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Office of Research

High Volume/High Speed Asphalt Roadway Preventive Maintenance Surface Treatments

— Final Report —

SD99-09

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DISCLAIMER

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16. Abstract

The South Dakota DOT has made extensive use of chip seal and sand seal surface treatments in the maintenance of their AC pavements. Such surface treatments have been found to provide a cost-effective means of extending the life of AC pavements in South Dakota. Although the use of chip seals and sand seals have for the most part been reliable treatments, there have been some notable failures, especially on high-volume, high-speed roadways. This project was undertaken to investigate the use of chip seals for such applications and to make recommendations to improve their performance. This project also involved the development of guidelines for the design and construction of chip seals.

To evaluate the use of chip seals in South Dakota, several efforts were undertaken. First, an extensive literature review was conducted to develop an understanding of the latest practices and experiences. Second, interviews were conducted with South Dakota DOT from all departments involved in the chip seal process to investigate their practices and to determine areas for improvement. Finally, test sections were constructed to evaluate the performance of standard and modified chip seal designs. The test sections consisted of 12 chip seal designs and included two aggregate types (quartzite and natural aggregate) and alternate chip seal designs with new gradations and other modifications and enhancements. Based on these efforts, recommendations are provided to improve chip seal performance. In addition, guidelines were developed to select feasible surface treatments for a specific project.

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1.0 Introduction

Problem Statement

Chip seal and sand seal surface treatments have been widely used by the South Dakota Department of Transportation (SDDOT) in the maintenance of their asphalt concrete (AC) pavements. Such treatments, while providing little structural improvement to the pavement, have been found by many agencies to be a cost-effective means of sealing the pavement, improving surface friction, and prolonging pavement life (Raza 1992; Geoffroy 1996).

Chip seals and sand seals have seen the greatest use on lower volume roadways (typically roadways with average daily traffic [ADT] volumes less than 1000 vehicles per day), but many agencies, including the SDDOT, have extended the use of these low-cost maintenance activities to higher volume roadways. Unfortunately, the use of chip seals and sand seals on higher volume AC roadways may result in:

- Vehicle damage due to loose chips.
- Excess dust.
- Excess noise and roughness.
- Shortened life expectancy (compared to the same treatment applied to low-volume roads).

While even one dramatic failure can be a serious setback to a surface treatment program, many agencies continue to believe that chip seals and sand seals offer a low-cost, effective means of extending pavement life for selected high-volume roadways. Indeed, some experimental chip seal installations have been constructed on high-volume roadways, with many showing promising results when special modifications are made to the mix design and construction practices of the application (Shuler 1991; Shuler 1998).

Because of the successes that they and others have experienced, SDDOT is conducting this three-pronged research effort into the use of surface treatments on high-volume roadways. First, the appropriate uses of chip seals must be defined, in terms of such variables as the existing pavement condition, current traffic levels (and/or truck volumes), and prevailing climatic conditions. Second, if chip seals are to be used on heavily-trafficked roadways, special mix design enhancements (such as precoating the aggregate or using a polymer-modified binder) and construction techniques (such as applying a fog seal cover or sweeping the chip seal surface) must be identified to reduce loose stones, which are the single most serious problem with chip seal failure. Finally, alternative surface treatment techniques must be identified that can be used on high-volume roadways when conditions are such that chip seals are not appropriate.

Project Objectives

The objectives of this project are as follows:

- To develop guidelines to allow proper selection of surface treatments.
- To develop design guidelines for chip seals.
- To develop construction guidelines for chip seals.
- To construct chip seal test sections to validate design and construction guidelines.

This document describes the research that was conducted to achieve the four objectives and also presents the results of that research.

Task Descriptions

The SDDOT identified eleven tasks to achieve the objectives of this project, as described below:

1. *Kick-off Meeting*. Meet with the technical panel to review the project scope and work plan.
2. *Conduct Literature Review*. Review and summarize literature pertinent to asphalt surface treatments, paying particular attention to the design and construction of chip seals.
3. *Interview Department Personnel*. Interview department personnel to determine South Dakota's current asphalt surface sealing design and construction practices.
4. *Evaluate and Recommend Appropriate Treatments*. Evaluate various asphalt surface treatments and determine which are appropriate for South Dakota highways. The evaluation should include, but not be limited to, other state and agency experiences, cost effectiveness, compatibility with materials unique to South Dakota, availability of specialized equipment, traffic volume, and location (urban vs. rural).
5. *Develop Guidelines for a Treatment Selection Process*. Develop guidelines for a selection process of appropriate asphalt surface treatments for use on all highways of all traffic levels in South Dakota. The selection process should include pavement surface condition, available aggregate, equipment, and environmental conditions, among others.
6. *Provide Technical Memorandum*. Provide a technical memorandum describing the first five tasks.
7. *Recommend Treatment Designs for Construction*. With panel guidance, recommend appropriate chip seals or other surface treatments to be constructed and tested in South Dakota during the 2000 construction season.
8. *Monitor and Evaluate Test Sections*. Monitor and evaluate the construction of the test sections and document the test results obtained during initial construction and periodic on-site evaluations.
9. *Develop Guidelines for Treatment Design and Construction*. Prepare guidelines for the design and construction of asphalt surface treatments for use on highways of all traffic levels in South Dakota. The guidelines should include recommendations on aggregate type and gradation, particle size and shape, spread rates, bitumen type and amount, additives, and rolling patterns.
10. *Prepare Final Report*. Prepare a final report and executive summary of the literature review, research methodology, findings, conclusions, and recommendations.

11. *Executive Presentation*. Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project.

The execution and findings of each task are described in this report.

Report Content

This document is divided into seven chapters. The title and description of each chapter is provided below:

1. *Introduction*. This chapter describes general background information concerning this project and report, such as the problem statement, project objectives, task descriptions, and report content.
2. *State of the Practice*. A detailed summary of the findings from the literature review on chip seals and other surface treatments is presented in this chapter. The focus of this chapter is on chip seals, but findings concerning other surface treatments are also provided.
3. *Summary of South Dakota Practices*. This chapter summarizes South Dakota's surface treatment practices, based on interviews conducted with South Dakota DOT personnel and a review of pertinent literature and specifications.
4. *Design and Monitoring of Test Sections*. This chapter summarizes the design, construction, and monitoring of twelve test sections constructed for this study. In addition, recommendations developed as a result of the construction and monitoring activities, and recommendations for continued monitoring of the test sections, are also presented.
5. *Treatment Selection Guidelines*. This chapter presents an evaluation of the available surface treatments and provides the framework and details of the guidelines for selecting the most appropriate surface treatment.
6. *Summary*. This chapter summarizes the recommendations and presents methods for implementing the results of this project.

In addition to these chapters, two supporting appendices are provided. Appendix A includes photographs taken during the construction and monitoring of the test sections. Appendix B presents the results of the pavement condition surveys for each monitoring section.

2.0 State of the Practice

Introduction

At the heart of successful preventive maintenance programs are the effective selection, design, and construction of preventive maintenance treatments. These are treatments that do not provide any significant structural benefit to the pavement, but do enhance pavement performance and extend pavement service life when applied at the proper time in the life of the pavement. Of most interest to the SDDOT in this research project is the use of preventive maintenance surface treatments for AC pavements, of which the most common types are chip seals, slurry seals, microsurfacing, ultrathin friction courses, and thin AC overlays. Information on each of these treatments is provided in this summary of the state of the practice for surface treatments.

Pavement Preventive Maintenance

Concepts

Since the late 1980s, there has been a growing interest within the highway community to adopt and implement preventive maintenance programs as a more effective way of maintaining a pavement network (Peshkin et al. 1999). Preventive maintenance programs begin with the concept that there are cost-effective treatments that can be applied early in a pavement’s life. These treatments are thinner, constructed comparatively rapidly and with much less disruption to the traveling public, and reach or exceed their design lives because they are applied to pavements in good condition.

In contrast to a preventive maintenance philosophy, the more common approach to project selection within a network has been “worst-first” programming, in which pavements that are triggered for treatment or rehabilitation are those that are closest to failure. As such, treatments that are applied are more extensive, more expensive, more time-consuming to construct, and often do not achieve their design lives. Figure 1 illustrates the concept that the cost of performing preventive maintenance on a pavement in good condition is 20 to 25 percent of the cost of performing rehabilitation later in the life of the pavement. Furthermore, because these more expensive treatments consume more of the available funding, less money is available for treating or rehabilitating other projects.

Benefits

Agencies that use a preventive maintenance approach speak of the extension to pavement life realized by applying these thin treatments at the proper time; other benefits include the following (Peshkin et al. 1999):

- Higher customer satisfaction.
- Better informed decisions.
- Improved strategies and techniques.
- Improved pavement condition.
- Cost savings.
- Increased safety.

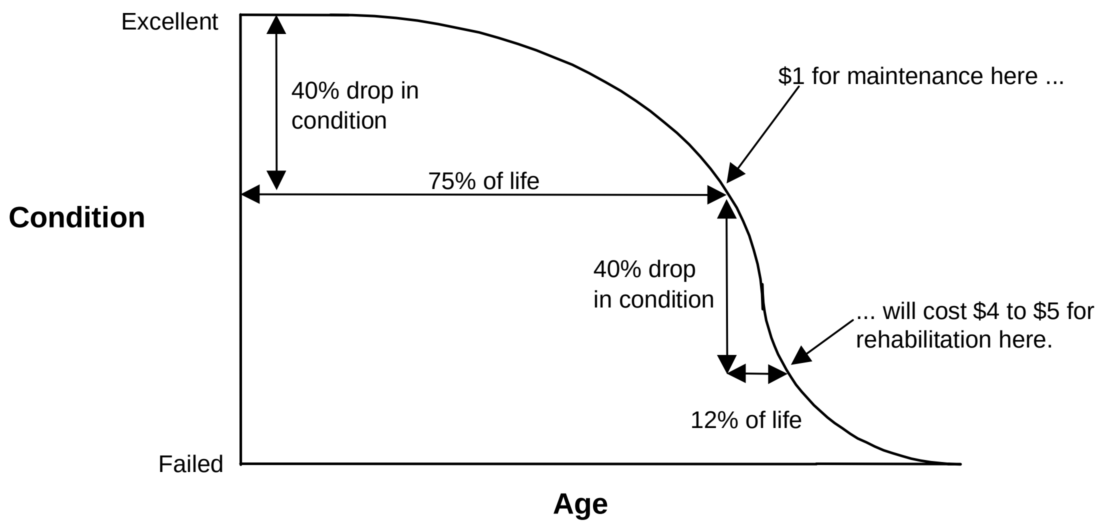

Figure 1. Pavement condition versus cost of repair.

Moreover, recent changes to Federal regulations now make many preventive maintenance activities eligible for Federal funding (FHWA 1998).

Chip Seals

Description and Purpose

Chip seals, sometimes referred to as surface treatments or bituminous surface treatments, are an application of asphalt (generally an asphalt emulsion) directly on the existing pavement followed by a layer of aggregate chips. The resulting treatment is then rolled to embed the aggregate into the asphalt. Chip seals are used primarily to seal the surface of a pavement with nonload-associated cracks and to improve surface friction. Although typically used on low-volume roads, chip seals have more recently seen some application on high volume roadways (Shuler 1991, Shuler 1998).

There are several variations of conventional chip seals that are also used (see figure 2). For example, South Dakota uses a sand seal, which uses a similar gradation as a chip seal but the aggregate is not crushed. Rubberized asphalt chip seals are similar to chip seals except that the asphalt binder is replaced with a blend of ground tire rubber (or latex rubber) and asphalt cement (Raza 1992). The rubber additive enhances the elasticity and adhesion characteristics of the binder. Similarly, some agencies use polymer-modified emulsions in the design of chip seals, particularly on high-volume roadways (Zaniewski and Mamlouk 1996). The polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, and allows the road to be opened to traffic earlier (Zaniewski and Mamlouk 1996).

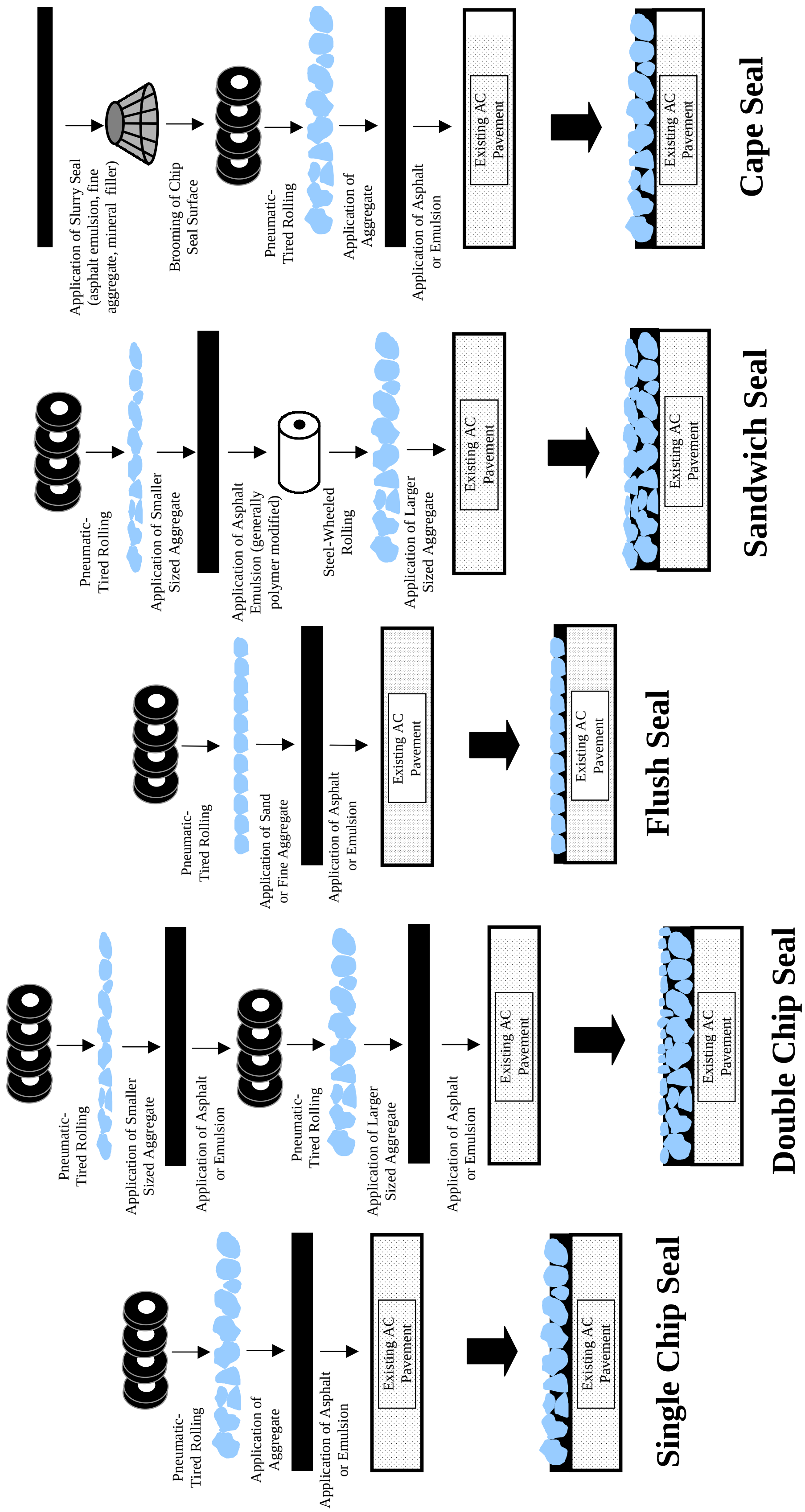

Figure 2. Schematic illustration of various chip seal types (Peshkin et al. 1999).

Chip seals may also be placed in two or more consecutive layers. Multiple chip seals are dense-wearing, waterproofing applications that can approach thicknesses of 25 mm (1 in) (AI 1997). Double or triple chip seals are constructed by placing two or three applications of a chip seal operation over the same roadway, each subsequent layer being placed after the previous layer has cured.

Other types of chip seals that are used occasionally are sandwich seals and cape seals. Sandwich seals consist of the application of a large aggregate followed by spray of asphalt emulsion that is in turn covered with an application of smaller aggregate. Cape seals are a chip seal covered with a slurry seal. The application of the slurry seal aids in reducing loose stones. Sandwich seals are used to seal the surface and improve skid resistance, whereas cape seals are used to provide a dense, waterproof surface with improved skid resistance (Raza 1992).

Design

When considering the design of a chip seal, the objective is to produce a pavement surface one stone thick with enough asphalt to hold the aggregate in place, but not so much asphalt that it will bleed (AI 1997). When the aggregate is initially spread, the particles are randomly oriented. After compaction and traffic, the particles will realign with about 20 percent voids between the particles. Mix designs are typically based upon having 60 to 75 percent of the voids filled with emulsion. Several theoretical procedures exist for determining the quantity of cover aggregate. These usually involve determining the average least dimension, the voids, and loose unit weight of the cover aggregate. Traffic volume and pavement condition should also be considered in chip seal design (AI 1997).

One theoretical design procedure for chip seals has been widely accepted (McLeod 1969). This procedure uses the aggregate gradation, shape, and specific gravity to determine the aggregate application rate, while the asphalt application rate is determined by the aggregate gradation, shape, and absorption, traffic volume, existing pavement conditions, and asphalt properties (McLeod 1969).

The aggregate application rate is determined by the following equations:

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

$$V = 1 - \frac{W}{62.4G}$$

where:

C = the coverage aggregate application rate, lb/yd^2.
V = the voids in the loose aggregate, percent.
W = loose unit weight of the cover aggregate (ASTM Method C29), lb/yd^3.
G = bulk specific gravity of the aggregate.
H = average least dimension, in.
E = wastage factor for traffic whip-off.

The average least dimension of the aggregate, which is a reduction of the median particle size to account for flat particles, is determined from the median particle size and the flakiness index of the aggregate. The median particle size is defined as the theoretical sieve size that 50 percent of the material passes. The flakiness index is a measure of the percentage by weight of flat particles. Particles are considered to be flat if the least dimension of the particle is less than 60 percent of the mean of the coarse sieve. The lower the flakiness index, the more cubical the material.

The emulsion application rate is determined by the following equation:

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

where:

B = binder application rate, gal/yd^2.
H = average least dimension, in.
T = traffic factor (based on expected vehicles/day).
S = surface condition factor, gal/yd^2.
A = aggregate absorption factor, gal/yd^2.
R = residual asphalt content of binder, percent.

Minnesota uses a slightly modified version of the McLoed design procedure, in which the emulsion application rate is designed twice: first using the average least dimension and then using the average median particle size (Janisch and Gaillard 1998). The average least dimension provides the desired application rate in the wheelpath, where traffic helps with the embedment. The average median particle size provides the desired application rate outside the wheelpath, where traffic does not help the embedment and more emulsion is required to achieve the same embedment. The two results are then averaged together to determine the target application rate in the field. Minnesota has found that failure to make this modification will lead to insufficient binder in the non-traffic areas, and snow plows will shave off chips.

Similar design procedures are the Lovering spread modulus design method, the American Bitumul design method, and the Asphalt Institute method (Kandhal 1983). These methods use many of the same material properties as McLeod uses to determine application rates, but generally use different factors to account for aggregate spread, traffic, and surface conditions.

One very simplified method for determining aggregate and asphalt emulsion application rates is to place a layer of quality aggregate in its densest possible pattern into a pan of known dimensions. The pan is then filled with water until the layer of aggregate is just covered. The volume of binder required is approximately two-thirds the volume of water in the pan (Zaniewski and Mamlouk 1996). Typical asphalt and aggregate application rates are shown in table 1.

After a mix design is performed, the asphalt application rate may need to be adjusted for pavements that are excessively dry or cracked. This adjustment can be made on site. As much as 0.09 to 0.14 L/m^2 (0.02 to 0.03 gal/yd^2) of asphalt can be added to a dry, cracked pavement to get the proper chip embedment (Montana DOT 1996).

Table 1. Typical binder application rates (Zaniewski and Mamlouk 1996).

Aggregate Nominal Size, mm (in)	**AASHTO Size No.**	**Aggregate Application Rate, kg/m^2 (lb/yd^2)**	**Asphalt Emulsion Application Rate, L/m^2 (gal/yd^2)**
19.0–9.5 (0.75–0.38)	6	22–27 (40–50)	1.8–2.3 (0.40–0.50)
12.5–4.75 (0.50–0.19)	7	14–16 (25–30)	1.4–2.0 (0.30–0.45)
9.5–2.36 (0.38–0.09)	8	11–14 (20–25)	0.9–1.6 (0.20–0.35)
4.75–1.18 (0.19–0.05)	9	8–11 (15–20)	0.5–0.7 (0.10–0.15)
Sand	M-6	5–8 (10–15)	0.5–0.7 (0.10–0.15)

Materials

Asphalt emulsions are typically used with conventional chip seals. An asphalt emulsion is asphalt cement suspended in a mixture of water and emulsifying agents. Asphalt emulsions are graded based on setting speed and the relative viscosity of the emulsion. The setting speed refers to the quickness with which the asphalt particles fall out of the water suspension; grades RS, MS, and SS are commonly available (referring to rapid setting, medium setting, and slow setting, respectively). The number of the emulsion grade indicates the relative viscosity (i.e., resistance to flow) of the emulsion; thus, an SS-2 is more viscous than an SS-1. Finally, the “h” attached to some of the grades indicates that a harder grade of base asphalt is used in the production of the emulsion (AI 1997).

Anionic grades are intended for use with positively charged aggregates (such as limestone) and cationic grades are intended for use with negatively charged aggregates (such as siliceous gravel) (Roberts et al. 1991). The emulsions generally used for chip seals are rapid setting emulsions (anionic grades RS-1 and RS-2 or cationic grades CRS-1 and CRS-2) that are designed to react quickly with the aggregate. During this reaction, which is referred to as “breaking” or “setting,” the asphalt particles fall out of the water suspension.

Some agencies also use asphalt cement as the binder for chip seals. Soft asphalt cement grades, such as AC-2.5 and AC-5, are recommended for use in chip seal applications (AI 1996). AC-10 grade asphalts have also been used. Adhesion agents may be added to these asphalt cements to enhance chip retention.

Some agencies use polymer-modified emulsions in the design of chip seals, particularly on high-volume roads (Zaniewski and Mamlouk 1996). The polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, and allows the roadway to be opened to traffic earlier (Zaniewski and Mamlouk 1996). These emulsions are designated with a “P” (e.g. CRS-2P).

Cutback asphalts have also been used in the construction of chip seals, although emulsions are typically preferred because of both environmental concerns and cost savings (Zaniewski and Mamlouk 1996). Cutback asphalts are produced by adding a petroleum solvent to asphalt cement. Rapid curing cutbacks (RC) were most commonly used for surface treatments, but most states have discontinued the use of cutbacks for the reasons cited above.

Aggregates used in chip seals should be clean to enhance the coating of the asphalt and durable to resist wear from traffic. Most states specify a maximum dust content of 2 percent (Kandhal and Motter 1991). Aggregate that has greater than 3 percent dust content was found to have a higher rate of loss than cleaner aggregates (Kandhal and Motter 1991, Shuler 1998). Aggregate should be as close to one size as possible, typically in the range of 6 to 16 mm (0.25 to 0.62 in) (AI 1997). Typical aggregate gradations are shown in table 2. The size of the aggregate will largely dictate the resultant thickness of the chip seal. Most states have moved from the use of larger chips to smaller sized chips to reduce vehicle damage and to provide a smoother riding surface. The most common top size is 9.5 mm (3/8 in).

Table 2. Typical aggregate gradations (MDT 1996).

	Percent Passing					
Sieve Size	Montana Grade 4A	Montana Grade 5A	Tulsa	Palm Springs Owl	Tazewell 8P	Del Mar
12.5 mm (1/2 in)	100	100	100	100	100	100
9.5 mm (3/8 in)	100	100	95	100	98	100
4.75 mm (No. 4)	0-30	9-50	32	18	10	21
2.36 mm (No. 8)	0-15	2-20	0	5	0	1
1.18 mm (No. 16)				3		1
0.600 mm (No. 30)				1		0
0.075 mm (No. 200)	0-2	2-5				

The ideal aggregate shape for chip seals is cubical. Flat or elongated particles tend to align on their flat sides and may be completely covered with asphalt, whereas rounded aggregates may roll under traffic and dislodge (AI 1997). Aggregate embedment of 70 percent after compaction is desirable, with embedment increasing to 80 percent after traffic has been applied.

Construction Practices

The following sequence of construction is recommended for placing a chip seal (AI 1997, Zaniewski and Mamlouk 1996):

1. *Patch potholes and repair damaged areas in the existing pavement*. Allow enough time for curing of the patch mix. If a coarse patch mix is used, fog sealing may be advisable.
2. *Clean the surface with a power sweeper or rotary broom or by another approved method.* If the pavement surface is not completely clean, the asphalt may not adhere to the existing surface. Sweeping is also recommended after the surface treatment is completed to remove any loose stones that may cause windshield damage.
3. *Spray the asphalt emulsion binder at the specified rate and proper temperature*. The asphalt distributor is the most important piece of equipment used in surface treatment construction (AI 1997). The spray nozzle angle settings and the spray bar height on the distributor are very important. The angle of the nozzles, typically 15 to 30 degrees, must be set such that the spray fans will not interfere with one another when providing overlapping patterns. The spray bar height should be kept at the proper distance from the pavement surface. If it is set too high, wind may cause distortion of the spray fans,

resulting in uneven spread. Best results occur when a double coverage is used. Although distributors typically have precise controls, the application rate should be checked in the field to ensure proper coverage.

4. *Spread the cover aggregate at the specified rate immediately behind the asphalt spray application (emulsion still brown in color) to achieve maximum possible chip wetting*. Waiting to spread the chips may result in poor adhesion if the emulsion has already set.
5. *Roll the cover aggregate adequately to properly seat particles in the asphalt film*. This rolling process ensures better adhesion of the chips to the existing pavement surface. Pneumatic-tired rollers produce the best results with single surface treatments (AI 1997). The tires are able to seat the chips into the emulsion without fracturing the aggregate or bridging over depressions.

Traffic Control and Opening to Traffic

Traffic may be allowed on the chip seal after rolling is completed; however, traffic speed should be limited to about 32 km/hr (20 mi/hr) for about 2 hours after placement (Raza 1992). The use of a pilot car is helpful in keeping traffic speeds low through the construction zone. Allowing slow moving traffic on a chip seal is one of the best means to reduce chip loss as the vehicular interaction provides a level of chip orientation not achievable by conventional pneumatic rollers (Shuler 1998). Montana specifies that traffic be limited to 40 km/hr (25 mi/hr) for a period of 24 hours (Janisch and Gaillard 1998).

Performance

The performance of chip seals has been somewhat variable and is dependent upon the proper application of the asphalt binder and aggregate chips and the subsequent compaction of the resulting treatment. Typical performance lives of 4 to 7 years are often given in the literature: Texas reports an average life of 6 to 7 years (Raza 1992); New York reports that chip seals with an asphalt emulsion have lasted 3 to 4 years; and Washington State reports that chip seals with a polymer-modified sealer have lasted 5 to 7 years under heavy traffic (Geoffroy 1996). Multiple chip seals are reported to give up to 10 years of performance in some cases (Raza 1992). A recent survey of highway agencies indicates that single application chip seals on low volume roads can increase life by an average of 5 to 6 years, while multiple application chip seals can increase life by an average of 9 to 10 years (Geoffroy 1996).

Chip seals are being evaluated under the FHWA's Long-Term Pavement Performance (LTPP) Special Pavement Studies (SPS) program. Under that program, chip seal test sections were constructed in all four climatic regions on pavements with varying condition levels. The 5-year evaluation of these installations shows that the chip seals are generally performing well (Morian et al. 1997). The effects of climate are also apparent from that study, as the chip seal installations in the non-freeze climates are showing the best performance (Morian et al. 1997). Moreover, the results of the 5-year evaluation suggest that chip seals are cost-effective treatments that result in extended life (Morian et al. 1998).

The effectiveness of chip seals is also related to the brittleness of the asphalt binder in the existing pavement. For example, Wisconsin found that chips seals were not cost effective when placed on older pavements in which the binder had prematurely aged and hardened (Rutkowski 1994).

A study focusing on the performance chips seals placed on roads with traffic volumes of 2,000 ADT or less in Washington State was assembled in the late 1980's (Jackson et al. 1990). This study identified the causes and possible mitigating actions for problems associated with flushing and raveling. The following causes of flushing in chip seals were identified*:*

- Existing pavements that have had flushing problems prior to the placement of the chip seal and cold mix patches will have a tendency to migrate through the chip seal, producing "reflective flushing."
- Emulsion application rates that were too heavy caused the seal to flush.
- Joints in the chip seal were often improperly constructed, leading to a double application of emulsion causing flushing along the joint.
- Chips placed after the emulsion had broken caused minimal chip retention resulting in uncovered emulsion.
- Crack sealant that had been placed in a "band-aid" fashion tended to bleed though the chip seal.

Actions suggested by this study to alleviate flushing problems are as follows:

- Conduct pre-construction evaluations of existing pavement conditions. For areas of 0.40 km (0.25 mi) or longer in which the existing surface is too rich or too dry, adjust emulsion application rates to the field conditions.
- Perform embedment checks throughout construction. Chips should be embedded 70 percent after the initial rolling and 80 percent after two or more weeks of traffic.

The probable causes of raveling in chip seals were also identified in this study*:*

- Pavements with a very dry or open surface absorb some of the emulsion during construction, reducing the amount of emulsion left to hold chips in place.
- Recently placed hot-mix patches also tended to absorb some of the emulsion applied during construction.
- Application of excess chips not only created a potential for windshield damage, but the chips also tended to remove some emulsion as they left the pavement surface.
- Chips that are too wet or dusty will not adhere to the emulsion.
- Chip retention after the emulsion breaks is minimal, which results in raveling and potential windshield damage.
- Chip seals constructed late in the paving season had a strong potential for raveling due to less curing time and less time for chips to be further embedded by traffic.

Actions suggested by this study to alleviate raveling problems are as follows:

- Perform embedment checks.
- Perform pre-construction evaluations.
- Ensure that chip and emulsion application rates are correct, and then use embedment checks to verify the application rates.
- Apply chips to the emulsion in a timely manner, before the emulsion breaks.
- Time contracts so that work is performed during the optimal paving season.

Precoating the aggregate chips with asphalt prior to placement has been found to decrease the initial amount of chip loss (Kandhal and Motter 1991). Chips that were 90 percent precoated were found to have up to an 80 percent lower initial loss than uncoated aggregates. Texas commonly uses precoated aggregates (typically coated with softer asphalt cements such as AC-2.5 and AC-5) to help control dust problems and to provide a darker surface that creates more visible lane markings (TXDOT 2000).

As with other surface treatments, chip seals provide little additional structure to the existing pavement, so pavements that are structurally deficient are not good candidates for chip seals. In addition, because wide cracks or cracks experiencing large movements are expected to reflect through the chip seal treatment, pavements with extensive amounts of these distresses are also not candidates.

Considerations for High-Volume Applications

Several factors should be considered to prevent vehicle damage and short service life when constructing chip seals for high volume applications. The most common causes of vehicle damage from chip seals are excess chips, inadequate traffic control, and inadequate sweeping (Shuler 1998).

The application of excess chips is one of the most common problems during chip seal construction. Excess chips are often applied to prevent chips from sticking to the wheels of construction equipment, which is good practice; however, this excess should be limited to 5 to 10 percent (Shuler 1998). It becomes difficult to sweep off excess chips in quantities higher than 10 percent, and the excess chips can lead to windshield damage. Excess chips can also dislodge embedded chips under traffic, leading to failure of the chip seal (Shuler 1998).

Vehicle damage can also be prevented through adequate traffic control. After chip seal placement and sweeping, pilot cars can be used to control traffic speeds to 40 km/hr (25 mi/hr). This can reduce whip-off created by high-speed traffic and also helps orient and embed chips (Shuler 1998). However, pilot cars are often not used because of the delay and inconvenience to motorists.

Sweeping is essential to high traffic chip seal applications. Vehicle damage can be avoided if the excess chips placed to minimize chip pickup on equipment tires are swept from the pavement surface before opening to traffic. Sweeping should be properly timed because the sweeping process can dislodge chips (Shuler 1998).

Causes for aggregate loss that occur soon after placement have been described. In cases where chip seals fail after a period of months either though loss of aggregate or flushing, the problems may be caused by material, design, or construction problems (Shuler 1998):

- Poor binder quality can lead to inadequate embedment and adhesion of chips resulting in aggregate loss. Binders can also oxidize, resulting in increased brittleness of the asphalt film and loss of chips.
- Binder and surface temperatures that are too low can lead to poor adhesion of the asphalt emulsion to both the existing pavement surface and the aggregate.

- Cool weather during and immediately after construction can also lead to poor embedment of chips resulting in shortened service life.

High Traffic Suitability

Although predominantly used on low- to medium-volume roadways, several agencies are experimenting with chip seals installed on higher volume roadways (Shuler 1991, Shuler 1998). Problems with the use of chip seals on high volume roads generally are vehicle damage due to loose stones, excessive dust, noise, and roughness, and shorter service lives. A series of experimental chip seal installations in Tulsa, Oklahoma; Palm Springs, California; Tazewell, Virginia; and Del Mar, California have provided considerable insight into factors affecting good chip seal performance on high-volume roadways; some of these factors include the following (Shuler 1998):

- Use of one-aggregate thick application rate to reduce excess stone.
- Precoating the aggregate with binder prior to application to enhance adhesion.
- Use of polymer-modified binders to enhance adhesion.
- Application of a “choke” stone to prevent larger aggregates from coming loose.
- Sweeping of the surface after rolling.
- Use of a low-speed traffic control car directly on the chip seal for 1 to 3 hours after construction to help embed chips.

Cost Effectiveness

Average 1997 cost data from Ohio show a cost range of \$0.96 to \$1.32/m^2 (\$0.80 to \$1.10/yd^2) for the construction of chip seals (ODOT 1998). These costs are equivalent to \$6,900 to \$9,500 per two-lane kilometer (\$11,300-\$15,500 per two-lane mile). Data from the SPS-3 studies indicate a range in costs from \$0.40/m^2 to 1.81/m^2 (\$0.34/yd^2 to \$1.51/yd^2), which is equivalent to \$2,900-\$13,000 per two-lane kilometer (\$4,800 to \$21,300 per two-lane mile) (Morian et al. 1998). By comparison, SDDOT’s costs typically range from \$4,000 to \$6,200 per two-lane kilometer (\$6,500 to \$10,000 per two-lane mile) with an average cost around \$5,000 per two-lane kilometer (\$8,000 per two-lane mile).

Fog Seal

Description and Purpose

Fog seals are an application of diluted asphalt emulsion placed directly on the pavement surface without an aggregate cover (Raza 1992). Fog seals are used to seal the pavement and also to inhibit raveling and provide some enrichment to oxidized AC surfaces that have become dry and brittle. They can also be used on shoulders to provide delineation between the mainline pavement and shoulder (Raza 1992). Fog seals are not recommended for high-volume roadways due to the length of time required for slow setting emulsions to break, which reduces the amount of surface friction immediately after application.

Materials

Anionic or cationic slow-setting asphalt emulsions (grades SS-1 and SS-1h; CSS-1 and CSS-1h) are most customarily used for fog seals. These slow setting emulsions are usually diluted with water (typically one part water to one part emulsion) for better control of the lower asphalt application rate. Medium-setting emulsions are sometimes used and may be polymer modified.

Performance

Fog seals generally last about 1 to 2 years before the pavement requires either another application or the placement of a more substantial surface restoration treatment such as a chip seal. Fog seals are a low-cost method of inhibiting raveling and rejuvenating the surface of the pavement and, when placed early enough in the life of the pavement, can be effective at prolonging its life. Applying fog seals at regular intervals may increase effectiveness; however, no formal studies of the effect of fog sealing on increasing pavement performance or pavement life are available. Fog seals are not effective for sealing cracks, and will not repair major raveling.

Costs

The costs of fog sealing range from about \$0.24 to \$0.30/m^2 (\$0.20 to \$0.25/yd^2) based on 1997 cost data from Ohio (ODOT 1998). These costs are equivalent to \$1,700 to \$2,200 per two-lane kilometer (\$2,800 to \$3,500 per two-lane mile). The Foundation for Pavement Preservation reports a typical cost of \$0.54/m^2 (\$0.45/yd^2) or \$4,000 per two-lane kilometer (\$6,300 per two-lane mile).

Flush Seal

Flush seals are a variant of chip seals. Flush seals are an application of asphalt emulsion followed by a light covering of sand or other fine aggregate. They are used to enrich a dry, oxidized surface and to prevent infiltration of moisture and air (AI 1997). The service life range of flush seals is approximately 2 to 7 years for traffic up to 5,000 vehicles per day and 2 to 5 years for higher traffic levels (NCHRP 1997). Agencies that have used flush seals have reported that this surface treatment can extend pavement life, increase surface friction, and prevent raveling (NCHRP 1997). South Dakota does not currently use flush seals as surface treatment.

Costs for flush seals range from \$0.60 to \$1.50/m^2 (\$0.50 to \$1.25/yd^2) (NCHRP 1997). These costs are equivalent to \$4,300 to \$10,800 per two-lane kilometer (\$7,000-\$17,600 per two-lane mile).

Slurry Seal

Description and Purpose

A slurry seal is a mixture of well-graded fine aggregate, mineral filler (if needed), and slow-setting asphalt emulsion (AI 1997). Specially designed equipment is available that combines these ingredients into a homogenous mixture and then places the material on the pavement (see figure 3). The mixture is prepared in the form of a creamy-textured slurry and applied in an average thickness of about 3 to 12 mm (0.12 to 0.50 in) (AI 1997).

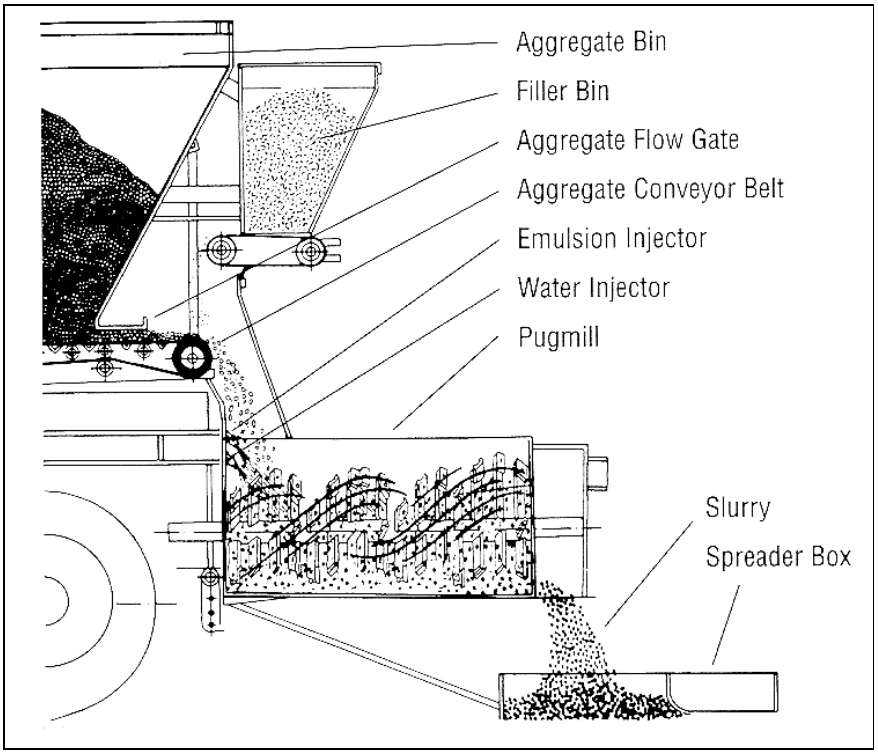

Figure 3. Slurry seal operation (AI 1997).

Slurry seals are used to stop raveling and loss of matrix and to improve surface friction (AI 1996). They should not be used on deteriorated pavements. Slurry seals are appropriate when the primary deterioration is related to excessive oxidation and hardening of the existing asphalt (Raza 1992). As with other surface treatments, slurry seals should not be used where sealing the pavement will cause a stripping problem or where the underlying pavement is cracked.

Materials and Construction

The International Slurry Surfacing Association (ISSA) has defined three types of slurry seals, which differ primarily in aggregate gradation. Each type has a specific application (ISSA 1997, ISSA 1998):

- Type I
  - 3.2 mm (0.12 in) maximum aggregate size.
  - 10 to 16 percent residual asphalt.
  - Used for surface crack sealing on low traffic roadways.
- Type II
  - 6.4 mm (0.25 in) maximum aggregate size.
  - 7.5 to 13.5 percent residual asphalt.
  - Used to correct raveling and oxidation on roadways with moderate to heavy traffic.

- Type III
  - 9.5 mm (0.38 in) maximum aggregate size.
  - 6.5 to 12 percent residual asphalt.
  - Used to fill minor surface irregularities, correct raveling and oxidation, and restore surface friction.

Type I slurry seals are used as a thin sealing course that penetrates cracks and seals the surface and performs well when used for low-volume applications (AI 1997). The Type II gradation is the most widely used slurry seal type, and is suitable for most general applications, although slurry seals can be custom designed based on specific applications and available materials. This type is used to protect the pavement from oxidation and water damage as well as to improve surface friction. The aggregate gradation used in Type III slurry seals can be used for heavy application rates and to achieve high surface friction values (AI 1997).

Similar to chip seals, the aggregate used in slurry seals must be clean and angular, and must additionally be durable, well-graded, and uniform (AI 1997). A 100 percent crushed material should be used when available (AI 1997).

The asphalt emulsion used in slurry seals may be SS-1, CSS-1, SS-1h, QS-1h, CSS-1h, or CQS-1h (AI 1997). The "QS" are quick-setting emulsions designed to break a little earlier than the SS variety. Before choosing an emulsion and aggregate gradation, a mix design must be performed to ensure that the desired properties and break times are achieved. Mineral fillers may be added to the mixture to improve mix characteristics or to adjust break times (AI 1997). Portland cement, lime, and aluminum sulfate are common mineral fillers.

Specialized equipment is required for the blending and placement of slurry seals. A curing period is necessary before traffic is returned to a newly finished surface. Traffic may be returned to the pavement in about 2 hours, preferably longer in cooler weather (Raza 1992).

Performance

The performance lives of slurry seals are generally reported to be in the range of 3 to 5 years on roads with moderate to heavy traffic (Raza 1992). Specific findings from the 5-year evaluation of slurry seals under the LTPP SPS-3 study include the following (Morian et al. 1997):

- Slurry seals are effective in reducing the development of pavement cracking and raveling.
- Slurry seals perform better in warmer climates.
- Slurry seals perform best when applied to pavements in relatively good condition (before extensive cracking developed).
- Slurry seals are marginally effective in preventing reflection cracking. Reflective cracking returns within 1 year under most conditions.

As with most preventive maintenance techniques, slurry seals should not be used on deteriorated pavements. Localized areas of severe distress should be repaired prior to the slurry seal, and working cracks should be sealed with crack sealant. If a considerable number of working cracks are present, slurry seals may not be an appropriate maintenance action.

High Traffic Suitability

Slurry seals have seen some limited use on high-volume roadway facilities (ADT greater than 5,000 vehicles per day). In such applications, special aggregate gradations are recommended to provide a sufficiently durable wearing surface (Raza 1992). However, when used on higher volume roadways, many agencies use a polymer-modified binder to increase the durability of the treatment.

Costs

Average 1997 costs from Ohio for the application of a slurry seal treatment range from \$0.84 to \$1.14/m^2 (\$0.70 to \$0.95/yd^2) or \$6,000 to \$8,200 per two-lane kilometer (\$9,900 to \$13,400 per two lane mile) (ODOT 1998). The Foundation for Pavement Preservation reports a typical cost of \$1.08/m^2 (\$0.90/yd^2) or \$7,900 per two-lane kilometer (\$12,700 per two-lane mile).

Microsurfacing

Description and Purpose

Microsurfacing is a type of slurry seal that uses a polymer-modified emulsion binder, higher quality aggregates, and a set control additive. Microsurfacing has been used effectively to improve surface friction characteristics, to fill wheel ruts and other minor surface irregularities, and to seal the pavement surface, thereby addressing oxidation and raveling (Raza 1992). It can provide surfacings of 10 to 20 mm (0.38 to 0.75 in) thick and can fill wheel ruts up to 40 mm (1.5 in) deep in a single pass (AI 1997). Microsurfacing has been used successfully on both low- and high-volume roadways. Figure 4 illustrates the microsurfacing operation (ISSA 1991).

Microsurfacing is a mixture of crushed, dense-graded aggregate, polymer-modified asphalt emulsion, mineral filler, additives, and water (AI 1997). As indicated above, microsurfacing is a member of the slurry seal family except that it uses a polymer-modified material binder and higher quality aggregates. The polymer that is added to the emulsion typically increases the stiffness of the asphalt and improves its performance in terms of adhesion, cohesion, and temperature susceptibility (Raza 1994a).

As with other treatments, microsurfacing does not add significant structure to the existing pavement, so its use should be limited to pavements exhibiting little structural deterioration. That is, pavements with fatigue cracking and/or significant linear cracking are not candidates for microsurfacing, unless these deteriorated areas are repaired prior to microsurfacing. One exception to this, however, is rutting, as microsurfacing is well suited to filling ruts on an otherwise sound pavement (Raza 1994a).

Materials and Construction

High quality, clean, 100 percent crushed aggregate should be used for microsurfacing. (Raza 1994a). The maximum aggregate size for microsurfacing is typically 9.5 mm (0.38 in). Table 3 shows two commonly accepted aggregate gradations. The gradation chosen depends largely upon the type of application: Type II is typically used for general resurfacing and sealing activities,

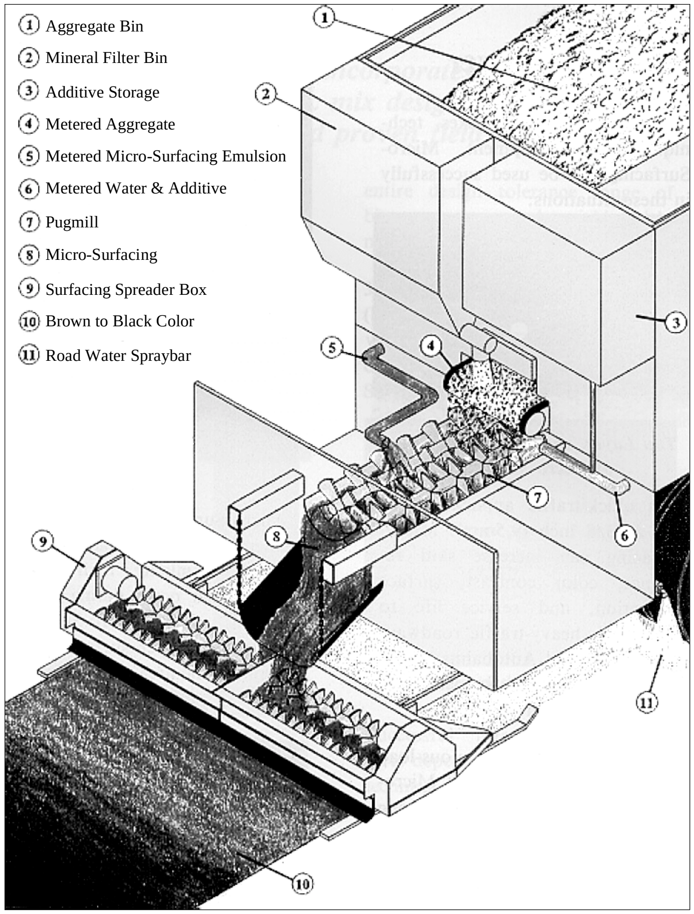

Figure 4. Schematic of microsurfacing process (ISSA 1991).

Table 3. Typical microsurfacing aggregate gradations (ISSA 1996).

Sieve	Percent Passing	
	Type II	Type III
9.5 mm (0.38 in)	100	100
4.75 mm (No. 4)	90–100	70–90
2.36 mm (No. 8)	65–90	45–70
1.18 mm (No. 16)	45–70	28–50
0.60 mm (No. 30)	30–50	19–34
0.33 mm (No. 50)	18–30	12–25
0.15 mm (No. 100)	10–21	7–18
0.075 mm (No. 200)	5–15	5–15

and Type III for high-volume roadway resurfacing, rut filling, or where high friction values are desired (AI 1997). Limestone, slag, silicate, granite, flint, and basalt aggregates are typically used in microsurfacing (Raza 1994a).

A polymer-modified cationic asphalt emulsion, CSS-1hp, is the most commonly used binder for microsurfacing (AI 1997). The polymer is added to the emulsion to increase the stiffness of the asphalt and improve its adhesion, cohesion, and temperature susceptibility properties (Raza 1994a).

Mineral filler is used in microsurfacing mixtures to minimize aggregate segregation and to control the rate at which the binder breaks or sets (Raza 1994a). Mineral filler is also required for most aggregate types for the mixture to set properly. Two types of mineral fillers typically used in microsurfacing are portland cement and hydrated lime (Raza 1994a). A mix design must be performed in the laboratory to determine the compatibility and correct proportions of the component materials that produce a microsurfacing mixture with the desired properties (e.g. adequate coating, no emulsion runoff, and desired break time).

Similar to slurry seals, microsurfacing requires special paving equipment. The machine used for microsurfacing is similar to that used for slurry seals, but it requires a more powerful and faster mixer. A test strip is required by some agencies to validate the mix proportioning and placement of the microsurfacing (Raza 1994a).

Depending on the design of the microsurfacing mix and the temperature and humidity at construction, traffic can generally resume operation on a microsurfaced pavement within 1 hour of placement (Raza 1994a).

Performance

The service life of microsurfacing is generally reported to be about 4 to 7 years (Raza 1994a). However, in judging its performance, it must be recognized that microsurfacing can be placed for different reasons and therefore its performance is tied closely to its application. For example, microsurfacing has had the following performance when used to correct rutting (Raza 1994a):

- Kansas is obtaining up to 5 years of service before recurrence of 15 mm (0.60 in) of rutting.
- Pennsylvania found that microsurfacing resisted the reformation of ruts, particularly in areas where initial rut depths were less than 20 mm (0.75 in). Initial ruts of 25 to 50 mm returned to levels of 6 to 13 mm (0.25 to 0.50 in) after 3 years and to levels of 16 mm (0.62 in) after 5 years. Original ruts of less than 20 mm returned to levels of 3 mm (0.12 in) after 5 years.
- Microsurfacing in Oklahoma has provided 5 to 7 years of performance in rut filling applications.
- On a project in Arkansas, no significant reformation of rutting was noted after 4 years.

Highway agencies have reported the following when microsurfacing is used to provide increased surface friction on existing pavements (Raza 1994a):

- States have reported initial surface friction numbers ranging from the mid 40s to the high 50s following microsurfacing projects. Furthermore, long-term results indicate good skid resistance over the service life.
- Oklahoma has found that microsurfacing provides adequate surface friction for at least 4 years under traffic volumes up to 70,000 ADT.
- On several high-volume roadways, Pennsylvania found average surface friction values between 40 and 50 for microsurfaced pavements with up to 5.5 years of service.

Microsurfacing has also been found to perform well for over 5 years on interstate pavements with minor raveling and has delayed the development of reflective cracking when underlying cracks are inactive (Raza 1994a).

Since microsurfacing does not add significant structural capacity to the existing pavements, its use should be limited to pavements exhibiting little structural deterioration and avoided in cases where the existing pavements have fatigue cracking or significant linear cracking unless these deteriorated areas are repaired prior to the placement of the microsurfacing

High Traffic Suitability

Microsurfacing has been widely used on many high-volume roadways. For example, Oklahoma has found that microsurfacing provides adequate surface friction for at least 4 years under traffic volumes up to 70,000 vehicles per day (Raza 1994a). Also, on several high-volume roadways, Pennsylvania found average surface friction values between 40 and 50 for microsurfaced pavements with up to 5.5 years of service (Raza 1994a). It should be noted that microsurfacing was originally developed in Europe, where it was routinely used for profile correction, rut filling, and improved surface friction on many heavily trafficked roadways (ADT between 10,000 and 40,000 vehicles per day) (Raza 1994a).

Costs

Average 1997 cost data for microsurfacing ranges from about \$1.50 to \$2.40/m^2 (\$1.25 to \$2.00/yd^2) (ODOT 1998). These costs are equivalent to \$10,800 to \$17,300 per two-lane kilometer (\$17,600-\$28,200 per two-lane mile). Typical costs for microsurfacing in Oklahoma from 1983 to 1991 ranged from \$70 to \$100 per metric ton (\$77 to \$109 per ton), with average application rates of 8 to 14 kg/m^2 (21 to 37 lb/yd^2) (Hixon and Ooten 1993). These costs are equivalent to \$4,900 to \$12,100 per two-lane kilometer (\$11,400 to \$28,400 per two-lane mile). The Foundation for Pavement Preservation reports a typical cost of \$1.50/m^2 (\$1.25/yd^2) or \$11,000 per two-lane kilometer (\$17,600 per two-lane mile).

Hot In-Place Recycling

Description and Purpose

Hot in-place recycling (HIR), sometimes called hot surface recycling, is a technique used to address surface distresses while re-using the existing material. HIR is a cost effective method for repairing distresses such as rutting, corrugations, raveling, flushing, loss of surface friction, and minor thermal cracking that are located within the upper 50 mm (2 in) of the asphalt surface (ARAA 1992, Button et al. 1994). Since HIR only addresses the surface of the pavement, the existing pavement should be free of structural distresses.

Materials and Construction

To ensure the performance of the project, the properties of the existing pavement materials should be evaluated (Kandhal and Mallick 1997). Once the material properties of the existing pavement are determined, the need for recycling agent and virgin aggregate can be determined. Most HIR projects use an asphalt emulsion or an emulsified recycling agent as an additive to the recycled mix.

HIR consists of the following steps (Button et al. 1994):

- Heat and soften the existing pavement surface.
- Scarify or mill existing surface to specified depth.
- Combine scarified material with recycling agent.
- Add, if specified or required, virgin asphalt or aggregate to the material.
- Place the material back on the pavement.

A single-pass operation where the pavement surface material is combined with virgin material or a two-pass operation in which the restored surface is recompacted before a new wearing surface is placed can be used for construction.

Three commonly used HIR techniques are heater scarification, repaving, and remixing. *Heater-scarification,* the earliest form of HIR, was widely used in the 1960s and early 1970s. This simple process involves heating the existing pavement, scarification with a set of scarifying teeth, mixing with a recycling agent, and leveling and compacting (Button et al. 1994). Scarification depths between 19 and 25 mm (0.75 to 1.0 in) are common, although depths up to 50 mm (2 in) can be achieved (Button et al. 1994). No new aggregate materials are added during the process, although a new wearing course is often placed after the heater-scarification operation. Figure 5 illustrates the basic heater-scarification process (Button et al. 1994).

In the *repaving process,* the existing pavement is heated, scarified or milled to a depth of about 19 to 25 mm (0.75 to 1.0 in), and mixed with a rejuvenating agent. This recycled material is then placed as a leveling course and followed with a hot-mix wearing surface that forms a thermal bond between the layers (ARRA 1992; Button et al. 1994). The reworking of the pavement surface material and laydown of the new wearing surface can be accomplished in a single pass using special equipment or in a two-pass operation using a heater-scarifier and conventional paving equipment (Button et al. 1994). Figure 6 illustrates the HIR repaving process.

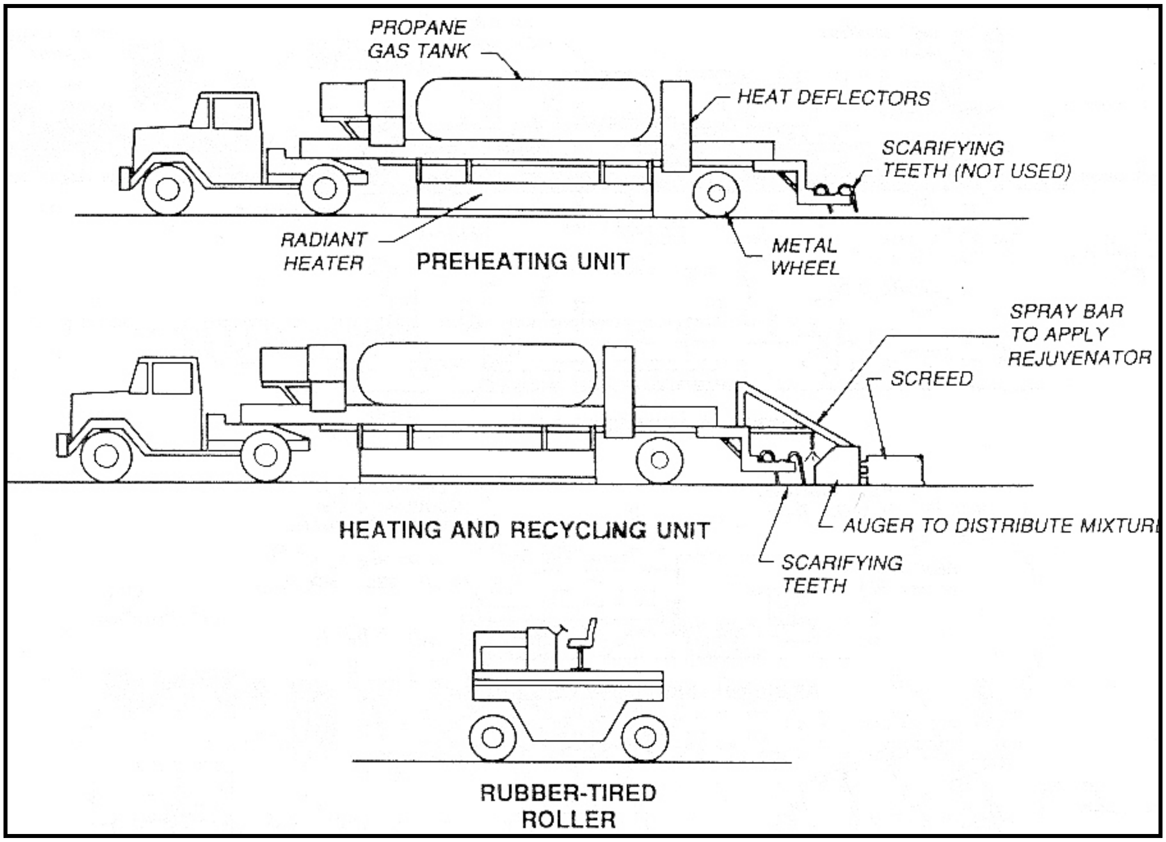

Figure 5. Heater-scarification process (Button et al. 1994).

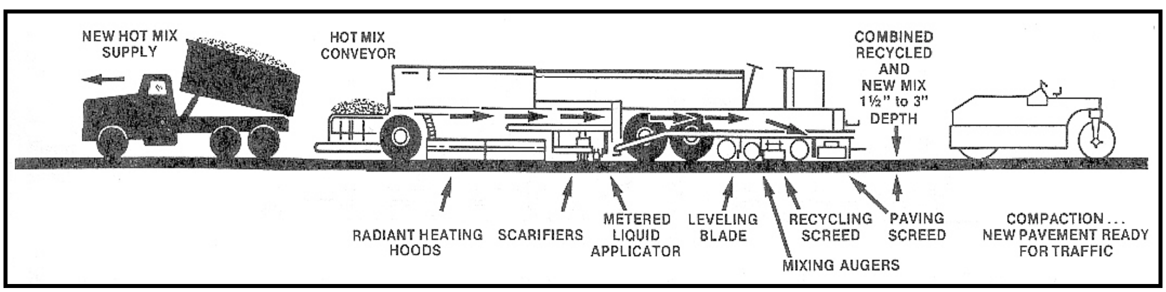

Figure 6. Single-pass repaving process (Button et al. 1994).

In the *remixing process*, the surface of the existing pavement is scarified and mixed with controlled amounts of virgin mix and rejuvenating agents in an on-board pugmill; the resultant mixture is then placed as a single, homogenous course (ARRA 1992). Thus, this approach upgrades the existing pavement by changing the aggregate gradation or adjusting the binder properties. Figure 7 is an example of a single-pass HIR remixing process.

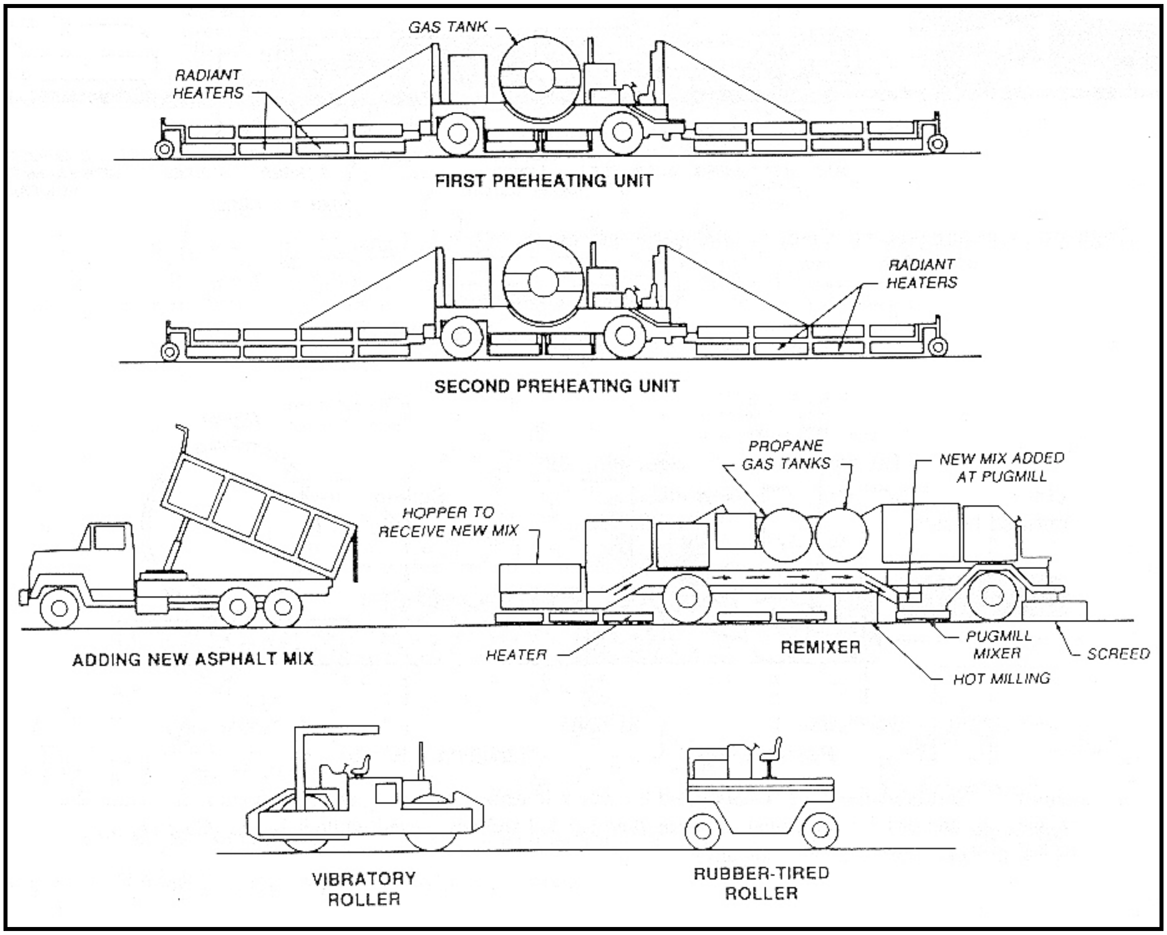

Figure 7. Single-pass remixing process (Button et al. 1994).

Performance

Like many surface treatments, HIR should be used for pavements that are in good structural condition (Kandhal and Mallick 1997). Only the top 25 to 50 mm (1 to 2 in) are reconditioned and little if any additional thickness is added to the pavement structure (Button et al. 1994). Localized areas of major deterioration (such as base failures) must be repaired before performing HIR; however, if the pavement has extensive patching or poor drainage conditions, HIR may not be a suitable maintenance activity (Button et al. 1994).

An HIR project that is well designed and constructed should be expected to perform similarly to typical HMA pavements. Greater variability can be expected within and between HIR projects since the HIR process involves more steps during the mix design process and construction (Button et al. 1994).

Heater-scarification is expected to provide 3 to 5 years of performance, although some heater-scarified pavements provide more than 10 years of service (Button et al. 1994). HIR projects that have used the repaving process reportedly have service lives of 8 to 12 years (Button et al. 1994). The continuing development and evolution of HIR makes it difficult to assess the long-term performance capabilities of the modern techniques.

Costs

Reported costs for the various HIR techniques are as follows:

- Heater-scarification to a depth of 25 mm (1 in) and addition of a recycling agent: $0.90 to 1.61/$m^2$ ($0.75 to $1.35/$yd^2$) or $6,500 to $11,600 per two-lane kilometer ($10,600 to $19,000 per two-lane mile).
- Recycling the top 25 mm (1 in) and using the repaving process: $1.50 to $2.40/$m^2$ ($1.25 to 2.00/$yd^2$) or $10,800 to $17,300 per two-lane kilometer ($17,600 to $28,200 per two-lane mile).
- Recycling the top 25 mm (1 in) using the remixing process: $2.40 to $3.90/$m^2$ ($2.00 to $3.25/$yd^2$) or 17,300 to $28,100 per two-lane kilometer ($28,200 to $45,760 per two-lane mile).

Thin Hot-Mix AC Overlay

Description and Purpose

Thin HMA overlays are plant-mixed combinations of asphalt cement and aggregate applied to the pavement in thicknesses between about 19 and 38 mm (0.75 and 1.50 in). Three different types of thin HMA overlays may be used, each differing in the gradation of the aggregate:

- Dense-graded overlays, consisting of a blend of asphalt cement and a well-graded (also called dense-graded) aggregate. A well-graded aggregate is uniformly distributed throughout the full range of sieve sizes.
- Open-graded friction courses (OGFC), consisting of a blend of asphalt cement and open-graded (also called uniformly graded) aggregate. An open-graded aggregate consists of particles of predominantly a single size.
- Stone matrix asphalt (SMA) overlays, consisting of a blend of asphalt, stabilizer material, and gap-graded aggregate. A gap-graded aggregate is similar to an open-graded material but is not quite as open. Significant coarse size fractions are present, as are the fine aggregate sizes, but there is a “gap” in the medium aggregate sizes.

Schematic representations of the gradation structure of each thin HMA overlay type are shown in figure 8.

Thin HMA overlays are placed for a variety of reasons, including restoration of pavement rideability and the improvement of pavement surface friction (Raza 1992). OGFC also offer ancillary benefits in the reduction of hydroplaning, tire splash and spray, headlight glare, and roadway noise (Smith 1992). However, no significant structural improvement is expected from thin HMA overlays, and they should not be used on deteriorated pavements.

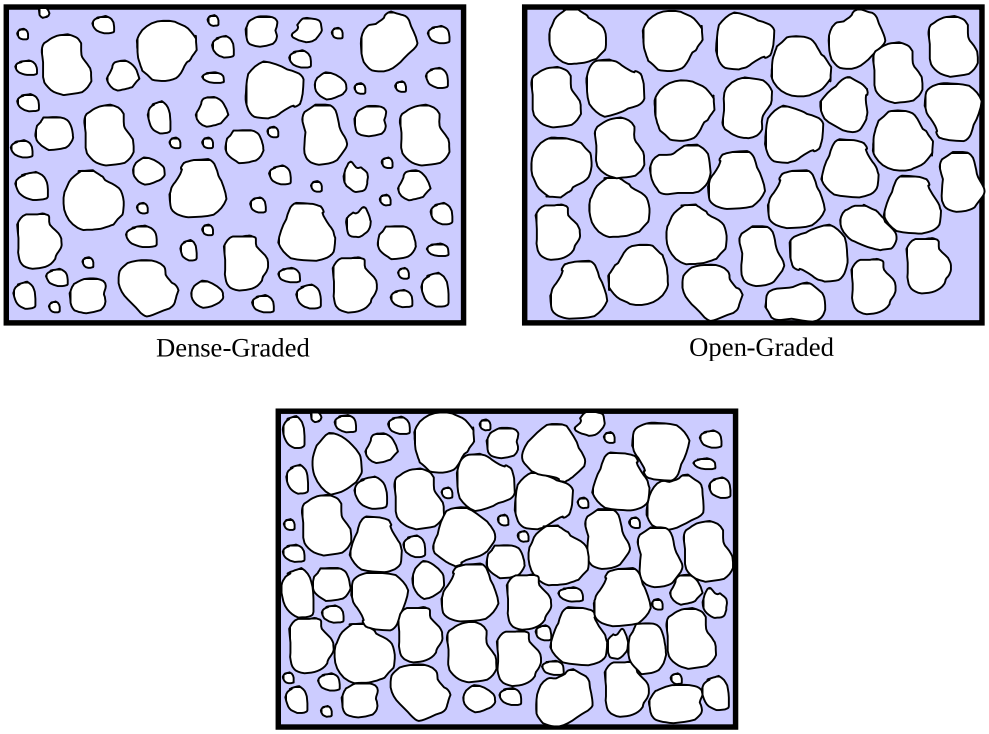

Figure 8. Schematic representations of aggregate gradation structures.

Materials and Construction

Conventional mix design procedures (Marshall, Hveem, and Superpave) are used to design dense-graded thin HMA overlays. Aggregate selection for thin HMA overlays is based upon traffic volumes, while binder selection is based on climate and traffic. Aggregates chosen for SMA and OGFC should have a maximum nominal aggregate size of one half the layer thickness to provide maximum stability (Acott 1995)

Open-graded friction courses are designed to have a high voids content (15 to 25 percent), which provides internal drainage of water. They also reduce surface spray and have good skid resistance and noise reduction properties. OGFCs are prepared in a hot-mix plant and placed using conventional paving equipment. OGFCs should be used on structurally sound pavement with adequate cross slope (Acott 1995)

Draindown of the asphalt in OGFCs is a potential problem if the mix is not designed properly. Draindown is the settling of the asphalt to the bottom of OGFC mixtures, which can lead to non-homogeneous mixtures and increased raveling. Draindown can be prevented through use of FHWA procedures or other tests to establish mix temperatures (Kandhal and Mallick 1998). Polymer-modified binders and fibers have been used to improve performance by reducing binder draindown and increasing durability of OGFCs.

Like typical dense-graded HMA mixtures, stone matrix asphalt is produced in a hot-mix plant. SMA mixtures require high-quality, crushed aggregates to provide resistance to permanent deformation and higher asphalt contents for wearing resistance and durability. Mineral fillers and stabilized additives such as fibers or polymers are needed in SMA mixtures to reduce draindown and control segregation.

Performance

Dense-graded, thin HMA overlays are a common treatment used by most highway agencies. Their performance, however, has been mixed. Some highway agencies report as little as 2 to 4 years of performance, whereas other agencies report as much as 9 to 10 years (Raza 1992). The condition of the existing pavement, the adequacy of the mix design, and the quality of the overlay construction are factors likely responsible for the wide range in reported service lives. For example, the Illinois Department of Transportation has found that its thin (25 to 38 mm [1 to 1.5 in]) overlays provide 7 to 10 years when targeted to pavements meeting specified criteria pertaining to pavement type, traffic levels, and condition (Reed 1994).

The performance of OGFC has generally been good, with estimates ranging from 8 years on high-volume roadways to 12 years on low-volume roadways (Raza 1992). For example, Florida reports OGFC service lives of 10 to 12 years on its Interstate pavements (Page 1993). Similarly, Oregon has found that, after up to 8 years of service and 2.5 million ESAL applications, OGFC are performing better than dense-graded HMA (Huddleston et al. 1993).

A study on the performance of SMA mixtures constructed in the United States yields the following results (Brown et al. 1997a):

- Over 90 percent of the SMA projects have rutting measurements less than 4 mm (0.16 in). Approximately 25 percent of the projects have no measurable rutting.
- Construction of good longitudinal joints has taken some effort. Most projects have good joints and as contractors become more experienced with construction of SMA, the quality of joints will improve.
- Cracking (thermal and reflective) has not been a significant problem. SMA mixtures appear to be more resistant to cracking than dense mixtures.
- There is no evidence of raveling on the SMA projects.
- Fat spots appear to be the biggest performance problem. These are caused by segregation, draindown, high asphalt content, or improper type or amount of stabilizer.

High Traffic Suitability

Thin HMA overlays are suitable for all traffic levels, provided that the existing pavement is structurally sound.

Costs

Material costs for dense-graded HMA are generally between $28 and $34 per metric ton ($31 and $38 per ton), compared to material costs for OGFC of $39 to $40 per metric ton ($43 to $44 per ton) (Raza 1994b). Assuming a 25 mm (1 in) thickness and HMA costs of $28 per metric ton

($31 per ton), the unit costs for an HMA overlay are about $2.00/m^2 ($1.68 /yd^2). These costs are equivalent to $11,400 per two-lane kilometer ($23,700 per two-lane mile). Unit costs for OGFC overlays are reported to be between $1.50 to $1.70/m^2 ($1.25 to $1.42/yd^2), which are equivalent to $10,800 to $12,200 per two-lane kilometer ($17,600 to $20,000 per two-lane mile) (Raza 1994b). Cost information for SMA overlays is not available, but is speculated to be 20 to 40 percent greater than for a typical dense-graded HMA (Raza 1994b).

Ultrathin Friction Course

Description and Purpose

Another emerging maintenance treatment is the ultrathin friction course. This treatment uses a single piece of equipment to place a thin, gap-graded HMA layer onto a relatively thick layer of polymer-modified asphalt emulsion tack coat (Kandhal and Lockett 1998). It is typically placed in thicknesses between 10 and 20 mm (0.40 and 0.80 in) (Estakhri and Button 1994). This treatment may be used in the following applications (Kandhal and Lockett 1998):

- As a surface seal to reduce deterioration caused by weathering, raveling, and oxidation.
- To seal narrow, non-working cracks.
- To provide a wearing surface with excellent frictional resistance.
- To restore pavement surface smoothness.

Materials and Construction

Aggregates used for this application are commonly in the size range of 6 to 10 mm (0.25 to 0.40 in). The aggregate is coated with a bituminous film that is thickened with a mortar of fine mineral materials (Serfass et al. 1991). This coating ensures that there is a strong bonding between the chips and the pavement surface, which results in the chips being held firmly in place, nearly eliminating whip-off. The coating mortar is typically 20 to 25 percent by weight of the total mix.

Application rates for the binder layer, which is usually a latex or elastomer-modified emulsion, are 0.6 to 1.2 kg/m^2 (1.1 to 2.2 lb/yd^2), which are somewhat higher application rates than for a traditional chip seal (Serfass et al. 1991).

A single-pass machine has been designed to complete all operations of constructing ultra-thin friction courses with the exception of rolling. It is comprised of the following components (Serfass et al. 1991):

- A receiving hopper for gap-graded HMA.
- A scraper type conveyor.
- A storage chamber for the chips with appropriate thermal insulation.
- Binder tanks with a capacity to hold more than half a day’s binder.
- A conveyor to transfer chips to the screed unit.
- A variable-width spray bar.
- Two spreading screws.
- A variable-width heating screed unit.

Being able to spray the binder, apply the precoated chips, and smooth the course using one machine in a quick application results in the following advantages (Serfass et al. 1991):

- Good bonding of coated chips to binder layer and to other chips.
- Clean site with no traffic on the binder layer.
- Short construction time, which decreases inconvenience to the traveling public.

Performance

Although long-term performance data are limited, preliminary performance evaluations of this treatment are promising (Kandhal and Lockett 1998). Skid resistance numbers were found to be around 60 one year after placement of an ultrathin friction course (Keiter 1993) and around 45 and remained nearly constant for 2 years after placement for two projects in Texas (Estakhri and Button 1995).

Scrub Seal

Scrub seals are a surface restoration treatment intended to rejuvenate the asphalt surface and to fill voids and surface cracks (Missouri DOT 1998). Scrub seals have actually been used since the 1950s in California and Arizona, and are just now receiving interest in other states. Scrub seals consist of the application of a polymer-modified asphalt agent to the pavement surface followed by the broom-scrubbing of asphalt into cracks and voids, the application of an even coat of sand or small aggregate, and a second brooming of the aggregate and asphalt mixture (Missouri DOT 1998). The seal is then rolled with a pneumatic tire roller. Scrub seals are showing good performance on lower volume roadways (ADT less than 7,500 vehicles per day) (Missouri DOT 1998).

Selection of Surface Treatments

The selection of an appropriate preventive maintenance surface treatment can be a very difficult task. Each treatment offers its own advantages and disadvantages, and each also has its own “niche” in which it performs the best. A variety of factors can ultimately affect how well a treatment performs, including the following:

- Existing pavement condition (including types and severities of distress).
- Surface preparation.
- Current and anticipated traffic levels (including truck traffic).
- Drainage conditions.
- Location of roadway (rural vs. urban setting).
- Prevailing climatic conditions (temperature, precipitation).
- Climatic conditions at time of placement.
- Available materials.
- Adequacy of mix design.
- Quality of construction.

A good deal of information on how these different factors affect the performance of a surface treatment is available in the literature. Some attempts have been made by a few highway agencies to assemble that information into useful guidelines or decision trees. For example, Washington State has produced some simple guidelines on when to apply certain asphalt maintenance and rehabilitation treatments (WSDOT 1995). The Ohio Department of Transportation has also developed a draft document providing guidelines for the use and application of preventive maintenance techniques (ODOT 1999). As another example, a process for selecting the most cost-effective preventive maintenance techniques using weighting factors for ten variables was presented at the 1999 Annual Meeting of the Transportation Research Board (Hicks et al. 2000). Unfortunately, documents such as these have not been widely disseminated among the pavement community.

It should be noted that one additional problem hampering the development of guidelines on the use of preventive maintenance treatments is recognizing those "early indicators" in an existing pavement that suggest it is ready for the application of a maintenance treatment. Current practice is to identify critical distresses that have developed, but by the time many of these distresses occur it is too late to apply a maintenance treatment. Greater attention must be paid to other factors (such as surface raveling, oxidation, or any other type of early indicator) that can be used to trigger the application of a maintenance treatment.

Summary

Information on the concept of preventive maintenance, descriptions of preventive maintenance surface treatments, and information on the selection of preventive maintenance treatments are provided in this literature review. A description of each surface treatment is provided as well as the purpose of each treatment and recommended applications. A brief discussion of materials and construction processes are included, followed by a summary of the performance and possible suitability for high traffic volumes. Typical costs, where available, are also provided for each surface treatment.

This state of the practice summary is intended to provide an overview of each surface treatment and provide a general understanding of their application, capabilities, and performance. It is not intended to cover all of the critical design and construction aspects of each technique; resource documents are cited in the discussion of each of the treatment options that contain more detailed information.

3.0 Summary of South Dakota Practices

Introduction

This chapter summarizes the results of the interviews conducted with South Dakota personnel and others associated with the chip seal process. In all, interviews were held with 24 staff members from various regions within South Dakota, representing personnel involved in design, maintenance, construction, research, and pavement management. In addition, the interviews included one industry representative, one Federal Highway Administration representative, and two contractors. Interviews were also conducted with personnel from Montana, Washington, Minnesota, and Texas.

Treatment Selection Process

South Dakota does not have any formal guidelines for selecting the most appropriate treatment for a given pavement section. Surface treatments other than chip seals or sand seals have not been used except occasionally on an experimental basis. Thus, surface treatment selection generally is a choice between whether to place a chip seal or an AC overlay. This selection process is described further in the subsequent section on project selection for chip seals.

Chip Seal Practices

Project Selection

Each year, SDDOT's Planning and Programs office produces a map of pavements that are eligible for a chip seal. Chip seal-eligible pavements are defined as pavements that have been surfaced 3 or more years and have not yet received a chip seal. Typical cycles for application of chip seals and overlays are built into the pavement management system (PMS). However, although the PMS does incorporate several requirements for triggering treatments, these do not impact when the treatments are actually applied.

The Area Engineer and Maintenance Supervisors are responsible for triggering the treatments. Together they conduct a windshield survey of the eligible pavements, looking for the presence of distresses that would trigger the need for a chip seal. Such distresses include cracking, oxidation, and raveling, but the decision is based on the overall condition of the roadway. If the pavement already has a chip seal, the loss of chips is also examined. A bituminous inspection team follows with a more detailed condition survey.

The inspections are typically conducted during the spring to identify the pavements to chip seal during the following summer, which leaves a 12-month to 18-month lag between the decision to chip seal and the placement of the chip seal. Occasionally, the pavement deteriorates over that time. In such cases, the problems are typically corrected prior to placing the chip seal. On one project, a decision was made to conduct extensive patching and then chip seal the following year. Nonetheless, there are times, albeit limited, in which chip seals are placed on pavements that are considered too deteriorated.

A chip seal is only recommended if at least 4 years of life can be expected before an overlay is needed. A 3-year maintenance and rehabilitation program is developed so a chip seal will not be placed if the pavement is scheduled for an overlay within those 3 years. If there is too much damage on the roadway, a mill and overlay will be placed instead of a chip seal.

Timing

For the most part, the timing of preventive maintenance activities follows a standard sequence following construction of a new AC pavement or an AC overlay. The typical sequence is to crack seal during the second year and chip seal during the third year. This sequence varies slightly from time to time and within some regions but changes are only minor. Some regions indicate that the timing is based more on a visual inspection of the roadways, looking mainly at raveling and stripping. Loss of skid resistance is also considered. Although the timing may vary slightly, a chip seal is almost always placed between 3 and 5 years after placing the AC surface.

The timing of the second application of chip seal shows greater variance. Chip seals are expected to provide at least 5 years of service, so the pavements are not re-evaluated until that time. The selection process follows the same process as discussed for the initial application. The second application chip seal is usually placed 6 to 8 years after the first application. Occasionally, a third chip seal is applied. However, there have not been many third applications because by that time the pavement is usually a candidate for a mill and overlay.

AC overlays are expected to provide a design life of at least 15 years and typically last between 15 and 20 years. A third chip seal application may be necessary to obtain a design life of 20 years. In order to reach these expected design lives, the chip seals must not be placed much earlier than triggered under the standard program. The program is adhered to unless the pavement is too badly deteriorated for a chip seal. This is usually not a problem until the third application of chip seal. The most common conditions that would trigger an earlier chip seal include oxidation or loss of aggregate. Pavements have been sealed earlier where friction was a problem and the pavement was expected to become too slick through the winter. Chip seals have also been placed where the pavement surface is exhibiting raveling or oxidation.

Materials

Aggregates (Chips)

Three aggregate types—quartzite, limestone, and natural aggregates—are most commonly used throughout the state. For the most part, the aggregate type used is based on availability of aggregates in the area. Quartzite is more common in the eastern part of the state, whereas limestone is more common in the western part of the state. Natural aggregates are found in the central as well as the northeast portion of the state (when natural aggregates are used, the surface treatment is referred to as a sand seal). Occasionally, other aggregate types are used; one interviewee indicated the use of a river run gravel and another the use of granite.

The selection of aggregate type is typically based on availability. However, the aggregate type that is most common to the area is not always used. For example, the Pierre Region typically uses a natural aggregate (sand seal) because the nearest quarry is about 240 km (150 mi) away. However, for applications on high-volume roadways or in urban areas, they use crushed aggregate or quartzite chips. Personnel from the Sioux Falls Area (Mitchell Region) indicate that they allow contractors to submit bids with either quartzite or natural aggregates. In the past, the costs have typically favored quartzite, but the costs have worked out in favor of the natural aggregates in 1999.

There have been concerns with quartzite as an aggregate. It is not very absorbent, which limits adhesion between the aggregate and the emulsion. In addition, quartzite is a very hard aggregate so any loose chips are likely to cause more damage to vehicles. The performance has thus been of concern. In a recent chip seal failure on I-29, quartzite aggregate was used, although it may not have contributed to the failure. Minnesota commonly uses quartzite aggregate and it seems to perform well. One advantage of the quartzite is that it is easier to control the gradation.

The limestone aggregates have seemed to perform well. The biggest problem with limestone is controlling the dust. The limestone aggregate needs to be clean, with a limited amount of fines. The abrasive action from handling and transporting of limestone will create more fines.

Natural aggregates are abundant throughout the state and are fairly inexpensive because they are a byproduct. When natural aggregates are used, the treatment is referred to as a sand seal. The natural aggregates are more rounded and softer, which results in less damage to vehicles. They also provide an aesthetically pleasing surface. For the most part, chip seal performance with natural aggregates has been good, although there have been a few failures.

Regardless of the type of aggregate, the maximum chip size is 9.5 mm (3/8 in). A larger, 12.7-mm (1/2 in) aggregate was previously used. Although it performed well overall, a lot more damage resulted when failures did occur. There is some sentiment that a larger chip should be used to provide better retention. However, the advantages of using a larger chip do not appear to outweigh the increased damage to vehicles. Nearly every state that has used a 12.7-mm (1/2-in) chip has now switched to a 9.5-mm (3/8-in) chip to reduce vehicle damage and to provide a smoother riding surface.

Another concern is the gradation of the aggregate chips. The current aggregate bands are too wide, which allows too much variation of chips meeting the same gradation specification. Several comments were made regarding the use of a tighter gradation and the use of a more single-sized chip. A more uniformly graded aggregate is recommended for chip seals to provide a more consistent layer thickness. A comparison of the gradations to those used in Montana is provided in table 4. Montana uses a much tighter gradation as well as a higher percentage of chips between the 9.5- and 4.75-mm (3/8-in and No. 4) sieves.

The reason that gradation is so important is that smaller aggregate particles can completely embed in the emulsion, and then larger aggregate particles are unable to achieve sufficient embedment on top of the smaller particles. This issue is thought to be at least partly responsible for the I-29 failure. The same result can occur if flat or elongated particles are used. ASTM D 4791 provides a test method for determining the amount of flat and elongated particles. Minnesota uses the flakiness to measure the amount of flat particles (Janisch and Gaillard 1998).

It is recommended that a tighter gradation be developed and that testing be conducted to limit the amount of flat and elongated particles.

Table 4. Comparison of aggregate gradations for chip seals.

Sieve	South Dakota Type IA	South Dakota Type 1B	South Dakota Type 2A	Montana Grade 4A	Montana Grade 5A
12.7 mm (1/2 in)	100	100	100	100	100
9.5 mm (3/8 in)	40 – 70	100	100	100	100
4.75 mm (No. 4)	0 – 15	10 – 90	0 – 70	0 – 30	9 – 50
2.36 mm (No. 8)	0 – 5	0 – 30	0 – 28	0 – 15	2 – 20
0.424 mm (No.40)		0 – 4	0 – 4		
0.075 mm (No. 200)	0 – 1			0 – 2	2 – 5

Emulsions

The type of emulsion that is used is primarily a function of the aggregate type. With limestone and natural aggregates, an AE-150S emulsion is typically used. Sometimes an AE-200S emulsion is used, generally in conjunction with coarser aggregates. With quartzite aggregates, a CRS-2 emulsion is used. Bleeding has not been a problem with either emulsion.

Polymer-modified emulsions have been used on a few projects. The project on I-29 that resulted in windshield damage used a polymer-modified emulsion, although its use did not appear to contribute to the failure. Rather, the problem was due to loose chips and windshield damage after construction and not any failure of the chip seal itself. Other studies and experience from other states have noted better performance with polymer-modified emulsions, especially on high-volume roadways. Polymer modification is recommended on roadways where brooming, adhesion, and chip retention are concerns. High float emulsions have also been used; they are recommended in cases where the aggregate is dusty or dust is thought to be problematic.

Design and Testing

Standard Design

The designs appear to have been adjusted over time and are now at the point where the same design is used on all projects in a particular area. The application rates for asphalt emulsion typically range from 1.18 to 1.27 L/m^2 (0.26 to 0.28 gal/yd^2). For the aggregate chips, the application rate generally varies from 13 to 15 kg/m^2 (24 to 28 lb/yd^2). The design application rates may vary slightly based on the aggregate type or source. Further adjustments to the application rates are also made in the field as needed. The concept is to try to maximize the emulsion application rate without getting bleeding. The same designs are used for both low-volume and high-volume roads.

Based on comments from SDDOT personnel and a comparison with other states' practices, the emulsion application rates appear to be low and the chip application rates appear to be high.

Montana uses application rates of 1.45 to 1.72 L/m^2 (0.32 to 0.38 gal/yd^2) and the chips are spread at a rate of 11.9 to 12.5 kg/m2 (22 to 23 lb/yd^2) (MDT 1996). Several SDDOT personnel commented that they are not using enough emulsion, which has been the cause of some of the chip seal failures.

Some failures have been due to problems in design; there is currently no design procedure or engineering justification for emulsion and chip application rates. The rates have been modified over the years through field experience and trial and error. In addition, there have been problems with incompatibilities between the aggregate and the emulsion. Minnesota conducts numerous tests on project-specific materials and uses the results in a modified McLeod design procedure (Janisch and Gaillard 1998). Tests are conducted to determine the gradation, bulk specific gravity, absorption, flakiness index, loose unit weight, and voids in the loose aggregate. The design procedure further considers the traffic volume and pavement condition to determine the required application rates. A similar design procedure using project-specific materials is recommended for South Dakota.

Modifications

Few modifications are ever made to the standard design. Different aggregate types are used throughout the state, so the binder requirements may change slightly; for example, the limestone aggregates require a little more emulsion. The emulsion application rate is adjusted in the field and is a function of the pavement condition and aggregate type and properties. For example, rounded aggregates and aggregates with fewer fines require less emulsion.

Another modification to the standard chip seal is the application of a flush seal or fog seal placed on the chip seal to help with chip retention. This additional application is typically used on chip seals in which early problems with chip retention are observed.

Material Sampling and Testing

Both the aggregate and emulsion are sampled prior to use and during construction and are sent to the central laboratory for testing. In the field, samples are taken for every 450 metric tons (500 tons) of material. If the requirements are not met in the field, the most likely option is to apply a deduct factor to the payment; another option is to stop construction until the situation is rectified. Tests on the aggregate chips include gradation, hardness, plasticity, soundness, and crushed particles. Stripping tests are no longer performed.

No project-specific testing or design is conducted to determine the compatibility between the aggregate and emulsion and the required application rates. Several interviewees noted that problems have been caused by such incompatibilities. Montana conducts an adhesion test, in which the aggregate is coated with emulsion and shaken in water (MDT 1996). The aggregate is required to have an asphalt adhesion of greater than 70 percent. Minnesota conducts numerous tests on project-specific materials and uses the results in a modified McLeod design procedure (Janisch and Gaillard 1998). Tests are conducted to determine the gradation, bulk specific gravity, absorption, flakiness index, loose unit weight, and voids in the loose aggregate. A similar testing program using project-specific materials is recommended for South Dakota.

Construction

Preparation

Crack sealing is conducted the year before placing the chip seal. There is generally no additional crack sealing immediately prior to placing the chip seal. If the condition dictates, badly deteriorated areas such as potholes and localized failures are also patched. Otherwise, the only preparation is to sweep the surface using a rotary power broom. The specification indicates that the surface is to be clean of all foreign material. The sweeping operation usually runs about 1.6 km (1.0 mi) ahead of the seal coat application.

The general consensus is that the pre-treatment preparations are adequate. Chip seal failures are not believed to be a result of improper sweeping or placement on pavements that are not candidates for a chip seal.

Calibration of Equipment

The distributor and spreader are calibrated before almost every job. Neither the equipment nor achievement of the specified application rates is believed to be a problem. The application rates are also monitored throughout the day.

Application

In the past, application of the chips was delayed until the emulsion began to break. Now the objective is to try to get the aggregate spreader as close to the emulsion applicator as possible. This practice has resulted in better performance of the chip seals. Several people indicate that there is a need to pay closer attention to keeping the emulsion applicator and chip spreader closer together.

To limit the amount of excess chips, the preference is to run the chips at the design level and adjust the oil to meet the chips. At least one person is convinced that some failures have been due to insufficient binder. Insufficient binder results in less embedment of the aggregate chips and thus less adhesion to keep the chips in place.

Rolling Patterns

The rolling specification requires four complete passes using pneumatic tired rollers. Rolling should begin immediately behind the spreader and keep within 0.8 km (0.5 mi) of the asphalt and cover aggregate applications. Rolling should be completed within 40 minutes. Four rollers are required on the project and the speed of the rollers is not to exceed 8 km/hr (5 mi/hr).

The consensus is that the rolling specification is adequate but is not always observed. One interviewee indicated that the rolling is “mediocre at best.” Another recognizes the importance of proper rolling but emphasizes the fact that there is no means of measuring its significance (i.e., what is the effect of doing it wrong?). Enforcement of the specification needs to be emphasized. Improper rolling can lead to loss of chips up to a week or even a month later.

The biggest problem appears to be the speed of the rollers. The specification requires that the speed of the rollers not exceed 8 km/hr (5 mi/hr). However, in order to keep up with the distributor, they are operating at about 16 to 19 km/hr (10 to 12 mi/hr). Some of the big chip seal operations are running at about 1.6 to 2.4 km/hr (1.0 to 1.5 mi/hr). They are paving up to 16 to 24 km (10 or 15 mi) each day. The number of rollers as specified can not keep up with this pace. More rollers or slower production speeds are needed on some projects.

In some cases, the aggregate spreader gets too far behind the distributor. The specification only stipulates that the roller should be kept close. There needs to be better guidance for the roller. Others indicated that on some projects they are not getting either four rollers or four passes.

Final Brooming

The specification requires that "loose material left on the surface shall be lightly broomed off during the cool period of early morning after a waiting period of 24 hours from the time of application." On two-lane roadways, the roadway is opened that evening and swept the following morning. On four-lane roadways, the roadway is swept the next morning and then opened to traffic. In some instances, the pavement is swept again a day or two later.

Windshield and other vehicular damages are for the most part limited to the construction period and the first few days following construction. One interviewee indicates that there are few if any complaints after the final brooming is complete, emphasizing the importance of more timely brooming.

Acceptance Criteria

There are currently no testing or acceptance criteria for chip seals in South Dakota. Montana requires several criteria be met. First, a sweeping test is performed in the field. For this test, the amount of excess chips is swept up and weighed. The amount of excess chips must be less than 10 percent of the application rate. Montana also performs an embedment check in the field. About 6 to 8 chips are popped off with a knife and the percentage of embedment of the average chip is estimated. It is a subjective measurement but nonetheless provides a valuable piece of information. These simple tests are recommended in South Dakota.

Traffic Control

Traffic control is accomplished using pilot vehicles and flaggers during application of the chip seal. In this process, traffic is stopped at both ends of the project. The pilot vehicle leads the traffic on the adjacent lane at speeds of 48 km/hr (30 mi/hr). The pilot vehicle then turns around and leads traffic back in the other direction on the adjacent lane. This system is sufficient for 3 to 5 km (2 or 3 mi), where traffic only has to wait about 5 minutes. However, the contractors are often placing up to 24 km (15 mi) per day and it is impractical to back traffic up while the pilot vehicle drives through the entire project. Traffic could be waiting for 20 minutes or longer, which is unacceptable to motorists.

On the chip seal itself, the specification requires that "the speed of pilot vehicles should not exceed 32 km/hr (20 mi/hr) on the freshly applied surface treatment for a period of at least four hours after application." Construction personnel indicate that they are lucky if traffic speeds can be controlled for 2 hours on the fresh chips. Again, it is a matter of convenience to the motorists. If the 4-hour limitation is enforced, the pilot vehicle will have to travel over 9.7 km (6 mi), which means motorists are waiting 15 to 20 minutes. Therefore, the beginning of the chip seal project is opened to traffic after several hours, and traffic speeds are not controlled.

There are no easy solutions to this problem. One possible solution is to limit the length of chip seal that can be placed in one day or the speed of the operation. However, this option will result in greater construction times and higher costs. For example, a 24-km (15-mi) long section that could be placed in one day will take 3 days if the project length is limited to 8 km (5 mi). This commitment will not come without an extra cost from the contractor.

Other precautions are also taken to control traffic during construction. Flaggers at each end of the project provide motorists with flyers indicating that there are loose chips on the roadway and the motorists should take an alternate route or proceed with caution. The flyers also include the name of the contractor so they can be contacted to report damage claims. The flyers should be distributed during daylight hours until the chips have been swept, but indications are that this is not always done. Signs are also posted on the project indicating that there is loose rock and speeds should be limited to 64 km/hr (40 mi/hr). These signs are posted until final sweeping is performed, usually 1 to 2 days following construction.

Opening to Traffic

As mentioned, the specification requires that traffic should not exceed 32 km/hr (20 mi/hr) on freshly applied chip seals for at least 4 hours after application. Otherwise, there are no criteria for opening to traffic. On two-lane roadways, the roadway is typically opened that evening and swept the next morning. On four-lane roadways, the roadway is swept the next morning and then opened to traffic.

Performance

The performance results are mixed. Several people do not feel that there are any problems with chip seals. Meanwhile, others certainly feel that there are problems and that modifications definitely need to be made. Overall, the performance of the chip seals has been reasonably good, but a few failures have overshadowed the many good performances. Regardless, failures have occurred and changes need to be incorporated to prevent more failures in the future.

One issue is the measure of performance. For example, performance can be measured in terms of the performance of the chip seal itself. Such measures include the condition of the chip seal and retention of chips over its service life. Performance can also be measured in terms of the number of complaints or damages that are reported. This seems to be the more common means of determining success or failure of the chip seal in South Dakota.

The most notable failure, and the impetus for this research study, is the project on I-29 near Brookings. There were over 800 claims for damaged windshields totaling more than $200,000. The project involved a polymer-modified emulsion (CRS-2P) and a quartzite chip. The cause of the problem has not been exactly identified. Several people thought that the failure was due to smaller chips and flat and elongated chips preventing the larger chips from fully embedding in the emulsion. Others noted that most of the problems occur with quartzite chips. They also received several large rainstorms after the chip seal was placed. A fog seal was later placed on the chip seal, which seemed to reduce the problem. A year later, the chip seal apparently looks good and is performing well.

As mentioned, some people feel there are more problems with quartzite. However, others indicate the same number or more problems with other aggregate types. Some regions will only use quartzite on high-volume or urban roadways, while others indicate that there are more problems on two-lane roadways because traffic is travelling in opposite directions.

The major problem is loose stones causing damage to vehicles. However, there is no consensus as to the cause of the problem. The following reasons are cited for one or more failures resulting from loose chips:

- Smaller chips preventing embedment of the larger chips.
- Flat and elongated particles preventing embedment of chips.
- Not enough binder to achieve proper embedment.
- Excess chips after rolling.
- The aggregate contains too many fines or is too dirty.
- The aggregate is either too wet or not wet enough.
- The application rates are not designed for the specific project.
- The chips are placed too far behind the spreader.
- Insufficient number of roller passes.
- Rolling in excess of the 8 km/hr (5 mi/hr) speed restriction.
- Poor conditions during placement (e.g., low temperatures, high humidity, and cloud cover).
- Poor conditions following placement (usually a hard rain within a few days).
- Placement too late in the season.

Excess dust was also noted to be a problem, especially with the limestone aggregate. Neither bleeding nor noise problems have been much of an issue.

Seasonal and Climatic Restrictions

The construction of surface treatments is restricted to the period from June 1 to September 15. The specification further includes a minimum temperature limitation of 21 °C (70 °F) and indicates that "surface treatment operations will be permitted only during daylight hours, when conditions are dry and when wind does not adversely affect the spraying operation."

There is concern about some of the late season work. Several people indicated that chip seal placement conducted in late August or early September is suspect. The specification only requires a minimum temperature at placement, but the temperature needs to be sustained over a period of at least a few weeks to allow traffic to further embed and reorient the chips. There is no way to specify the temperature following chip seal placement so the only way to address this concern is to limit the construction season. Therefore, consideration should be given to limiting the construction season to June 1 through August 31, at least in certain regions.

There are also concerns about the ambient conditions at the time of placement. The specification allows placement at 21 °C (70 °F) with high humidity and cloud cover. The specification should control conditions for emulsions so that they are able to break. The emulsions may not be able to break under low temperatures, heavy cloud cover, or high humidity levels.

Costs

Costs reported for chip seals varied from $4,000 to $6,200 per two-lane kilometer ($6,500 to $10,000 per two-lane mile). The average cost is about $5,000 per two-lane kilometer ($8,000 per two-lane mile).

Other Surface Treatments

Fog Seals

Fogs seals have been used sparingly in South Dakota. They are primarily used in conjunction with a chip seal or sand seal to improve retention and limit the amount of loose chips. They have been used immediately following chip seal placement and, as in the case with the I-29 failure, on roadways in which loose chips became problematic. Fog seals have worked well for this purpose and should be a consideration for low- to medium-volume roadways.

Flush Seals

Flush seals are sometimes placed immediately following placement of an AC overlay. Their primary purpose is to seal and enrich the pavement surface and to prevent oxidation and infiltration. In some opinions, a flush seal simply "takes a new roadway and makes it look old." Flush seals have also been used to improve skid resistance and extend the life until an AC overlay is placed, where a chip seal would not be practical at that time.

Slurry Seals

Slurry seals have not been used in South Dakota. Furthermore, this operation requires specialized equipment, which may prohibit its consideration for future use.

Microsurfacing

Microsurfacing has been used sparingly in South Dakota. Its primary purpose has been to fill ruts in the wheelpaths. On a recent project on I-29, rutting was approximately 50 mm (2 in) before construction. After microsurfacing, rutting levels were approximately 9.5 mm (3/8 in). As with slurry seals, this operation requires specialized equipment.

Thin AC Overlays

Thin AC overlays, including open-graded friction courses, have been used in South Dakota, mostly in urban areas. The performance has been good, providing up to 10 years of service, nearly double the life expected from a chip seal. However, the costs are in the range of $15,500 to $18,600 per two-lane kilometer ($25,000 to $30,000 per two-lane mile), over three times the cost of a chip seal.

Ultrathin Friction Courses

Ultrathin friction courses use specially designed equipment to apply a thin, gap-graded HMA layer onto a relatively thick layer of polymer-modified asphalt emulsion tack coat. A few ultrathin friction courses with the brand name NOVACHIP® have been placed in South Dakota, some as research studies and some as competitive bid projects. Preliminary results from the most recent projects have been positive. The major concern with ultrathin friction courses is that they are typically proprietary products and may also require special equipment. Their initial cost is also significantly higher than more conventional, non-proprietary products. For example, the cost of a NOVACHIP® project on I-90 near Murdo [IM90-4(00)198] was $34,200 per two-lane kilometer ($55,000 per two-lane mile).

Summary

This chapter summarizes the surface treatment practices in South Dakota. The information was obtained from interviews with South Dakota DOT personnel and others involved in the surface treatment process. Throughout this chapter, suggestions for improvement of the chip seal process are provided. These considerations are summarized in table 5. It should be noted that these are not the final recommendations but rather considerations for improving the performance of chip seals. These considerations have been integrated into the construction of the test section and in the development of the guidelines.

Table 5. Considerations for improving the performance of chip seals (based on interviews).

Category	Considerations for Improvement
Design	• Develop a design procedure to determine application rates for each specific project • Use a higher emulsion application rate to achieve greater aggregate embedment
Materials	• Develop a tighter and more gap-graded gradation to ensure uniformity and provide a single layer of chips • Limit the amount of fines (material passing the 0.075-mm [No. 200] sieve) in the chips • Conduct testing to limit the amount of flat and elongated particles (ASTM D 4791 or flakiness index) • Conduct testing to determine the adhesion between the aggregate chips and the emulsion
Construction	• Sweep the pavement surface approximately 2 hours following placement (before opening to traffic) • Run the pilot vehicle on the chip seal to help with chip embedment and orientation • Enforce the speed restriction on the rollers and/or provide more rollers on the project • Limit the amount of paving per day or limit the speed of the operation to meet rolling requirements • Wet the aggregate stockpile the morning of construction and rewet in the field as needed • Prevent late season paving by changing seasonal restriction to June 1 through August 31
Field Testing	• Conduct an embedment check to ensure adequate embedment of the aggregate • Conduct a sweeping test to limit the amount of excess aggregate to between 5 and 10 percent of the total
Traffic Control	• Limit the amount of paving that can be conducted each day
Modifications	• Use a polymer-modified emulsion to obtain better adhesion, especially on high-volume roadways • Apply a fog seal or a flush seal over the chip seal to help with retention • Apply a choke stone layer of small chips over the chip seal to lock in the larger aggregate particles • Precoat the aggregate chips to reduce dust and improve adhesion
Training	• Develop a Surface Treatment Manual for design and construction personnel • Conduct training for staff and contractors

4.0 Design and Monitoring of Test Sections

Introduction

To investigate the performance of various chip seal features, twelve test sections were constructed on State Route 50, approximately between milepost 396 and 406 in the westbound outer traffic lane. The test sections include two aggregate types (quartzite and natural aggregate), standard and modified aggregate gradations and emulsion rates, and other design modifications and enhancements to address potential problems encountered with chip seals on past projects. The test sections were constructed in June 2000; the original pavement was evaluated immediately prior to construction and performance evaluations were performed immediately after construction and again 3 months later. This chapter describes the development, construction, and monitoring of the field test sections.

Development of Field Testing Plan

The objective of the field testing plan was to evaluate the performance of various surface treatments under high-volume, high-speed applications to provide insight regarding their performance and to develop recommendations for the future use of surface treatments in South Dakota. Initially, the test sections were designed to investigate all feasible surface treatments, including microsurfacing, ultrathin friction courses, open-graded friction courses, and thin, dense-graded HMA overlays. However, the Technical Panel ultimately decided to limit the study to an evaluation of various chip seal designs only. Additionally, the test sections were to include the use of the three aggregate types—quartzite, limestone, and natural aggregates—commonly used in South Dakota. However, limestone, which is common in western South Dakota, was eliminated from the study due to the inability to locate a suitable candidate in that part of the State at the time of the project.

A suitable candidate for inclusion in the study was found on State Route 50 between Vermillion and Yankton. The project, which is approximately 15.8 km (9.8 mi) long, extends from milepoint 396.04 + 0.549 to milepoint 406.17 + 0.200 in the westbound outer traffic lane. This highway has an average daily traffic (ADT) of approximately 2125 vehicles per day and an average daily truck traffic (ADTT) of 355 vehicles per day (approximately 16.7 percent trucks).

Layout of Test Sections

Twelve test sections were constructed under this project, as presented in table 6. The test site includes six treatments which use quartzite aggregate and six sections with natural aggregate. A control section, consisting of the standard design and construction practices being used in South Dakota, is included for each aggregate type. The control section provides a basis from which to evaluate the remaining test sections. For each aggregate type, several variations in the chip seal design are also included. These design variations, such as the use of a polymer-modified emulsion or precoated aggregate, were identified from previous studies and experience from other states as a means to improve the performance of chip seals on higher volume roadways. These designs also incorporate other recommendations identified to improve performance, such as a different aggregate gradation and modified application rates.

Table 6. Layout of test sections on State Route 50.

Test Section	Application	Variation	Aggr. Type	Length, ft
1	New Chip Seal Design	Polymer-Modified Emulsion	Quartzite	4,000
2	New Chip Seal Design	None	Quartzite	4,000
3	New Chip Seal Design	Fog Seal	Quartzite	4,000
4	New Chip Seal Design	Choke Stone	Quartzite	4,000
5	New Chip Seal Design	Precoated Aggregate	Quartzite	4,000
6	SDDOT Standard Design*	None	Quartzite	6,000
7	SDDOT Standard Design*	None	Natural	5775.68
8	New Chip Seal Design	None	Natural	4,000
9	New Chip Seal Design	Fog Seal	Natural	4,000
10	New Chip Seal Design	Choke Stone	Natural	4,000
11	New Chip Seal Design	Precoated Aggregate	Natural	4,000
12	New Chip Seal Design	Polymer-Modified Emulsion	Natural	4,000

* These sections extend through the reduced speed zone in Meckling; the portion within the reduced speed zone is not included in the study.

Each section has a minimum length of 1220 m (4000 ft). Within each section, a 305-m (1000-ft) long monitoring section is identified as the pavement area studied in detail under this project. In general, the monitoring section is located at least 610 m (2000 ft) from the beginning of the test section to allow application rates to be adjusted before entering the monitoring section. The limits of the entire section and of the monitoring section are identified in table 7.

Table 7. Location of test sections on State Route 50.

Test Section	Length, ft	Entire Section (Station to Station)	Monitoring Section (Station to Station)
1	4,000	0+00 to 40+00*	20+00 to 30+00
2	4,000	40+00* to 80+00	60+00 to 70+00
3	4,000	80+00 to 120+00	100+00 to 110+00
4	4,000	120+00 to 160+00	140+00 to 150+00
5	4,000	160+00 to 200+00#	180+00 to 190+00
6	6,000	200+00# to 260+00	220+00 to 230+00
7	5775.68	260+00 to 317+75.68	290+00 to 300+00
8	4,000	317+75.68 to 357+75.68	340+00 to 350+00
9	4,000	357+75.68 to 397+75.68	380+00 to 390+00
10	4,000	397+75.68 to 437+75.68	420+00 to 430+00
11	4,000	437+75.68 to 477+75.68	460+00 to 470+00
12	4,000	477+75.68 to 517+75.68	490+00 to 500+00

Note: Stationing begins at the west end of the project and proceeds eastward.
* Station adjusted to 38+70 during construction.
# Station adjusted to 219+50 during construction.

Design of Test Sections

Aggregate Gradations

The SDDOT standard designs (test sections 6 and 7) employ the aggregate gradations typically used by the state for chip seals. These gradations are shown in table 8. The remaining test sections use the gradations presented in table 9, which are the standard gradation currently used by the Minnesota DOT (Janisch and Gaillard 1998). There are several noticeable differences between the gradations. For example, the modified gradation has much tighter limits on each sieve, which provide a more uniform product. The modified gradation is also a more gap-graded gradation, which ensures more particles of a common size to provide a uniform layer thickness. The modified gradation also includes a limit on the percent passing the 0.075 mm (No. 200) sieve, which could otherwise create a dust problem and affect the required emulsion rates.

Table 8. Aggregate gradations for SDDOT standard designs.

Sieve Size	**Percent Passing**	
	Type 1B	**Type 2A**
9.52 mm (3/8 in)	100	100
4.75 mm (No. 4)	10 – 90	0 – 70
2.36 mm (No. 8)	0 – 30	0 – 28
0.424 mm (No. 40)	0 – 4	0 – 4
0.075 mm (No. 200)	–	–

Table 9. Aggregate gradations for modified chip seal designs.

Sieve Size	**Percent Passing**	
	Aggregate Chips	**Choke Stone**
12.7 mm (1/2 in)	100	100
9.52 mm (3/8 in)	90 – 100	100
6.35 mm (1/4 in)	40 – 70	100
4.75 mm (No. 4)	0 – 15	85 – 100
2.36 mm (No. 8)	0 – 5	10 – 40
1.18 mm (No. 16)	–	0 – 10
0.300 mm (No. 50)	–	0 – 5
0.075 mm (No. 200)	0 – 1	0 – 1

Material Properties

The SDDOT provided the properties of the aggregates and emulsions to be used for the test sections. These properties are presented in table 10 for the quartzite and natural aggregates. These properties are required inputs to determine the design application rates for the aggregate chips and the emulsion.

Table 10. Material properties for test sections.

Property	Natural Aggregate	Quartzite Aggregate
Loose Unit Weight, kg/m^3 (lbs/yd^3)	56 (95)	49 (82)
Bulk Specific Gravity	2.40	2.61
Absorption, %	2.60	0.55
Absorption Factor, L/m^2 (gal/yd^2)	0.09 (0.02)	0.00 (0.00)
Emulsion Type	HFRS-2	CRS-2
Residual Asphalt Content	0.635	0.665

Design Application Rates

The control (SDDOT standard) test sections used the standard application rates for aggregate chips and emulsion. The application rates for the remaining test sections were designed using the modified McLeod design procedure. The McLeod design procedure is based on the following two principles:

- The aggregate application rate is designed to provide a seal coat that is one stone thick (i.e., there should be a single layer of uniformly sized chips).
- The voids in the aggregate are designed to be 70 percent filled with asphalt cement for good performance (i.e., the chips should be 70 percent embedded).

In addition to the material properties, the following inputs to the design procedure were assumed or determined based on available data:

- Flakiness Index: 27 percent
- Aggregate Wastage Factor: 1.1 (10 percent)
- Traffic Correction Factor: 0.60 (based on ADT of 2,125 vehicles per day)
- Surface Correction Factor: 0.06 (slightly pocked, porous, and oxidized)

Because the recommended aggregate gradation was not available at the time the designs were developed, the flakiness had to be assumed for design. In the future, the flakiness index can be determined for the specific aggregate to be used for the chip seal. The aggregate wastage factor of 1.10 is used to represent the recommended excess aggregate of 10 percent. The remaining factors, namely the traffic correction factor and surface correction factor, were obtained from selection tables provided in the McLeod design procedure.

Based on these inputs, the application rates for the aggregate chips and emulsion were determined using the modified McLeod design procedure. The resulting application rates for each section are presented in table 11. For the sections with a double chip seal (i.e., second application with choke stone), the application rates for each layer are determined by first adding the binder contents of the aggregate chips and the choke stone together. Then 60 percent of the total is applied to the first course and 40 percent of the total is applied to the second course. For example, the quartzite aggregate has emulsion application rates of 1.40 and 0.82 L/m^2 (0.31 and 0.18 gal/yd^2) for the aggregate chips and choke stone, respectively. The total emulsion rate is 2.22 L/m^2 (0.49 gal/yd^2), of which 1.31 L/m^2 (0.29 gal/yd^2) or 60 percent should be applied before placing the aggregate chips and 0.91 L/m^2 (0.20 gal/yd^2) or 40 percent should be applied before placing the choke stone layer.

Table 11. Design application rates for test sections.

Test Section	Description	Aggr. Type	Aggr. Gradation Type	Agg. Rate (lb/yd^2)		Emulsion Rate (gal/yd^2)		
				Aggregate Chips	Choke Stone	Aggr. Chips	Choke Stone	Fog Seal
1	Poly-Mod Emulsion	Quartzite	New	19.0	n/a	0.31	n/a	n/a
2	New Design	Quartzite	New	19.0	n/a	0.31	n/a	n/a
3	Fog Seal	Quartzite	New	19.0	n/a	0.31	n/a	0.10
4	Choke Stone	Quartzite	New	19.0	8.2	0.29	0.20	n/a
5	Precoated Aggregate	Quartzite	New	19.0	n/a	0.31	n/a	n/a
6	DOT Standard Design*	Quartzite	Standard	24.0	n/a	0.27	n/a	n/a
7	DOT Standard Design*	Natural	Standard	24.0	n/a	0.27	n/a	n/a
8	New Design	Natural	New	19.0	n/a	0.31	n/a	n/a
9	Fog Seal	Natural	New	19.0	n/a	0.31	n/a	0.10
10	Choke Stone	Natural	New	19.0	8.2	0.31	0.21	n/a
11	Precoated Aggregate	Natural	New	19.0	n/a	0.28	n/a	n/a
12	Poly-Mod Emulsion	Natural	New	19.0	n/a	0.31	n/a	n/a

* SDDOT standard application rates were used; no design was performed.

Construction of Test Sections

The test sections were constructed on June 19 and 20, 2000. The initial application was placed on June 19 with follow-up applications, such as the fog seal and choke stone, being placed on June 20. During placement, members of the project team and the SDDOT monitored the construction process, including the following aspects:

- Surface preparation.
- Emulsion and chip application rates.
- Lag time between emulsion and chip application.
- Lag time between chip application and rolling.
- Roller speeds and patterns.
- Stopping and starting techniques.
- Brooming.
- Traffic control procedures.
- Climatic conditions (e.g., temperature and wind speeds).

A primary concern during chip seal placement is the emulsion and aggregate application rates. These rates were closely evaluated to meet the following conditions:

- The emulsion rate should be such that it fills the void between the aggregate to about the top of an average-sized chip. Upon breaking of the emulsion and loss of water, the voids will then be 70 percent filled as designed.
- The chip rate should be such that only a single layer of chips is placed with minimal excess chips.

An approximation of the chip and emulsion application rates was determined by estimating the amount of material used and the length over which it was placed. The reported measured application rates are averages for the section even though adjustments were sometimes made within the test section. For the most part, the design and measured applications rates compare favorably, as shown in table 12. The exceptions are sections 10 and 11, in which the measured emulsion application rates exceed the design rates by 0.27 and 0.40 L/m^2 (0.06 and 0.09 gal/yd^2), respectively. Slightly lower emulsion applications rates were used for the choke stone application based on a visual evaluation. On the other hand, a slightly higher application rate was required to achieve adequate coverage for the fog seal application. Sections 8 and 9 used a higher chip application rate than was designed.

Table 12. Comparison of measured and design emulsion application rates.

Application	**Section**	**Aggregate Type**	**Chip Rate, lb/yd^2**		**Emulsion Type**	**Emulsion Rate, gal/yd^2**	
			Measured	**Design**		**Measured**	**Design**
Chip Seal	1	Quartzite	21.5	19.0	CRS-2P	0.333	0.31
	2	Quartzite	18.1	19.0	CRS-2	0.301	0.31
	3	Quartzite	19.9	19.0	CRS-2	0.324	0.31
	4	Quartzite	19.0	19.0	CRS-2	0.298	0.29
	5	Quartzite	16.3	19.0	CRS-2	0.319	0.31
	6	Quartzite	23.0	24.0	CRS-2	0.296	0.27
	7	Natural	26.1	24.0	AE150S	0.274	0.27
	8	Natural	22.0	19.0	HFRS-2	0.328	0.31
	9	Natural	23.4	19.0	HFRS-2	0.331	0.31
	10	Natural	17.7	19.0	HFRS-2	0.368	0.31
	11	Natural	19.8	19.0	HFRS-2	0.368	0.28
	12	Natural	19.8	19.0	HFRS-2P	0.331	0.31
Fog Seal	3	Quartzite	n/a	n/a	CSS-1	0.124	0.10
	9	Natural	n/a	n/a	CSS-1	0.141	0.10
Choke Stone	4	Quartzite	8.7	8.2	CRS-2	0.190	0.20
	10	Natural	8.6	8.2	HFRS-2	0.164	0.21

The lag time between the application of the emulsion and the chips was 10 to 15 seconds, and the lag time between the application of the chips and the initial roller pass was typically less than 1 minute. Rolling was generally completed within 20 minutes. These times are all adequate and meet the current SDDOT specification. However, the roller speeds often exceeded the maximum speed of 8 km/hr (5 mi/hr). Higher speeds were necessary at some times to keep up with the emulsion and chip applications and still achieve the required four coverages.

Another issue is the start and stop locations for the emulsion applicator and chip spreader, in which two coverages of emulsion and chips are applied. This is problematic, especially for the emulsion, because the excess emulsion can and did result in bleeding at such locations. A better technique is to use building paper or other material at start and stop locations to prevent double applications.

Traffic control was accomplished by closing the outer traffic lane using signs and cones. Before entering the construction zone, flyers were distributed to motorists indicating that they may encounter loose chips that could cause damage to their vehicles and that speeds should be limited to 64 km/hr (40 mi/hr). Once placed, the sections were opened to traffic without any traffic control measures. However, the two precoated aggregate sections remained closed throughout the night because the chips were still tacky and were being picked up by vehicle tires.

No brooming was performed on the first day of placement. Thus, traffic was allowed to operate on the pavement before it was swept. Sweeping occurred on the morning following the chip seal placement.

On the first day, when the initial application was placed, temperatures ranged from 22 to 29 °C (72 to 85 °F) under mostly sunny skies. During the evening, the area received a thunderstorm with heavy rainfall. The following day was again sunny with slightly colder temperatures. The temperature was approximately 21 °C (70 °F) and rising when application began around 9:00 am. Sunny skies and warming temperatures continued throughout the day as the chip seal placement continued in the passing lane.

Monitoring of Test Sections

Monitoring of the test sections occurred at various stages during the construction process. Prior to chip seal placement, a complete condition survey (including rutting measurements) and sand patch testing was conducted. A subjective rating on a 1-to-10 scale was also made regarding the amount and severity of bleeding, raveling, and cracking (where 10 is a pavement that is free of all signs of the particular distress). Immediately following construction, the sand patch test was repeated and an assessment of the average chip embedment was performed. The excess chips were swept up and measured to determine the percentage of chips retained. Additional monitoring was conducted 3 months following construction, at which time the condition surveys and rutting measurements were performed. Sand patch testing was repeated, as was an assessment of the average aggregate embedment and subjective ratings of bleeding, raveling, and cracking. The results of the monitoring phases are described.

Condition Surveys

Condition surveys were performed on all 12 sections prior to construction of the test sections and repeated approximately 3 months following construction. The initial surveys are essential to provide a basis from which to evaluate the effect of specific conditions on the performance of the chip seals. The follow-up surveys provide a direct evaluation of the ability of the chip seal to address the existing distress. A summary of condition survey data is provided in tables 13 and 14 and in figures 9 and 10. Table 13 summarizes the distress quantities exhibited 3 months after chip seal placement. Table 14 compares the total distress quantity between the two surveys (i.e., the percentage of each distress that has reflected through the chip seal). Figures 9 and 10 illustrate the quantity and recurrence of longitudinal and transverse cracking, respectively. A more detailed summary of the survey results, showing distresses and severities for all sections, is provided in Appendix B.

Table 13. Summary of pavement condition 3 months after chip seal placement.

Section	Longitudinal Cracking, m (ft)	Transverse Cracking		Bleeding, m^2 (ft^2)	Raveling, m^2 (ft^2)
		Number	Length, m (ft)		
1	8.8 (29)	8	26 (85)	20.8 (224)	0.2 (2)
2	—	6	15 (49)	0.4 (4)	0.3 (3)
3	—	17	45 (148)	0.5 (5)	—
4	30 (95)	21	53 (173)	0.6 (6)	—
5	—	22	52 (170)	—	—
6	18 (58)	37*	111 (364)*	0.6 (6)	—
7	20 (64)	15	35 (114)	—	0.5 (5)
8	7.0 (23)	15	39 (128)	—	0.3 (3)
9	—	19	62 (204)	0.4 (4)	0.3 (3)
10	35 (114)	12	37 (121)	3.4 (37)	29.5 (318)
11	61 (199)	9	18 (58)	—	0.2 (2)
12	0.6 (2)	7	15 (50)	0.6 (6)	—

* Two cracks totaling 7.3 m (24 ft) are medium severity; all other distresses are low severity.

Table 14. Percent recurrence of distresses after 3 months.

Section	Fatigue Cracking	Longitudinal Cracking	Transverse Cracking	
			Number	Length
1	n/a	26.1	17.0	19.8
2	n/a	0.0	15.8	15.9
3	0.0	0.0	30.9	30.6
4	n/a	18.8	31.3	30.8
5	0.0	5.2	44.0	37.9
6	n/a	7.7	62.7	65.1
7	0.0	12.9	37.5	29.7
8	0.0	3.4	30.6	29.2
9	n/a	0.0	38.8	43.9
10	0.0	20.2	27.9	30.0
11	0.0	61.0	22.5	16.5
12	0.0	0.2	16.3	16.2

Note: n/a indicates not applicable because no distress at initial survey.

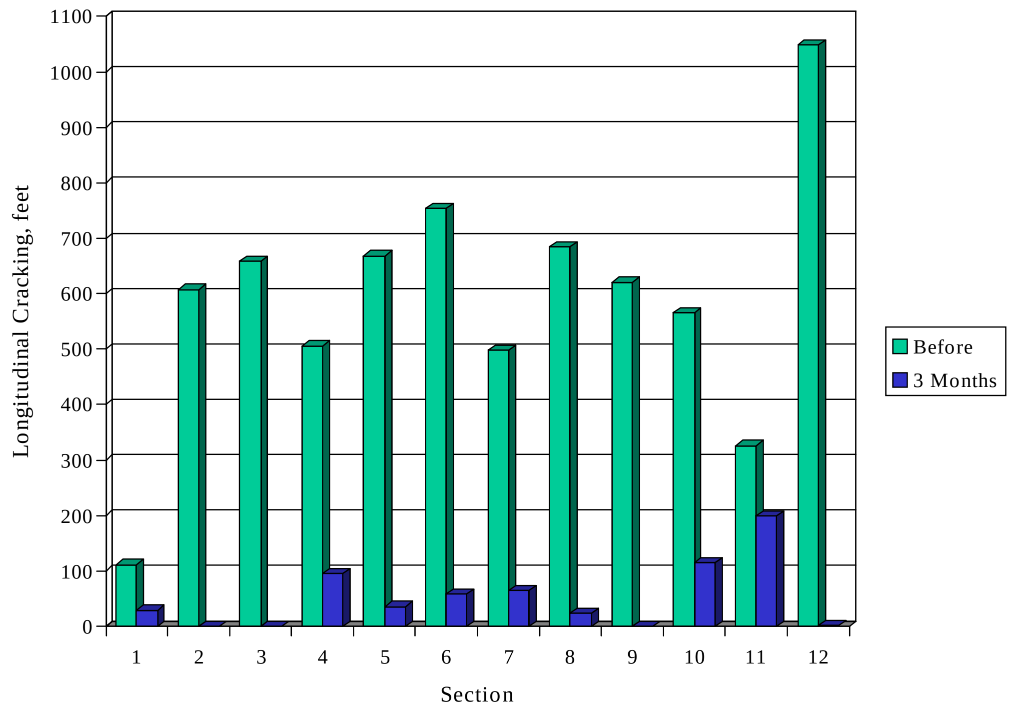

Figure 9. Quantity and recurrence of longitudinal cracking.

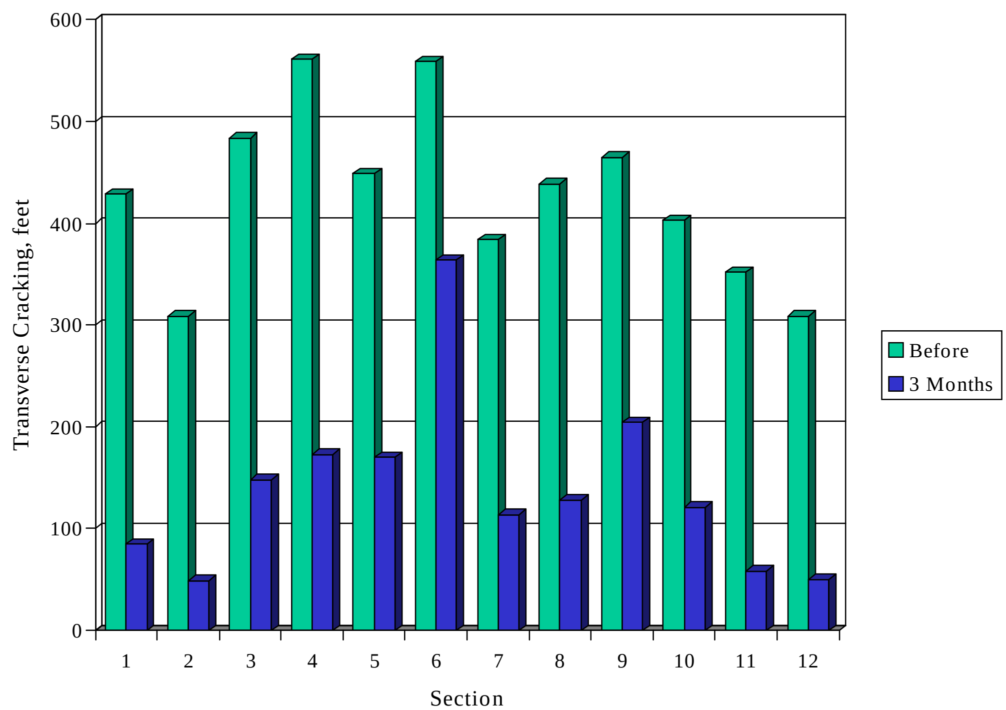

Figure 10. Quantity and recurrence of transverse cracking.

Two variables—the number of cracks and the total length of the cracks—are shown for transverse cracking, and for the most part, the two variables are well correlated. Of the sections with quartzite aggregate, the SDDOT standard test section (section 6) exhibits significantly more cracking and a higher percentage of recurring cracks both in terms of the number and length of cracks. The precoated aggregate section (section 5) exhibits a slightly higher percentage of recurring cracks as compared to the other sections, which have about 30 percent or less recurring cracks. Of the sections with natural aggregate, the SDDOT standard (section 7) and fog seal (section 9) test sections have the highest percentage of recurring cracks. The precoated aggregate (section 11) and polymer-modified (section 12) test sections show the best performance in terms of reducing the amount of cracking.

In terms of longitudinal cracking, the precoated natural aggregate section (section 11) stands out as having significantly more cracking, with 61 percent of the cracks reflected through the chip seal. A portion of the reflective longitudinal cracking is due to raveling around the cracks on the original surface. Both choke stone sections (sections 4 and 10) have about 20 percent of the longitudinal cracks that have reflected through the chip seal, and the polymer-modified section with quartzite aggregate (section 1) has 26 percent. The remaining sections have only limited amounts of longitudinal cracking.

A significant amount of bleeding is exhibited on the polymer-modified section with quartzite aggregate (section 1). However, the majority of the bleeding is due to the presence of medium-severity bleeding in the wheelpath of the existing pavement surface, which emphasizes the need for either correcting the problem or adjusting the emulsion rate in these areas. Bleeding is also observed on the choke stone section with natural aggregate (section 10). This section had the highest measured emulsion application rate, and was 0.27 L/m^2 (0.06 gal/yd^2) higher than the design rate, which certainly contributed to the bleeding. The remaining sections have little or no bleeding and the bleeding that is observed is typically limited to overlapping at start and stop locations.

Raveling is most significant on the choke stone section with natural aggregate (section 10). Raveling occurred on this section within a few days of placing the choke stone layer and initially appeared as small areas of missing pieces (approximately quarter sized) that began to spall and interconnect to form larger areas. Both the chip seal and choke stone layers were completely removed in some areas, exposing the original pavement surface. A possible explanation for this occurrence is that the chip seal absorbed moisture from the previous night's rainfall and the moisture was then trapped within the chip seal when covered with the choke stone. Bubbles were also observed on the surface, which could be attributed to moisture being released from the initial chip seal layer. Raveling has not been observed on any of the remaining test sections.

The results of the rutting measurements taken prior to chip seal placement and 3 months after placement are summarized in table 15. Rutting measurements were taken in both wheelpaths at 30-m (100-ft) intervals throughout the 305-m (1000-ft) monitoring section. Table 15 shows the average of those measurements. Rutting typically exceeded 6.4 mm (0.25 in) before chip seal placement and returned to similar levels within 3 months.

Table 15. Summary of rutting measurements before and after chip seal placement.

Section	Inner Wheelpath Average Rut Depth, mm (in)		Outer Wheelpath Average Rut Depth, mm (in)		Percent Recurrence	
	Before Chip Seal	3 Months After Chip Seal	Before Chip Seal	3 Months After Chip Seal	Inner Wheelpath	Outer Wheelpath
1	8.6 (0.34)	5.6 (0.22)	8.6 (0.34)	8.1 (0.32)	64.7	94.1
2	7.9 (0.31)	6.1 (0.24)	9.1 (0.36)	9.1 (0.36)	77.4	100.0
3	8.9 (0.35)	5.8 (0.23)	8.9 (0.35)	8.9 (0.35)	65.7	100.0
4	6.9 (0.27)	4.8 (0.19)	8.6 (0.34)	8.1 (0.32)	70.4	94.1
5	7.6 (0.30)	5.3 (0.21)	7.9 (0.31)	9.4 (0.37)	70.0	119.4
6	8.1 (0.32)	5.8 (0.23)	8.9 (0.35)	9.1 (0.36)	71.9	102.9
7	9.7 (0.38)	7.6 (0.30)	8.9 (0.35)	9.4 (0.37)	78.9	105.7
8	7.6 (0.30)	7.1 (0.28)	10.2 (0.40)	10.4 (0.41)	93.3	102.5
9	7.6 (0.30)	6.4 (0.25)	8.9 (0.35)	8.9 (0.35)	83.3	100.0
10	8.9 (0.35)	7.9 (0.31)	10.2 (0.40)	9.9 (0.39)	88.6	97.5
11	8.1 (0.32)	6.6 (0.26)	8.4 (0.33)	7.4 (0.29)	81.3	87.9
12	9.1 (0.36)	8.1 (0.32)	10.7 (0.42)	9.7 (0.38)	88.9	90.5

Subjective Ratings

Subjective ratings of the extent and severity of bleeding, raveling, and cracking were also made before chip seal placement and 3 months after placement. The ratings are based on a 1-to-10, scale with 10 indicating a pavement in perfect condition (in terms of the particular distress) and 1 indicating a badly distressed pavement. The results of the subjective ratings are presented in table 16. The evaluation of the results focuses on the rating performed 3 months after chip seal placement. The ratings before chip seal placement simply provide an indication of the existing condition and how such a condition may be reflected in the performance of the chip seal.

Most of the sections are performing well in terms of limiting bleeding, with ratings of 8 and 9. The exceptions are the two choke stone sections—section 4 (quartzite) and section 10 (natural)—with ratings of 4 and 6, respectively. In both cases, it is believed that the bleeding is the result of emulsion application rates that were too high, especially on the second coverage for the choke stone, but also on the initial coverage on the natural aggregate section. The polymer-modified section with quartzite aggregate (section 1) is rated 6 in the areas where medium-severity bleeding was present before the chip seal.

Raveling is only a problem on the choke stone section with natural aggregate (section 10), as has been discussed. The remaining sections have ratings of 8 to 10.

For cracking, several factors are considered in the rating: the amount of cracking and the condition of the cracks. The SDDOT standard section with quartzite aggregate (section 6) has the lowest rating (6). This section has the most cracking as well as the most deteriorated cracks; it is also the only section with medium-severity cracks. Three sections have a rating of 7, with the remaining sections rated as 8 or 9. Also worth mentioning is the polymer-modified section with natural aggregate (section 12), which had a rating of 5 before chip seal placement and a rating of 8 at the 3-month follow-up. The polymer-modified chip seal was able to reduce the amount of reflective cracking even of the many medium-severity cracks exhibited on the original pavement surface.

The degree of bonding between the chips and the emulsion was also subjectively evaluated by prying up chips with a knife. The bonding condition was subjectively rated as EXCELLENT, GOOD, FAIR, and POOR. The results are provided in table 16. Only one section, the choke stone section with natural aggregate (section 10), was rated POOR. This section has the debonding problem and the excess emulsion content. The SDDOT standard section with quartzite aggregate (section 6) was rated FAIR because chips could be removed with minimal effort. The highest degree of bonding was observed on the fog seal section with quartzite aggregate (section 3), which is rated EXCELLENT. It required considerable effort to remove chips on this section.

Table 16. Subjective ratings of performance of chip seal test sections.

	Before Chip Seal Placement			3 Months After Chip Seal Placement			
Section	Bleeding	Raveling	Cracking	Bleeding	Raveling	Cracking	Bonding Condition
1	5	6	7	6/8*	9	8	Good
2	7	7	7	8	9	9	Good
3	7	6	7	9	10	8	Excellent
4	7	8	7	4	9	8	Good
5	7	8	7	9	9	7	Good/Fair
6	7	8	6	9	9	6	Fair
7	7	6	7	8	9	8	Good/Fair
8	7	7	7	9	8	9	Good
9	7	8	8	8	8	8	Good
10	7	8	8	6	4	7	Poor
11	5	7	7	8	9	7	Good
12	6	7	5	9	9	8	Good

* Bleeding rated as 6 in areas of medium-severity bleeding on original surface; otherwise, bleeding is rated 8.

Sand Patch Tests

As an alternative to friction testing (which is preferred but was not able to be conducted), sand patch testing was conducted at two locations within each 305-m (1000-ft) monitoring section. Testing was conducted prior to chip seal placement, immediately following placement (after sweeping and opening to traffic), and 3 months after placement. The test was performed in accordance with ASTM E 965-96, *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*. The sand patch test involves spreading a specified volume of glass spheres and determining the average diameter of the spread material. The average macrotexture depth (MTD) is then determined from the following equation:

$$MTD = \frac{4V}{\pi D^2}$$

where:

MTD = macrotexture depth, mm (in).
V = sample volume, mm^3 (in^3).
D = average diameter of the spread material, mm (in).

The results of the sand patch testing are provided in table 17 and figure 11. Also shown is the percent loss of macrotexture depth after 3 months of traffic. This factor is affected by the realignment of chips and bleeding caused by repeated traffic loadings.

Table 17. Sand patch test (macrotexture depth) results.

Section	Before Chip Seal		After Chip Seal		3 Months After Chip Seal		Loss, %
	mm	in	mm	in	mm	in	
1	0.61	0.0240	2.46	0.0968	2.21	0.0871	10.00
2	0.75	0.0296	2.38	0.0937	2.10	0.0828	11.65
3	0.59	0.0232	2.40	0.0947	1.54	0.0605	36.05
4	0.78	0.0309	1.52	0.0598	1.02	0.0403	32.68
5	0.70	0.0277	2.44	0.0962	1.98	0.0781	18.85
6	0.74	0.0293	2.10	0.0826	2.23	0.0877	-6.25
7	0.77	0.0301	1.94	0.0762	1.63	0.0640	16.02
8	0.73	0.0288	2.25	0.0887	1.82	0.0715	19.43
9	0.81	0.0320	2.14	0.0841	1.31	0.0516	38.66
10	0.74	0.0292	1.71	0.0672	0.92	0.0363	45.91
11	0.52	0.0204	2.27	0.0893	1.73	0.0682	23.56
12	0.81	0.0321	2.49	0.0979	1.92	0.0754	22.93

Although a relative comparison of the macrotexture depths and an evaluation of the percent macrotexture loss do provide meaningful results, it is difficult to understand the true significance of macrotexture depth and its effect on traffic. A more meaningful and more commonly used parameter is the skid number. The skid number was thus estimated using the following equation (Henry and Wambold 1992):

$$Skid\ Number = -20.5 + 0.65\,BPN + 16.4\,MTD$$

where BPN is the British Pendulum Number and was assumed to be 65 for the purpose of this evaluation. It should be noted, however, that this is an assumed value and that testing was not conducted to determine this value. The skid numbers determined from the above equation should thus be used only as a relative comparison between the sections and not as an evaluation of the safety characteristics or other purposes. Table 18 shows the results of this correlation.

Evaluating both the macrotexture depths and the skid numbers, it is apparent that the two choke stone sections have the least skid resistance. The choke stone sections, along with the fog seal sections, also have the greatest percentage loss in macrotexture depth and skid number. The remaining sections have a more reasonable reduction that is consistent with the expected loss caused by traffic loadings.

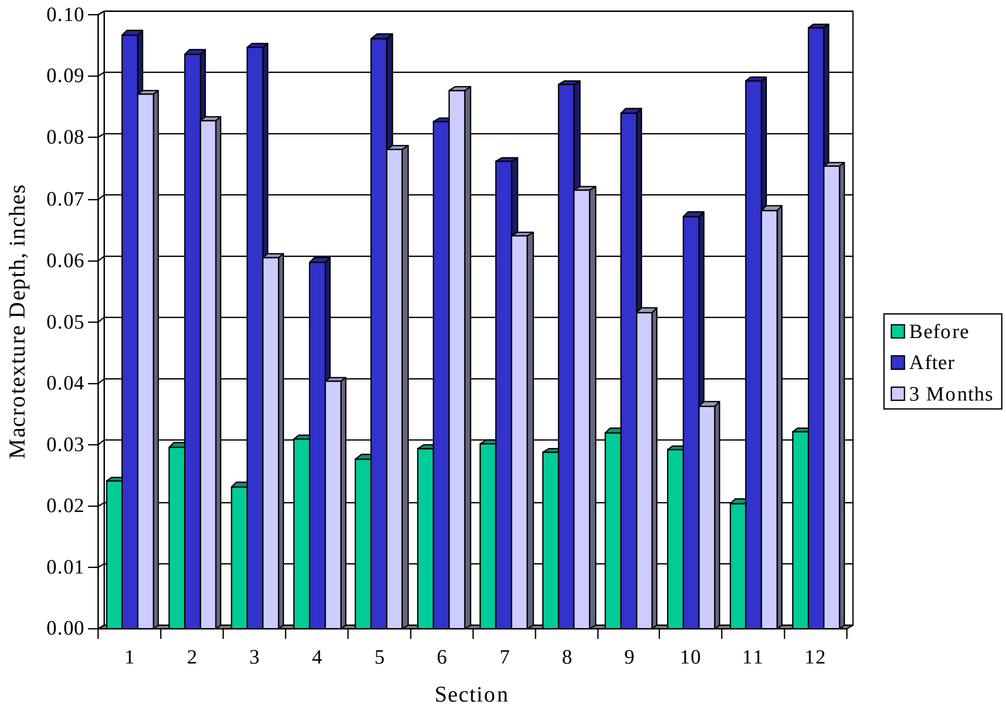

Figure 11. Comparison of macrotexture depths.

Table 18. Skid numbers developed from correlation with macrotexture depths.

Section	Before Chip Seal	After Chip Seal	3 Months After Chip Seal	Loss, %
1	31.8	62.1	58.0	6.49
2	34.1	60.8	56.2	7.48
3	31.4	61.2	47.0	23.23
4	34.6	46.7	38.5	17.45
5	33.3	61.8	54.3	12.22
6	33.9	56.1	58.3	-3.83
7	34.3	53.5	48.4	9.51
8	33.7	58.7	51.5	12.23
9	35.1	56.8	43.3	23.86
10	33.9	49.7	36.9	25.83
11	30.3	58.9	50.2	14.86
12	35.1	62.5	53.2	14.95

Chip Retention

Chip retention provides a measure of the percentage of chips that are retained on the roadway versus the amount of chips that are applied to the roadway. It is determined using the following equation:

$$Chip\ Retention = 100 \times \left(1 - \frac{Weight\ of\ \ Loose\ Chips}{Aggregate\ Application\ Rate} \right)$$

Loose chips were retrieved at two locations within each monitoring section by sweeping up excess chips within a 0.37 m^2 (4 ft^2) area identified using a template. The samples were retrieved approximately 2 to 4 hours after placement but before sweeping or opening to traffic. The two chip samples were then weighed and compared to the design application rate using the above equation. The results are summarized in table 19.

Table 19. Chip retention of chip seal test sections.

Application	Section	Application Rate, lb/m^2 (lb/yd^2)	Average Sample Weight, kg/m^2 (lb/yd^2)	Average Chip Retention, %
Chip Seal	1	10.3 (19.0)	0.42 (0.77)	96.0
	2	10.3 (19.0)	0.65 (1.19)	93.7
	3	10.3 (19.0)	1.06 (1.96)	89.7
	4	10.3 (19.0)	0.29 (0.53)	97.2
	5	10.3 (19.0)	0.60 (1.11)	94.1
	6	13.0 (24.0)	1.94 (3.58)	85.1
	7	13.0 (24.0)	2.97 (5.48)	77.2
	8	10.3 (19.0)	1.05 (1.94)	89.8
	9	10.3 (19.0)	0.76 (1.41)	92.6
	10	10.3 (19.0)	0.87 (1.61)	91.5
	11	10.3 (19.0)	0.22 (0.41)	97.9
	12	10.3 (19.0)	0.47 (0.86)	97.8
Choke Stone	4	4.4 (8.2)	1.25 (2.31)	71.9
	10	4.4 (8.2)	0.04 (0.07)	99.2

The most obvious observation is the much higher weight of loose chips on the SDDOT standard test sections (sections 6 and 7). The weights are at least twice, and in many cases four to five times, the weight of the other samples, which certainly strengthens the likelihood of damage to vehicles due to the much larger amount of excess chips. Chip retention is also lower on these two sections even though the application rate is higher. The remaining sections were designed using a 10 percent aggregate wastage factor (i.e., 90 percent chip retention) and each section is near or above the target chip retention level. Chip retention is only 71.9 percent for quartzite choke stone (section 10), far lower than the design level.

For long-term performance, perhaps the most important factor is the long-term retention of the chips. However, measuring this is problematic. First, it is difficult to measure the loss of chips over time, as once the pavement has been opened to traffic loose chips are unlikely to remain on the pavement surface to be swept up and measured. Second, the chip seals were only 3 months old at the time of the follow-up survey and long-term performance data simply are not available yet. Nonetheless, some signs of the continued loss of chips were observed, such as emulsion pockets that previously contained chips and loose chips on the roadway and shoulder. Such signs were most noticeable on the SDDOT standard section with quartzite (section 6), but were also noticed on section 2 (quartzite, no design variation) and section 4 (quartzite, choke stone).

Chip Embedment

A subjective rating of the chip embedment was performed immediately after chip seal placement and during the 3-month follow-up survey. To perform the subjective rating, several chips were removed from the roadway and an assessment was made of the average depth of the emulsion on the chip. Table 20 presents the results of the evaluation; the results are also illustrated graphically in figure 12. The target or design embedment depth is 70 percent of the mean particle size at initial placement, eventually increasing to 80 percent after traffic forces the chips to lay on their flattest side.

Table 20. Subjective rating of aggregate embedment.

Section	Immediately After Chip Seal Placement	3 Months After Chip Seal Placement	
		Wheelpath	Non-Wheelpath
1	50 %	70 %	60 %
2	60 %	70 %	60 %
3	70 %	70 %	65 %
4	85 %	95 %	80 %
5	70 %	70 %	60 %
6	30 %	60 %	50 %
7	30 %	60 %	50 %
8	70 %	80 %	65 %
9	65 %	85 %	70 %
10	90 %	90 %	90 %
11	80 %	90 %	80 %
12	70 %	75 %	70 %

Evaluating the embedment percentages immediately following chip seal placement, two observations are apparent. First, the chips on the choke stone sections (sections 4 and 10) are embedded to depths of 85 and 90 percent, respectively. As previously mentioned, the emulsion rates are thought to be too high on these sections. The second observation is the 30 percent embedment percentage for the two SDDOT standard test sections. The standard chips used on these sections have a large amount of flat and elongated particles, which become completely embedded and create layers of chips that cannot embed to the proper depth.

Similar trends are observed from an evaluation of the embedment percentages after 3 months. The choke stone sections still have the greatest embedment and bleeding is exhibited on both sections. However, the precoated natural aggregate section (section 11) also has 90 percent chip embedment in the wheelpath, although the asphalt from precoating may have obscured it. The embedment percentage for the SDDOT standard sections improved, but is still low at 60 percent in the wheelpath and 50 percent outside the wheelpath.

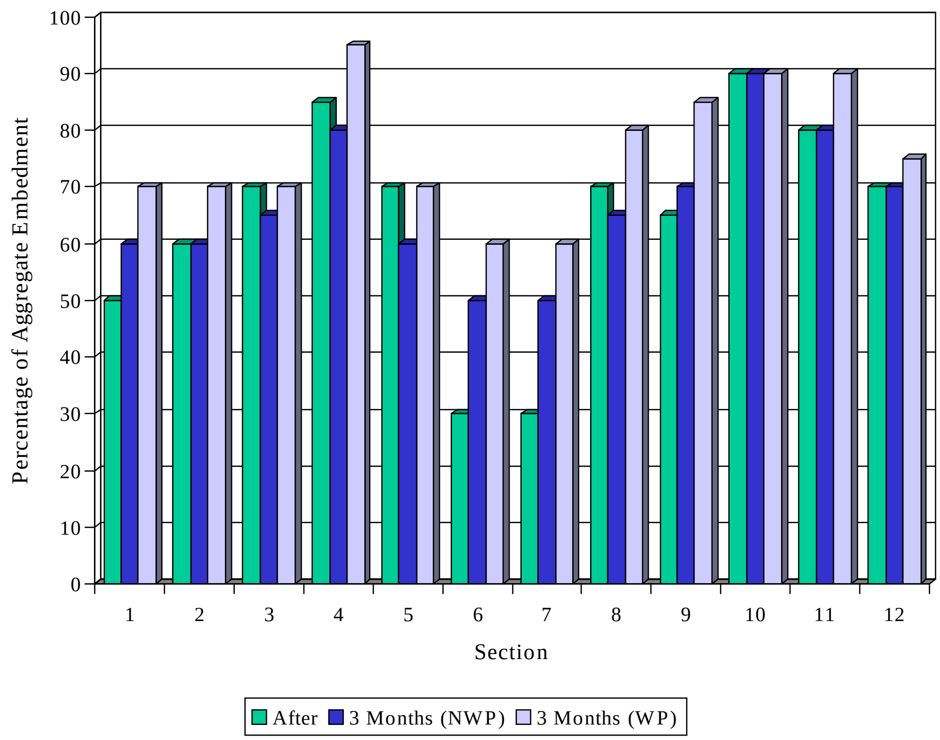

Figure 12. Comparison of aggregate embedment depths.

Summary of Key Findings and Recommendations

This section presents a summary of the key findings resulting from the design, construction, and evaluation of the field test sections. Also included are future recommendations for the continued use of chip seals.

Design and Materials

- A formal design process needs to be developed and implemented to determine the application rates for the emulsion and aggregate chips.
- A more gap-graded gradation, such as the one used for the new design test sections, should be adopted to provide greater uniformity and provide a single layer of chips.
- The gradation should also include a limit on the amount of fines (material passing the 0.075-mm [No. 200] sieve) to reduce dust and allow a more consistent coating of the aggregate chips.
- Testing (such as ASTM D 4791 or the flakiness index) should be performed to limit the amount of flat and elongated particles.
- Project-specific testing should be performed to evaluate the adhesion properties between the aggregate chips and the emulsion.

Construction

- The emulsion rates should be closely monitored in the field to achieve the desired embedment of 70 percent.
- The chip application rates should be closely monitored in the field to achieve uniform coverage and to limit the amount of excess chips to 10 percent.
- Building paper or other suitable material should be used when stopping and starting the emulsion applicator and chip spreader to avoid a double application of material in localized areas.
- Roller speed restrictions (8 km/hr [5 mi/hr]) should be more strictly enforced, which may require slowing the entire operation or providing more rollers on the project.
- The pavement should be swept before opening to traffic at normal speeds.
- Special traffic control methods need to be employed when using precoated aggregate because the chips remain tacky for a longer period. Precoated aggregate sections need to be closed overnight and swept before opening to traffic. A possible alternative is to precoat the chips further in advance of the chip seal placement.

Performance

- The use of the new chip gradation and design application rates should be continued in the future for all chip seal projects. The new designs have performed well and should reduce the variability and sensitivity to changes that have been problematic on past projects.
- The polymer-modified emulsion provides the strongest bond with the aggregate chip and also exhibits the greatest elasticity. The use of polymer-modified emulsion is encouraged on high-volume, high-speed roadways.
- The emulsion application rate needs to be reduced where bleeding is present on the existing roadway and where an AC overlay or patch has been placed.
- The fog seal sections present the most aesthetically pleasing roadway surface (looks similar to an asphalt concrete pavement surface), but it is difficult to ascertain any performance differences after 3 months as compared to the new design sections without the fog seal cover.
- Several problems have been encountered on the choke stone sections. On the natural aggregate section, the chip seal and choke stone layers became debonded and created loose pieces. The reason is not immediately obvious, but is believed to be due to trapping of moisture within the initial chip seal layer. On both choke stone sections, bleeding and excessive chip embedment are encountered. This problem may be corrected by reducing the emulsion application rate, especially for the choke stone layer. The use of choke stones should not be undertaken on a widespread basis until additional test sections can be constructed and evaluated.
- The SDDOT standard sections had considerably more loose chips on the pavement surface after placement, creating a greater potential for vehicle damage.
- The SDDOT standard sections initially had, and continue to have, insufficient chip embedment. Chip embedments were initially 30 percent and increased to 50 to 60 percent after 3 months, compared to target values of 70 and 80 percent. Chip retention continues to be a problem on the quartzite section, as missing chips were observed.

- The choke and fog seal sections exhibit a greater loss of macrotexture depth and skid number after 3 months. Although these have not deteriorated to the point where skid resistance is a concern, these sections should be monitored to determine if it is a continuing trend.

Recommendations for Continued Monitoring

Although the 3-month follow-up evaluation certainly provided meaningful results, it is recommended that continued monitoring of the test sections be conducted to assess the longer-term performance trends. Monitoring is recommended twice a year during the Spring and Fall. The following measurements and evaluations are recommended within each 305-m (1000-ft) monitoring section:

- Visual condition survey.
- Subjective ratings of bleeding, raveling, cracking, and bonding condition.
- Sand patch testing.
- Visual assessment of chip embedment.
- Photographs of key observations.

The 3-month evaluation was certainly beneficial, especially given the fact that many chip seal failures can be observed relatively quickly. However, it only provided an early indication of the performance of these treatments. Continued monitoring of the test sections is essential for assessing the chip seal performance over time. Chip seals are typically expected to provide about 5 years of service and thus need to be evaluated and compared over at least that time period. Such evaluations will also be beneficial for assessing the cost effectiveness of the chip seal variations as compared to the current chip seal designs.

Summary

This chapter presents a summary of the design, construction, and monitoring of the twelve chip seal test sections. The test sections were constructed on State Route 50 between Yankton and Vermillion during June of 2000 and included two aggregate types and various design modifications. Detailed monitoring and evaluation occurred prior to chip seal placement, immediately following placement, and approximately 3 months following placement. The results of these evaluations are summarized and assessed in this chapter. Many of the new design sections are performing better than the standard design sections and are thus recommended for future use. In addition, future recommendations are presented based on the results of the evaluations. Finally, recommendations for the continued monitoring and evaluation of the test sections are presented.

5.0 Treatment Selection Guidelines

Introduction

One of the primary objectives of this project is the development of guidelines for selecting the most appropriate surface treatments for South Dakota's pavements. This chapter presents treatment selection guidelines, based on a review of treatments that are deemed appropriate for use in South Dakota. Drawing on existing pavement conditions, traffic levels, and location, a decision matrix is presented that facilitates the selection of feasible treatments.

Evaluation of Available Surface Treatments

A detailed summary of common surface treatments is provided in Chapter 2, and a brief summary of the characteristics of each surface treatment is provided in table 21. Based on that detailed summary and a thorough consideration of the conditions in South Dakota (such as climate, available materials, and previous performance), recommendations for the use of surface treatments in South Dakota have been developed. In developing the recommendations, the following factors are considered:

- Experience of other states, including those with conditions similar to South Dakota.
- Distress types expected to be addressed by surface treatments.
- Performance of the surface treatment.
- Cost effectiveness of the surface treatment.
- Compatibility with the materials available in South Dakota.
- Availability of specialized equipment.
- Traffic volumes and speeds.
- Location (urban versus rural).

The following sections describe the evaluation of each surface treatment and the factors that are considered in developing the recommendations. This information is followed by a summary of the surface treatments that are believed to be appropriate for use by the South Dakota DOT.

Fog Seals

Fog seals are an economical method of sealing and enriching the pavement surface and inhibiting raveling. Fog seals do not address distresses such as cracking or surface defects, nor do they improve roughness or surface friction, so they should not be used where those conditions are present. Fog seals are also not recommended on medium- and high-volume roadways due to the length of time required for slow setting emulsions to break, which reduces the surface friction immediately after application. However, fog seals are appropriate for the following applications:

- To cover a chip seal to improve retention and limit the amount of loose chips.
- To preserve the pavement for 1 to 2 years before placing a chip seal or AC overlay (based on the above-noted limitations).
- To rejuvenate an aging but otherwise intact asphalt concrete surface.

Table 21. Summary of available surface treatments.

Surface Treatment	Description	Purpose	Typical Life, years	Typical Cost, $
Fog Seals	Light application of slow setting asphalt emulsion placed directly on pavement surface without aggregate cover	Seal and enrich pavement surface and inhibit raveling	1 to 2	0.24 to 0.30/m^2 (0.20 to 0.25/yd^2)
Flush Seals	Application of asphalt emulsion followed by a light covering of sand or other fine aggregate.	Seal and enrich pavement surface and prevent infiltration	2 to 5	0.60 to 1.50/m^2 (0.50 to 1.25/yd^2)
Scrub Seals	Application of polymer-modified asphalt and broom scrubbing followed by application of sand or small aggregate and a second brooming	Rejuvenate the asphalt and fill voids and surface cracks	3 to 4	0.50 to 0.60/m^2 (0.40 to 0.50/yd^2)
Slurry Seals	Mixture of asphalt emulsion and well-graded aggregate placed directly on the pavement in thicknesses of 3 to 6 mm (1/4 to 1/2 in)	Seal surface cracks, inhibit raveling, improve surface friction	3 to 5	0.85 to 1.15/m^2 (0.70 to 0.95/yd^2)
Microsurfacing	Mixture of polymer-modified emulsion and aggregate placed on the pavement in thicknesses of 10 to 20 mm (3/8 to 3/4 in)	Seal pavement surface, improve surface friction, fill ruts	4 to 7	1.50 to 2.40/m^2 (1.25 to 2.00/yd^2)
Chip Seals	Application of asphalt emulsion or asphalt followed by a layer of aggregate chips	Seal pavement, improve surface friction, address oxidation and raveling	4 to 7	0.70 to 1.20/m^2 (0.60 to 1.00/yd^2)
Cold In-Place Recycling	Reworking of pavement surface material without heat with new binder and virgin materials to serve as a base for a new surface	Address surface distresses such as block cracking, thermal cracking, raveling	5 to 10	1.00 to 3.70 m^2 (0.80 to 3.00/yd^2) depending on thickness
Hot In-Place Recycling	Hot reworking of pavement surface material in place and placement of new surface course using existing or blended materials. Types: Heater-scarification, Remixing, Repaving	Address surface distresses such as rutting, corrugations, raveling, and bleeding	Heater-scarify: 3 to 5 Remixing: 8 to12 Repaving: unknown	Heat-scarify: 1.25/m^2 (1.05/yd^2) Remixing: 3.50/m^2 (2.90/yd^2) Repaving: 2.15/m^2 (1.80/yd^2)
Ultrathin Friction Courses	Application of thick layer of polymer-modified emulsion and thin, gap-graded HMA layer using specialized equipment	Seal pavement, improve surface friction, address oxidation and raveling	Not available	4.70/m^2 (3.90/yd^2)
Thin Hot-Mix Asphalt Overlays	Plant-mixed combinations of asphalt and aggregate placed 13 to 38 mm thick (0.5 to 1.5 in). Types: Dense-graded HMA, OGFC, SMA	Restore ride, improve friction (OGFC also reduces hydroplaning and tire splash)	Dense HMA: 4 to 10 OGFC: 8 to 12 SMA: unknown	Dense HMA: 2.00/m^2 (1.70/yd^2) OGFC: 1.60/ m^2 (1.35/yd^2) SMA: 2.60/m^2 (2.20/yd^2)

Although not a treatment that should be used extensively, fog seals are appropriate for limited use by the South Dakota DOT under the proper conditions.

Flush Seals

Flush seals provide the same benefits as fog seals with the added benefit of improving surface friction, at least for a few years. In addition, flush seals can be used on high-volume roadways. Flush seals are appropriate for the following applications:

- To provide surface friction to a newly placed AC surface.
- To cover a chip seal to improve retention and limit the amount of loose chips.
- To improve surface friction and extend the time (by 2 to 4 years) before placing a chip seal or AC overlay.

Flush seals are recommended for these particular applications.

Scrub Seals

Scrub seals can be used to rejuvenate the asphalt surface and to fill small voids and surface cracks. These treatments are similar to a flush seal, with the primary difference being that they eliminate the need to seal cracks in a separate operation. Like flush seals, however, scrub seals do not provide long-term surface friction and do not address the raveling problem that is common in South Dakota. Although scrub seals are less expensive than chip seals, chip seals provide longer service lives and maintain higher levels of surface friction. Scrub seals are recommended for limited applications in South Dakota. In particular, they can be used on low-volume roadways to address pavements with both cracking and surface defects such as oxidation and raveling.

Slurry Seals

Slurry seals can be used to seal the pavement, to inhibit oxidation and raveling, and to improve surface friction. However, slurry seals have the following limitations:

- Slurry seals provide some of the same benefits as chip seals at a higher cost.
- The typical life of slurry seals is equal to or shorter than the life of a chip seal.
- Slurry seals perform best in warm-weather climates.
- Slurry seals require the use of crushed aggregates, which are not always locally available.
- Slurry seals require specialized equipment not available in South Dakota.
- Local contractors are largely unfamiliar with slurry seal operations.
- Slurry seals do not perform well when placed over cracked pavements.

For these reasons, the use of slurry seals is not recommended in South Dakota.

Microsurfacing

Like slurry seals, microsurfacing seals the pavement, inhibits surface aging and degradation, and improves surface friction. Similarly, many of the same arguments against the use of slurry seals can also be made against microsurfacing. However, one advantage of microsurfacing is that the process can correct non-progressing rutting up to 40 mm (1.5 in) deep, a benefit that most surface treatments cannot claim. In addition, microsurfacing has been more widely used and has performed well on high-volume roadways. Its service life is at least equal to that provided by chip seals. Furthermore, loose chips are not a problem with microsurfacing.

Based on these factors, microsurfacing is recommended in South Dakota. However, because of its higher cost in comparison to chip seals, its use should be limited to specialized applications such as to address rutting and to avoid loose chips on high-volume applications. Although specialized equipment required for microsurfacing may not be available in South Dakota, it is available in nearby states.

Chip Seals and Sand Seals

Chips seals and sand seals have been widely used in South Dakota and this practice should continue. Although there have been problems with these surface treatments, they have for the most part served their purpose well. There are some enhancements to the standard design that should improve the performance of chip seals and sand seals for all applications. These recommendations, which include a tighter aggregate gradation, a more restrictive limitation on the percent fines, and the development of a design procedure to determine application rates, are outlined in Chapter 4. The incorporation of these recommendations should result in improved performance and fewer problems when these treatments are applied to roadways at all traffic levels.

Additional modifications are recommended for chip seals placed on medium-volume to high-volume roadways and other roadways in which limiting the number of loose chips is critical. These recommendations include the use of a polymer-modified asphalt emulsion, precoating the aggregate chips, and sweeping the pavement before opening to traffic. Although these enhancements will result in additional costs compared to the standard chip seal, they are necessary to limit the amount of damage to vehicles. More specific recommendations about the conditions in which these enhancements should be employed are provided later in this chapter.

In-Place Recycling

Cold in-place recycling (CIR) can be used to address surface distresses such as block cracking, thermal cracking, oxidation, and raveling. Hot in-place recycling (HIR) addresses these distresses in addition to rutting, corrugations, and bleeding. However, the cost of recycling can be four to six times more than the cost of chip seals and can be higher than the cost of providing a thin dense-graded hot-mix asphalt (HMA) overlay or an open-graded friction course (OGFC). Moreover, recycling requires specialized equipment. Consequently, the use of in-place recycling techniques is not recommended as a surface treatment in South Dakota.

Ultrathin Friction Courses

Ultrathin friction courses are an emerging technology that has yet to receive widespread use. Thus, their long-term performance is unknown, although the short-term results are promising. Ultrathin friction courses do eliminate the problem of loose chips, which is especially beneficial on high-volume/high-speed roadways. The cost of this surface treatment has been five or more time higher than that of conventional chip seals in South Dakota. Nonetheless, the use of ultrathin friction courses is worth investigating for high-volume roadways under certain conditions.

Thin HMA Overlays

Thin, dense-graded HMA overlays and OGFCs have been used in South Dakota and have performed well. Their cost is about three times the cost of conventional chip seals, while their expected service life is about twice that of chip seals. Thus, thin HMA overlays have not been shown to be cost effective on a widespread basis. Their application is best suited for high-volume roadways where eliminating loose chips is critical. They can also be constructed during cooler weather and under other adverse conditions when applications of emulsion-based treatments are not indicated.

Feasible Surface Treatments

As described previously, an evaluation of all available surface treatments was conducted to identify those that are feasible for conditions in South Dakota. The feasible surface treatments, and those that are recommended for use in South Dakota (or at least continued evaluation), are as follows:

- Fog seals.
- Flush seals.
- Scrub seals.
- Microsurfacing.
- Conventional sand seals and chip seals.
- Modified sand seals and chip seals.
- Ultrathin friction courses.
- Thin HMA overlays.

The most appropriate use of each of these surface treatments is addressed further in the treatment selection guidelines.

Treatment Selection Guidelines

Project Selection

Although the guidelines focus on the selection of the most appropriate alternative, the first step is to determine if a surface treatment is even applicable. There are several conditions under which a surface treatment should not be considered. For example, a surface treatment should not be considered if any of the following conditions exist:

- More than 10 percent medium-severity or 2 percent high-severity alligator cracking.
- Wide or deteriorated transverse and longitudinal cracks that cannot be adequately sealed prior to applying a surface treatment.
- Deteriorated or extensive patches (greater than 20 percent medium- and high-severity patches by area).
- Medium- or high-severity potholes.
- Rutting resulting from an unstable asphalt mix.
- Rutting in excess of 25 mm (1.0 in).
- International roughness index (IRI) greater than 160 in/mi.
- Inadequate structure as evidenced by structural-related distress.
- Shoving of the asphalt concrete surface.
- Poor support conditions.
- Poor drainage or other moisture-related problems.

If any of these conditions exist, the use of a surface treatment should not be considered as an appropriate maintenance or rehabilitation technique. Such pavements are candidates for more extensive rehabilitation, such as a structural overlay or reconstruction, and are not addressed in these guidelines. Many of these distress definitions are defined in *SDDOT's Enhanced Pavement Management System, Visual Distress Survey Manual* (SDDOT 2001).

Treatment Selection Matrix

Once the project is selected for a surface treatment, the decision must then be made as to which surface treatment is most appropriate for the specific application. The selection process involves a balancing act between a number of factors, which complicates the selection of the most appropriate treatment. The following factors need to be considered when selecting the surface treatment:

- Pavement condition.
- Traffic volumes.
- Project location (urban versus rural).
- Availability of aggregates.
- Availability of specialized equipment.
- Cost effectiveness of the surface treatment (this factor incorporates the cost of the treatment, the expected life of the treatment, and the benefit that the treatment imparts to the pavement during its life).

Table 22 presents a decision matrix that provides guidelines for selecting the most appropriate surface treatment. Some of the key factors, such as pavement condition, traffic volumes, and project location, figure prominently in the decision matrix. Other factors, although not directly included in the decision matrix, are indirectly considered and incorporated in the decision process. A discussion of each of the key factors considered in the decision process is provided in subsequent sections.

Each cell within the matrix provides recommendations regarding the most feasible alternatives for the given condition. Narrowing the selection down to a single alternative is believed to be impractical; a single solution cannot be recommended for every case. Other factors, such as the cost effectiveness of the surface treatments, the availability of the aggregate types, and agency experience, must then be used to select among the feasible alternatives.

Although many other approaches to treatment selection are available, this type of decision matrix was selected based on its simplicity and effectiveness. The use of a decision tree was found to be too complicated to include all of the factors that must be considered.

Factors Affecting Treatment Selection

Pavement Condition

The condition of the existing pavement surface is the primary factor affecting the selection of the most appropriate surface treatment and is thus prominently displayed in the decision matrix. The decision matrix includes seven distresses that are addressed by surface treatments. The objective in using the matrix is to identify the distress types that are present in significant quantity (i.e., the distress types that need to be addressed by the surface treatment). The quantity and/or severity that are listed for each distress indicate the degree that is considered significant. Distress types that are only present in small quantities should not be included because they should not control the selection process.

As an example, if a surface treatment is being considered to address poor transverse and longitudinal cracking on a medium-volume rural roadway, the feasible alternatives include a sand seal and a chip seal. Determination of the most appropriate treatment between these two feasible alternatives is then based on other factors (e.g., available aggregate types and cost effectiveness) as discussed later.

Although the decision matrix does not include severity levels for each distress type, the distress severity is indirectly considered in two ways. First, a surface treatment is only considered a feasible alternative if it meets the limiting conditions provided in the project selection guidelines. For example, one condition for eliminating surface treatments as a feasible alternative is rutting of more than 25 mm (1.0 in). Secondly, the quantity and severity of distress given in the table indicate if a distress is considered significant and should be addressed by a surface treatment.

The decision matrix also allows the consideration of more than one distress type (i.e., when two or more distress types are present in significant quantities and need to be addressed by the same surface treatment). The distress types are listed in such an order that the feasible surface treatments provided can also address all distress types at lower levels. For example, a chip seal is given as a feasible alternative for roughness on a medium-volume rural roadway, which means

Table 22. Guidelines for selecting surface treatments.

Significant Distresses	Rural Roadway			Urban Roadway		
	Low Volume	Med. Volume	High Volume	Low Volume	Med. Volume	High Volume
Rutting 12-25 mm (0.5-1.0 in)	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay
Bleeding > 10%	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Chip Seal*	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Chip Seal*	Microsurfacing Thin Overlay Chip Seal*
Roughness (IRI) 100-160 in/mi	Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Alligator Cracking 0-2% high 2-10% med 4-25% low	Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Long./Trans. Cracking 0-2% high > 2% med > 4% low	Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Poor Surface Friction SN < 40	Flush Seal Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Raveling 0-2% high 5-25% med 10-50% low	Flush Seal Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Oxidation (Asphalt Hardening)	Fog Seal Flush Seal Scrub Seal Sand Seal Chip Seal	Flush Seal Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay

Traffic levels are defined as follows:

- Low Volume: < 1,000 ADT
- Medium Volume: 1,000 to 2,500 ADT
- High Volume: > 2,500 ADT

* Indicates that one or more of the following additional modifications should be considered:

- Use of high-quality aggregate that may not be locally available
- Use of polymer-modified asphalt emulsion
- Application of a fog seal or flush seal over the chip seal
- Use of precoated chips
- Sweeping of chips before opening to traffic

that a chip seal can also address each of the distress types listed below roughness, namely cracking, poor surface friction, raveling, and oxidation. Likewise, a feasible alternative for bleeding on a low-volume urban roadway is a thin overlay, which can also address each distress type listed below bleeding.

To use the decision matrix most effectively, the first step is to list all distress types that need to be addressed by the surface treatment. Then, enter the decision matrix with the distress type that appears first in distress type column. For example, if designing a surface treatment to address roughness, poor surface friction, and raveling, only roughness needs to be used in the design chart because it appears higher in the list than the other distress types.

Traffic Volumes

Traffic volumes are also a key factor in the selection process. The different traffic volume levels are defined as follows:

- Low volume: less than 1,000 vehicles per day.
- Medium volume: between 1,000 and 2,500 vehicles per day.
- High volume: more than 2,500 vehicles per day.

Traffic volumes are important for several reasons. First, the surface treatment must be able to handle the applied traffic over its entire design life. For this reason, flush seals are only recommended on low-volume roadways. Additionally, the surface treatment must also address other potential issues. For example, the surface treatments recommended for high-volume roadways should be designed to limit the amount of loose chips.

Location

The location of the roadway, in terms of whether it is in a rural or urban setting, is also directly considered in the decision matrix. The treatment selection process for roadways located in urban locations must address two additional concerns. First, the roadway will be more visible to the public and the treatment must be aesthetically pleasing. Secondly, urban roadways are subject to turning movements and must be designed to withstand such forces. For these reasons, more durable surface treatments are recommended for urban locations.

Availability of Aggregates

The availability of aggregates is not directly considered in the decision matrix. This factor should be considered once the feasible alternatives have been selected from the matrix. For example, if both a chip seal and a sand seal are given as feasible alternatives, the decision as to which alternative to use should be based on the cost effectiveness of the treatment, which may favor the aggregate type that is locally available.

Availability of Equipment

The availability of specialized equipment is not directly considered in the decision process. Rather, this factor was considered in the evaluation of feasible alternatives for South Dakota. That discussion is provided previously in this chapter.

Environmental Conditions

The temperature restriction for surface treatments is a minimum of 21 °C (70 °F) and the construction season is limited to June 1 through September 15. OGFCs can be placed at 16 °C (60 °F) and must adhere to the same seasonal restrictions. Thin HMA overlays can be placed from May 1 through October 15 and temperatures must be greater than 4 or 7 °C (40 or 45 °F), depending on placement thickness. Consideration should be given to these restrictions in the selection process. Several surface treatment failures in South Dakota appear to have been related to constructing the treatment beyond the specified season.

Cost Effectiveness

Costs associated with the surface treatments are always a consideration and must be included in any selection process. Costs are considered in two ways. First, the costs of the surface treatments are considered indirectly in the decision matrix by listing feasible alternatives that are most cost effective for the particular application. For instance, an open-graded friction course is certainly a feasible alternative to address oxidation on a low-volume rural roadway. However, it is not listed because there are other surface treatments that address the problem equally well at a much lower cost.

Secondly, the life cycle costs of each of the feasible alternatives should be evaluated to determine the most appropriate alternative. The life cycle cost analysis requires a reasonable projection of the expected life of the treatment. The analysis should then include all costs expected throughout the life of the treatment, including initial construction costs, maintenance costs, future rehabilitation costs, and salvage value. Guidelines for evaluating the cost effectiveness of treatment methods is provided elsewhere (Zimmerman 1997).

Summary

The suitability of the most common surface treatments used for maintaining asphalt concrete pavements is reviewed and recommendations are made for those treatments that should be used in South Dakota. These are identified as “feasible” treatments. Then, guidelines are proposed for selection of a recommended treatment from among the list of feasible treatments. The recommendations are based on the existence of primary, significant distresses on the pavement surface, coupled with considerations of the roadway’s traffic volume and location. Other factors, including environmental considerations, equipment availability, and aggregate selection, are addressed separately. The guidelines are presented in the form of a decision matrix, which is a readily understandable and easily followed tool that can be implemented by the South Dakota DOT.

6.0 Summary

Introduction

The South Dakota DOT has made extensive use of chip seal and sand seal surface treatments in the maintenance of their AC pavements. Such surface treatments have been found to provide a cost-effective means of extending the life of AC pavements in South Dakota. Although the use of chip seals and sand seals have for the most part been reliable treatments, there have been some notable failures, especially on high-volume, high-speed roadways. This project was undertaken to investigate the use of chip seals for such applications and to make recommendations to improve their performance. This project also involved the development of guidelines for the design and construction of chip seals.

Project Findings and Recommendations

To evaluate chip seals and their performance in South Dakota, several methods were employed. First, an extensive review of pertinent literature was conducted to acquire the latest information and experience in regards to chip seals and other surface treatments. Secondly, interviews were conducted with South Dakota DOT personnel from design, maintenance, construction, research, and pavement management to cover all aspects of chip seals. Additional interviews were conducted with industry representatives, FHWA representatives, contractors, and DOT staff from other states.

The most extensive effort involved the design, construction, and monitoring of twelve pavement test sections on State Route 50 between Yankton and Vermillion. The test sections included chip seals constructed with two aggregate types (quartzite and natural aggregate), variations in aggregate gradation and emulsion rates, as well as other design modifications and enhancements for high-volume, high-speed applications. Monitoring of the test sections occurred before, during, and after chip seal placement as well as 3 months following placement.

Based on these extensive evaluation efforts, several observations regarding South Dakota's current chip seal practices were made. In addition, recommendations were developed to improve the performance of chip seals on South Dakota's roadways. These observations and recommendations are presented throughout this report and are summarized below.

Chip Seal Design

South Dakota does not currently follow any type of design process for chip seals. Application rates are determined based on previous experiences from each region. A formal design process needs to be developed and implemented to determine the application rates for the emulsion and aggregate chips. The current application rates appear to be on the low side for the emulsion and on the high side for the aggregate chips. Minnesota employs a modified McLeod design procedure that accounts for specific material properties, traffic volumes, and pavement condition. A similar procedure needs to be adopted in South Dakota.

Materials

The most obvious observation regarding the aggregate chips is that the gradation is not ideal for use with chip seals. The objective for chip seals is to achieve a gradation with the majority of the chips having a similar size to provide a uniform layer of chips. A more uniform-graded gradation should be adopted to provide greater uniformity and to provide a single layer of chips. Such a gradation was used for the test sections and performed well. This gradation should be used for all chip seals.

The gradation should also include a limit on the amount of fines (material passing the 0.075-mm [No. 200] sieve). The current gradation does not include a limit on the material passing the 0.075-mm (No. 200) sieve. The fines should be limited to about 1 percent by weight of the material to reduce dust and allow a more consistent coating of the aggregate chips.

The current gradation also includes a large amount of flat and elongated particles. These aggregate particles become completely embedded in the emulsion, thus preventing additional aggregate particles from achieving the proper embedment depth. Testing (such as ASTM D 4791 or the flakiness index) should be performed to limit the amount of flat and elongated particles.

Construction

Although the use of a formal design procedure will provide more desirable application rates, adjustments will nonetheless still need to be made in the field. Adjustments should be made in the field with the following goals in mind:

- The emulsion rate should be such that it fills the void between the aggregate to about the top of an average-sized chip. Upon breaking of the emulsion and loss of water, the embedment will then be 70 percent as designed.
- The chip rate should be such that only a single layer of chips is placed with between 5 to 10 percent excess chips.

One problem that was observed during construction was when the application was stopped. At such locations, to restart the application the equipment was backed up slightly, resulting in a double application of emulsion. This practice tends to cause bleeding in the overlapped area, as was observed during the follow-up surveys. Building paper or other suitable material should be used when stopping and starting the emulsion applicator and chip spreader to avoid this problem.

Another observation during construction is that the existing restrictions on roller speeds (8 km/hr [5 mi/hr]) need to be more strictly enforced . At higher speeds, it is difficult for the rollers to keep pace with the chip seal application and either more rollers need to be provided or the entire operation needs to be slowed down.

The biggest problem with chip seals is the vehicular damage caused by the tremendous amount of excess chips. Reducing the amount of chips to limit the excess to 10 percent will certainly help. Another action that should be taken is to sweep the pavement before opening to traffic at normal speeds.

Finally, special traffic control methods need to be employed when using precoated aggregate because the chips remain tacky for a longer period. Precoated aggregate sections need to be closed overnight and swept before opening to traffic. Another possible alternative is to precoat the chips further in advance of the chip seal placement.

Field Testing

As previously mentioned, the application rates should be continuously monitored in the field. A few other simple tests are also recommended. The depth of aggregate embedment into the emulsion should also be continuously monitored. This can be done by removing several chips with a knife or other pointed object and evaluating the degree of emulsion coating on the aggregate. The target is 70 percent embedment.

Another simple test is the sweep test. For this test, the excess aggregate over a measured area is swept and weighed. A comparison to the application rate will provide a quick estimate of the amount of excess chips being placed. The excess chips should be limited to between 5 and 10 percent.

Performance Monitoring

Several observations and recommendations can be made based on monitoring of the field test sections. For one, the use of the new chip gradation and design application rates should be continued in the future for all chip seal projects. The new designs have performed well and should reduce the variability and sensitivity to changes that have been problematic on past projects.

On both the quartzite and natural aggregate sections, the polymer-modified emulsion provided the strongest bond with the aggregate chip and also exhibits the greatest elasticity. The use of polymer-modified emulsion is encouraged on high-volume/high-speed roadways.

The fog seal sections present the most aesthetically pleasing roadway surface (similar to a newly-constructed asphalt concrete pavement surface) but it is difficult to ascertain any performance differences after 3 months as compared to the new design sections without the fog seal cover.

Several problems were encountered on the choke stone sections. On the natural aggregate section, the chip seal and choke stone layers became debonded and created loose pieces. The reason has not been definitively identified, but is believed to be due to trapping of moisture within the initial chip seal layer. On both choke stone sections, bleeding and excessive chip embedment were observed. This problem may be corrected by reducing the emulsion application rate, especially for the choke stone layer. Choke stones should not be used on a widespread basis until additional test sections can be constructed and evaluated.

The SDDOT standard sections had considerably more loose chips on the pavement surface after placement, creating a greater potential for vehicle damage. In addition, the SDDOT standard sections initially had and continue to have insufficient chip embedment. Chip embedments were initially 30 percent and increased to 50 to 60 percent after 3 months as compared to target values of 70 and 80 percent. Furthermore, chip retention continues to be a problem on the quartzite section, as missing chips were observed.

Project Selection

Guidelines were developed for the selection of surface treatments on asphalt-surface roadways. The guidelines consist of two parts. The first step is to determine if a surface treatment is in fact a feasible option at all. This determination is based on critical distress levels that deem a surface treatment unfeasible. The second step is to determine the appropriate surface treatment based on the given conditions. This selection guideline is presented in the form a decision matrix and accounts for the pavement condition, project location (rural vs. urban), and traffic volume.

Implementation and Future Recommendations

Although the 3-month follow-up evaluation certainly provided meaningful results, it is recommended that continued monitoring of the test sections be conducted to assess the longer-term performance. Monitoring is recommended twice a year during the Spring and Fall. The following measurements and evaluations are recommended within each 305-m (1000-ft) monitoring section:

- Visual condition survey.
- Subjective ratings of bleeding, raveling, cracking, and bonding condition.
- Sand patch testing.
- Visual assessment of chip embedment.
- Photographs of key observations.

The 3-month evaluation was certainly beneficial, especially given the fact that many chip seal failures can be observed relatively quickly. However, it only provided an early indication of the performance. Continued monitoring of the test sections is essential for assessing the chip seal performance over time. Chip seals are typically expected to provide about 5 years of service and thus need to be evaluated and compared over at least that time period. Such evaluations will also be beneficial for assessing the cost effectiveness of the chip seal variations as compared to the current chip seal designs.

Another recommendation is to construct a similar series of test sections in the western part of the state using limestone and natural aggregate. Limestone is commonly used in the west, yet no test sections were constructed to evaluate the new recommendations using limestone aggregate. Although originally part of this project, a suitable candidate was not available for inclusion in this project. The test sections should be constructed when a suitable candidate is available.

In terms of implementation, two items are recommended. First, the guidelines presented for selection, design, and construction presented in Appendix C should be reproduced as a stand-alone document. This document will serve as a useful guideline and reference manual for SDDOT personnel and contractors. Where applicable, the recommendations should also be incorporated into the construction specifications. In addition, the development of a training course is recommended. Again, this course should cover the entire chip seal process, although emphasis can be placed on certain topics depending on the audience. Both of these items are critical and would be timely given the new design and construction recommendations described in this report.

The distress levels and guidelines for the selection of surface treatments were based on the experiences and recommendations of South Dakota and other state highway agencies. As the decision matrix is incorporated into the selection process, the distress levels may need to be modified based on the performance of the surface treatments. This selection process should also be incorporated into South Dakota's pavement management system.

Conclusion

An extensive research effort was undertaken to evaluate South Dakota's design and construction practices for chip seals and other surface treatments. Based on this research, recommendations have been made to improve the consistency and performance of chip seals. A summary of the final recommendations is provided in table 23. Although the project focused on chip seal applications for high-volume, high-speed roadways, many of the recommendations apply to roadways of all traffic levels. In addition, guidelines were developed for selecting a surface treatment for a specific roadway project. With the implementation of these guidelines and recommendations, the performance of chip seals in South Dakota should be greatly enhanced.

Table 23. Summary of final recommendations for implementation by SDDOT.

Number	Recommendation	Reason/Benefit of Recommendation
1	Adopt the chip seal design procedure outlined in Volume II of the guidelines. The design procedure should be used for all future chip seal designs.	South Dakota currently does not design the application rates but rather uses the same rates for all pavements. The rates are affected by pavement condition, traffic, and material properties, among others, and should be taken into account in design. Implementation of a design procedure will result in improved and more consistent performance of chip seals.
2	For all future chip seal projects, use the new gradation presented in table II-1 of the guidelines.	The current gradation has several shortcomings: • It is a gap-graded gradation that allows too many smaller-sized particles. • It does not include a limitation on the amount of fine particles. The new gradation is a more uniform gradation with the majority of the particles of a similar size. This will provide a more uniform thickness and more consistent chip embedment. The limit on fines will reduce dust and provide a more consistent coating of the aggregate chips.
3	For all future chip seal projects, perform the Flakiness Index test to measure the amount of flat and elongated particles. Such particles should be limited to 25 percent on high-volume, high-speed roadways and to 30 percent on all other roadways.	Flat and elongated particles become completely embedded in the emulsion and prevent larger chips from achieving proper embedment. This limitation will reduce the amount of chips with insufficient embedment and improve chip seal performance.

Table 23. Summary of final recommendations for implementation by SDDOT (continued).

Number	Recommendation	Reason/Benefit of Recommendation
4	For high-volume roadways, consider other means to enhance chip adhesion, such as the use of a polymer-modified emulsion, precoated aggregate, or a fog seal cover.	Such enhancements will help improve performance and reduce the amount of excess chips. The use of a polymer-modified emulsion is especially encouraged on high-volume roadways.
5	During chip seal placement, monitor the rates to achieve the following goals: • The emulsion rate should be adjusted to achieve 70 percent embedment of chips after curing (check by removing chips and evaluating embedment). • The chip application rate should be adjusted to achieve a single layer of chips with 5 to 10 percent excess (check using the sweep test).	Continuous monitoring and adjustments in the field are required to achieve these objectives. The design application rates are based on average conditions. Actual conditions will vary and adjustments will be needed.
6	Use building paper or other suitable material when starting and stopping the equipment to avoid double applications.	Double applications produce bleeding (which is detrimental to performance) and excess chips (which can cause vehicle damage).
7	Provide more strict enforcement on roller speeds.	The specification limits roller speeds to 8 km/hr (5 mi/hr) but speeds often exceed this limit. Lower speeds will provide better initial embedment and reorientation of the chips.
8	Sweep the pavement before opening to traffic at normal speeds, especially on high-volume roadways.	The biggest problem with chip seals is with vehicle damage. Removing the excess chips before allowing normal speed traffic will drastically reduce damage complaints.
9	Implement the surface treatment selection guideline provided in Volume I of the guidelines (at least on a trial basis), with the eventual goal of incorporating the trigger values into SDDOT's pavement management system.	The selection guidelines will help ensure that the most appropriate surface treatment is being placed on the roadway. The distress trigger levels should be monitored and adjusted, if needed, as performance data are available.
10	Continue to monitor the performance of the field test section on U.S. 50 at least twice a year until it is rehabilitated.	Only a 3-month performance evaluation was conducted as part of this project. Continued monitoring is needed to evaluate the long-term performance of the various chip seal sections.
11	Construct test sections in the western part of the state using limestone and natural aggregates.	Limestone is commonly used in the west but was not included in this study. The test sections will help investigate its performance along with the new design enhancements and special modifications for high-volume, high-speed roadways.
12	Reproduce the guidelines as a stand-alone document for easy reference.	The document needs to be easily accessible to planning, design, and construction personnel.
13	Develop and teach a training seminar describing the chip seal process and the recommendations from this study.	The recommendations from this study need to be conveyed to SDDOT personnel and contractors in order to be effectively implemented.

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Appendix A

Photographic Summary

Figure A-1. Typical pavement condition before chip seal placement.

Figure A-2. Typical wheelpath surface texture before chip seal placement.

Figure A-3. Typical raveling along centerline before chip seal placement.

Figure A-4. Medium-severity raveling before chip seal placement.

Figure A-5. Typical alligator cracking before chip seal placement.

Figure A-6. Typical longitudinal crack before chip seal placement.

Figure A-7. Typical medium-severity transverse crack before chip seal placement.

Figure A-8. Isolated area of bleeding before chip seal placement.

Figure A-9. Application of CRS-2 emulsion.

Figure A-10. Application of quartzite chips.

Figure A-11. Chip seal surface (quartzite chips) before rolling.

Figure A-12. Close-up of chip seal surface (natural aggregate chips).

Figure A-13. Choke stone surface (quartzite chips) after opening to traffic.

Figure A-14. Choke stone surface (natural aggregate chips) after rolling.

Figure A-15. Overview of fog seal surface (quartzite chips).

Figure A-16. Sweeping operation (natural aggregate chips).

Figure A-17. Sweeping operation in passing lane (SDDOT standard design).

Figure A-18. Excess chips after two broom passes (SDDOT standard design).

Figure A-19. Elasticity of CRS-2P emulsion.

Figure A-20. Elasticity of HFRS-2P emulsion.

Figure A-21. Chip embedment on SDDOT standard design section.

Figure A-22. Measurement of diameter for sand patch test.

Figure A-23. Overview of polymer-modified section with quartzite aggregate.

Figure A-24. Missing chips on new design section with quartzite aggregate.

Figure A-25. Typical transverse reflective crack at 3-month follow-up.

Figure A-26. Missing chips on SDDOT standard section with quartzite chips.

Figure A-27. Bleeding on choke stone section with quartzite aggregate.

Figure A-28. Overview of choke stone section with natural aggregate.

Figure A-29. Failed choke stone surface (natural aggregate) after 1 week.

Figure A-30. Choke stone surface (natural aggregate) at 3-month follow-up.

Figure A-31. Precoated aggregate chip pile.

Appendix B

Condition Survey Summary Forms

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

ID: SD (State) 50 (Hwy No.) 20 (Beg. ST)

Section Number: 01

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	0	0	0	0	0	0	n/a	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	111	0	0	29	0	0	26.1	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	43	4	0	8	0	0	17.0	
	Length	feet	381	48	0	85	0	0	19.8	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.34			0.22		64.7	
	Outer Wheelpath	inches		0.34			0.32		94.1	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	302	357	0	224	0	0	34.0	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	201	0	0	2	0	0	1.0	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 60 (Beg. MP)

Section Number: 02

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	0	0	0	0	0	0	n/a	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	607	0	0	0	0	0	0.0	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	35	3	0	6	0	0	15.8	
	Length	feet	273	36	0	49	0	0	15.9	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.31			0.24		77.4	
	Outer Wheelpath	inches		0.36			0.36		100.0	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	16	0	0	4	0	0	25.0	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	47	0	0	3	0	0	6.4	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 100 (Beg. MP)

Section Number: 03

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	26	0	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	653	5	0	0	0	0	0.0	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	49	6	0	17	0	0	30.9	
	Length	feet	412	72	0	148	0	0	30.6	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.35			0.23		65.7	
	Outer Wheelpath	inches		0.35			0.35		100.0	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	12	0	0	5	0	0	41.7	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	16	2	0	0	0	0	0.0	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

CONDUR ID: SD 50 140
State Hwy No. Beg. MP

Section Number: 04

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	0	0	0	0	0	0	n/a	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	491	15	0	95	0	0	18.8	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	61	6	0	21	0	0	31.3	
	Length	feet	489	72	0	173	0	0	30.8	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches	0.27			0.19			70.4	
	Outer Wheelpath	inches	0.34			0.32			94.1	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	18	0	0	6	0	0	33.3	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	2	0	0	0	0	0	0.0	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 180 (Beg. MP)

Section Number: 05

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	22	8	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	668	0	0	35	0	0	5.2	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	41	9	0	22	0	0	44.0	
	Length	feet	347	102	0	170	0	0	37.9	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.30			0.21		70.0	
	Outer Wheelpath	inches		0.31			0.37		119.4	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	0	0	0	0	0	0	n/a	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	0	0	0	0	0	0	n/a	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/26/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 220 (Beg. MP)

Section Number: 06

	Distress Type	Distress Measure	Severity Level			Severity Level			%	Comments
			Low	Mod	High	Low	Mod	High		
Cracking	Fatigue	square feet	0	0	0	0	0	0	n/a	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	754	0	0	58	0	0	7.7	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	47	12	0	35	2	0	62.7	
	Length	feet	415	144	0	340	24	0	65.1	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches	0.32			0.23			71.9	
	Outer Wheelpath	inches	0.35			0.36			102.9	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	0	0	0	6	0	0	n/a	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	36	0	0	0	0	0	0.0	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 290 (Beg. MP)

Section Number: 07

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	160	0	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	498	0	0	64	0	0	12.9	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	39	1	0	15	0	0	37.5	
	Length	feet	372	12	0	114	0	0	29.7	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.38			0.30		78.9	
	Outer Wheelpath	inches		0.35			0.37		105.7	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	13	0	0	0	0	0	0.0	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	40	12	0	5	0	0	9.6	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD 50 340
State Hwy No. Beg. MP

Section Number: 08

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	43	0	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	684	0	0	23	0	0	3.4	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	45	4	0	15	0	0	30.6	
	Length	feet	391	48	0	128	0	0	29.2	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches	0.30			0.28			93.3	
	Outer Wheelpath	inches	0.40			0.41			102.5	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	0	0	0	0	0	0	n/a	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	69	0	0	3	0	0	4.3	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 380 (Beg. MP)

Section Number: 09

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	0	0	0	0	0	0	n/a	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	620	0	0	0	0	0	0.0	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	45	4	0	19	0	0	38.8	
	Length	feet	417	48	0	204	0	0	43.9	
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.30			0.25		83.3	
	Outer Wheelpath	inches		0.35			0.35		100.0	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	0	0	0	4	0	0	n/a	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	20	0	0	3	0	0	15.0	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 420 (Beg. MP)

Section Number: 10

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	40	0	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	565	0	0	114	0	0	20.2	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	40	3	0	12	0	0	27.9	
	Length	feet	376	27	0	121	0	0	30.0	
	Length sealed	feet	10	0	0	0	0	0	0.0	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformationss	Rutting									
	Inner Wheelpath	inches	0.35			0.31			88.6	
	Outer Wheelpath	inches	0.40			0.39			97.5	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	0	0	0	37	0	0	n/a	
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	0	3	0	318	0	0	n/a	
Other										

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 460 (Beg. MP)

Section Number: 11

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	149	0	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	326	0	0	199	0	0	61.0	152 feet of cracking within overlay
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	36	4	0	9	0	0	22.5	
	Length	feet	307	45	0	58	0	0	16.5	121 feet of cracking within overlay
	Length sealed	feet	0	0	0	0	0	0	n/a	
Patching & Potholes	Patch/ Patch	number	0	2	0	0	0	0	0.0	
	Deterioration	square feet	0	2	0	0	0	0	0.0	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches	0.32			0.26			81.3	
	Outer Wheelpath	inches	0.33			0.29			87.9	
	Shoving	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Defects	Bleeding	square feet	25	0	0	0	0	0	0.0	Bleeding on overlay portion
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	181	54	8	6	2	0	3.3	Low raveling along edge for 150 ft
Other										

Note: Distress measurements taken over 660 feet; the remaining 340 feet had an AC overlay.

MODIFIED LTPP DISTRESS SUMMARY FORM

Date of Survey: 06/16/00 & 09/25/00

Survey Crew: mjw / do / gh

CONDUR ID: SD (State) 50 (Hwy No.) 490 (Beg. MP)

Section Number: 12

	Distress Type	Distress Measure	Severity Level Low	Severity Level Mod	Severity Level High	Severity Level Low	Severity Level Mod	Severity Level High	%	Comments
Cracking	Fatigue	square feet	10	6	0	0	0	0	0.0	
	Block	square feet	0	0	0	0	0	0	n/a	
	Edge	feet	0	0	0	0	0	0	n/a	
	Longitudinal									
	Length	feet	964	85	0	2	0	0	0.2	
	Length sealed	feet	0	0	0	0	0	0	n/a	
	Transverse	number	30	13	0	7	0	0	16.3	
	Length	feet	168	141	0	50	0	0	16.2	
	Length sealed	feet	109	0	0	0	0	0	0.0	
Patching & Potholes	Patch/ Patch	number	0	0	0	0	0	0	n/a	
	Deterioration	square feet	0	0	0	0	0	0	n/a	
	Potholes	number	0	0	0	0	0	0	n/a	
		square feet	0	0	0	0	0	0	n/a	
Surface Deformations	Rutting									
	Inner Wheelpath	inches		0.36			0.32		88.9	
	Outer Wheelpath	inches		0.42			0.38		90.5	
	Shoving	number	1	0	0	0	0	0	0.0	
		square feet	4	0	0	0	0	0	0.0	
Surface Defects	Bleeding	square feet	0	0	0	6	0	0	n/a	Slight bleeding alon in wheelpaths
	Polished Aggregate	square feet	0	0	0	0	0	0	n/a	
	Raveling	square feet	113	5	1	0	0	0	0.0	Slight raveling along edges
Other										

APPENDIX C

SURFACE TREATMENT GUIDELINES

Volume I. Guidelines for Treatment Selection

Volume II. Guidelines for Design of Chip Seals

Volume III. Guidelines for Construction of Chip Seals

Volume I. Guidelines for Treatment Selection

Introduction

This volume presents the guidelines for the selection of the most appropriate surface treatment for a specific project. First, the available surface treatments are described and their applicability for use in South Dakota is investigated. Next, the surface treatment techniques that are determined to be feasible for South Dakota are presented. Finally, the specific guidelines for selecting the most appropriate treatment are described. The guidelines, presented in the form of a decision matrix, include a consideration of the existing pavement conditions, traffic levels, location (urban versus rural), aggregate sources, availability of equipment, and environmental conditions.

Evaluation of Available Surface Treatments

A detailed evaluation of available surface treatments has been conducted and is described elsewhere (Wade, DeSombre, and Peshkin 2001). This section provides a summary of the characteristics of each surface treatment and evaluates the applicability of each surface for use in South Dakota. A brief summary of the characteristics of each surface treatment is also provided in table I-1. Based on the comprehensive evaluation and a thorough consideration of the conditions in South Dakota (such as climate, available materials, and previous performance), recommendations for the use of surface treatments in South Dakota have been developed. In developing the recommendations, the following factors are considered:

- Experience of other states, including those with conditions similar to South Dakota.
- Distress types expected to be addressed by surface treatments.
- Performance of the surface treatment.
- Cost effectiveness of the surface treatment.
- Compatibility with the materials available in South Dakota.
- Availability of specialized equipment.
- Traffic volumes and speeds.
- Location (urban versus rural).

The findings and recommendations for each surface treatment are described below.

Fog Seals

Fog seals are an economical method of sealing and enriching the pavement surface and inhibiting raveling. Fog seals do not address distresses such as cracking or surface defects, nor do they improve roughness or surface friction, so they should not be used where those conditions are present. Fog seals are also not recommended on high-volume roadways due to the length of time required for slow setting emulsions to break, which reduces the surface friction immediately after application. However, fog seals are appropriate for the following applications:

Table I-1. Summary of available surface treatments.

Surface Treatment	Description	Purpose	Typical Life, years	Typical Cost, $
Fog Seals	Light application of slow setting asphalt emulsion placed directly on pavement surface without aggregate cover	Seal and enrich pavement surface and inhibit raveling	1 to 2	0.24 to 0.30/m^2 (0.20 to 0.25/yd^2)
Flush Seals	Application of asphalt emulsion followed by a light covering of sand or other fine aggregate.	Seal and enrich pavement surface and prevent infiltration	2 to 5	0.60 to 1.50/m^2 (0.50 to 1.25/yd^2)
Scrub Seals	Application of polymer-modified asphalt and broom scrubbing followed by application of sand or small aggregate and a second brooming	Rejuvenate the asphalt and fill voids and surface cracks	3 to 4	0.50 to 0.60/m^2 (0.40 to 0.50/yd^2)
Slurry Seals	Mixture of asphalt emulsion and well-graded aggregate placed directly on the pavement in thicknesses of 3 to 6 mm (1/4 to 1/2 in)	Seal surface cracks, inhibit raveling, improve surface friction	3 to 5	0.85 to 1.15/m^2 (0.70 to 0.95/yd^2)
Microsurfacing	Mixture of polymer-modified emulsion and aggregate placed on the pavement in thicknesses of 10 to 20 mm (3/8 to 3/4 in)	Seal pavement surface, improve surface friction, fill ruts	4 to 7	1.50 to 2.40/m^2 (1.25 to 2.00/yd^2)
Chip Seals	Application of asphalt emulsion or asphalt followed by a layer of aggregate chips	Seal pavement, improve surface friction, address oxidation and raveling	4 to 7	0.70 to 1.20/m^2 (0.60 to 1.00/yd^2)
Cold In-Place Recycling	Reworking of pavement surface material without heat with new binder and virgin materials to serve as a base for a new surface	Address surface distresses such as block cracking, thermal cracking, raveling	5 to 10	1.00 to 3.70 m^2 (0.80 to 3.00/yd^2) depending on thickness
Hot In-Place Recycling	Hot reworking of pavement surface material in place and placement of new surface course using existing or blended materials. Types: Heater-scarification, Remixing, Repaving	Address surface distresses such as rutting, corrugations, raveling, and bleeding	Heater-scarify: 3 to 5 Remixing: 8 to12 Repaving: unknown	Heat-scarify: 1.25/m^2 (1.05/yd^2) Remixing: 3.50/m^2 (2.90/yd^2) Repaving: 2.15/m^2 (1.80/yd^2)
Ultrathin Friction Courses	Application of thick layer of polymer-modified emulsion and thin, gap-graded HMA layer using specialized equipment	Seal pavement, improve surface friction, address oxidation and raveling	Not available	4.70/m^2 (3.90/yd^2)
Thin Hot-Mix Asphalt Overlays	Plant-mixed combinations of asphalt and aggregate placed 13 to 38 mm thick (0.5 to 1.5 in). Types: Dense-graded HMA, OGFC, SMA	Restore ride, improve friction (OGFC also reduces hydroplaning and tire splash)	Dense HMA: 4 to 10 OGFC: 8 to 12 SMA: unknown	Dense HMA: 2.00/m^2 (1.70/yd^2) OGFC: 1.60/ m^2 (1.35/yd^2) SMA: 2.60/m^2 (2.20/yd^2)

- To cover a chip seal to improve retention and limit the amount of loose chips.
- To preserve the pavement for 1 to 2 years before placing a chip seal or AC overlay (based on the noted limitations).
- To rejuvenate an aging but otherwise intact asphalt concrete surface.
- To differentiate between the shoulder and mainline.

Although not a treatment that should be used extensively, fog seals are appropriate for limited use by the South Dakota DOT under the proper conditions.

Flush Seals

Flush seals provide the same benefits as fog seals with the added benefit of improving surface friction, at least for a few years. In addition, flush seals can be used on high-volume roadways. Flush seals are appropriate for the following applications:

- To enrich a dry, oxidized surface and to prevent infiltration of air and moisture.
- To provide surface friction to a newly placed AC surface.
- To cover a chip seal to improve retention and limit the amount of loose chips.
- To improve surface friction and extend the time (by 2 to 4 years) before placing a chip seal or AC overlay.

Flush seals are recommended for these particular applications.

Scrub Seals

Scrub seals can be used to rejuvenate the asphalt surface and to fill small voids and surface cracks. They are similar to a flush seal, with the primary difference being that they eliminate the need to seal cracks in a separate operation. Like flush seals, however, scrub seals do not provide long-term surface friction and do not address the raveling problem that is common in South Dakota. Although scrub seals are less expensive than chip seals, chip seals provide longer service lives and maintain higher levels of surface friction. Scrub seals are recommended for limited applications in South Dakota. In particular, they can be used on low-volume roadways to address pavements with both cracking and surface defects such as oxidation and raveling.

Slurry Seals

Slurry seals can be used to seal the pavement, to inhibit oxidation and raveling, and to improve surface friction. However, slurry seals have the following limitations:

- Slurry seals provide some of the same benefits as chip seals at a higher cost.
- The typical life of slurry seals is equal to or shorter than the life of a chip seal.
- Slurry seals perform best in warm-weather climates.
- Slurry seals require the use of crushed aggregates, which are not always locally available.
- Slurry seals require specialized equipment not available in South Dakota.
- Local contractors are largely unfamiliar with slurry seal operations.
- Slurry seals do not perform well when placed over cracked pavements.

For these reasons, the use of slurry seals is not recommended in South Dakota.

Microsurfacing

Like slurry seals, microsurfacing seals the pavement, inhibits surface aging and degradation, and improves surface friction. Similarly, many of the same arguments against the use of slurry seals can also be made against microsurfacing. However, one advantage of microsurfacing is that the process can correct non-progressing rutting up to 40 mm (1.5 in) deep, a benefit that most surface treatments cannot claim. In addition, microsurfacing has been used and has performed well on high-volume roadways. Its service life is at least equal to that provided by chip seals. Furthermore, loose chips are not a problem with microsurfacing.

Based on these factors, microsurfacing appears to be a viable option for South Dakota. However, the higher cost of microsurfacing as compared to chip seals suggests that its use should be limited to specialized applications. Furthermore, specialized equipment required for microsurfacing is not available in South Dakota, although it is available in nearby states. Consequently, the use of microsurfacing in South Dakota should be limited to specific applications, such as to addressing rutting.

Chip Seals and Sand Seals

Chips seals and sand seals have been widely used in South Dakota and this practice should continue. Although there have been problems with these surface treatments, they have for the most part served their purpose well. There are some enhancements to the standard design that should improve the performance of chip seals and sand seals for all applications. These recommendations, which include a tighter aggregate gradation, a more restrictive limitation on the percent fines, and the development of a design procedure to determine application rates, are outlined in other volumes of the guidelines. The incorporation of these recommendations should result in improved performance and fewer problems when these treatments are applied to roadways at all traffic levels. The standard design is recommended for most applications on low-volume to medium-volume roadways.

Additional modifications are recommended for chip seals placed on medium-volume to high-volume roadways and other roadways in which limiting the number of loose chips is critical. These recommendations include the use of a polymer-modified asphalt emulsion, precoating the aggregate chips, and sweeping the pavement before opening to traffic. Although these enhancements will result in additional costs compared to the standard chip seal, they are necessary to limit the amount of damage to vehicles. More specific recommendations about the conditions in which these enhancements should be employed are provided in subsequent guidelines.

In-Place Recycling

Cold in-place recycling (CIR) can be used to address surface distresses such as block cracking, thermal cracking, oxidation, and raveling. Hot in-place recycling (HIR) addresses these distresses in addition to rutting, corrugations, and bleeding. However, the cost of recycling can be four to six times more than the cost of chip seals and can be higher than the cost of providing a thin dense-graded hot-mix asphalt (HMA) overlay or an open-graded friction course (OGFC). Moreover, recycling requires specialized equipment. Consequently, the use of in-place recycling techniques as a surface treatment is not recommended in South Dakota.

Ultrathin Friction Courses

Ultrathin friction courses are an emerging technology that has yet to receive widespread use. Thus, their long-term performance is unknown, although the short-term results are promising. Ultrathin friction courses do eliminate the problem of loose chips, which is especially beneficial on high-volume/high-speed roadways. The cost of this surface treatment has been five or more times higher than that of conventional chip seals in South Dakota. Ultrathin friction courses may be appropriate for high-volume roadways under certain conditions.

Thin HMA Overlays

Thin, dense-graded HMA overlays and OGFCs have been used in South Dakota and have performed well. Their cost is about three times the cost of conventional chip seals, while their expected service life is about twice that of chip seals. Thus, thin HMA overlays have not been shown to be cost effective on a widespread basis. Their application is best suited for high-volume roadways where eliminating loose chips is critical. They can also be constructed during cooler weather and under other adverse conditions when applications of emulsion-based treatments are not feasible.

Feasible Surface Treatments

As described previously, an evaluation of all available surface treatments was conducted to identify those that are feasible for conditions in South Dakota. The feasible surface treatments, and those that are recommended for use in South Dakota are as follows:

- Fog seals.
- Flush seals.
- Scrub seals.
- Microsurfacing.
- Conventional sand seals and chip seals.
- Modified sand seals and chip seals.
- Ultrathin friction courses.
- Thin HMA overlays.

The most appropriate use of each of these surface treatments is addressed further in the treatment selection guidelines.

Treatment Selection Guidelines

Project Selection

Although the guidelines focus on the selection of the most appropriate alternative, the first step is to determine if a surface treatment is even applicable. There are several conditions under which a surface treatment should not be considered. For example, a surface treatment should not be considered if any of the following conditions exist:

- More than 10 percent medium-severity or 2 percent high-severity alligator cracking.
- Wide or deteriorated transverse and longitudinal cracks that cannot be adequately sealed prior to applying a surface treatment.
- Deteriorated or extensive patches (greater than 20 percent medium- and high-severity patches by the pavement area).
- Medium- or high-severity potholes.
- Rutting resulting from an unstable asphalt mix.
- Rutting in excess of 25 mm (1.0 in).
- International roughness index (IRI) greater than 30 mm/km (160 in/mi).
- Inadequate structure as evidenced by structural-related distress.
- Shoving of the asphalt concrete surface.
- Poor support conditions.
- Poor drainage or other moisture-related problems.

If any of these conditions exist, the use of a surface treatment should not be considered as an appropriate maintenance or rehabilitation technique. Such pavements are candidates for more extensive rehabilitation, such as a structural overlay or reconstruction, and are not addressed in these guidelines. Many of these distress definitions are defined in *SDDOT's Enhanced Pavement Management System, Visual Distress Survey Manual*.

Treatment Selection Matrix

Once the project is selected for a surface treatment, the decision must then be made as to which surface treatment is most appropriate for the specific application. The selection process involves a balancing act between a number of factors, which complicates the selection of the most appropriate treatment. The following factors need to be considered when selecting the surface treatment:

- Pavement condition.
- Traffic volumes.
- Project location (urban versus rural).
- Availability of aggregates.
- Availability of specialized equipment.
- Cost effectiveness of the surface treatment (this factor incorporates the cost of the treatment, the expected life of the treatment, and the benefit that the treatment imparts to the pavement during its life).

Table I-2 presents a decision matrix that provides guidelines for selecting the most appropriate surface treatment. Some of the key factors, such as pavement condition, traffic volumes, and project location, figure prominently in the decision matrix. Other factors, although not directly included in the decision matrix, are indirectly considered and incorporated in the decision process. A discussion of each of the key factors considered in the decision process is provided in subsequent sections.

Each cell within the matrix provides recommendations regarding the most feasible alternatives for the given condition. Other factors, such as the cost effectiveness of the surface treatments, the availability of the aggregate types, and agency experience, must then be considered to select among the feasible alternatives.

Factors Affecting Treatment Selection

Pavement Condition

The condition of the existing pavement surface is the primary factor affecting the selection of the most appropriate surface treatment. The decision matrix includes eight distresses that are addressed by surface treatments. The objective in using the matrix is to identify the distress types that are present in a significant enough quantity that they need to be addressed by the surface treatment. The quantity and/or severity that are listed for each distress indicate the degree that is considered significant. Distress types that are only present in small quantities should not be included because they should not control the selection process.

As an example, if a surface treatment is being designed to address longitudinal and transverse cracking on a medium-volume rural roadway, the feasible alternatives include a sand seal and a chip seal. Determination of the most appropriate treatment between these two feasible alternatives is then based on other factors (e.g., available aggregate types and cost effectiveness) as discussed later.

Although the decision matrix does not include severity levels for each distress type, the distress severity is indirectly considered in two ways. First, a surface treatment is only considered a feasible alternative if it meets the limiting conditions provided in the project selection guidelines. For example, one condition for eliminating surface treatments as a feasible alternative is rutting of more than 25 mm (1 in). Secondly, the quantity and severity of distress given in the table indicate if a distress is considered significant and should be addressed by a surface treatment.

The decision matrix also allows the consideration of more than one distress type (i.e., when two or more distress types are present in significant quantities and need to be addressed by the same surface treatment). The distress types are listed in such an order that the feasible surface treatments provided can also address all distress types at lower levels. For example, a chip seal is given as a feasible alternative for roughness on a medium-volume rural roadway, which means that a chip seal can also address each of the distress types listed below roughness, namely cracking, poor surface friction, raveling, and oxidation. Likewise, a feasible alternative for bleeding on a low-volume urban roadway is a thin overlay, which can also address each distress type listed below bleeding.

Table I-2. Guidelines for selecting surface treatments.

Significant Distresses	Rural Roadway			Urban Roadway		
	Low Volume	**Med. Volume**	**High Volume**	**Low Volume**	**Med. Volume**	**High Volume**
Rutting 12-25 mm (0.5-1.0 in)	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay	Microsurfacing Mill/Inlay and Thin Overlay
Bleeding > 10%	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Chip Seal*	Microsurfacing Thin Overlay Sand Seal Chip Seal	Microsurfacing Thin Overlay Chip Seal*	Microsurfacing Thin Overlay Chip Seal*
Roughness (IRI) 100-160 in/mi	Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Alligator Cracking 0-2% high 2-10% med 4-25% low	Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Long./Trans. Cracking 0-2% high > 2% med > 4% low	Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Poor Surface Friction SN < 40	Flush Seal Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Raveling 0-2% high 5-25% med 10-50% low	Flush Seal Scrub Seal Sand Seal Chip Seal	Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay
Oxidation (Asphalt Hardening)	Fog Seal Flush Seal Scrub Seal Sand Seal Chip Seal	Flush Seal Sand Seal Chip Seal	Chip Seal* Friction Course Thin Overlay	Sand Seal Chip Seal	Sand Seal Chip Seal Chip Seal*	Chip Seal* Friction Course Thin Overlay

Traffic levels are defined as follows:

- Low Volume: < 1,000 ADT
- Medium Volume: 1,000 to 2,500 ADT
- High Volume: > 2,500 ADT

* Indicates that one or more of the following additional modifications should be considered:

- Use of high-quality aggregate that may not be locally available
- Use of polymer-modified asphalt emulsion
- Application of a fog seal or flush seal over the chip seal
- Use of precoated chips
- Sweeping of chips before opening to traffic

To use the decision matrix most effectively, the first step is to list all distress types that need to be addressed by the surface treatment. Then, enter the decision matrix with the distress type that appears first in the *Significant Distress* column. For example, if designing a surface treatment to address roughness, poor surface friction, and raveling, only roughness needs to be used in the design chart because it appears higher in the list than the other distress types. The treatment selected to address roughness will also address poor surface friction and raveling.

Traffic Volumes

Traffic volumes are also a key factor in the selection process. The different traffic volume levels (two-way ADT) are defined as follows:

- Low volume: less than 1,000 vehicles per day.
- Medium volume: between 1,000 and 2,500 vehicles per day.
- High volume: more than 2,500 vehicles per day.

Traffic volumes are important for several reasons. First, the surface treatment must be able to handle the applied traffic over its entire design life. For this reason, flush seals are only recommended on low-volume roadways. Additionally, the surface treatment must also address other potential issues. For example, the surface treatments recommended for high-volume roadways should be designed to limit the amount of loose chips.

Location

The location of the roadway, in terms of whether it is in a rural or urban setting, is also directly considered in the decision matrix. The treatment selection process for roadways located in urban locations must address two additional concerns. First, the roadway will be more visible to the public and the treatment must be aesthetically pleasing. Secondly, urban roadways are subject to turning movements and must be designed to withstand such forces. For these reasons, more durable surface treatments are recommended for urban locations.

Availability of Aggregates

The availability of aggregates is not directly considered in the decision matrix. This factor should be considered once the feasible alternatives have been selected from the matrix. For example, if both a chip seal and a sand seal are given as feasible alternatives, the decision as to which alternative to use should be based on the cost effectiveness of the treatment, which may favor the aggregate type that is locally available.

Availability of Equipment

The availability of specialized equipment is not directly considered in the decision process. Rather, this factor is considered in the evaluation of feasible alternatives for South Dakota, which was discussed previously.

Environmental Conditions

The temperature restriction for surface treatments is a minimum of 21 °C (70 °F) and the construction season is limited to June 1 through September 15 when using a Type 2 cover aggregate and from June 1 through August 31 when using a Type 3 cover aggregate. Open-graded friction courses (OGFC) can be placed at 16 °C (60 °F) and must adhere to the same seasonal restrictions. Thin HMA overlays can be placed from May 1 through October 15 and temperatures must be greater than 4 or 7 °C (40 or 45 °F), depending on placement thickness. For Class S asphalt concrete, the construction season is limited to June 1 through September 15. These restrictions should be adhered to when selecting the most appropriated surface treatment.

Cost Effectiveness

Costs associated with the surface treatments are always a consideration and must be included in the selection process. Costs are considered in two ways. First, the costs of the surface treatments are considered indirectly in the decision matrix by listing feasible alternatives that are most cost effective for the particular application. For instance, an open-graded friction course is certainly a feasible alternative to address oxidation on a low-volume rural roadway. However, it is not listed because there are other surface treatments that address the problem equally well at a much lower cost.

Secondly, the life cycle costs of each of the feasible alternatives should be evaluated when selecting the most appropriate alternative. The life cycle cost analysis requires a reasonable projection of the expected life of the treatment. The analysis should then include all costs expected throughout the life of the treatment, including initial construction costs, maintenance costs, future rehabilitation costs, and salvage value. Guidelines for evaluating the cost effectiveness of treatment methods are provided elsewhere (Zimmerman 1997).

Selection Process

In summary, the process for selecting the most appropriate surface treatment for a specific application consists of the following steps:

1. Conduct a pavement condition survey and record all surface distresses.
2. List the distress types, quantities, and severities observed during the condition survey.
3. Check to ensure that the observed distresses can be addressed by the application of a surface treatment.
4. Identify the significant distresses (those exceeding the limits specified in table I-2) that need to be addressed by the surface treatment.
5. Select the feasible alternatives from table I-2 for the most significant distress (the significant distress that appears first in the table).
6. Identify and evaluate other considerations and constraints of the project.
7. Select the most appropriate of the feasible alternatives considering all other factors and constraints.

Example Problem

Select the recommended surface treatment for a roadway given the following information:

- Roadway characteristics
  - 2-lane roadway
  - Rural location
  - Lane width = 3.8 m (12.5 ft)
  - ADT = 1,400 vehicles per day
  - ADTT = 12 percent of ADT
- Existing pavement condition (distresses observed on 305-m [1,000-ft] section)
  - Alligator cracking: 6.0 m^2 (65 ft^2) low severity
  - Transverse cracking: 155 m (509 ft) low severity and 22 m (72 ft) medium severity
  - Longitudinal cracking: 25 m (82 ft) low severity and 7 m (23 ft) medium severity
  - Rutting: 7.4 mm (0.29 in)
  - Bleeding: 3.0 m^2 (32 ft^2) low severity
  - Raveling: 1.5 m^2 (16 ft^2) low severity and 0.4 m^2 (4 ft^2) medium severity

In addition, the project is located in the eastern part of the state and both quartzite and natural aggregate are available.

Example Problem Solution

Step 1. Conduct a pavement condition survey and record all surface distresses. A condition survey was conducted over a 305-m (1,000-ft) pavement section.

Step 2. List the distress types, quantities, and severities observed during the condition survey. The distress types and quantities are provided in the problem statement.

Step 3. Check to ensure that the observed distresses can be addressed by the application of a surface treatment. Each distress is checked against the limiting distress criteria. None of the observed distresses exceed the limiting distress criteria so a surface treatment is feasible for this pavement section.

Step 4. Identify the significant distresses (those exceeding the limits specified in table I-2) that need to be addressed by the surface treatment. To evaluate the extent of the distress, first calculate the percentage of area affected by a particular distress (assume a width of 0.3 m [1 ft] for cracks). Of the distresses exhibited on this section, only transverse cracking is considered a significant distress (4.1 percent low severity).

Step 5. Select the feasible alternatives from table I-2 for the most significant distress (the significant distress that appears first in the table). Using the decision matrix (table I-2) for a medium-volume (ADT = 1,400) rural roadway, the feasible alternatives to address transverse cracking are a sand seal and a chip seal.

Step 6. Identify and evaluate other considerations and constraints of the project. One factor to consider is the availability of aggregate in the area. In this case, both quartzite and natural aggregate are available. Other factors to consider include the experience of contractors in the area, the performance of the feasible treatments, the future rehabilitation plans for the roadway, and the cost effectiveness of the feasible treatments. If adequate information is available, a detailed life cycle cost analysis could be conducted.

Step 7. Select the most appropriate of the feasible alternatives considering all other factors and constraints. Collectively considering all factors, the most appropriate alternative is a chip seal using quartzite aggregate. A sand seal using natural aggregate is also feasible but the quartzite is believed to be a better option given the traffic volume on the roadway.

Summary

The suitability of the most common surface treatments used for maintaining asphalt concrete pavements is reviewed and recommendations are made for those treatments that should be used in South Dakota. These are identified as “feasible” treatments. Then, guidelines are proposed for selection of a recommended treatment from among the list of feasible treatments. The recommendations are based on the existence of primary, significant distresses on the pavement surface, coupled with considerations of the roadway’s traffic volume and location. Other factors, including environmental considerations, equipment availability, and aggregate selection, are addressed separately. The guidelines are presented in the form of a decision matrix, which is a readily understandable and easily followed tool that can be implemented by the South Dakota DOT.

Volume II. Guidelines for Design of Chip Seals

Introduction

This volume presents the guidelines for the design of chip seals. The guidelines first cover some general information regarding the aggregate chips and the asphalt emulsion. The guidelines then address the specific material properties that are used in the recommended design procedure. Finally, the design equations for the aggregate and emulsion application rates are presented. An example design problem, illustrating the design procedure in a step-by-step manner, is also presented.

Aggregate Chips

Aggregate Type

Three aggregate types—quartzite, limestone, and natural aggregates—are commonly used throughout the state. Quartzite is more common in the eastern part of the state, whereas limestone is more common in the western part of the state. Natural aggregates are found in the central as well as the northeast portion of the state. Other aggregate types, such as river gravel and granite, have been used for chip seals but are not common.

The selection of the aggregate type should be based on the availability and cost of aggregates in the area. The performance of chip seals with specific aggregate types should also be considered in the selection. On specialized applications, such as for high-volume roadways, additional considerations may need to be taken into account. For example, crushed aggregate can provide improved retention and durability characteristics.

Aggregate Shape

The ideal shape for aggregate chips is cubical and angular, as opposed to flat and rounded. Flat particles tend to orient on their flattest side under traffic loadings and can become completely covered with emulsion and create a bleeding problem. In addition, these completely embedded chips prevent proper embedment of chips that lie on top of the embedded chips, resulting in continued chip loss. With cubical aggregates, the chip height is essentially the same regardless of its orientation, resulting in more uniform chip embedment.

Angular or crushed aggregate particles are preferred over rounded particles. Rounded aggregates are more susceptible to rolling and displacement under traffic, especially in locations of stopping or turning traffic. Angular particles tend to lock together and provide better long-term retention and stability.

Aggregate Gradation

The aggregate gradation plays a key role in the design, construction, and performance of chip seals. The ideal gradation comprises the following characteristics:

- The aggregate chips should be similarly sized. A one-size aggregate provides a more uniform thickness and a more consistent and proper embedment of the chips, which improves the retention and performance of the chip seal. Similarly sized chips also help improve the surface friction and drainage capabilities of the chip seal.
- The aggregate bands should not be too wide. Allowing a wide range of aggregate retained on a particular sieve will result in widely varying gradations and differing performance. A tight gradation band ensures consistency and uniformity of the chip seal.
- The gradation should limit the amount of fines (material passing the 0.075 mm [No. 200] sieve). Fine materials create dust and can be a safety hazard for passing vehicles. Furthermore, fine materials absorb emulsion and can affect the bonding characteristics and performance of the chip seal.

To better account for these ideal properties, the aggregate gradations in table II-1 are recommended for all roadways. The maximum aggregate size is 9.52 mm (3/8 in). The gradation also forces the majority of the aggregate to a small range to create a more uniform chip seal. The gradation also addresses the amount of fines by limiting the material passing the 0.075 mm (No. 200) sieve to one percent. The recommended gradation for sections using a second choke stone layer are also provided in the table.

Table II-1. Recommended aggregate gradations for chip seal designs.

Sieve Size	**Percent Passing**	
	Aggregate Chips	**Choke Stone**
12.7 mm (1/2 in)	100	100
9.52 mm (3/8 in)	90 – 100	100
6.35 mm (1/4 in)	40 – 70	100
4.75 mm (No. 4)	0 – 15	85 – 100
2.36 mm (No. 8)	0 – 5	10 – 40
1.18 mm (No. 16)	–	0 – 10
0.300 mm (No. 50)	–	0 – 5
0.075 mm (No. 200)	0 – 1	0 – 1

Flat and Elongated Particles (Flakiness Index)

Like small particles, flat and elongated particles can become completely embedded in the emulsion and thus prevent larger aggregate particles from achieving proper embedment. The flakiness index—determined in accordance with the Central Federal Lands Highway Division (CFLHD) DFT-508, *Standard Method of Determining the Flakiness Index and Average Least Dimension of Aggregates*—should be performed to limit the amount of flat and elongated particles. The Flakiness Index is a measure of the percentage, by weight, of flat particles. For most applications, the Flakiness Index should be limited to 30 percent (i.e., the weight of flat and elongated particles should not exceed 30 percent of the total aggregate weight). For special applications such as high-volume roadways, the limit should be tightened to 20 or 25 percent.

Asphalt Emulsion

Emulsification is a process in which two otherwise incompatible materials are blended together. In the case of asphalt emulsion, the two incompatible materials are asphalt and water. An asphalt emulsion consists of asphalt particles dispersed in water, which is stabilized using a chemical solution (also known as an emulsifier). Upon application, the water and asphalt separate, a process referred to as "breaking" of the emulsion. The water then evaporates leaving the asphalt as the bonding agent.

Emulsion Classification

Asphalt emulsions are classified into three categories—anionic, cationic, and nonionic—referring to the electrical charge of the emulsifier surrounding the asphalt particles. Anionic emulsions have a negative electrical charge surrounding the asphalt particles, and cationic emulsions have a positive charge. Because opposite electrical charges attract, anionic emulsions should be used with aggregates that have a positive charge (such as limestone and natural aggregates). Likewise, cationic emulsions should be used with aggregates that have a negative charge (such as quartzite).

Emulsions are further identified based on how quickly they revert back to asphalt cement. The following terms are used to classify the emulsion grades:

- Rapid-setting (RS)
- Medium-setting (MS)
- Slow-setting (SS)
- Quick-setting (QS)

The grades indicate the speed at which the emulsion will become unstable and "break" coming into contact with the aggregate. An RS emulsion breaks very quickly and has little or no ability to mix with an aggregate. An MS emulsion will mix with coarse aggregate but not fine aggregate. SS and QS emulsions are designed to mix with fine aggregates.

High-float emulsions (designated as HF) allow a thicker film of asphalt material on the aggregate, which enhances the bonding and retention. They are designated as such because they pass the Float Test (ASTM D139 or AASHTO T50). High-float emulsions are recommended for use with dusty aggregates (greater than 2 percent fines).

Numbers are used in the classification to indicate the relative viscosity of the emulsion. Lower numbers indicate a lower viscosity or more fluid material (i.e., an MS-2 is more viscous than an MS-1). Letters are also sometimes used following the designation: "h" indicates a harder base asphalt, "s" indicates a softer base asphalt, and "p" indicates a polymer-modified asphalt.

Table II-2 shows the classifications for asphalt emulsion. Standard specifications are available for anionic asphalt emulsions (ASTM D977 or AASHTO M140) and for cationic asphalt emulsions (ASTM D2397 or AASHTO M208).

Table II-2. Classifications of asphalt emulsions.

Anionic Asphalt Emulsions	Cationic Asphalt Emulsions
RS-1	CRS-1
RS-2	CRS-2
HFRS-2	—
MS-1	—
MS-2	CMS-2
MS-2h	CMS-2h
HFMS-1	—
HFMS-2	—
HFMS-2h	—
HFMS-2s	—
SS-1	CSS-1
SS-1h	CSS-1h

Chip Seal Design

Chip seals should be designed so that the proposed materials are of sufficient quality and have the desired properties to provide the expected performance. Proper design also ensures that the proper application rates are being used. The design procedure presented herein is a modified version of the McLeod design procedure (McLeod 1969) and is currently being used by the Minnesota Department of Transportation (Janisch and Gaillard 1998).

The procedure is based on two basic principles:

- The aggregate application rate is designed to provide a chip seal that is one stone thick (i.e., there should be a single layer of uniformly sized chips) with minimal excess.
- The voids in the aggregate are designed to be 70 percent filled with asphalt cement for good performance (i.e., the chips should be 70 percent embedded).

Emulsion Properties

Residual Asphalt Content

A portion of an asphalt emulsion consists of water, which evaporates as the binder breaks. The amount of asphalt cement that remains after breaking is referred to as the residual asphalt content. It is important to consider the residual asphalt content because it represents the amount of material that is available for bonding to the aggregate. In general, the residual asphalt content is about 65 to 70 percent (i.e., 65 to 70 percent of an asphalt emulsion consists of asphalt cement).

As mentioned, the objective of this design procedure is to achieve 70 percent embedment of the average-sized aggregate. To accomplish this, the emulsion must be at the top of the average-sized aggregate before curing. If only 70 percent of the aggregate is covered initially, the asphalt height will be about 30 percent too low after curing.

Aggregate Properties

Median Particle Size

The median particle size is the theoretical size through which 50 percent of the material passes. It is determined from the gradation chart using the following sieve sizes: 25.0 mm (1 in), 19.0 mm (3/4 in), 12.5 mm (1/2 in), 9.5 mm (3/8 in), 6.3 mm (1/4 in), 4.75 mm (No. 4), 2.36 mm (No. 8), 1.18 mm (No. 16), 0.300 mm (No. 50), and 0.075 mm (No. 200).

Flakiness Index

The Flakiness Index is a measure of the percentage, by weight, of flat particles. It is determined by testing a sample of aggregate particles for their ability to fit through a slotted plate. The test is conducted in accordance with the Central Federal Lands Highway Division (CFLHD) DFT-508, *Standard Method of Determining the Flakiness Index and Average Least Dimension of Aggregates*. The weight of the material passing the slots is divided by the total weight of the aggregate sample to determine the percent of flat particles or Flakiness Index.

Average Least Dimension

The average least dimension represents a reduction of the median particle size after accounting for the amount of flat particles. It represents the chip seal thickness in the wheelpath after traffic has reoriented the chip on their flattest side. It is determined from the median particle size and flakiness index using the following equation:

$$H = \frac{M}{1.139285 + 0.011506FI} \qquad \text{(Eq. II-1)}$$

where:

H = Average least dimension, in.
M = Median particle size, in.
FI = Flakiness index, percent.

Loose Unit Weight

The loose unit weight is required in order to determine the voids in the aggregate in a loose condition. The voids represent the available space for the asphalt binder after placement and rolling. The loose unit weight is a function of the gradation, shape, and specific gravity of the aggregate. It should be determined in accordance with ASTM C29.

Bulk Specific Gravity

Bulk specific gravity represents the weight of aggregate as compared to the weight of water. Different aggregate types have different unit weights or specific gravities. This factor affects the application rate of the aggregate chips because a heavier aggregate will require more weight of chips (or a higher application rate) than a lighter aggregate to cover the same area. Bulk specific gravities for aggregates typically range from 2.40 to 3.00. Natural aggregates are generally about 2.40, and quartzite and limestone aggregates are generally around 2.60.

Voids in the Loose Aggregate

The voids in the loose aggregate represent the voids after the aggregate chips are placed on the pavement. It is based on the loose unit weight and can be determined using the following equation:

$$V = 1 - \frac{W}{62.4G} \quad \text{(Eq. II-2)}$$

where:

V = Voids in the loose aggregate.
W = Loose unit weight of the aggregate chips, lb/ft^3.
G = Bulk specific gravity of the aggregate.

For one-sized chips, this factor will typically be around 50 percent. Rolling will reduce the amount of voids, typically to around 30 percent. Traffic will further reduce the amount of voids to around 20 percent.

Aggregate Absorption

Aggregates, especially porous aggregates, will absorb a portion of the asphalt emulsion. This will affect the amount of asphalt binder that is available for bonding with the aggregate chips. To ensure that enough binder remains, this factor must be taken into account when designing the emulsion application rate. An absorption correction factor of 0.09 l/m^2 (0.02 gal/yd^2) is recommended for aggregates with absorption greater than 1.5 percent. Quartzite is generally not too absorptive and will not require an adjustment. Some limestone and natural aggregates, however, may require an adjustment to the emulsion application rate.

Other Design Properties

Traffic Volume

The traffic volume will influence the amount of asphalt binder that is required to provide sufficient embedment of the aggregate chips. All other factors equal, roadways with higher traffic volumes will require less asphalt binder. This may appear to be the opposite of what is typically expected. However, consider that traffic causes a reorientation of the chips until they eventually lie on their flattest side. More traffic thus results in a greater probability that the chips will be laying on their flattest side and will result in a thinner chip seal. Less traffic will result in a thicker chip seal and will thus require more asphalt binder to achieve sufficient embedment. Table II-3 provides the recommended traffic correction factor to be used in determining the emulsion application rate. Failure to account for this factor will result in bleeding in the wheelpaths.

Table II-3. Recommended traffic correction factors.

Traffic (ADT)	Traffic Factor
< 100	0.85
100 – 500	0.75
500 – 1000	0.70
1000 – 2000	0.65
> 2000	0.60

Traffic Whip-Off

A portion of the aggregate chips will get thrown off the roadway before final curing and embedment under traffic has occurred. This is accounted for in the procedure using a traffic whip-off factor. The factor is based on the traffic volume and traffic speed of the roadway. Low-volume, residential streets will have about a 5 percent loss, whereas the loss on high-volume, high-speed roadways will be around 10 percent. The factor can be computer using the following equation:

$$E = 1 + \frac{P}{100} \qquad \text{(Eq. II-3)}$$

where:

E = Traffic whip-off factor.
P = Expected loss of aggregate chips, percent.

Thus, an expected loss of 10 percent results in a traffic whip-off factor of 1.10.

Existing Pavement Condition

The surface condition of the existing pavement will greatly influence the amount of asphalt emulsion that is required. A dry, porous pavement will absorb a tremendous amount of asphalt binder and thus affect the emulsion application rate. Conversely, a new pavement (or a pavement with bleeding on the surface) will absorb much less binder. The varying condition is accounted for in the design procedure by the surface correction factor. The recommended value, based on the pavement surface texture, is provided in table II-4.

The same application rate cannot be used for all roadways with varying conditions. Similarly, the surface condition should be monitored during placement, and the application rate adjusted as needed to address areas of differing condition.

Table II-4. Recommended surface correction factors.

Existing Pavement Surface Texture	Surface Correction Factor, gal/yd^2
Black, flushed asphalt	-0.01 to -0.06
Smooth, non-porous	0.00
Slightly porous and oxidize	+0.03
Slightly pocked, porous, and oxidized	+0.06
Badly pocked, porous, and oxidized	+0.09

Design Equations

Once the inputs are determined, the application rates can be calculated using the McLeod design equations. The equations for aggregate and emulsion application rates are presented below.

Aggregate Application Rate

The following equation is used to determine the aggregate application rate:

$$C = 46.8\left(1 - 0.4V\right) \times H \times G \times E \qquad \text{(Eq. II-4)}$$

where:

C = Chip application rate, lbs/yd^2.
V = Voids in loose aggregate.
H = Average least dimension, in.
G = Bulk specific gravity.
E = Traffic whip-off factor.

Emulsion Application Rate

The emulsion application rate is determined using the following equation:

$$B = \frac{2.244 \times H \times T \times V + S + A}{R} \qquad \text{(Eq. II-5)}$$

where:

B = Binder application rate, gal/yd^2.
H = Average least dimension, in.
T = Traffic correction factor.
V = Voids in loose aggregate.
S = Surface correction factor.
A = Aggregate absorption factor, gal/yd^2.
R = Residual asphalt content of binder.

Minnesota performs an additional calculation of the emulsion application rate to account for snow plow damage (Janisch and Gaillard 1998). The emulsion application rate is recalculated using the median particle size instead of the average least dimension. This new emulsion rate provides the required rate if the chips are not reoriented, and thus is more representative of the rate required outside the wheelpath. The average of the two rates is then used as the starting point in the field. Minnesota has found that if this additional calculation is not performed, insufficient binder is applied in non-traffic areas, and snow plows shave off the chips (Janisch and Gaillard 1998).

Example Design Problem

A 68 kg (150 lb) sample of quartzite aggregate has been submitted for design. The roadway has traffic levels of 2,125 vehicles per day. The pavement surface is slightly pocked, porous, and oxidized. A CRS-2 emulsion with a residual asphalt content of 66.5 percent will be used as the binder. Determine the emulsion and aggregate application rates for this project.

Step 1. Determine the aggregate gradation, bulk specific gravity, and percent absorption.

Laboratory testing of the aggregate revealed the gradation as shown in table II-5. Testing in accordance with AASHTO T 84-94 indicates a bulk specific gravity of the aggregate of 2.61. The aggregate absorption based on AASHTO T 84-94 is 0.55 percent, so no correction is needed.

Table II-5. Gradation results for design project.

Sieve Size	Percent Passing
12.7 mm (1/2 in)	100
9.52 mm (3/8 in)	95
6.35 mm (1/4 in)	62
4.75 mm (No. 4)	12
2.36 mm (No. 8)	3.2
0.075 mm (No. 200)	1.3

Step 2. Determine the mean particle size.

The median particle size (M) is determined by plotting the gradation results and reading off the size at which 50 percent of the particles pass. The median particle size represents the theoretical size at which half the stones are larger and half are smaller. For the given gradation, the median particle size is determined to be 5.8 mm (0.23 in).

Step 3. Determine the flakiness index.

To determine the flakiness index, the aggregate particles are fitted through slots. The results of this testing is shown in table II-6.

Table II-6. Results of flakiness index test.

Size Fraction	Weight Retained on Slot, grams	Weight Passing Slot, grams
12.5 to 9.5 mm (1/2 to 3/8 in)	54.2	12.3
9.5 to 6.3 mm (3/8 to 1/4 in)	123.3	43.5
6.3 to 4.75 mm (1/4 in to No. 4)	184.4	89.5
Total	**361.9**	**145.3**

Using these results, the flakiness index (FI) is determined as follows:

$$FI = \frac{Weight\ of\ \ Flat\ Chips}{Weight\ of\ \ Sample} = \frac{145.3}{361.9 + 145.3} = 0.286 = 28.6\ percent$$

Step 4. Determine the average least dimension.

The average least dimension (H) is the expected thickness of the chip seal after the chips have been reoriented on their flattest side from traffic. It is determined using equation II-2 as follows:

$$H = \frac{M}{1.139285 + 0.011506FI} = \frac{0.23\,in}{1.139285 + 0.011506 \times 28.6} = 0.157\ in$$

Step 5. Determine the loose weight of the aggregate.

A metal cylinder with a volume of 0.014 m^3 (0.50 ft^3) was loosely filled with aggregate and weighed. This process was repeated three times, the results of which are shown in table II-7.

Table II-7. Results of loose unit weight testing.

Test Number	Weight of Aggregate, kg (lbs)
1	20.57 (45.25)
2	20.60 (45.32)
3	20.59 (45.29)
Average	**20.59 (45.29)**

The loose unit weight (W) is then determined as follows:

$$W = \frac{Weight\ of\ \ Aggregate}{Weight\ of\ \ Cylinder} = \frac{45.29\ lbs}{0.50\ \ ft^3} = 90.58\ lbs\,/\ ft^3$$

Step 6. Determine the voids in the loose aggregate.

The voids in the loose aggregate (V) is determined using equation II-3 as follows:

$$V = 1 - \frac{W}{62.4G} = 1 - \frac{90.58\ lbs/ft^3}{62.4\ lbs/ft^3 \times 2.61} = 0.44$$

Step 7. Determine the aggregate application rate.

With the inputs determined above, equation II-4 is used to determine the aggregate application rate (C):

$$\begin{aligned} C &= 46.8\,(1 - 0.4V) \times H \times G \times E \\ &= 46.8\,(1 - 0.4 \times 0.44) \times 0.157 \times 2.61 \times 1.10 = 17.3\ lbs/yd^2 \end{aligned}$$

Step 8. Determine the emulsion application rate.

The emulsion application rate is determined using equation II-5. The calculation is performed twice—once for the wheelpath areas (using the average least dimension) and again for the non-wheelpath areas (using the median particle size). These calculations are shown below:

$$B = \frac{2.244 \times H \times T \times V + S + A}{R} = \frac{2.244 \times 0.157 \times 0.60 \times 0.44 + 0.06 + 0.00}{0.665} = 0.23\ gal/yd^2$$

$$B = \frac{2.244 \times M \times T \times V + S + A}{R} = \frac{2.244 \times 0.23 \times 0.60 \times 0.44 + 0.06 + 0.00}{0.665} = 0.30\ gal/yd^2$$

The average of the two results (0.27 gal/yd^2) is used as the starting point in the field.

Volume III. Guidelines for Construction of Chip Seals

Introduction

This volume presents the guidelines for the construction of chip seals. The guidelines present information on the required equipment and recommendations on each step of the construction process. Seasonal and weather limitations and guidance on traffic control are also provided.

Equipment Considerations

Emulsion Distributor

The emulsion distributor shall be capable of applying a uniform layer of emulsion to the correct depth and width. The distributor shall be a self-propelled and shall be equipped with pressure-type mechanical circulating pumps and valves, as well as a heating system and insulated tank, such that it is capable of maintaining a uniform temperature throughout the entire contents of the distributor tank. The distributor shall have a capacity of at least 3000 liters (800 gallons).

The distributor shall uniformly apply the heated material to the roadway surface in accurately measured quantities and shall maintain the specified application rate during the distribution of the entire tank. The spray nozzles shall be designed, sized, and arranged to ensure uniform distribution of heated material at the designated rate, in an overlapping fan spray without surge, streaks, ridges, or bare spots. Calibration runs shall be made at the start of the work to verify proper operation.

Aggregate Spreader

The aggregate spreader shall be self-propelled and have positive controls capable of applying a uniform layer of aggregate across the entire width of the roadway being sealed. Calibration of the chip spreader shall be conducted prior to the start of the work to ensure uniform and accurate application.

Power Broom

A rotary power broom shall be used for sweeping prior to and after chip seal placement. The broom shall be capable of removing all loose dirt and debris and providing a clean, dry surface for bonding of the asphalt emulsion.

Rollers

Rollers shall be self-propelled pneumatic smooth tired rollers. A minimum of four rollers per spreader shall be supplied, or more if needed to meet the required rolling requirements. Each roller shall completely cover an overall surface width of at least 1.5 m (5 ft) and furnish a uniform rolling weight of 4.5 kg/mm (250 lbs/in) of rolling width.

Seasonal and Weather Limitations

The placement of chip seals shall be permitted only during daylight hours, when conditions are dry and when wind conditions do not adversely affect the spraying operation. The air and surface temperature shall be 21 °C (70 °F) in the shade. The construction season for chip seals shall be limited to between June 1 and August 31.

Construction Sequence

Surface Preparation

All potholes and other high-severity distresses shall be repaired before chip seal placement. The patch shall be placed sufficiently ahead of the chip seal to allow for curing of the patch. Failure to repair these areas will result in localized deterioration in the chip seal shortly after placement.

Immediately prior to placement, the pavement surface shall be thoroughly swept with a rotary power broom and cleaned of all foreign material. Otherwise, dust and other debris on the pavement surface will reduce the ability of the chip seal to adequately bond to the surface.

Emulsion Application

The asphalt emulsion shall be maintained within a temperature range of 49 to 82 °C (120 to 180 °F) during application. The emulsion shall be applied by a pressure distributor in a uniform and continuous manner. The angle of the spray nozzles and the height of the spray bars shall be set to obtain uniform distribution across the roadway width. The distributor shall travel at the established speed when the spray bar is opened. Skipped areas and areas of deficiencies shall be immediately corrected. Areas that are inaccessible to the distributor shall be effectively covered by hand spray methods.

When starting and stopping emulsion application, a strip of building paper or other suitable material, at least 1 m (3 ft) in width and at least 0.3 m (1 ft) longer than the width of the spray bar, shall be used to prevent a double application of emulsion.

Spraying operations shall not proceed when it is evident that the emulsion spread will not be covered with aggregate and rolled in accordance with the prescribed schedule.

Aggregate Application

Cover aggregate shall be spread immediately following application of the emulsion. For wind conditions of 8 km/hr (5 mi/hr) or less, the cover aggregate shall be spread within 5 minutes of the application of the emulsion. For wind conditions greater than 8 km/hr (5 mi/hr), the time may be reduced in the field to ensure the aggregate is applied before the emulsion breaks. Time limits for spreading of cover aggregate when using high-float or rapid-setting emulsions shall be adjusted as directed to satisfy project conditions. The aggregate shall be applied before the emulsion begins to break (emulsion still brown in color).

Complete aggregate coverage, with an excess of 5 to 10 percent of the aggregate, shall be maintained. A strip of asphalt emulsion approximately 100 mm (4 in) wide along the edge of the spread forming a longitudinal joint with the adjacent spread shall be left uncovered. The adjacent emulsion and cover aggregate applications shall overlap this strip. In lieu of this procedure, a butt joint may be constructed using special end nozzles. Longitudinal joints, other than at the roadway centerline, shall not be permitted within the center 7.2 m (24 ft).

Monitoring of Application Rates

The use of the design procedure outlined in Volume II of the Guidelines will produce desirable application rates. However, the rates shall be continuously monitored in the field to achieve the following goals:

- The emulsion application rate shall be such that it fills the void between the aggregate to about the top of an average-sized chip. Upon breaking of the emulsion and loss of water, the embedment shall be 70 percent as designed.
- The aggregate application rate shall be such that a single layer of chips is placed with between 5 and 10 percent excess chips.

Two simple tests to evaluate the application rates are recommended.

First, the average chip embedment shall be checked by removing several aggregate particles and estimating the depth of emulsion coverage. This test shall be conducted after breaking of the emulsion. The emulsion application rate shall be adjusted as needed to achieve an average embedment depth of 70 percent.

The second test is the aggregate sweep test. To perform this test, a template of known area shall be placed on the chip seal surface after curing. All loose chips within this known area shall be swept up and weighed. The aggregate application rate shall be adjusted as needed to achieve between 5 and 10 percent excess chips by weight.

Rolling

Rolling shall begin immediately behind the spreader and shall consist of four complete coverages using pneumatic tired rollers. Rolling shall be completed within 40 minutes after the cover aggregate is applied. Rollers shall be operated in unison at a close interval, and if the width of the spread allows, in a staggered formation. Rollers speeds shall be limited to a maximum of 8 km/hr (5 mi/hr) and shall not extend beyond 0.8 km (0.5 mi) of the emulsion and aggregate applications.

The weight and tire pressures of the rollers shall be varied as directed to obtain optimum embedment of the material without undue crushing of the aggregate. Special attention shall be given to ensure adequate rolling at transverse and longitudinal joints. Unsatisfactory joints shall be corrected without additional compensation. Turning of rollers on the newly placed surface shall be prohibited. Rolling at night or when light conditions create a traffic hazard will not be allowed.

Final Brooming

Loose material left on the surface shall be lightly broomed off. Where feasible, the loose material shall be swept off before allowing normal speed traffic on the pavement. The final brooming shall not occur before the emulsion has adequately cured. If additional aggregate is dislodged by the brooming operation, sweeping shall be postponed until such time that this does not occur.

Traffic Considerations

Construction operations shall be coordinated to minimize traffic delays. One-way traffic shall be maintained during application of the chip seal on driving lanes. Upon completion of rolling, traffic shall be permitted on the newly placed surface. Traffic shall be controlled by pilot vehicles and flaggers during application on driving lanes. Vehicle speeds shall be limited to at most 64 km/hr (40 mi/hr) on the freshly applied surface for a period of at least 4 hours after application, and preferably until final brooming is completed. Limiting vehicle speeds to 32 km/hr (20 mi/hr) are preferred but may not always be feasible, such as on high-speed roadways and roadways with lengthy closures.