NCHRP Project 14-17

MANUAL FOR EMULSION-BASED CHIP SEALS FOR PAVEMENT PRESERVATION

APPENDICES A to J

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APPENDIX A - Literature Review

Introduction

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 A1. 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 A2. 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 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.
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.

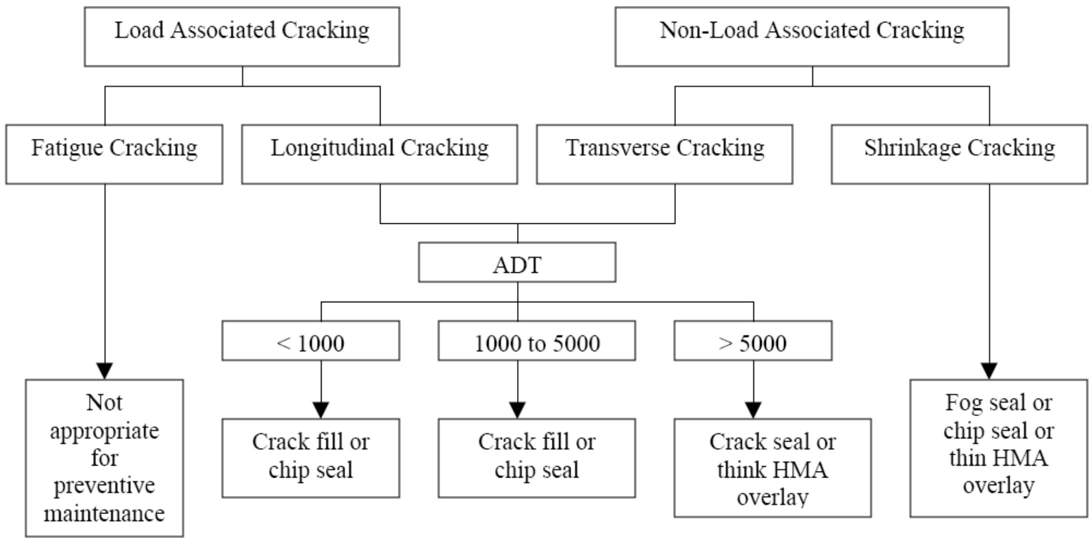

Figure A1. (Zimmerman, & Peshkin, 2003).

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.

5.1.4 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.

5.1.5 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.

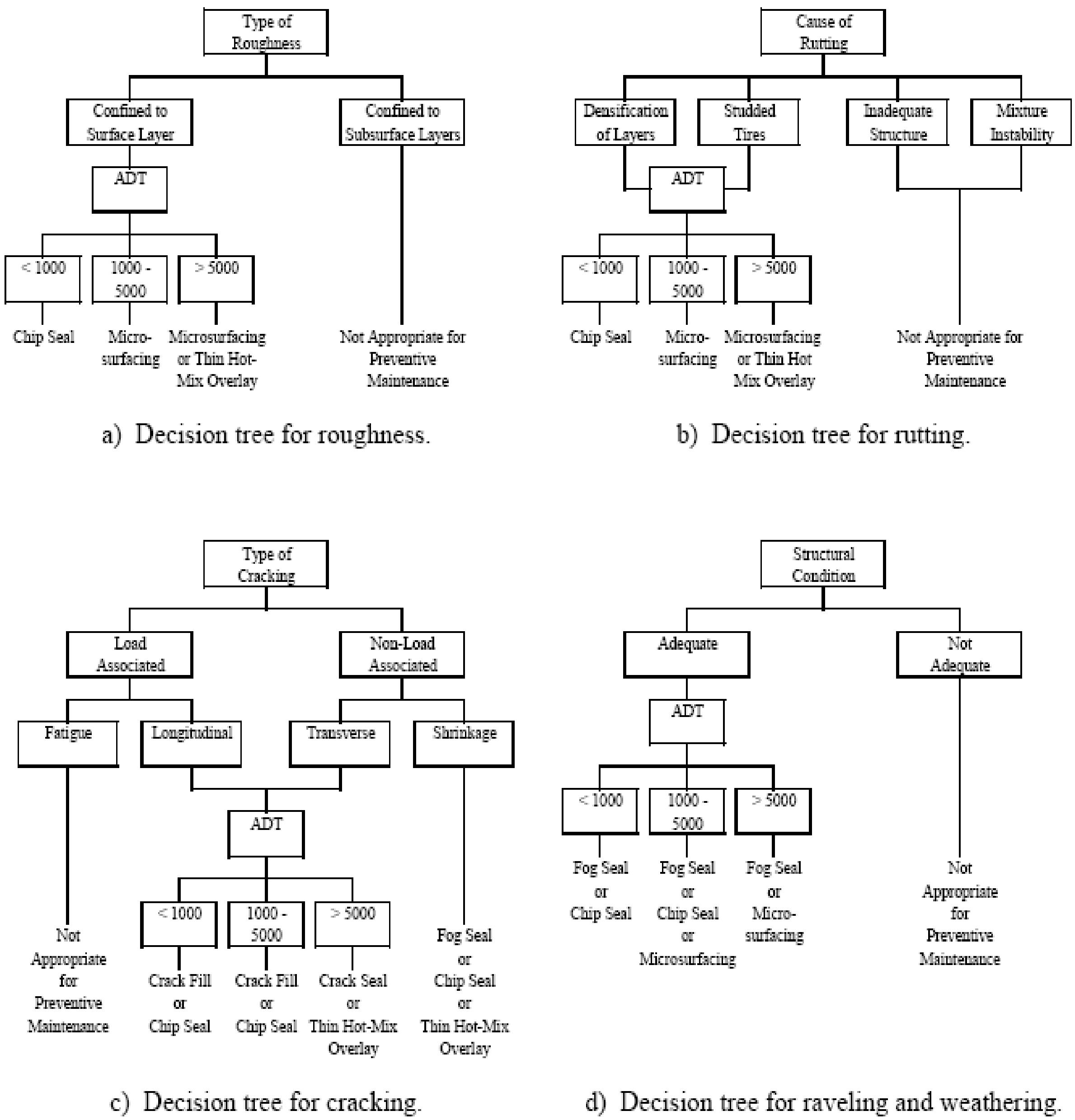

Figure A2. Decision Tree for Selecting Preventive Maintenance Techniques (Hicks et al., 2000)

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

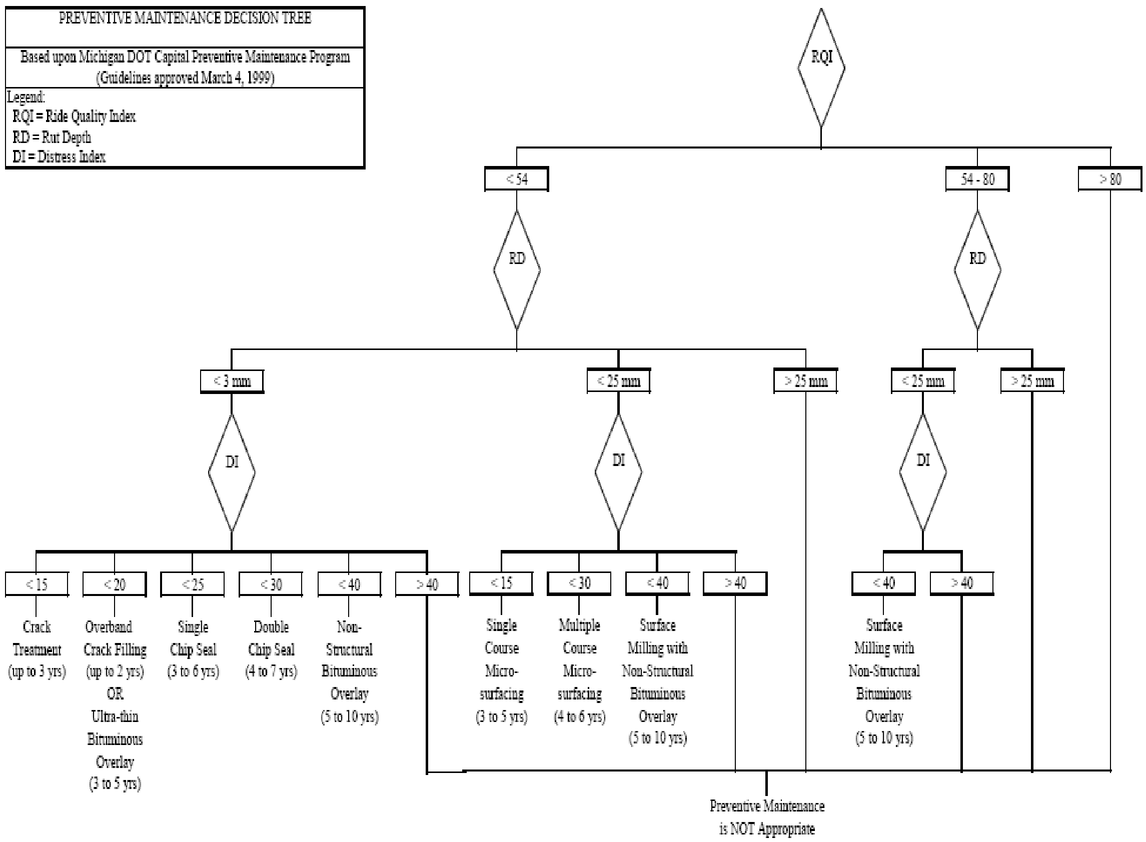

Figure A3. Distress Level Preventive Maintenance Decision Tree. (Hicks, Seeds, & Peshkin, 2000)

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 A3 lists appropriate binder/chip seal combinations for addressing various distress mechanisms. Generally, chip seals are not used on roads with AADT > 40,000.

Table A3. 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);
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 A3 describes a procedure for the calibration and certification of bitumen sprayers in Australia. (Austroads work tips, 2002)

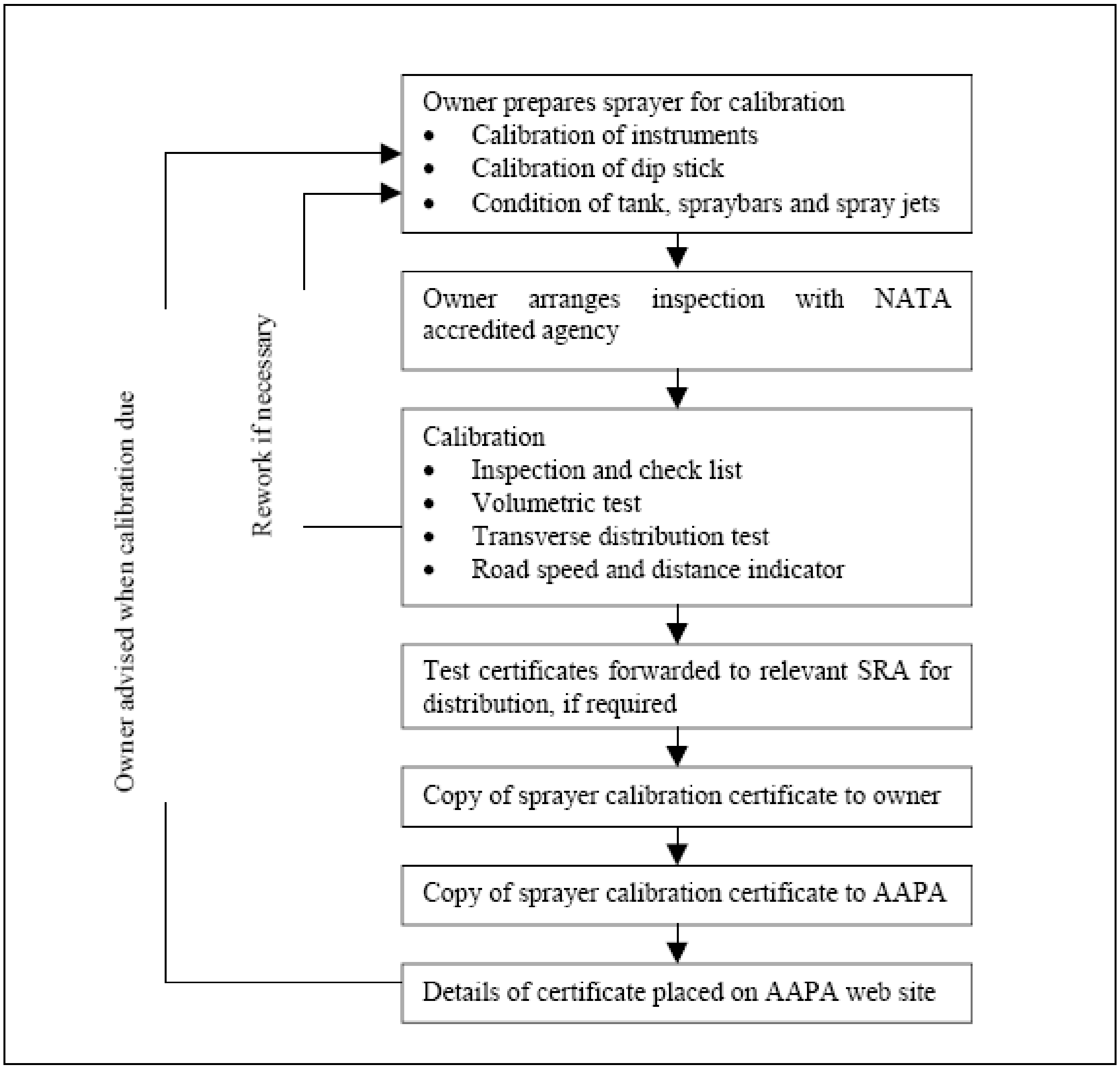

Figure A3. Calibration and Certification of Distributors in Australia

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/m^2)
H = average least dimension (ALD) (m)
T = Traffic Factor
V = Voids in Loose Aggregate (%)
S = Surface Condition Factor (l/m^2)
A = Aggregate Absorption (l/m^2)
P = Surface Hardness Correction for Soft Pavement (L/m^2)
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 A4 and A5 shows the influence of angle for nozzle discharge and the influence of spray bar height.

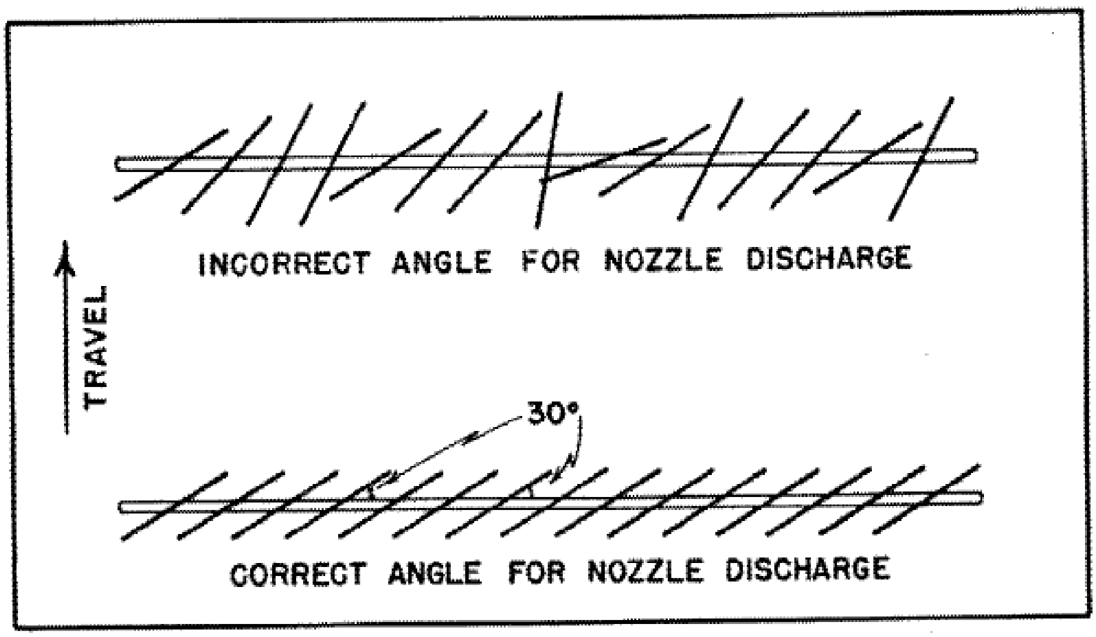

Figure A4. Influence of Angle for Nozzle Discharge (McLeod, 1960).

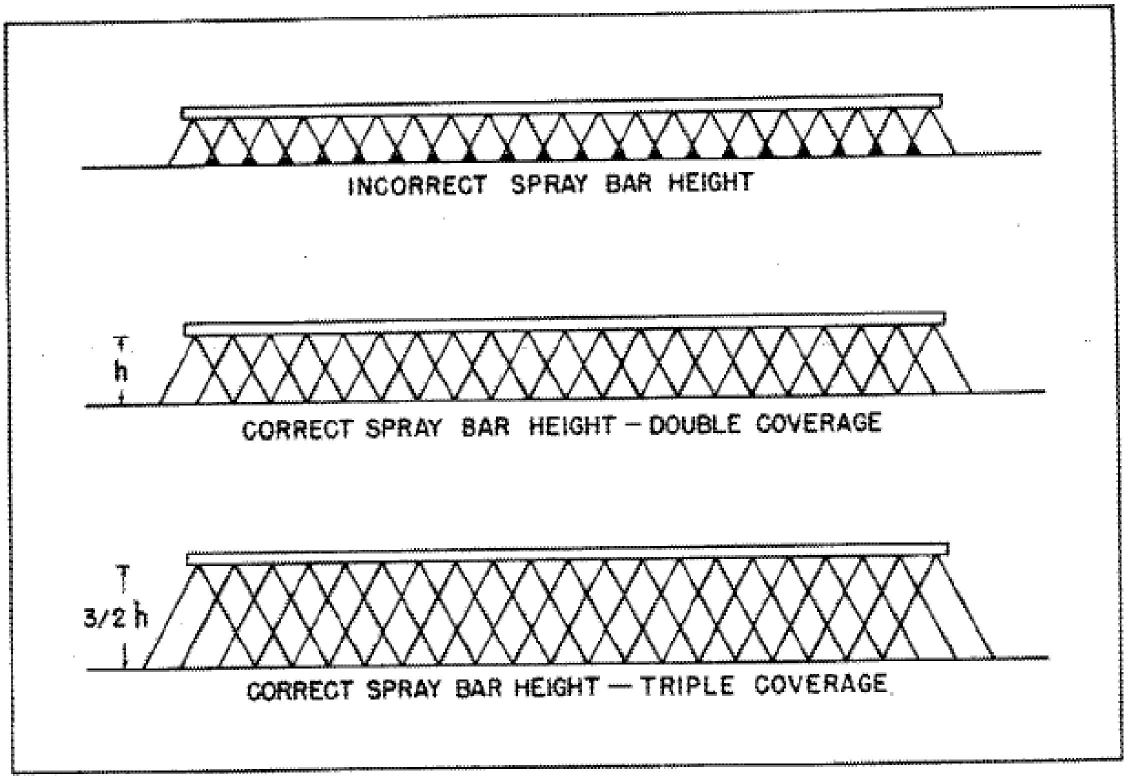

Figure A5. Influence of Spray Bar Height (McLeod, 1960).

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 more daylight hours during this time of the year, also. 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 A4. 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) – (See Page 5.7)
G = Bulk Specific Gravity – (See CT 206 & CT 208)
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 A6 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.

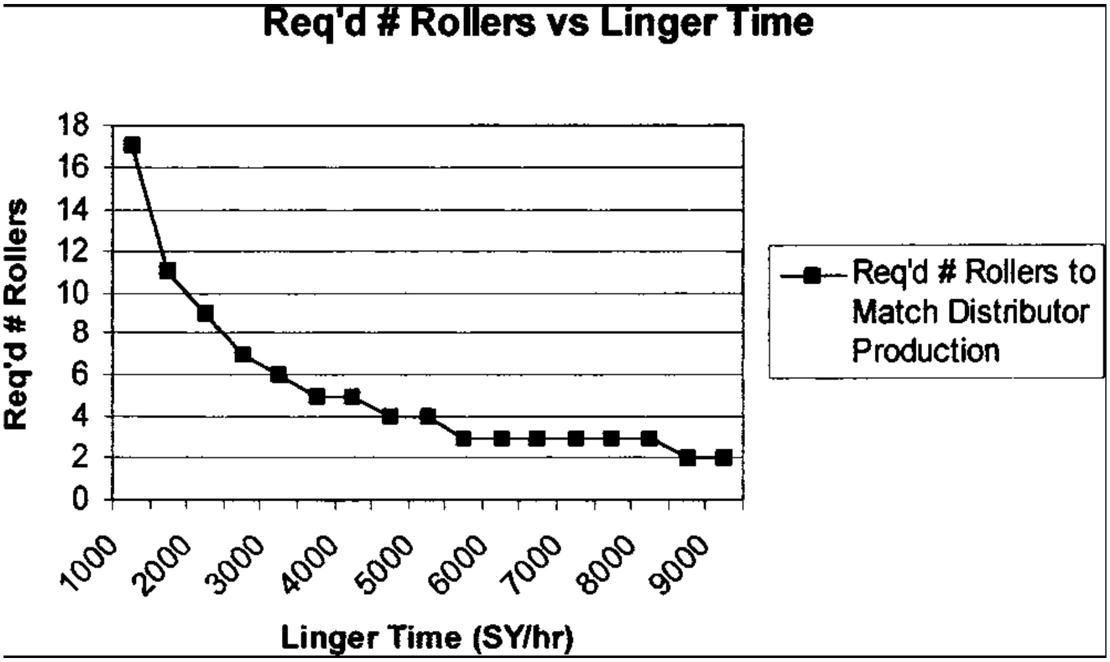

Figure A6. Linger Time Versus Number of Rollers required (Gransberg, et al., 2004).

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).

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 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 to in excess of one-half hour some cases. The standard specifications in effect at that time provided on 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 after study by 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 also provide 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 increases 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 A5 shows the recommended grading of aggregates for chip seals by Kearby from 1953.

Table A5. Recommended Grading of Aggregates for Chip Seals (Kearby,1953).

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 A6 lists typical chip seal gradations taken from various state DOT manuals in the United States.

Table A6. Examples of Chip Seal Gradations in the U. S (Gransberg & James, 2005).

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	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
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 A6 shows the average least dimension (ALD), the effects of flakiness and changes in voids based on compaction (Caltrans Division of Maintenance, 2003).

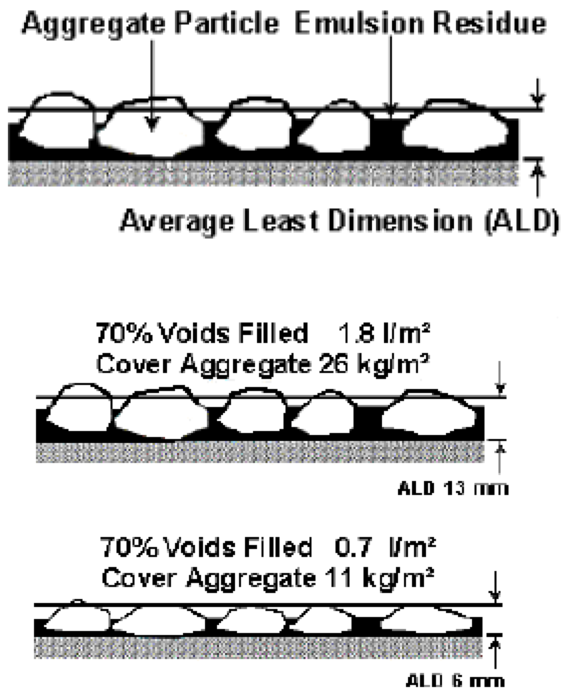

Figure A6. (Caltrans Division of Maintenance, 2003)

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
G = Bulk Specific Gravity of the Aggregate

Potter & Church developed the relationship shown in Figure A7 showing the reduction in voids with decreasing layer depth.

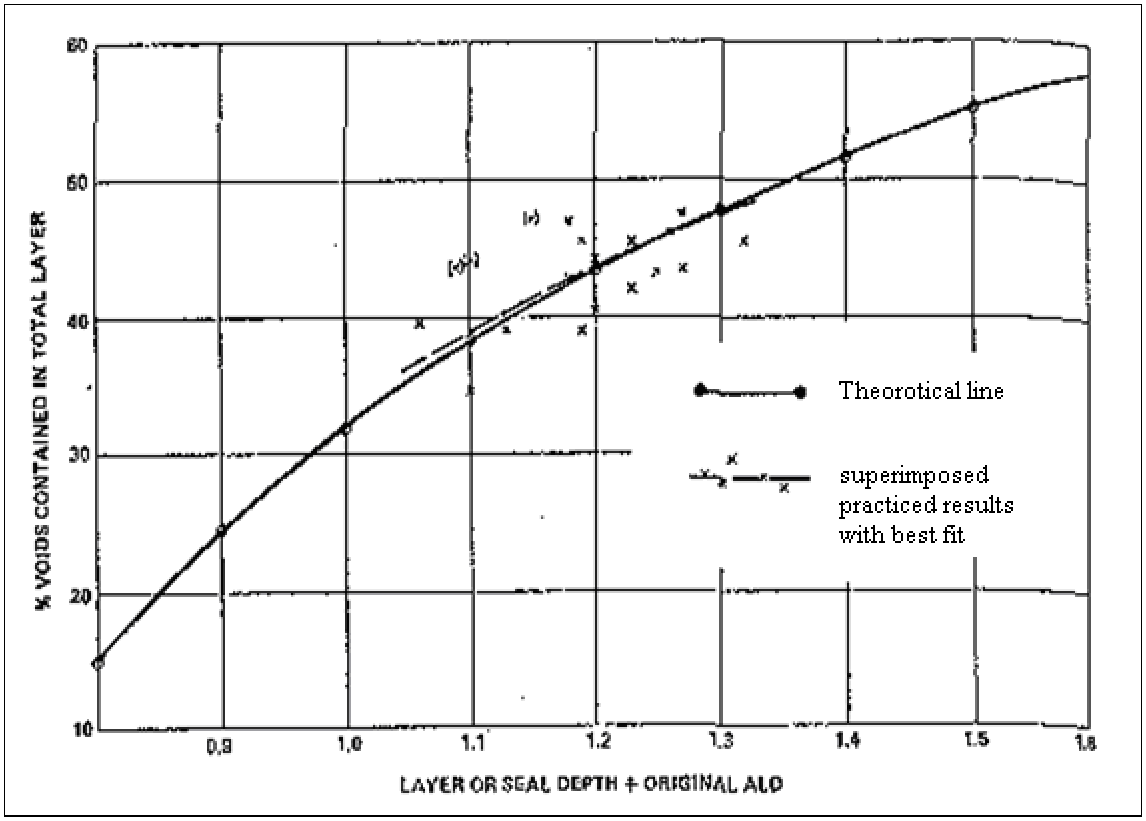

Figure A7. Reduction in voids with decreasing layer depth (Potter & Church, 1976).

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 A8 is a graph showing aggregate loss compared with asphalt application rate from a study done by Gallaway, & Harper, 1966.

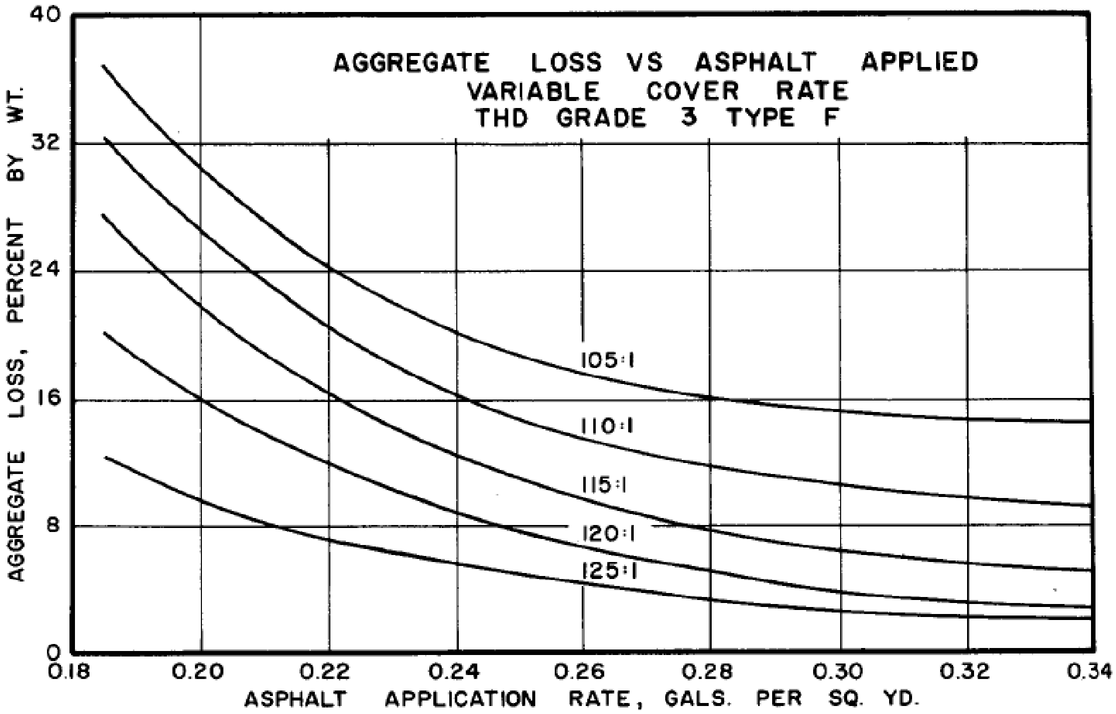

Figure A8. (Gallaway, & Harper, 1966).

Gallaway, & Harper, 1966 found that light weight 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 measured in this research indicates this may only be true before the emulsion has set and that after the binder becomes a residue, no effect exists.

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 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. 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). Resistance to weathering and freeze-thaw degradation is generally measured by either magnesium sulfate loss or sodium sulfate loss (AASHTO T104) (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
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 A9.

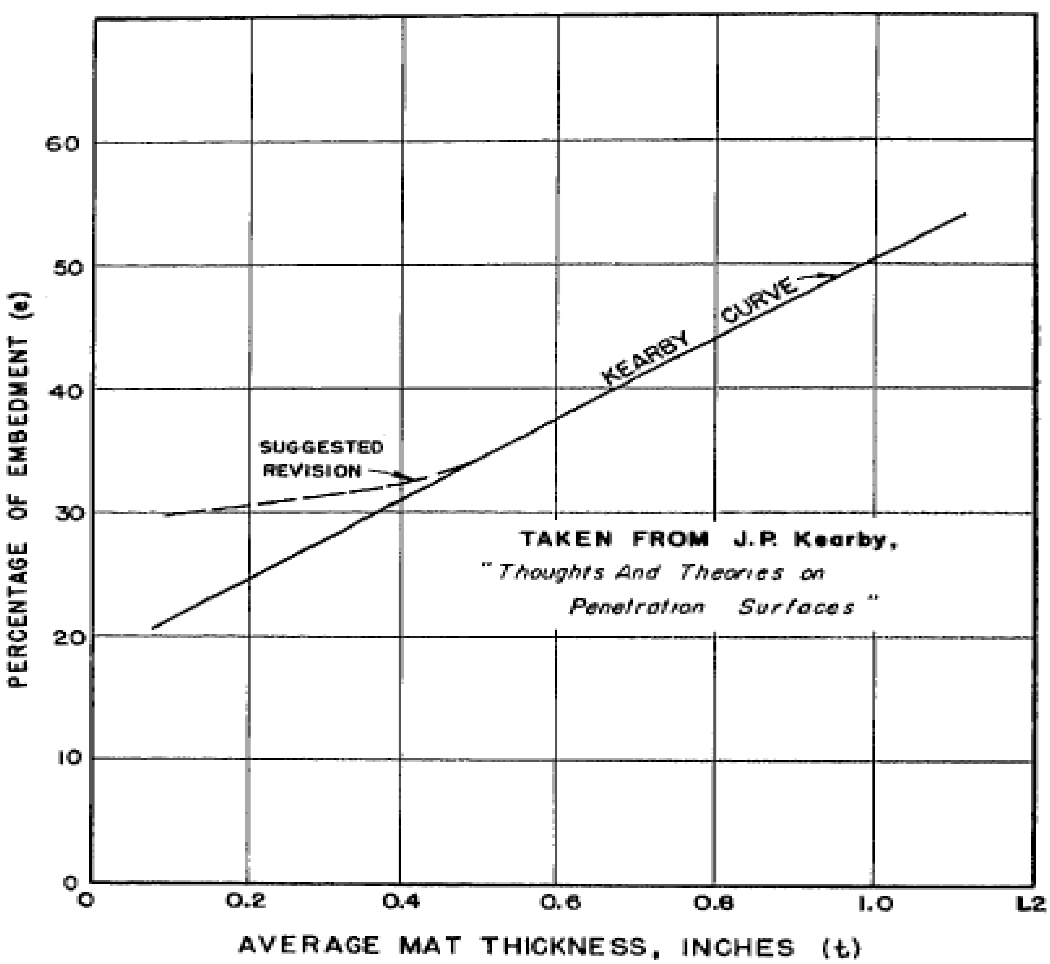

Figure A9. Embedment as a Function of Average Mat Thickness (Kearby, 1953)

Benson and Gallaway suggested a revised Kearby relationship shown in Figure A9 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 A9 = 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 85th –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 A6. 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 $G^*/\text{Sin}\ \delta$ 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 A7.

Table A7. 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 A8.

Table A8. 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).

Recovery of Emulsion Residues
Some state agencies use an evaporation method to recover asphalt residue from asphalt emulsions (Caltrans, 1998; Colorado DOT, 2002), while others specify the distillation test (Ohio DOT, 2002; Saskatchewan, 1999). Both of these test methods were developed before widespread use of polymer modified asphalt emulsions. Neither of these methods simulates field curing conditions of asphalt emulsions and are likely to cause changes to the emulsion residue not occurring when applied to an actual pavement. Other methods which allow the emulsion to dry at ambient room temperature using forced air methods (Takamura 2000) may provide one means of recovering residues without detrimental effects. Other methods, such as vacuum recovery (Arizona 504) have been investigated.

Epps et al (2001) conducted an extensive evaluation into the influence of the method of recovery on asphalt binder properties. These researchers investigated:
- Hot oven (ASTM D5404-97) with nitrogen blanket
- Rotovap method as modified by Burr et al.
- Hot plate method used by TxDOT
- ASTM 244-97C (distillation)
- Stirred can method

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APPENDIX B - Chip Adhesion Test

The objective of this portion of the research was to develop a repeatable laboratory test that measures the adhesive strength of emulsified asphalt for aggregate chips as the emulsion sets and becomes a residual binder. This laboratory test has been developed and can be used to determine at what moisture content the chip seal can accept traffic with minimal chip loss. This correlation has been developed and is described in the next section.

Background

The process specified in ASTM D7000, Sweep Test, involves spreading the aggregate over the surface of the emulsion by hand and visually estimating uniformity. This process was followed in this research but resulted in highly variable results. Therefore, an improvement has been developed which allows consistent and repeatable aggregate spread rates. Aggregate embedment depth should affect aggregate sweep loss. Therefore, each of the four research aggregates were embedded to equal depths of emulsion so embedment is not a variable. To determine what embedment depth to use a comparison was done between the Texas and Asphalt Institute (AI) chip seal design methods and ASTM D7000. The idea being to develop a laboratory test method that can be correlated to initial construction field performance.

The following is a summary of the results of this comparison. The aggregate compared below are the limestone (LSTN), granite (GRNT), basalt (BSLT) and alluvial (ALLVL) materials included in the study. Discussion of the contents of this table follows.

Method	Coverages	LSTN	GRNT	BSLT	ALLVL
D-7000	(1) Aggregate (lb/sy)	13.3	14.9	14.9	13.5
	(2) Emulsion (gal./sy)	0.35	0.35	0.35	0.35
	(3) embedment from Texas design	65%	33%	48%	41%
	(4) embedment from AI design	71%	31%	43%	40%
Texas	(5) Aggregate (lb/sy)	10.3	16.1	14.3	14.1
	(6) Emulsion (gal./sy) after SC1, T1, temp,	0.183	0.270	0.197	0.210
	(7) Embedment	24%	27%	25%	25%
	(8) Emulsion (gal/sy) after no SC, T=1, temp, assumed embedment = 40%	0.299	0.405	0.315	0.332
Asphalt Institute Original Formula (compacted state)	(9) Aggregate (lb/sy)	16.48	26.11	22.95	21.73
	(10) Asphalt emulsion (gal./sy) after SC2, T2	0.184	0.268	0.212	0.214
	(11) Embedment	65%	65%	65%	65%

Asphalt Institute (non-compacted state)	(12) Aggregate (lb/sy)	9.98	16.69	15.04	14.33
	(13) Asphalt emulsion (gal./sy) after SC2, T2	0.184	0.268	0.212	0.214
	(14) Embedment	26%	26%	26%	26%
	(15) Asphalt emulsion (gal./sy) after no SC, T=1, temp, assumed embedment = 40%	0.289	0.420	0.332	0.336

Discussion

Aggregate

5.1.6 ASTM D7000

The ASTM D-7000 formula for calculating aggregate spread rate appears to be based on an assumption of an aggregate with 50 percent voids between particles, cubical shape and gradation of 6.5mm (1/4 inch) and 4.75mm (No. 4). Correspondence with the authors of the standard contributed to this understanding along with some laboratory experimental runs. Calculated aggregate coverage for our research aggregate, therefore, produces differing spread rates because of differences between the aggregates with respect to these characteristics.

The D-7000 test method does not necessarily produce one stone thickness, as is desirable for proper chip seal construction. Therefore, the two chip seal design methods were utilized to obtain the required spread rate.

5.1.7 Texas Design

The Texas design uses aggregate loose unit weight and hand placement of aggregate on a board to determine spread rate and asphalt embedment. This method provides practical results regarding how much aggregate will fit in a unit area one stone thick. It also highlights the fact that, while flat particles influence the volume of particles that will fit in a unit area, this volume is also influenced by particle edge-shape.

The Texas mat depth formula is: d, in.= (4 x board weight, psy)/(3 x loose unit weight, pcf). This gives a good approximation of the average particle height in a mat where particles are laid flat.

5.1.8 Asphalt Institute (AI)

The average least dimension of aggregate chips is determined using the median size of each aggregate and flakiness index assuming flat-laid particles.

AI assumes the void volume between aggregate particles is initially 60 percent after rolling, but 40 percent after trafficking. Because the Texas design does not account for traffic compaction, the AI aggregate quantities are higher than the Texas values.

In order to compare the Texas and AI methods, we equalized the effect of compaction. To do this, we modified AI to not allow reduction of voids due to traffic. When this is done the AI values were 1 to 5 percent higher than Texas values, except for the flatter limestone, for which the Texas procedure produced a coverage rate about 3 percent higher. We believe this is because of the flatter limestone which produces a tighter packing in the board test and, therefore, higher coverage.

Emulsion

5.1.9 ASTM D7000

Emulsion volume is fixed at 0.35 gal/sy for D7000. The test aggregate average particle height varies, so aggregate embedment also varies from 31 to 71 percent depending on the particle height determined by the Texas or AI design procedures.

5.1.10 Texas Design

The Texas method uses embedment charts for different average aggregate particle heights and, for the test aggregates, embedment was approximately 25% including correction of -0.03gal./sy for a slightly pocked, slightly porous surface, traffic correction factor =1.0 (over 1000 vehicles per day, vpd) and temperature correction of 0.98 (from 60F to the application temperature of 140F).

5.1.11 Asphalt Institute (AI)

In contrast to Texas, AI requires the user to correct the emulsion volume for temperature (this correction is not included in the formula). Other differences between the two methods include the values assumed for correction factors.

AI defines its Traffic Factor, T as: the percent of voids to be filled. For over 1000 vpd it sets T = 0.65 to avoid bleeding. AI also assumes a void volume reduction to 40% of initial void volume. Together these two factors provide embedment of 26 percent = (0.65*0.4) of the initial uncompacted void volume or 65 percent of the final void volume after compaction.

When correction factors for traffic and surface for both methods are normalized, and initial aggregate embedment is set at 40 percent, we find the emulsion application rate is very similar for the two methods (lines 8 and 15). The emulsion difference is a result of the different mat depths (and, thus, mat void volume) calculated by the two methods.

Embedment

5.1.12 ASTM D7000

The formula used in ASTM D7000 to determine aggregate spread rate requires aggregate size and void volume remain within a limited range. The Texas and AI methods utilize void volumes and particle shape specific to the aggregates to be used in construction.

Additionally, application of the aggregates using the D7000 procedure does not always produce the desired one stone mat thickness. Therefore, a modification to the D7000 procedure has been developed that removes some of this variability and allows a more precise application of aggregate.

The formula for aggregate spread rate in D7000 is based on an assumption of 50 percent voids between particles. This is based on cubical particles with sizes of 9.5mm to 4.75mm . A template fabricated from 16 gauge steel is specified in D7000 which provides an approximate 0.35 gal/sy emulsion application rate.

Embedment varies, then, depending on actual aggregate gradation. This variation can be shown to range between 34.2 percent for 9.5 to 6.35 mm particles and 45.8 percent for 6.35 to 4.75 mm particles. And, if half the mass consists of 6.35 mm particles and half consists of 4.75 mm particles, the embedment is 41.6 percent.

Summary

Based on the above analysis, it was decided to use templates of varying thickness to provide a constant 40 percent chip embedment in the emulsion residues for the four research aggregates. The 26 to 30 percent embedment specified by the two design procedures was judged too little for the laboratory experiment and would likely result in significant aggregate loss during testing with little difference observed between independent variables. Also, it was judged that 50 to 70 percent embedment in the laboratory would be high enough that differences between independent variables would also be indistinguishable.

Aggregate spread rate was based on the Asphalt Institute method without accounting for traffic reduction of voids. This provided an aggregate spread rate similar to the Texas and D7000 procedures providing a one-stone thickness. It was judged that placing the additional chips specified by the original procedure would produce high chip loss resulting in poorer discrimination between variables.

Approach

An existing sweep test described by ASTM D7000 was used as the basis for this research. The test appeared to be a reasonable approach to simulating the forces present in the field which dislodge aggregate chips in chip seals. Therefore, an experiment was designed to measure the ability of the test to discriminate between independent variables believed to affect early chip seal performance. These variables were curing level of the emulsion and moisture content in the aggregate chips. In addition, the effect of aggregate type on emulsion type was desired to determine if the mineralogy of the aggregate affects chip loss as a function of emulsion chemistry. Therefore, four aggregates and five emulsions were chosen to evaluate early chip seal performance between positively and negatively charged aggregates and commonly used anionic and cationic emulsions.

Experiment Design

Independent Variables

Independent variables in this experiment are shown below:

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

A full-factorial experiment was designed for each emulsion according to the model shown below:

$Y_{ijkl} = \mu + A_i + W_k + M_l + AW_{ik} + AMil + WMkl + AWMikl + \varepsilon_{ikl}$

Where,

Y_{ijklm} = Chip Loss, %
μ = mean loss, %
A_i = effect of aggregate i on mean
W_k = effect of water removed k on mean
M_l = effect of aggregate moisture l on mean
AW_{ik}, etc. = effect of interactions on mean
e_{iklm} = random error for the ith aggregate, kth water removed, lth moisture content and mth replicate

The experiment was blocked with respect to emulsion so that each emulsion could be utilized at the same time after formulation. This eliminated potential variability that could be associated with differences in emulsion age.

Materials

Emulsions were manufactured by SEM Materials in Commerce City, Colorado with properties shown in Table B1. Limestone (LSTN) aggregate was obtained from the Castle Materials quarry in Colorado Springs, CO, granite (GRNT) was obtained from the Lafarge quarry in Pueblo, CO, basalt (BSLT) from the Asphalt Paving Company quarry in Golden, CO and the alluvial (ALLV) from Everist Materials in Silverthorne, CO. The properties of these materials are presented in Table 2.

Table B1. Emulsion Properties

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

Revised Sweep Test Procedure

The revised sweep test procedure described here is based on ASTM D7000-08, "Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment." However, the revised method refines certain procedures described in the ASTM

Table B2. Aggregate Properties

		Passing, %			
Sieve No. (in.)	Sieve Size (mm)	LSTN	GRNT	BSLT	ALLV
3/4"	19.0	100	100	100	100
1/2"	12.5	100	100	100	100
3/8"	9.5	100	99	100	99
5/16"	8.0	100	50	79	73
1/4"	6.3	48	9	30	33
4	4.75	1	1	1	2
8	2.36	1	1	1	2
16	1.18	1	1	1	2
30	0.60	1	1	1	2
50	0.30	1	1	1	2
100	0.15	1	1	1	2
200	0.075	1	1	1	2

Bulk specific gravity	2.615	2.612	2.773	2.566
Loose unit weight, lbs/cf	78.3	84.0	92.2	86.1
L.A Loss, %	26.3	27.8	20.1	22.0
Flakiness Index	33.8	5.8	13.1	10.5
Mat depth, in.= 4Q/3W	0.176	0.256	0.206	0.219
Median Size, in.	0.252	0.315	0.277	0.277
Median Size, mm	6.4	8.0	7.0	7.0
ALD, mm from nomograph	4.5	7.1	5.8	5.8

procedure that can contribute to variability in test results. Two important revisions include the ability to apply specific quantities of aggregate chips based on design calculations and a means of determining the cure level of the emulsion prior to testing. This cure level is a factor that has been determined to be significant with respect to chip retention in this research.

Aggregate

Good chip seal performance requires that the aggregate spread rate suits the particular aggregate gradation. Several procedures and tests are performed on the aggregate since absorption of moisture, aggregate shape and coverage rate are factors that feed into the design of the chip seal and, therefore, the laboratory specimen.

The revised sweep test is performed on chip seal aggregate of a standard maximum and minimum size. Aggregate is sieved to remove any material retained on the 3/8-inch sieve and passing the No. 4 (4.75mm) sieve. The material is then washed to remove the minus No. 200 fraction.

5.1.13 Materials Application Rates

Aggregate and emulsified asphalt application rates were determined using the Mcleod (*7*) chip seal design procedure. Because this design is based on embedment of aggregate chips to specific depths of emulsion, templates were fabricated of varying thickness to accommodate these variations.

Test Specimen Substrate

Asphalt impregnated 30 pound per 100 square foot roofing felt (ASTM D226) forms the substrate upon which the laboratory chip seal is fabricated. Twelve inch circles are cut from the felts upon which the emulsified asphalt and aggregate are applied.

Apparatus

5.1.14 Glass Bowl

Where specimens are to be made with saturated aggregate, a glass bowl is required for mixing aggregate and water. The bowl must carry an airtight cover to allow the bowl to be shaken and inverted, enabling mixing of its contents and absorption of the water into the aggregate pores.

5.1.15 Templates

Steel templates are made with 11-inch diameter cut-outs. These are used to form asphalt emulsion in a filled circular pattern on felt circlets. When sizing the steel template for fabrication, adequate space should be allowed at the bottom of the template where excess asphalt emulsion is screeded off the mold. Templates must be of different thicknesses to accommodate different coverage rates and embedment required by aggregates of different heights.

5.1.16 Screed Rod

These are hollow or solid rods used to move emulsified asphalt over the entire mold and to screed it level with the top of the mold. Depending on emulsion viscosity, a flat rod or a round rod may be used. The screed rod is moved in a side to side fashion as it is moved, simultaneously, in a perpendicular direction.

5.1.17 Manufacturing Platform

Specimen manufacture is performed on a raised platform with leveling screws. This is to ensure that even low viscosity emulsions will fill the molds uniformly. The platform is marked to allow for consistent central placement of the felt circlet. The platform also carries a fixed guide at the top edge to enable quick and accurate placement of the template.

5.1.18 Dropper

The dropper is a mechanism consisting of two horizontal plates, butted together at the center line of the specimen, and slid apart on a pair of rails. It serves as a platform on which aggregate may be configured in the same manner as the aggregate is intended to be in when applied to the specimen.

Aggregate is assembled on the dropper's horizontal (trap) doors. This aggregate is shaped into a circular configuration with the use of a hoop, 11-inches in diameter and three-quarters of an inch in height. With the hoop removed from the dropper, the grabber is positioned over the dropper and the combined unit is placed on the manufacturing platform over the felt circle previously topped with emulsified asphalt.

The dropper is designed to lock in position over the specimen circlet and to be vertically offset from the surface of the emulsified asphalt. When the dropper doors are slid horizontally, the aggregate, held in place horizontally by the grabber, falls vertically onto the felt, covering the entire area of the emulsified asphalt in a single layer. Figure B1 shows the apparatus with the chips being placed before the grabber is placed on top.

Figure B1. Dropper Apparatus

5.1.19 Grabber

The grabber is a mechanism, consisting of thousands of retractable metal pins, which holds the aggregate in its assembled configuration over the emulsion as the dropper doors are slid away. The grabber allows the aggregate to fall vertically in a circular, closely packed, configuration as shown in Figures B2 and B3.

5.1.20 Compactor

The weighted compactor is a curved plate that simulates the steel wheel of a field compactor. It is rolled over the aggregate three times in each of two perpendicular directions. The compactor is wide enough to cover the entire specimen in each roll. No additional operator force is to be transmitted to the specimens.

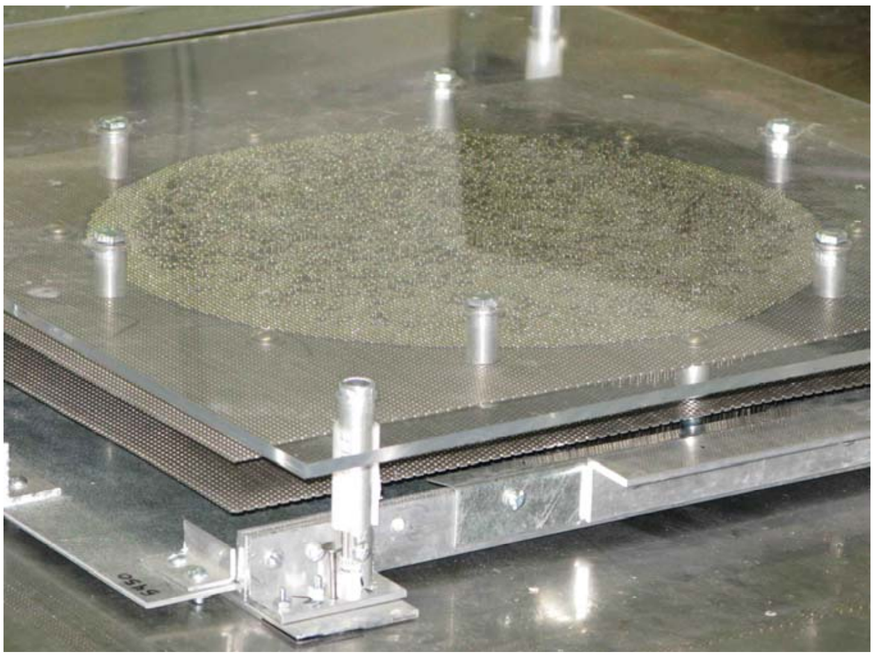


Figure B2. Grabber on Top of Chips

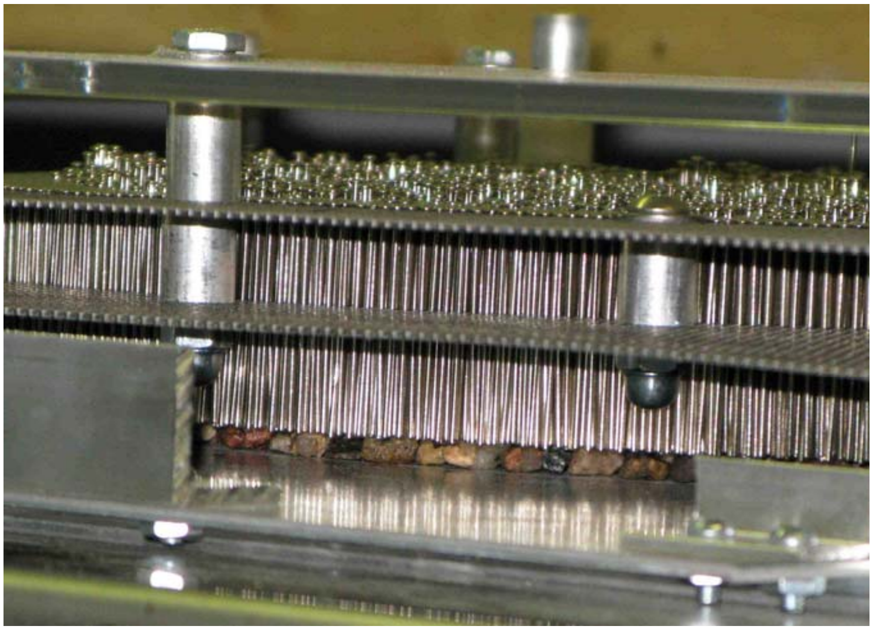


Figure B3. Complete Apparatus from the Side

Figure B4. Compactor in Use

5.1.21 Sweep Platform

The sweep platform is fabricated from 1/8” thick steel plate. It is installed perpendicular to the mixer axis and made level. Attached to the platform is a pair of clamps for securing the sweep pan. The platform should be designed to accommodate the sweep pan in a single marked orientation to enable accurate and consistent positioning of the specimen under the sweep brush.

5.1.22 Sweep Pan

The cured specimen is placed in a flat-bottom baking pan to equilibrate prior to being brushed. The pan is designed for consistent positioning on the sweep platform.

The pan is also marked such that the center of the specimens may be consistently aligned with the center of the brush path as shown in Figure B5.

Figure B5. Sweep Pan and Sweeper Dislodging Chips

5.1.23 Mixer

The mixer is a 1/3 horsepower Hobart model A120 producing planetary (the brush rotates on the mixer's offset attachment head as it orbits the mixer's central axis) motion of the brush head at a rate of 0.83 gyrations per second. The mixer is shown in Figure B5.

5.1.24 Collar, Brush Head and Weight

The collar is installed on the mixer attachment head and serves to hold the brush head in place.

The brush head is pinned to the collar but may move vertically through a distance of 3/4 inch (less the diameter of the pin). A removable brush, 5-inches in length, is fixed in the brush head.

A weight rests on the brush head applying a downward force upon the brush, which, in turn, imparts this force to the specimen as the brush is turned by the motor.

Approximately 60% of the specimen area is brushed by this apparatus.

The Cure Log

Where a particular cure level is to be achieved, the required specimen cure time, in the oven, may be arrived at by making preliminary specimens with emulsified asphalt and dried aggregate on felt. These specimens are to be placed in an oven at 160F to allow rapid curing of the emulsion. The emulsion mass loss is recorded every 15 minutes for the first hour and every hour thereafter for the next four hours. This will enable the plotting of a graph of time versus percent emulsion mass loss (% cure). From this plot, we can interpolate the required time to achieve our pre-determined cure level.

Where specimens area also to be made with, and testing is to be performed on, wet aggregate specimens, it is assumed that the emulsion will cure at the same rate for wet aggregate specimens as for dry aggregate specimens. That is, breaking and evaporation may be considered to take the same time, even though the strength of bonds achieved with wet aggregate may differ from those achieved with dry aggregate. The duration in the oven is, therefore, kept the same for both wet and dry aggregate specimens at the same cure level. These durations are obtained from the same cure log plot derived from the cure results of dry aggregate specimens.

Procedure Summary
Asphalt emulsion is applied to the felt substrate in a perfect circle by means of a steel plate mold, known as the template, with 11-inch diameter cut-out. The emulsified asphalt is screeded level with the template by means of a strike-off rod. Aggregate is then placed mechanically and, thereafter, set in a layer, one stone depth in thickness, by means of a compactor.

The specimen is placed in a 160F oven to allow the emulsified asphalt to cure to the desired level (40% moisture loss or 80% moisture loss). After the specified cure duration, the specimen is removed from the oven. It is then cooled, and obviously loose particles are removed.

The specimen is then swept in a pan under the action of a weighted brush which is spun by a planetary motion mixer for one minute. The specimen, having been removed from the machine, is brushed by hand to remove all particles that were mechanically dislodged from the specimen surface.

The mass loss is then determined and used to gauge performance of the aggregate/emulsified asphalt combination.

Test Method

5.1.25 Emulsified Asphalt Preparation

Asphalt emulsion in a quart bottle is placed in a 140F (60C) oven to equilibrate. Where the turnaround time between specimens is short, multiple bottles may be necessary in order to ensure that a 140F bottle is always available.

5.1.26 Aggregate Preparation

The prescribed mass of aggregate is weighed out to achieve the required coverage rate over the 11-inch diameter circle of emulsion. Where the specimen is to be made with saturated aggregate, the required water is weighed out and applied to the weighed aggregate in a glass bowl. At this stage, water in excess of the absorption quantity should be added to the aggregate to allow for water lost to the surfaces of the glass bowl, the dropper, the grabber and to the air during manufacture. The bowl is tightly covered and shaken.

5.1.27 Felt Circle Preparation

The mass of the felt circlet is recorded and the felt is centered on the manufacturing platform. The felt circle should lay flat and be free of any surface defects.

The template is positioned centrally over the felt circlet and a screed rod is placed on top.

5.1.28 Shaping the Aggregate Layer

The aggregate hoop is placed on the dropper platform. Where saturated aggregate is being used, the operator must not uncover the glass bowl or spread the aggregate on the dropper platform unless he is ready to complete the specimen manufacture process.

Having recorded the start time, spread the prepared aggregate on the platform such that it completely fills the hoop one layer deep. Level the aggregate by hand. Where saturated aggregate is being used, this step should not take more than four minutes to avoid the aggregate drying out.

5.1.29 Configuring Grabber and Dropper

After shaping the aggregate layer, remove the hoop. At this point, the completion of the manufacturing process may be delayed for dry aggregate specimens only. Where completion will be delayed, the grabber should not be placed until such time as the specimen manufacture will continue.

For wet aggregate specimens, place the grabber over the dropper to form the combined unit and proceed immediately to the next step. For wet aggregate specimens, configuration of the grabber and dropper should be done within the four minutes also designated to the shaping of aggregate.

This step concludes with the start of molding the emulsion circle.

5.1.30 Molding the Emulsion Circle

At the commencement of this step, record the start time for molding the asphalt emulsion circle. Immediately thereafter, using a bottle of emulsion that has been equilibrated to 140F in the oven, pour approximately 150% of the required emulsion mass onto the felt circlet. This emulsion is to be poured only along the top arc of the felt circle in the area formed by the template.

Level the emulsion and remove excess by moving the screed rod side to side and from the top arc to the bottom arc of the template (do not regress with the screed rod). This should take approximately four seconds. Immediately remove the template.

Do not pour emulsion in the center of the felt. Doing so will cause localized expansion, due to heating, of the air under the center of the felt where the weight of the template cannot restrain expansion of the hot air.

5.1.31 Recording Emulsion Mass

At this point, record the mass of the felt and emulsified asphalt.

For dry aggregate specimens, this record will later enable calculation of the cure level. At the end of curing, the emulsion mass loss (cure level) is equal to the change of specimen mass since the masses of the felt and the dry aggregate are known and do not change appreciably.

For wet aggregate specimens, this record allows calculation of the initial aggregate moisture content in the specimen: the difference between the initial specimen mass and the combined masses of felt, emulsion and dry aggregate. At the end of curing we can make an assumption about the percent of aggregate water still present in the aggregate to arrive at the final emulsion mass and, therefore, at the emulsion cure level.

5.1.32 Placing Aggregate Onto the Emulsion

Next position the combined grabber and dropper unit on the manufacturing platform and ensure that the locking pins are engaged. Slide the trap doors out swiftly and set them aside. Next, tap the topside of the grabber to ensure that all aggregate has been released by the grabber.

Remove the grabber and dropper unit. Remove the grabber from the unit and turn it on its side, checking to ensure that all aggregate particles have been released.

The grabber, dropper and manufacturing platform should all be permanently located on the same work table to ensure that no aggregate falls on the ground when moving the grabber and dropper to and from the manufacturing platform.

5.1.33 Compact the specimen

With the compactor, press the aggregate particles together and into the emulsion using three half cycles in one direction and three half cycles in a perpendicular direction. Take care to use only the compactors weight in this process and to not impart any additional force onto the compactor.

5.1.34 Record Specimen Mass

Immediately record the specimen mass and the time of its completion. This step concludes specimen manufacture.

The time from commencement of molding the emulsion circle to the end of this step should be no more than four minutes.

5.1.35 Oven Curing of Specimen

Curing starts when the manufactured specimen mass is recorded. The specimen is placed, as quickly as possible thereafter, in a 160F oven. The cure duration, previously determined with the help of the cure log, starts with the recording of the manufactured specimen mass and ends with the removal of the specimen from the oven.

Conclude this step by recording the mass of the cured specimen at the time of, or as near as possible to the time of, the end of oven curing.

5.1.36 Cooling Specimen

The specimen is then placed in a 40F refrigerator to cool for 8 minutes. It is the intention of this step to bring the average temperature of the specimen down to approximately ambient room temperature.

Conclude this step by recording the mass of the cooled specimen. From oven to refrigerator should take no more than one minute. The entire step should take no more than ten minutes.

5.1.37 Stuck Mass of Specimen

Turn the specimen on its side, over a trash container, and allow any loose aggregate to fall off. By holding the felt firmly at the top of the specimen with one hand, and slight brushing of the specimen with the ungloved back of the fingertips of the other hand, assist loose particles to fall off without dislodging otherwise properly stuck aggregate particles.

Next, rotate the specimen, at least two times, through 120 degrees, and repeat the brushing procedure at each turning to ensure that the entire specimen has been suspended and brushed from various angles. Any particles that are obviously hanging on by a thread should be removed at this stage.

Conclude this step by recording the stuck mass of the specimen (which includes the felt mass). This step should take no more than one minute.

5.1.38 Equilibrating Specimen

With the sweep platform lowered, position and clamp the specimen in the sweep pan to equilibrate at room temperature for 3 minutes $\pm$ 30 seconds. At this time a clean brush may be placed in the brush head of the sweep test apparatus (if this hasn't been done previously).

In order to ensure equality of test conditions, note and record the average specimen surface temperature toward the end of the equilibrating period. Tests should be performed on specimens that are within $\pm$ 5F of a chosen average test temperature.

This step will conclude with the start of specimen sweeping.

5.1.39 Sweeping Specimen

Sweeping is to be initiated at the end of the equilibration period. Raise the sweep platform and lower the weight onto the brush head. Ensure that the brush head is free to move up and down. Noting the time, start the mixer and a sweep timer simultaneously.

After one minute turn off the mixer and let the brush head come to a stop.

5.1.40 Retained Mass: removing dislodged mass

Lower the sweep pan, unclamp the specimen and remove it from the sweep pan. Most dislodged material remains on the specimen itself since it is confined by the sides of the pan. Bear in mind that the intent of this step is to remove any particles that would otherwise have been dislodged in the field, and removed from the road surface, by a moving vehicle.

Turn the specimen on its side, over a trash container, and allow any loose particles to fall off. By holding the felt firmly at the top of the specimen with one hand, and slight brushing of the specimen with the fingertips of another gloved hand, assist loose particles to fall off without dislodging otherwise properly stuck aggregate particles.

Next, rotate the specimen, at least two times, through 120 degrees, and repeat the brushing procedure at each turning to ensure that the entire specimen has been suspended and brushed from various angles. Any particles that are obviously hanging on by a thread should be removed. It may be assumed that any mass of aggregate and asphalt that is not stuck to the felt substrate would have been removed by the wheel of a car.

Conclude this step by recording the retained mass of the specimen (which includes the felt mass). This step should take no more than four minutes.

5.1.41 Specimen Swept Ratio

The mass loss resulting from the sweep test is due to the brush head coming into contact with the brushed area. The swept ratio is the ratio of the swept area to the specimen area. Bear in mind that the specimen area is that of an 11-inch diameter circle.

The swept ratio is approximately 0.6:1 for the mixer used in this project but should be determined separately for each mixer.

5.1.42 Equivalent Percent Mass Loss

The equivalent mass loss is the loss that an 11-inch diameter specimen would suffer if its entire area were swept. Numerically, it is the swept specimen's percentage mass loss divided by the swept ratio.

Equivalent % mass loss = (stuck mass - retained mass) * 100%
(stuck mass – felt mass)*(swept ratio)

5.1.43 Initial and Final Aggregate Moisture

Dry aggregate specimens have no initial moisture. Therefore, any specimen mass loss may be immediately attributed to emulsion mass loss and correlated with cure level.

For wet aggregate specimens, recall that initial aggregate moisture is calculable:

Initial Agg Moisture = initial specimen mass – (initial felt & emulsion mass + dry aggregate mass)

Final aggregate moisture, however, may not be determined. If we can make an assumption of **X%** for the volume of water still present below the surface of the emulsion at the end of curing, then:

Final Agg Moisture = (X% * initial agg moisture)

Aggregate embedment in this research was 40 percent. The maximum volume of unexposed aggregate pores is, therefore, 40 percent.

It is likely that some of the pores below the asphalt surface are not linked to pores above the surface. It is therefore likely that some aggregate pores will become blocked by absorbed asphalt and some aggregate moisture becomes locked in these pores. This may or may not happen prior to the aggregate moisture becoming heated. Heating would cause the moisture to expand and to partially exit the 40% of subsurface pores. At that point some of this water may bubble through, and evaporate from, the emulsion.

It is likely, therefore, that X is neither equal to 0 nor to 40; and that X may be represented by the inequality 40>X>0 (the first scenario). It is probably more likely, however, that 30>X>0 (the second scenario) is a closer representation of the limits of X.
As we would require further, impractical, aggregate tests to determine the actual pore structure, and the actual value of X to use, we will make the assumption that X = 15%.

The first, unlikely, case scenario has the effect of a 16.67% variation in the calculated cure level:

The case where we assume X = 0% (but is actually 40%)
With initial (SSD) aggregate moistures of 5 grams, and final aggregate embedment of 40%, final aggregate moisture is, at most, 2 grams of water. The largest effect of an incorrect assumption on the final aggregate moisture will be made to emulsion with the lowest final moisture content.

Our initial emulsion water content is a minimum of 24 grams for low coverage rates with final water contents of 4.8 grams at the 80% cure level. The effect of incorrectly assuming X = 0 where 2 grams of aggregate moisture exist, is that the cure level which is assumed to be 80% (4.8 grams of emulsion water) is actually 88.33% (2.8 grams of emulsion water).

The case where we assume X% = 40% (but is actually 0%)
The effect of incorrectly assuming X = 40 where 0 grams of aggregate moisture exist, is that the cure level which is assumed to be 80% (4.8 grams of emulsion water plus 2 grams of agg moisture) is actually 71.66% (6.8 grams of emulsion water).

The more probable case scenario, on which our assumption is based, has the effect of a 6.25% variation in calculated cure level or a $\pm$ 3.125% error:

The case where we assume X% = 15% (but is actually 30%)
With initial (SSD) aggregate moistures of 5 grams, final aggregate moisture is, at most, 1.5 grams (30%) of water. The largest effect of an incorrect assumption on the final aggregate moisture will be made to emulsion with the lowest final moisture content.

Our initial emulsion water content is a minimum of 24 grams for low emulsion coverage rates with final water contents of 4.8 grams at the 80% cure level. The effect of incorrectly assuming X = 15 where 1.5 grams of aggregate moisture exist, is that the cure level which is assumed to be

80% (4.8 grams of emulsion water plus 0.75 grams of agg moisture) is actually 83.125% (4.05 grams of emulsion water plus 1.5 grams of agg moisture).

The case where we assume X% = 15% (but is actually 0%)
The effect of incorrectly assuming X = 15 where 0 grams of aggregate moisture exist, is that the cure level which is assumed to be 80% (4.8 grams of emulsion water plus 0.75 grams of agg moisture) is actually 76.875% (5.55 grams of emulsion water).

5.1.44 Cure Level

For the purposes of this project, the emulsion cure level is a percentage that indicates how much water has evaporated, or broken away, from the emulsion.

$$\text{Cure Level (\%)} = \frac{\text{(initial water in emulsion – final water in emulsion)}}{\text{(100\% – Residual Content (RC))}}$$

$$= \frac{\text{(emulsion mass loss)}}{\text{(100\% – RC)}}$$

But, felt and dry aggregate masses are assumed constant, therefore,

For dry aggregate specimens:

$$\text{Cure Level (\%)} = \frac{\text{(initial specimen mass - final specimen mass)}}{\text{(100\% – RC)}}$$

For wet aggregate specimens, this becomes:

$$\text{Cure Level (\%)} = \frac{\text{(emulsion mass loss)}}{\text{(100\% – RC)}}$$

$$= \frac{\text{(initial specimen mass -(final specimen mass – initial agg moisture) – final agg moisture)}}{\text{(100\% – RC)}}$$

The only unknown is final aggregate moisture.
But, because we have made an assumption for final percent of (known) initial aggregate moisture, X% = 15%:

For wet aggregate specimens:

$$\text{Cure Level, \%} = \frac{\text{(initial specimen mass -(final specimen mass– initial agg moisture) – X\%[initial agg moisture])}}{\text{(100\% – RC)}}$$

Correction Factors

Two correction factors should be considered when conducting the revised sweep test. These are called the felt correction and the locked-moisture correction. Neither of these corrections practically affects the final swept loss result. They do, however, affect the calculated cure level of the specimens. Both corrections tend to act in opposite directions with regard to the calculated cure result. However, while the felt correction can be performed on all samples, the locked-moisture correction only applies to SSD specimens.

5.1.45 Felt Correction

Because the felt mass loss is small compared with the combined mass of the aggregate and emulsion, the felt mass correction would cause an imperceptibly small change to the swept mass loss. The felt mass loss is, however, noticeable when compared to the emulsion mass loss; this correction decreases the assumed emulsion mass loss by approx 1.2% (of the 30% moisture). That is, after the correction a 12.2% assumed emulsion mass loss would actually work out to be 11%. Put another way, the cure percentage would decrease 4 percent from 40.66% (12.2%/30%) to 36.66% (11%/30%).

5.1.46 Locked-in Moisture Correction

The opposite occurs when correcting for moisture locked in the aggregate below the asphalt surface. If we assume that 50% of the SSD moisture is still locked in the aggregate after curing, then more of the actual mass loss is attributable to the emulsion giving up its water (and less to the aggregate giving up its water). In the case where 50% SSD aggregate moisture is locked below the asphalt surface, the calculated emulsion mass loss would increase approx 2.72% and, therefore, the cure percent would increase. After the correction an assumed 11% emulsion mass loss would actually work out to be 13.72%; the cure percentage would increase 9 percent from 36.66% (11%/30%) to 45.73% (13.72%/30%).

Results

Results of chip loss after the sweep test are shown in Figures B6 through B9 for each of the dry, SSD, 40 percent and 80 percent cured test conditions.

Analysis

Results of the ANOVA in Table 4 and the Newman-Keuls multiple comparison test in Table 5 indicate significant differences between the 40 percent and 80 percent cured test specimens for all four emulsions. The dry aggregates average approximately 70 percent and 15 percent loss, respectively and the SSD aggregates approximately 65 percent and 10 percent loss, respectively.

The test indicates a real difference in chip loss between aggregates that are dry when embedded in the emulsion compared with those that are in the SSD condition when embedded. Newman-Keuls from Table 5 indicates that dry has significantly higher loss than SSD for all aggregates except the CRS-2. This finding is consistent with common beliefs that damp aggregates allow the emulsion to wick into the aggregate pores, providing improved adhesion and cohesion properties.

There are significant differences between the emulsions. The RS-2P performed approximately equal to the other emulsions at 40 percent cure with either dry or SSD chips but poorer than the other emulsions at 80 percent cure with either dry or SSD chips. The CRS-2P performed approximately equal to the other emulsions under all conditions except at 80 percent cure with SSD chips, where it outperformed the other binders.

The particle charge on the emulsion appears to have little effect on chip loss at 40 percent cure based on Figures B1 and B3. That is, the anionic RS-2 adheres equally well to the limestone as the granite and basalt, and the cationic CRS-2 equally well to all of the aggregates. Some difference may be significant with respect to the polymer modified RS-2P where adhesion appears much better on the limestone. However, in general, the anionic emulsions do not appear to have a greater affinity to limestone and the cationic do not appear to favor the granite nor basalt. In fact, from Table B5 the opposite is true for the CRS-2P, which adhered better to the limestone (25 percent loss) than the granite (38 percent loss), results that are significant at $\alpha = 0.05$.

Table B4. Results of ANOVA for Laboratory Sweep Tests

	Pr > f			
Source	RS-2	RS-2P	CRS-2	CRS-2P
aggregate	<0.0001	<0.0001	0.3887	0.0049
moisture	0.0169	0.0220	0.1597	0.0003
cure	<0.0001	<0.0001	<0.0001	<0.0001
agg x moist	0.2468	0.3618	0.0994	0.7574
agg x cure	0.0001	0.0020	0.3927	0.0005
moist x cure	0.5425	0.0136	1.0000	0.9546
agg x moist x cure	0.1064	0.2088	0.8805	0.0114

Note: Significance at $\alpha = 0.05$ or greater indicated in Yellow

Table B5. Results of Student Newman-Keuls Multiple Comparison Test for Aggregate

RS-2		RS-2P		CRS-2		CRS-2P	
ALL	A(47)	ALL	A(57)	ALL	A(50)	ALL	A (38)
GRN	B(39)	GRN	A(51)	GRN	A(49)	GRN	AB

							(33)
LS	B(36)	LS	A(51)	LS	A(47)	LS	AB (32)
BST	C(29)	BST	B(18)	BST	A(47)	BST	B (25)

Note: Values in parentheses represent Sweep Test Loss, %
Letter designations indicate means of same population at $\alpha = 0.05$

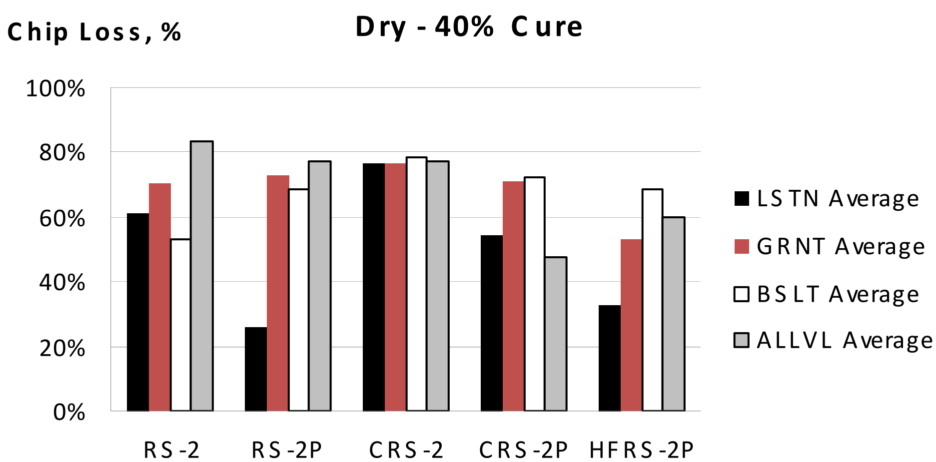


Figure B6. Sweep Test Results for Dry Aggregates at 40% Cured Emulsion

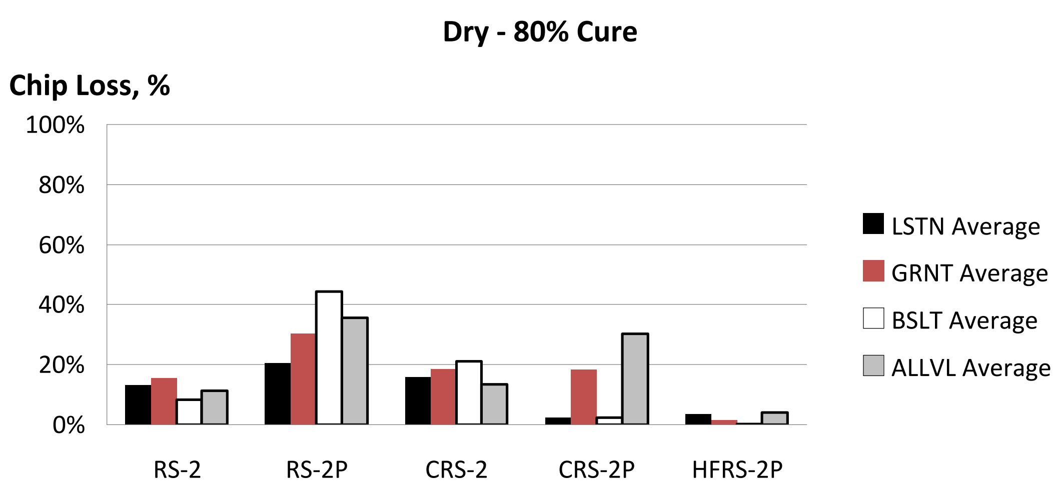


Figure B7. Sweep Test Results for Dry Aggregates at 80% Cured Emulsion

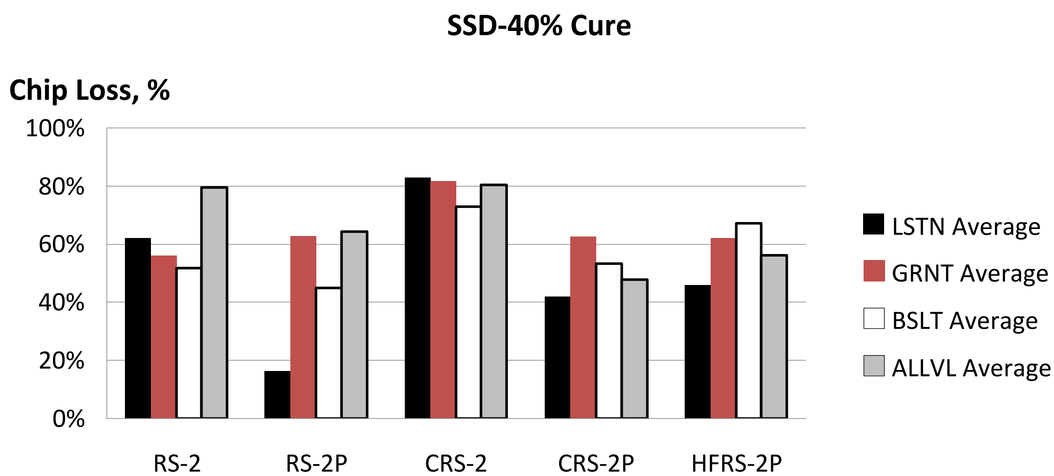


Figure B8. Sweep Test Results for SSD Aggregates at 40% Cured Emulsion

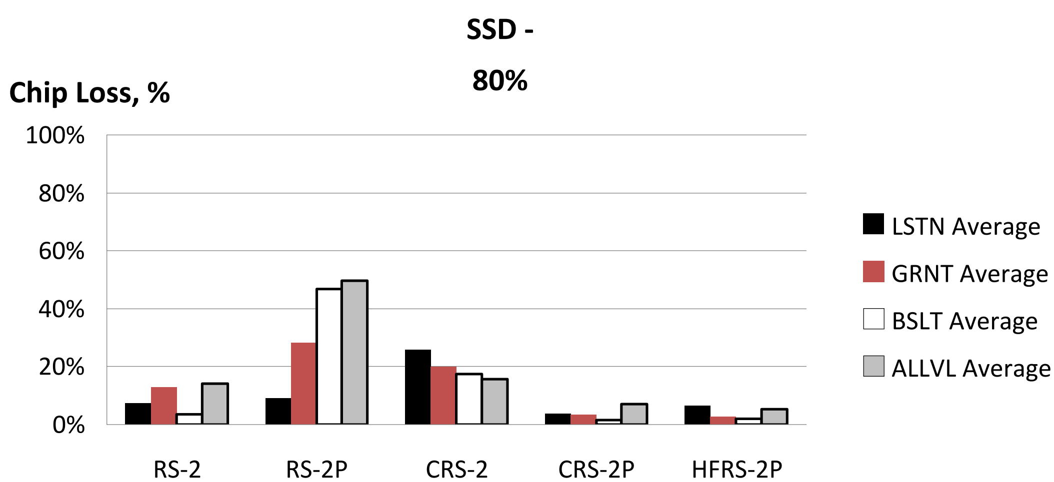


Figure B9. Sweep Test Results for SSD Aggregates at 80% Cured Emulsion

Conclusions

A revised version of the ASTM D7000 sweep test has been developed which can compare different aggregates and emulsions under various curing conditions.

Sweep test results indicate the amount of water remaining in the emulsion has a large effect on chip retention.

Significantly higher chip loss was measured for test specimens fabricated with dry aggregates compared with saturated surface dry aggregates.

No significant differences in chip loss could be measured either at 40 or 80 percent cure when cationic emulsions were compared with anionic emulsions on either calcareous or siliceous aggregates.

A correlation of laboratory sweep test results to field moisture content in chip seals should result in a method to predict when traffic control can be released with less risk of vehicular damage.

APPENDIX C – Field Emulsion Viscosity

Scope: This test determines emulsion viscosity using a plastic cup. The cup viscosity may then be correlated to laboratory Saybolt viscosity values to determine if the emulsion meets specifications.

Apparatus: Field Emulsion Viscosity Test Kit

a. Plywood box with hinged door for windbreak and storage
b. Plastic paint viscosity cups - Wagner Part# 0153165 (1-800-328-8251 option 6)
c. 16 or 20 oz plastic party cups
d. Stopwatch/timer
e. Stem Thermometer
f. Gloves
g. Waste newspaper

Procedure:

1. Position the field test kit on a level surface in a manner such that the sample will be protected from wind during testing. Premature cooling can affect test results.

2. Hang a clean, unused viscosity cup on the horizontal support and place newspaper in the bottom of the box to protect it from spills. Adjust the lid so that the opening in the bottom of the paint cup is visible.

3. Collect an emulsion sample from the tanker in a plastic party cup. The cup should be approximately 2/3 full. The emulsion will be hot; therefore wear appropriate gloves.

4. Using the thermometer, determine the emulsion temperature.

5. Lift the party cup with emulsion so that the viscosity cup is fully immersed in the emulsion.

6. Simultaneously start the stopwatch/timer and lower the party cup.

7. When there is a break in the flow of emulsion from the paint cup, and the opening in the neck of the paint cup is first visible, stop the timer.

8. Record the emulsion temperature and the time recorded on the stopwatch/timer.

9. Dispose of the paint cup and party cup. Reuse may result in inaccurate test results.

10. Record any followup comments about the application of the emulsion such as Athick@, Athin@, Aplugging spray bar@, Ano problems@, etc.

APPENDIX D - Emulsion Residue Recovery

Introduction

Recommendation of an emulsion residue specification requires identification of a standardized emulsion residue recovery method that produces a material representative of the emulsion residue in situ. An alternative to the traditional emulsion residue recovery by distillation (ASTM D 6997) that exposes the material to high temperatures and may destroy or change any polymer networks through agitation is needed.

This appendix describes the experiment utilized to compare emulsion residue recovery methods and recommend an emulsion residue recovery method for use as part of an emulsion residue specification.

Experiment Design

The standard PG system (Asphalt Institute, SP-1) and the modified SPG system (Epps et al., 2001; Barcena et al., 2002; Walubita et al., 2005; Walubita et al., 2004) were both used to grade all of the base binders and the recovered emulsion residues in this research. The climate in which a pavement is placed is the main criterion used to determine the selection of a binder grade in both of these systems. In the future, the expected traffic level may be incorporated by an adjustment to the binder grade selection for traffic speed and loading.

Materials

Eight emulsions were included in this research. Five of the emulsions were laboratory prepared. These are identified as Emulsions 1 -5. The other three emulsions were obtained from the full scale chip seal projects. These are Arches National Park, Utah; Frederick, Colorado, CR11; and Forks, WA on US101. Table D1 indicates the types of emulsions and, when known, the PG grades of the base binders as reported by the supplier.

Emulsion Recovery Methods

Two emulsion residue recovery methods were used in NCHRP 14-17 to extract the water from the emulsions and to supply de-watered bitumen residue for the material properties testing. The residue recovery methods employed were:

- Hot oven (with nitrogen blanket)
- Stirred can (with nitrogen purge)

The hot oven method is similar to the recovery method described in ASTM D244-97C (ASTM International, 1997) with the modification that nitrogen flows over the sample to prevent oxidation and consequent aging of the material. A beaker containing 50 g of emulsion is placed in a 163˚ C oven with nitrogen flowing over it. After 2 hours in the oven, the emulsion is stirred with a glass rod and then remains in the oven for 1 hour more. The residue, about 30 g from each beaker, is then stored in an ointment tin until testing.

Table D1. Materials Tested Indicating PG and SPG Grades

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

For the stirred can method, a gallon can containing 1250 to 1300 g of emulsion is wrapped in heating tape and placed over a burner. The emulsion is stirred constantly with an impeller blade while being heated at 163˚C for 170 minutes. Nitrogen is bubbled up through the can and also flows over the top of the material to prevent oxidation and consequent aging of the material.

After 170 minutes, the can is removed from the heat source and covered. The residue, about 800 g, is stored in the gallon can until testing.

A third residue recovery method known as the low temperature evaporative technique (ASTM International, 2009) is currently being recommended by other researchers (Kadrmas, 2008; Hanz et al., 2009) to preclude destruction of the polymer matrix during residue recovery. This project conducted a preliminary comparison of the residue recovery methods used in this study with the low temperature evaporative method, and the findings have been presented elsewhere. (Prapaitrakul et al., 2009).

Laboratory Tests

Rheology Tests
The binder characterization tests utilized the same equipment and some of the same tests as specified in the PG system (Asphalt Institute, SP-1), but with different limiting criteria.

The dynamic shear rheometer (DSR) was used to measure the rheological properties of the binders, complex shear modulus G* and phase angle δ in the form (G*/sin δ), at high temperatures. Unaged binder was tested at the high temperatures, which is the critical condition for early strength development in chip seals.

All of the binders in this project were aged using only the pressure aging vessel (PAV), as described in the PG specification Asphalt Institute, SP-1. Rolling thin film oven (RTFO) aging was omitted as RTFO is not applicable to emulsions because they are not heated to high temperatures during emulsification and construction.

The bending beam rheometer (BBR) was used to measure bending properties of the binders (stiffness, S, and rate of change in binder stiffness with time, m-value) at cold temperatures.

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

The DSR was also used to measure the properties G* and δ in the form (G* sin δ) which is related to fatigue in HMAC at intermediate temperatures on PAV aged material. The (G* sin δ) parameter was used to check that the materials met the intermediate temperature criteria for the PG grade as determined from the high and low temperature testing.

Chemical Tests
Gel permeation chromatography (GPC) was performed on each recovered residue to determine that all of the water had been removed during the residue recovery process. GPC is a size exclusion chromatography (SEC) method of molecular analysis. Presence or absence of a peak at a time of 35 to 37.5 minutes on the GPC chromatogram indicates the presence or absence of water in the residue.

Fourier transform infrared (FT-IR) spectroscopy was performed on the residues from the five laboratory emulsions to obtain an indication of whether the recovery methods caused oxidation of the materials. The emulsions from the 3 field projects were not included in the spectroscopy testing. The infrared spectra were plotted, and then the area under the wavenumber band from 1820 to 1650 cm^{-1} was integrated to determine the carbonyl area. The integrated carbonyl area can be used to represent the extent of oxidation in the materials (Epps et al., 2001; Prapraitrakul et al., 2009; Woo et al., 2006). This can be compared for the base asphalt versus the recovered residues to determine if the emulsifying and residue recovery processes caused oxidation. It can also be compared among different residue recovery methods to determine if one recovery method causes more oxidation than another.

Binder Grading

Emulsion residues from the two recovery procedures and some of their base asphalts were graded according to the PG system developed for HMAC (Asphalt Institute, SP-1) and the SPG system developed for surface treatments (Epps et al., 2001; Barcena et al., 2002; Federal Highway Administration, 2004; Walubita et al., 2005) but both without RTFO aging. As compared to the PG system, the SPG system incorporates the following modifications:

- tests are performed at 3° increments, allowing material performance to be discriminated over a finer scale of temperature;
- the high temperature design condition for the SPG system is specified as the pavement surface temperature;
- DSR testing at high temperatures on unaged binders is expected to reflect the critical condition for early-age surface treatments; and a threshold value of 0.650 kPa minimum is used as the limiting value for ($G^*/\sin \delta$) for SPG high temperature grading, as recommended by TAMU (Walubita et al., 2004; Walubita et al., 2005) ;
- DSR testing at intermediate temperature(s) in the SPG system is not performed because previous research (Epps et al., 2001; Barcena et al., 2002) found that the intermediate temperature test results did not discriminate between binders that performed well and those that did not;
- DSR strain sweep testing at an intermediate temperature of 25˚ C was instead performed for a revised SPG system to assess strain susceptibility and resistance to raveling of the emulsion residues;
- BBR testing at low temperatures is expected to reflect the critical condition for raveling caused by traffic loading on stiff materials; therefore, low temperature properties based on BBR testing were determined at the fastest possible loading time, 8 seconds, and the actual test temperature was used;
- threshold values used for BBR tests at 8 seconds were 500 mPa maximum for SPG flexural stiffness and 0.240 minimum for SPG m-value;
- the SPG criteria used were developed using Texas chip seal projects (Epps et al., 2001; Barcena et al., 2002). These criteria should be developed or verified for other states or regions in the future.

Results and Analysis

DSR Results: High Temperatures

For the high temperature characterization in both grading systems, plots were generated of (G*/sin δ) versus temperature. At the high temperatures, the base binders in every case exhibited lower test parameters (G*/sin δ) than did the recovered residues. This is possibly due to stiffening and aging of the residues during either the emulsification process or the residue recovery process.

BBR Results: Low Temperatures

For the low temperature characterization in both grading systems, plots were generated of S versus temperature and of m-value versus temperature. The plots from the BBR test results indicated that the base binders and the recovered emulsion residues had similar cold temperature properties. Aging of the materials (and possibly exposure to cold temperatures) seemed to affect the base asphalts and the recovered residues so that they exhibited similar properties at cold temperature after PAV aging. This could be due to deterioration of the polymer additive structure over time and with aging (Woo et al., 2006).

DSR Results: Intermediate Temperatures

All of the materials passed the PG (G*sin δ) criterion at the SP-1 specified intermediate temperatures. All of the materials also passed for at least one additional (i.e. colder) temperature.

PG and SPG Grading

Both PG and SPG grades were determined for all of the base binders and recovered residues, and the results are shown in Table D1. Interpolation was used to determine the continuous grades. The continuous grades can be used to discriminate more accurately the differences in grading among the different recovery methods for the same emulsion residue.

In general, the PG grades were consistent for the base binder and the residues from both recovery methods, as were the SPG grades. However, examination of the continuous grades indicated that the base binder grades were slightly different from the grades of the recovered residues.

Use of the SPG system resulted in a higher continuous grade at both the high and the low temperature ends than the continuous grade with the PG system. The average difference in the high temperature continuous grades (SPG minus PG) was +3.6º C. The average difference in the low temperature continuous grades (SPG minus PG) was +11.3º C.

Chemical Analysis Results

The GPC chromatograms from all of the residues from both of the recovery processes indicated that water was absent from the recovered emulsion residues and had therefore been completely removed from the emulsions during the recovery procedures. Figure D1 provides a typical GPC chromatogram for the residues evaluated with no water peak exhibited at 35 to 37.5 minutes.

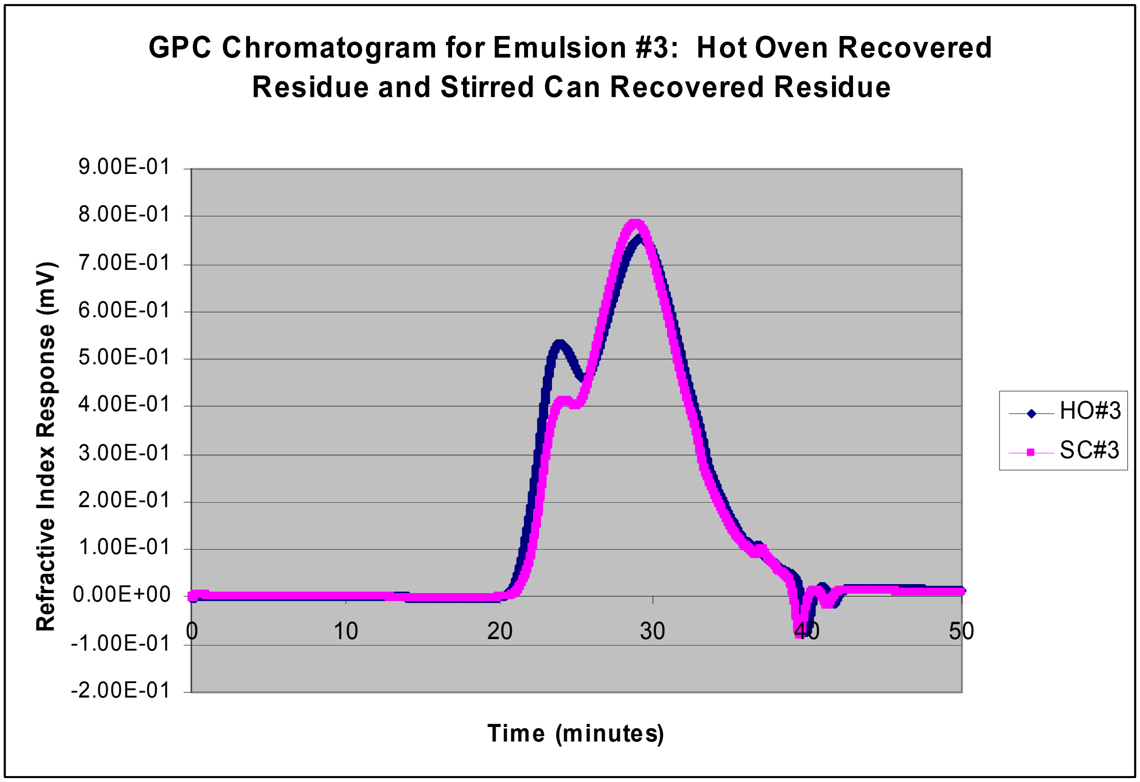


Figure D1. GPC Chromatogram for Emulsion #3 Hot Oven (HO) and Stirred Can (SC) recovered residues.

The carbonyl areas calculated from FT-IR spectra (Figure D2) for the five laboratory emulsions indicated that the recovered binders were all slightly more oxidized than the base binders. This oxidation could have occurred during emulsification or during the residue recovery process.

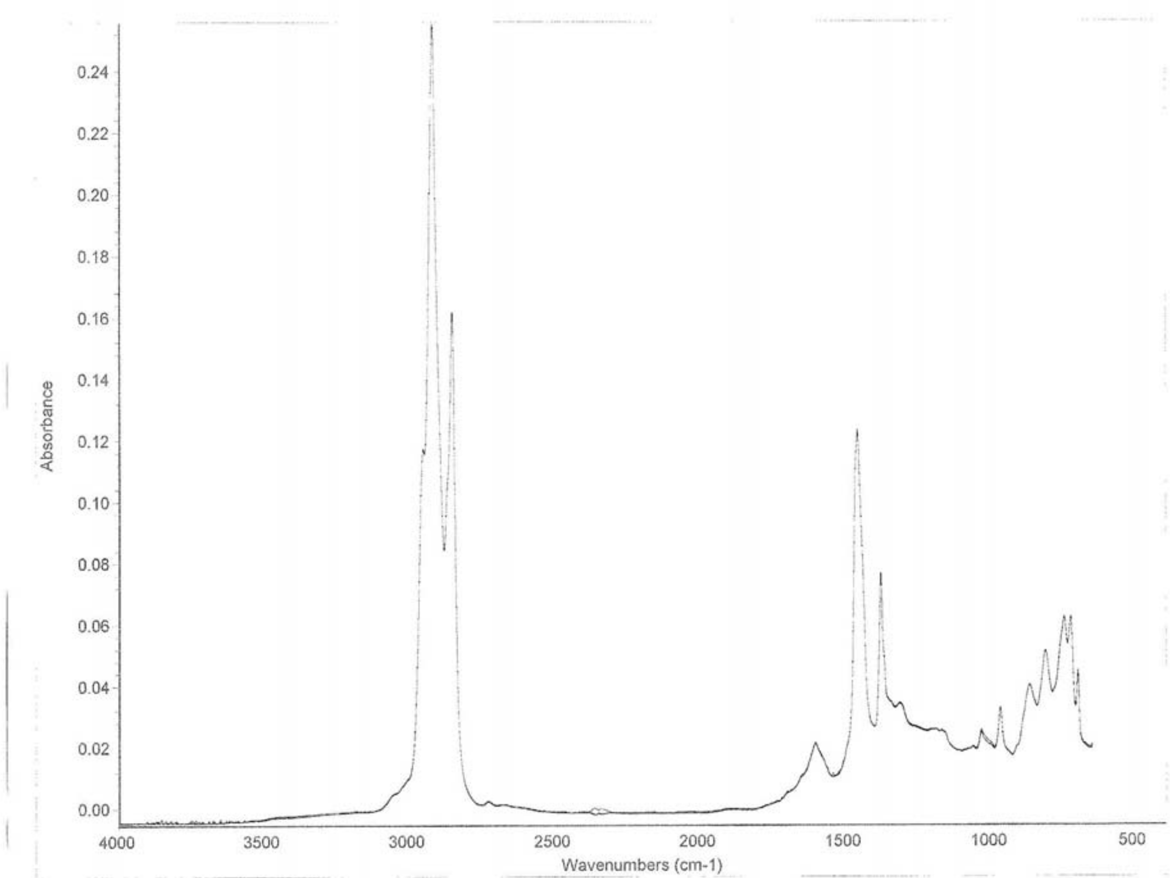


Figure D2. FT-IR Spectrograph for Emulsion #4 Stirred Can (SC) recovered residue.

Statistical Analyses of Rheological Test Results

The rheological data collected with the DSR and the BBR were analyzed statistically using Analysis of Variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison techniques. A level of confidence of α =0.05 was used in all of the analyses. The objective was to determine if there were statistical differences between the emulsions and between the recovery methods. Researchers were most interested in the results from comparing the recovery methods for each emulsion. Note that all of the materials for each emulsion came originally from one bucket of each emulsion or from one can of each base binder.

DSR and BBR tests were performed on base binder, stirred can recovered residue, and hot oven recovered residue for emulsions 1-5; but no base binder was available for testing for emulsions 6-7. Because base binders were available for some materials but not all, the statistical analyses were performed in several different ways.

For the materials with the base binder available, the base binder was treated statistically as a recovery method, that is as "no recovery."

Statistical Analyses of High Temperature DSR Properties
When the data from the high temperature DSR testing for emulsions 1-7 were analyzed in aggregate, emulsions 1, 3, and 4 were statistically grouped together by their high-temperature properties. All other emulsions were grouped separately, each in its own group. This indicated that emulsions 1, 3, and 4 were statistically similar and that the other emulsions were each different in terms of log (G*/sin δ) at high temperatures. Emulsions 1, 3, and 4 were known to be similar emulsion types, and their base binders had the same high temperature grade, PG 64. Thus the statistical result verified what was known about the materials.

When comparing the data by recovery method, the analysis results statistically grouped the recovery methods of stirred can and hot oven together, and the base binder (“no recovery”) was grouped separately for the emulsions with base binders available (1-5). This indicated that the two recovery methods produced emulsion residues with similar high temperature properties in terms of log (G*/sin δ), and these were different from the high temperature properties of the base binders. Both recovered residues were stiffer, with larger values of log (G*/sin δ), than the base binders, but not stiff enough to change the high-temperature PG grade (Table 1) for emulsions 1-5. With smaller temperature increments, the high-temperature SPG grade did change to a larger value for four of emulsions 1-5.

When the high temperature data for emulsions 1-5 (including base binder) and the data from emulsions 6-7 (no base binder) were analyzed in two separate groups, the results for the group of emulsions 1-5 were similar to those previously indicated for the aggregated data set. However, the analysis results of emulsions 6-7 indicated that the recovery methods made a difference for emulsion 6 residue properties at high temperatures. This statistical result verified the results from the PG and the SPG grading which graded the emulsion 6 residue differently for the two recovery methods. Emulsion 6 was the only latex-modified type emulsion in the study, and the latex modifier may have resulted in a different polymer structure Reference Takamura? from other polymers and for different recovery methods that affected the high temperature results.

The high temperature test results for each of the seven emulsions were then analyzed separately so that the effects of the recovery variable could be analyzed in more detail. From this analysis, emulsion residues 3 and 6 showed the recovery effect to be statistically significant. However, examination of the interaction plots did not show this statistical difference to be of practical significance. Therefore, it was concluded that the recovery method (including base binder as “no recovery”) did not make a practical difference in any of the high temperature results for any of the emulsions when each emulsion was analyzed separately.

Statistical Analyses of Low Temperature BBR Properties
The statistical analyses of the BBR results were more complicated because of the addition of the time variable (test measurements were taken at 8 seconds for SPG grading and at 60 seconds for PG grading) and because there were 2 responses being evaluated (stiffness, S, and slope, m-value). Analyses were conducted separately for the 2 response variables, S and m-value. The time interaction effects were not shown to be practically significant throughout the analysis.

When the data from the low temperature BBR testing for emulsions 1-7 were analyzed with an aggregated data set, the results of the statistical analysis indicated that the recovery method was not significant for either the stiffness (S) response or for the slope (m-value) response.

When the data for emulsions 1-5 and the data from emulsions 6-7 were analyzed in two separate groups, the emulsion*recovery interaction was statistically significant for the stiffness (S) response only for emulsions 1-5. For each emulsion, however, the three recovery states (including base binder as "no recovery" for the statistical analyses, along with hot oven residue and stirred can residue) were grouped together by Tukey's HSD comparison. This means that, for each emulsion, the recovery method (including the base binders) did not affect the response variables S and m-value. Also, emulsions 2 and 5 were grouped together to indicate similar responses for those materials in low-temperature stiffness (S). Emulsions 2 and 5 were both graded as PG 58-28, and therefore similar cold temperature properties were expected.

When the low-temperature data were analyzed by emulsion, the recovery method was not significant for emulsions 1, 3, 6, or 7. Emulsions 2 and 4 could not be analyzed because of the data structure. For emulsion 5, the recovery method was statistically significant; further analysis indicated that the base binder was different but the two recovered residues were grouped together. Both residues were softer and better able to relax stresses at low temperatures, with smaller values of S and larger m-values, than the base binders. Again, these changes were not sufficient to change the low-temperature PG grade (Table 2) for any of the 7 materials tested. With the smaller temperature increments, the low temperature SPG grade did change for only three of the seven materials tested.

The recurring result from all of the analyses of the BBR measurements was that the recovery method (with base binders included as "no recovery") did not practically affect the response variables S or m-value for any of the recovered residues. This result seemed to indicate that, after PAV aging and consequent oxidation, the polymers and additives no longer had an effect on the stiffness properties.

Statistical Analyses of FT-IR Spectroscopy Results

The spectroscopic data were also analyzed statistically using Analysis of Variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison techniques. A level of confidence of $\alpha = 0.05$ was used in all of the analyses.

Statistical analyses of carbonyl areas indicated that aging due to the two recovery methods used in this experiment did not differentiate the recovery methods from each other. The base binders and the recovered residues were statistically different, but the two recovery methods were similar to each other in terms of oxidative effects (Prapraitrakul et al., 2009).

Conclusions and Recommendations

Based on the methods evaluated in this experiment, the stirred can emulsion residue recovery method is recommend for use with this proposed specification. Recovered emulsion residues were shown to be different from their base binders at high temperatures in the unaged state, but they were similar to their base binders at cold temperatures after aging. Recovered residues from two recovery methods were oxidized more than their base binders but at similar levels.

Further evaluation of the residue recovery methods is needed to determine which most closely simulates emulsion residue in the field. Additional comparisons of the recommended stirred can residue recovery method with the recently standardized and adopted warm oven method (ASTM D 7497) are strongly recommended to address possible destruction or change in any polymer networks in many commonly used modified emulsions caused by the stirred can recovery method.

APPENDIX E - Desirable Residue Properties for Chip Seals

Introduction

The Performance Grading (PG) asphalt binder grading system (Asphalt Institute, SP-1) is widely used as the specification for grading and selecting asphalt binders. The PG specification was developed for use in hot mix asphalt concrete (HMAC) pavement layers. However, the PG system is not applicable to classifying and choosing binders for use in pavement chip seals. Typically, chip seals are thin layers of spray-applied emulsion and aggregate placed on the pavement surface to protect and restore the surface. Chip seals differ from full depth HMAC layers in construction methods, structural functions, behavioral responses, distress types, and environmental exposure. The Surface Performance Grading (SPG) binder grading system was created in the early 2000s to classify emulsion residues or hot-applied binders for use in chip seals (Epps et al., 2001; Barcena et al., 2002). However, the SPG system has not previously been widely accepted or utilized.

This appendix describes the experiment utilized to characterize the emulsion residues by both the PG and SPG grading systems and some additional tests and recommend a strawman emulsion residue specification.

The Surface Performance-Graded (SPG) Specification

In 2000, the Texas Department of Transportation (TXDOT) initiated a research project with Texas A&M University (TAMU) to develop a performance based grading and specification system for chip seal binders (Epps et al., 2001; Barcena et al., 2002). The surface performance-graded (SPG) specification was created. The tests used in the specification are conducted with standard PG testing equipment; and the analyses are performance-based and consistent with chip seal design, construction, behavior, in-service performance, and associated distresses (Epps et al., 2001; Barcena et al., 2002). TAMU researchers recommended that the SPG needed field validation; and in 2005, TXDOT and TAMU completed an initial field validation study in Texas (Walubita et al., 2005; Walubita et al., 2004) which assessed and modified the SPG specification (Table D1). Only three chip seal binder grades are shown in Table D1; but the grades are unlimited and can be extended in both temperature directions using 3 or 6˚ C increments (Walubita et al., 2005; Walubita et al., 2004).

An ASTM specification for SPG was initiated in 2005 and a draft of the specification was under development (ASTM WK-5321, 2004), but the approval process was halted due to lack of information on how to apply the specification in regions other than Texas.

Table E1. Original SPG specification showing three grades.

Performance Grade	SPG 58				SPG 61				SPG 64			
	-10	-16	-22	-28	-10	-16	-22	-28	-10	-16	-22	-28
Average 7-day Maximum Surface Pavement Design Temperature, °C	<58				<61				<64			
Minimum Surface Pavement Design Temperature, °C	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28	>-10	>-16	>-22	>-28
Original Binder												
Viscosity ASTM D 4402 (*6*) Maximum: 0.15 Pa·s*; Minimum: 0.10 Pa·s Test Temperature, °C	≤205				≤205				≤205			
Dynamic Shear, AASHTO TP315 (*51*) $\frac{G^*}{Sin\,\delta}$, Minimum: 0.65 kPa Test Temperature @10 rad/s, °C	58				61				64			
Pressure Aging Vessel (PAV) Residue (AASHTO PP1) (*51*)												
PAV Aging Temperature, °C	90				100				100			
Creep Stiffness, AASHTO TP313 (*51*) S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8s, °C	-10	-16	-22	-28	-10	-16	-22	-28	-10	-16	-22	-28

*Pa·s = Pascal-seconds

Experiment Design

The standard PG system (Asphalt Institute, SP-1) and the modified SPG system (Epps et al., 2001; Barcena et al., 2002; Walubita et al., 2005; Walubita et al., 2004) were both used to grade all of the base binders and the recovered emulsion residues in this research. The climate in which a pavement is placed is the main criterion used to determine the selection of a binder grade in both of these systems. In the future, the expected traffic level may be incorporated by an adjustment to the binder grade selection for traffic speed and loading.

Materials

Eight emulsions were included in this research. Five of the emulsions were laboratory prepared. These are identified as Emulsions 1 -5. The other three emulsions were obtained from the full scale chip seal projects. These are Arches National Park, Utah; Frederick, Colorado, CR11; and Forks, WA on US101. Table E2 indicates the types of emulsions and, when known, the PG grades of the base binders as reported by the supplier.

Emulsion Recovery Method

Based on the comparison described in Appendix D, the stirred can emulsion residue recovery method was used to extract the water from the emulsions and to supply de-watered bitumen residue for the rheological testing.

In the stirred can method, a gallon can containing 1250 to 1300 g of emulsion is wrapped in heating tape and placed over a burner. The emulsion is stirred constantly with an impeller blade while being heated at 163˚C for 170 minutes. Nitrogen is bubbled up through the can and also flows over the top of the material to prevent oxidation and consequent aging of the material. After 170 minutes, the can is removed from the heat source and covered. The residue, about 800 g, is stored in the gallon can until testing.

Laboratory Tests

Rheology Tests

The binder characterization tests utilized the same equipment and some of the same tests as specified in the PG system (Asphalt Institute, SP-1), but with different limiting criteria.

The dynamic shear rheometer (DSR) was used to measure the rheological properties of the binders, complex shear modulus G* and phase angle δ in the form (G*/sin δ), at high temperatures. Unaged binder was tested at the high temperatures, which is the critical condition for early strength development in chip seals.

All of the binders in this project were aged using only the pressure aging vessel (PAV), as described in the PG specification Asphalt Institute, SP-1. Rolling thin film oven (RTFO) aging was omitted as RTFO is not applicable to emulsions because they are not heated to high temperatures during emulsification and construction.

The bending beam rheometer (BBR) was used to measure bending properties of the binders (stiffness, S, and rate of change in binder stiffness with time, m-value) at cold temperatures.

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

The DSR was also used to measure the properties G* and δ in the form (G* sin δ) which is related to fatigue in HMAC at intermediate temperatures on PAV aged material. The (G* sin δ) parameter was used to check that the materials met the intermediate temperature criteria for the PG grade as determined from the high and low temperature testing.

Strain sweeps were also performed using the DSR at 25º C on both unaged and PAV aged material. The critical performance parameters for a chip seal during its first year are resistance to raveling and aggregate loss at both high and low temperatures. Strain sweep testing of emulsion residue in the DSR is currently being investigated elsewhere (Hanz et al., 2009; Kucharek, 2007) to assess whether an emulsion residue develops adequate strain tolerance and stiffness to prevent the bond between aggregate and emulsion residue from failing.

Strain Sweep Tests

Strain sweeps and their correlation with the sweep test, ASTM D-7000 (ASTM International, 2009), have been investigated elsewhere (Kucharek, 2007) for evaluating the potential of emulsions to resist raveling during curing after chip seal construction. Strain sweep testing was investigated in this study as an addition to the SPG system for evaluating strain tolerance and resistance to raveling of emulsion residues during curing and at early ages.

The reduction in G* at certain percent strains has been proposed for evaluating strain tolerance and bond failure (Hanz et al., 2009). Researchers believe that this information would be useful to assess both the emulsion curing (water evaporation) process as well as aging of the emulsion residue.

Strain sweep testing at 25˚ C was performed for this project on all of the base binders and the emulsion residue from the stirred can recovery method. The temperature of 25˚ C was chosen because it is an average temperature at which chip seals are commonly constructed, and also because other researchers (Hanz et al., 2009) have run strain sweeps at this temperature.

Strain sweep test results are affected by how the testing is performed and by the parameters input into the DSR. The DSR is continually oscillating during strain sweep testing. Therefore, loading and strain occur before the first measurement is taken and continue for the duration of the test, even during any time delay after strain is incremented and before measurements are taken. With these considerations in mind, it is important that different researchers conducting strain sweeps perform the tests using the same parameters if the results are to be compared.

Strain sweep testing was conducted for this project using a Malvern/Bohlin DSR-II with Bohlin R6.50.5.7 research software and the 8 mm plates with a 2 mm gap. Input to the DSR requested strains of 1 to 50%, but these strain levels could not always be attained by the DSR. With the stiffer materials, especially the PAV aged materials, the DSR ran out of torque capability before it could attain the desired strains. The test continues after the maximum stress is reached until the number of samples (or measurements) is completed; but the stress level does not increase above the maximum. At that point it becomes a repeated load test.

The strain sweeps in this study were initiated at 1% strain (rather than at a lower strain) because the G* versus strain curve was still flat below 1% strain, indicating that permanent strain had not yet begun to accumulate in the material. Also, due to the manner in which the DSR performs strain sweeps, there is elastic deformation that is not completely recovered between strain level increments. When starting at 1% strain, the unrecovered elastic deformation from repeated very small strains had not accumulated.

A thermal equilibrium time of 10 minutes after mounting the sample and before testing began was chosen to be consistent with Superpave testing. Also, for an 8 mm diameter sample, 10 minutes allows for thermal equilibrium of a small sample of bituminous material.

An angular frequency of 10 radians/second was used to be consistent with Superpave and to approximate the frequency of traffic loading.

A linear loading sequence with time was used because the part of the G* versus strain curve that is of interest occurs at the specific reductions in G* that are chosen for defining the distresses and for comparing materials. Because these points can occur at different places in the curve for different materials, a linear loading sequence was chosen so as to evenly space the strain increments with time. Also, a logarithmic loading sequence places many load increments at very small strain levels and therefore accumulates unrecovered elastic deformations at low strain levels.

A delay time of 1 second after the load (strain) was incremented but before the measurements were taken was chosen. This allowed the sample a short time to come to equilibrium at each strain level, but little time for deformations to accumulate. When a delay time of 4 seconds was used, the samples tended to deteriorate before the end of the test which indicated that there was damage accumulating between strain increments (although some of that may be recoverable strain).

Between 20 and 30 strain increments were imposed and measured during each test. Each strain increment damages the sample, and so a large number of strain increments may not be desirable and also increases the amount of testing time needed.

Using the parameters discussed in this section, the test time for each strain sweep was approximately 1 to 2 minutes (after thermal equilibrium).

Binder Grading

Emulsion residues from the stirred can recovery procedure and some of their base asphalts were graded according to the PG system developed for HMAC (Asphalt Institute, SP-1) and the SPG system developed for surface treatments (Epps et al., 2001; Barcena et al., 2002; Federal Highway Administration, 2004; Walubita et al., 2005) but both without RTFO aging. As compared to the PG system, the SPG system incorporates the following modifications:

- tests are performed at 3° increments, allowing material performance to be discriminated over a finer scale of temperature;
- the high temperature design condition for the SPG system is specified as the pavement surface temperature;
- DSR testing at high temperatures on unaged binders is expected to reflect the critical condition for early-age surface treatments; and a threshold value of 0.650 kPa minimum is used as the limiting value for ($G^*/\sin \delta$) for SPG high temperature grading, as recommended by TAMU (Walubita et al., 2004; Walubita et al., 2005) ;
- DSR testing at intermediate temperature(s) in the SPG system is not performed because previous research (Epps et al., 2001; Barcena et al., 2002) found that the intermediate temperature test results did not discriminate between binders that performed well and those that did not;
- DSR strain sweep testing at an intermediate temperature of 25˚ C was instead performed for a revised SPG system to assess strain susceptibility and resistance to raveling of the emulsion residues;
- BBR testing at low temperatures is expected to reflect the critical condition for raveling caused by traffic loading on stiff materials; therefore, low temperature properties based on BBR testing were determined at the fastest possible loading time, 8 seconds, and the actual test temperature was used;
- threshold values used for BBR tests at 8 seconds were 500 mPa maximum for SPG flexural stiffness and 0.240 minimum for SPG m-value;

- the SPG criteria used were developed using Texas chip seal projects (Epps et al., 2001; Barcena et al., 2002). These criteria should be developed or verified for other states or regions in the future.

Results and Analysis

DSR Results: High Temperatures

For the high temperature characterization in both grading systems, plots were generated of (G*/sin δ) versus temperature. At the high temperatures, the base binders in every case exhibited lower test parameters (G*/sin δ) than did the recovered residues. This is possibly due to stiffening and aging of the residues during either the emulsification process or the residue recovery process.

BBR Results: Low Temperatures

For the low temperature characterization in both grading systems, plots were generated of S versus temperature and of m-value versus temperature. The plots from the BBR test results indicated that the base binders and the recovered emulsion residues had similar cold temperature properties. Aging of the materials (and possibly exposure to cold temperatures) seemed to affect the base asphalts and the recovered residues so that they exhibited similar properties at cold temperature after PAV aging. This could be due to deterioration of the polymer additive structure over time and with aging (Woo et al., 2006).

DSR Results: Intermediate Temperatures

All of the materials passed the PG (G*sin δ) criterion at the SP-1 specified intermediate temperatures. All of the materials also passed for at least one additional (i.e. colder) temperature.

PG and SPG Grading

Both PG and SPG grades were determined for all of the base binders and recovered residues, and the results are shown in Table E2. Interpolation was used to determine the continuous grades. The continuous grades can be used to discriminate more accurately the differences in grading among the base binder and the corresponding emulsion residue.

In general, the PG grades were consistent for the base binder and the residue, as were the SPG grades. However, examination of the continuous grades indicated that the base binder grades were slightly different from the grades of the recovered residue.

Table E2. Materials Tested Indicating PG and SPG Grades

Emul -sion	Emulsion Type	Expected Base Grade	Batch #	Recovery Method	PG Grade from Tests	Continuous PG Grade	SPG Grade from Tests	Continuous SPG Grade
1	RS-2P	PG 64-28	1	Base Asphalt	PG 64-34	67.8 - 34.2	SPG 70 -24	71.7 - 24.0
			6	Stirred Can with N	PG 64-34	69.3 - 34.1	SPG 73 -18	73.0 - 21.3
2	CRS-2	na	2	Base Asphalt	PG 58-28	60.2 - 30.7	SPG 61 -18	63.1 - 19.4
			7	Stirred Can with N	PG 58-28	62.9 - 31.0	SPG 64 -18	66.4 - 19.2
3	RS-2	PG 64-22	3	Base Asphalt	PG 64-22	66.9 - 27.1	SPG 67 -12	69.7 - 14.7
			8	Stirred Can with N	PG 64-22	68.2 - 26.8	SPG 70 -12	71.4 - 15.9
4	CRS-2P	PG 64-28	4	Base Asphalt	PG 64-28	67.6 - 32.9	SPG 70 -18	70.8 - 22.2
			9	Stirred Can with N	PG 64-28	68.6 - 33.2	SPG 70 -18	72.3 - 22.9
5	HFRS-2P	PG 70-28	5	Base Asphalt	PG 58-28	62.3 - 30.4	SPG 64 -18	65.7 - 18.7
			10	Stirred Can with N	PG 58-28	63.4 - 31.6	SPG 67 -18	67.0 - 20.1
6 - UT	LMCRS-2	na	16	Stirred Can with N	PG 70-22	74.7 -26.4	SPG 76 -12	78.7 - 15.3
7 - CO	HFRS-2P	na	18	Stirred Can with N	PG 70-28	72.0 - 32.0	SPG 76 -18	76.6 - 21.1
8 - WA	CRS-2P	PG 64-22	20	Hot Oven-N Blnkt	PG 64-28	64.1 - 28.0	SPG 67 -18	67.6 - 18

Use of the SPG system resulted in a higher continuous grade at both the high and the low temperature ends than the continuous grade with the PG system. The average difference in the high temperature continuous grades (SPG minus PG) was +3.6º C. The average difference in the low temperature continuous grades (SPG minus PG) was +11.3º C.

Statistical Analyses Summary

The rheological data collected with the DSR and the BBR were analyzed statistically using Analysis of Variance (ANOVA) and Tukey's Honestly Significant Differences (HSD) multiple comparison techniques. A level of confidence of $\alpha = 0.05$ was used in all of the analyses, and a summary of the complete results detailed in Appendix D are provided in this section. The objective was to determine if there were statistical differences between the emulsions and between the recovery methods where the base binder when available was treated statistically as "no recovery" method.

When comparing the DSR data by recovery method, the analysis results statistically grouped the stirred can recovery method separate from the base binder ("no recovery") for the emulsions with base binders available (1-5). The recovered residue was stiffer, with larger values of log ($G^*/\sin \delta$), than the base binder, but not stiff enough to change the high-temperature PG grade (Table E2) for emulsions 1-5. With smaller temperature increments, the high-temperature SPG grade did change to a larger value for four of emulsions 1-5.

The recurring result from all of the analyses of the BBR measurements was that the recovery method (with base binders included as "no recovery") did not practically affect the response variables S or m-value for the stirred can recovered residue. This result seemed to indicate that, after PAV aging and consequent oxidation, the polymers and additives no longer had an effect on the stiffness properties.

Strain Sweep Results

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

Comparison of the plots of G* versus % strain indicate that the magnitudes of the G* and strain values and the shapes and rates of change of the curves are significant for comparing materials and characterizing strain tolerance. For comparison, the strain sweep curves from the stirred can recovery residues for aged and unaged materials in this project are shown in Figure E3.

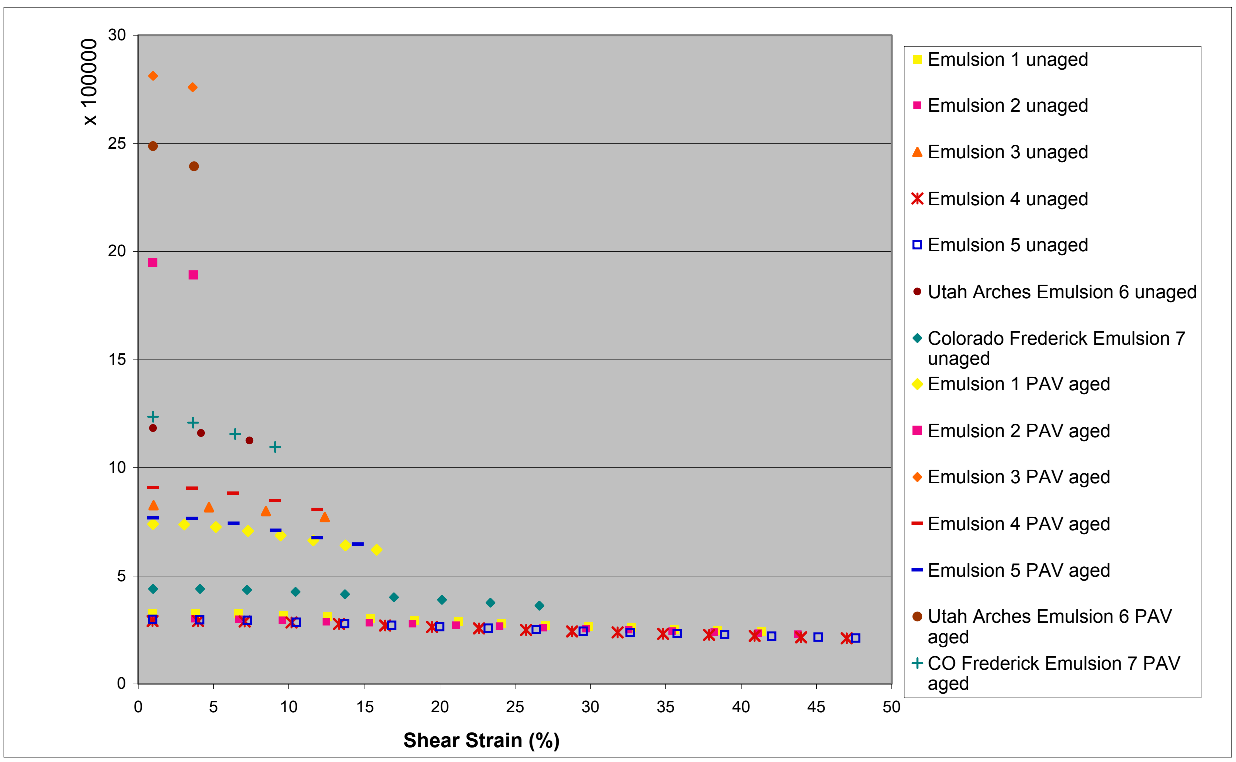


Figure E3. Strain Sweeps for Stirred Can Recovery Method

Materials with high strain tolerance exhibit slow deterioration of G* with increasing strain level, indicating that the material maintains stiffness and holds together under repeated and increasing loads. Emulsions 1, 2, 4, and 5 in an unaged state in Figure 1 exhibited this behavior. These materials were sticky, stretchy, and stringy to handle in the laboratory, even after strain sweep testing. Materials with less strain tolerance have curves that quickly develop steeper downward slopes, indicating that the material loses stiffness with increasing strain. Emulsions 2, 3 and Utah Arches in a PAV aged state in Figure 1 are examples of this type of behavior. These materials were very stiff and broke off of the test plates in a brittle manner after the strain sweep testing was completed. The slopes of the curves were steeper for the PAV aged materials than for the unaged materials, as can be seen by comparing the Utah Arches unaged and the Colorado Frederick PAV aged curves in Figure E1. This relationship can also be seen by looking at the curve for emulsion residue 3 unaged versus those for emulsion residues 4 and 5 PAV aged.

During early curing, the binder material must develop enough stiffness to be able to carry vehicle loads before the chip seal is opened to traffic. A minimum level of G* must be attained at which an emulsion has cured enough and lost enough water for emulsion residue to support traffic. Emulsion curing after chip seal construction is commonly used in the field to determine when a chip seal can be opened to traffic. This could be correlated with the initial G*, or G_i*, from the strain sweep testing to determine a minimum G* for traffic bearing capacity.

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

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

This study found that, the more stiff the emulsion residue initially is and the more cured and then aged it becomes, the more difficult it is to reach 50% G_i* and even 90% G_i* in strain sweep testing. This is especially true for PAV aged materials. The maximum stress that the Malvern-Bohlin DSR II can induce is 99,470 Pa. None of the materials in this study reached 50% of G_i* using the test parameters described previously. Most of the unaged and only a few of the PAV aged materials reached 80% G_i*, as shown in Table E3. It is possible that intermediate reductions in G_i* might be used so that the behavior of the fully cured residues can be characterized even when 50% or 90% G_i* cannot be attained. Another solution could be the use of different test parameters.

Table E3. Strain Sweep Test Results

Emul-sion	Recovery	UNAGED G_i* (Pa, at 1% γ)	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*	AGED G_i* (Pa, at 1% γ)	% γ at $0.98G_i$*	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*

1	base	241,120	21.23	34.74	n/a	987,120	4.95	10.88	12.67	n/a
1	stirred can	326,460	19.20	31.22	n/a	883,620	5.01	11.86	14.15	n/a
2	base	248,290	25.72	6.18	84.03	1,448,300	3.93	7.31	8.62	n/a
2	stirred can	298,170	22.17	38.31	n/a	1,948,300	2.77	5.29	6.40	n/a
3	base	747,630	14.84	16.71	n/a	3,329,800	2.31	n/a	n/a	n/a
3	stirred can	825,740	13.26	15.13	n/a	2,811,300	3.62	n/a	n/a	n/a
4	base	219,060	25.41	44.14	n/a	954,040	5.24	10.92	13.11	n/a
4	stirred can	289,860	20.77	34.51	n/a	905,480	5.58	11.27	13.82	n/a
5	base	266,850	22.03	38.45	n/a	1,260,200	4.92	8.81	9.91	n/a
5	stirred can	297,360	17.79	31.46	67.95	765,620	5.18	10.76	16.35	n/a
6 – UT	stirred can	1,182,300	9.18	10.56	n/a	2,486,600	2.45	4.46	n/a	n/a
7 - CO	stirred can	440,260	18.16	28.36	45.86	1,235,400	3.36	8.41	10.11	n/a
Grey shading = after max DSR stress was reached; n/a = test didn't run that far										

Besides differing in the rate at which G* deteriorated with increasing strain, the materials differed in their original stiffness, G_i*, and in the amounts of increase in G_i* that occurred between the unaged state and the PAV aged state. Table 3 includes a summary of the G_i*s. The stiffest material in the unaged state was the Utah Arches emulsion residue (emulsion 6), a latex modified rapid-setting emulsion. The stiffest material in the aged state was the emulsion 3 residue, a rapid-setting unmodified emulsion. G* increased the most from the unaged to the aged state for the emulsion 3 residue. It was followed by the emulsion 2 residue, also a rapid-setting unmodified emulsion, and then by the Utah Arches emulsion 6 residue. Emulsion residues for 1, 4, 5, and Colorado Frederick (emulsion 7), all polymer modified emulsions, increased in G* and exhibited aged behavior after the PAV aging, but not by as much as emulsion residues 2, 3, and Utah Arches (emulsion 6). Also, for emulsions 1, 4, and 5 the base binder increased in G* considerably more than the recovered residue did, possibly indicating that either the emulsification process or the residue recovery process reduced the susceptibility of these materials to the PAV aging process.

Based on the results of the strain sweep testing, emulsions 1, 2, 4, 5, and Colorado Frederick (emulsion 7) would be expected to resist raveling due to their high strain tolerances. Emulsions 3 and Utah Arches (emulsion 6), which had very stiff residues even when unaged, would be expected to resist flushing and also might be able to be opened to traffic earlier; however, they became more brittle with aging and could therefore exhibit raveling with age. The Utah Arches project was located in the high desert where there is high heat and intense sun, and the road carries more traffic in the summer than in the winter. A stiff binder would resist deformation and raveling in these conditions. The high stiffness of the Utah Arches emulsion 6 residue might be beneficial in this environment.

Field Site Assessment After One Year

The chip seal project at Frederick, Colorado was assessed visually after one year and it looked very good. The site was snowplowed last winter for an estimated 48 days and there is only slight damage at the crown for approximately 1500 feet in over 3 miles. Embedment is approximately 60-75 percent as expected.

Conclusions and Recommendations

Surface Performance Grading (SPG) with additional tests but using the same equipment as used in the Performance Graded (PG) system is a step in the right direction for a performance graded specification for chip seal materials. A strawman emulsion residue specification based on that proposed through TxDOT research (Table E1) and modified based on the results of this experiment is shown in Table E4. The strain sweep thresholds were selected to reflect the significantly different performance of emulsion 3 and the Utah Arches emulsion 6.

The thresholds provided for the DSR and BBR parameters are based on validation with Texas field sections, and they likely need to be adjusted for more extreme climates such as that in Utah and Colorado as examined in this experiment. The current thresholds result in grades of SPG 76-12, SPG 76-18, and SPG 67-18 for the residues from the Utah Arches emulsion 6, the Colorado emulsion 7, and the Washington emulsion 8, respectively. The closest LTPPBIND weather stations (LTPPBIND Version 3.0/3.1) and Long Term Pavement Performance (LTPP) Pavement Temperature Models require SPG 61-12, SPG 58-24, and SPG 52-12 at 50% reliability, respectively, for adequate performance in Utah, Colorado, and Washington (FHWA, 1997). As shown in Figure E4, this discrepancy between the required emulsion residue grade for the selected climate and the actual grade of the material utilized illustrates that the thresholds, particularly for the low temperature BBR properties, may need adjustment if the field performance after the first critical year in Colorado is indicative.

Table E4. Strawman Emulsion Residue Specification

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

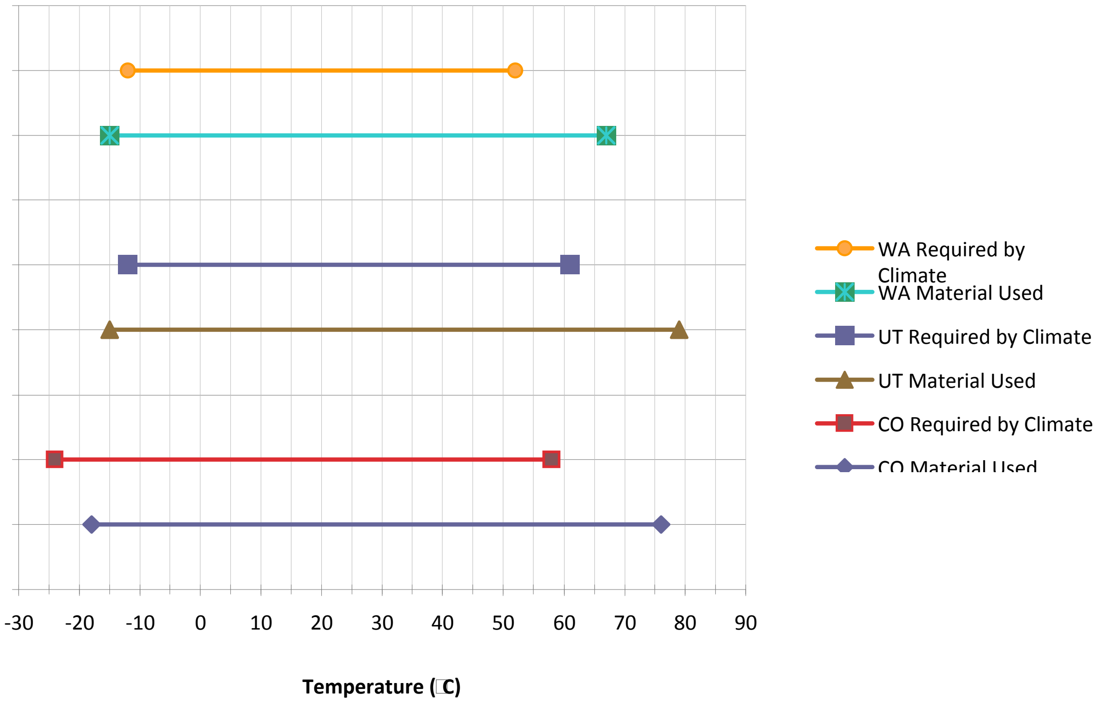


Figure E4. SPG Material Specifications Compared with Actual Materials Used

Strain sweeps performed with the DSR on curing and unaged emulsion residues are recommended to evaluate strain resistance and stiffness development. These tests could be used to predict when emulsion based chip seals will develop enough stiffness to be opened to traffic. Strain sweeps could also be used to assess a material's resistance to raveling, both in newly constructed chip seals and after the critical first seasons of weather and aging.

Further field validation of the SPG specification criteria and extension of the grading criteria to regions other than Texas are needed before the specification for SPG can be approved and used on a national level.

Further performance monitoring of the three full scale test pavements constructed and studied in this project is recommended.

It is commonly agreed that there is a need to replace cold temperature testing using the BBR with an alternative test which measures G* at cold temperatures directly. Research being done at University of Wisconsin Madison and at Western Research Institute (Pavement Preservation Emulsion Task Force, 2008) may produce a replacement test.

APPENDIX F - Estimating Embedment in the Field

The percent embedment of aggregate particles in asphalt is a function of the aggregate void ratio, the volume of aggregate and the available volume of asphalt after allowances have been made for the absorption and texture of the existing pavement over which the chip seal is placed. Determining percent embedment in the field is often difficult since the constructed chip seal varies from place to place and design values of asphalt and aggregate coverage rates are never achieved precisely. In fact the design often provides for a range of acceptable coverage rates.

Usually, the aggregate gradation and specific gravity are documented, however, the in-situ aggregate void ratio is often guessed. Assumptions are usually made regarding the achieved compaction of voids between the chip seal aggregate relative to the void ratio which exists in the loose-state aggregate. Even when the aggregate coverage rate (pounds per square yard) is known, void ratio evaluation is difficult since the volume, or the height, of the chip seal layer must also be determined. That is, although the coverage rate can help us to determine the solid volume of the chip seal layer, the total volume including voids is not as easily determined when the chip seal is still undergoing compaction of voids by means of particle orientation.

In cases where the void ratio and average height of the chip seal layer have been determined, it is conceivable that the percent embedment of particles may be approximated using a known volume of fine quartz sand or glass beads to fill the voids between the particles. This proposal is based on an assumption that the entire surface of the asphalt, around each particle, is accessible to the fine glass beads.

The chip seal's texture height (T) is the average height of aggregate that is exposed above the surface of the asphalt. The theoretical texture height can be calculated from the following:

$$T = \frac{\text{volume of beads and aggregate above the asphalt surface and below the average particle height}}{\text{plan area of beads and aggregate}} \qquad (1)$$

The above statement may be re-written as:

$$T = \frac{B + (T * A * S)}{A} = \frac{B}{A} + T * S \; ; \qquad \therefore \; T - T * S = \frac{B}{A} \quad \text{, and} \quad T = \frac{B}{A * (1 - S)} = \frac{B}{A * V} \qquad (2)$$

And embedment may then be determined using:

$$\text{embedment (\%)} = \frac{H - T}{H} \qquad (3)$$

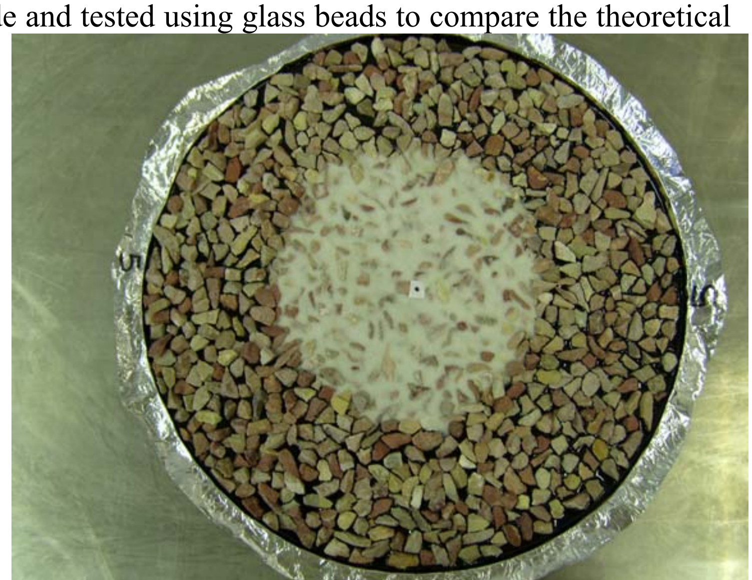
Where:

T = texture height (mm),
B = volume of glass beads (mm^3) below the average particle height,
A = plan area of chip seal (mm^2),
S = the solid ratio (1-void ratio),
V = the known void ratio, and
H = average particle height (mm).

Equation 2 assumes that the volume of glass beads is spread over the chip seal up to the peak of each particle. That is, the glass beads must follow the profile of the particle peaks. In this way, the average height of the glass beads on the actual chip seal is equivalent to the void height that would be seen between equal-height particles of a chip seal that is built with exactly one-sized aggregate.

According to equations 2 and 3, for a chip seal of known void ratio and average particle height, it is theoretically possible to calculate the texture depth (T) and, ultimately, the percent embedment by spreading a fixed volume of glass beads in the aforementioned manner and measuring the resulting area.

In this regard, an experiment was devised, dubbed "the spreading procedure," where chip seal specimens, with approximately 20% and 80% particle embedment, were made and tested using glass beads to compare the theoretical diameters with the practical diameters achieved after spreading approximately 25 cubic centimeters of glass beads with unit weight of 1.42 g/cc.



Two aggregate types were used. The first was Limestone (LSTN) with a specific gravity of 2.615, an average least dimension (ALD) of 4.196mm, a unit weight of 1,254.285 kg/cubic meter, and actual specimen void ratio of 0.5062. This limestone sample had a flakiness index of 33.78% and was useful for comparison with the second aggregate sample, Granite (GRNT), whose flakiness index was only 5.77%. GRNT had a specific gravity of 2.612, an average least dimension (ALD) of 6.629mm, a unit weight of 1,345.016 kg/cubic meter, and actual specimen void ratio of 0.4768.

On the chip seal specimens, the particles were oriented on their widest faces so that the average particle heights were their average least dimensions. Void ratio and embedment percentage were determined for each specimen based on the specimen aggregate's average least dimension for LSTN and GRNT. The known void ratio and average chip seal height, along with proposed diameters and proposed volumes of glass beads were entered into an Excel spreadsheet to calculate theoretical textures and embedment percents using equations 2 and 3.

Figure F1 shows measured glass bead diameters obtained using the spreading procedure on chip seal specimens of approximately 20 % and 80 % particle embedments. On the same chart, for comparison, theoretical diameters are plotted for a range of embedment percentages.

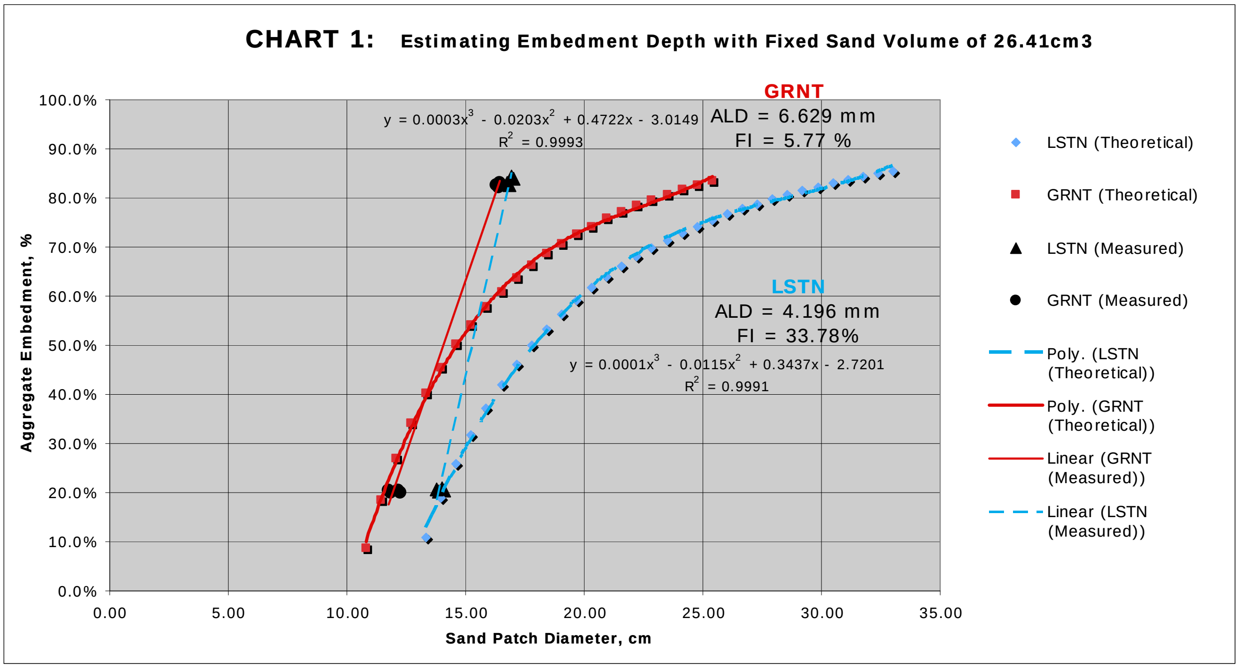


Figure F1. Estimating Embedment Depth With Fixed Sand Volume

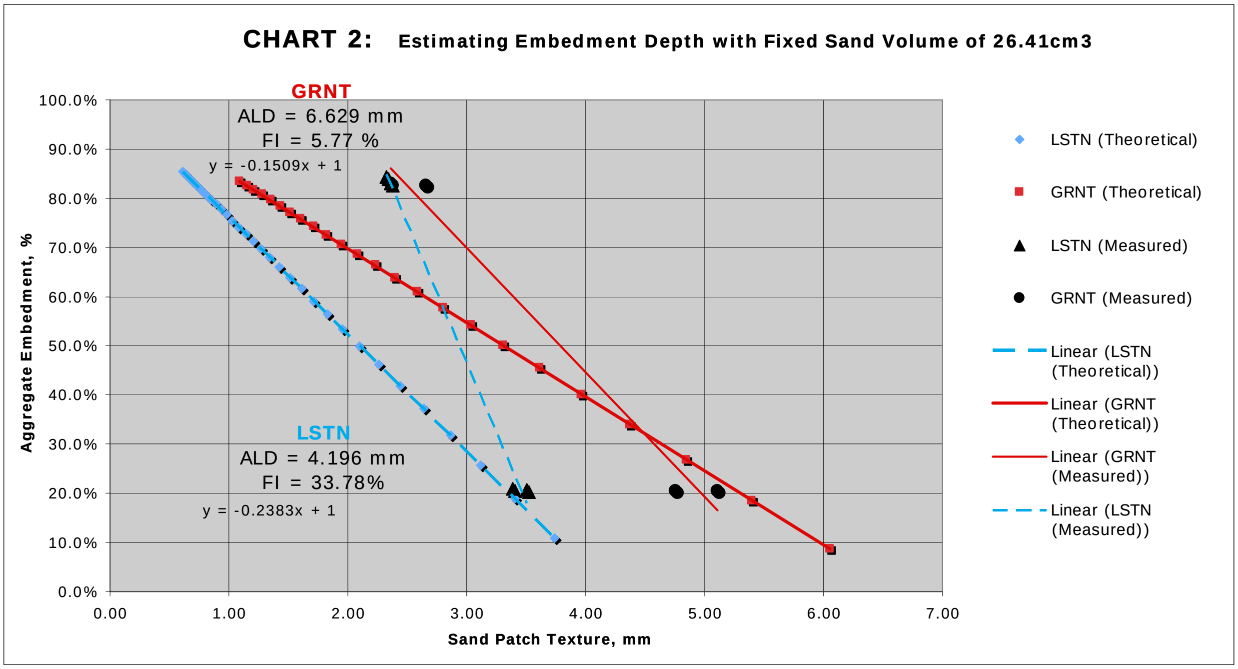


Figure F2. Estimating Embedment Depth From Texture

For chip seal specimens of approximately 20 % embedment, the measured diameters are fairly close to the theoretical diameters. At 80 % embedment, however, the measured diameters are only 53% of the theoretical diameter for LSTN and 65 % of theoretical for GRNT.

The calculated texture heights are plotted in Figure F2. Again, these show measured textures that are similar to theoretical values at 20% embedment. However, at approximately 80% embedment, the measured textures are much greater than the theoretical texture values, with LSTN showing a higher degree of deviation compared with GRNT.

In practice, the requirement, of the spreading procedure, that glass beads just meet the peak of each particle, is not easy to accomplish. In instances, the angle of repose of the glass beads makes it impossible to achieve this requirement. However, even when this requirement is relaxed, and an average fill height is used, fairly good results were achieved at the lower embedment level. This might be the case because at 20 % embedment, voids are deep, taking in much of the beads, and the procedure of leveling between the particle peaks contributes less to error than it does at higher embedment percentages.

At the higher embedment level, however, many particles, in the chip seal specimens, were fully covered by asphalt and their peaks were not discernible. In keeping with the requirement to fill the spaces between particles to the average particle height, one should shape the profile of the glass beads, above the asphalt level, the same way for all asphalt heights. While this is possible for low embedments, it becomes impossible to bridge between all the peaks with glass beads at very high embedments. In such a case, theoretically, isolated peaks should have just a small area of glass beads surrounding them. But this is difficult to accurately estimate in practice, with the result that pools of asphalt end up being covered with sand where there shouldn't be any. This results in smaller diameters and thicker calculated textures.

The submerged-peak locations were even more difficult to discern with the flatter LSTN particles which may be the reason for the larger deviations seen with LSTN compared to the blockier GRNT. Additionally, aggregates with smaller textures, LSTN in this case, should be naturally more sensitive and will exhibit larger diameter changes, for a particular volume of sand, than more angular or blocky aggregates would. This condition is exacerbated at higher embedments.

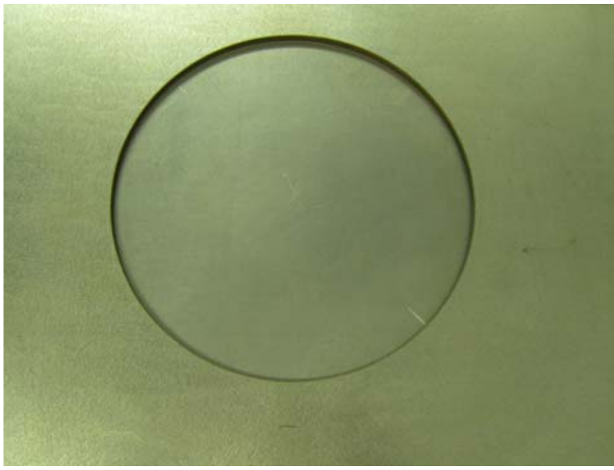
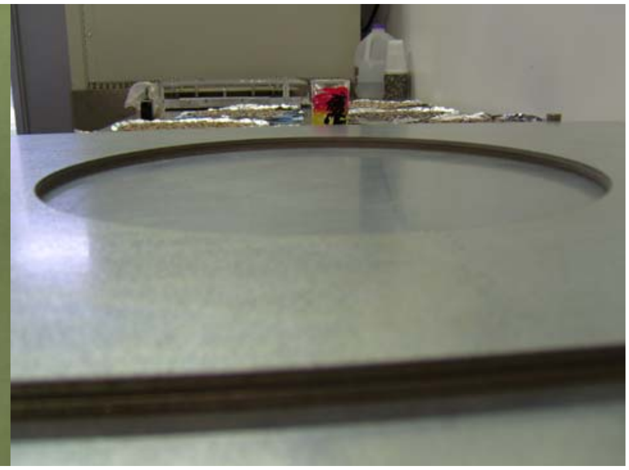
By contrast, at 20 % embedment, the lower required angle of repose to fill between the mildly undulating peaks of the flat and elongated LSTN particles, when compared to the angle required to bridge between the widely varying peak height of the less elongated GRNT particles, may be the reason why the measured LSTN diameters and textures correspond better with the theoretical values than those for GRNT.

All the measured results indicate that it may be possible for the procedure to find use in the field where chip seal particle embedments are closer to 50 % or where particles are not submerged. However, higher embedments pose a practical problem.

In order to address the problem, encountered in the lab, of not being able to discern the peaks of completely embedded chip seal particles, and in an effort to eliminate the difficulty of contouring the glass bead profile to match that of the aggregate peaks, a variant on the spreading procedure was conceived. In this variant, "the fixed-diameter submerging procedure," chip seal specimens of known embedments, approximately 20 % and 80 % embedments, were covered with glass beads to full submergence in a mold. By a process of subtracting the volume of beads above the average particle height of a fixed area specimen, the volume of beads below the average particle height could be determined.

The submerging procedure requires that the void ratio as well as the average particle height, or ALD as in the specific case of the performed experiment, be known. Additionally, the density of beads filling the mold of fixed cross-sectional area and height must be carefully determined by precisely measuring the volume of the mold, the height of the mold and weighing the mass of beads that will fill it.

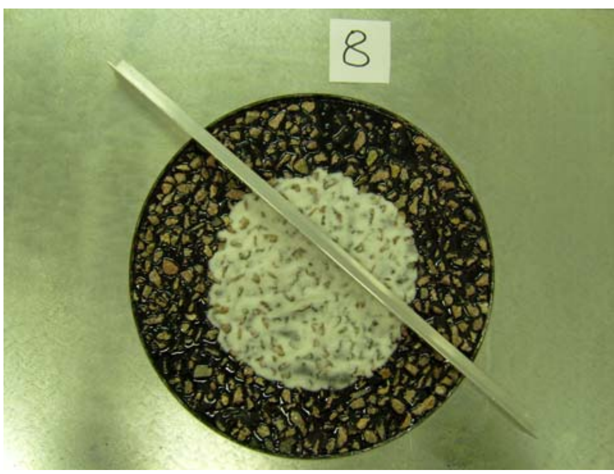
To determine embedment percent, the chip seal specimen is placed in the mold. The mold is filled with glass beads to overflowing, and the level top of the mold is struck flush. The total

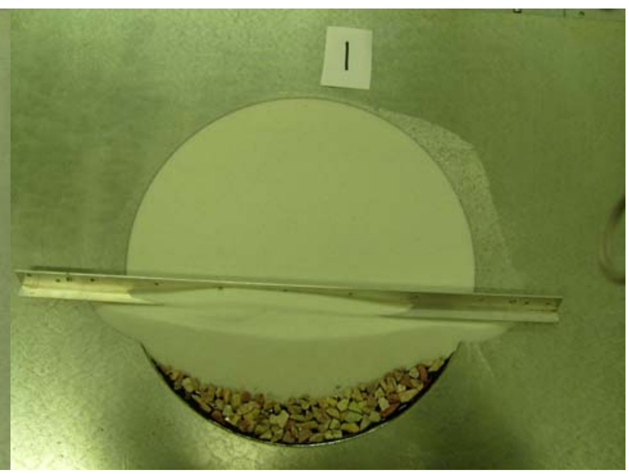



mass of beads which fills the space above the specimen is determined and its volume is calculated using its density value. Knowing the average height of the chip seal aggregate, the excess volume of glass beads between the top of the struck mold and the top of the average particle is calculated from the following:

$$\text{Excess Volume of Beads} = (M - H) * A \tag{4}$$

Where:
M = max height of mold (mm),
H = average particle height (mm), and
A = plan area of chip seal (mm^2).





By subtracting the result of equation 4 from the total volume of beads, we arrive at the measured void volume, between aggregate particles, which is filled with beads (to the average particle height). The texture and percent embedment are respectively determined using equation 2 and 3.

The theoretical void volume is determined for assumed embedment percentages from:

$$\text{Void Volume} = (H * A) * (1 - e\%) * V \tag{5}$$

Where:
H = average particle height (mm),
A = known plan area of chip seal (mm^2),
e% = percentage embedment (equation 3), and
V = the known void ratio

The known void ratio, the specimen's plan area and theoretical void volume are then used in equation 2 to calculate theoretical textures.

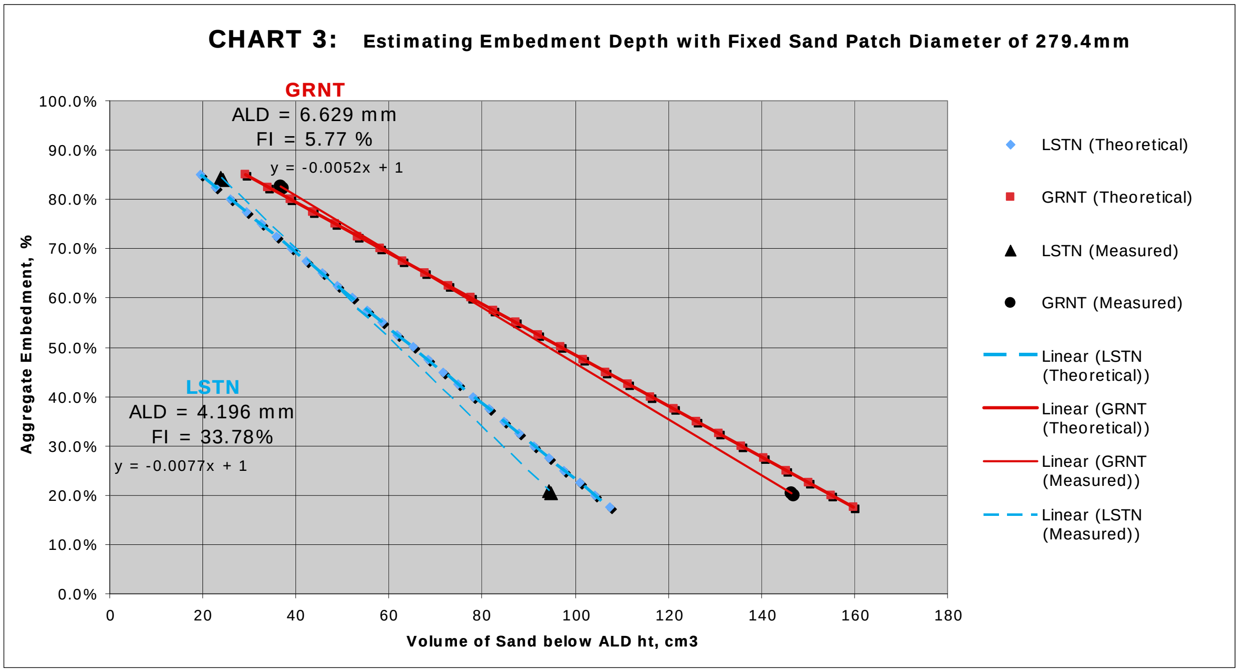


Figure F3. Estimating Embedment Depth With Fixed Sand Diameter

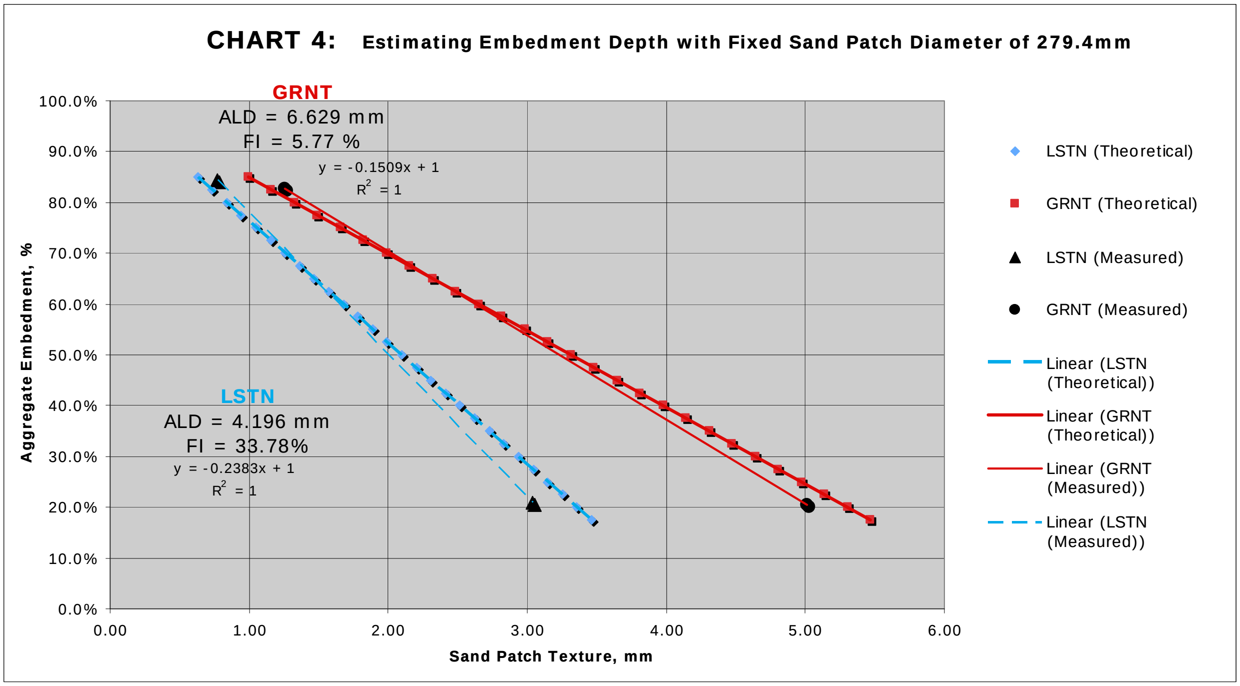


Figure F4. Estimating Embedment Depth From Texture

Figure F3 shows the measured volumes of glass beads that fill the voids between particles, compared with theoretical values for void volume. These measured results, obtained using the same chip seal specimens as those used for the spreading procedure, indicate that the spreading procedure is indeed flawed at higher embedment percentages. The submerging procedure is able to provide results that are very similar to the theoretical void volumes and texture depths at high embedment percentages as shown in Figure F4.

At 20% embedment, the measured values are some 10% smaller than the theoretical. At approximately 80% embedment, the deviation is less at 5% larger than theoretical. Deviations were similar for LSTN and GRNT at both levels of embedment.

Measured values deviated, from theoretical values, positively at approximately 80 % embedment and negatively at approximately 20 % embedment, a similar trend to that observed with the results of the spreading procedure. It is important to note that the results are very sensitive to small changes in density of glass beads. This suggests that determination of density should be performed in the same manner that bead placement on chip seal specimens is expected to occur. It is possible to rectify the deviations from the theoretical values by employing a lower actual density of glass beads for the 20% embedment specimen and a higher actual density for the 80% embedment specimen. It would seem plausible to make such adjustments, however it is unknown whether such adjustments would reflect the actual densities.

Where trusted values for average particle height and void ratio exist, and where it is possible to perform the submerging procedure, better results may be possible, particularly at higher embedment percentages. To use the submerging procedure in the field, the level of the bottom of the chip seal layer must be precisely established in order to determine the height of a level plane to which the chip seal test area may be filled with glass beads to submerge the chip seal and evaluate embedment. It is doubtful whether the achievable accuracy warrants the use of such a procedure.

The spreading procedure is certainly a more practical procedure although the accuracy which is possible at high embedment levels appears to be very low. At lower embedments, however, especially when only a rough check is required, the spreading procedure is promising for its simplicity.

APPENDIX G - Guide Specifications

Asphalt Emulsions

Current specifications for asphalt emulsions were not developed specifically for chip seal construction. In fact, current specifications provide broad enough tolerances on material properties so that a wide assortment of materials can be supplied. This provides flexibility for both owners and suppliers. However, success of a chip seal often depends on the properties of the materials utilized. Therefore, the guide specification given below in Table G1 identifies specific properties of asphalt emulsions important for specific chip seal construction and traffic conditions. This specification is based on current consensus standards and state specifications for both conventional and polymer modified emulsions. Anionic, cationic and high float emulsions are included. Because of the wide array of emulsions available in the U. S., not every

Table G1. Guide Specification for Asphalt Emulsions Used for Chip Seals

		Min.	Max.	Min.	Max.
		RS-2		**Polymer Modified RS-2**	
Viscosity SSF,@ 122□F., sec	AASHTO T 59	100	300	100	300
Storage Stability, 1 day, %	AASHTO T 59		1		1
Sieve Test, %	AASHTO T 59		0.1		0.1
Demulsibility, 35 ml. 0.02 N CaCl2, %	AASHTO T 59	60	95	60	95
Residue by Evaporation, %	Appendix D	63		63	
Float Test, 140F, s	AASHTO T50				
Penetration, 77F,, 100g, 5s	AASHTO T49	100	200	100	200
Ductility, 77F, 5cm/min, cm	AASHTO T5	40		40	
Torsional Recovery, %	CT-332*			18	
Toughness, in-lbs	CPL-2210**			70	
Tenacity, in-lbs	CPL-2210**			45	
Elastic Recovery, %	CPL-2211**			58	
		CRS-2		**Polymer Modified CRS-2**	
Viscosity SSF, @ 122□F., sec.	AASHTO T 59	100	400	100	400
Storage Stability, 1 day, %	AASHTO T 59		1		1
Sieve Test, %	AASHTO T 59		0.1		0.1
Demulsibility, 35 ml.0.8% sodium dioctyl sulfo succinate,	AASHTO T 59	60	95	60	95
Particle Charge	AASHTO T 59	Positive		Positive	
Oil distillate by volume of emulsion, %	AASHTO T 59		3		3
Residue by Evaporation, %	Appendix D	65		65	
Penetration, 77F,, 100g, 5s	AASHTO T49	100	250	100	250
Ductility, 77F, 5cm/min, cm	AASHTO T5	40		40	
Torsional Recovery, %	CT-332*			18	
Toughness, in-lbs	CPL-2210**			70	
Tenacity, in-lbs	CPL-2210**			45	
Elastic Recovery, %	CPL-2211**			58	
		HFRS-2		**Polymer Modified HFRS-2**	
Viscosity SSF,@ 122□F., sec	AASHTO T 59	100	300	100	300
Storage Stability, 1 day, %	AASHTO T 59		1		1
Sieve Test, %	AASHTO T 59		0.1		0.1
Demulsibility, 35 ml. 0.02 N CaCl2, %	AASHTO T 59	60	95	60	95
Residue by Evaporation, %	Appendix D	63		63	
Float Test, 140F, s	AASHTO T50	1200			
Penetration, 77F,, 100g, 5s	AASHTO T49	100	200	100	200
Ductility, 77F, 5cm/min, cm	AASHTO T5	40		40	
Torsional Recovery, %	CT-332*			18	
Toughness, in-lbs	CPL-2210**			70	
Tenacity, in-lbs	CPL-2210**			45	
Elastic Recovery, %	CPL-2211**			58	

* California Test Method
** Colorado Test Methods

combination of conventional and modified emulsion could be included. However, those included below have provided successful chip seal construction over a wide array of environments and traffic conditions.

Guide Specification for Asphalt Emulsion Residue Properties for Chip Seals

The Guide Specification presented in Table G2 is proposed as a Surface Performance Grading (SPG) specification which uses the same laboratory testing equipment as the Performance Graded (PG) system for asphalt cement binders used in the Superpave specification. The strain sweep thresholds shown were selected to reflect the significantly different performance of emulsion 3 and the Utah Arches emulsion 6.

Table G2. Emulsion Residue Guide Specification

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

Aggregates for Chip Seals

Several state specifications were compared as a means of determining a reasonable guide specification for chip seal aggregates. A summary of the gradations from six of the states reviewed are shown in Table G3.

Table G3. Chip Seal Aggregate Requirements in Six States

California

3/4	100			
1/2	95-100	100		
3/8	50-80	90-100	100	100
4	0-15	5 - 30	30-60	60-85
8	0-5	0-10	0-15	0-25
16		0-5	0-5	0-5
30			0-3	0-3
50				
200	0-2	0-2	0-2	0-2

Arkansas

3/4	100		
1/2	90-100	100	
3/8		80-100	100
4	0-15		50-90
8	0-3	0-15	0-15
16			
30			
50			
200		0-3	0-8

Utah

3/4			
1/2	100		100
3/8	85-100		70-90
4	0-20	100	0-5
8	0-5	85-100	0-3
16		10--25	
30			
50		0-5	
200	0-1	0-2	0-1

Colorado

3/4	100		
5/8	90-100		
1/2	80-100	100	
3/8	0-80	90-100	100
1/4	0-20	0-60	90-100
4			
8	0-3	0-3	0-3
16			
30			
50			
200	0-2.5	0-2.5	0-2.5

Alaska

3/4			
5/8			
1/2	100		100
3/8	90-100	100	90-100
1/4			
4	10 --30	85-100	0-10
8	0-8		0-5
16			
30			
50		0-20	
200	0-1	0-1	0-1

Alabama

3/4	100
5/8	
1/2	90-100
3/8	40-70
1/4	
4	0-15
8	0-5
16	0-5
30	
50	
200	

Based on these state specifications, the gradations shown in Table G4 provide reasonable limits for obtaining nearly one-sized chip seal aggregates.

Table G4. Guide Specification for Chip Seal Aggregates

NCHRP 14-17

3/4	100		
1/2	90-100	100	
3/8	5-30	90-100	100
4	0-10	5-30	90-100
8		0-10	5-30
16	0-2		0-10
30		0-2	
50			0-2
200	0-1	0-1	0-1

In addition to gradation the aggregate should meet other physical requirements, as well. These are shown in Tables G5 through G8.

Table G5. Los Angeles Abrasion and Micro-Deval Loss Versus Traffic Level

Traffic, veh/day/lane	L. A. Abrasion Loss, % max	Micro-Deval Loss, % max
<500	40	15
500 - 1500	35	13
> 1500	30	12

Table G6. Mechanically Fractured Requirements for Chip Seal Aggregates

		Vehicles per Day per Lane		
Parameter	**Test Method**	**<500**	**500-1500**	**>1500**
One Fractured Face	ASTM D5821	90	95	100
Two Fractured Faces	ASTM D5821	85	90	90

Table G7. Flakiness Index Requirements for Chip Seal Aggregates

		Vehicles per Day per Lane		
Parameter	**Test Method**	**<500**	**500-1500**	**>1500**
Flakiness Index	Tex 224-F, Mn/DOT FLH T508	35	30	25

Table G8. Other Physical Requirements

Soundness Loss, max %	AASHTO T104	10
Passing No. 200, max, %	AASHTO T11 and T27	1
Polished Stone Value, max	AASHTO T279	31

APPENDIX H - Ball Penetration Test

This test was conducted at Arches, Frederick and Forks to determine utility and determine the values of penetration for the three sites to determine utility of the test and for input into the South African design procedure.

The apparatus is shown in Figure H1 with results in Table H1.

Figure H1. Ball Penetration Apparatus

Table H1. Ball Penetration Results

Date	Surface Pavement Temp, F	Pavement Description	Test No.	Pen, mm	Avg, mm	Std Dev, mm
9-8-08 Arches	110		1	1.54	1.36	0.54
			2	0.83		
			3	1.42		
			4	2.53		
			5	0.99		
			6	1.43		
			7	1.87		
			8	0.75		
			9	0.92		
			10	1.31		
9-8-08 Arches	125		1	2.13	2.59	0.42
			2	2.16		
			3	3.30		
			4	2.28		
			5	2.20		
			6	2.41		
			7	2.88		
			8	2.90		
			9	3.05		
			10	2.55		
9-10-08 Frederick NE Corner CR 11 and CR 18	98	Old chip seal, pocked and rigid	1	1.68	1.87	0.25
			2	2.23		
			3	1.80		
			4	1.76		
9-10-08 Frederick SE Corner CR 11 and CR 18	110	Old chip seal, pocked and rigid	1	1.87	2.04	0.18
			2	1.96		
			3	2.28		
			4	2.06		
8-25-09 Forks MP 163.4	77	Rough, pocked texture chip seal	1	1.80	1.80	0.01
			2	1.79		
8-25-09 Forks MP 162.1	75	New Hot Mix Patch	1	1.33	1.72	0.40
			2	2.13		
			3	1.69		
8-25-09 Forks MP 164.55	76	New Hot Mix Overlay	1	2.12	1.91	0.19
			2	1.75		
			3	1.86		

Consistent results are somewhat difficult to obtain with this test if the surface of the substrate is uneven, pocked or has significant texture. The problem is with the 19 mm ball bearing moving before the hammer contacts the ball, after the hammer strikes the ball, and before the difference in height is measured with the calipers. Traffic control is required in order to conduct the test to protect the technicians. However, on substrates with soft surfaces where embedment of aggregate chips is of concern, this test would provide a means to evaluate the effect on emulsion spray quantities quantitatively. On hard substrate surfaces such as those studied in this research, the ball penetration values of 1 to 3 mm result in no binder adjustment for the traffic levels expected on these pavements. And, even if traffic were 5000 vehicles per day per lane, the difference in binder application rate would only be 0.03 gallons per square yard. Therefore, this test is difficult to justify unless traffic is very high and penetration is also higher than 3 mm.

BALL PENETRATION TEST (after S. Africa)

Calculation

$$Pen\ T_0 = Pen\ T_1 - K(T_1 - T_0)$$

Where

Pen T_0 = penetration depth at suggested design road surface temperature (mm)

Pen T_1 = penetration depth at measured road surface temperature (mm)

K = temperature-susceptibility of penetration (mm/C) =0.04 mm/C for single and multiple chip seals on non-flushed substrates

However, because the ball does not always penetrate the surface, but instead, fractures old chip seal aggregates, or is prevented from penetrating the hard, brittle surface of an old hot mix asphalt pavement, there have been suggested modifications (van Zyl 2007) to the K value above. These are presented in Table H2.

T_1 = temperature at time of ball test (C)
T_0 = design temperature of road suggested for the particular location (C)

Existing surface type and degree of fattiness	Recommended K –factor (mm/°C)			
	Dry/ Brittleness (TMH9)		Fattiness/ Bleeding (TMH9)	
	(Degree >=3)	(Degree <3)	(Degree 3 - 4)	(Degree 5)
Single and multiple seals	0,0	0,02	0,04	0,08
Slurry seals and sand seals	0,03	0,05	0,06	0,08
Cape Seals	0.03	0,06	0,07	0,08
Asphalt (Sand Mastic)	0,05	0,07	0,08	0,08
Asphalt (Stone mastic)	0,02	0,04	0,05	0,08

Table H2. Revised K-Values (from van Zyl 2007)

APPENDIX I - Modified Tray Test

Apparatus

Circular tray with an area of 0.05 m^2 and a wall height of 50 mm. A shoulder fits snugly over the top of the tray with internal diameter equal to the tray. A cloth membrane fits inside the tray and held in place by the top membrane. The purpose of the membrane is to prevent the ‘density sand’ from flowing into the voids between the chips placed on the bottom of the tray. Figure M1 illustrates the apparatus.

Calculations

Volume of chips plus voids, V3 = V1 - V2 = (M1 – M2) / Ws

Where,

V1 = volume of density sand required to fill circular tray
V2 = volume of density sand required to fill tray with chips
M1 = mass of density sand required to fill circular tray
M2 = mass of density sand required to fill circular tray with chips
Ws = bulk density of density sand

Effective Layer Thickness (ELT) of chips = V3 / A

Where,

A = area of tray = 0.05 m^2

Void Content of Chips, Vl = (V3 – Vchips)/V3 x 100 = (V3 – (Mchips/Wchips))/V3 x 100

Where,

Mchips = mass of the chip layer
Wchips = relative density of chips

The practical spread rate of the chips and the bulk void content of the chips are determined by taking the chip sample from the tray and pouring it into a graduated cylinder of 2000 ml capacity and measuring the bulk volume of the chips. Repeat several times and calculate the average bulk volume of the chips, V4.

The practical spread rate of the chips is = V4 / A, m3/m2

The bulk void content, Vb = (V4 – Vchips)/ V4 x 100
= (V4 – (Mchips/Wchips))/V4 x 100

Theoretical Spread Rate = ELT (100 – Vl) / (100 – Vb) x 10^{-3}, m^3/m^2

The practical and theoretical spread rates should be approximately equal. If not, there was an error in the procedure or calculations.

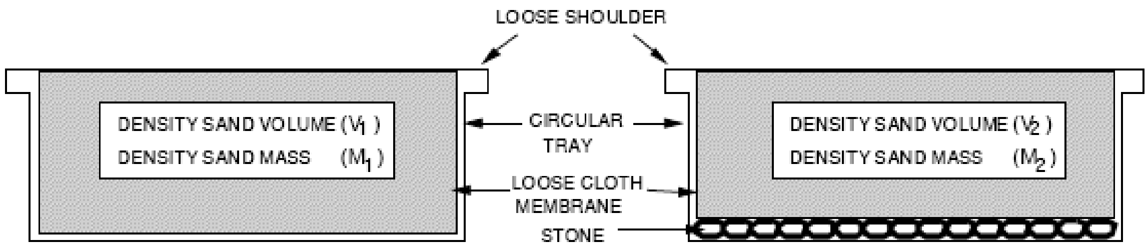


Figure I1. Modified Tray Apparatus

APPENDIX J - Chip Seal Design Comparisons

J.1 Asphalt Institute/McLeod/Hanson

The basis for determining the aggregate spread rate and emulsion spray rate in this procedure is that chips will be close to one-sized and applied in a single layer. Then, the asphalt binder will be applied so that the aggregate layer is embedded to approximately 70 percent of the average chip height. Aggregate information needed to determine spread rate includes average least dimension, voids in the loose aggregate, specific gravity, and waste during construction. Additional information needed to determine emulsion quantity is residue content of emulsion, aggregate absorption, traffic volume, and substrate texture.

J.1.1 Average Least Dimension

Uniformly graded aggregates usually do not make acceptable chip seals. This is because the aggregates fit together in a tighter matrix than one-sized chips. While this may seem like a good idea because it creates interlock between particles, it also creates less room for asphalt. So, in order to apply enough binder to hold the largest of the matrix in place, the chip seal flushes under traffic because some of the space needed for binder between the aggregates is occupied by smaller aggregates. Therefore, chip seal aggregates should ideally be one size and cubical. If they were, the dimension needed to determine asphalt application rate would be the height of the particle. Chips are often not one size, however. So, to determine the binder quantity needed to embed these particles to 70 percent of the average height the average least dimension (ALD) for the chips was developed. Originally, the ALD was determined using the nomograph shown in Figure J1 as published by Shell (Jackson 1963). These nomographs were developed by measuring the smallest dimension of many aggregate particles in the laboratory with a calipers and relating this dimension to the median particle size and the shape of the particles. For ease of calculation these nomographic techniques have been replaced by the relationship shown below for the Asphalt Institute:

Where,

$$ALD = \frac{\text{Median Particle Size, in or mm}}{1.139285 + (0.011506 \text{ x Flakiness Index})}$$

Other nomographs for ALD have also been used, however, these have been largely replaced by physically measuring ALD and using a computational technique to determine ALD (Dumas 2004).

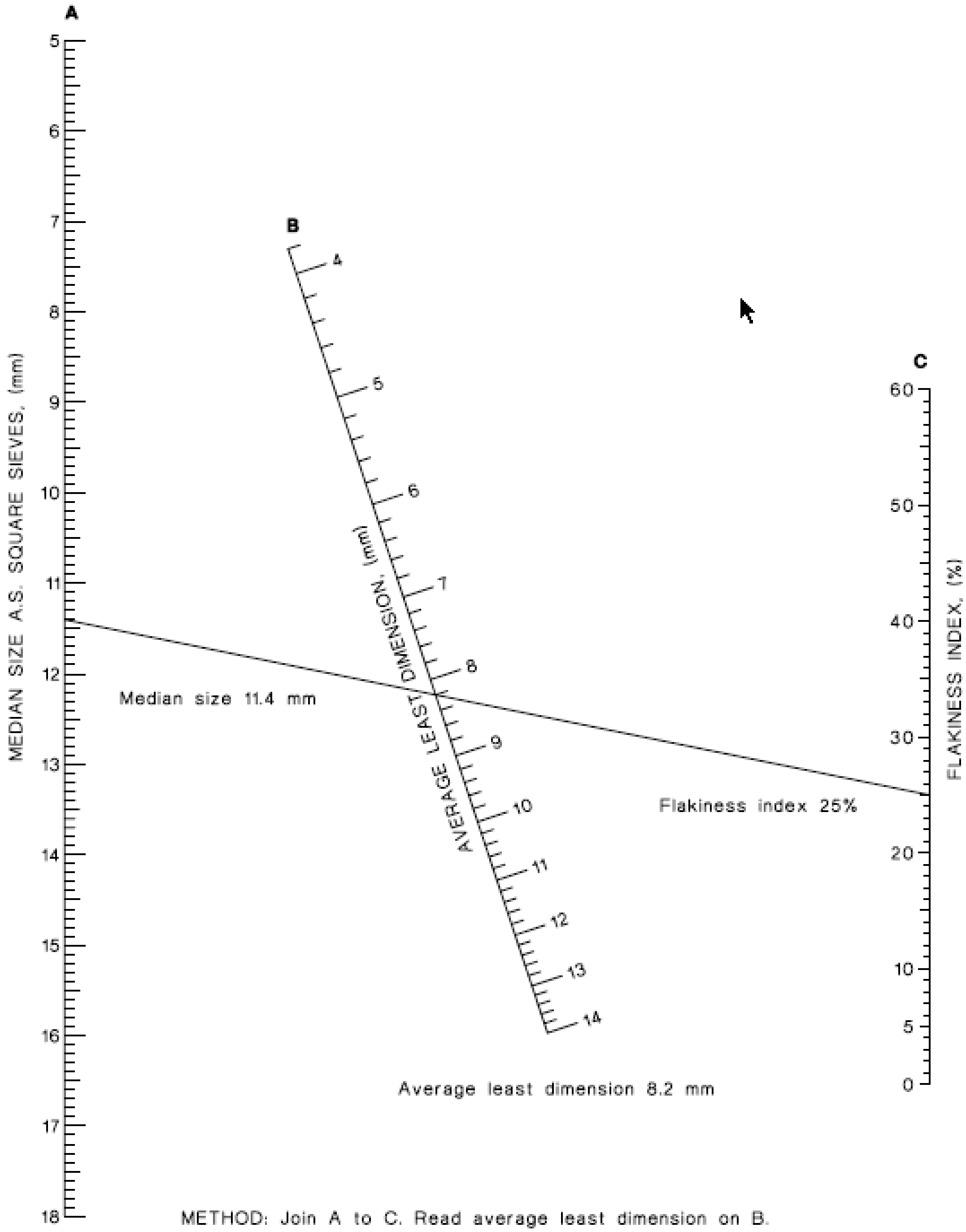


Figure J1. Nomograph for Determining ALD from Shell (Jackson 1963)

J.1.1.1 Median Particle Size

The median particle size is a theoretical size for which 50 percent of the aggregate particles are larger and 50 percent are smaller. There may not actually be any particles this size. Therefore, this is one source of error for this method. However, to determine median particle size a sieve analysis is conducted using the sieves shown in Table H1. The median particle size is then the dimension where 50 percent of the material passes or is retained as shown in Figure J3.

Table H1. Sieves to Determine Median Particle Size

Sieve	Sieve Opening, inches	Sieve Opening, mm
1-inch	1.000	25.0
¾-inch	0.750	19.0
½-inch	0.500	12.5
3/8-inch	0.375	9.5
No. 4	0.187	4.75
No. 8	0.0937	2.36
No. 16	0.0469	1.18
No. 50	0.0117	0.300
No. 200	0.0029	0.075

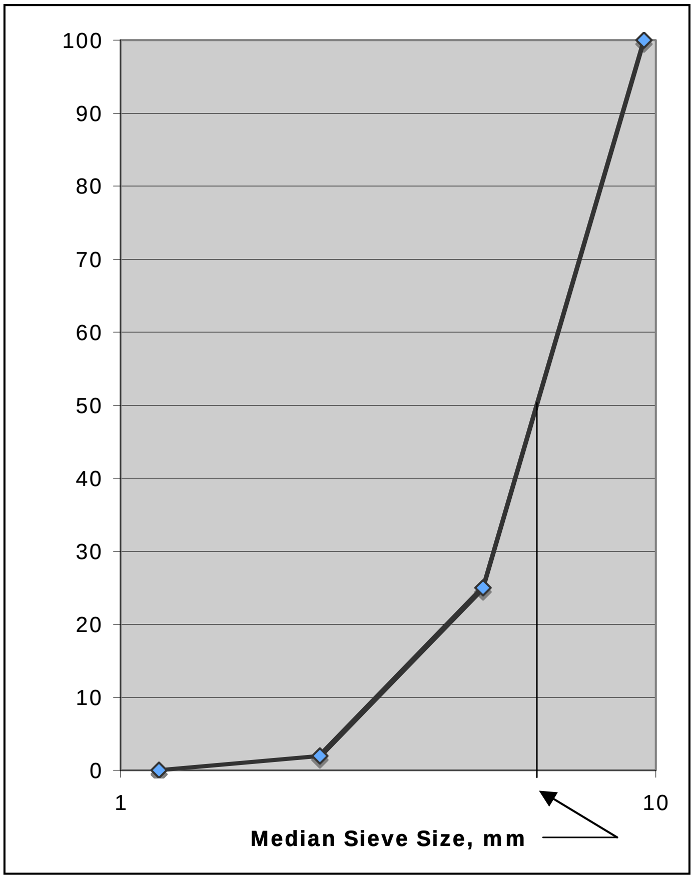


Figure J3. Determining Median Particle Size from Sieve Analysis

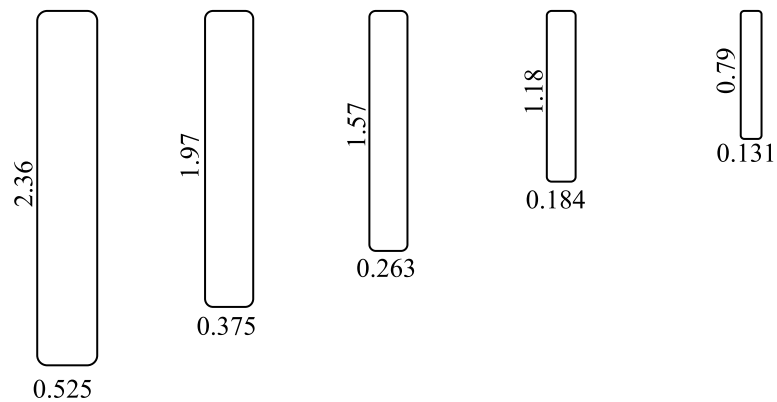
J.1.1.2 Flakiness Index

This test is intended to evaluate the shape of the aggregate particles. Representative particles are separated into five fractions of 1-inch to ¾-inch, ¾-inch to ½-inch, ½-inch to 3/8-inch, 3/8-inch to ¼-inch and ¼-inch to No. 4. Not all fractions may be utilized depending on the size of the aggregate. Then, an attempt is made to fit each particle within each sieve fraction through the corresponding slot in a steel plate with dimensions shown in Figure J4. The slots in the plate are approximately the width of the smaller of the two sieve sizes of the fraction tested. Therefore, if the particle fits through the slot, it is considered 'flakey'. The total weight of particles passing the appropriate slots is compared with the total weight retained above the slots. The percent of particles passing to the total weight of particles is the flakiness index.

Slot Dimensions* for Flakiness Index

Aggregate Fractions**

Passing Sieve, in.	1	¾	½	3/8	¼
Retained on Sieve, in.	¾	½	3/8	¼	No. 4



* Dimensions in inches, not to scale
** U. S. Standard Sieves

Figure J4. Slot Dimensions for Flakiness Index Test

Since this test evaluates discrete particle sizes, it is subject to errors with respect to the actual particle shape present. In addition, the tedious nature of the test may lead to some operator error. In response to these concerns an automated version of the test has been suggested using a video analysis technique (Bouquety, et al 2006).

J.1.2 Voids in Loose Aggregate

The voids present in the loose aggregate chips when placed on the pavement and rolled in place must be known to determine how much asphalt binder will be required to partially fill these voids and bind the aggregate to the substrate pavement. These voids are determined using the familiar relationship:

$$V = 1 - [W / (62.4\ G)]$$

Where,

V = voids in loose aggregate, percent expressed as a decimal
W= loose unit weight of aggregate, lbs/ft^3 (ASTM C29)
G= bulk specific gravity of aggregate (AASHTO T85)

J.1.3 Aggregate Absorption

Absorption of emulsion into the aggregate can be approximated by measuring the water absorption potential during the specific gravity determination (ASTM C127). A correction in the residue application rate of 0.02 gallons per square yard has been suggested (McLeod 1969) if absorption is 1 percent, however, others (Wood, et al 2006) have recommended this correction be applied when chip seal aggregates have more than 1.5 percent absorption.

J.1.4 Traffic Whip-Off

If traffic is allowed on the fresh chip seal before the emulsion has completely set, some chips may become dislodged. The amount of this loss will vary depending on traffic volume and speed. However, the amount of loss should be estimated and included in the design spread rate. Reasonable values for low volume roads, low speed roads is 5 percent while higher traffic volumes and speeds may produce 10 percent loss. This value is applied to the aggregate spread rate relationship to increase the spread rate based on the potential whip-off anticipated.

J.1.5 Chip Embedment Percent Corrected for Traffic

Traffic volume influences the amount of embedment of the chips because theoretically the higher the traffic, the more likely each chip will be forced to lie on the flattest side. The problem with this is that the more one-sized the chip, the less influence traffic has on this since every side is the same dimension. Consequently, for higher traffic roads where the embedment percent is reduced from 70 percent, more loss of aggregate could occur if chips are close to a single size. The factors for traffic correction to embedment are shown in Table H2.

Table H2. Correction Factor for Chip Embedment Due to Traffic Volume

Traffic Factor, T The percent, expressed as a decimal, of the ultimate 20 percent void space in the cover aggregate to be filled with asphalt				
Traffic, vehicle per day				
< 100	100-500	500-1000	1000-2000	> 2000
0.85	0.75	0.70	0.65	0.60

J.1.6 Substrate Surface Correction

The surface texture of the substrate pavement affects the amount of binder required to hold chips in place. Smooth, or flushed surfaces will not absorb any binder while porous, oxidized surfaces may absorb significant binder. If this is not accounted for, the new chip seal could become flushed because of too much binder or chips could become dislodged due to too little binder. A description of the surface conditions and the amount of binder to add or subtract is shown in Table H3.

Table H3. Substrate Surface Condition Correction

Substrate Texture	Correction, S	
	S.I., l/m^2	U. S., gal/yd^2
Black, flushed asphalt	-0.04 to -0.27	-0.01 to -0.06
Smooth, non-porous	0.00	0.00
Slightly porous, oxidized	+0.14	+0.03
Slightly pocked, porous, oxidized	+0.27	+0.06
Badly pocked, porous, oxidized	+0.40	+0.09

J.1.7 Snow Plow Damage

The binder quantity should be adjusted to account for very cubical aggregates. This is the method used in this design to account for potential lack of embedment if aggregates have little flakiness. The ALD in the binder quantity relationship is replaced with the median aggregate size and the emulsion quantity recalculated. This is the value of binder needed if none of the particles are flakey. The average of the two emulsion quantities is then used as a starting point for a test section to evaluate which binder quantity to utilize in the remaining chip seal.

J.1.8 Aggregate Spread Rate

The above parameters are combined in the relationship below to estimate the aggregate spread rate for the Asphalt Institute/McLeod/Hanson design:

$$C = 46.8\,(1 - 0.4V)\,H\,G\,E$$

Where,

C = aggregate spread rate, lbs/yd^2
V = voids in loose aggregate, in percent expressed as a decimal
H = average least dimension, inches
G = bulk specific gravity of aggregate
E = wastage for traffic whip-off

J.1.9 Emulsion Application Rate

Additional parameters are combined in the relationship below to estimate the emulsion application rate for the Asphalt Institute/McLeod/Hanson design:

$$B = \frac{2.244\,H\,T\,V + S + A}{R}$$

Where,

B = Emulsion Application Rate, gal/yd^2
H = average least dimension, inches

T = Traffic Factor
V = voids in loose aggregate, in percent expressed as a decimal
S = Surface Correction, gal/yd^2
A = Aggregate Absorption, gal/yd^2
R = Residual Asphalt Content of Emulsion, percent expressed as decimal

J.2 South Africa

The basis for determining the aggregate spread rate and emulsion spray rate in this procedure is based on the Hanson (Hanson 1934-35) concept of partially filling the voids in the cover aggregate. The volume of these voids is a function of the average least dimension (ALD) of the cover aggregate. Figure J5 is from the South African Technical Recommendations for Highways TRH3 2007 and illustrates the various factors used in the design.

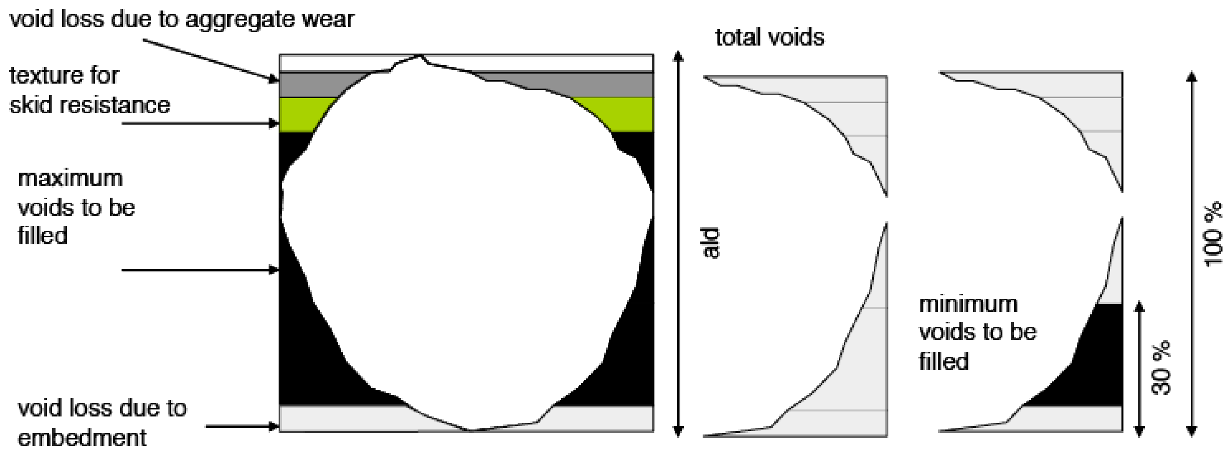


Figure J5. Factors Considered by South Africa in Chip Seal Design

However, this design has evolved to be somewhat different than the Asphalt Institute/McLeod design as follows:

a. The minimum volume of voids to be filled with binder to prevent chip loss when there is no chip embedment in the substrate is 42 percent for single seals and 55 percent for double seals.
b. The amount of void loss due to traffic wearing the surface of the chips is dependent on the hardness of the chips and traffic. When the hardness is assumed not less than 210kN, the loss ranges from 0.39 mm for 125 vehicles per day per lane to 0.89 mm for 40,000 vehicles per day per lane.
c. The required texture depth to provide skid resistance is 0.7 mm. However, design charts are available for seals with low ALD and for texture depths of 0.3 and 0.5 mm.
d. The amount of embedment during construction is assumed to be 50 percent of the embedment under traffic.

e. Total embedment potential is determined from corrected ball-penetration tests. The effective layer thickness (ELT) of a single seal is equivalent to:

$$ELT = (0.85679 \text{ x } ALD) + 0.46715 \text{ mm}$$

The ELT of a double seal is a function of the sum of the ALD's of the two aggregates:

$$ELT_d = (0.86028 \text{ x } (ALD_1 + ALD_2)) + 0.19188 \text{ mm}$$

f. The ELT and percentage of voids for any aggregate/binder combination may be determined by the modified tray test (Appendix I)
g. The percentage of voids in the chip layer is a function of the ELT.
h. Estimated void content for single seals = 45.3333 – 0.333 x ELT
Estimated voids content for double seals = $63.01263 + 0.04743 \text{ x } ELT_d^2 - 2.41172 \text{ x } ELT_d$

Binder spray rate is a function of ALD, traffic, and embedment of the chips due to construction and traffic. Design charts are provided for each ALD, four texture depths of 0.3, 0.5, 0.7 and 1.0 mm and a minimum value.

E.2.1 Design Process

E.2.1.1 Traffic

The process for designing chip seals using the South African procedure involves first determining the traffic volume in Equivalent Light Vehicles per lane per day. The relationship used is:

Total ELV/lane/day = Number of light vehicles + (40 x Number of heavy vehicles)

E.2.1.2 Embedment

Potential embedment of chips into the substrate is determined by conducting ten ball penetration tests as described in Appendix B.

E.2.1.3 Binder Application Rate

A range of binder application rate is determined from the charts in Appendix B after deciding what the appropriate texture depth should be for the surface based on vehicle speed and the average least dimension of the cover aggregates.

The required texture depth is a function of the typical vehicle speed. Suggested values are:

< 60 km/h (37 mph)	texture minimum 0.5 mm
60 – 100 km/h (37 – 62 mph)	texture minimum 0.7 mm
> 100 km/h (62 mph)	texture minimum 1.0 mm

E.2.1.4 Adjustments

Existing Texture – The average texture depth is measured using the sand patch test. The adjustment to binder quantity is determined from Figure B3 in Appendix B. Adjustments are only made for substrate surfaces with ball penetration values less than or equal to 2 mm.

Climate – The binder application rate can be adjusted for climate using the Weinert N-value (Weinert 1984) which is:

$$N = 12\ E_j/P_a$$

Where,

E_j = evaporation during the warmest month
P_a = annual precipitation

The guide for adjustment based on the N-value is as follows:

10 percent reduction in net cold binder in wet or humid areas where $N < 2$
10 percent increase in net cold binder in dry areas where $N > 5$

Slow Moving and Channelized Traffic – This was revised from the 1998 version of the specification which contained an adjustment for pavement gradients. The revision was based on the thesis that chip seal performance was more closely related to slow moving, channelized truck traffic than to gradients. Therefore, a reduction in binder content of up to 10 percent is suggested depending on the speeds, stopping, starting and turning of heavy vehicles.

Aggregate Spread Rate – The aggregate matrix is considered 'dense shoulder-to-shoulder' by design and the quantity of aggregate is estimated from Figure J6. If the matrix is either of two other textures described as 'medium dense shoulder-to-shoulder', and 'open shoulder-to-shoulder' the rate can be adjusted upward by up to 10 percent for the medium dense matrix and up to 20 percent upward for the open shoulder-to-shoulder matrix. This adjustment is only suggested for aggregates with flakiness indices less than 10 percent. Photos are provided in the S. African design manual to illustrate the appearance of these matrices.

J.2.1.5 Sensitivity Analysis

This design process recognizes that variations in all of these input parameters will occur. Therefore, it is recommended that sensitivity to variations be analyzed. The maximum variation in rates would result from the following:

Minimums	Highest expected traffic Highest ball penetration Smoothest texture Lowest ALD
Maximums	the opposites of the above

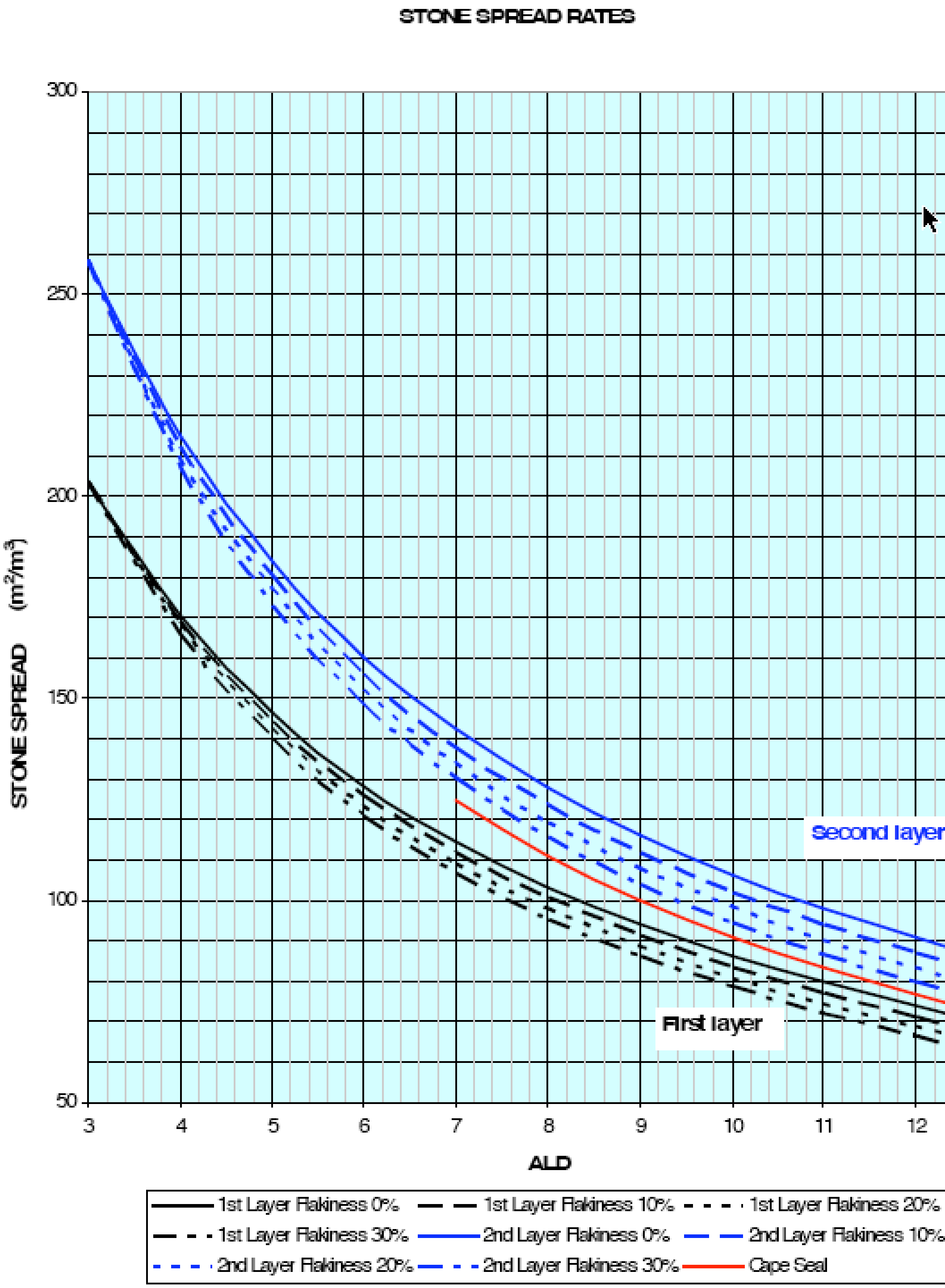


Figure J6. Aggregate Spread Rates from S. Africa (S. Africa 2007)

J.2.1.6 Practical Minimum and Maximum Binder Application Rates

Select Possible Binders
Convert to Hot Spray Rates
Check for Practical Minimum Spray Rates (accuracy) = 0.15 gal/yd^2
Check practical maximum spray rate to prevent run-off = 0.33 gal/yd^2

J.2.1.7 Final Decision and Specification for a Target Spray Rate

The South African design method indicates that the contractor bye provided a specified application rate for each road section. They suggest that when selecting the specified rate that the 5 percent permissible variation allowed in application rate be considered and that the final decision be supported by documentation indicating the input parameters and rationale for adjustments.

J.2.1.8 Policy and Maintenance Strategy

The level of risk tolerance is considered with respect to aggregate loss and friction and how this relates to the uncertainty with respect to traffic.

J.3 Texas/Epps/Kearby

This method is a modified version of a procedure originally proposed by Kearby (Kearby 1953) and modified by Benson (Benson and Gallaway 1953). Parameters needed for the design include dry loose unit weight of the aggregate, bulk specific gravity of the aggregate, and the results of the 'board test' of the aggregate. The dry loose unit weight and specific gravity are determined by familiar methods, however, the board test may not be familiar and is described below:

J.3.1 Board Test

The apparatus needed for this test is a one square-yard sheet of plywood. During this research we found it helpful to add 1 inch by 2 inch strips of lath to the edge of the board to help retain aggregates. The procedure is to add the aggregate chips to be used in the construction of the chip seal to the board in a single layer until no additional aggregate can be added without removing aggregate from the board. The aggregate should be placed on the board so the average least dimension is perpendicular to the board to simulate the rearrangement due to rolling and traffic. Once the aggregate is on the board in as dense as possible a configuration, the board and aggregate is weighed and the mass of aggregate determined. The result is represented in pounds of aggregate per square yard of board surface.

J.3.2 Aggregate Spread Rate

The aggregate spread rate for the chip seal is determined using the following expression:

$$S = 27\ W / Q$$

Where,

S = aggregate spread rate, square yards of surface/cubic yard of aggregate

W = dry loose unit weight of aggregate (ASTM C29 rodding procedure), lbs/ft^3
Q = aggregate quantity from Board Test, lbs/yd^2

J.3.3 Asphalt Spray Rate

The asphalt binder spray rate is determined from the relationship below:

$$A = 5.61\ e\ d\ (1 - (W/62.4\ G))\ T + V$$

Where,

A = asphalt cement spray rate at 60F, gal/yd^2
e = percent embedment recommended
d = average mat depth, in where d = 1.33Q/W
G = dry bulk specific gravity of aggregate
T = traffic correction
V = substrate surface condition correction

Note that this expression is valid for asphalt cement. When emulsions are used, the rate requires correction for residue content.

J.3.3.1 Percent Aggregate Embedment Recommended

The recommended aggregate embedment is determined from relationships developed by Kearby and Benson and Gallaway using the graph in Figure J7

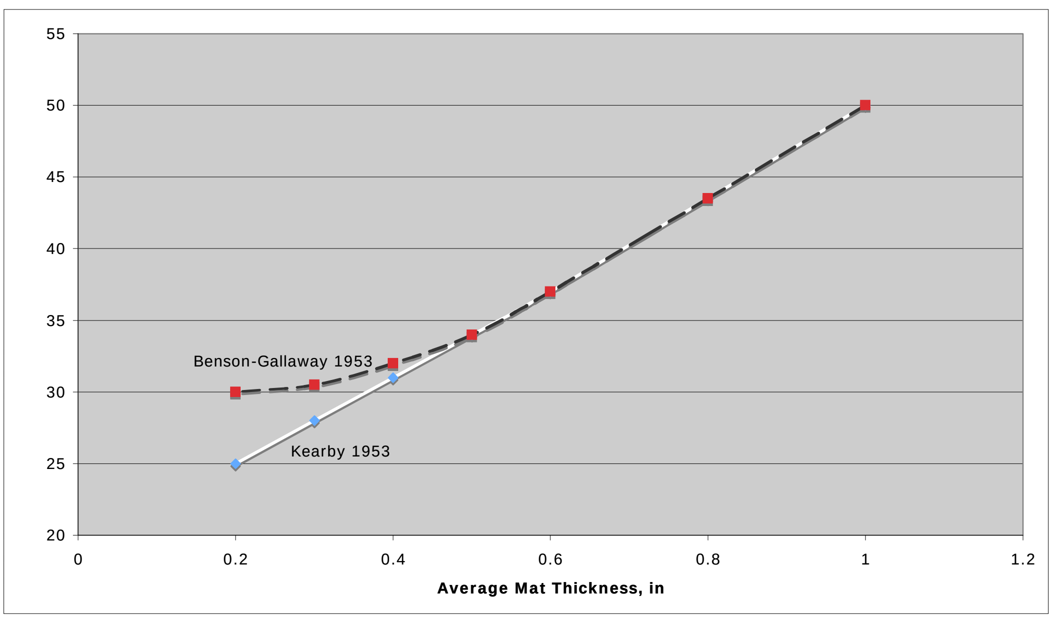


Figure J7. Aggregate Embedment for Texas Chip Seal Design

J.3.3.2 Traffic Correction

The asphalt binder is increased as traffic decreases below 1000 vehicles per day per lane as shown below:

Traffic, vehicles per day per lane	Traffic Factor, T
<1000	1.00
500 to 1000	1.05
250 to 500	1.10
< 250	1.20

J.3.3.3 Substrate Surface Correction

The asphalt binder is adjusted for the texture of the substrate pavement surface as shown below:

Substrate Surface Condition	Substrate Correction Factor, gal/yd^2, V
Flushed Asphalt	-0.06
Smooth, non-porous	-0.03
Slightly porous/oxidized	0.00
Slightly pocked/porous/oxidized	+0.03
Badly pocked/porous/oxidized	+0.06

J.3.3.4 Seasonal Correction

A seasonal correction is suggested, although stated as not based on extensive field trials. The correction is applied after the design is adjusted for traffic and substrate condition using the following relationship:

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

Where,

$A_{recommended}$ = recommended quantity of emulsion (or cutback), gal/yd^2
A = residual asphalt from design, gal/yd^2
$A_{theoretical}$ = A / residue content, % expressed as decimal

The correction factor K suggested is:

Season of Construction	K
Spring	0.60
Summer	0.40
Fall	0.70

Winter	0.90

So, if the design residue spray rate were 0.25 gal/yd^2 and the residue content of the emulsion was 70 percent, the recommended spray rate for summer construction would be:

$$0.25 + 0.40\ ((0.25/.70)\text{-}0.25)) = 0.293\ \text{gal/yd}^2$$

J.3.3.5 Application Temperature Correction

The design relationship is valid for asphalt cement at 60F. Therefore, application temperatures typical for emulsion application must be utilized to correct the spray quantity for this difference. The factors provided for emulsions range from 0F to 150F, a somewhat limited range, since application of emulsion is typically above 150F, however, the factor at 150F is 0.9775, so if the design recommended rate is 0.293 gal/yd^2 the corrected quantity would be 0.293/0.9775 = 0.30 gal/yd^2.

J.3.3.6 Aggregate Embedment

The percent embedment of the cover aggregate during the life of the chip seal is suggested using the following guidelines:

Immediately after construction	30 +/- 10%
Immediately after construction (low traffic volume)	30-40%
Immediately after construction (high traffic)	20-30%
Start of cool weather (first year)	35+/- 10%
Start of cold weather (first year)	45 +/- 10%
After two years service	70 +/- 10%

Unfortunately, ‘low traffic’ and ‘high traffic’ are not specified, so these values must be used with some caution and judgment.

J.4 Austroads

Austroads is a collaboration between Australian and New Zealand road transport and traffic authorities. This group writes specifications and test methods for all forms of roadway construction including chip seals. The design method used in Australia and New Zealand is directly related to the original Hanson work (Hanson 1934-5). The method currently used by Austroads is based on over ten years of field trials beginning in the early 1990s’. The field trials were conducted to evaluate the original assumptions regarding how the voids in the cover aggregate change under traffic. A major objective of these trials was to develop a reliable prediction of the voids over a range of traffic conditions, from less than 200 vehicles per day per lane day, to approximately 10,000 vehicles per day per lane. Voids were measured from field test specimens over a number of years and performance judged by an expert task group. Results indicated that instead of the original assumption by Hanson that initial voids in the aggregate matrix was equal to 50 percent, that this value could vary from 40 to 60 percent depending on traffic, aggregate size, gradation and shape. During development of the new design method design algorithms used in New Zealand were considered. However, a practical relationship could not be developed between traffic, aggregate size, the type of seal and substrate surface condition. Therefore, Austroads decided to base the current design on the original philosophy but to revise it based on the field trials. After monitoring the field trials for over a decade, the researchers discovered three issues that remain for further research. These issues are:

- predicting future aggregate embedment after trafficking,
- effect of large heavy vehicles on the rolling/packing of aggregate,
- development of a quicker and safer method of measuring surface texture

The objective of this design is similar to other methods which is for the residual binder to be about 50 percent to 65 percent of the height of the cover aggregate two years after construction. The quantity of binder required will depend on the size, shape and orientation of the aggregate particles, embedment of aggregate into the substrate, texture of the substrate, and absorption of binder into either the substrate or aggregate.

This design method is based on:

- One-sized aggregates with a flakiness index of 15 to 25 percent
- Traffic with 10 percent, or less, heavy vehicles
- Allowances for existing surface texture conditions, aggregate and pavement absorption
- Hardness of the existing substrate

The eight steps in determining aggregate spread rate and emulsion spray rate follow.

J.4.1 Design Binder Application Rate

The design binder application rate is the spray quantity of emulsion to be applied during construction. This value is determined as follows:

$$B_d = [B_b * EF * PF] + A_s + A_e + A_{as} + A_{aa}$$

Where,

B_d = design binder application rate, L/ m^2
B_b = basic binder application rate, L/ m^2
EF = emulsion factor
PF = polymer factor (for polymer modified emulsions, only)
A_s, A_e, A_{as}, A_{aa} = corrections for substrate texture, embedment, absorption into substrate, absorption into cover aggregate, L/m^2

And,

$$B_b = VF \times ALD$$

Where,

VF = design voids factor, L/m^2/mm
ALD = average least dimension of cover aggregate

And VF = Vf + Va + Vt

Where,

Vf = basic voids factor
Va = aggregate shape adjustment factor
Vt = traffic effects adjustment factor

So, Design Binder Application Rate, B_d =

$\{ [(Vf+Va+Vt) \times ALD] \times EF * PF \} + A_s + A_e + A_{as} + A_{aa}$

Each of these parameters is discussed below.

J.4.1.1 Basic Voids Factor, Vf

The starting point for this design method is the basic voids factor. This parameter is dependent on traffic level since traffic will determine how much of the aggregate is embedded in the binder. The charts shown in Figures J8 and J9 are used to determine this factor based on traffic less than or greater than 500 vehicles per day per lane.

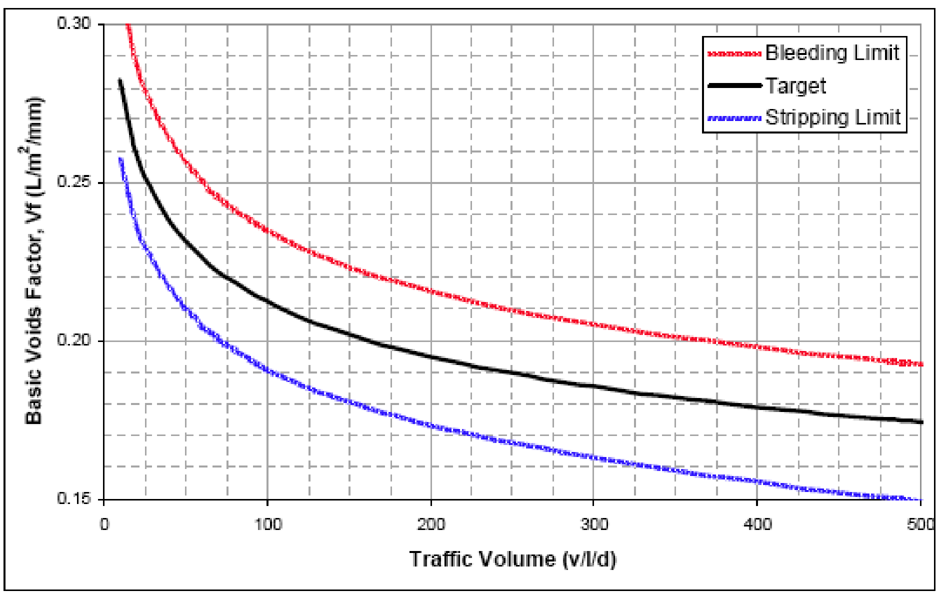


Figure J8. Basic Voids Factor for Traffic = 0 to 500 vehicles/lane/day

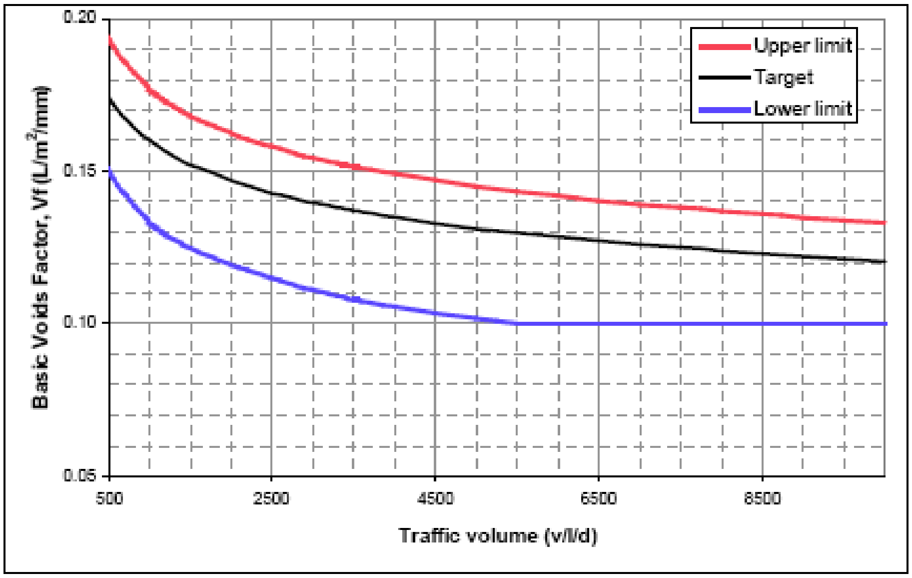


Figure J9. Basic Voids Factor for Traffic = 500 to 10,000 vehicles/lane/day

J.4.1.2 Adjustment of Basic Voids Factor for Aggregate Shape

Since the assumption of the design method is that the flakiness index will be between 15 and 25, when aggregates are outside this range an adjustment must be made to the binder application rate. The table below describes the adjustment.

Table J4. Aggregate Shape Adjustment, Va, to Basic Voids Factor

Aggregate type	Aggregate shape	Flakiness index (%)	Shape adjustment Va ($L/m^2/mm$)
Crushed or partly crushed	Very flaky	> 35	Considered too flaky and not recommended for sealing
	Flaky	26 to 35	0 to - 0.01
	Angular	15 to 25	Nil
	Cubic	< 15	+ 0.01
	Rounded	n.a	0 to + 0.10
Not crushed	Rounded	n.a	+ 0.01

J.4.1.3 Adjustment of Basic Voids Factor for Traffic

The Basic Voids Factor was developed for an average mix of light and heavy vehicles in a free traffic flow situation. When this is not correct an adjustment, Vt, needs to be made to compensate for variations. These could be due to composition, non-trafficked areas, overtaking lanes with few heavy vehicles or for large proportions of heavy vehicles, channelization and slow moving heavy vehicles in climbing lanes or stop/start conditions.

The table below describes the adjustment.

Table J5. Traffic Adjustment, Vt, to Basic Voids Factor

Traffic	Adjustment to Basic Voids Factor ($L/m^2/mm$)			
	Flat or downhill		Slow moving – climbing lanes	
	Normal	Channelised*	Normal	Channelised*
On overtaking lanes of multi-lane rural roads where traffic is mainly cars with ≤10% of HV	+0.01	0.00	n.a.	n.a.
Non-trafficked areas such as shoulders, medians, parking areas	+0.02	n.a.	n.a.	n.a.
0 to 15% Equivalent Heavy Vehicles (EHV)	Nil	-0.01	-0.01	-0.02
16 to 25% Equivalent Heavy Vehicles (EHV)	-0.01	-0.02	-0.02	-0.03
26 to 45% Equivalent Heavy Vehicles (EHV)	- 0.02	- 0.03	- 0.03	- 0.04**
> 45% Equivalent Heavy Vehicles (EHV)	- 0.03	- 0.04**	- 0.04**	- 0.05**

Equivalent Heavy Vehicles (EHV)% = HV% + LHV% x 3
Where, HV = vehicles over 3.5 tonnes and LHV = vehicles with seven or more axles

If adjustments for aggregate shape and traffic effects result in a reduction in Basic Voids Factor of 0.4 L/m2/mm or more, special consideration should be given to the suitability of the treatment and possible selection of alternative treatments. Note that the recommended MINIMUM Design Voids Factor is 0.10 L/m2/mm in all cases.

J.4.2 Average Least Dimension

The concept of an aggregate particle tending to lie with its least dimension vertical is central to the volumetric design of a sprayed seal. The least dimension is defined as the smallest dimension of a particle when placed on a horizontal surface. The shape is most stable when lying with its least dimension vertical. Thus in a seal, the final orientation of most particles is such that the least dimension is near vertical, providing there is sufficient room for the particles to realign. The ALD is determined directly using calipers, slotted plate, or dial gauge (Australian Standard AS1141.20.1) for 10mm and larger chips or by calculation or nomograph (Australian Standard AS1141.20.3). The relationship used to calculate ALD is:

$$ALD = MS/(1.09 + (0.0118 \times FI))$$

Where,

MS = median size of the aggregate, mm
FI = flakiness index

However, on comparing the ALD from the above relationship to that from the nomograph, there is disagreement. The nomographic solution compares closer to the relationship for ALD provided by the Asphalt Institute as previously reported in the above discussion.

The nomograph used to determine ALD is shown in Figure J10.

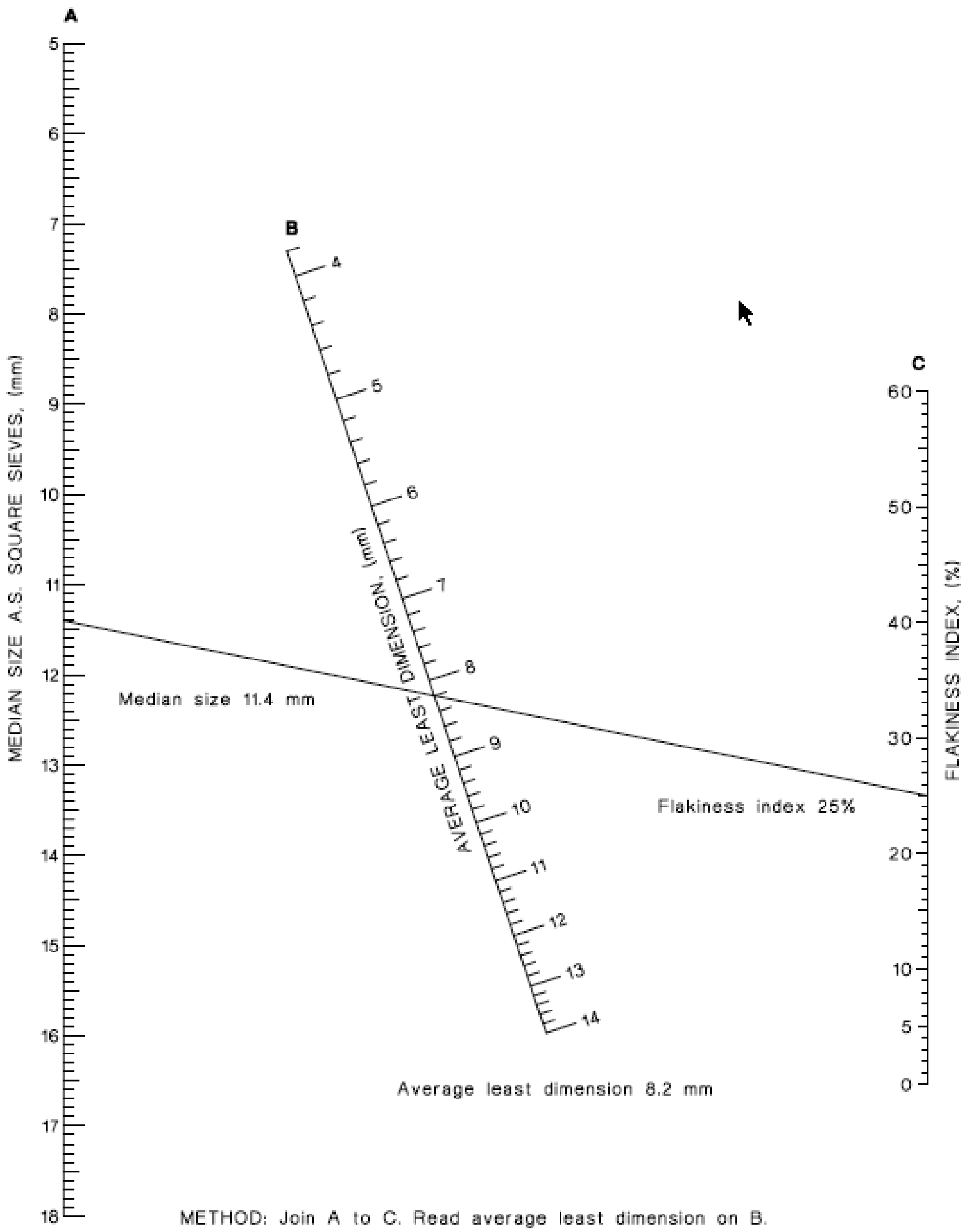


Figure J10. Nomograhic Solution to ALD from Austroads

J.4.3 Emulsion Factor

An emulsion factor is applied to the Basic Binder Application Rate (before allowances) when using asphalt emulsions. This factor allows a greater volume of binder around the aggregate particles to compensate for reduced aggregate reorientation as a result of rapid increase in binder stiffness after the initial breaking of the emulsion.

The Basic Binder Application Rate for emulsions, Bb_e, is calculated as follows:

$$Bb_e = Bb \times EF$$

Where,

Bb_e = Basic Binder Application Rate (emulsion) rounded to the nearest 0.1 L/m2
Bb = Basic Binder Application Rate
EF = Emulsion Factor (from Table J6).

*Note: Binder application rates are residual binder and do not include the water content of emulsion.

Table J6. Emulsion Factors, EF

Product	Emulsion Factor, EF
Conventional Emulsion (60% residue)	1.0
High Residue Emulsion (>67% residue)	1.1 to 1.2

J.4.3.1 Polymer Modified Emulsion Factor

When polymer modified binder (PMB) emulsions are used, the emulsion factor is adjusted using the polymer factors (PF) shown in Table J7.

Table J7. Polymer Factors (PF)

Class of PMB	PMB factor	Type of treatment
		Aggregate retention (AR)
S10E	1.1	The factors for AR may be increased by 0.1 on low traffic applications, but reduced by 0.1 on high to very high traffic applications and/or high temperature locations in order to minimise flushing.
S35E	1.1	
		Holding treatment (HT)
S10E	1.2	The factors for HT may be increased by 0.1 on low traffic applications, but reduced by 0.1 on high to very high traffic applications and/or high temperature locations in order to minimise flushing.
S35E	1.2	
S45R/S15RF	1.3	
		Weak pavements (WP)
S20E	1.3	The factors for WP may be increased by 0.1 on low traffic applications where maximum waterproofing is desired and the potential for flushing is low, but reduced by 0.1 on very high traffic volume applications.
S45R/S15RF	1.3	

The factors in the table are based on the type of polymer modified binder utilized in the emulsion and the type of chip seal.

The Polymer Modified Basic Binder Application Rate, Bbpm, for polymer modified asphalt emulsions is calculated as follows:

$$Bb_{ep} = Bb \times EF \times PF$$

Where,

Bb_{ep} = Basic Binder Application Rate (emulsion, polymer modified)
Bb = Basic Binder Application Rate
EF = Emulsion Factor from Table J6.
PF = Polymer Factor from Table J7

*Note: Binder application rates are residual binder and do not include the water content of emulsion.

J.4.3.2 Correction Factors

The following corrections may need to be considered to complete the design.

- surface texture of existing surface
- potential aggregate embedment into substrate
- potential binder absorption into the substrate
- potential binder absorption into the chip seal aggregate.

a. Surface Texture
The surface texture of the existing substrate may have some demand for emulsion and should be corrected for. This depends on the texture depth of the substrate, the type of substrate (existing chip seal, hot mix asphalt or slurry seal), and the size of cover aggregate to be applied. The corrections range from 0 gal/yd2 (L/m^2) when texture depth is 0 to 0.1 mm over hot mix asphalt to +0.11 gal/yd2 (+0.5 L/m^2) for 5 to 7 mm chip seals over texture greater than 2.9 mm. Corrections factors are also suggested for concrete pavements and timber surfaces (+0.04 to +0.08 gal/yd^2), primed surfaces (0 to +0.06 gal/yd^2), and fresh patches where it is recommended to wait three to six months before chip sealing to avoid flushing.

b. Embedment into Substrate
The embedment correction factor compensates for loss of voids in the chip seal under traffic due to chips being forced into the surface of the substrate. The depth of embedment will depend on the volume and type of traffic and resistance of the substrate.

Recommended corrections are shown in Figure J11.

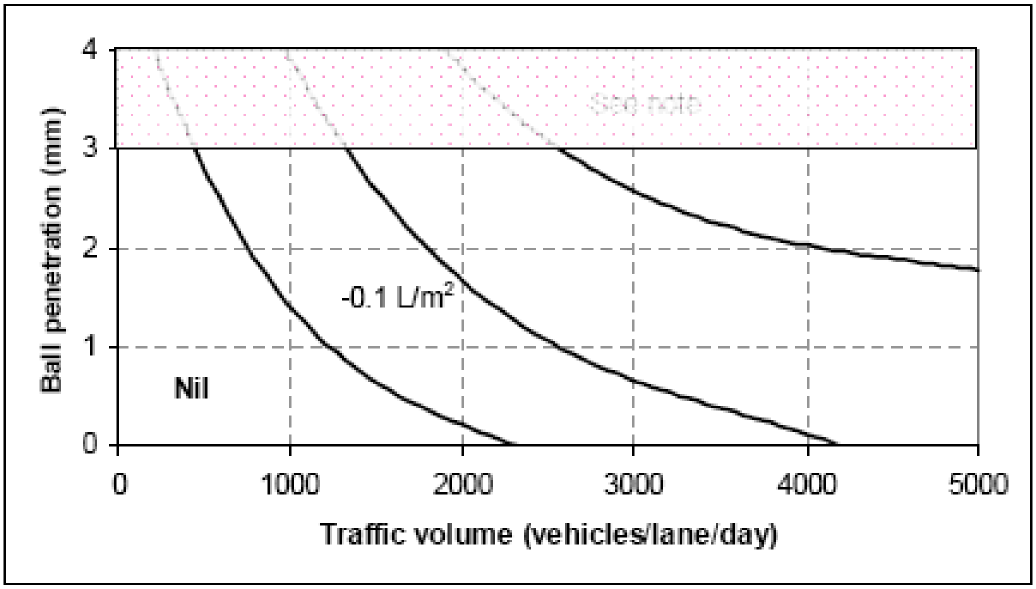


Figure J11. Correction Factors for Potential Chip Penetration Into Substrate

Ball penetration is determined using a standard test method (Austroads AG:PT/T251) consisting of a ¾-inch (19 mm) ball bearing driven into the substrate surface with one blow of a Marshall compaction hammer. Several tests are conducted and averaged. When ball penetration exceeds 3 mm, the pavement is considered too soft to chip seal and alternative preventive maintenance techniques are recommended.

c. Absorption of Emulsion into Substrate

The correction for potential loss of emulsion to the substrate by absorption is applied primarily to chip seals constructed over other than hot mix asphalt pavements or previous chip seals. The corrections for these other substrates are shown below:

- granular unbound pavements +0.04 to +0.06 gal/yd^2 (+0.2 to +0.3 L/m^2)
- pavements using cementitious binders +0.02 to +0.04 gal/yd^2 (+0.1 to +0.2 L/m^2)
- asphalt stabilized surfaces -0.04 to 0 gal/yd^2 (-0.2 to 0.0 L/m^2)

d. Absorption of Emulsion into Chips

The Austroads design does not consider this to be a problem unless the aggregate being used for the chip seal is a porous sandstone, rhyolite, volcanic scoria or slag. The correction suggested is +0.02 gal/yd^2 (+0.1 L/m^2).

J.4.4 Design Aggregate Application Rate

The design aggregate application rate is considerably simpler to calculate than binder rate. This is based on the ALD, traffic volume and chip size. For 10 mm and larger chips the relationship is:

Aggregate Spread Rate, m^2/m^3 = 750/ALD <200 vehicles/day/lane

Aggregate Spread Rate, m^2/m^3 = 700/ALD >200 vehicles/day/lane

When chips are 7 mm and smaller there is a range of spread rates depending on whether there are one or two layers of chips placed. The range for a single layer is 260 to 290 m^2/m^3 and for two layers the range is 200 to 250 m^2/m^3.

J.5 UK

The UK selects the size of chip to be used in chip seals based on traffic and substrate condition. The higher the commercial vehicles per day per lane and the softer the substrate, the larger the recommended chip size. This is illustrated in Table J8 Appropriate binders are selected based on road surface temperature during construction, chip characteristics, road crown and superelevation (in the case of emulsions), type of equipment available to spray the binder, and binder availability.

Table J8. Chip Size Selection Criteria in UK (TRL 1996)

	Approximate number of commercial vehicles with an unladen weight greater than 1.5 tonnes currently carried per day in the design lane				
Type of surface	*2000-4000*	*1000-2000*	*200-1000*	*20-200*	*Less than 20*
Veryhard	10	10	6	6	6
Hard	14	14	10	6	6
Normal	20⊘	14	10	10	6
Soft	*	20⊘	14	14	10
Very soft	*	*	20⊘	14	10

J.5.1 Design Asphalt Application Rate

The design method utilized in the UK is based on Hanson theory of filling the voids in the chip layer assuming the voids occupy 50 percent of the volume of the loose chips upon dropping on the surface of the substrate, are reduced to 30 percent on rolling during construction, and finally, to 20 percent after traffic. The method estimates average least dimension from either the nomograph solution using median particle size and flakiness index or by direct measurement. Then, selection of binder application rate and aggregate spread rate are determined using factors developed empirically. The following relationship is used to determine binder application rate:

$$R = 0.625+(F*0.023)+[0.0375+(F*0.0011)]ALD$$

Where,

F	=	Overall weighting factor
ALD	=	the average least dimension of the chippings (mm)
R	=	Basic rate of spread of bitumen (kg/m^2)

The overall weighting factor is determined from the total traffic, existing surface condition, climate, and character of the chips. For example, for 1000 vehicles per day per lane the factor is -1, for a 'lean' asphalt surface the factor is 0, for a wet and cold climate the factor is +2, and for round/dusty chips the factor is +2. These are summed to provide the overall weighting factor F of -1+0+2+2= +3. So, for an aggregate with median size of 9.5 mm and flakiness index of 10 percent, the ALD equals 7.7 mm. Therefore, the binder spread rate would be 0.986 kg/m^2 or approximately 0.218 gal/yd^2. This is residual binder and must be converted for emulsions. So an emulsion with 70 percent residue would be 0.218/0.70 = 0.311 gal/yd^2.

J.5.2 Design Aggregate Application Rate

Aggregate spread rate is estimated based on an empirical relationship between loose unit weight and ALD when loose unit weight equals 84.3 lbs/ft^3 (1.35 Mg/m^3). This relationship is:

$$\text{Chip Application Rate, kg/m}^2 = 1.364 \times \text{ALD}$$

It is suggested that this is only an estimate and when more precise aggregate spread rates are needed to conduct a board test, similar to that utilized in the Texas procedure. An additional 10 percent is recommended to account for whip-off by traffic, as well.

J.6 Comparison of Five Chip Seal Designs

The five designs summarized above were compared to see how each predicted the aggregate spread rate and emulsion application rates for the four laboratory and three field test section aggregates studied in this research. Traffic was assumed to be 1000 vehicles per day per lane, substrates were considered to be relatively non-porous, smooth hot mix asphalt with little or no penetration potential and there was no consideration given for whip-off by traffic. Results for the aggregate spread rates and emulsion spray rates are presented in Table J9 and graphical results in Figures J12 and J13. Units have been converted to pounds per square yard and gallons per square yard for all methods.

Although four of the designs compared are based on work originally proposed by Hanson (Hanson 1934-35) there are some significant differences in design application rates recommended. However, the order in which these designs predict aggregate application rates and emulsion spray rates are generally the same for all seven aggregates compared. This order is as follows:

Aggregate Spread Rate		Emulsion Spray Rate	
1 (lowest)	S. Africa	1 (lowest)	Asphalt Institute
2	Austroads	2	Austroads
3	UK	3	S. Africa
4 (highest)	Asphalt Institute	4 (highest)	UK

Table J9. Comparison of Materials Application Rates for Five Chip Seal Designs

		Passing, %						
Sieve No. (in.)	Sieve Size (mm)	LSTN	GRNT	BSLT	ALLV	US101	Arches	CR11
3/4"	19.0	100	100	100	100	100	100	100
1/2"	12.5	100	100	100	100	95	100	100
3/8"	9.5	100	99	100	99	47	100	100
5/16"	8.0	100	50	79	73	20	68	77
1/4"	6.3	48	9	30	33	6	28	30
no. 4	4.75	1	1	1	2	2	1	1
no. 8	2.36	1	1	1	2	1	0	0
no. 16	1.18	1	1	1	2	1	0	0
no. 30	0.60	1	1	1	2	0	0	0
no. 50	0.30	1	1	1	2	0	0	0
no. 100	0.15	1	1	1	2	0	0	0
no. 200	0.075	1	1	1	2	0	0	0

Bulk specific gravity	2.615	2.612	2.773	2.566	2.628	2.473	2.768
Loose unit weight, lbs/cf	78.31	83.97	92.20	86.05	83.53	80.11	92.89
Mat depth, in.= 4Q/3W	0.176	0.256	0.206	0.219	0.279	0.289	0.197
Median Size, in.	0.252	0.315	0.277	0.277	0.383	0.286	0.278
Median Size, mm	6.4	8.0	7.0	7.0	9.7	7.3	7.1
Flakiness Index	33.8	5.8	13.1	10.5	20.6	14.0	9.0
ALD, mm from nomograph	4.5	7.1	5.8	5.8	7.5	5.8	6.1

Chip Spread Rates

TX. lb/sy	10.3	16.1	14.3	14.1	17.5	17.4	13.8
S. Africa, lbs/sy	14.4	21.6	20.2	19.2	23.7	18.5	21.9
Austroads, lbs/sy	14.9	25.1	22.5	21.0	26.4	19.6	23.9
UK, lbs/sy	16.1	25.5	20.8	20.8	26.9	20.8	21.9
TAI, lb/sy	17.2	27.5	24.1	22.3	29.2	21.3	25.4

Emulsion Spray Rates

TAI, gal/sy	0.13	0.18	0.15	0.15	0.20	0.15	0.15
TX. gal/sy	0.16	0.22	0.17	0.18	0.24	0.25	0.16
Austroads, gal/sy	0.23	0.42	0.32	0.34	0.42	0.32	0.36
S. Africa, gal/sy	0.31	0.43	0.38	0.38	0.51	0.38	0.38
UK, gal/sy	0.39	0.48	0.46	0.46	0.49	0.46	0.46

Based on this comparison, the Asphalt Institute design appears to recommend the highest aggregate quantities and lowest emulsion spray rates. In contrast, the S. African design recommends the lowest aggregate spread rates and next to the highest emulsion spray rates. The UK design suggests next to the highest aggregate spread and the highest emulsion spray rates, while the Austroads design is second lowest both in aggregate spread rate and emulsion spray

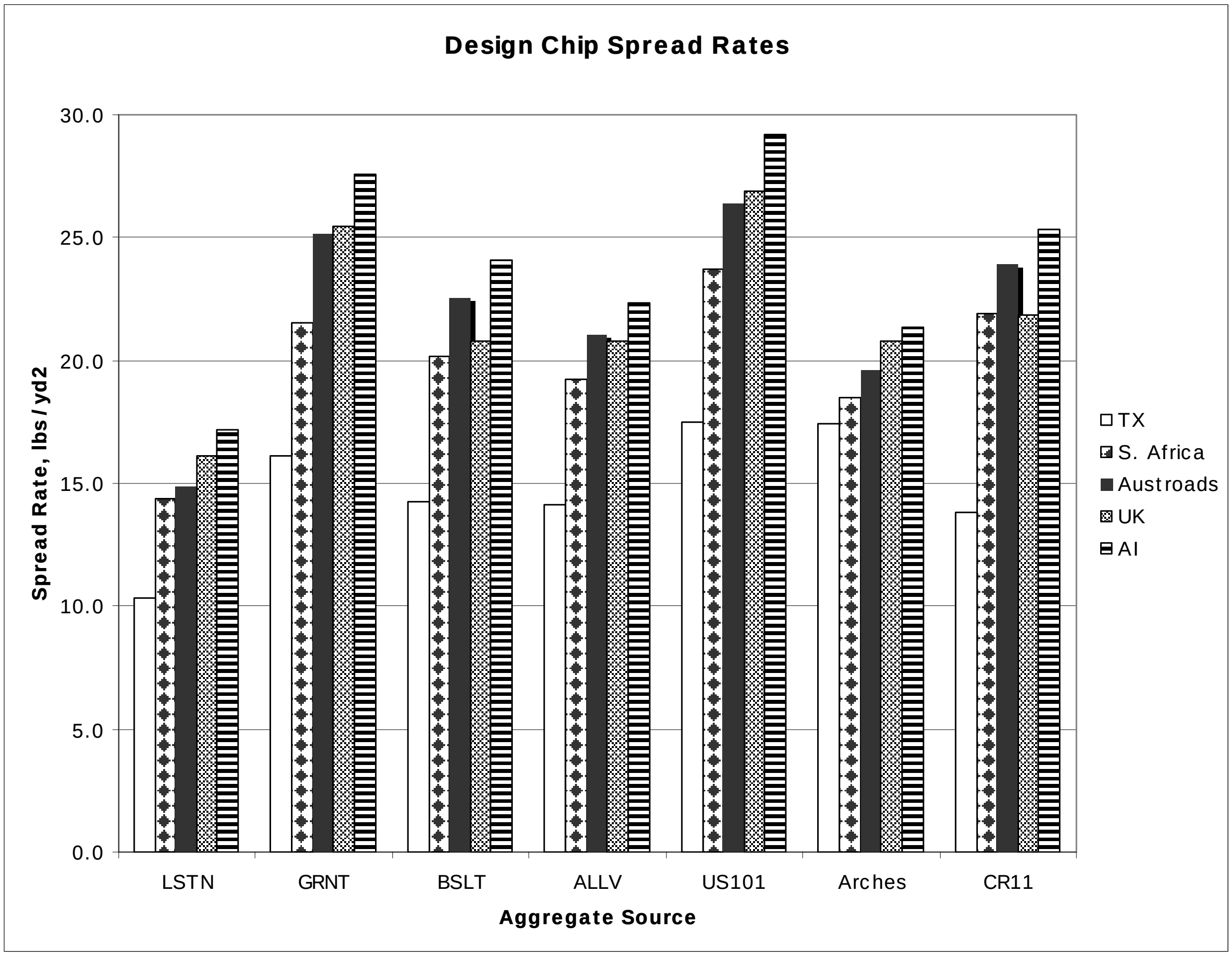


Figure J12. Chip Spread Rates for Five Design Methods

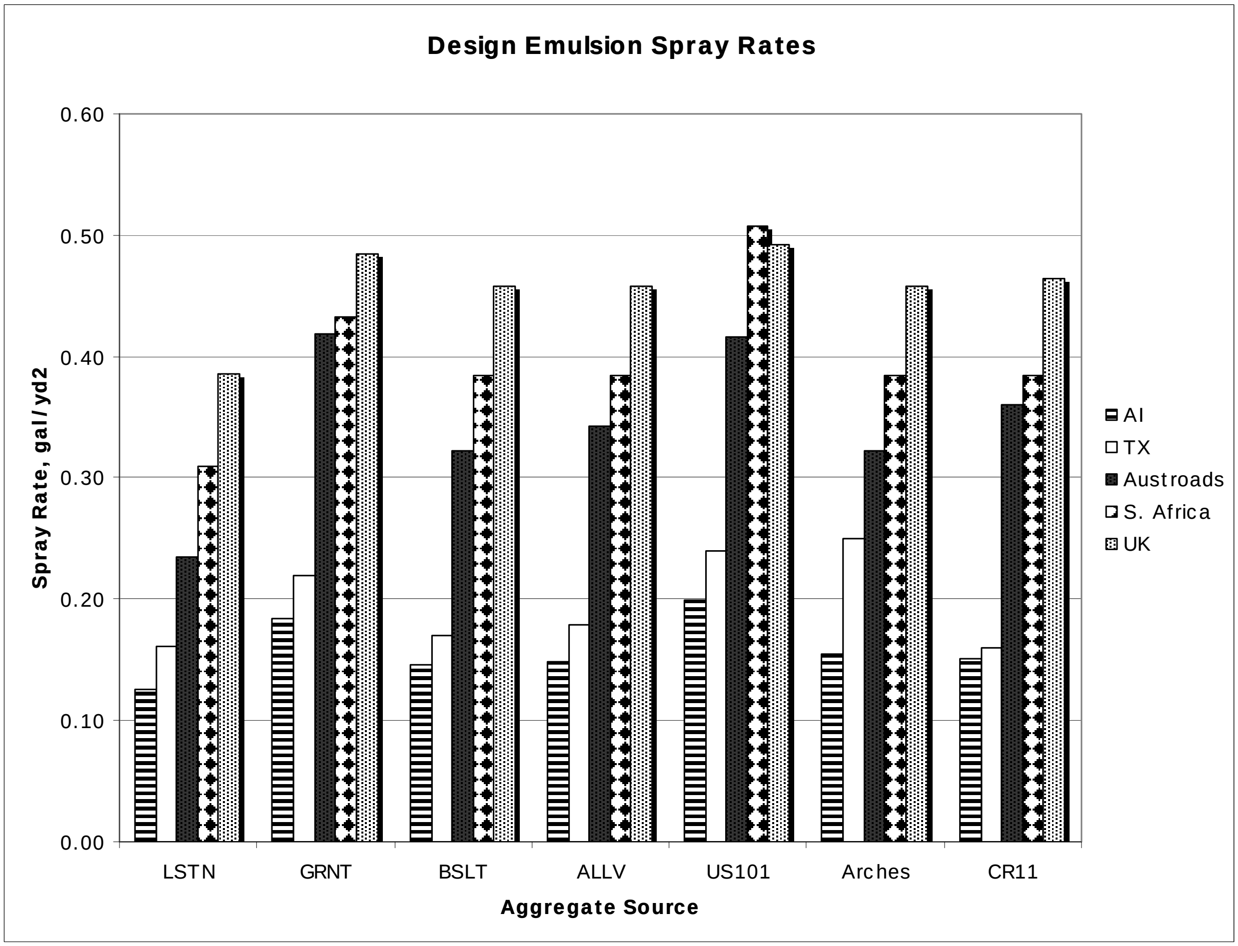


Figure J13. Emulsion Spray Rates for Five Design Methods

application. The Texas design recommends the lowest aggregate spread rate and the second to lowest emulsion spray rate.

In an effort to determine which, if any, of these methods matches what would be considered 'correct' in a field application in the U. S., the rates applied at the three field test pavements are plotted with the design recommendations on Figure J14 and Figure J15. Assuming observations of the research team are correct regarding aggregate spread rate and emulsion application rate, the South Africa and UK design methods match the aggregate application rate on CR11 best, the Austroads and Asphalt Institute methods overestimate the 'correct' rate and the Texas method underestimates the rate. The aggregate rates at the US101 and Arches sites were higher than needed by approximately 15 to 20 percent. If the actual rate is reduced by this amount, the rates would be 18 to 20 pounds per square yard at Arches and 24 to 26 pounds per square yard on US101. The South African, UK and Austroads procedures match these application rates closest, while the Asphalt Institute overestimates the rate and the Texas procedure underestimates the rate.

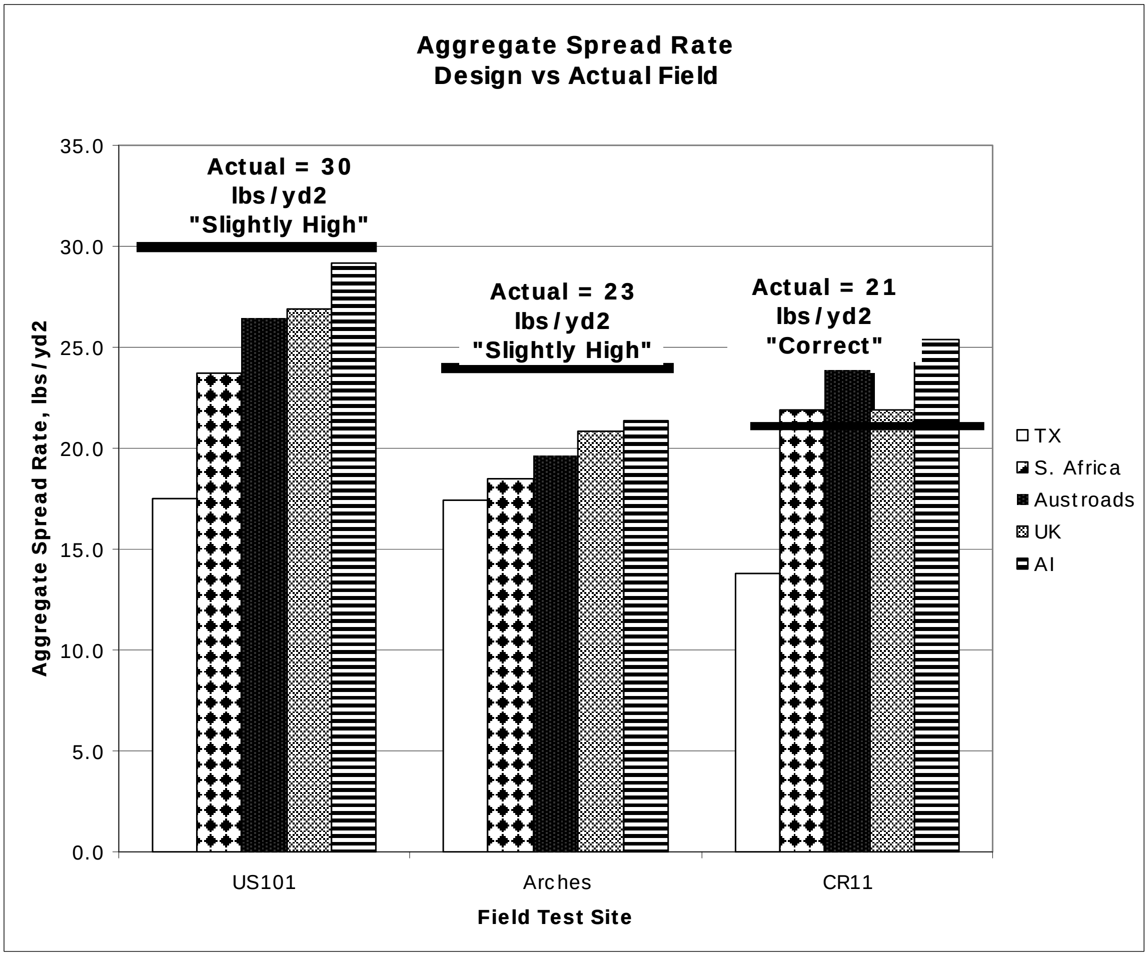


Figure J14. Five Designs Compared With Actual Aggregate Spread Rates at Three Sites

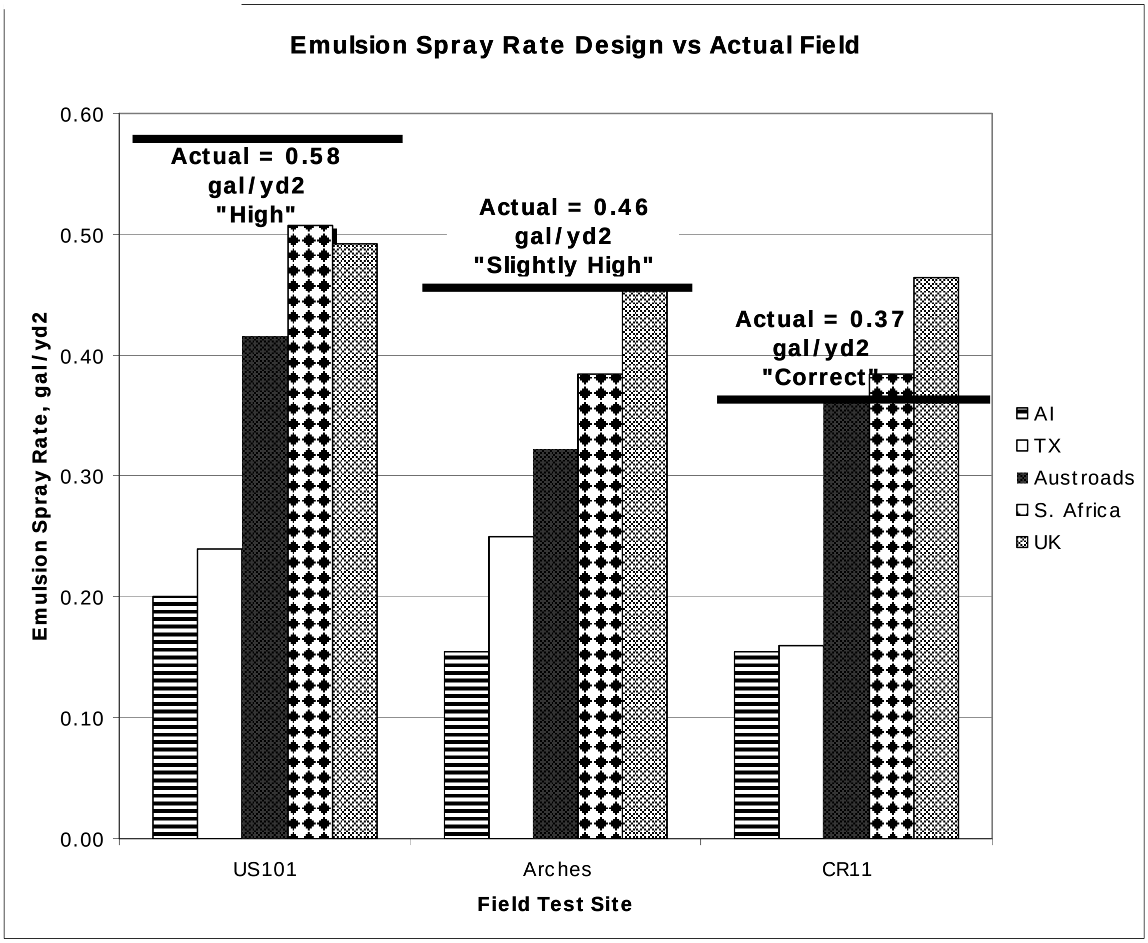


Figure J15. Five Designs Compared With Actual Emulsion Spray Rates at Three Sites

The Austroads and South African procedures match the 'correct' emulsion application rate best on CR11, while the Asphalt Institute and Texas methods underestimate the rate and the UK procedure overestimates the rate. Although the rates at Arches and US101 appeared slightly higher and higher than needed respectively, it was difficult to judge how much excess binder was present. However, the Austroads, South Africa and UK designs are probably closer to the correct application rate than either Asphalt Institute or Texas.