development, which may include such tests as mini-fretting, toughness and tenacity, Vialit, and rheological characteristics. Compliance requirements have to be based on one or more provisional test methods, or a performance criterion, or local experience on previous jobs.

The addition of polymers to bituminous binders modifies the performance in a number of ways depending on the polymer used. Typically, improved performance in one or more of the following areas is possible (Colwill, et al., 1995):

- Reduced temperature susceptibility in service;
- Improved low temperature adhesion and elasticity;
- Improved elasticity to bridge hairline cracks in the underlying surface;
- Improved early "grip" on the aggregate;
- Improve long term cohesion of the system
- Improved durability as thicker films are possible and
- Earlier release of the site to free-flowing traffic

High viscosity binders should be used on roads in which the 85^{th} –percentile traffic speed exceeds 100 km/hr (60 mph) in order to resist displacement of chippings by high-speed traffic. (Colwill, et al., 1995).

Gransberg, & Zaman, (2002), found that emulsion chip seals performed as well as hot asphalt cement seals and emulsion chip seals also furnished better long term friction (Gransberg, & Zaman, 2002).

Walubita, et al., (2005) quotes that from the 2001 and 2002 TxDOT district surface treatment programs, seven different types of binders (designated B1 to B7) were identified, and all were modified. These binders are summarized in Table 5. The binders were sampled, tested, and graded according to the SPG specification.

Table 6. Typical binders used by TxDOT 2001 – 2002 (Walubita et al., 2005).

#	Designation	Binder	Brief Description	# of HSs
1	B1	AC15-5TR	Asphalt cement with 1500 poises viscosity @ 60 °C, modified with 5% tire rubber.	18 (40%)
2	B2	AC-15P	Asphalt cement with 1500 poises viscosity @ 60 °C, modified with a polymer.	5 (11%)
3	B3	AC5-2% Latex	Asphalt cement with 500 poises viscosity @ 60 °C, modified with 2% latex	7 (15.6%)
4	B4	AC10-2% Latex	Asphalt cement with 1000 poises viscosity @ 60 °C, modified with 2% latex	3 (6.7%)
5	B5	CRS-2P	Cationic, rapid setting, high viscosity emulsion modified with a polymer	3 (6.7%)
6	B6	CRS-2H	Cationic, rapid setting, high viscosity emulsion with a hard base asphalt	4 (9%)
7	B7	PG76-16	Performance graded asphalt cement with a temperature susceptibility of 76 °C to -16 °C.	5 (11%)
Total number of HSs				45

Researchers recorded most of the sections passing the SPG criteria with PG 76-16, AC10-2% latex, AC15-P, CRS-2P, CRS-2H, and AC15-5TR binders. All AC10-2% latex, CRS-2P, CRS-2H, and AC15-P materials passed the SPG specification. Of the total eighteen AC15-5TR samples, only four failed, representing a 78 percent pass rate for the SPG specification. Only one out of the seven PG 76-16 samples failed. With a revised $G^*/\mathrm{Sin}\ \delta$ limit of 0.65 kPa, the majority of the failures were recorded with the AC5-2% latex material. In fact, only one out of the seven AC5-2% latex binder samples passed. Of the total eleven binder samples that failed, six were AC5-2% latex (HS34, HS35, HS41, HS42, HS43, and HS44), predominantly at the higher temperature limit. Four failures were AC15-5TR binders, two (HS2 and HS13) at the lower temperature limit and the other two (HS39 and HS40) at both higher and lower temperature limits. One was a PG 76-16 (HS27), which failed at the lower temperature limit mainly due to the 3 C binder grade increment (Walubita, et al., 2005).

Chip Adhesion Requirements

To attain good adhesion of the binder to the chip, binder viscosity during chipping and rolling must be sufficiently low for the binder to “wet” the chip. Maximum values of binder viscosity are available and are summarized in Table 7.

Table 7. Viscosity Limits for Chip Adhesion

Viscosity Limits for Chip Adhesion

Wetting of Chip

Chip type	*Viscosity not more than*
Dusty chip	100,000 centistrokes
Clean, dry, uncoated	300,000 centistrokes
Precoated, damp conditions	1,500,000 centistrokes
Precoated, dry conditions	5,000,000 centistrokes

Retention of Chip

Grade of chip	*Viscosity not less than*
Grade 1	50,000 centistrokes
Grade 2	30,000 centistrokes
Grade 3	10,000 centistrokes
Grade 4	2,000 centistrokes
Grit	500 centistrokes

To obtain good retention of the chip, the binder must be sufficiently viscous to retain the chip under the action of passing traffic. Field experience shows that a very fluid binder can retain only a small chip. These limits are also summarized in the above table for local chip sizes.

The question of best spraying viscosity has been examined by Major (1965) in several ways (Major, 1965).

The Asphalt Institute makes the recommendation that binder viscosity for spraying should be in the range 50 to 200 centistokes. McLeod recommends a viscosity range of 50 to 100 centistokes.

Examination of current New Zealand practice, and questioning of experienced field staff in terms of what spray temperatures they would recommend for various binders, produced data indicating a range of 30 to 80 centistokes. Work by the South African National Institute for Road research indicates that for Copley jets there is little change of spray pattern: (i) at 12 lb/sq inch from 20 to 220 centistokes; (ii) at 75 centistokes from 8 to 16 lb/ sq inch.

The country Roads Board, Victoria, which consistently produces excellent chip seals, specifies that binder temperature must be adjusted to give a viscosity of 25 to 50 centistokes at spraying.

The conclusion to be drawn is that for satisfactory spraying the binder temperature should be adjusted to a target viscosity of approximately 70- centistokes. Binder temperature may vary between tank and nozzle, and although this should not be significant with current insulation practices, it is worth consideration. The South African findings on desirable pressure range (8 to 16 lb/ sq inch at jet) do not seem to agree with recently specified values(20 to 60 lb/ sq inch at pump) (Major, 1965).

Binder consistency during application is an important factor in surface treatment performance. Binder sprayed at temperatures colder than optimum tend to be viscous and do not allow proper embedment of the aggregate, possibly resulting in aggregate loss. If they are sprayed too hot, they are prone to flow, which causes the same effect. The rotational viscometer (AASHTO TP48) was used for selected binders to obtain temperatures that correspond to recommended viscosity ranges. Spraying temperatures corresponding to viscosities between 0.10 and 0.15 Pa were recommended for inclusion in the SPG specification. A maximum temperature of 180°C was also set to prevent alteration of the binder and modifiers (Griffith & Hunt, 2000).

The tendency at times to use a grade of bituminous binder that is too hard or viscous for the weather and road surface conditions, frequently leads to serious loss of cover aggregate and a badly flushed surface treatment or seal coat. Because the bitumen is too hard, the particles of cover aggregate fail to make adequate contact with the binder (at times they do little more than dent the surface of the binder even after being rolled), and a considerable percentage is removed sooner or later by traffic. The surface treatment or seal coat is left with a deficiency of cover stone and the flushing of the binder may be so pronounced that section of the entire surface treatment of seal coat may be lifted off by the tires of passing vehicles. A flushed surface can result from the assumption that surface treatments and seal coats made with graded cover aggregates should be constructed on-stone particle thick, as is usual practice with one-size cover stone. When this principle is followed, it is inevitable that the quantity of binder required to cement the larger particles of a graded cover aggregate into place, tends to submerge the finer particles in the appreciable areas they occupy. Tires make contact with the binder in these areas and black surface results. This may be even accentuated if a smaller amount of binder is applied, leading to loss of a considerable portion of the coarser sizes, which in turn results in an overall deficiency of cover aggregate in the surface treatment. It will be seen later that better surface treatments or seal coats are likely to result when made with graded cover aggregates, if they are considered to be 2-stone particles thick (McLeod, 1960).

Adhesion to the Road

In second coat seals and reseals there is rarely any problem of adhesion of the sprayed binder to the existing road surface. Normal brooming in preparation for sealing will produce a fairly dust free surface and the initial contact between the binder at near spraying temperature and the surface will be under conditions of low binder viscosity which promotes rapid wetting. For first coat seals, where the surface necessarily exhibits some dustiness, adhesion is promoted by the use of more fluid binders (Major, 1965).

Flow on the Road

When a binder of low viscosity is sprayed on a sloping impervious surface there will be some tendency for the material to flow downhill while it is still fluid before cooling to road surface temperature. This is unlikely to be significant at low application rates, but could be of importance at high rates. Few data are available on this point, but indications are that flow becomes significant for road viscosities of 500,000 centistokes and under at application rates of 0.35 gal/sq yd and upwards on cross falls of over ¾ in/ft. The normal solution to this problem is to limit the binder application rate and use as small a chip as this rate limitation dictates (Major, 1965).

Residual Binder Properties

Two factors govern the required residual binder properties for sealing an impervious surface. These are climate and traffic density. The conflicting demands imposed by climate are a hard enough binder to withstand peak summer temperatures without softening to the stage where traffic can displace stone, or the seal become susceptible to bleeding, and a soft enough binder to not become brittle under minimum winter temperatures. It is impracticable to obtain full compaction of the layer of sealing chips with construction rolling, which is aimed at making the chips secure against traffic damage. Hence, the traffic will be expected to compact the chips to their optimum position for durability. With light traffic, this is achieved only slowly, the process is aided considerably by the use of a soft residual binder. Thus residual binder should be harder in warm climates than in cold ones, and softer for low traffic densities than high ones. It is suggested that the range of residual binders for New Zealand use should vary between 80/100 penetration grade bitumen, for very heavy traffic and high temperatures and light road oil(approx, 400/500pen.) for very light traffic in cold areas (Major, 1965).

Binder Properties at Chip Application

There is a range of binder viscosities at the time of chip application that will allow adequate wetting of the chip and good chip retention. Target binder viscosity will vary with the chip size and chip treatment. Suggested target values for viscosity under various conditions are set out in Table 8.

Table 8. Binder Viscosity Relative to Chip Size and Condition

Target Binder Viscosities (centistokes) at Chip Application			
Chip size	*Plain*	*Precoated*	
		Damp conditions	*Dry conditions*
Grade 1	120,000	250,000	500,000
Grade 2	80,000	180,000	320,000
Grade 3	60,000	140,000	250,000
Grade 4	45,000	100,000	180,000

Standard constituents needed are penetration grade bitumens, no-volatile diluent and volatile diluent. The grades of asphalt cement available in New Zealand within the range of interest in surface sealing are 80/100 pen. The latter is freely available, but supplies of the former are currently limited. The most readily available suitable heavy diluent is class D fuel oil, which is not completely non-volatile, but is nearly so at the concentrations envisaged for surface sealing. Ideally, the volatile diluent used should be rapid curing a crude gasoline or naphtha-but there are difficulties of supply, transport and storage with materials of such low flash points. The more readily available power kerosene, already in use as a standard cut-back material, is less hazardous and a more practicable choice (Major, 1965).

Binder consistency in terms of viscosity during application is an important factor in surface treatment performance and is largely controlled by the spraying temperature.
Optimum binder temperature is essential to ensure optimum binder viscosity, uniformity, and adequate aggregate embedment at the time of construction to prevent run-off and minimize aggregate loss. Spraying the binder at temperatures lower or higher than optimum could be a potential source of aggregate loss, due to either high or low viscosity, respectively. Binders that are sprayed at colder temperatures than optimum tend to be viscous and do not allow proper embedment of the aggregate, resulting in potential aggregate loss. If the binder is sprayed too hot, it is prone to flow, causing the same effect. Extremely high temperatures can also increase aging and/or alter the binder properties to the detriment of performance. High-temperature properties are critical in specifying surface treatment binders to preclude aggregate loss and to minimize bleeding at high service temperatures due to low shear resistance and the inability of the binder to hold the aggregate in place under traffic forces (Walubita, et al., 2005).

EXPERIMENT DESIGN

This experiment was designed to determine if aggregate characteristics affect performance of chip seals on low volume roads. To test this hypothesis the performance of two aggregates was evaluated on two two-lane state highways. Therefore, independent variables included two aggregates and two highways. This resulted in a 2 x 2 factorial experiment.

One aggregate was the material routinely used for chip seal construction by CDOT maintenance with a history of acceptable performance. The second aggregate represented a locally available and marginal material not meeting CDOT specifications with unknown performance. These materials will be identified as Control and Experimental, respectively.

Test sections were constructed on SH71 north of Snyder, CO and on SH59 south of Sedgwick, CO as shown in Figure 10. Both of these pavements are rural, farm to market two lane highways with 12 foot wide driving lanes, no shoulders on SH71 and 10 foot shoulders on SH59. Traffic volumes are 360 AADT with 30 single unit trucks and 120 combination trucks on SH71 and between 160 and 470 AADT with 20 single unit trucks and 20 combination trucks on SH59.

Evaluation sections were established on each highway to measure performance over time for each aggregate being evaluated. Two 500-foot-long evaluation sections were established for each highway for each aggregate. This resulted in four 500 foot long evaluation sections for each highway or eight evaluation sections total.

Analysis of this design is accomplished using conventional analysis of variance (ANOVA) techniques using the model shown below:

$$Y_{ij} = \mu + A_i + \varepsilon_{ij}$$

where:

Y_{ijk}= dependent variable, e. g. cracking, raveling, or chip loss,

μ = overall mean,

A_i = Effect due to ith aggregate, and

ε_{ijk}= Random error.

Figure 10. Location of Evaluation Sections

The approximate locations of the evaluation sections on each pavement are shown in Figures 11 and 12. Note that SH59 is a north-south trending highway but is aligned in an east-west direction in the location of the evaluation sections.

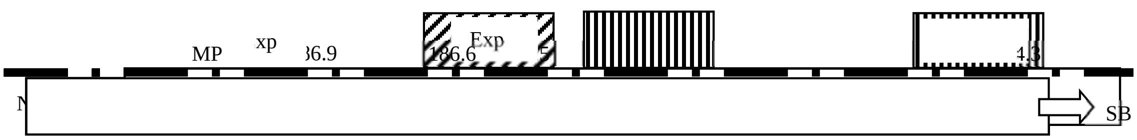


Figure 11. Evaluation Sections on SH71

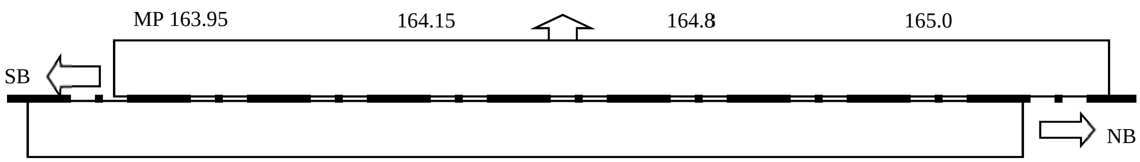


Figure 12. Evaluation Sections on SH59

Dependent Variables

Performance of the chip seals was evaluated by conducting visual condition surveys of the sites after the winter and before fall each year. These condition surveys evaluated performance by measuring cracking, raveling and chip loss.

METHODOLOGY

The process used to conduct this experiment consisted of the following steps:

1. Evaluate condition of the pavement in the area of the evaluation sections prior to application of the chip seals.
2. Sample the materials used for construction and determine physical properties
3. Construct evaluation sections
4. Evaluate condition of the evaluation sections after winter and before fall each year for three years.

Pavement Condition Prior to Construction of Test Sections

Prior to construction of the test sections condition surveys were performed in the areas of the evaluation sections to determine pre-chip seal condition. These surveys were conducted visually following the procedures outlined by the Strategic Highway Research Program (SHRP 2003). Results of this survey are shown in Appendix A and consisted primarily of longitudinal, transverse, alligator cracking, and chip loss.

Materials

The two aggregates used in this study were obtained from L. G. Everist and McAtee Construction. One aggregate is representative of what is typically used in eastern Colorado for chip seal construction on low volume roads. This will be referred to as the control aggregate. The cost of this aggregate chip was $40.90 per ton. The other aggregate is finer in gradation and less processed with respect to crushing. This aggregate will be referred to as the experimental aggregate. The cost of this aggregate chip was $24.80 per ton. The gradations, percent of fractured faces and soundness loss measured for each of these aggregates is shown in Table 9 and compared with CDOT Table 703-6 for chip seal aggregate and the Nebraska Department of Roads (NDOR) Section 1033 specification for what is termed ‘armour coat’ by NDOR. Armour coat is a chip seal constructed with minimally processed aggregates for use on low volume roads.

Table 9. Aggregates Used in Experimental Chip Seal Evaluation Sections

Sieve	Passing, %			
	Control	Experimental	CDOT Table 703-6	NDOR 1033
¾				100
3/8	100	100	100	94-100
4	32	62	0-15	
8	6	13		
10	5	10		30-35
50	3	6		0-10
200	1	3	0-1	0-4
L. A. Loss, %	29	31	< 35	< 40
2 Fractured Faces, %	25	15	> 90	n/a
Soundness Loss, %	3	3	n/a	< 12

Asphalt emulsion used on the project was obtained from Cobitco in Denver with the properties shown in Table 10.

Table 10. Asphalt Emulsion

Property	**CRS-2P**	
	Spec	**Project**
Tests on Emulsion		
Viscosity, 50C, Saybolt-Furol, s	50-450	120
Storage Stability, 24 hr, % max	1.0	0
Particle Charge Test	Positive	Positive
Sieve Test, % max	0.10	0
Demulsibility, % min	40	70
Oil Distillate by Volume, % max	3.0	0
Residue by Evaporation, % min	65	69
Tests on Residue		
Penetration, 25C, 100g, 5s, dmm, min	70-150	105
Solubility in TCE, % min	97.5	100
Toughness, in-lbs, min	70	95
Tenacity, in-lbs, min	45	75

Construction

Construction of the test sections was conducted by CDOT Region 4 maintenance forces in the summer of 2009. Equipment utilized consisted of a conventional asphalt distributor, self-propelled aggregate spreader and two pneumatic tired rollers. Traffic control consisted of diverting traffic on each of the two lane pavements around the chip seal operations until the strength of the emulsion was high enough to resist chip dislodgement.

Materials application rates for SH71 evaluation sections were 28 pounds per square yard for the control and 26 pounds per square yard for the experimental aggregate. Emulsion was applied at 0.28 gallons per square yard for both control and experimental sections. Chips on SH59 were applied at 28 pounds per square yard for both control and experimental aggregates and at 0.29 gallons per square yard for the emulsion. Design application rates were estimated using the Texas chip seal design procedure (Epps, et al., 1981). Results of this design are shown in Table 11.

Table 11. Design Quantities for Materials

	SH 71		SH 59	
	Control	Experiment	Control	Experiment
Quantity of chips*, Q, psy	26	24	27	28
Loose Unit Weight, W, pcf	113	115	113	115
Design Embedment, e, %	40	40	40	40
Traffic Correction, T	1.1	1.1	1.1	1.1
Surface Correction, V	-0.03	-0.03	-0.03	-0.03
Emulsion, gsy	0.30	0.26	0.32	0.31

* From Board Test during laboratory design

This design procedure uses a one-square yard board to estimate the quantity of chips required to cover the surface one stone thick. The asphalt quantity is estimated by calculating the amount of asphalt to fill the voids between the chips to a specific embedment depth. That relationship is as follows:

$A = \{5.61\ e\ \ [1.33Q/W][1-(W/(62.4G))]\ T + V\}/\ R$ (Epps, et al., 1981)

where:

A = Emulsion, gsy,

e = Design Embedment, %,

Q = Quantity of chips*, psy,

W = Loose Unit Weight, pcf,

G = aggregate specific gravity,

T = Traffic Correction,

V = Surface Correction, and

R = emulsion residue, %.

Construction proceeded with no difficulties for either test pavement. Aggregate embedment was achieved after approximately four passes of the pneumatic tired rollers and vehicular traffic was allowed back onto the fresh chip seals after approximately two hours from the time of application.

The environmental conditions at the time of construction are summarized in Table 12.

Table 12. Environment During Construction

Location	Pavement Temp, F	Weather	Wind
SH 71	90-105	Clear/Sun/Dry	270 @ 10 mph
SH 59	80-95	Clear/Sun/Dry	270 @ 5 mph

Pavement Condition After Construction of Test Sections

Evaluation sections were monitored to measure performance from the spring of 2010 until the fall of 2012. Methods used to evaluate performance were visual condition surveys conducted by walking along the shoulders of the pavements and observing condition according to the methods described by SHRP (SHRP 2003) for the cracking and flushing and Epps (Epps, et al., 1981) for the chip loss. The results of these surveys are shown in Figures 13 to 17 for SH71 and Figures 18 to 22 for SH59. The evaluation sections are presented separately on the graphs. That is, sections 1 to 5 are the first five, 100 foot long control sections, sections 6 to 10 are the second five, 100 foot long control sections; sections 11 to 15 are the first five, 100 foot long experimental sections, and sections 16 to 20 are the second five, 100 foot long experimental sections.

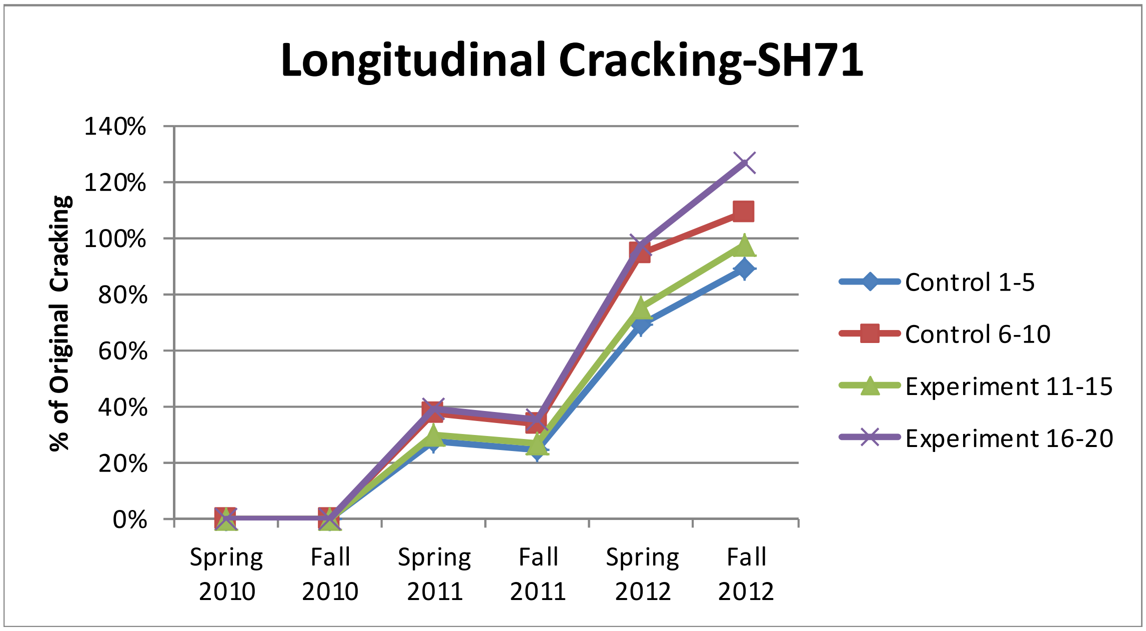


Figure 13. Longitudinal Cracking on SH71

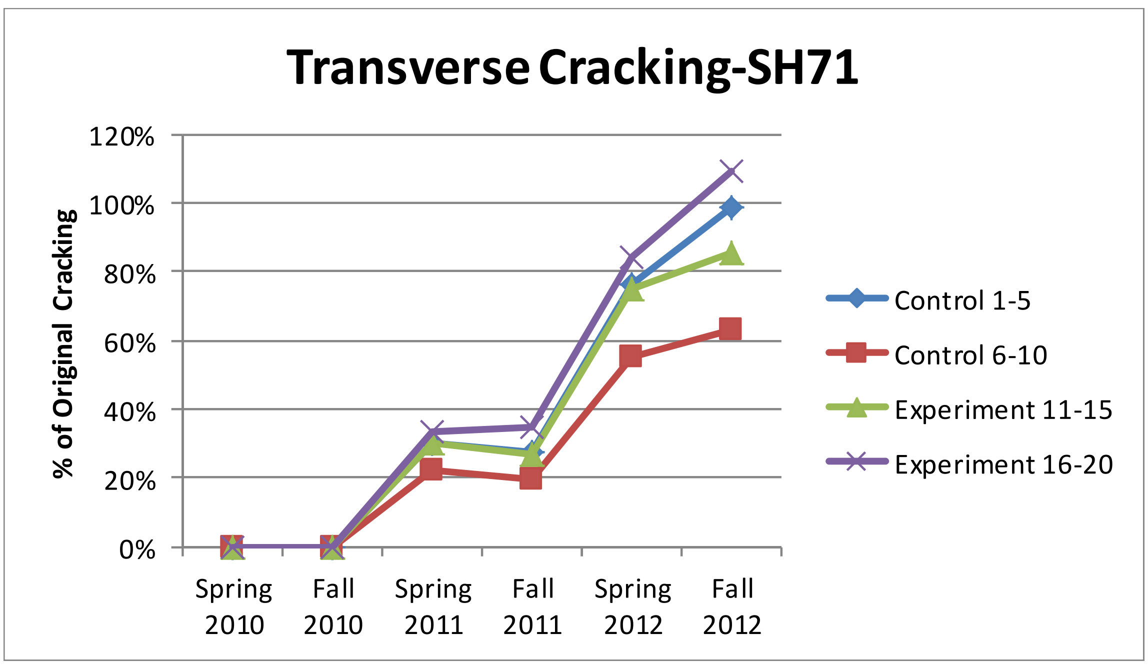


Figure 14. Transverse Cracking on SH71

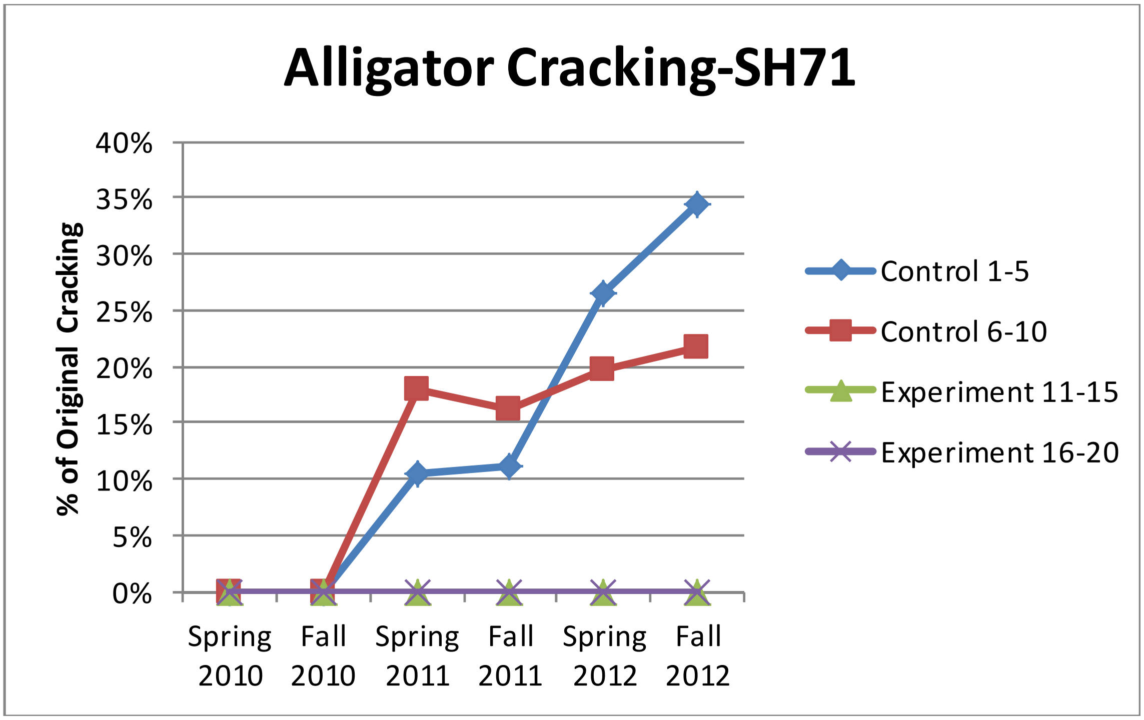


Figure 15. Alligator Cracking on SH71

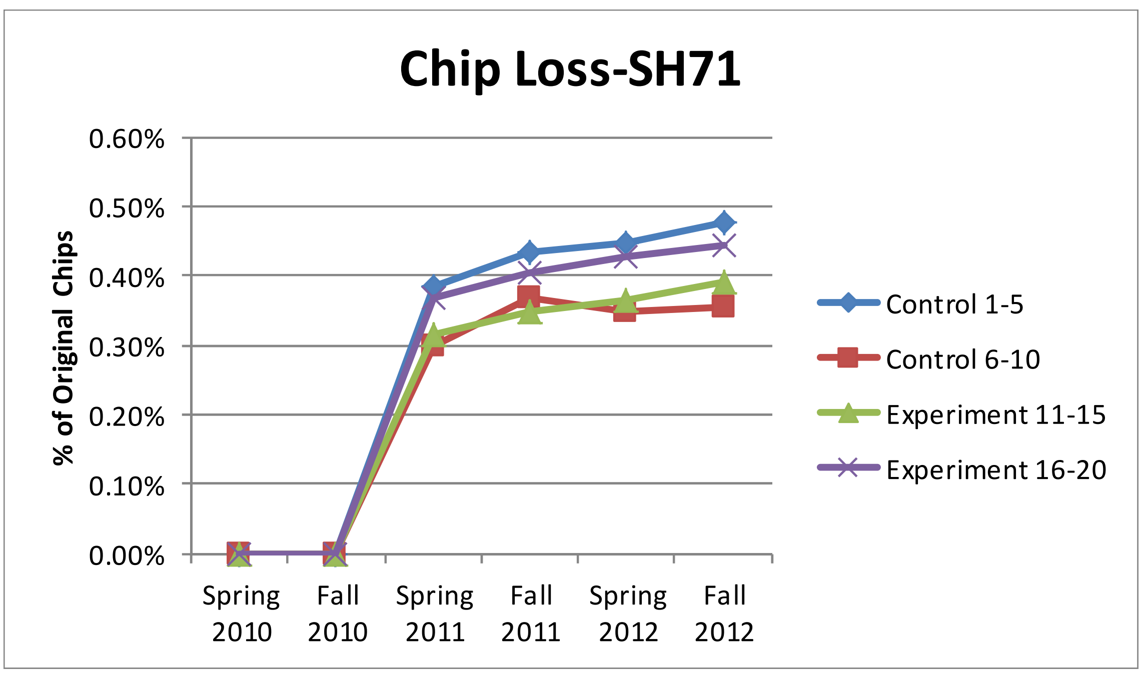


Figure 16. Chip Loss on SH71

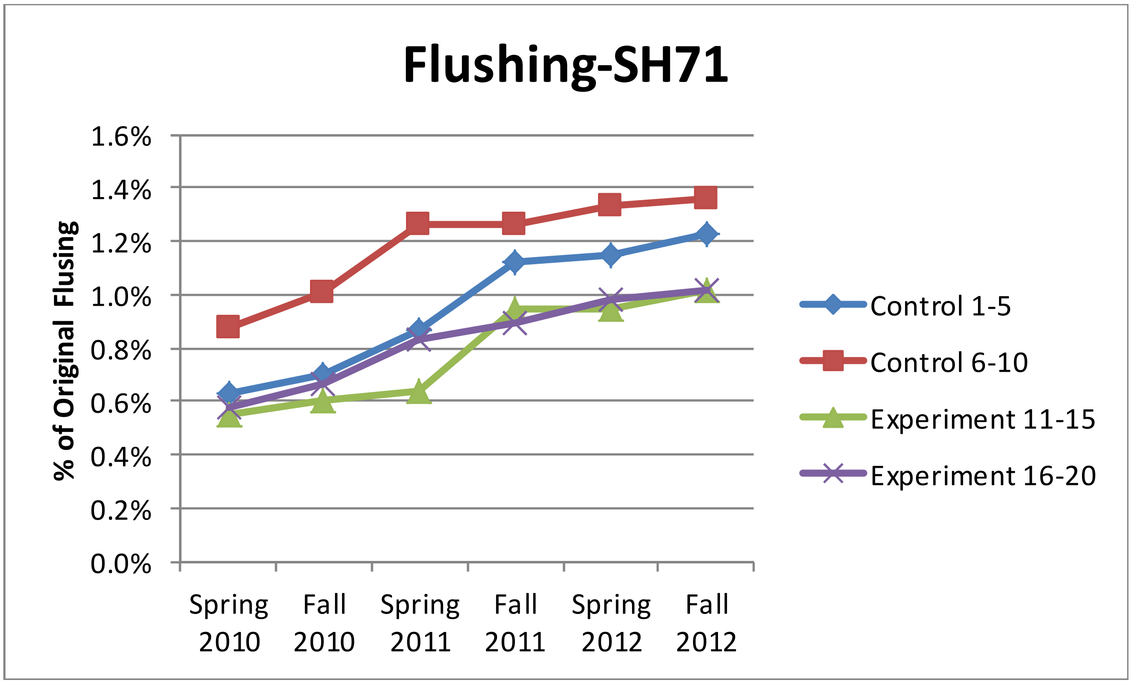


Figure 17. Flushing on SH71

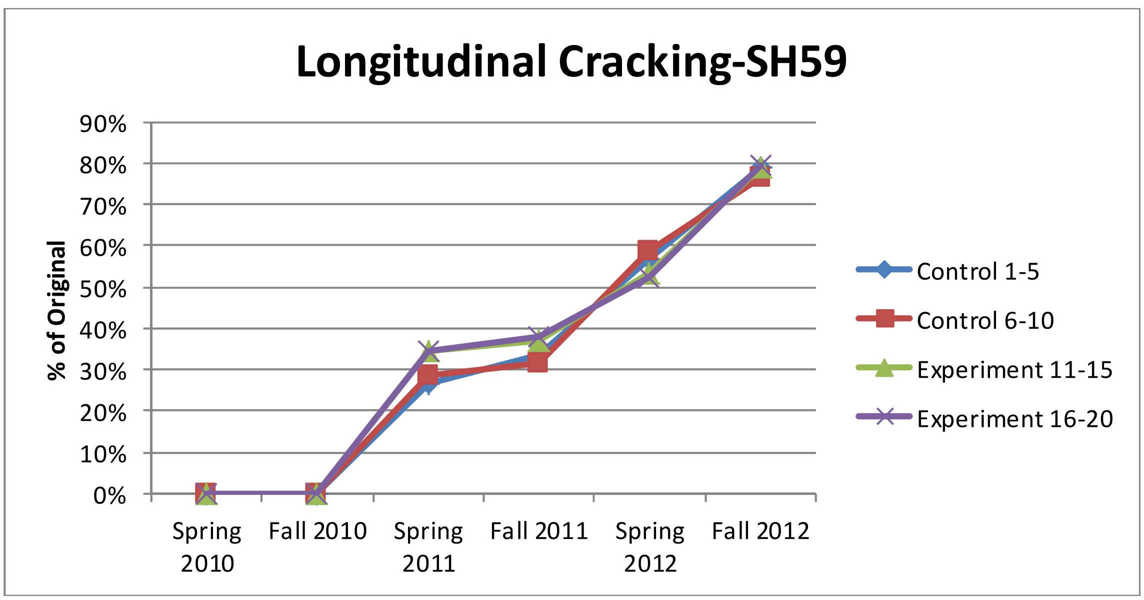


Figure 18. Longitudinal Cracking on SH59

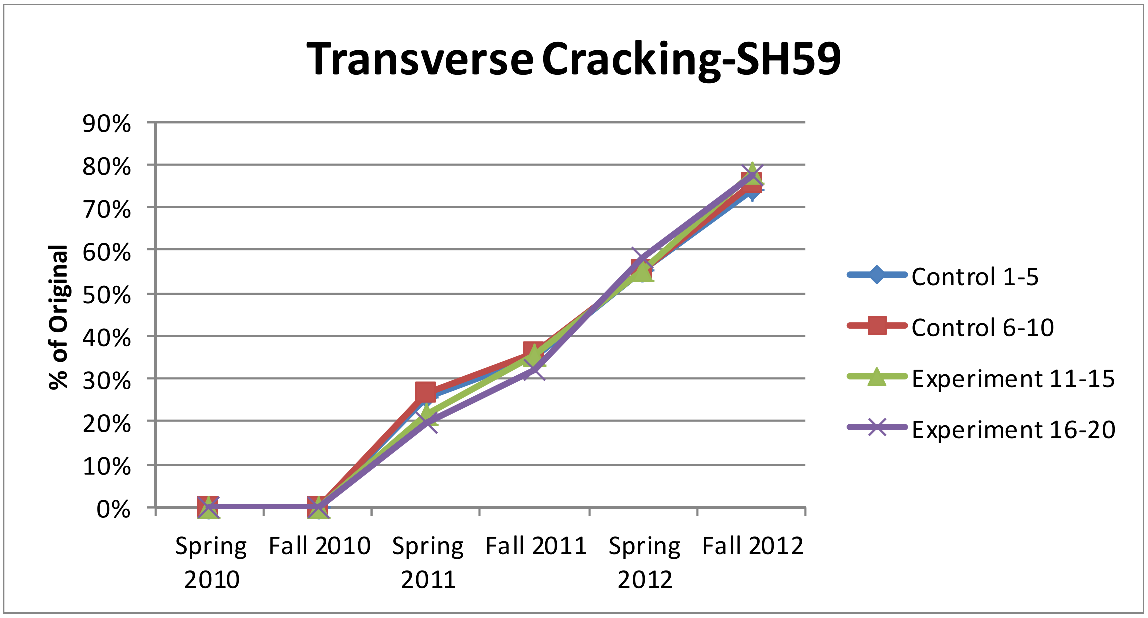


Figure 19. Transverse Cracking on SH59

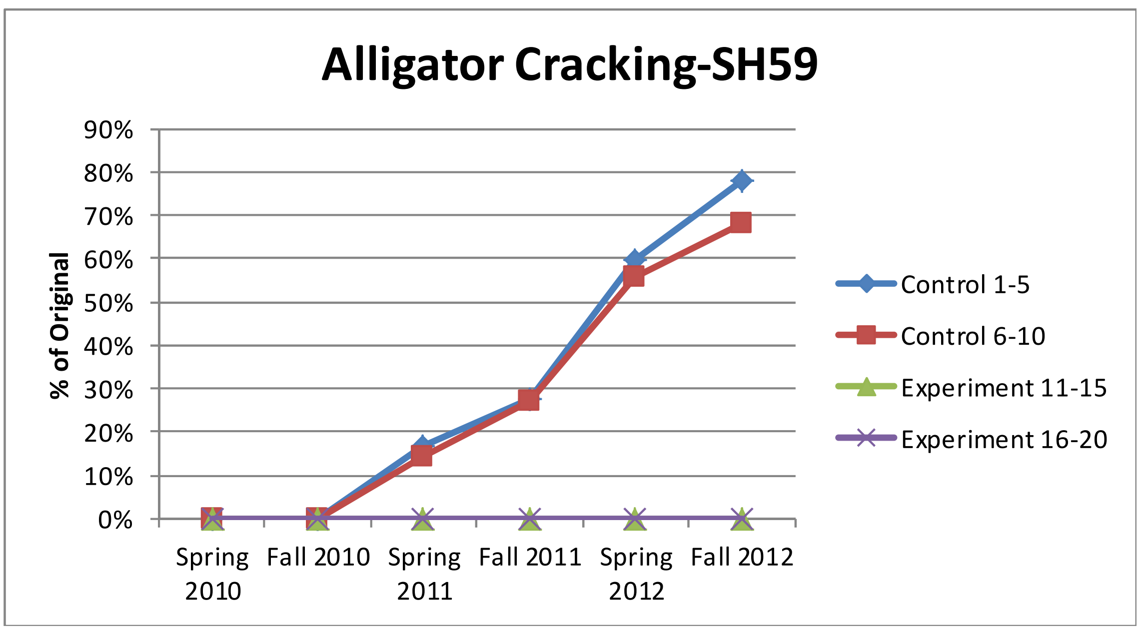


Figure 20. Alligator Cracking on SH59

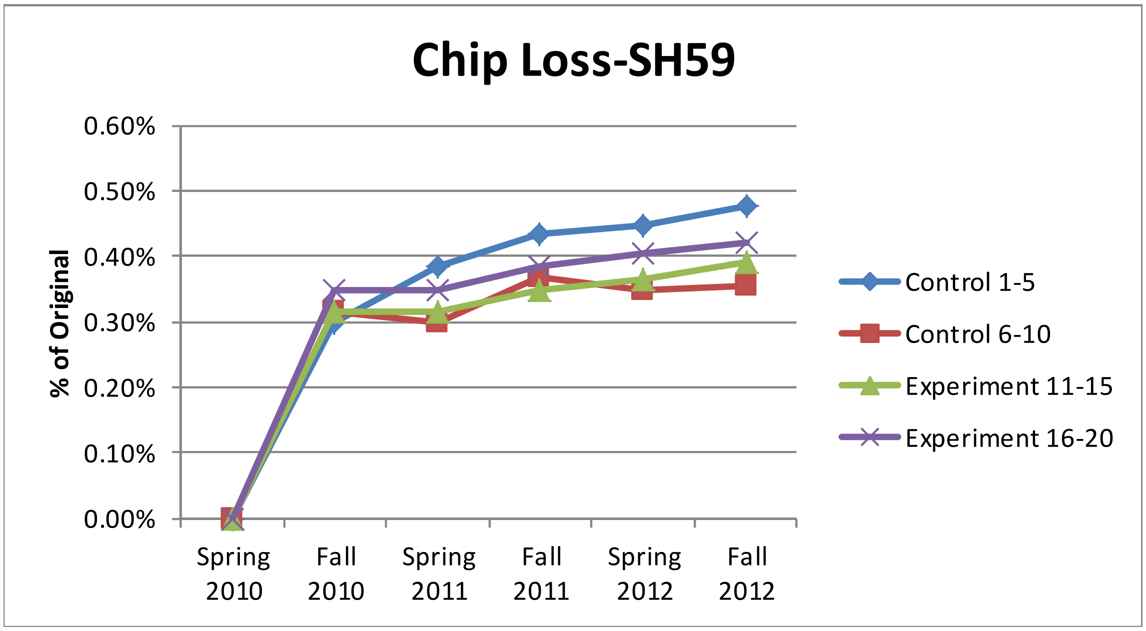


Figure 21. Chip Loss on SH59

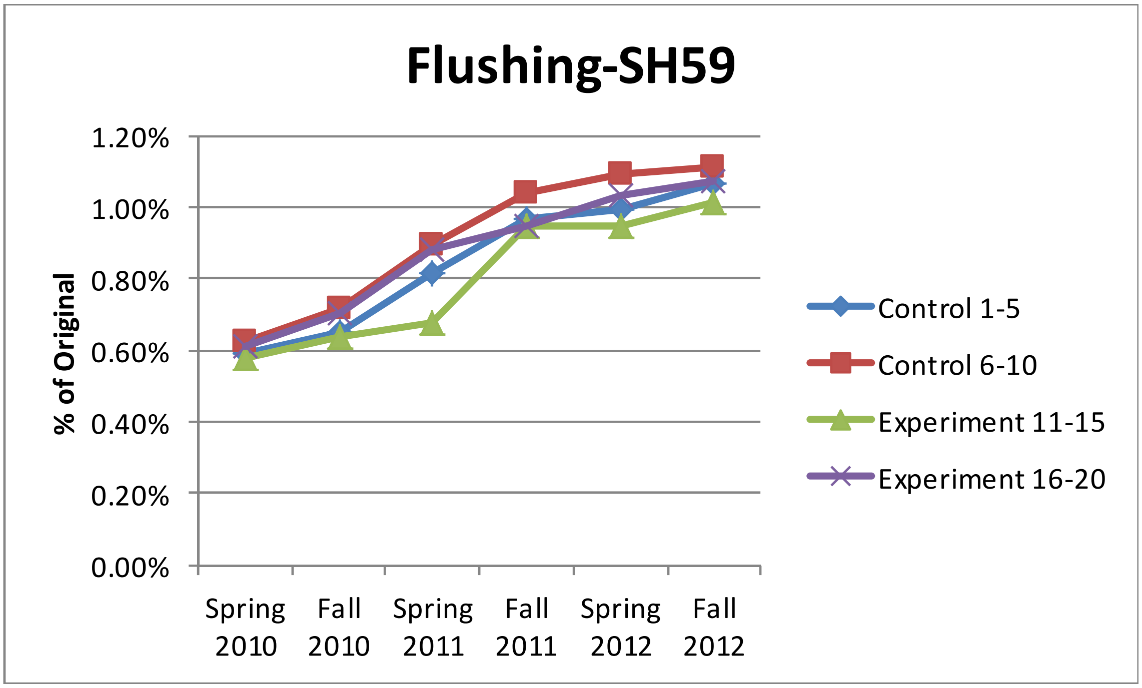


Figure 22. Flushing on SH59

Distress in both pavements is limited to a return of transverse and longitudinal cracks to pre-chip seal conditions after approximately 2.5 years. Alligator cracking, which was only present in the control sections prior to treatment, has returned to approximately 22 to 35 percent of that present prior to treatment.   Chip loss ranges from 0.35 to approximately 0.50 percent of the area of the evaluation sections. Some areas of the pavements also contain longitudinal flushing streaks where distributor nozzles may not have been adjusted correctly and higher quantities of asphalt were applied. The cause of this is not related to either type of chip, but is reported for thoroughness.

ANALYSIS

The results of the condition surveys after three years of service were analyzed using conventional analysis of variance techniques (ANOVA) to determine whether any significant differences exist in performance for any of the evaluation sections. The results of this analysis are shown in Tables 13 to 17 for SH71 and Tables 18 to 22 for SH59. The dependent variable analyzed to determine differences in performance was the percent of the original distress observed for each evaluation section at the end of the performance period in the fall of 2012. For example, Table 13 indicates that the control sections on SH71 had an average of 99 percent of the original longitudinal cracking returning during the fall 2012 condition survey while the experimental sections had an average of 107 percent. The ANOVA indicates that at α=0.05 significance, there is no statistical difference between these values, that is, the P-value = 0.67 in this case. This means there is only a 33 percent probability that a difference exists between the cracking observed in the control section compared with the experiment section.

Table 13. ANOVA for Longitudinal Cracking on SH71

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	9.90	0.99	0.10
Experiment	10	10.66	1.07	0.20

ANOVA[1]

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.03	1	0.03	0.19	0.67	4.41
Within Groups	2.75	18	0.15			
Total	2.78	19				

[1] Columns in these tables are traditional ANOVA parameters of Sum of Squares (SS), degrees of freedom (df), Mean Square Error (MS), the F-statistic (F), the probability of no statistical significance between the treatment variables (in this case between the control and experiment chips), and the critical F-statistic (F-crit) for which a value of F greater than this value would indicate statistical significance between the treatment variables at α = 0.05.

Table 14. ANOVA for Transverse Cracking on SH71

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	7.65125	0.765125	0.117613
Experiment	10	10.1125	1.01125	0.217923

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.302888	1	0.302888	1.8054	0.195755	4.413873
Within Groups	3.019817	18	0.167768			
Total	3.322705	19				

Table 15. ANOVA for Alligator Cracking on SH71

Groups	*Count*	*Sum*	*Average*	*Variance*
Control 1	5	1.07	0.21	0.06
Control 2	5	0.22	0.04	0.01

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.07	1	0.07	2.07	0.19	5.32
Within Groups	0.28	8	0.04			
Total	0.36	9				

Table 16. ANOVA for Chip Loss on SH71

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	0.0417	0.0042	0.0000
Experiment	10	0.0418	0.0042	0.0000

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0000	1	0.0000	0.0001	0.9912	4.4139
Within Groups	0.0000	18	0.0000			
Total	0.0000	19				

Table 17. ANOVA for Flushing on SH71

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	0.13	0.013	0.00
Experiment	10	0.10	0.010	0.00

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	4.70	0.04	4.41
Within Groups	0.00	18	0.00			
Total	0.00	19				

Table 18. ANOVA for Longitudinal Cracking on SH59

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	6.20	0.62	0.11
Experiment	10	5.55	0.56	0.15

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02	1	0.02	0.16	0.69	4.41
Within Groups	2.33	18	0.13			
Total	2.35	19				

Table 19. ANOVA for Transverse Cracking on SH59

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	7.48	0.75	0.01
Experiment	10	7.05	0.71	0.06

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.01	1	0.01	0.25	0.63	4.41
Within Groups	0.68	18	0.04			
Total	0.68	19				

Table 20. ANOVA for Alligator Cracking on SH59

Groups	*Count*	*Sum*	*Average*	*Variance*
Control 1-5	5	3.13	0.63	0.12
Control 6-10	5	3.27	0.65	0.01

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1	0.00	0.03	0.87	5.32
Within Groups	0.53	8	0.07			
Total	0.54	9				

Table 21. ANOVA for Chip Loss on SH59

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	0.0417	0.0042	0.0000
Experiment	10	0.0407	0.0041	0.0000

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0000	1	0.0000	0.0309	0.8624	4.4139
Within Groups	0.0000	18	0.0000			
Total	0.0000	19				

Table 22. ANOVA for Flushing on SH59

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	10	0.1089	0.0109	0.0000
Experiment	10	0.1043	0.0104	0.0000

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0000	1	0.0000	0.1404	0.7123	4.4139
Within Groups	0.0001	18	0.0000			
Total	0.0001	19				

A summary of the previous ANOVA results indicates the following:

Table 23. Summary of ANOVA Results for SH71

Performance Criteria, % of Original at 3 Years	Control Average	Experiment Average	P-value
Longitudinal Cracking	99	107	0.67
Transverse Cracking	77	101	0.20
Alligator Cracking	n/a	n/a	n/a
Chip Loss	0.42	0.42	0.99
Flushing	1.3	1.0	0.04

Table 24. Summary of ANOVA Results for SH59

Performance Criteria, % of Original at 3 Years	Control Average	Experiment Average	P-value
Longitudinal Cracking	62	56	0.69
Transverse Cracking	75	71	0.63
Alligator Cracking	n/a	n/a	n/a
Chip Loss	0.42	0.41	0.86
Flushing	1.1	1.0	0.71

The results of the performance analysis for SH71 indicate there were no significant differences between the control and the experimental chips for any of the performance criteria except flushing. Flushing occurred in the control sections over 1.3% of the area while the experimental sections had flushing on 1.0% of the area. Results of the performance analysis for SH59 indicate no significant differences in performance for any of the criteria.

CONCLUSIONS

1. Locally available, minimally processed aggregates can be successfully applied as chip seal aggregate on low volume roadways. After three years of service two experimental pavements provided the same performance with respect to cracking, chip loss and flushing for both control and experimental aggregate chips.

2. The design procedure used to estimate aggregate chip application quantity and emulsion spray rates matched the actual quantities placed reasonably well and these quantities resulted in acceptable performance for three years.

RECOMMENDATIONS AND OBSERVATIONS

The chip seal design procedure used to estimate aggregate chip and emulsion quantities correlated well with the quantities actually used to construct the test sections on SH71 and SH59. Therefore, this design procedure is recommended for all chip seals planned on low volume roads in Colorado. The method is described in Appendix C for reference.

Longitudinal streaking of the emulsion occurred on both pavements which lead to flushing. This over application could have been caused by plugged nozzles in parts of the spraybar, spraybar height, or nozzles not adjusted to the same angle. In addition, although chip loss was minimal, much of the loss occurred at or near the roadway centerline. An edge nozzle designed to provide half the fan of a full nozzle can be used to reduce this potential loss of chips.

In some cases, tandem dump trucks delivering chips to the aggregate spreader overfilled the spreader hopper and excess chips were applied to the surface. These excess chips may also have been a source of some of the flushing observed.

REFERENCES

Abdullah, I., Sinha, K. & Kuczek, T. (1994, January/February). Effects of Routine Maintenance on Flexible Pavement Condition. *Journal of Transportation Engineering*, 120(1), 65-73.

Abe, H., T. Akinori, J.J. Henry, and J. Wambold, "Measurement of Pavement Macrotexture with Circular Texture Meter", *Transportation Research Record 1764*, Transportation Research Board, Washington, D. C. (2001).

AFNOR, T66-017, "Determination of the Index of Rupture of Cationic Emulsions".

Al- Mansour, A.I. and Sinha, K.C., "Economic analysis of effectiveness of pavement preventive maintenance", *Transportation Research Record 1442*, pp. 31-37 (1995).

Anderson, V., and Epps, J. E., "Durable Asphalt Emulsion Seal Coats, Volume I: Research Report", FHWA-RD-89-230, October, 1989.

Arizona Department of Transportation, AZ 233, "Flakiness Index of Coarse Aggregates".

Arizona Department of Transportation, AZ 504, "Vacuum Recovery of Asphalt Emulsion Residue".

ASTM, "Standard Test Methods and Practices for Emulsified Asphalts", ASTM D244-97C, ASTM International, West Conshohocken, Pennsylvania (1997).

ASTM D5624-02, "Standard Test Method for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications", American Society for Testing Materials, Vol. 04.03, *Road and Paving Materials; Vehicular-Pavement Systems*.

ASTM, "Standard Test Method for Distillation of Emulsified Asphalt", ASTM D6997-04, ASTM International, West Conshohocken, Pennsylvania (2004).

ASTM D7000-04"Standard Test Method for Sweep Test of Bituminous Surface Treatment Samples", ", American Society for Testing Materials, Vol. 04.03, *Road and Paving Materials; Vehicular-Pavement Systems*.

ASTM, "Standard Practice for Recovering Residue from Emulsified Asphalt Using Low Temperature Evaporative Technique", ASTM D7497-09, ASTM International, West Conshohocken, PA (2009).

ASTM E965-96, "Standard Test Method for Measuring Pavement Macrotexture Using a Volumetric Technique", American Society for Testing Materials, Vol. 04.03, *Road and Paving Materials; Vehicular-Pavement Systems*.

ASTM, "Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth," ASTM E 1845-01, Volume 04.03, ASTM, West Conshohocken, Pennsylvania (2003).

ASTM, "Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter," ASTM E 2157-01 (Reapproved 2005), Volume 04.03, West Conshohocken, Pennsylvania (2005).

ASTM, "New Proposed Standard Specification for Surface Performance Graded Asphalt Binder", Draft Under Development, ASTM WK5321, ASTM International, West Conshohocken, PA (2004).

Australian Standard AS 1141.20.1 "Methods for sampling and testing aggregates, Method 20.1: Average Least Dimension – Direct Measurement (nominal size 10 mm and greater)", Published by Standards Australia International Ltd, GPO Box 5420, Sydney, NSW 2001, Australia

Australian Standard AS 1141.20.3—2000, "Methods for sampling and testing aggregates Method 20.3: Average least dimension—Calculation (nomograph)", Published by Standards Australia International Ltd, GPO Box 5420, Sydney, NSW 2001, Australia ISBN 0 7337 3476 6

"Update of the Austroads Sprayed Seal Design Method", Austroads Project No. TT1132, Austroads Publication No. AP–T68/06, *Prepared by* Allan Alderson, ARRB Group Published by Austroads Incorporated, ISBN 1 921139 65 X

Austroads Work Tips: Aggregate Pre-Coating
http://www.aapa.asn.au/content/aapa/download/worktips23.pdf Accessed June 2005

Austroads Work Tips: Aggregate Pre-coating. (2000, september). retrieved on september, 28th from http://www.aapa.asn.au/content/aapa/download/worktips23.pdf

Austroads Work Tips: Calibration of Bitumen Sprayers
http://www.aapa.asn.au/content/aapa/download/worktips34.pdf Accessed June 2005

Austroads Work Tips: High Pressure Water Retexturing
http://www.aapa.asn.au/content/aapa/download/worktips44.pdf Accessed June 2005

Barcena, R, A. Epps Martin, and D. Hazlett, "Performance Graded Binder Specification for Surface Treatments", *Transportation Research Record 1810"*, Transportation Research Board (TRB), Washington D.C. (2002).

Barnat, J., McCune, W., and Vopat, V., "The Sweep Test: A Performance Test for Chip Seals", Asphalt Emulsion Manufacturers Association, San Diego, CA, February, 2001.

Benson, F., & Gallaway, B. (1953). Retention of cover stone by asphalt surface treatments. Texas Engineering Experiment Station, 133, 1-58

Bouquety, M. N., Descantes, Y., Barcelo, L., de Larrard, F., and Clavaud, B., "Automated measurement of aggregate properties: Part 2—flakiness index", RILEM, 2006.

British Standard (BS) EN 12272-3: Surface dressing - Test methods - Part 3: "Determination of binder aggregate adhesivity by the Vialit plate shock method"

British Standard (BS) EN 933-3: Surface dressing - Test methods - Part 3: "Flakiness Index of aggregates for Surface Dressings"

Burr, B. (1990). Solvent removal from asphalt. Transportation Research Record, 1269(9), 1-8.

California Department of Transportation Test Method 331, "Method of Test for Residue by Evaporation of Latex Modified Emulsified Asphalt", September 1998.

Caltrans, "Chip Seals: Chapter 5," Caltrans Division of Maintenance. Oct. 2003

Caltrans, California Standard Test Methods, October 31, 2003, "Vialit Test for Aggregate Retention in Chip Seals".

Chen, D., Lin, D., & Luo, H. (2003, August). Effectiveness of Preventative Maintenance Treatments Using Fourteen SPS-3 Sites in Texas. *Journal of Performance of Constructed Facilities*, 136-143

Colorado Department of Transportation Standard Specifications for Road and Bridge Construction, 1999.

Colorado Department of Transportation, Standard Specifications for Road and Bridge Construction, 2011.

Colorado Department of Transportation Study No.-10.50, "Evaluation of the Performance, Cost-Effectiveness, and Timing of Various Preventive Maintenances", 2004.

Colorado Department of Transportation, Colorado Procedure L-2212, "Residue by Evaporation of Asphalt Emulsion, August 2002.

Colwill, D., & Mercer, J., & Nicholl, J. (1995). U.K. Design Procedure for Surface Dressing. Transportation Research Record, 1507, 13-22.

Cornet, E. (1999). ESSO Abrasion Cohesion Test A Description of the Cohesive Breaking Emulsions for Chip Seal. *International Symposium on Asphalt Emulsion Technology: Manufacturing, application and Performance*, 346-355

Croteau, J., Linton, P., Davidson, K., & Houston, G. (2005). Seal Coat Systems in Canada: performances and practice, 2005 Annual Conference of the Transportation Association of Canada, 1-15.

Davis, D., Stroup-Gardiner, M., Davis, K., and Epps, J.A. *Evaluation of 1989 Chip Seal Test Sections on US 95A between Wabuska and Yerington, Nevada: Vol. 1*. University of Nevada, Reno report for Nevada department of Transportation. 1991.

Davis, L., "Chip Sealing Over Fabric in Borrego Springs, California, USA", *Proceedings of the International RILEM Conference, Limoges*, France, 5-8 May 2004.

Dumas, B., Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04) 12 – 16 September 2004, Sun City, South Africa. ISBN Number: 1-920-01718-6

Elmore, W. E., Solaimanian, M., McGennis, R. B., Phromson, C., and Kennedy, T. W. (1995) "Performance-based Seal Coat Specifications." *CTR Research Report No. 1367-1*, Center for Transportation Research, Austin, Texas.

Epps, A.L., C.J. Glover, and R. Barcena, "A Performance-Graded Binder Specification for Surface Treatments", Report No. FHWA/TX-02/1710-1, Texas Department of Transportation and U.S. Department of Transportation, Federal Highway Administration (FHWA), Washington, D.C. (2001).

Epps, J. A., Gallaway, B. M., and Hughes, C. H., "Field Manual on Design and Construction of Seal Coats", Texas Transportation Institute, Research Report 214-25, July, 1981.

Federal Highway Administration (FHWA), "LTPP Seasonal Asphalt Concrete (AC) Pavement Temperature Models", Report No. FHWA-RD-97-103, Federal Highway Administration, Washington, D.C. (1997).

Gallaway, B. M. and W. J. Harper, "A Laboratory and Field Evaluation of Lightweight Aggregates as Coverstone for Seal Coats and Surface Treatments," Research Report 51-2, Texas Transportation Institute, Texas A&M University, College Station, 1966.

Geoffroy, D. N. 1996. *Cost-Effective Preventive Pavement Maintenance*. NCHRP Synthesis of Highway Practice 223. Transportation Research Board, Washington, DC.

Gransberg, D. and James, D.M. B., "Chip Seal Best Practices, A Synthesis of Highway Practice, NCHRP Synthesis 342, Transportation Research Board, Washington, D. C., 2005.

Gransberg, D., & Zaman, M. (2002). *Comparing the Performance of Emulsion Versus Hot Asphalt Chip Seal Projects in the Texas Department of Transportation's Atlanta District*, Asphalt Emulsion Manufacturer's Association, Annapolis, Md.

Gransberg, D., Karaca, I., & Senadheera, S. (2004, May/June). Calculating Roller Requirements for Chip Seal Projects. Journal of Construction Engineering and Management, 130 (3), 378-384.

Gransberg, D., Pidwerbesky, B., Stemprok, R., and Waters, J., "Measuring Chip Seal Surface Texture with Digital Imagery", *International Conference on Surface Friction of Roads and Runways*, Christchurch, NZ, May 2005.

Gransberg, D., Senadheera, S., & Karaca, I. (1999). Analysis of statewide seal coat constructability review. *Texas Dept. of Transportation Research Rep. No. TX-98/0-1787-1R*, Texas Tech Univ., Lubbock, Texas.

Gransberg, D; & James, D. (2005). Chip Seal Best Practices. *A NCHRP Synthesis 342 of Highway Practice.* Transportation Research Board, Washington D.C.

Griffith, A., & Hunt, E. (2000, June). Asphalt Cement Chip Seals in Oregon Construction Report. *Oregon Department of Transportation Research Group*, Oregon.

Hall, J.W., Smith, K.L., Titus-Glover, L., Wambold, J.C., Yager, T.J., and Rado, Z., "Guide for Pavement Friction," Final Report, Project 1-43, National Cooperative Highway Research Program (NCHRP), Transportation Research Board, Washington, D.C. (2006).

Hanson, F. M., "Bituminous Surface Treatments on Rural Highways", Proceedings of the New Zealand Society of Civil Engineers, Vol. 21, 1934-1935, p 89.

Hanson, D.I. and B.D. Prowell, "Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements," National Center for Asphalt Technology (NCAT), Auburn, AL (2004).

Hanz, A., Z. A. Arega, and H. U. Bahia, "Rheological Evaluation of Emulsion Residues Recovered Using Newly Proposed Evaporative Techniques", Paper #09-2877 Presented at the 88th Annual Meeting of the Transportation Research Board, January (2009).

Hicks, G., Seeds, S., & Peshkin, D. (2000, June). *Selecting a Preventive Maintenance Treatment for Flexible Pavements*. Foundation for Pavement Preservation, Washington, DC.

Hicks, R., Dunn, K., & Moulthrop, J. (1997). Framework for Selecting Effective Preventive Maintenance Treatments for Flexible Pavements. *Transportation Research Record 1597*, Transportation Research Board, Washington, D.C., 1-10.

Hitch, L., (1981). Surface Dressing in Developing Countries: Research in Kenya, *Transport and Road Research Laboratory*: Crowthorne, Berkshire.

Howard, Isaac L, Hemsley Jr, Mike, Baumgardner, Gaylon L, Jordan III, Walter Stephens, "Chip and Scrub Seal Binder Evaluation by Frosted Marble Aggregate Retention Test", Transportation Research Board Annual Meeting 2009 Paper #09-1662.

Howard, Isaac L., Shuler, S., Jordan, Walter S. III, Hemsley, James M. Jr., and McGlumphy, Kevin, 2011, Correlation of Moisture Loss and Strength Gain in Chip Seals, Transportation Research Record: Journal of the Transportation Research Board, No. 2207 Asphalt Materials and Mixtures, Transportation Research Board of the National Academies, Washington, D.C., pp. 49-57.

ISSA TB 100, "Wet Track Abrasion Test".

Jackson, D. (1990). Washington State Chip Seal Study. Transportation Research Record, 1259, 1-10.

Jackson G.P., 1963 Surface Dressing. Bitumen Division, Shell International Petroleum Co. Ltd. London.

Jahren, C., and Behling, K. R., (2004). Thin Maintenance Surface Treatments: Comparative Study. *Journal of the Transportation Research Board*, TRR 1866, pp. 20-27.

Janisch, D. & Gaillard, F. (1998). Minnesota Seal Coat Handbook, MN/RC-1999-07, *Minnesota Department of Transportation*, Maplewood, 112.

Kadrmas, A., "Report on Comparison of Residue Recovery Methods and Rheological Testing of Latex and Polymer Modified Asphalt Emulsions", Annual Meeting of the American Emulsion Manufacturers Association, Report #4-AEMA ISAET 08 (2008).

Kadrmas, Arlis, Personal Communication, February 2009.

Kandhal, P. & Motter, J. (1991). Criteria for Accepting Precoated Aggregates for Seal Coats and Surface Treatments. *Transportation Research Record 1300,* 80–89.

Kari, W. J., Coyne, L. D., and McCoy, P. E., (1962). Seal Coat Performance-Interrelation of Variables Established by Laboratory and Field Studies, *Proceedings of the Association of Asphalt Paving Technologists*, Vol 31, pp 1-34.

Kearby, J. P., "Tests and Theories on Penetration Surfaces", *Proceedings, Highway Research Board*, Vol 32, 1953.

Kucharek, A., "Measuring the Curing Characteristics of Chip Sealing Emulsions", Paper Presented at the Joint ARRA-ISSA-AEMA Meeting, Asphalt Emulsion Manufacturers Association and McAsphalt (2007).

Lee, Ju Sang, and Kim, R. Y. "Performance-Based Uniformity Coefficient of Chip Seal Aggregate", presented at 88th Annual Meeting of Transportation Research Board, Washington, D. C., 2009.

LTPPBIND, Version 3.0/3.1, http://www.fhwa.dot.gov/PAVEMENT/ltpp/ltppbind.cfm, Federal Highway Administration, Washington, D.C. (page modified 2009).

LTPP DataPave. SPS-3 Construction Report SHRP North Atlantic Region. Pavement Management Systems Limited. Oct. 1990.

LTPP DataPave. SPS-3 Construction Report SHRP Southern Regional Coordination Office. Brent Rauhut Engineering Inc. Jan. 1991.

LTPP DataPave. SPS-3 Construction Report SHRP Western Region. Nichols Consulting Engineers, Chtd. Reno, NV. Dec. 1990.

Maintenance Chip Seal Manual, (2000). Montana Department of Transportation, Helena.

Maintenance Treatments, Instructor's Guide. *Report No. FHWA-SA-96-028*, Federal Highway Administration, Washington, D.C.

Major, N. G. (1965). A basis for selection of binders for chip sealing. *New Zealand Engineering*, Vol 20, Issue 12, pp 521-528.

Marais, C. P., "Rational Design of the Single Surface Treatment Technique for Road Maintenance, *The Civil Engineer in South Africa*, August, 1981.

Marchal, Julien Boussad, "Bitumen Emulsion Testing: Toward a Better Understanding of Emulsion Behaviour", *Proceedings, Eurobitume*, 1993.

Masad, Eyad, "Aggregate Imaging System (AIMS): Basics and Applications," Implementation Report FHWA/TX-05/5-1707-01-1, Texas Transportation Institute (TTI), College Station, TX (2005).

McHattie, R., (2001). *Asphalt Surface Treatment Guide*, Report FHWA-AK-RD-01-03, Alaska Department of Transportation and Public Facilities, Juneau, 136.

McLeod, N. (1960). Basic Principles for the Design and construction of Seal Coats and Surface Treatments. *Proceedings of the Association of Asphalt Paving Technologist*, 29, 1-150.

McLeod, N. W., "Seal Coat Design", *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 38, February, 1969.

Miller, John S. and Bellinger, William Y., "Distress Identification Manual for the Long-Term Pavement Performance Program (Fourth Revised Edition), FHWA-RD-03-031, June 2003, http://www.tfhrc.gov/pavement/ltpp/reports/03031/index.htm

Morgenstern, Bruce, Wyoming 538.0 (under review), Field Emulsion Viscosity Test

NCHRP Report 523 (2004). *Optimal Timing of Pavement Preventive Maintenance*. Transportation Research Board, Washington, D. C.

NCHRP Synthesis 342. (2005). *Chip Seal Best Practices*, Transportation Research Board, Washington, D. C.

Nebraska Department of Roads, Standard Specifications for Highway Construction, 2007 edition.

Nixon, Wilfrid. Thin Maintenance Overlays and Winter Maintenance, May 2000.

Novi, Michigan. http://ci.novi.mi.us/community/PASER/PASERratingsystem.htm accessed May 2005

Notes for the Specification for Bituminous Reseals. TNZ P17. Transit New Zealand, Wellington, 2002.

Outcalt, W. SHRP Chip Seal. Colorado Research Report No. CDOT-DTD-R-2001-20. Dec. 2001.

Pavement Preservation Emulsion Task Force Meeting Minutes, Online at www.pavementpreservation.org/expert/12-15-08-ETG-ETF-Final.pdf, Lexington, Kentucky, December (2008), Accessed July 31, 2009.

Performance Graded Asphalt Binder Specification and Testing. Superpave Series No. 1 (SP-1). Asphalt Institute, Lexington, KY.

"Pavement Preservation Concepts and Techniques", FHWA Publication No. FHWA-RC-BAL-04-0015, Federal Highway Administration (FHWA), Washington, D.C. (2004).

Pidwerbesky, B., J. Waters, D. Gransberg, and R. Stemprok, "Road Surface Texture Measurement Using Digital Image Processing and Information Theory," Land Transport New Zealand Research Report 290, New Zealand.

Plummer, R. (1996). Chip Seal Use- Back to the Basics. Better Roads, 66(4), 36-38.

Potter, J. L., and Church, M., "The Design of Sprayed Seals", *Proceedings of the Australian Road Research Board*, Vol 8, 1976, pp 18-23.

Prapaitrakul,N., R. Han, X. Jin, C. J. Glover, D. Hoyt and A. Epps Martin, "The Effect of Three Asphalt Emulsion Recovery Methods on Recovered Binder Properties", Petersen Asphalt Research Conference (2009).

Preventive Maintenance. *Transportation Research Record 1442*, Washington D.C., p 31-37.

Reigle, J. (2000). *Development of an Integrated Project-Level Pavement Management Model Using Risk Analysis. Dissertation*. West Virginia University: West Virginia.

Roque, R., D. Anderson, and M. Thompson, "Effect of Material, Design, and Construction Variables on Seal-Coat Performance," *Transportation Research Record 1300*, Transportation Research Board, National Research Council, Washington, D.C., 1991.

Santi, Michael, "Case Study of a State Emulsion QA Program", presentation to the Rocky Mountain Pavement Preservation Partnership, Airport Hilton, Salt Lake City, UT, October 30, 2009.

Saskatchewan Highways and Transportation, Specifications for Manufactured Materials, Asphalt Emulsions, SMM 103-3.4, 1999.

Seal Coat Placement, (2004). Indiana Department of Transportation Training Manual, Indianapolis, Retrieved from http://www.in.gov/dot/div/training/manuals/hotmix/chapter_09.pdf

Sebaaly, P. E., Lani, S., and Hand, A., (1995). Performance Models for Flexible Pavement Maintenance Treatments, *Journal of the Transportation Research Board*, TRR 1508, pp. 9-21.

Semmelink, C. J., "The Determination of the Average Least Dimension and the Void Ratio of Stone for Surface Seals by Means of a Modified Tray Test", National Institute for Transport and Road Research, Technical Note: TC/67/82, December, 1982.

Sezen, H., Principal Investigator, "Validation of ODOT's Laser Macrotexture System," The Ohio Department of Transportation Office of Research and Development, Executive Summary Report, Project FHWA/OH-2008/12, 2008.

SHRP Distress Identification Manual for the Long-Term Pavement Performance Program, FHWA RD-03-031, June 2003.

Shuler, S. (1991). "High Traffic Chip-Seal Construction: The Tulsa Test Road" Transportation *Research Record 1300*. Transportation Research Board, National Research Council, Washington, D.C., 1991.

Shuler, S., (1996)."Chip Seals for High-Traffic Volume Asphalt Concrete Pavements", NCHRP Final Report for Project 14-8A, 1996.

Shuler, S. (1998). "Design and Construction of Chip Seals for High Traffic Volume." *Flexible Pavement Rehabilitation and Maintenance.* ASTM Special Technical Publication (STP) Number 1348. American Society for Testing and Materials. West Conshohocken, PA.

Shuler, S. (2007). "Interim Report: Pavement Preventive Maintenance Treatments." Project 10.50 Colorado Department of Transportation, Denver, CO.

Shuler, Scott, 2011, When to Safely Broom or Remove Traffic Control on Fresh Emulsified Asphalt Chip Seals, Transportation Research Record: Journal of the Transportation Research Board, No. 2235, Maintenance and Preservation of Pavements, Transportation Research Board of the National Academies, Washington, D.C., pp. 82-87.

Shuler, S., Epps-Martin, A., Lord, A., and Wiley-Cunnigan, D., "Manual for Emulsified Asphalt Chip Seal Design and Construction", NCHRP Report 680, National Academies, 2011.

Sprayed Sealing Guide (2004). AP-676/104, Austroads, Sydney, Australia, , p 104.

Stevenson, James, Maintenance Chief, MDT Billings District, Montana Department of Transportation, email correspondence September 20, 2006.

Stony Brook Scientific Falling Needle Viscometer (http://www.stonybrooksci.com/)

Stroup-Gardiner, M, Newcomb, D. E., Epps, J. A., and Paulsen, G. L. (1990). Laboratory Test Methods and Field Correlations for Predicting the Performance of Chip Seals, *Asphalt Emulsions, ASTM STP 1079*, H. W. Muncy, Ed., ASTM, Philadelphia, PA, pp. 2-19.

Stroup-Gardiner, Mary, summaries of LTPP database developed from 2002-2006 for use in Auburn University CIVL 7850.

Design and Construction of Surfacing Seals, *Technical Recommendations for Highways, TRH3 2007*, South African National Roads Agency, Ltd, Pretoria, South Africa, pp 1-276.

Takamura, K., “Comparison of Emulsion Residues Recovered by Forced Air Flow and RTFOT Drying”, International Slurry Surfacing Association/Asphalt Emulsion Manufacturers Association, Joint Annual Meeting, Amelia Island, FL, March 2000.
Temple, W. (2002). Performance of Louisiana’s Chip Seal and Microsurfacing Program. *Transportation Research Record*, 1795, 3-16.

Texas Test Method Tex-224-F, “Flakiness Index”.
Transport Research Laboratory (1996). *Design guide for road surface dressings.* Road Note 39 4th edition. (TRL Limited, Crowthorne).

Urbac, R.R., and Skok, E.L. Strategic Highway Research Program Long Term Pavement Performance North Central Region SPS-3 Program: Effectiveness of Routine Maintenance Treatments on the Performance of flexible Pavements. March 1993

Vagher, B., President, A-1 Chip Seal, Denver, Colorado, personal communication, June 2004.

Van Zyl, Gerrie, “Measurement and Interpretation of Input Parameters Used in the SA Surface Seal Design Method”, presented at CAPSA 07, *9th Conference on Asphalt Pavements for South Africa*, 2007, retrieved on October 7, 2009 from:
http://www.capsa07.co.za/CapsaDocs/papers/012%20van%20Zyl.pdf

The Vialit Plate Shock Test , BS EN 12272-3 : 2003 : Surface Dressing - Test Methods - Part 3

Virginia Department of Transportation, Special Provisions for Project US19/460, Tazewell, 1991.

Wade, M., DeSombre, R. & Peshkin, D. (2001). *High Volume/High Speed Asphalt Roadway Preventive Maintenance Surface Treatment,* Research Report SD99-09,

Walubita, L.F., A. Epps Martin, D. Hazlett, and R. Barcena, “Initial Validation of a New Surface Performance-Graded Binder Specification”, *Transportation Research Record 1875,* Transportation Research Board, Washington D.C. (2004).

Walubita, L.F., A.E. Martin, and C.J. Glover, "A Surface Performance-Graded (SPG) Specification for Surface Treatment Binders: Development and Initial Validation", Report No. FHWA/TX-05/0-1710-2. Texas Department of Transportation and U.S. Department of Transportation, FHWA (2005).

Washington State Department of Transportation. (2003, March). Asphalt Seal, *Technology Transfer*, 1-30.

Wegman, S., (1991). *Design and Construction of Seal Coats.* Minnesota Department of Transportation, Mendota Heights, 34.

Weinert, H. H., "Climate and the durability of South African road aggregates", Bulletin of Engineering Geology and the Environment, Vol 29, Number 1, June 1984.
Whitcomb, W. G., Terrel, R. L., Paulsen, G., Hicks, R. G., Wyckoff, C.,

Woo, J.W., E. Ofori-Abebresse, A. Chowdhury, J. Hilbrich, Z. Kraus, A. Epps Martin, and C. Glover, "Polymer Modified Asphalt Durability in Pavements", Report #FHWA/TX-07/0-4688-1, Texas Transportation Institute (2006)

Yazgan, B. and Senadheera, S., (2003). *A New Testing Protocol for Seal Coat (Chip Seal) Material*, Texas Tech University, Lubbock,

Zaniewski, J and Mamlouk, M. (1996). Preventive Maintenance Effectiveness – Preventive

Zimmerman, K., and Peshkin, D. (2003, August). Integrating Preventive Maintenance and Pavement Management Practices. Retrieved on October 15, 2006 from http://www.ctre.iastate.edu/pubs/midcon2003/ZimmermanPreventive.pdf

APPENDIX A – PRECONSTRUCTION CONDITION SURVEYS

CRACK SURVEY FORM

Date Apr-09

Roadway No./Name: SH71

Site no. 1: Snyder
North East CO

Lane: north bound

Station From	Station To	Test Section	Severity	Longitudinal (ft)	Transverse (ft)	Alligator (sq. ft)	Notes
0	100	1	Low	64	10	0	ch loss along road 1'-10" width total
			Moderate	1	6	0	1 ft width of loss is next to road C.L.
			High	0	3	0	Long cracks loss agg in spots
100	200	2	Low	72	27	0	
			Moderate	0	3	0	"
			High	0	2	0	
200	300	3	Low	39	32	30	
			Moderate	0	8	0	"
			High	0	0	0	
300	400	4	Low	36	5	27	
			Moderate	33	2	0	"
			High	0	0	0	
400	500	5	Low	40	31	55	
			Moderate	35	8	0	"
			High	0	0	0	
500	600	6	Low				
			Moderate	100	54	0	
			High				
600	700	7	Low				
			Moderate	100	66	0	
			High				
700	800	8	Low				
			Moderate	80	60	0	
			High				
800	900	9	Low				
			Moderate	100	60	30	
			High				
900	###	10	Low				
			Moderate	80	62		
			High				
###	###	11	Low				About MP 186.5 is boundary of section 10 and section 11
			Moderate	80	68		
			High				
###	###	12	Low				
			Moderate	100	76		
			High				
###	###	13	Low				
			Moderate	100	66		
			High				
###	###	14	Low				
			Moderate	100	48		
			High				
###	###	15	Low				
			Moderate	70	46		
			High				

CRACK SURVEY FORM

Date Apr-09

Roadway No./Name: SH71

Site no. 1: Snyder
North East CO

Lane: north bound

Station From	Station To	Test Section	Severity	Longitudinal (ft)	Transverse (ft)	Alligator (sq. ft)	Notes
0	100	16	Low		48		
			Moderate	24	10		
			High				
100	200	17	Low		72		
			Moderate	16	12		
			High				
200	300	18	Low		72		
			Moderate	6	12		
			High				
300	400	19	Low		36		
			Moderate	10	24		
			High				
400	500	20	Low				
			Moderate	25	56	0	
			High				

CRACK SURVEY FORM

Date Jul 8, 09

Roadway No./Name: SH59

Site no. 3: Sedgwick
North East CO

15 ft lane including shoulder
section 1 starts at mm 165

Lane: south bound

Station From	Station To	Test Section	Severity	Longitudinal (ft)	Transverse (ft)	Alligator (sq. ft)	Notes
0	100	1	Low	76	34	0	scraped flush (except for shoulder);
			Moderate	10	5	0	chipseal approx nil in lane
			High	0	0	0	15 ft lane
100	200	2	Low	105	25	6	
			Moderate	1	6	0	"
			High	0	3	0	
200	300	3	Low	97	26	16	
			Moderate	5	0	60	"
			High	0	0	0	
300	400	4	Low	4	0	288	
			Moderate	0	8	0	"
			High	40	2	0	
400	500	5	Low	0	0	308	
			Moderate	0	9	0	"
			High	0	0	0	
500	600	6	Low	52	56	24	
			Moderate	0	13	0	"
			High	0	3	0	
600	700	7	Low	57	15	0	
			Moderate	2	4	24	"
			High	0	8	0	
700	800	8	Low	43	14	12	
			Moderate	0	20	4	
			High	0	3	0	
800	900	9	Low	84	12	12	
			Moderate	10	7	0	
			High	0	3	0	
900	1000	10	Low	0	6	0	
			Moderate	0	30	68	
			High	0	3	0	

CRACK SURVEY FORM Date Jul 8, 09

Roadway No./Name: SH59 Site no. 3: Sedgwick

15 ft lane including shoulder North East CO

Lane: south bound

Station From	Station To	Test Section	Severity	Longitudinal (ft)	Transverse (ft)	Alligator (sq. ft)	Notes
0	100	**11**	Low	40	25	0	
			Moderate	0	0	0	chipseal approx nil in lane
			High	0	0	0	
100	200	**12**	Low	11	8	0	
			Moderate	13	0	0	"
			High	0	1	0	
200	300	**13**	Low	4	5	0	
			Moderate	7	2	0	"
			High	0	0	0	
300	400	**14**	Low	0	6	0	
			Moderate	2	5	0	"
			High	0	0	0	
400	500	**15**	Low	5	13	0	ipseal evident 5' from shoulder edg
			Moderate	0	0	0	o chseal on inner 10 feet of roadwa
			High	0	0	0	
500	600	**16**	Low	2	12	0	
			Moderate	3	4	0	"
			High	0	6	0	
600	700	**17**	Low	1	4	0	
			Moderate	0	0	0	"
			High	3	15	0	
700	800	**18**	Low	0	2	0	
			Moderate	0	12	0	"
			High	0	15	0	
800	900	**19**	Low	0	10	0	.5" w chseal streaks along roadwa
			Moderate	0	0	0	nly minus no. 4 remaining in chsea
			High	0	15	0	
900	1000	**20**	Low	0	0	0	
			Moderate	0	0	0	"
			High	0	0	0	

APPENDIX B – DRAFT SPECIFICATION FOR COVER COAT AGGREGATE

703.05 Aggregate for Cover Coat Material for Traffic Greater Than 500 AADT. Aggregates for cover coat material shall be crushed stone, crushed slag, crushed gravel, or natural gravel. Aggregates shall be composed of clean, tough, durable fragments free from an excess of flat, elongated, soft, or disintegrated pieces and free from fragments coated with dirt or other objectionable matter. Slag shall be air-cooled blast-furnace slag reasonably uniform in density.

The aggregate shall conform to the following requirements for traffic volumes exceeding 500 AADT

(1) Percentage of wear, Los Angeles Abrasion Test (AASHTO T 96), not more than 35.

(2) When blast-furnace slag is used, weight per cubic foot shall be at least 70 pounds.

(3) For Type I, II, or III cover coat material, 90 percent by weight of the particles retained on the 4.75 mm (No. 4) sieve shall have at least two fractured faces when tested in accordance with Colorado Procedure 45.

(4) Lightweight aggregate used for cover coat material shall be an aggregate prepared by expanding shale, clay, or slate in a rotary fired kiln. Lightweight aggregate shall have a dry loose unit weight of 35 to 55 pounds per cubic foot determined in accordance with AASHTO T 19, Shoveling Procedure. The total mass of the test sample of lightweight aggregate used in AASHTO T 96 (Los Angles Abrasion) shall be 2000 g.

Table 703-6a
GRADATION SPECIFICATIONS FOR COVER COAT AGGREGATE

Sieve Size	Percent by Weight Passing Square Mesh Sieve		
	9.5 mm (3/8") Type 1	**12.5 mm (½") Type II**	**19.0 mm (¾")* Type III**
19.0 mm (¾")			100
12.5 mm (½")		100	95-100
9.5 mm (3/8")	100	70-100	60-80
4.75 mm (No. 4)	0-15	0-4	0-10
75 µm (# 200)	0-1.0	0-1.0	0-1.0

*Type III shall be used only with lightweight aggregates.

703.051 Aggregate for Cover Coat Material for Traffic Less Than 500 AADT. Aggregates for cover coat material shall be crushed stone, crushed slag, crushed gravel, or natural gravel. Aggregates shall be composed of clean, tough, durable fragments free from an excess of flat, elongated, soft, or disintegrated pieces and free from fragments coated with dirt or other objectionable matter. Slag shall be air-cooled blast-furnace slag reasonably uniform in density.

The aggregate shall conform to the following requirements for traffic volumes less than 500 AADT

(1) Percentage of wear, Los Angeles Abrasion Test (AASHTO T 96), not more than 35.

(2) Type IV cover coat material shall have greater than 15 percent by weight of the particles retained on the 4.75 mm (No. 4) sieve with two fractured faces when tested in accordance with Colorado Procedure 45.

(3) Flakiness Index less than 35 (Tex 224F)

Table 703-6b

GRADATION SPECIFICATIONS FOR COVER COAT AGGREGATE

Sieve Size	Passing, %
	9.5 mm (3/8") Type 1V
9.5 mm (3/8")	100
4.75 mm (No. 4)	20-70
2.37 mm (No. 8)	0-15
75 µm (# 200)	0-3

APPENDIX C – DRAFT DESIGN METHOD FOR CHIP SEALS

Design of chip seals involves estimating the quantities of aggregate chips and asphalt emulsion to be applied to the surface of the pavement to be sealed. The method that has been found to estimate the appropriate quantity of materials closest for low volume (500 AADT or less) traffic roadways in Colorado is based on a method originally proposed by Kearby (1953) revised by Benson and Gallaway (1953), then further revised based on recent research (Shuler, 2011).

This method requires some simple laboratory apparatus and tests to conduct. The tests and method are listed below:

Dry Loose Unit Weight- AASHTO T19 (rodding procedure)

Bulk Specific Gravity – AASTHO T84 and T85

Sieve Analysis of Fine and Coarse Aggregate – AASHTO T27

Board Test. Fabricate a rectangular board from 5/8-inch thick plywood, melamine, or particle board measuring 18 inches by 36 inches. Attach 1-inch x 2-inch pieces of lumber to the perimeter of the board to create an edge. Weigh the completed board and edging. Place a representative sample of aggregate chips on the board so that the quantity of chips is one stone thick and so there is little or no space between the chips. Testing has verified this process should require approximately 30 minutes to complete. It is important that as many chips be placed on the board so no room remains for additional chips without obtaining more than one layer of chips. Record the quantity of chips in terms of pounds of chips per square yard of board. This is the design aggregate quantity, Q.

The quantity of emulsion to be applied to the pavement to cement this quantity of chips is calculated as follows:

$$E = \frac{\{3Q/W\}\,\{1 - [W/62.4G]\}(T) + V}{R}$$

where:

E = emulsion spray rate, gal/square yard,

Q = Aggregate quantity from Board Test, lbs/square yard,
W = Dry Loose Unit Weight, pounds/square yard,
G = Bulk Specific Gravity of Aggregate Chips,
T = Traffic Correction from Table C1,
V = Substrate Surface Condition from Table C2, and
R = Asphalt Residue Content of Emulsion (expressed as a decimal).

Table C1. Traffic Correction

Traffic Factor, T	AADT		
	< 100	100-250	250-500
	1.20	1.15	1.10

Table C2. Substrate Surface Condition

Existing Surface Condition	Correction Factor, V, gal/square yard
Flushed-bleeding	-0.06
Smooth, non-porous	-0.03
Slightly porous, slightly oxidized	0.00
Slightly pocked, porous, oxidized	+0.03
Badly pocked, porous, oxidized	+0.06

An example of how this method works is as follows:

Q= 26 psy,
W=113 pcf,
G = 2.65,
T = 1.1 (AADT=250-500),
V = -0.03 gsy (smooth, non-porous), and
R= 0.69

then: $$E = \frac{\{3\,(26)/113\}\,(\{1 - [113/62.4\,(2.65)]\}\,1.1\,) - 0.03}{0.69} = 0.27 \text{ gsy}$$