Manual for Emulsion-Based Chip Seals for Pavement Preservation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Manual for Emulsion-Based Chip Seals for Pavement Preservation

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The work was done under the general supervision of Dr. Scott Shuler, Associate Professor of Construction Management at CSU, who served as the Principal Investigator. The other authors of this report are Anthony Lord, Ph.D. candidate and Research Assistant at CSU, Amy Epps-Martin, Associate Professor at TAMU, and Denise Hoyt, M.S. candidate and Research Assistant at TAMU. Additional contributors to this work include Charles Leudders, FHWA Federal Lands Division, Ben Vagher, A-1 Chip Seal, William Trudahl, Washington state DOT, and Roy Guevera, Colorado Department of Transportation. The authors gratefully acknowledge the work and technical assistance of Nikornpon Prapaitrakul, Rongbin Han, Xin Jin, and Charles J. Glover of the Artie McFerrin Department of Chemical Engineering, Texas A&M University, and of Rick Canatella of the Texas Transportation Institute McNew Laboratory, Texas A&M University.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents a manual for the use of emulsion-based chip seals for pavement preservation. The manual addresses the factors affecting chip performance, discusses design and construction considerations, and identifies procedures for selecting the appropriate chip seal materials. The report also contains recommended test methods for use in the design and quality control of chip seals. The test methods are presented in AASHTO format to facilitate incorporation into the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing.* The material contained in the report should be of immediate interest to state maintenance engineers and others involved in the maintenance and preservation of flexible pavements.

Emulsion-based chip seals are the most commonly used chip seal type in the United States. These seals are frequently used as pavement preservation treatments on flexible pavements to seal fine cracks in the underlying pavement's surface and prevent water intrusion into the base and subgrade. Because chip seals are not expected to provide additional structural capacity to the pavement, benefits ideally are accrued by their application early in a pavement's life before a great degree of distress is exhibited. Although a large body of research is available on chip-seal design practices, the design process in the United States remains empirical in nature—based on experience and judgment. Procedures that consider the surface condition of the existing pavement, traffic volume, environment, and other relevant factors in determining the characteristics and application rates of aggregates and binder have not been widely used in the United States.

In spite of their apparent benefits, the use of chip seals for pavement preservation in the United States is hampered by the lack of nationally accepted guidance on their design and construction and appropriate specifications and testing procedures for constituent materials. Thus, research was needed to identify the factors that influence chip-seal design and performance and to develop a manual that documents design and construction practices and delineates necessary testing and specifications. Such a manual will provide highway agencies with the information necessary for designing and constructing long-lasting chip seals and preserving pavements.

Under NCHRP Project 14-17, "Manual for Emulsion-Based Chip Seals for Pavement Preservation," Colorado State University of Fort Collins conducted a review of available information relevant to design and construction practices of emulsion-based chip seals, conducted laboratory tests and field investigations to evaluate the factors affecting chip seal performance, and prepared a manual for designing and constructing chip seals over hot-mix asphalt pavements together with test methods for evaluating some aspects of chip seal construction. In addition to the manual and test methods, the report includes a summary of the research performed, related findings and recommendations, and appendices that provide further elaboration on the research.

The manual and test methods presented in this report will be particularly useful to highway agencies because the manual provides a rational approach for the design of chip seals used in the preservation of pavements and the test methods provide appropriate means for control of chip seal construction. The adoption of this manual and test methods by AASHTO is, therefore, suggested.

The appendices contained in the research agency's final report provide further elaboration on the work performed in this project. These appendices are not published herein but are available on the *NCHRP Report 680* summary webpage at http://www.trb.org/Main/Blurbs/164090.aspx.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

Manual for Emulsion-Based Chip Seals for Pavement Preservation

This proposed manual, prepared as part of NCHRP Project 14-17, Manual for Emulsion-Based Chip Seals for Pavement Preservation, is a recommendation by NCHRP Project 14-17 staff at Colorado State University. This manual has not been approved by NCHRP or any AASHTO committee or formally accepted for adoption by AASHTO.

CHAPTER 1

Introduction

This manual was developed for use in designing and constructing chip seals over hot mix asphalt pavements. It documents best practices based on the findings of research during NCHRP Project 14-17, Manual for Emulsion-Based Chip Seals for Pavement Preservation. A summary of the research performed in this project is provided in the attachment. Also, test methods developed in this research for use in conjunction with this manual are provided in the appendix. In addition, certain subjective or qualitative judgments previously needed during chip-seal construction have been eliminated in favor of field and laboratory testing. These include the moisture content of the seal before traffic can be released, judging surface condition so emulsion application rate can be adjusted for surface demand, and measuring the emulsion consistency in the field. The introduction of these new techniques should improve the probability of success when designing and constructing chip seals, but they do not replace the significant judgment required. Also, the success of any chip seal depends on conformance to best practices, and variance or elimination of these practices often leads to disappointing performance.

1.1 Definition of Chip Seals

Chip seals described in this manual are based on emulsified asphalt binders and natural mineral aggregate chips. The chip seal is constructed by spraying the asphalt emulsion onto the existing asphalt pavement and then dropping the aggregate chips into the asphalt emulsion. The purpose of the chip seal is to seal minor cracks in the surface of the asphalt pavement and provide additional friction.

CHAPTER 2

Factors Affecting Chip-Seal Performance

The performance of a chip seal depends on many factors, including the condition of the pavement to which the chip seal is to be applied, pavement geometry, traffic volume and type, materials, and construction practices. The following discussion describes these factors and their effects on the performance of the chip seal.

2.1 Pavement Behavior and Condition

2.1.1 Deflection of Substrate

The amount of deflection is an indication of whether future fatigue can be expected. If deflection is significant, a chip seal may be inappropriate. The maximum level of deflection will vary depending on the traffic volume; however, if fatigue cracking is already present, chip-seal performance may be reduced. However, a chip seal may reduce moisture infiltration into the subgrade, thus reducing the potential for future fatigue. Therefore, the decision to chip seal over existing fatigue cracking requires judgment depending on the performance expectation of the existing pavement.

2.1.2 Cracking Severity

Chip seals are most effective as a pavement preservation technique before cracks are ranked as high severity (Peshkin et al. 2004), defined as a crack width of ⅜ in. Although the chip-seal binder has the ability to seal cracks greater than this width, as crack width increases, the emulsion residue is less effective at bridging the gap across the crack and sealants should be used to fill these cracks prior to chip sealing.

2.1.3 Flushing/Bleeding

Chip seals may be applied to remedy friction loss, but penetration of chips into flushed pavement surfaces may limit effectiveness unless chips can be retained with lower emulsion application rates. Flushing and bleeding of the existing surface often occurs in wheel paths. If this occurs, the emulsion application rate must be reduced in the wheel paths to prevent future flushing and bleeding. This can only be accomplished with variable spray rate distributors or by varying the size of the nozzles in the distributor spray bar.

2.1.4 Texture

Surface roughness affects the amount of emulsion needed to hold aggregate chips in place. The texture of the substrate pavement should be evaluated using the sand patch test or CT meter prior to chip sealing to determine whether an adjustment to the design emulsion application rate is appropriate and to what level.

2.1.5 Soft Substrate Surface

A soft substrate surface can allow chips to be embedded in the surface after trafficking, resulting in possible flushing. The ball penetration test has been shown to be an effective tool for measuring this potential.

2.1.6 Uniformity

The amount of emulsion applied to the substrate may need to be varied if the substrate surface does not have the same texture and compliance along the alignment. Uniformity should be mapped prior to construction to identify locations where emulsion application rates should vary from design. Uniformity can also vary transverse to the centerline, which often occurs when wheel paths are flushed. In this case the emulsion application rate should be reduced in the wheel paths by using a distributor equipped with a variable application spray bar or placing smaller nozzles in the conventional distributor spray bar in locations that will affect the wheel paths (Shuler 1991, Martin 1989).

2.2 Traffic Characteristics

The traffic volume and type of traffic affect the selection of materials used on chip seals. Generally, higher traffic volume and a higher percentage of heavy trucks on an undivided roadway present a greater likelihood for vehicle damage if traffic is not adequately controlled during construction. In addition, the volume and type of the traffic are directly related to the potential for chip embedment in the substrate. Also, traffic acceleration affects chip-seal performance as chips are more likely to be dislodged under these loads than at constant speeds, which can lead to flushing and bleeding of the surface. This section discusses the factors that influence the material's selection process depending on traffic volume, type of traffic, and speeds.

2.2.1 Chip Selection

Larger chips provide more tolerance for emulsion application variance and are less likely to become totally embedded by traffic if the substrate is resistant to embedment. Larger chips require higher emulsion application rates for proper embedment, thus increasing the sealing ability of the chip seal. However, large chips are noisier and provide higher risk of vehicular damage during construction.

2.2.2 Emulsion Selection

Emulsions modified with elastomeric polymers provide higher adhesion for aggregate chips, often both during construction and later in the life of the seal. Also, research (Shuler 1991) indicates that on high traffic facilities (i.e., greater than 7,500 vehicles per day per lane), modified asphalt emulsions are required to hold chips in place due to reduced emulsion application rates that are necessary to reduce the potential for embedment in the substrate and consequent flushing.

2.2.3 Fog Seal

The application of a fog seal over a fresh chip seal provides high color contrast that improves visibility of striping, and short-term performance improvement (Shuler 2007). Care should be taken whenever applying a fog seal since pavement friction could be reduced if the fog seal is applied at too high an application rate, the fog seal emulsion has a high residue content, or the fog seal has not broken sufficiently to support uncontrolled traffic.

2.3 Geometry

2.3.1 Divided/Undivided

Divided alignments generally reduce the possibility for vehicle damage caused by loose, flying chips because of the separation of opposing traffic.

2.3.2 Gradient/Curves

Steep inclines and curves may adversely affect performance due to tractive forces and slower moving vehicles. Therefore, traffic control may need to remain in place until the emulsion has cured sufficiently to retain the chips.

2.3.3 Intersections

Turning, acceleration, and deceleration can cause chip loss and flushing. Therefore, traffic control may need to remain in place until the emulsion has cured sufficiently to retain the chips.

2.3.4 Width

Vehicle movement tends to be more concentrated on narrow, secondary roads than on wider primary facilities. This results in a greater tendency for flushing in the wheel paths on these types of pavements.

2.4 Highway, Residential, Urban, or Rural

2.4.1 Highway

Chip seals can be successfully constructed on highways with over 7,500 vehicles per day per lane with little or no consequences with respect to vehicle damage (Shuler 1991) if important principles are followed. However, other factors should be considered regarding the use of chip seals on high traffic highway pavements. Because noise increases with increasing traffic volume and chip size, smaller aggregates are often desired for high traffic facilities. However, more accuracy relative to emulsion spray rate is needed when using smaller aggregates because the smaller embedment depth increases the potential for chip loss.

2.4.2 Residential

Chip seals constructed with larger aggregates are rough textured. This rough surface texture is often unpopular among residential users such as roller skaters and skateboarders or individuals who need to lie on the pavement to repair vehicles.

2.4.3 Rural

Rural settings are the most appropriate for chip seals. Traffic tends to move more consistently with less stopping and starting, and volumes are often lower, creating wider vehicle separation providing less possibility for vehicle damage.

2.4.4 Urban

Urban environments are often the most challenging environment for chip seals because of the higher traffic volumes and frequent turning, stopping, and starting. Although chip seals can be constructed in such environments with success, the time required for emulsions to gain sufficient strength to resist the turning, acceleration, and deceleration of vehicles in large volumes is often long enough to preclude their use.

2.5 Materials

2.5.1 Aggregate Chips

Aggregate properties, including size, shape, and gradation; cleanliness; moisture content; toughness and durability; and porosity influence chip-seal performance.

2.5.1.1 Size, Shape, and Gradation

Aggregates that interlock after construction rolling and early trafficking provide higher stability under loads. This interlocked aggregate surface is more resistant to displacement and thus has a lower potential for dislodgement of chips and vehicle damage and flushing.

Larger aggregates require higher emulsion application rates in order to provide an equivalent embedment percentage to smaller aggregates. This higher application rate allows slightly more tolerance during construction with respect to depth of chip embedment in the binder. Also, the higher binder application provides greater sealing ability.

Aggregates retained between two adjacent sieve sizes provide the best interlock, followed by aggregates that occupy the space between three adjacent sieve sizes; these are often described as one- and two-sized aggregate chips, respectively. The performance of the one- and two-sized chips is related to the manner by which the chips are embedded in the emulsion. If well-graded aggregates are used, the fine aggregate often enters the emulsion before the coarse aggregate, causing the coarse aggregate to have less binder available for adhesion and resulting in loss of the coarse fraction, vehicle damage, and flushing.

2.5.1.2 Cleanliness

Emulsified asphalts can be produced with the ability to coat aggregate chips containing small quantities of minus no. 200 aggregate. The maximum amount of this fine aggregate is dependent on the emulsion. For example, medium setting emulsions can tolerate a higher percentage than most rapid setting emulsions; this is often related to the demulsibility of the emulsion. The higher the demulsibility, the less minus no. 200 can be tolerated before setting occurs and there is loss of adhesion to the coarse chips.

2.5.1.3 Moisture Content

Aggregates in the saturated surface dry condition provide better resistance to sweeping than dry aggregates when asphalt emulsions are used. Therefore, construction aggregates should be moistened by spraying water on the stockpile and mixing with a front-end loader before chip-seal operations begin.

2.5.1.4 Toughness and Durability

Aggregates must have enough strength to resist crushing during construction and trafficking. Breakdown of the aggregate during construction and trafficking could lead to inundation and flushing if the coarse particles are reduced to fine particles.

2.5.1.5 Porosity

Porous aggregates will absorb more asphalt than nonporous aggregates. Therefore, the amount of asphalt absorbed must be accounted for during the design stage.

2.5.2 Asphalt Emulsion

The performance of a chip seal is largely dependent on the asphalt emulsion. Performance is related to the adhesive ability of the binder for the aggregate chips and the underlying pavement, the durability and flexibility of the binder, and the ability of the binder to maintain these properties over a wide range of environmental conditions and snowplow action.

2.5.2.2 Emulsion Type

Emulsified asphalts should be rapid setting types. Although rapid setting emulsions allow faster removal of traffic control, they can set too quickly in very hot weather or even form a skin on the surface after application, creating a barrier to chip embedment. Medium setting emulsions require more time to set, requiring traffic control to remain in place longer and increasing the possibility for vehicle damage. However, while rapid setting emulsions are the most desirable as a chip-seal binder, medium setting emulsions have been used successfully on low volume roads when strict traffic control is maintained. Medium setting emulsions have also been successful when chips are more uniformly graded or contain higher quantities of minus no. 200 particles.

2.5.2.3 Emulsion Class

Emulsions are classified based on the particle charge of the asphalt droplets within the water phase of the suspension. Anionic emulsions have a negative charge and cationic emulsions a positive charge. There are also a limited number of emulsions classified as nonionic with no appreciable charge. These emulsions can be considered interchangeable as both classifications should provide equal performance with respect to adhesion to aggregate chips. Research has shown no difference in the adhesion of different classes of emulsions to aggregates (Shuler and Lord 2009). However, the selection of emulsion should take into consideration the environmental conditions present during construction. For example, anionic emulsions break by evaporation so humid site conditions could lead to longer setting times for anionic compared with cationic materials. High float emulsions are a class of emulsion that can be either anionic or cationic and are formulated with a gel structure to produce a thicker asphalt coating on aggregate chips. Some high float emulsions contain oil distillates that increase setting time, so increased traffic control may be needed for these products.

2.5.2.4 Viscosity Grade

Emulsions are produced in two viscosity categories, designated "–1" and "–2" for low and high viscosity, respectively. Because aggregate chips require approximately 40% initial embedment during construction, the high viscosity emulsions should always be used since the low viscosity emulsions would flow off the substrate.

The viscosity of the emulsion during construction is an important factor. Emulsions with too low viscosity could flow off the pavement before the aggregate chips are embedded, resulting in a loss of chips under traffic and potential environmental issues. Emulsions with too high viscosity may not provide adequate coating of the aggregate chips, leading to a loss of chips.

2.5.2.5 Application Rate

The binder application rate must be correct during construction to achieve optimum performance of the chip seal. Too little emulsion will not retain chips in place under traffic, and too much emulsion will lead to flushing and loss of friction. The optimal application rate is a function of the volume of voids in the compacted aggregate chip layer, the volume and type of traffic, the pavement gradient, and the condition of the substrate pavement.

2.5.2.6 Emulsion Application Temperature

Emulsion application temperature should be within a range to provide uniform transverse and longitudinal spraying but should not exceed 185°F (85°C).

2.6 Construction Preparation

Preparation of the pavement surface prior to chip-seal operations can influence performance of the chip seal. This preparation varies depending on the condition of the existing pavement but at a minimum should include sweeping the surface to remove loose debris, dust, or other contaminants.

2.6.1 Fog Seal Pre-Treatment of Substrate

If the pavement surface is extremely dry or porous or there is possible loss of some of the chip-seal binder to the pavement, a light fog seal application should be considered prior to chip sealing. Sometimes hot mix asphalt patches are needed to repair the existing pavement prior to chip sealing. These patched areas should be sprayed with a light fog seal prior to applying the chip seal since fresh hot mix asphalt can absorb the emulsion after chip sealing, resulting in significant loss of chips.

2.6.2 Repairs

Alligator cracking, potholes, failing patches, and active cracks greater than ¼ in. in width should be repaired to provide a stable surface for the new chip seal.

2.7 Maintenance

Fog seals are often applied to a new chip seal to provide additional binder and higher contrast for pavement striping paint. Care should be taken whenever applying a fog seal since pavement friction could be reduced if the fog seal is applied at too high an application rate, the fog seal emulsion has a high residue content, or the fog seal has not broken sufficiently to support uncontrolled traffic.

CHAPTER 3

Design and Construction Considerations

Before a chip seal can be designed, there are certain factors that must first be known about the project. The first part of this process involves selecting the pavement to chip seal. The second part is selection of the type of seal to be placed.

3.1 Identifying Appropriate Pavements to Chip Seal

Chip seals are most effective for pavement preservation when applied to pavements with limited or no distress (i.e., cracking has not begun or is less than ⅛-in. wide, rutting is less than ⅜ in., and structural distress is isolated with low-severity fatigue). Pavements with severe cracking and rutting may require multiple patches and crack sealing prior to chip sealing. In general, pavements in poor condition will achieve shorter service lives than pavements in good condition.

3.2 Type of Seal

The types of chip seal include single, double, and single chip seal with choke stone; any of these chip seals may have a fog seal applied afterward.

3.2.1 Single Chip Seal

A single chip seal consists of a spray application of asphalt emulsion followed by an application of aggregate chips, preferably one stone layer thick.

3.2.2 Double Chip Seal

A double chip seal is two applications of a single chip seal. The first chip seal is constructed with aggregate one sieve size larger than the second chip seal.

3.2.3 Single Chip Seal with Choke Stone

This type of seal is a single chip seal but with crushed fine aggregate applied to the surface of the chip seal prior to rolling.

3.2.4 Fog Seal Applied to Chip Seals

A fog seal may be applied to a fresh chip seal to provide slightly more asphalt to account for possible deficiencies in emulsion application rate, to provide a higher contrast between pavement markings and the surrounding surface, and to provide possible improved cracking performance. Care should be taken whenever applying a fog seal since pavement friction could be reduced if the fog seal is applied at too high an application rate, the fog seal emulsion has a high residue content, or the fog seal has not broken sufficiently to support uncontrolled traffic.

3.3 Chip Seal Selection

The type of chip seal used depends on many factors. Under high traffic volumes, double seals or seals with choke stone have lower potential for chip loss and vehicle damage. Double and choke stone seals should provide less tire–pavement noise due to smaller aggregate size. The life expectancy of double seals and seals with choke stone should be higher and the sealing ability should also be greater than single seals under the same conditions. However, the cost of double seals is obviously higher.

3.4 Selecting the Aggregate Size

The chip seals described in this manual are single chip seals consisting of one application of asphalt emulsion and one layer of aggregate chips. The gradation of the chips should consist of one or two consecutive sieve sizes with little or no material passing the 0.075-mm sieve (no. 200). The maximum aggregate size in the chip seal influences the performance of the chip seal. Larger aggregates provide greater sealing performance because of the higher asphalt volume needed to retain the chips in place. However, larger aggregates produce more traffic noise, have rougher texture, and have greater potential to damage vehicles. These advantages and disadvantages must be considered when making decisions regarding chip-seal selection.

3.5 Evaluating the Pavement

Some aspects of the pavement surface can have an effect on the performance of the chip seal. For example, texture of the surface, resistance of the pavement surface to penetration of the chips under traffic, variability of the pavement surface along the alignment, and pavement gradient all affect chip-seal performance. These factors must be considered during the chip-seal design process.

3.5.1 Surface Texture

The texture of the pavement surface must be known prior to chip sealing so that an adjustment can be made for the design emulsion spray rate. Texture of the surface can be measured using either sand patch (ASTM E 965) or CT meter (ASTM E 2157) to obtain the texture depth. The correlation between these two tests has been established. An adjustment to emulsion spray rate needs to be applied to account for the texture.

3.5.2 Penetration of Chips into Surface

The pavement surface should be tested using the ball penetration test to determine if chips are likely to penetrate the substrate pavement after trafficking and to what level. If penetration is possible, adjustment to the emulsion application rate will be required.

3.5.3 Variability of Surface along Alignment

The surface of the pavement affects the emulsion application rate. Therefore, if the surface varies along the alignment, the application rate must change to match these conditions. A thorough map should be made indicating where material application rates should change in accordance with the changing surface conditions. These changes can be communicated to equipment operators by painting on the pavement surface in front of the distributor truck.

3.6 Materials

The suitability of all materials to be used in the chip seal should be evaluated before construction begins.

3.6.1 Aggregates

Aggregate properties relevant for chip seals include gradation, toughness, soundness, cleanliness, fracture, and polish resistance.

3.6.1.1 Gradation

The gradation of the aggregate used in the chip seal is critical to performance. Generally, the more one-sized the aggregate, the better the performance potential. One-sized aggregates include those materials retained within two consecutive sieve sizes. Two-sized aggregates are materials retained between three consecutive sizes. Good performance should be expected for any chip seal with up to two-sized gradations. However, as the gradation becomes less uniform (a wider variety of sizes), obtaining good performance will be more difficult to achieve. Uniformity can be quantified by using the coefficient of uniformity (C_u) used for soil and aggregate classification (ASTM D 2487).

C_u is defined as the ratio of the size for which 60% passes divided by the size for which 10% passes. Thus, a more one-sized material will have a smaller C_u.

An example of how the C_u value can be used to judge uniformity is provided in Table 1 for hypothetical aggregate gradations. Aggregates 1, 2, and 3 are examples of one-sized materials, and Aggregates 4, 5, and 6 are two-sized. Aggregate 7 has many sizes. A C_u value less than 4.0 is defined as uniformly graded (ASTM D 2487). The first six aggregates all have C_u values of less than 2.0 and, therefore, would be defined as uniformly graded. The seventh aggregate, with C_u of 7.2, would be considered well graded.

Another approach has been proposed which evaluates the ratio of material passing 70% of the median size to that passing 140% of the median size, termed the performance-based uniformity coefficient (PUC) (Lee and Kim 2008). It is expected that particles at 70% of the median size will be submerged in asphalt when fully compacted, and particles at 140% of the median size will not have enough binder to hold them in place. Thus, the closer the PUC ratio is to zero, the more one-sized the gradation. For aggregates in Table 1, the PUC ratios for the first six aggregates range from 0 to 0.21, with 0.58 for the seventh aggregate.

Aggregate gradations A, B, and C in Table 2 are recommended for chip-seal aggregates. While they are not as uniform as those for Aggregates 1 through 6 in the hypothetical example, they present practical materials suitable for chip-seal construction. These aggregates have PUC ratios of 0.04 to 0.31 and C_u values of 1.18 to 3.28.

3.6.1.2 Toughness

Toughness is defined as the ability of an aggregate to resist crushing forces. Toughness is an important consideration during aggregate processing to ensure that the gradation produced does not change during handling by loaders or other construction equipment while stockpiling, loading, or spreading on the pavement during construction. Crushing resistance is also important during service when vehicles travel over the chip-

Table 1. Coefficient of uniformity for selected chip-seal aggregates.

		Hypothetical Aggregate Gradations						
		1	2	3	4	5	6	7
Sieve, mm	Sieve	Passing, %						
19	3/4	100	100					
12.5	1/2	0	60	100	100			100
9.5	3/8		0	0	60	100	100	75
4.75	4				0	0	60	45
2.38	8						0	25
1.19	16							12
0.60	30							
0.30	50							
0.075	200							2
	D60 >	16.33	12.5	11.2	9.5	7.5	4.75	7.2
	D10 >	13.1	9.9	9.8	5.5	5.1	2.7	1
	Cu >	1.25	1.26	1.14	1.73	1.47	1.76	7.20
	Median (M) >	15.75	12	11	8.7	7.2	4.3	5.5
	% Passing @ 0.7M >	0	0	0	18	7.5	15	37
	% Passing @ 1.4M >	100	88	100	95	100	71	64
	PUC >	0.00	0.00	0.00	0.19	0.08	0.21	0.58

seal aggregate. Crushing resistance historically was judged using the Los Angeles Abrasion test (AASHTO T 96), but more recently the Micro-Deval test (AASHTO T 327) has been included as an indicator of toughness. Specifications often limit the abrasion loss to 35%, but this value should vary depending on traffic level. Several state specifications have stipulated the values shown in Table 3.

Lightweight aggregates manufactured from expanded shale, clay, and other materials have been used in chip seals on low-traffic facilities for many years (Gallaway 1966). Although Los Angeles Abrasion test results indicate the materials are acceptable, on high-traffic facilities they degrade prematurely (Shuler 1991). This suggests the Los Angeles Abrasion test is not an appropriate measure of toughness for such materials.

3.6.1.3 Soundness

Freeze–thaw resistance and weathering are not common performance issues for chip-seal aggregates because water should drain freely from the surface of chip seals. However, magnesium and sodium sulfate loss tests (AASHTO T 104) are routinely used to evaluate soundness of concrete and hot mix asphalt aggregates and, therefore, should be included for evaluating chip-seal aggregate suitability. A limit of 10% loss is considered appropriate for chip-seal aggregates.

3.6.1.4 Cleanliness

Although asphalt emulsions have the ability to coat dusty aggregates, the fraction passing the no. 200 (0.075 mm) sieve

Table 2. Recommended aggregate gradations.

		Passing, %					
Sieve, mm	Sieve	Gradation A		Gradation B		Gradation C	
19	3/4	100	100				
12.5	1/2	90	100	100	100		
9.5	3/8	5	30	90	100	100	100
4.75	4	0	10	5	30	90	100
2.38	8			0	10	5	30
1.19	16	0	2			0	10
0.60	30			0	2		
0.30	50					0	2
0.075	200	0	1	0	1	0	1
	D60 >	11.4	10.8	7.8	6.8	3.9	3.4
	D10 >	9.65	4.75	2.38	2.38	2.5	1.19
	Cu >	1.18	2.27	3.28	2.86	1.56	2.86
	Median (M) >	11.1	10.3	7.3	6.15	3.7	3.1
	% Passing @ 0.7M >	3.5	20	11	27	11	26
	% Passing @ 1.4M >	95	100	92	86	91	89
	PUC >	0.04	0.20	0.12	0.31	0.12	0.29

Table 3. Los Angeles Abrasion and Micro-Deval loss versus traffic level.

Traffic, veh/day/lane	L.A. Abrasion Loss, % max	Micro-Deval Loss, % max
<500	40	15
500–1,500	35	13
>1,500	30	12

should be limited to 1% or less. However, higher values can be tolerated by many emulsions, especially if medium setting materials are used. Adhesive ability of the emulsion should be evaluated in the laboratory using the sweep test; the aggregate should be considered suitable for use when 90% retention of the aggregate can be achieved. Sieve analyses should be conducted using washed samples since the material passing the no. 200 sieve often adheres to coarse aggregates. Sieve analysis (AASHTO T 27) must be done in conjunction with the washing procedure (AASHTO T 11).

3.6.1.5 Angularity

The amount of interlock present in a chip-seal aggregate surface is directly related to the amount of angularity of the individual aggregate particles. The higher the interlock, the greater the resistance to dislodgement of particles and the potential for vehicle damage and flushing of the surface. The forces present at the chip-seal surface are directly related to the amount and type of traffic expected. Therefore, a greater percentage of mechanically fractured particles should be used for roads with high traffic volumes and truck percentages. The literature provides some guidance, summarized in Table 4, regarding fracture requirements for chip-seal aggregates.

3.6.1.6 Polish Resistance

Because vehicular traffic may cause aggregates to polish and reduce friction, the aggregates used for chip seals should be evaluated if polishing is suspected. The polished stone value obtained using the British Wheel (AASHTO T 279) is the most common test used for this purpose. A limit of 31 is recommended (Utah DOT 2008).

3.6.2 Aggregate Properties for Design

The size and shape of the aggregates used for chip seals determine the spread rate of the aggregate and spray rate of the emulsion. Aggregate gradation is determined during sieve analysis to ensure that materials meet the specifications for the roadway to be sealed. The shape of the particles is needed to make sure they are not too flat or elongated and for input into the design process. These properties are discussed below.

3.6.2.1 Flakiness

The flakiness index, a measure of the percentage of particles that are long and slender in comparison to the width, is used in many designs of chip seals. A low flakiness index is desired because it indicates cubical-shaped aggregates. Aggregates with a high flakiness index tend to lie flat and become submerged in the binder during construction and later under traffic, resulting in flushing. Limits on flakiness index recommended in Table 5 (Austroads 2006, South African Roads Agency 2007, Wood et al. 2006) are based on the experience of several agencies.

3.6.2.2 Average Least Dimension

It is assumed that the aggregates will orient to the flattest direction after construction and trafficking. Therefore, to be sure the aggregate chips are not submerged in binder during service, the average of the least dimension of the aggregates is used to determine aggregate spread rate and emulsion spray rate. The median aggregate size determined from sieve analysis and the flakiness index is needed to determine the average least dimension (ALD). Although ALD can be

Table 4. Mechanically fractured requirements for chip-seal aggregates.

Parameter	Test Method	Vehicles per Day per Lane		
		<500	500–1,500	>1,500
One Fractured Face	ASTM D 5821	90	95	100
Two Fractured Faces	ASTM D 5821	85	90	90

Table 5. Flakiness index requirements for chip-seal aggregates.

Parameter	Test Method	Vehicles per Day per Lane		
		<500	500–1,500	>1,500
Flakiness Index	Tex 224-F (Tx DOT 2004) FLH T508 (Mn/DOT 2005)	35	30	25

Table 6. Asphalt emulsions used for chip seals.

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

* California Test Method
** Colorado Test Methods

measured directly (Austroads 2005), the following relationship can be used to estimate ALD more quickly (Jackson 1963):

$$ALD = [M/1.139285 + (0.011506) \times FI]$$

Where
M = median particle size from sieve analysis and
FI = flakiness index.

An alternative method has been proposed (Dumas 2004) that uses five sieves in the aggregate gradation to obtain ALD instead of just one, the median. When this method was used, the calculated ALD values were within the 98% confidence limits for ALD determined using the equation above.

3.6.2.3 Loose Unit Weight, Specific Gravity, and Absorption

Loose unit weight (AASHTO T 19) and specific gravity (AASHTO T 85) are used to estimate the volume of voids in the loose aggregate chips and to determine how much asphalt to apply to the pavement surface so that the appropriate embedment of chips occurs during construction. Aggregate absorption is also needed and is obtained at the same time as specific gravity measurements. A correction in the residue application rate of 0.02 gallons per square yard has been suggested (McLeod 1969) if absorption is 1%. However, for cubical aggregates embedded to 50% initially, a correction of approximately 0.014 gallons per square yard is estimated for absorption of 1%. Therefore, an adjustment of 0.01 to 0.02 seems reasonable for each percent of aggregate absorption.

3.6.3 Emulsion Properties

The properties of the emulsion used for chip seals are important and should be checked to ensure compliance with requirements. Desirable emulsion properties are provided in Table 6.

These properties are based on current state specifications for both conventional and polymer modified emulsions, including anionic, cationic, and high-float emulsions. Because of the wide array of emulsions available in the United States, not every combination of conventional and modified emulsion could be included. However, those included in Table 6 have been successfully used in chip-seal construction over a range of environments and traffic conditions.

CHAPTER 4

Selecting the Appropriate Chip Seal

Selecting the appropriate chip seal to use on a specific facility is important. For example, a chip seal using ¾-inch maximum size aggregate may be appropriate for a rural farm-to-market road with 500 vehicles per day per lane but not for an urban street carrying 10,000 vehicles per day per lane. The following discussion will provide information regarding the seal that is most appropriate for a given project.

4.1 Single Seal

The single application chip seal is the most commonly used chip-seal process. These chip seals have been used with success on all pavement types. However, potential disadvantages, including vehicle damage, tire noise, and roughness, are reasons for considering variations from the single seal. In addition, the sealing ability of a single chip seal is limited based on chip size. An increase in chip size increases sealing ability because of the greater binder volume required to hold the stone in place, but it also increases the potential for the noted disadvantages.

4.2 Single Seal with Choke Stone

This type of seal is a single chip seal with choke stone applied to the chip seal prior to rolling. The choke stone should meet the same physical requirements of the chip-seal aggregate and the gradation shown in Table 7 when used with chip seals with aggregate maximum size exceeding ⅜ inch (9.5 mm).

Table 7. Example of choke stone gradation.

Sieve	Passing, %
¼-inch	100
No. 4	85–100
No. 8	10–40
No. 40	0–5
No. 200	0–1

The choke stone helps lock the chip-seal aggregate in place and produces a surface that is less likely to produce dislodged larger chip-seal aggregates under traffic. It results in less risk of loose stones and a quieter and smoother surface.

4.3 Double Seal

The double chip seal is used when pavement conditions require substantially higher sealing ability, such as for facilities with higher traffic volume. The first chip-seal application uses a maximum size aggregate that is one sieve size larger than that of the second chip seal. In comparison to other seal types, double chip seals provide higher sealing capability, longer service life, less risk of dislodgement of the larger aggregates, smaller aggregate in contact with traffic and snow plows, and a quieter surface. However, double seals are higher in cost and require longer to construct.

CHAPTER 5

Chip Seal Materials Selection

The performance of a chip seal is largely dependent on the materials used. Therefore, selecting the appropriate aggregates and asphalt emulsion and deciding whether to apply a fog seal to the surface play a significant role in the success of the project. The following discussion provides guidance regarding these factors.

5.1 Chip Gradation

The gradation of the chip should be one- or two-sized, but the maximum size should be selected based on traffic volume, pavement texture, and the required level of sealing. Generally, larger aggregate provides greater ability to seal because of the higher volume of binder required to hold the chips in place, and depending on traffic volume, provides longer life expectancy. However, larger aggregates increase the chances for vehicle damage, noise, and roughness.

5.2 Modified or Unmodified Emulsion

Modified emulsions usually refer to some sort of elastomeric polymer or rubber added to the emulsion or to the base asphalt binder prior to emulsification. Because modified emulsions should offer greater adhesivity and potentially shorter time required before opening to traffic, they are generally used on higher traffic pavements, where vehicle damage potential is greater and where limited time under traffic control is usually desirable.

5.3 Fog Seal After Chip Seal

A fog seal may be applied to any completed chip seal as a means of providing a high color contrast for paint stripes. There are also some preliminary indications that the fog seal provides some additional waterproofing (Shuler 2007). Care should be taken whenever applying a fog seal since pavement friction could be reduced if the fog seal is applied at too high an application rate, the fog seal emulsion has a high residue content, or the fog seal has not broken sufficiently to support uncontrolled traffic.

5.4 Emulsion–Aggregate Compatibility

There is anecdotal evidence of apparent incompatibility arising from use of anionic or cationic emulsions with siliceous or calcareous aggregates, respectively. This incompatibility manifests itself with a loss of aggregate from the chip seal. This behavior was not observed during the NCHRP Project 14-17 research, in which 20 combinations of aggregates and emulsions were represented. Therefore, unless impractical, anionic emulsions should be pared with positively charged aggregates (i.e., calcareous), and cationic emulsions should be matched with negatively charged aggregates (i.e., siliceous) to avoid possible incompatibility between the materials.

CHAPTER 6

Chip-Seal Design

The basic chip-seal design methods proposed by Hanson (1934–1935) and by Kearby (1953) provided the basis for future design methods. From the original Hanson concepts evolved the McLeod procedure (McLeod 1960, 1969) that was later adopted by the Asphalt Institute (Asphalt Institute MS19) and the Austroads and South African methods (South African Roads Agency 2007). The Kearby method was later improved (Benson and Gallaway 1953, Epps et al. 1981) and adopted by Texas. The United Kingdom designs "surface dressings" or chip seals using some of the Hanson concepts combined with ideas of Jackson (1963).

Several methods have been used for the design of chip seals. The following discussion describes a design method based on the Austroads method.

The purpose of chip-seal design is to select aggregate and asphalt emulsion application rates that will result in a durable pavement seal. The quantity of binder required depends on the size, shape, and orientation of the aggregate particles; embedment of aggregate into the substrate; texture of the substrate; and absorption of binder into either the substrate or aggregate.

This design method is based on the following assumptions for aggregate, traffic, and embedment:

- Aggregate: one-sized aggregates with a flakiness index of 15% to 25%
- Traffic: 10%, or less, heavy vehicles
- Embedment: 50% to 65% chip embedment after two years

6.1 Emulsion Application Rate

The emulsion application rate is the spray quantity of asphalt emulsion applied during construction; it is determined as follows:

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

Where

B_d = design binder application rate, gal/yd² (L/m²);
B_b = basic binder application rate, gal/yd² (L/m²);
EF = emulsion factor;
PF = polymer factor (for polymer modified emulsions, only); and
A_s, A_e, A_{as}, A_{aa} = adjustments for substrate texture, embedment, absorption into substrate, and absorption into cover aggregate, gal/yd² (L/m²).

Where

$B_b = VF \times ALD$;
VF = design voids factor, gal/yd²/in (L/m²/mm); and
ALD = average least dimension of cover aggregate.

Where

$VF = Vf + Va + Vt$,
Vf = basic voids factor,
Va = aggregate shape adjustment factor, and
Vt = traffic effects adjustment factor.

Thus the design binder application rate is:

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

Each of these parameters is discussed below.

6.1.1 Basic Voids Factor, Vf

The basic voids factor depends on traffic level because traffic determines how much of the aggregate is embedded in the binder. Figures 1a and 1b use English and SI units, respectively, for traffic of less than 500 vehicles per day per lane. Figures 2a and 2b use English and SI units, respectively, for traffic of greater than 500 vehicles per day per lane. The three curves in each figure represent a range of basic voids factors

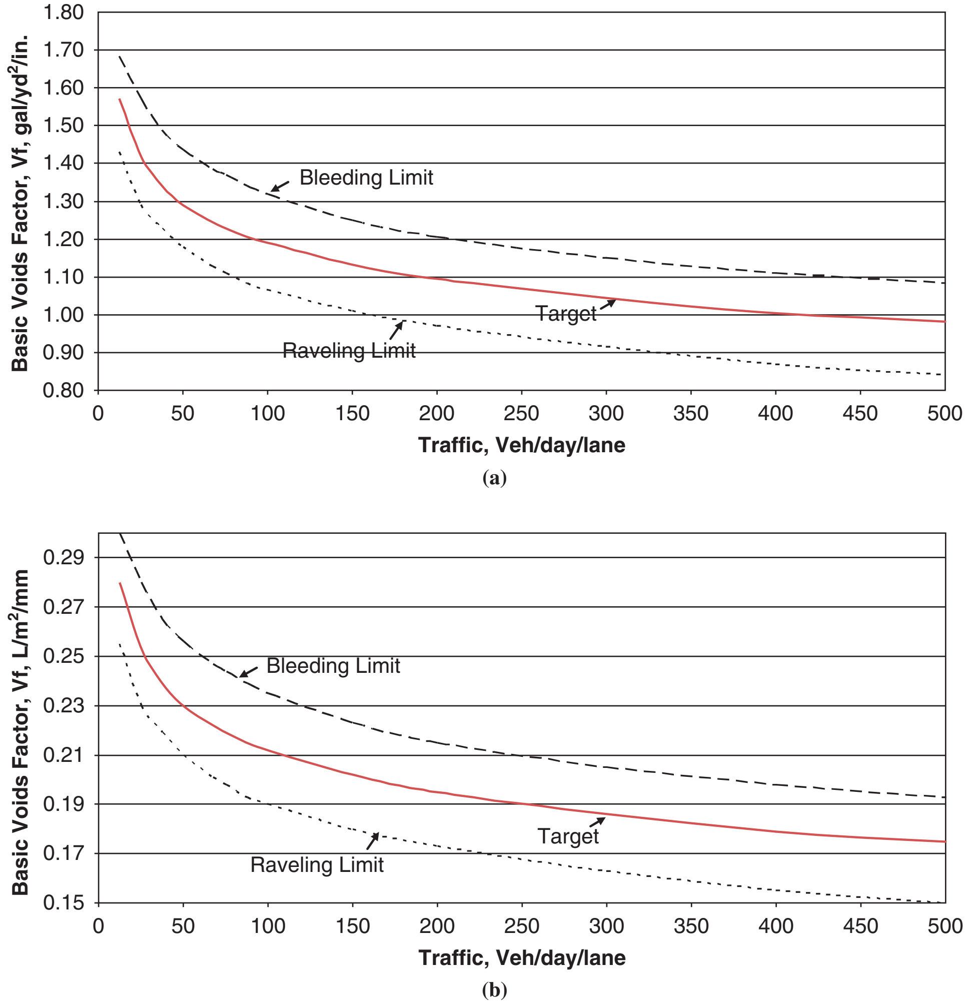

Figure 1. Basic voids factor versus traffic for 0 to 500 vehicles/lane/day (Austroads 2006).

from a low binder content (raveling limit) to a high binder content (bleeding limit), which should not be exceeded.

6.1.2 Adjustment for Aggregate Shape, Va

The design method assumes the flakiness index will be between 15 and 25; an adjustment must be made for aggregates outside this range. Table 8 provides suggested adjustment factors.

6.1.3 Adjustment for Traffic, Vt

The basic voids factor, Vf, was developed for an average mix of light and heavy vehicles in a free traffic flow situation. When this is not the case due to composition; non-trafficked areas; overtaking lanes with few heavy vehicles or for large proportions of heavy vehicles; channelization and slow-moving, heavy vehicles in climbing lanes; or stop/start conditions, an adjustment, Vt, needs to be made. Table 9 shows recommended adjustments.

6.1.4 Average Least Dimension

The volumetric design of a chip seal is based on the assumption that aggregate particles tend to lie with the least dimension vertical. The least dimension is defined as the smallest dimension of a particle when placed on a horizontal surface, the particle being most stable when lying with the least dimension vertical. Thus in a chip seal, the final orientation of most particles is such that the least dimension is near vertical, providing there is sufficient room for the particles to realign. This average least dimension, ALD, is as follows:

$$ALD, mm = M, mm/[1.139285 + (0.011506 \times FI)] \text{ or,}$$

$$ALD, in. = ALD, mm/25.4$$

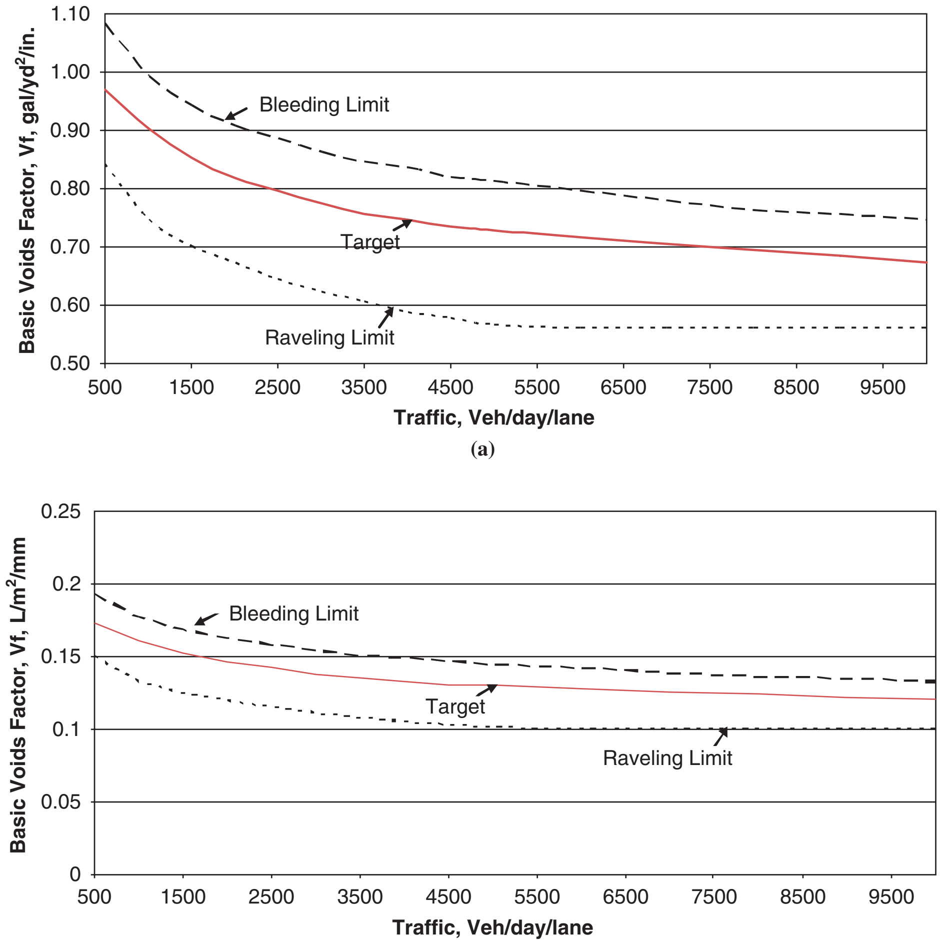

Figure 2. Basic voids factor versus traffic for 500 to 10,000 vehicles/lane/day (Austroads 2006).

Where
M = median size of the aggregate (mm) and
FI = flakiness index.

6.1.5 Emulsion Factor

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

The basic binder application rate for emulsions, B_{be}, is calculated as follows:

$$B_{be} = B_b \times EF$$

Where
B_{be} = basic binder emulsion application rate rounded to the nearest 0.2 gal/yd² [0.1 L/m²];
B_b = basic binder application rate, gal/yd² (L/m²); and
EF = emulsion factor = 1.0 for emulsions with less than 67% residue and 1.1 to 1.2 for emulsions with residues greater than 67%.

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

Table 8. Suggested adjustment for aggregate shape, Va (after Austroads 2006).

Aggregate Type	Aggregate Shape	Flakiness Index, FI, %	Va, gal/yd²/in. [L/m²/mm]
Crushed	Very Flaky	>35	Too flaky, not recommended
	Flaky	26–35	0 to –0.056 [0 to –0.01]
	Angular	15–25	0
	Cubic	<15	+0.056 [+0.01]
	Rounded	–	0 to +0.056 [0 to +0.01]
Uncrushed	Rounded	–	+0.056 [+0.01]

Table 9. Traffic adjustment, Vt (after Austroads 2006).

Traffic		Traffic Adjustment, Vt, gal/yd^2/in. [L/m^2/mm]			
		Flat or Downhill		Slow-Moving Climbing Lanes	
		Normal	Channelized	Normal	Channelized
Overtaking lanes of multilane rural roads where traffic is mainly cars with HV <=10%		+0.056 [+0.01]	0	0	0
Non-traffic areas such as shoulders, medians, and parking		+0.112 [+0.02]	0	0	0
EHV*, %	0–15	0	–0.056 [–0.01]	–0.056 [–0.01]	–0.112 [–0.02]
	16–25	–0.056 [–0.01]	–0.112 [–0.02]	–0.112 [–0.02]	–0.168 [–0.03]
	26–45	–0.112 [–0.02]	–0.168 [–0.03]	–0.168 [–0.03]	–0.224 [–0.04]**
	>45	–0.168 [–0.03]	–0.224 [–0.04]**	–0.224 [–0.04]**	–0.281 [–0.05]**

* Equivalent heavy vehicles, EHV, % = HV% + LHV% x 3
Where HV = vehicles over 3.5 tons and LHV = vehicles with seven or more axles

** If adjustments for aggregate shape and traffic effects result in a reduction in basic voids factor, Vf, of 0.224 gal/yd^2/in [0.4 L/m^2/mm] or more, special consideration should be given to the suitability of the treatment and the selection of alternative treatments. Note that a minimum design voids factor, Vf, of 0.56 gal/yd^2/in [0.10 L/m^2/mm] is recommended for any situation.

6.1.6 Polymer Modified Emulsion Factor

When polymer modified emulsions are used, the application rate should be adjusted using the factor *PF* listed in Table 10.

The basic binder polymer modified emulsion application rate is calculated as follows:

$$B_{bpme} = B_b \times EF \times PF$$

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

6.1.7 Correction Factors

Corrections should be considered to account for the following factors:

a) Texture of existing surface,
b) Aggregate embedment into substrate,
c) Binder absorption into the substrate, and
d) Binder absorption into the chip-seal aggregate.

Table 10. Polymer modified emulsion factors.

Traffic, veh/day/lane	PF
<500	1.0
500 to 2,500	1.1
>2,500	1.2

a) Texture of Existing Surface, A_s

The surface texture of the existing substrate may have some demand for emulsion and should be accounted for. This depends on the texture depth of the substrate, the type of substrate (existing chip seal, hot mix asphalt, or slurry seal), and the size of cover aggregate to be applied. The correction ranges from 0 gal/yd^2 (L/m^2) for chip seals over hot mix asphalt with texture depth no more than 0.1 mm to +0.11 gal/yd^2 (L/m^2) for ¼-in. to ⅜-in. (5 to 7 mm) chip seals over a surface with texture greater than 2.9 mm. A guide for estimating this correction is shown in Figures 3a and 3b for U.S. customary and SI units, respectively.

The pavement texture is commonly measured by the sand patch test (ASTM E 965). The test is accurate but is slow, exposes personnel to traffic, and wind effects can affect results. The sand patch test was correlated to the circular track meter (ASTM E 1845) test method that is faster, less susceptible to variation, and poses fewer safety concerns.

The sand patch test is a volumetric method for determining the average depth of pavement surface macrotexture. A known volume of small particles (either sieved sand or small glass beads) is poured onto the pavement surface and spread evenly into a circle using a spreading tool. Four diameters of the circle are measured, and an average profile depth is calculated from the known material volume and the averaged circle area. This depth is reported as the MTD in millimeters. The method is designed to provide an average depth value and is considered insensitive to pavement microtexture characteristics.

The CT meter test method (ASTM E 2157) is used to measure and analyze pavement macrotexture profiles with a laser

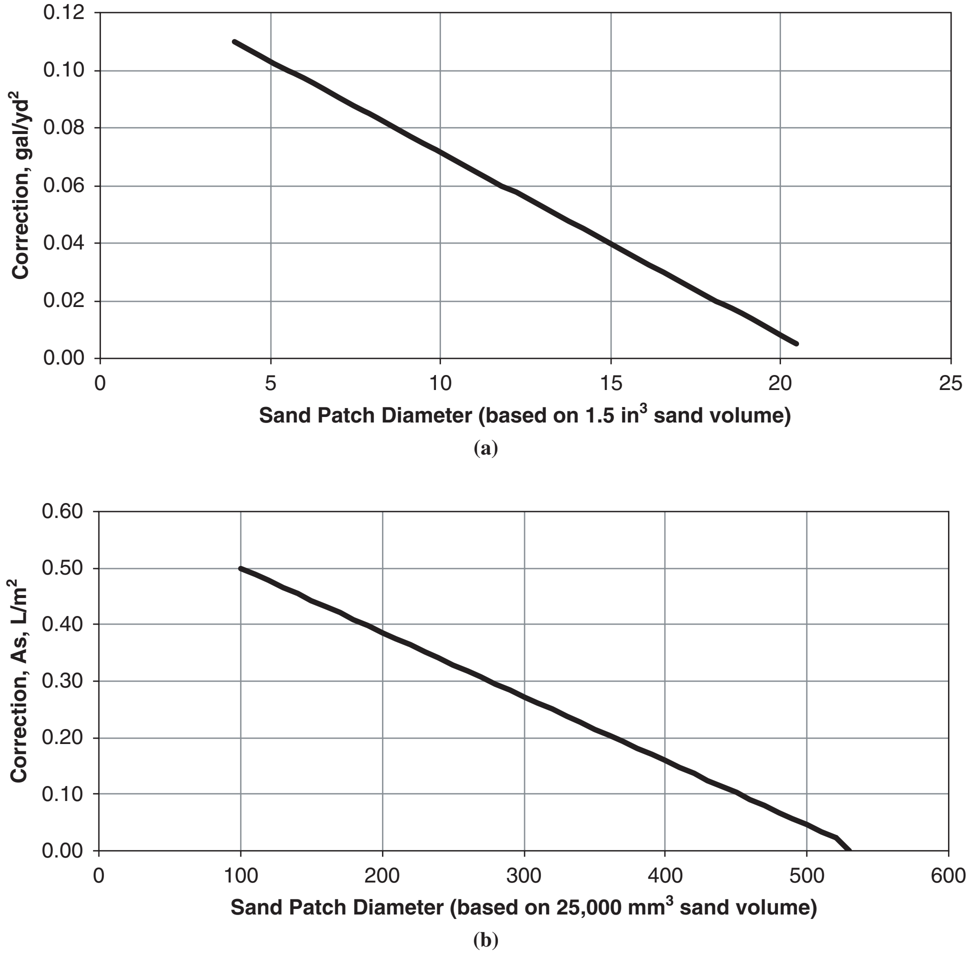

Figure 3. Surface texture correction factor, A_s versus sand patch diameter.

displacement sensor. The laser sensor is mounted on an arm which follows a circular track that has a diameter of 284 mm (11.2 in.). Depth profiles are measured at a sample spacing of 0.87 mm, and the data are segmented into eight 111.5-mm (4.39-in.) arcs of 128 samples each. A MPD is calculated for each segment, and an average MPD is then calculated for the entire circular profile.

Recent research under NCHRP Project 14-17 developed the following relationship between sand patch texture depth and CT meter texture depth:

$$\text{Sand patch texture, mm} = (0.9559 * \text{CT meter texture}) + 0.1401$$

b) *Embedment into Substrate, A_e*

The embedment correction factor compensates for loss of voids in the chip seal under traffic due to chips being forced into the surface of the substrate. The depth of embedment depends on the volume and type of traffic and resistance of the substrate. The corrections shown in Figure 4 are recommended using the results from the ball penetration test method. In this method, a ¾-in. (19-mm) ball bearing is driven into the substrate surface with one blow of a Marshall compaction hammer and several tests are conducted and averaged. When ball penetration exceeds 3 mm, the pavement is considered too soft to chip seal; alternative preventive maintenance techniques should be considered.

c) *Absorption of Emulsion into Substrate, A_{as}*

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

- Granular unbound pavements — +0.04 to +0.06 gal/yd^2 (+0.2 to +0.3 L/m^2)
- Pavements using cementitious binders — +0.02 to +0.04 gal/yd^2 (+0.1 to +0.2 L/m^2)
- Asphalt stabilized surfaces — –0.04 to 0 gal/yd^2 (–0.2 to 0.0 L/m^2)

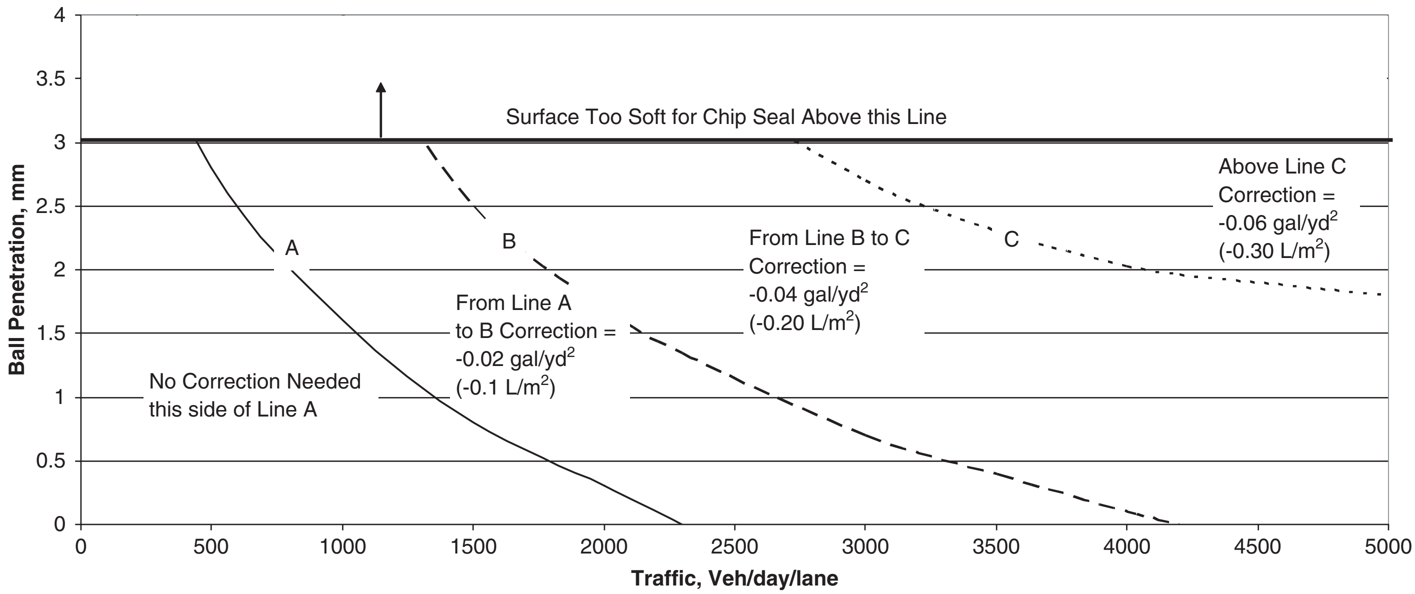

Figure 4. Correction factors for chip penetration into substrate (Austroads 2006).

d) Absorption of Emulsion into Aggregate Chips, A_{aa}

Absorption of emulsion into the chips requires a correction of +0.02 gal/yd² (+0.1 L/m²) for each 1% of water absorption.

6.2 Aggregate Application Rate

The aggregate application rate is determined based on ALD, traffic volume, and chip size.

The aggregate spread rate for ⅜-in. (10-mm) and larger chips depends on the traffic.

a) For pavements with less than 200 vehicles/day/lane:

$$\text{Aggregate spread rate, lbs/yd}^2 = [\text{ALD, in.} * \text{W}]/27.08$$

$$\text{Aggregate spread rate, m}^2/\text{m}^3 = 750/\text{ALD, mm}$$

Where W is loose unit weight, lb/yd³.

b) For pavements with more than 200 vehicles/day/lane:

$$\text{Aggregate spread rate, lbs/yd}^2 = [\text{ALD, in.} * \text{W}]/25.27$$

$$\text{Aggregate spread rate, m}^2/\text{m}^3 = 700/\text{ALD, mm.}$$

The range of spread rates for ⅜-in. (9-mm) and smaller chips depends on whether there are one or two layers of chips placed. It ranges from 0.104W to 0.093W (290 to 260 m²/m³) for a single layer to 0.089 W to 0.072W (250 to 200 m²/m³) for two layers.

6.3 Time Until Sweeping and Traffic

The time required before sweeping or before traffic can be allowed on the fresh chip seal is related to the moisture content in the chip seal (Shuler 2009). The laboratory test method in NCHRP Project 14-17 may be used to determine when the chip seal can withstand sweeping and traffic stresses. In this method, test specimens of the emulsion and chips are fabricated in the laboratory and tested at three moisture contents. The moisture at which less than 10% of the chips are dislodged during the test is the target moisture content to be achieved in the field before sweeping or traffic operations should commence.

6.4 Other Considerations

6.4.1 Chips Required to Avoid Roller Pickup

Additional aggregates than are actually estimated to produce a one-stone layer should be spread during chip-seal construction to aid in reducing the potential for embedded chips to be picked up by pneumatic rollers. The amount of additional material will vary, but generally is between 5% and 10%.

6.5 Example Design

An example of how to use the design method to determine the binder and aggregate spread rates follows.

If

Maximum aggregate size = ½ in.;
Median aggregate size = ⅜ in.;
Flakiness index = 30%;

Loose unit weight, W = 110 lbs/ft^3;
Traffic = 1,500 veh/day/lane, channelized, with equivalent heavy vehicles, EHV%=16;
Polymer modified emulsion binder with 70% residue;
Sand patch diameter for texture = 18 in.;
Ball penetration = 0.5 mm;
Substrate is old chip seal with no expected absorption potential; and
Chip-seal aggregate has 1% water absorption

Design binder application rate (from Section 6.1) is:

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

Vf = 0.85 gal/yd^2/in., from Figure 2b;
Va = –0.028 gal/yd^2/in., from Table 8;
Vt = –0.112 gal/yd^2/in., from Table 9;
ALD = 0.328 in.;
EF = 1.2, from Section 6.1.5;
PF = 1.1, from Table 10;
A_s = 0.02 gal/yd^2, from Figure 3a;
A_e = 0, from Figure 4;
A_{as} = 0, from Section 6.1.7c; and
A_{aa} = +0.02 gal/yd^2, from Section 6.1.7d.

$$B_d = [(0.85 - 0.028 - 0.112) * 0.328 * 1.2 * 1.1] + 0.02 + 0 + 0 + 0.02 = 0.35 \text{ gal/yd}^2$$

Aggregate spread rate (from Section 6.2)

$$= [\text{ALD, in} * \text{W, lbs/yd}^3]/25.27$$
$$= 0.328 * 110 * 27/25.27 = 38.5 \text{ lbs/yd}^2.$$

CHAPTER 7

Construction

7.1 Equipment Calibrations

7.1.1 Distributor

Because a uniform application of material laterally and longitudinally on the pavement is required, the machines used for this purpose, whether controlled by computer or not, must be calibrated prior to arrival on the project. First, the nozzles installed in the spray bar should be the appropriate size for the planned transverse application rate. Nozzles of equal size are required for a uniform transverse application rate. When the transverse rate is lower in the wheel paths, the nozzles should be sized accordingly. However, the number designation of the nozzle should be checked for flow rate against the published flow rate of the manufacturer using a laboratory flow bench. Nozzles used in the spray bar should be checked as a group. Nozzles deviating by more than 10% of the average flow rate of the group should be discarded, replaced, or corrected to allow flow that conforms to the average flow rate.

Nozzles that are calibrated to provide uniform lateral flow must be re-installed in the spray bar following manufacturer's recommendations and ensuring that each nozzle is aligned at the correct angle to provide desired spray overlap. Nozzle angle can usually be adjusted using the wrench provided by the distributor manufacturer, an adjustable wrench, or appropriate-sized open-end wrench. Nozzle angle usually ranges between 15 and 30 degrees.

After the nozzle angle is set properly, the height of the spray bar must be adjusted. If the bar is not set to the proper height, an excess or lack of emulsion will form ridges or streaks on the pavement, as depicted in Figure 5.

This adjustment process is accomplished by shutting off the appropriate nozzles to determine where the spray pattern contacts the pavement, as shown in Figure 6. Every other nozzle should be turned off for a double-lap application, and two nozzles should be turned off for every one that is left on for a triple-lap application. The distributor operator should spray emulsion onto the pavement surface for as short an interval as possible while an observer watches where the emulsion hits the pavement from each nozzle left open. Emulsion overlaps indicate that the bar is too high, and a gap indicates that the bar is too low. Note that the bar will rise as the distributor empties during spraying, but this rise does not usually cause significant streaking that requires spray bar adjustment.

Uniformity of lateral flow from the spray bar should be determined by collecting a measured volume of emulsion in containers placed under each nozzle. This process can be done using standard 6-in. by 12-in. concrete cylinder molds lined with one-gallon freezer bags (Shuler 1991). One bag is positioned under each nozzle and emulsion is sprayed into the lined cans until approximately 75% full. Flow is then stopped and each lined can is weighed. The weight of each lined can should be within 10% of the average for all of the nozzles. Any nozzles that deviate from this should be replaced and the test rerun. The cylinder molds can be re-used and the bags with the contents discarded appropriately.

Longitudinal calibration of the distributors is done by measuring the volume of the distributor before spraying and after spraying 70% to 90% of the distributor volume. The volume sprayed can be determined using the dipstick supplied with the distributor. The longitudinal spray rate can then be calculated by determining the area sprayed. This value should then be compared to that displayed by the distributor computer, if equipped, to evaluate computer accuracy; if the rate applied differs from design by more than 5%, corrective action should be taken and the calibration rerun. This calibration should be made each day. The following is an example of such a calibration:

Assuming:
1,800-gal capacity asphalt distributor, 12-ft-wide spray width, trial spray distance = 4,630 fe, 0.32 gal/yd^2 design spray rate, dipstick reading beginning of shot = 1,765 gal, dipstick reading end of shot = 185 gal

1. Check volume shot. 1,765 – 185 = 1,580 gal
   a. 1,580/1,765 = 89.5% > 70% and < 90%. *OK.*

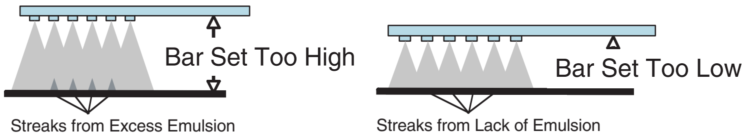

Figure 5. Streaks caused by incorrect bar adjustment (after Wood et al. 2006).

2. Calculate spray rate = 1,580 gal/(12 ft × 4,630 ft/9 ft^2/yd^2) = 0.26 gal/yd^2
   a. 0.32 – 0.26 = 0.06 gal/yd^2, which is greater than 5% of the difference between the actual spray rate and the design.
3. Therefore, make adjustments to distributor speed or spray bar until the rate applied is within 5% of 0.32.

7.1.2 Chip Spreader

The chip spreader should be checked for uniform application both laterally and transversely. Lateral distribution is best checked using ASTM D 5624, "Standard Test Method for Determining the Transverse-Aggregate Spread Rate for Surface Treatment Applications." Once accomplished and any spreader gates have been adjusted for variations, the longitudinal spread rate can be measured by applying the entire spreader capacity to the pavement and measuring the application rate. The mass of chips applied can be determined from weigh tickets of trucks loading the chip spreader. Conduct the calibration for three trucks and average the results. An example follows.

For 12-ton capacity tandem dump trucks, 12-ft-wide pavement, and 28 lbs/yd^2 design spread rate:

1. For truck no. 1:
   a. Load = 23,803 lbs
   b. Spreader distance = 213 ft
   c. Rate = 23,803/213 × 12/3 = 27.9 lbs/yd^2
2. For truck no. 2:
   a. Load = 23,921 lbs
   b. Spreader distance = 211 ft
   c. Rate = 23,921/211 × 12/3 = 28.3 lbs/yd^2
3. For truck no. 3:
   a. Load = 23,848 lbs
   b. Spreader distance = 213 ft
   c. Rate = 23,848/213 × 12/3 = 28.0 lbs/yd^2
4. Average rate = (27.9 + 28.3 + 28.0)/3 = 28.1 lbs/yd^2
5. No adjustment needed (measured rate is within 1% of design).

Compensation for moisture on chips must be taken into account when calibrating chip spreaders.

7.2 Operations

7.2.1 Pavement Preparation

The substrate pavement should be structurally sound before chip sealing. Areas exhibiting alligator cracking should be patched the full depth of the pavement section using hot mix asphalt. The surface of these areas should be sprayed with a light application of slow-setting asphalt emulsion diluted 50:50 with water at the rate of 0.10 gallons per square yard and allowed to cure thoroughly before chip sealing so that the new chip-seal binder will not be absorbed into the surface of the new patch. Failure to do this could lead to loss of chips under traffic.

The substrate pavement should be clean before commencing chip-seal operations. Dust and debris on the surface should be removed by power brooms. Pickup type brooms should be used in urban areas to avoid spreading surface contaminants onto adjacent properties. Push brooms may be used in rural areas when spreading excess chips onto shoulders does not affect property owners. The surface of the substrate pavement should be damp to dry. A damp surface is acceptable as long as

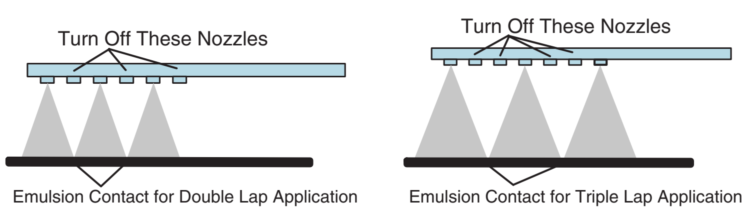

Figure 6. Obtaining no streaking for double and triple lap application.

moisture is present only in surface aggregate voids and is not present as free moisture between aggregates.

7.2.2 Environmental Conditions

The pavement temperature for chip-seal operations should be a minimum of 70°F with little or no wind. However, chip-seal operations may commence before the pavement temperature reaches 70°F as long as pavement temperatures are expected to be 70°F and rising within 60 minutes after commencing work.

Wind speeds in excess of 20 mph transverse to the pavement alignment can blow asphalt emulsion onto opposing traffic on two-lane facilities; therefore, chip-seal operations should be avoided under these conditions.

Chip-seal operations should not be pursued if rain is threatening. A rain storm could wash asphalt emulsion onto concrete gutters or into roadside ditches.

Ambient air temperatures in excess of 110°F with the sun shining or with moderate winds can cause emulsified asphalts to form a skin on the surface such that the emulsion does not set adequately. This situation may require the spread of chips closer to the distributor to obtain proper embedment. However, high air temperatures may lead to lower viscosity emulsion residue, resulting in higher potential for pickup on rubber tire rollers. Increasing the demulsibility of anionic emulsions may help remedy this situation (Shuler 1991).

There is anecdotal evidence to support limiting the season for chip sealing so chip seal construction does not occur when there may be periods of cool to cold weather.

7.2.3 Emulsion Application

Each emulsion application should start and stop by spraying on top of 15 lb/yd² roofing paper or similar dimensioned, equally heavy craft paper placed transverse to the centerline of the pavement. This creates a neat, sharp transverse joint. The distributor operator should position the spray bar at the rear of the paper on takeoff so that by the time the bar reaches the pavement the distributor speed is appropriate for the desired spray rate. Another sheet of roofing paper should be placed across the pavement before the distributor stops. Spraying should stop when the spray bar has passed over the paper. Calculating when approximately 90% of the distributor volume has been sprayed is a good method to determine the distance where the second strip of roofing paper should be placed.

7.2.4 Chip Application

Chips should be applied to the surface of the fresh emulsion before it begins to set but not necessarily immediately after spraying. If the chips are applied too early, there is risk that the chips will roll over in the emulsion due to momentum created by the forward movement of the chip spreader. Thus, less binder will be available to hold the chips in place and the exposed binder becomes susceptible to being picked up on roller tires. Therefore, the adhesive quality of the emulsion should be checked to determine when to apply the chips. This may be determined by throwing a handful of chips onto the emulsion and observing whether they stick to the surface or tend to roll over. Some experimentation is necessary to estimate the proper timing, which can be accomplished during the first distributor application. In many cases, changes in environmental conditions during construction will require this test be repeated during the day because humidity, chip moisture, emulsion properties, and ambient air temperature affect the adhesive quality of the emulsion.

7.2.5 Rolling

Different types of rollers have been used to embed chips on chip seals. Pneumatic rollers have a tendency to pick up chips due to the affinity of asphalt residues for rubber tires. However, these rollers do not crush chips in situ as do steel-wheeled rollers. Although lightweight steel rollers of three tons or less may provide a means of leveling the surface of a new chip seal after pneumatic rolling, caution must be applied to avoid breaking aggregate chips. Steel rollers with rubber-coated drums are also a good tool for embedding chips. However, any rigid drum roller will bridge over areas of the pavement with permanent deformation, causing these areas to be inadequately rolled.

Rollers must be able to keep up with the distributor and chip spreader and provide enough passes to embed the chips. If the rollers travel too fast, embedment will not be achieved. Therefore, the number of rollers used depends on roller speed, roller width, distributor and chip spreader speed, and the number of passes required to achieve embedment. The faster the rollers move, the more rollers will be required to achieve embedment. This is because rollers need to linger over an area of chip seal to obtain the desired chip embedment (Benson and Gallaway 1953, Elmore et al. 1995). The number of rollers required can be calculated based on this linger time and the assumption that the rollers should match the production of the distributor and chip spreader as follows (Gransberg et al. 2004):

$$N = 6.67\ Px/A$$

Where
N = number of rollers;
P = distributor speed, fpm;
x = lane width, ft; and

A = area covered in one hour by rollers to get minimum "linger," yd^2.

As an example, for a distributor traveling at 200 fpm and spraying 12-ft wide at a conservative 5000 square yards per hour coverage rate, N = 3.20 (i.e., use 4 rollers). Fewer rollers will not be able to keep up with the distributor and spreader while maintaining the 5000 yd^2/hr rolling rate. If they do keep up, the rollers will not spend enough time embedding aggregates because they are traveling too fast.

7.2.6 Initial Sweeping After Rolling

Light brooming should occur as soon as possible after rolling and before vehicular traffic is allowed on the surface to remove any excess chips. This should be possible when the moisture content of the chip seal reaches the level where 10% chip loss occurs after the laboratory sweep test. This moisture content, measured by the moisture loss test, was found to be approximately 15% to 25% of the total moisture present in the chip seal and indicated that total moisture consists of water in the emulsion plus moisture in the aggregate chips, but not moisture in the pavement (see attachment). Moisture content of the chip seal should be measured in areas of the project where moisture loss is expected to be least rapid, such as shady or cooler locations. Caution should be exercised when implementing this practice since it is based on limited research. Using vacuum brooms or push brooms with nylon (not steel) bristles should be applied with much care to avoid damage to the fresh seal.

7.2.7 Vehicular Traffic Under Traffic Control

Vehicular traffic may be allowed on the fresh seal after initial sweeping if speeds can be controlled to less than 20 mph using pilot vehicles. If speeds cannot be controlled to this speed, vehicles should not be allowed on the seal until final sweeping has been completed. Traffic control using pilot vehicles should be applied following the *Manual on Uniform Traffic Control Devices for Streets and Highways* (2009).

7.2.8 Removing Traffic Control

Traffic control may be removed and vehicular traffic allowed on the fresh chip seal after brooming has been completed to remove excess or loose chips and the moisture content of the seal reaches the level that results in less than 10% chip loss after the laboratory sweep test. This moisture content, measured by the moisture loss test, is approximately 15% to 25% of the total moisture present in the chip seal (which consists of the water in the emulsion plus moisture in the aggregate chips, but not moisture in pavement). Moisture content of the chip seal should be measured in areas of the project where moisture loss is expected to be slowest (e.g., shady or cooler locations).

CHAPTER 8

Quality Control

Quality control is required to ensure desired performance. The following section describes procedures that should be followed to improve the likelihood of good performance for a chip-seal project.

8.1 Aggregate Sieve Analysis

Aggregate gradation should be checked whenever there is potential for significant variation in the chip gradation. For example, if chips have been stockpiled near the project and there is sufficient quantity to supply the entire project, a complete gradation analysis before construction begins, and every 100 tons thereafter, should be adequate. Also, loader operations at the stockpile can produce excess material passing the no. 200 screen and should, therefore, be monitored. Aggregate gradation should not deviate from the target design gradation by more than the following tolerances:

Sieve	Tolerance, ±, %
¾	5
½	5
⅜	4
No. 4	3
No. 8	1
No. 200	0.5

When chips are supplied from multiple locations, sampling and testing for gradation should be done with more frequency, including checking each truck if high variability is suspected. Because a full sieve analysis may not be practical, hand sieving in the field using only the coarse aggregate screens can provide information on the suitability of the material or help determine if more laboratory testing is needed.

8.2 Moisture Content of System

The moisture content of the chips should be measured at the beginning and the end of the day for (1) calculating aggregate spread rate and (2) determining when sweeping can be done and when traffic control can be removed. Moisture content can be determined by complete moisture evaporation from the chips using a forced draft oven or a microwave oven. By weighing the chips before and after removing moisture, the moisture content (w) can be determined as follows:

$$w, \% = \frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \times 100$$

8.3 Embedment Depth Measurement During Construction

Embedment depth is usually determined during construction by pulling several chips out of the binder and visually estimating the amount of embedment. This is difficult and often subjective even if chips have a very low flakiness index. Therefore, a new method is recommended of spreading a volume of 50 cm^3 of glass beads over the surface of the embedded chips and measuring the diameter. During the chip-seal design, the relationship between glass bead diameter and aggregate embedment is determined. During construction the glass beads are spread on the pavement and the diameter measured. Embedment is then determined using the relationship between glass bead diameter and embedment from the design measurements.

8.4 Field Viscosity

The viscosity of the emulsion should be checked for each transport load. This can be done in the absence of a field laboratory using a Wagner flow cup. Flow times of 20 to 70 s at 85 to 150°F for a 6-mm orifice or 10 to 60 s at 85 to 140°F for a 7.5-mm orifice have been found to provide satisfactory flow rates. If flow rates using a Wagner cup are not within these limits, the temperature of the emulsion should be checked to determine if emulsion temperature is the cause. If temperature of the emulsion is not causing unacceptable flow rates, other causes should be investigated.

CHAPTER 9

Performance

9.1 Less Than One Year

Performance during the very early life of the chip seal is judged based on chip loss or flushing. Chip loss can happen as soon as a few hours after removing traffic control. If the loss is greater than 10% of the applied chip quantity (assuming a one-layer chip application), the cause should be investigated. Often, early failures of this type are due to high chip application rates, low emulsion application rates, or both. Early chip loss can also be due to excess material passing the no. 200 screen, or aggregate not meeting gradation requirements. Unexpected low temperatures, wet weather, or opening to traffic before adequate residue adhesion has developed can cause early chip loss.

Inundation of chips occurs because of high emulsion application rate, embedment of chips in the substrate, or both.

Streaking or roping is caused by the spray bar on the asphalt distributor being either too high or too low. Correction after construction is not possible without the application of another seal.

9.2 Greater Than One Year

Performance after one year can be measured using texture depth. Some specifications (Austroads 2006) limit design life based on texture of less than 0.9 mm on pavements with speeds greater than 43 mph. The following relationship has been proposed as a means of predicting approximate texture after one year (Gransberg et al. 2005):

$$Td_1 = 0.07\ ALD \log Y_d + 0.9$$

Where
Td_1 = texture depth in 1 year, mm;
Y_d = design life in years; and
ALD = average least dimension of the aggregate, mm.

Texture depth is determined using sand patch or CT meter tests. If texture is less than the predicted value, the texture should be monitored to determine if a loss of texture beyond 0.9 mm is expected.

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APPENDIX

Recommended Test Methods

The proposed test methods, prepared as part of NCHRP Project 14-17, Manual for Emulsion-Based Chip Seals for Pavement Preservation, are the recommendations of the NCHRP Project 14-17 staff at Colorado State University. These test methods have not been approved by NCHRP or any AASHTO committee nor have they been accepted as AASHTO specifications.

CONTENTS

Recommended Standard Method of Test for Embedment Depth of Chip-Seal Aggregates in the Lab and the Field

AASHTO Designation: Txxx-xx

1. SCOPE

1.1 This test method provides the average aggregate embedment depth, in asphalt, of field chip seals and laboratory specimens.

1.2 The values stated in SI units are to be regarded as the standard unless otherwise indicated.

1.3 A precision and bias statement for this standard has not been developed at this time. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purposes.

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1 *ASTM Standard:*

- D 8, Terminology Relating to Materials for Roads and Pavements

3. SUMMARY OF TEST METHOD

3.1 Where the void ratio of an area of chip seal may be estimated with acceptable accuracy, and where voids (Note 1) between all chip-seal particles are filled with a given mass of glass beads of known packing density, the average height of beads within the chip seal layer may be determined. This average height of beads between the surface level of the asphalt and the average height level of the chip-seal particles would reflect the chip seal's texture height. Given the average particle height of the chip-seal aggregate, one may perform a calculation, using the evaluated texture height, to yield the chip-seal embedment depth.

Note 1—For the purposes of this test method, it is assumed that the actual chip-seal voids are those that exist above the asphalt surface and below the profile of an imaginary, three-dimensionally undulating, flexible membrane that is draped over aggregate particles and forced to come into contact with the peak of each particle (see Figure 1 and Figure 2).

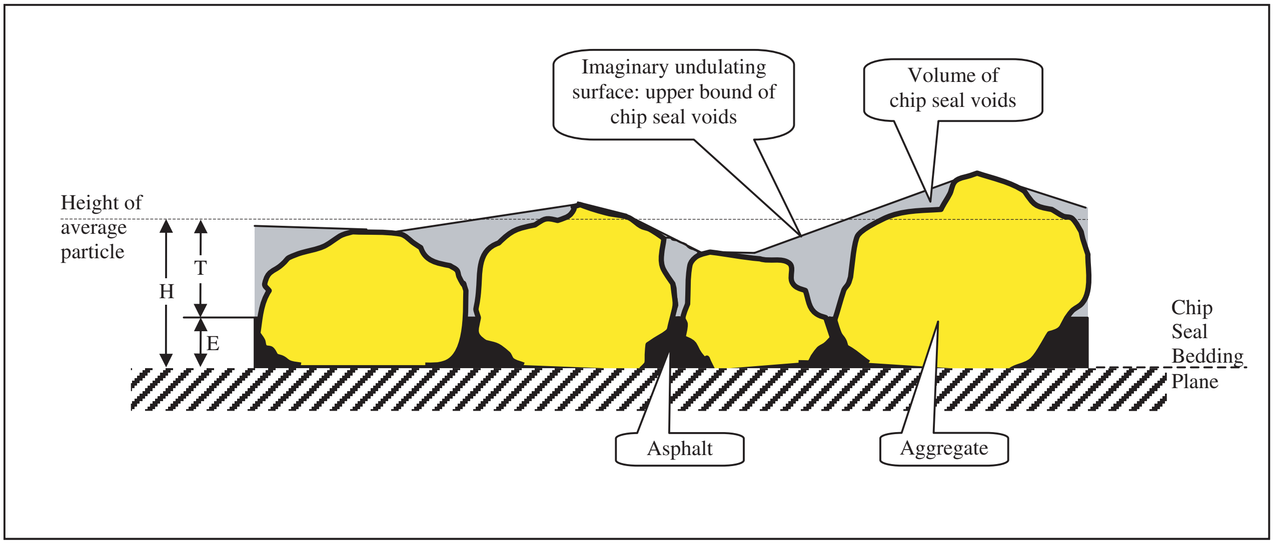

Figure 1. Undulating profile over particle peaks and voids.

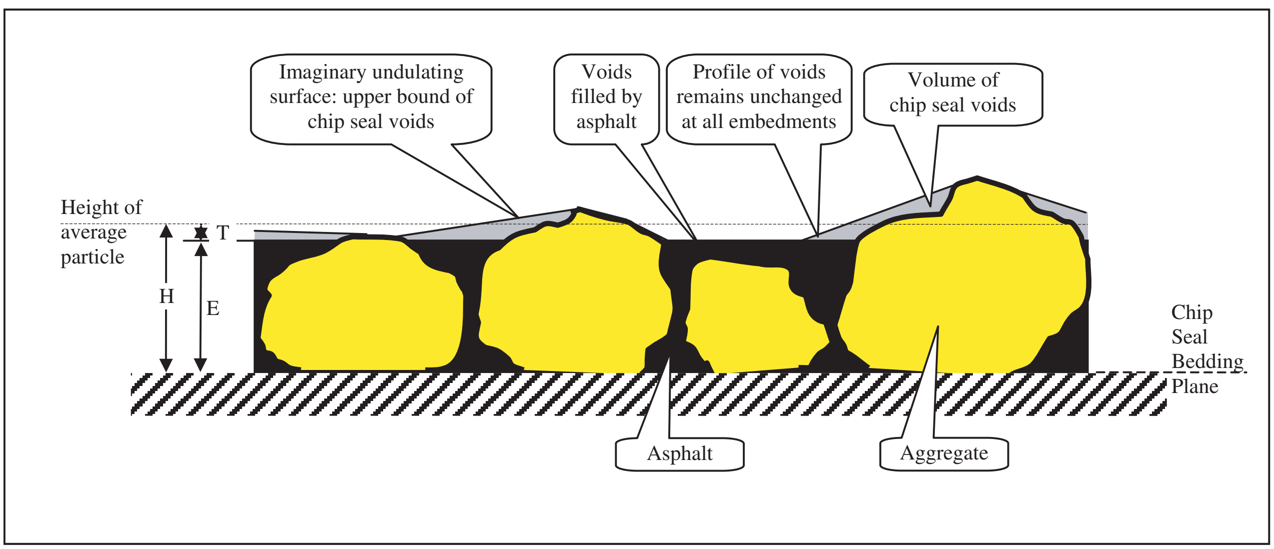

Figure 2. Profile remains unchanged at all embedments.

Two procedures are provided, each of which may be used to evaluate a field chip seal or a specimen chip seal for embedment depth. In the first, the "spreading procedure," a known, fixed volume of glass beads is spread into a circular area over the surface of a chip seal to fill the voids between the particles, which are illustrated in Figure 1. The glass beads bridge between the peaks of the chip-seal particles in all directions and form an undulating profile. Effectively the average height of glass beads covering the specimen is the same as the height of the chip seal's average particle (Note 2). The circular area, achieved with the fixed volume of glass beads, is used to evaluate embedment depth.

Note 2—For simplification, it is assumed that an "equivalent" chip seal, constructed with one-sized, identical particles, each with height equal to the average particle height, may be substituted for the actual chip seal that contains voids as defined in Note 1. It is further assumed that the constituents of such an equivalent chip seal, of the same area as the actual chip seal, would precisely reflect the height of asphalt and the volumes of asphalt, aggregate particles, and voids that exist in the actual chip seal. In this regard, the texture height is the height between the level of the asphalt surface and the level of the top of particles in the equivalent chip seal (Figure 3).

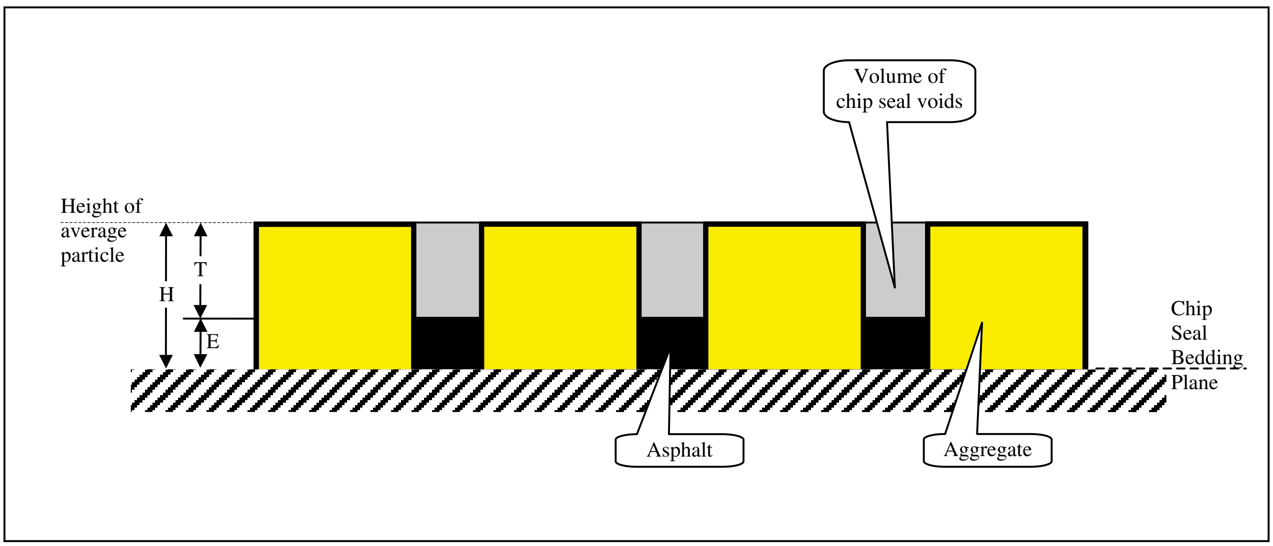

Figure 3. Equivalent chip seal.

In the second procedure, the "submerging procedure," a known, variable volume of glass beads is used to completely cover all chip-seal particles within a fixed area to a fixed level above the height level of the chip seal's average particle (Figure 4). In order to determine the volume of beads within the chip-seal voids, a calculation is first performed using the concept of the flat-topped equivalent chip seal (Note 2) to determine the excess volume of beads that occupies the space above the chip seal (Figure 5). The void volume is obtained by subtracting the excess volume of beads from the total volume of glass beads on the chip-seal area. This allows for evaluation of the embedment depth.

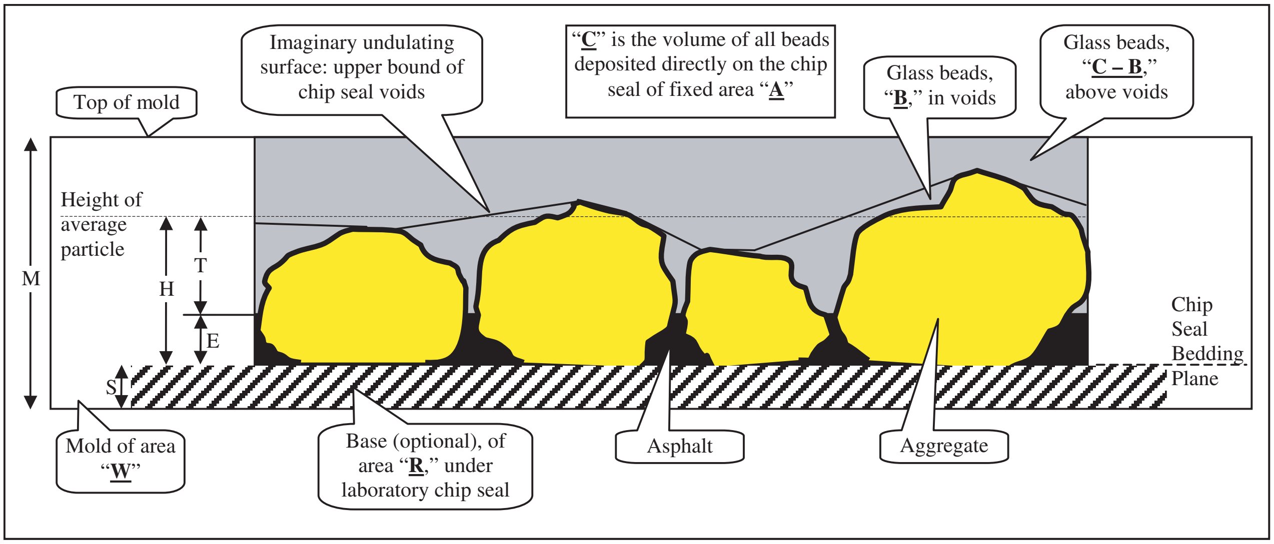

Figure 4. Submerging procedure.

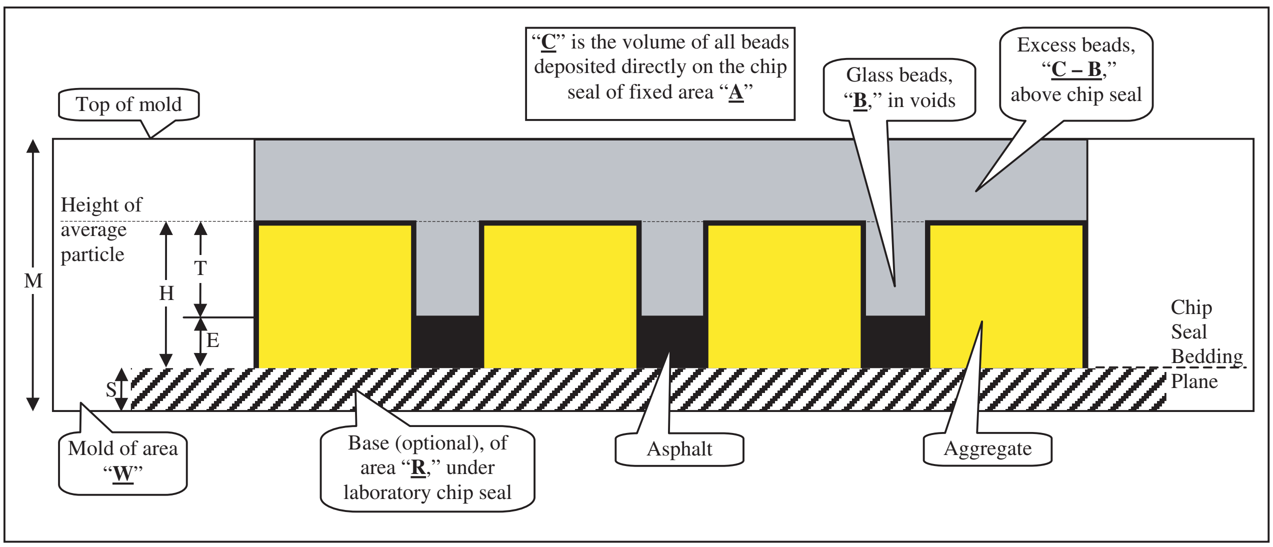

Figure 5. Equivalent model for the submerged chip seal.

Note 3—The submerging procedure, which may be used for any degree of embedment, has been devised primarily to account for the situation, at very high embedment depths, where the asphalt surface intersects the imaginary membrane defined in Note 1. In this situation, where some particle peaks are covered, it may become difficult to spread the beads to follow the required profile illustrated in Figure 2.

4. SIGNIFICANCE AND USE

4.1 This test method is intended to be used in the evaluation of embedment depth in field and specimen chip seals.

4.2 In predicting future performance of a chip seal, embedment depth evaluation is critical. This is because performance, in certain aspects such as reduced aggregate loss, is likely to increase as embedment depth increases. Performance in terms of high skid resistance and reduced construction cost, on the other hand, is likely to decrease with increased embedment beyond a certain level.

4.3 Additionally, embedment depth evaluation is important simply because it is often the only practical means by which an apparently sound field chip seal may be evaluated.

4.4 Ultimately, the results of embedment depth evaluations enable better quantification of the relative risk associated with apparently sound roads.

5. APPARATUS

5.1 *Balance* – The balance must be capable of weighing approximately 10,000 g of glass beads per square meter of chip seal to within $\pm$0.1 g.

5.2 *Glass Cylinder/Container* – A smooth-bottomed glass cylinder is to be used for the spreading procedure. A drinking glass (a shot glass) used for this purpose also doubles as a container for weighing glass beads and pouring them onto the chip-seal surface.

5.3 *Measuring Tape* – This is used to measure the diameter of glass bead circles achieved using the spreading procedure. The tape is to be graduated in millimeters.

5.4 *Laboratory Mold* – Used in the submerging procedure in the laboratory, the mold is to have a constant height (M) and a constant cross sectional area (W) large enough to accommodate the specimen chip seal. Additionally, when filled to its rim, the mold must provide for complete submergence of the specimen chip seal.

Note 4—The top elevation of the mold needs only to be some 3 mm higher than the tallest chip seal particle in order to allow smooth screeding of the surface.

5.5 *Working Platform* – For precision, the specimen chip seal and laboratory mold should always be prepared and configured on a flat and level platform.

5.6 *Offset Spacers* – To perform the submergence procedure in the field, offset spacers of known height are used to establish an offset distance from the bedding plane of the chip seal. The tops of the spacers are equidistant from the bedding plane and higher than the average particle height in order to achieve submergence of chip-seal particles.

Note 5—The submerging procedure is not a suitable candidate on steeply sloping roadways or where the level of the bedding plane is unknown. The procedure is suitable on areas where the bedding plane level has been recorded and where the plane is flat and approximately level in the area to be tested.

5.7 *Field Mold* – When carrying out the submerging procedure in the field, a field mold is to be used to form the glass beads over a fixed area of chip seal. The field mold is to be built up using a perimeter gasket wall and a flat metal surface with a cutout. The vertical-faced gasket wall, which may consist of moldable putty or silicone, must be shaped such that it dams the spaces between chip-seal particles and finishes flush with the cut-out area of the metal surface. Placement of the metal surface is to be accommodated by the use of offset spacers such that it is flat, at a known height above the average chip-seal particle, and allows full submergence of the chip seal.

6. PREPARATION OF MATERIALS

6.1 *Specimen Chip Seal* – For the purposes of this test method, a specimen chip seal is constructed on a flat and level base, or sheet, of known thickness (*S*) and area (*R*). Additionally, for the submerging procedure, it must be possible to place the specimen into a mold or to form a mold around the chip seal.

6.2 *Area of Chip Seal* – Precisely measure the chip seal area (*A*), which is being evaluated for embedment.

6.3 *Glass Beads* – These are fine particles of glass that are able to fit between chip-seal particles and, en masse, follow the contours of the particles' surface.

6.4 *Packing Density of Glass Beads* – Fill the tared mold, of known volume (*K*), with glass beads and weigh the filled container. Establish the packed glass beads' mass per unit volume (*P*) for use in the following procedures.

7. SPREADING PROCEDURE IN THE LAB AND IN THE FIELD

7.1 Using the tared glass cylinder/container, weigh out a pre-calculated mass of glass beads that will provide a chosen volume (*B*) at a packed density (*P*) (defined in section 6). Record the mass to the nearest 0.1 g.

7.2 Pour the glass beads onto the center of the specimen to form a pile. Position the glass cylinder on the pile of glass beads and move it in a circle to spread the beads into a circular area.

7.3 Use the fingers to continue spreading the beads outward in a circle while allowing the beads to accumulate between particle peaks, completely and exactly filling the void volume (Note 1). This is achieved when only the highest point of each aggregate particle (not otherwise submerged by asphalt) is exposed.

7.4 Place a marker at the approximate center of the circular area of beads. Rotating about the marker, take four diameter measurements, with the measuring tape, in line with the marker and rotationally offset 45 degrees from each other. Calculate the average circle diameter (D).

8. SUBMERGING PROCEDURE IN THE LAB AND IN THE FIELD

8.1 Weigh and record, to the nearest 0.1 g, the mass of a volume (Y) of glass beads, which will be more than enough to cover the chip seal and fill the mold.

8.2 For the lab procedure, place the specimen chip seal into the mold or form the mold around the specimen, ensuring that the mold and the specimen are flat and level and that complete submergence of the chip seal will be achieved.

8.3 For the field procedure, install the offset spacers such that they are elevated a known height above the bedding plane of the chip seal as a guide for the installation height of the field mold.

8.4 Sweep the field chip seal clean and install the mold over the area to be evaluated such that the mold's top surface is flat and at a known offset distance above the bedding plane of the chip seal.

8.5 Pour glass beads into the mold and screed the surface of the beads flush with the top of the mold. The chip-seal aggregate particles should be completely covered by glass beads.

8.6 Carefully recover the glass beads that were screeded off the mold. Weigh the unused portion of beads and calculate the total mass of beads deposited into the mold. In turn, use this result along with the packing density (P) to calculate the total volume (G) of beads deposited into the mold.

8.7 For laboratory molds that are larger in area than the specimen chip seal, also calculate the volume of beads (C) (section 9), which is deposited directly on the chip seal surface area under evaluation.

9. CALCULATIONS

9.1 The chip seal's texture height (*T*) is the average height dimension of the un-embedded portion of particles. The average height level of this un-embedded portion is the same as the average height level of the chip-seal particles. Therefore, the texture height is equivalent to the dimension difference between the depth of asphalt (*E*) and the average particle height (*H*). Where a volume of beads (*B*) is shaped such that it fills the chip seal voids, the texture height can be calculated from the following:

$$T = \frac{\text{volume of beads and aggregate above the asphalt surface}}{\text{plan area of beads and aggregate}}$$

That is:

$$T = \{B + [T\,(1 - V)\,A]\}/A; \quad T = B/(A * V) \tag{1}$$

And the embedment is obtained using the following:

$$E = H - T \tag{2}$$

Where
T = texture height (mm),
B = volume of glass beads (mm^3) on the chip seal surface, filling only voids between particles,
A = plan area of chip seal covered by beads (mm^2),
V = the void ratio,
E = the particle embedment depth in asphalt (mm), and
H = the average particle height (mm).

Where the submerging procedure has been used, whether in the lab or in the field, obtain *B* by subtracting the volume of beads that would lay above the top level of an equivalent chip seal (Note 2) from the total volume (*C*) of beads filling the voids and submerging the chip seal (Figures 4 and 5).

$$B = C - \left[(M - S - H) * A\right] \tag{3}$$

Where
B = volume of glass beads (mm^3) on the chip-seal surface, filling only voids between particles;
C = total volume of beads (mm^3) deposited directly on the chip-seal surface area;
S = thickness of base, or sheet, on which specimen chip seal has been constructed (mm)
(Note: $S = 0$ for field chip seals);
M = height of top of mold (mm) above bottom level of chip-seal base;
H = the average particle height (mm); and
A = plan area of chip seal covered by beads (mm^2).

For laboratory specimens where the plan area of the mold is larger than that of the chip seal under evaluation, obtain C using the following:

$$C = G - \left[(WM) - (RS) - (A\{M - S\})\right] \quad (4)$$

Where
C = total volume of beads (mm^3) deposited directly on the chip-seal surface area;
G = total volume of beads (mm^3) deposited into the mold;
W = area of mold (mm^2);
M = height of top of mold (mm) above bottom level of chip seal base;
S = thickness (mm) of base, or sheet, on which specimen chip seal has been constructed;
R = area of base (mm^2); and
A = plan area of chip seal covered by beads (mm^2).

Recommended Standard Method of Test for Laboratory Chip Loss from Emulsified Asphalt Chip Seal Samples

AASHTO Designation: Txxxx-xx

1. SCOPE

1.1 This test method measures the quantity of aggregate lost, at variable moisture levels of systems of asphalt emulsion and aggregate chips, by simulating the brooming of a chip seal in the laboratory.

1.2 The values stated in SI units are to be regarded as the standard unless otherwise indicated.

1.3 A precision and bias statement for this standard has not been developed at this time. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purposes.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards:*

- T 19, Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate
- T 85, Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
- T 27, Sieve Analysis of Fine and Coarse Aggregates
- T 2, Practice for Sampling Aggregates
- T 40, Practice for Sampling Bituminous Materials
- M 140, Specification for Emulsified Asphalt
- M 208, Specification for Cationic Emulsified Asphalt

2.2 *ASTM Standards:*

- D 226, Specification for Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing
- D 7000, Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples

2.3 *ISSA Document:* ISSA Technical Bulletin No. 100 Test Method for Wet Track Abrasion of Slurry Surfaces

2.4 Texas Transportation Institute: *Field Manual on Design and Construction of Seal Coats*, Research Report 214-25, July 1981

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

3. SUMMARY OF TEST METHOD

3.1 This test is effective for defining the film formation stage and relative binding ability of asphalt emulsions interacting with aggregates when the result of this test is compared to that produced by other combinations of emulsions and aggregates. A brush (designed to closely replicate the sweeping action of a broom) exerts a force on the aggregate used on surface treatments. Asphalt emulsion and a single layer of aggregate chips are applied to an asphalt felt disk. The sample is then conditioned in an oven to arrive at a prescribed emulsion/chip moisture content before testing. A mixer abrades the surface of the sample using a nylon brush. After 1 min of abrasion, the test is stopped, any loose aggregate is removed, and the percent mass loss is calculated.

4. SIGNIFICANCE AND USE

4.1 This test method is useful for classifying the interaction of rapid-setting asphalt emulsions with various aggregate types and is applicable to surface treatments that require a quick return to traffic. The test has the ability to predict the relative speed with which a binder–aggregate combination will develop a traffic-sustaining bond in comparison with other combinations. It also has the capability to predict surface treatment performance in the formative stage using project materials. This performance test is intended to evaluate the potential curing characteristics of a binder–aggregate combination to ensure that the surface treatment is sufficiently cured before allowing traffic onto the chip seal.

5. APPARATUS

5.1 *Mixer* – Use to abrade the sample.

5.2 *Quick-Clamp Mounting Base* – This base must be an adequate and level support for clamping the sample in place. The test sample should not move during abrasion.

5.3 *Pan* – An appropriate pan will contain the test sample on the mixer and hold dislodged aggregate.

5.4 *Oven* – The conditioning oven shall be a constant-temperature, forced-draft oven meeting the requirements given in Table 1 and containing shelves with at least 65% voids. The shelves shall be placed at least 120 mm apart and 100 mm away from the top and floor.

Table 1. Oven specifications.

Oven Type	Forced-draft oven
Min. Inside D x W x H	460 x 460 x 460 mm
Accuracy	± 1.0º C

5.5 *Balance* – A balance capable of weighing 800 g or more to within ±0.1 g. A minimum platform length and width of 240 mm is required.

5.6 *Removable Brush Holder* – The brush holder (Figure 1) shall be attachable to the mixer and capable of a free-floating vertical movement of 19 ± 1 mm and having the dimensions listed in the table below. The total mass of the brush head and the attached weight shall be 1,500 ± 15 g. The collar and nylon strip brush are not included in this mass. The brush clamping system shall hold the nylon strip brush in place so that it will not move or dislodge during testing.

Dimensions		
ID	Name	mm
A	Collar diameter	36
B	Collar height	76
C	Brush head length	128
D	Overall brush head height	19
E	Groove height	17
F	Groove width	18
H	Slot height	19
W	Slot width	7

Figure 1. Brush holder.

5.7 *Nylon Strip Brush* – The brush shall conform to the specifications given in Table 2.

Table 2. Brush specifications.

Overall Trim	25.4 mm
Overall Length	127 ± 1 mm
Backing Size	# 7
Fill Material	Crimped black nylon
Nylon Type	6.0
Fill Diameter	0.254 mm
Weight	35 ± 2 g

5.8 *Strike-Off Template* – The template should consist of a flat, stainless steel metal plate with approximate overall dimensions of 600 mm x 450 mm to allow for accumulation of excess (struck-off) emulsion on the template surface. It shall include a 280 ± 3-mm diameter circular cutout with a flush edge. A template fabricated from 16-gauge U.S. Standard (plate and sheet metal) material will suffice in most cases. Where several templates are to be used, it is helpful to fabricate all templates with the same overall dimensions and location of the circular cutout.

Note 1—Emulsion mass may vary according to emulsion viscosity and applied strike-off pressure. Alternative gauges may be necessary for emulsion mass correction for varying aggregate sizes and shapes. See Appendix A2 for guidelines to calculate the required emulsion volume (and, therefore, the required template gauge) for varying emulsion residual contents and aggregate sizes.

5.9 *Strike-Off Rod* – The 750 ± 100-mm-long rod shall be made of 12.5-mm electrical metal conduit or 12.5-mm wide x 3-mm thick metal for striking off emulsion from the template surface. See Note 2 for other recommendations.

Note 2—Emulsion viscosity and the cross-sectional thickness of the strike-off rod directly affect the formed emulsion volume. In this regard, it is prudent to experiment with differently shaped strike-off rods in order to arrive at a tool that is compatible with the emulsion in producing an emulsion volume that is consistently related to the template volume. A more viscous emulsion is recommended for this test since it enables easier handling and specimen manufacture. Additionally, a narrow area of contact, such as that between a 3-mm thick, rounded-edged strike-off rod and the emulsion, is recommended to allow for a more consistent strike-off result with a wide range of emulsion viscosities. The rod must be approximately 12.5-mm wide to avoid emulsion mounting over the top edge. It is crucial that the rod be stiff and resistant to flexure and be handled in a manner in order to avoid flexure.

6.0 *Sweep Test Compactor* – A suitable compaction device with a minimum curved surface radius of 550 ± 30 mm and weighing 7,500 ± 500 g. A picture of this apparatus can be seen in Figure 2.

Figure 2. Sweep test compactor.

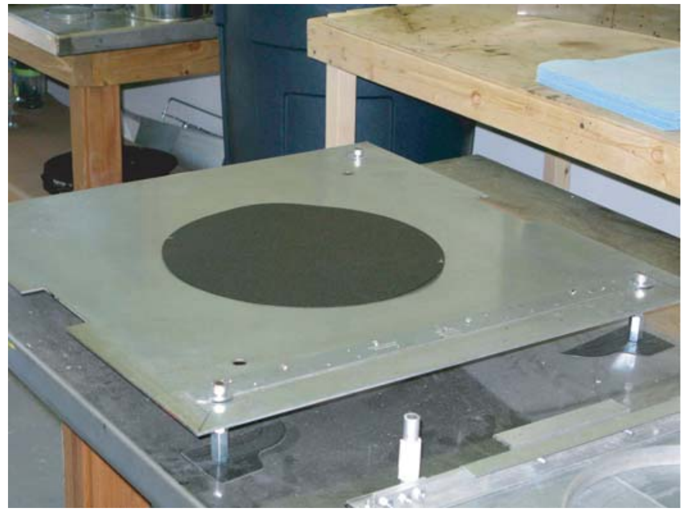

Figure 3. Working platform.

6.1 *Working Platform* – Specimens are manufactured on the 600-mm x 600-mm working platform, which shall be made horizontally level and shall be fixed to a stationary work table. It should be placed at a corner of the work table such that it is comfortably accessible from the two perpendicular sides at the corner of the table. A circular etching is made on the platform surface to allow positioning of the asphalt disks. A metal strip with appropriate markings is permanently fixed to the platform at a location such that the strike-off template may be quickly and easily positioned with its cutout centered over the asphalt disk. The platform also has markings and keyholes for positioning and temporarily fixing the sliding-plate chip-dropper apparatus. See Figure 3.

6.2 *Sliding-Plate Chip-Dropper* – It consists of rails elevating two sliding plates above the formed emulsion. This apparatus is temporarily attached to the working platform and centered over the emulsion previously formed on the asphalt disk. The plates are used to position and suspend aggregate chips. When pulled away, the sliding plates no longer suspend the aggregate chips and these fall onto the asphalt emulsion. See Figure 4.

6.3 *Aggregate Former* – A circular metal hoop of the same internal diameter as the circular cutout in the strike-off template. This device is positioned centrally on the sliding plates of the chip dropper and is used to form a pre-calculated mass of aggregate chips into a circular horizontal area one stone deep. See Figure 5.

6.4 *Pin Grabber* – After aggregate chips have been formed into a single layer, the aggregate former is removed and the pin grabber is positioned over the aggregate chips and attached to the chip dropper. The grabber consists of thousands of pins spaced apart from each other by uniformly perforated plates. The plates prevent any appreciable lateral motion of the pins and, practically, allow only vertical motion of the pins. As the grabber is

Figure 4. Sliding-plate chip-dropper.

Figure 5. Aggregate former.

lowered, by means of guides fixed to the chip dropper, over the aggregate chips, the pins come into contact with the aggregate chips. When the chip-dropper plates are slid horizontally, the pins prevent aggregate chips from moving horizontally. As the plates are slid from beneath aggregate chips, the chips fall vertically onto the asphalt emulsion and assume the same orientations that were given to them on the plates prior to sliding. See Figure 6.

6.5 *Glass Bowl* – A glass container with a secure and airtight cover that will allow mixing of the moisture with aggregate, thus enabling absorption.

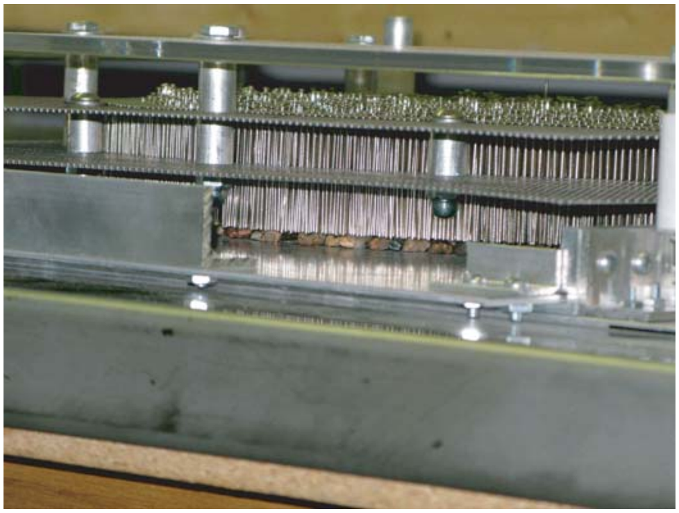

Figure 6. Pin grabber.

7. MATERIALS

7.1 *Aggregates* – The job aggregates should be sampled and split according to practice D 75. They shall be placed in an oven and dried to a constant weight. Unless naturally sourced aggregate samples are being tested, the aggregates shall be dry sieved to obtain a test sample that has 100% passing the 9.5-mm sieve and <1% passing the 4.75-mm sieve. The amount of aggregate used (Note 3) shall be calculated such that a single layer of aggregate is applied to the specimen.

Note 3—Aggregate mass will vary according to bulk specific gravity (BSG), flakiness index, and size and shape of the aggregate particles. Aggregate coverage rates are to be calculated for each source. See Appendix A1 for guidelines to calculate the required aggregate mass.

7.2 *Asphalt Emulsion* – The asphalt emulsion should meet all applicable specifications for the surface treatment application. The asphalt emulsion shall be equilibrated to a temperature of 60ºC for sample production.

Note 4—Emulsion volume will vary according to the void volume that exists between aggregate particles and the residual content of the emulsion. Asphalt emulsion coverage rates are to be calculated for each source and for each combination with different aggregates. See Appendix A2 for guidelines to calculate the required emulsion volume.

7.3 *Asphalt Felt Disk* – Produce sample disks from 30-lb asphalt felt paper, specification D 226, Type II. The asphalt felt disks shall not have breaks, cracks, tears, protuberances, indentations, or splices. The felt shall be cut to make 300 ± 10-mm diameter disks. The disks shall be placed in a 50°C oven for 24 to 72 h to flatten. Manipulate the disks until they are flat and store at room temperature at least three days before use.

8. TEST SPECIMENS

8.1 Pre-weigh and record the aggregate as dry aggregate mass. In a glass bowl, add sufficient water, of known mass (corrected for water loss during specimen production), to the pre-weighed aggregate, targeting the prescribed moisture content for the completed specimen. Immediately cover the bowl to prevent moisture loss. Gently shake, overturn, and orient the covered bowl and its contents to coat the particles with moisture and let stand for at least 5 min to enable absorption of the moisture by the aggregate. Weigh the asphalt felt disk to the nearest 0.1 g and record as the asphalt sample disk mass. Place the asphalt felt disk on a table. Manipulate the felt disk so that it lies flat against the surface. Replace the disk if the edges curl or bubble or the disk contains foreign matter. Position the disk on the working platform. During specimen manufacture and after the application of emulsion, the disk is moved to the scale and back to the working platform for application of aggregate chips. Where the disks are not perfectly circular or uniform, a system must be developed to enable accurate repositioning of the asphalt disk in its initial position when it is moved back to the platform for application of aggregate chips. A strike-off template is placed over the felt disk, centering the hole of the template over the felt disk.

Using the aggregate former, the pre-weighed (and moistened) aggregate is now formed on the sliding-plate chip-dropper apparatus, which is assembled near the working platform. The fingertips are used for spreading the aggregate one stone deep, compactly filling the circular area of the former. Next, the aggregate former is removed and the pin grabber is attached to the chip dropper to hold the aggregate in place. Asphalt emulsion in the amount of 83 $\pm$ 5 g (application rate of 1.42 kg/m^2) at 60°C is poured along the top arc of the exposed felt disk. With the thickness of the strike-off rod in contact with the surface of the template, and the width of the strike-off rod held approximately vertically (the top edge of the strike-off rod leaning toward the user), excess asphalt emulsion is removed with the strike-off rod in a gentle side-to-side continuous motion. This shall be completed within a 3 $\pm$ 1 s period. The strike-off motion should not be stopped until the excess materials are off of the felt disk. The template is quickly removed (Note 5). The asphalt disk is moved to a scale to determine the applied emulsion mass and then accurately repositioned on the working platform. A picture of the strike-off procedure can be seen in Figure 7.

Note 5—Downward pressure, strike-off speed, and template thickness can be adjusted to ensure correct emulsion mass. Neat removal of the template is often difficult when low viscosity emulsions are used. In such cases, a bubble forms between the emulsion and the circular edge of the template. When this bubble pops, it splatters, irregularly, onto the asphalt disk. This problem is usually not encountered with the use of thicker-bodied emulsions.

8.2 Immediately position the sliding-plate chip-dropper on the working platform, over the asphalt disk, and apply the pre-weighed aggregate sample onto the asphalt emulsion. Once the aggregate has been placed on the sample, compact the aggregates using the sweep test compactor three half cycles in one direction and three half cycles in a perpendicular direction to set the aggregate. Care should be taken not to apply any additional manual downward force to the compactor. Immediately weigh the sample and record as sample weight. Place the specimen in the forced-draft oven. Sample production and weighing should take no more than 4 min.

Figure 7. Emulsion strike-off in template.

9. CONDITIONING

9.1 The specimen is immediately placed in a forced-draft oven for the specified time, temperature (Note 6), and relative humidity based on desired field performance.

Note 6—Typically, where the performance of the binder–aggregate combination is being tested at various emulsion cure levels, specimens are cured at any convenient temperature and for any time period that provides the required specimen cure level.

9.2 The oven temperature shall be kept to a tolerance of 10% of the desired values (Note 7). The tolerance of the relative humidity shall be 25% of the desired value unless otherwise specified.

Note 7—To maintain constant curing conditions, the oven door should only be opened once within a 20-min period.

9.3 When the specimen has achieved the desired cure level ±2%, it is removed from the oven and allowed to cool to a convenient prescribed temperature. The weight is recorded in order to verify the cure level that is actually achieved. At the end of conditioning, the specimen is turned vertically and any loose aggregate is removed by gentle hand brushing of the technician's fingers back and forth across the sample. The specimen is then weighed, and the mass recorded to the nearest 0.1 g as the initial specimen mass. The time from end of conditioning to being placed in the test apparatus should be no greater than 2 min.

10. PROCEDURE

10.1 Attach and then leave the specimen in the clamping device for 180 $\pm$ 30 s. During the equilibration time, the brush is secured into the brush head, and the brush head with the weight is attached to the mixer. At the end of the equilibrating time, put the brush head into contact with the sample, making sure there is free-floating vertical movement of the brush head. The mixer is then turned on to setting #1 (0.83 gyrations per second) for 60 s. After the brush head has come to a complete stop, the table is lowered and the sample is removed from the clamping device. The specimen is held vertically, and any loose aggregate is removed by gentle brushing of the technician's fingers back and forth across the sample (Note 8). The abraded sample is weighed to the nearest 0.1 g, and this is recorded as the final specimen weight. A picture of the configured apparatus, with test specimen, can be seen in Figure 8.

Note 8—Brushing using the technician's fingers across the sample has proven to be the preferred method versus a brush for removing any loose aggregate that has not fallen off when the specimen is turned vertically.

Figure 8. Specimen under test in configured apparatus.

11. CALCULATION

11.1 This equation represents the total mass loss based on the initial aggregate sample weight. The mass loss as a percentage of the area exposed to the abrading force is

$$\%\ Mass\ Loss = \left(\frac{A-B}{A-C}\right) \times 100 \times 1.33 \qquad (1)$$

Where
A = initial specimen mass,
B = final specimen mass, and
C = asphalt sample disk mass.

APPENDICES

The laboratory specimen simulates a chip-seal layer. Aggregate, which is dropped onto the binder, is intended to be placed one stone thick and held in place by a combination of particle interaction, brought on by compaction, and binder–aggregate adhesion. The preceding manufacture and testing procedures account for and test the relative strength of the bond developed between asphalt binder and aggregate particles within the chip seal itself.

The required aggregate mass and asphalt cement volume depend on the average aggregate particle dimensions, on an assumed eventual degree of compaction of the aggregate particles, and on the assumption that each particle will eventually lay on its widest face. In the laboratory specimen, the degree of compaction of the aggregate simulates that which exists in a newly and properly built chip seal. The assumptions made with regard to calculation of the required binder volume (the residual asphalt content of the emulsion) intend to avoid bleeding by accounting for the compaction of the aggregate over time.

In determining the required chip-seal aggregate coverage, it is necessary to evaluate the proposed aggregate for its ability to compact. In this regard, our calculated required aggregate mass and asphalt volume will only be approximations since it is not possible to conclusively determine what will be the aggregate void volume immediately after construction or at ultimate aggregate density. The following useful guidelines for the calculation of required aggregate and emulsion masses used in the manufacture of laboratory specimens are taken from the McLeod and the modified Kearby single-surface-treatment design methods respectively referenced in the *FHWA Asphalt Emulsion Manual*, FHWA-IP-79-1, and the USDOT *Field Manual on Design and Construction of Seal Coats*, Research Report 214-25, July 1981.

APPENDIX A1. AGGREGATE MASS

A1.1 Although the laboratory compaction of specimen aggregate according to this standard is not equal to that possible in the field with rolling equipment, in the manufacture of the laboratory specimen, care should be taken to ensure that the appropriate mass of aggregate particles is positioned on the working platform as compactly as possible and such that the center of gravity of each particle is as low as possible, or such that a particle's stability against rotation is maximized.

A1.2 Physical properties of the aggregate are experimentally determined, including oven dry bulk specific gravity (G), loose unit weight (W), void volume (V), and particle size characteristics.

A1.3 Dry bulk specific gravity (G) is determined according to ASTM C 127, and dry loose unit weight (W) is determined according to ASTM C 29. These allow calculation of the initial void volume (V) between particles of the loose aggregate from

$$V = (1 - W/62.4G) \quad \text{(A1)}$$

A1.4 F. M. Hanson (1935) observed that the void volume between aggregate particles is approximately 50% (the loose condition) when the aggregate is dropped onto the asphalt binder. He theorized that due to reorientation, this reduces to approximately 30% (60% of 50% voids) immediately after rolling and to 20% (40% of 50% voids) after plenty of traffic. Hanson's theory, as it relates to surface treatment densification, is reflected in the following outline of the noted chip-seal design methods.

A1.5 Although one-sized and cubical aggregate performs best in chip seals and may simplify the design process, graded and non-cubical aggregate sources often find use. In these cases, it is often helpful to make use of the design method proposed by McLeod (1969), which calculates the required volume of aggregate at an assumed maximum density. This calculation is possible after approximating the ultimate average mat thickness (average least particle dimension) and through the assumption that, at the ultimate average mat thickness, voids have reduced, after considerable traffic, to 40% of the initial loose-aggregate void volume. Although the ultimate density is not achieved immediately after construction, this assumed ultimate state of the aggregate is also used to determine the asphalt requirement. In calculating the actual aggregate mass to be dropped from a spreader truck, the user may also use modifying factors to suit local conditions.

A1.6 The oven dry bulk specific gravity (G), the void volume (V) of the loose aggregate, and the ultimate average mat depth (H), in conjunction with an assumed ultimate void volume ($0.4V$), are used to calculate the required coverage mass per unit area at ultimate density. It is important to note that the procedure anticipates that the densification is due to particle reorientation and average mat depth reduction to H as a limit. The coverage mass per unit area, therefore, is assumed to remain practically constant as densification progresses.

A1.7 Using the assumption that particles will ultimately orient themselves on their widest sides, with the vertical dimension being the smallest, an approximation of the ultimate average mat height is made by determining the average least dimension of a representative sample of particles. The procedure involves determination of the median particle size and the flakiness index.

i. A sample of the aggregate material is first sieved according to ASTM C 136. From the aggregate gradation curve, the median size is determined as the theoretical sieve size through which 50% by mass of the aggregate would pass. The flakiness of the material is then determined by testing representative sample particles, taken from the various gradation fractions, on the appropriate slot of a slotted sieve. The flakiness index is the combined mass proportion of the total mass of tested material that passes through the slots.

ii. The median size and flakiness index results are used in conjunction with a chart for determining average least dimension to arrive at the approximate ultimate mat height of the chip seal.

A1.8 Refer to FHWA-IP-79-1 for a more detailed review of this procedure and its relevant modification factors.

A1.9 In applying the McLeod procedure for use with lab specimens, since it is assumed that specimen aggregate particles are placed on their widest sides, the average mat depth of the specimen is assumed to be equal to the average least dimension (H). However, since compact particle placement and specimen compaction in the lab is not as effective as what is possible in the field, it is usually necessary to modify the assumed ultimate void volume to a more practical value approaching that associated with the compact bulk density of the aggregate according to ASTM C 29.

A1.10 Where the maximum beneficial effect of aggregate chip/asphalt binder adhesion is being tested, the aggregate should be washed and dried prior to use.

APPENDIX A2. ASPHALT EMULSION VOLUME

A2.1 Asphalt emulsion is determined by volume, as opposed to by mass, since the required amount depends primarily on the void volume available, between aggregate particles, to be filled with asphalt cement.

A2.2 A balance must be struck so that the young chip seal is bound sufficiently by asphalt, such that it will endure its early life while avoiding the use of too much binder since this will cause the early onset of flushing, reducing the useful life of the chip seal to a shorter time period than otherwise possible. In the field, after a few years when the aggregate particles have been oriented by traffic and the ultimate aggregate density has been achieved, it is typically desired, for good road surface performance, that 70% of the voids be filled with asphalt binder. In this regard, depending on the road traffic volume and aggregate chip shape, which imply a certain compacted state of the aggregate in a few years, and also depending on the nominal size of aggregate chips, the requirements for initial embedment immediately following construction of the chip seal may vary between 20% and 40%. In the manufacture of laboratory specimens, observing these field principles will enable the construction of a representative specimen.

A2.3 The thickness of the strike-off template used in the manufacture of laboratory specimens is specified based on the average particle height and degree of compaction of the aggregate, such that it provides the appropriate struck emulsion volume with the required asphalt residual content.

A2.4 The McLeod method employs factors for surface correction (S) and seasonality (K) in an effort to avoid flushing. Specifically, however, the McLeod method applies a traffic factor to ensure that the ultimate void volume is filled a maximum of 60% to 85%, the higher percentage being applicable to lower volume roads. Additionally, the McLeod procedure assumes that the ultimate void volume is 40% of the initial void volume of the cover aggregate in the loose weight condition.

Refer to FHWA-IP-79-1 for a more detailed treatment of this procedure and for further references.

A2.5 In laboratory specimens, calculation of the required asphalt binder quantity should follow determination of the aggregate quantity and should reflect the void volume that exists in the specimen aggregate. It may be helpful to assume that the applied specimen aggregate has a void volume of 80% of that in the loose weight condition.

A2.6 The preceding standard is intended to allow performance evaluation of a combination of asphalt emulsion and aggregate chips as well as relative performance of several combinations of asphalt emulsions with aggregate chips at a certain level of cure. In this regard, it is up to the user to determine the required asphalt quantity based on the use of a constant percent embedment or, alternatively, a constant asphalt volume with different chip types and sizes.

A2.7 This standard is not intended to determine the potential for chip-seal flushing due to densification and reorientation of the cover aggregate. It provides the relative performance of chip-seal treatment materials, specifically those of a single surface treatment exhibiting compactly placed and oriented aggregate particles one stone in depth. Through the use of this standard, and as a result of the ability to precisely place a predetermined aggregate mass, it becomes possible to calculate the precise volume of required asphalt emulsion. Additionally, it is possible to repeatedly combine chip-seal materials in constant proportions.

A2.8 It is important to note that prior to using a template for a recorded test, several trials should be performed in order to determine the rate and repeatability of asphalt emulsion application using the template and the adopted striking-off technique.

Recommended Standard Method of Test for Measuring Moisture Loss from Chip Seals

AASHTO Designation: Txxxx-xx

1. SCOPE

1.1 This test method approximates the asphalt emulsion moisture content of a newly built chip seal as it cures by close monitoring of an equivalently constructed and cured specimen chip seal.

1.2 The values stated in SI units are to be regarded as the standard unless otherwise indicated.

1.3 A precision and bias statement for this standard has not been developed at this time. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purposes.

1.4 *It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1 *ASTM Standards:*

- D 7000, Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples

3. SUMMARY OF TEST METHOD

3.1 By quantifying the mass loss of a specimen chip seal, which is significantly equivalent to a field chip seal, and where the emulsion spray rate, the emulsion residual content, and initial aggregate moisture content can be approximated, it becomes possible to estimate the specimen's cure level at different monitoring points throughout a workday.

3.2 In this test, a chip-seal specimen is manufactured by site equipment on a board placed on the roadway while the field chip seal is being built. The water-mass loss of materials on the board is then monitored throughout the day to gauge the specimen's cure level. These results are projected in evaluating the moisture content of the field chip seal's asphalt emulsion.

4. SIGNIFICANCE AND USE

4.1 The rate at which the bond is developed between asphalt and aggregate in a chip seal depends on the chip seal's curing characteristics. When asphalt breaks with water in an asphalt emulsion, and films of water evaporate, the bond can be more readily developed and a chip seal is said to be curing.

4.2 This test method aims at estimating the mass of water that has evaporated from a field chip seal by monitoring a specimen chip seal that is significantly equivalent in material composition to the field chip seal. Where periodic monitoring is performed, the test indicates the approximate rates of curing that may be present in a field chip seal cured under particular environmental conditions. This information is usually intended to track curing throughout a workday and up to the point where the chip seal materials are bound. Additionally, when performance results from sweep tests (ASTM D 7000) at known moisture contents are available, moisture content tracking can assist in decision making regarding the capacity of the chip seal to safely accept traffic at certain moisture contents.

5. APPARATUS

5.1 *Balance and (Optional) Pedestal* – The balance must be capable of weighing 10 kg or more to within ±1 g. A tared pedestal, some 10 in. in height and placed on the scale, is usually required to raise the specimen enough above the scale to avoid the specimen area obstructing view of the scale reading.

Note 1—The mass of a configured specimen board is on the order of 1,500 g. In addition to the board mass, the masses of the pedestal and the expected chip seal materials must be considered when determining the adequacy of a scale to bear the full specimen mass (with pedestal).

5.2 *Weighing Platform and (Optional) Wind Shield* – The platform is any convenient flat surface, shimmed as necessary for levelness, on which the balance is placed for weighing specimens. This is usually sited on top of another stationary structure in the field or in the tray of a parked vehicle. Additionally, where windy conditions are expected, the ability to obtain reliable mass readings may depend on the use of a lightweight enclosure to shield the specimen and prevent wind-induced flutter.

5.3 *Pocket Level* – This is a portable bubble level that is placed on the weighing platform to check for approximate levelness.

5.4 *Infrared Thermometer* – This is used to check temperatures of the field chip seal and the specimen chip seal.

5.5 *Drying Pan* – This metal pan is used to dry sampled aggregate where the moisture content appears to be high or in question.

6. MATERIAL PREPARATION

6.1 *Specimen Board* – Each chip-seal specimen is manufactured on an 18-in. square and 3/16-in. thick plywood board (Figure 1) with an unconditioned surface. A continuous, light gauge, z-shaped metal strip is fixed to the perimeter of the board. The vertical legs of the z-shaped metal strip are oriented such that the board is suspended ¼ in. above the pavement by one leg (the inner) of the z-shaped metal edging (for easy removal from the roadway) while the other leg forms a vertical lip protruding above the surface of the board (to prevent the loss of any specimen material as the board is moved).

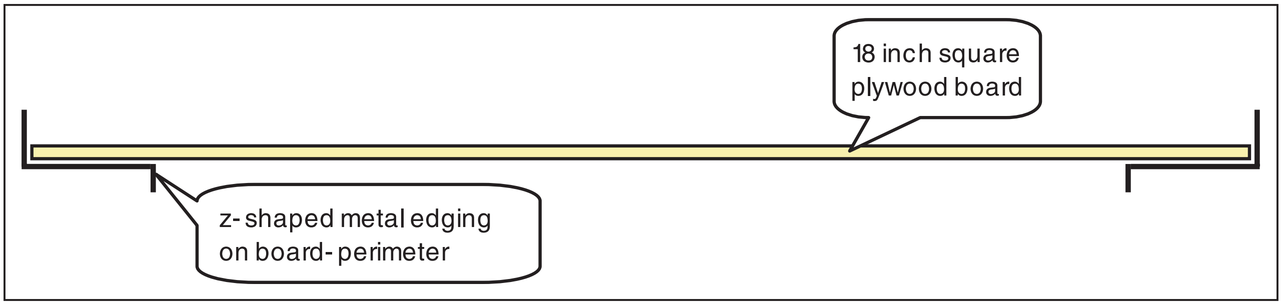

Figure 1. Configured specimen board.

6.2 *Aggregate and Asphalt Emulsion* – The chip-seal specimens are laid down by the distributor and chipper in the course of placing the actual field chip seal. In this regard, the properties of the specimen aggregate and asphalt emulsion are those of the field chip seal.

6.3 *Aggregate* – Sample the aggregate from the stockpile that is to be used in the manufacture of the chip seal and store in an airtight container. Where moisture content tracking is to be performed without the need for immediate results on site, laboratory determination of aggregate moisture content (*W*) may be performed. Alternatively, estimate moisture content (*W*) according to Note 2 where immediate moisture content results are required and where available time, sufficient resources, and the need for higher on-site accuracy warrant extra care.

Note 2—An acceptable on-site approximation of the aggregate moisture content may be obtained by drying a representative sample of chip-seal aggregate over a few hours of the workday. Place approximately 3 kg of aggregate (in its sample state) on the tared drying pan and record the wet aggregate mass. Place the drying pan and its contents in a warm (and, preferably, windy) location. When the aggregate becomes dry to the touch, record the mass loss of the aggregate. The aggregate moisture content (*W*) is the mass loss expressed as a percentage of the dried aggregate mass.

6.4 *Asphalt Emulsion* – Usually, a good approximation of the project asphalt emulsion's residual content (*R*) may be obtained from key site personnel. Where dependable figures are not available, the cure level of the chip seal must be based on conservative and conventional figures (approximately 70% residual content) until a simple lab experiment can be performed such as that outlined in Note 3.

Note 3—To evaluate the residual content of the asphalt emulsion that was used on site, dry approximately 50 g of the material, weighed to the nearest 0.1 g, in a 100°C oven, in the laboratory, to obtain the residual asphalt. The asphalt emulsion should be placed in a thin layer in an approximately 11-in.-diameter aluminum foil pan. Monitor the mass of the material until it no longer continues to lose mass over two consecutive readings taken 8 h apart. Record the mass loss and the final residual asphalt mass to the nearest 0.1 g. Estimate the moisture content of the asphalt emulsion to be the mass loss expressed as a percentage of the initial asphalt emulsion mass. The asphalt emulsion's residual content (R) is the final residual asphalt mass expressed as a percentage of the initial asphalt emulsion mass.

7. SPECIMEN MANUFACTURE AND WEIGHING

7.1 Set up the weighing platform (with optional wind shield) in an off-road location within short walking distance of the location where the specimen is intended to be manufactured. Level the platform and position the scale on the platform (with optional pedestal).

7.2 Record the tare mass (B) of an unused specimen board.

7.3 Place the weighed specimen board at a chosen location on the roadway (Note 4) that is to be chip sealed. Ensure that the board is not positioned in the wheel paths of the distributor, chipper, or other trucks.

Note 4—Locations at which specimen chip seals are to be made should be chosen based on the availability of similar off-road locations, in terms of temperature and exposure, to where the specimen may be cured. Additionally, at selected manufacture locations, manufacture should be fast and allow for removal and weighing of the specimens within 5 min of the asphalt emulsion being sprayed onto the board. When monitoring the field chip seal, observations should be made at a location immediately adjacent to where the specimen is manufactured.

7.4 Immediately after chips have been dropped onto the specimen board, move the specimen from the roadway and obtain its initial total mass reading (S).

7.5 Obtain the asphalt emulsion spray rate (E) from appropriate site personnel.

7.6 Throughout the workday, maintain a log of the temperatures and other environmental conditions affecting the cure rates of the specimen and the field chip seals. Relocate the specimen as necessary to ensure similar curing conditions relative to those of the field chip seal.

7.7 Record the total mass (C) of the specimen as it cures throughout the day to various cure levels.

Note 5—Record the specimen mass as often as practical but at least once per hour until a desired cure level has been achieved.

7.8 Where curing conditions throughout the workday are similar for the specimen and the field chip seal, it may be assumed that the chip-seal moisture content at a certain time after construction is approximated by that of the specimen.

8. CALCULATIONS

8.1 The mass of asphalt emulsion in the specimen is obtained from the following:

$$O = 3785\,(UEAG) \quad (1)$$

8.2 The mass of dry specimen aggregate is obtained from the following:

$$D = (S - B - O)/(1 + W) \quad (2)$$

8.3 The initial mass of all specimen moisture is obtained from the following:

$$I = S - B - D - (OR) \quad (3)$$

8.4 The mass of all specimen moisture at cure level (L) is obtained from:

$$F = C - B - D - (OR) \quad (4)$$

8.5 The percent moisture content of asphalt emulsion at cure level (L) is obtained from:

$$M = [100F]/[(OR) + F] \quad (5)$$

8.6 The cure level of the specimen asphalt emulsion is obtained from:

$$L = 1 - \{F/[\mathrm{O}\,(1 - R)]\} \quad (6)$$

Where
O = mass of asphalt emulsion on the specimen board (g),
U = unit weight of water (g/ml),
E = reported emulsion spray rate (gal/sy),
A = specimen board area (sy),
G = specific gravity of the asphalt emulsion,
D = mass of dry specimen aggregate (g),
S = initial specimen mass (including board) (g),
B = mass of the specimen board (g),
W = initial percentage moisture content of specimen aggregate (as percentage of dry aggregate mass),
I = initial mass of all specimen moisture (emulsion and aggregate moisture) (g),
F = moisture mass in specimen at cure level (*L*) (g),
C = specimen mass (including board) at cure level (*L*) (g),
L = the cure level at which specimen moisture content is being evaluated,
M = percentage specimen moisture content at cure level (*L*) (as percentage mass of current asphalt emulsion), and
R = percentage residual asphalt content of emulsion (as percentage mass of initial asphalt emulsion).

Recommended Standard Method of Test for Recovery of Asphalt from Emulsion by Stirred-Can Method

AASHTO Designation: Txxxx-xx

1. SCOPE

1.1 This method covers the recovery of asphalt from a water-based emulsion by the stirred-can evaporation method. The recovered asphalt reproduces the asphalt with the same properties as those used as the asphalt base in the emulsion and in quantities sufficient for further testing.

2. SUMMARY OF METHOD

2.1 The water in the asphalt emulsion is evaporated under a nitrogen atmosphere at an elevated temperature. Initially, the set point for the emulsion temperature is above the boiling point of water, but the temperature of the emulsion would stay at the boiling point of water while the evaporating process occurs. After most of the water has been evaporated, the temperature of the emulsion will increase to the initial set point and the remaining water will be completely removed. The recovered asphalt (evaporation residue) can then be subjected to further testing as required.

3. APPARATUS

3.1 *Laboratory Mixer* – The standard laboratory mixer with mixing blade and shaft that is capable of reaching a mixing speed of 1,000 to 2,000 rpm.

3.2 *Tin Can* – The can should have a volume capacity of 1 gal with a 6½-in. diameter to allow adequate access of mixing head, thermocouple, and nitrogen outlet.

3.3 *Heating Unit* – The heating unit consists of the heating tape and the Variac, which is used to control output power. The length of heating tape should be adequate to wrap around the tin can until it fully covers the bottom half of the can.

3.4 *Nitrogen Purge and Nitrogen Blanket System* – As shown in Figure 1, these should consist of a nitrogen piping system, nitrogen purge blanket, nitrogen sparge ring, and rotameters that are capable of measuring the gas flow up to 8.5 to 10 L/min.

3.5 *Temperature Controlling Unit* – The temperature control and thermocouple must be able to operate at the maximum temperature of 325°F.

3.6 *Heat Insulator* – The insulator pad should be large enough to cover the tin can that is wrapped with heating tape to prevent the heat from the tape escaping to the atmosphere.

4. REAGENTS AND MATERIALS

4.1 *Liquid Nitrogen* – A pressurized tank, with regulator or pressure-reducing valve.

5. SAMPLE

5.1 The sample must be a water-based asphalt emulsion. If a solvent-based emulsion is used, the set point temperature may need to be changed to ensure completion of solvent removal. Also, the properties of the recovered binder may not agree with the base asphalt if there is solvent residue left in the recovered binder.

5.2 Generally, asphalt binder will progressively harden when exposed to air, especially if the asphalt is placed in a high-temperature environment. Therefore, during the recovery process, the emulsion must be under a nitrogen atmosphere when the solvent is evaporated at a high temperature.

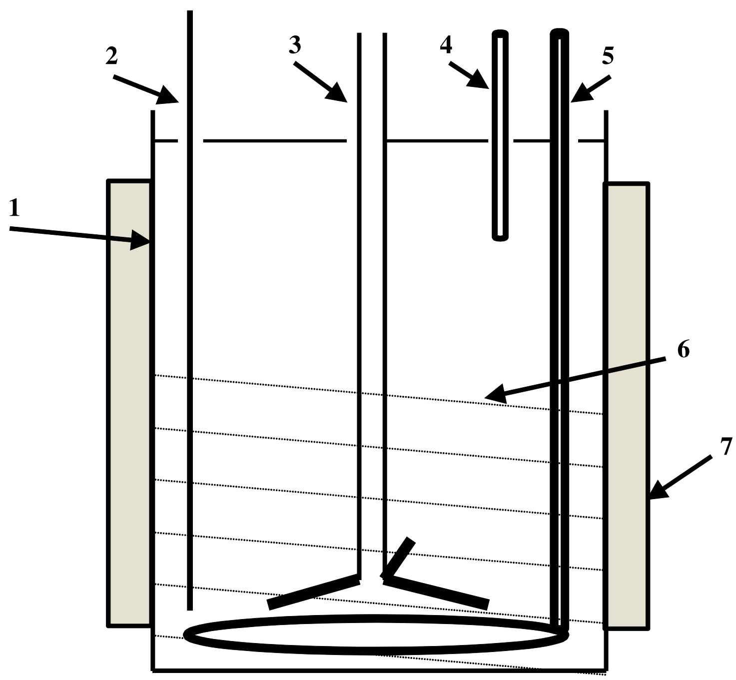

Figure 1. Schematic view of stirred-can setup: (1) Gallon can, (2) Thermocouple, (3) Impellor and shaft, (4) N_2 blanket tube, (5) N_2 sparger, (6) Heat tape, and (7) Thermal insulation.

6. PROCEDURE

6.1 The experimental setup for the stirred-can procedure is shown in Figure 1.

6.2 Weigh 1,250 ± 0.5 g of asphalt emulsion and add to the gallon can, then wrap the heating tape around the can until the tape covers the bottom half. Cover the side of the can with the heat insulation pad and place the container underneath the laboratory mixer.

6.3 Place the sparge ring into the can, but to prevent overflow due to foaming, do not turn the nitrogen sparge on at the beginning.

6.4 Lower the mixer head into the emulsion can and turn the mixer on. Then place the lid on top of the container and increase the mixing rate to 1,000 to 2,000 rpm, depending on how thick the emulsion is. After that, insert the thermocouple into the can. To ensure accurate temperature controlling, the thermocouple should not touch the side of the can or mixer head.

6.5 Turn on and adjust nitrogen flow to 8.5 to 10 L/min for the nitrogen blanket tube, then place the nitrogen blanket outlet on the emulsion surface to create a nitrogen blanket.

6.6 Connect the heating tape with the Variac and turn the Variac on to begin the heating process, then set the temperature controller to 163°C (325°F). The Variac providing power for the heating tape is set to 140 V, with corresponding power of approximately 430 W. After the heat is supplied to the system, the foaming process will start to occur.

6.7 Change the voltage on the Variac to about 100 V (corresponding power is 260 W) when the emulsion temperature reaches 100°C (212°F). The time from the beginning of the experiment to the time to change the voltage is approximately 20 to 30 min. Also, if foaming stops, start the nitrogen flow into the sparge ring (8.5 to 10 L/min). The emulsion temperature should stay at the boiling point of water until the majority of the water is evaporated; the emulsion temperature will then start to increase.

6.8 Let the emulsion temperature reach 325°F and wait for 10 min at this temperature (total recovery time is approximately 180 min). After 10 min, turn off the Variac, remove the heat insulation, and loosen the heat tape, but maintain the nitrogen flows and stirring while the sample is cooling.

6.9 Figure 2 shows a typical temperature versus time evolution curve. Four regions are evident. The first one is from the beginning to about 18 min. In this region, the temperature increases rapidly and nearly linearly from room temperature (around 72°F, or 22°C) to 212°F (100°C). The water evaporation rate is low in this region, and power input primarily increases the temperature. The second region is between 18 min to 110 min where the temperature increases slowly from 212°F (100°C) to 250°F (121°C) in about 90 min. Here the power input mainly provides water evaporation. The third region is between 110 min to 135 min, where the temperature increases linearly from 250°F (121°C) to 325°F (163°C) in about 25 min, a slower rate than in the first region. In this region, much of the water has evaporated and the power input primarily increases the temperature. In the fourth region, from 135 min to the end of the experiment at 170 min, the temperature is controlled at 325°F (163°C). (In Figure 2, the temperature evolution after 150 min is not shown because it changes little.)

6.10 As the sample starts to cool (<200°F), take out the nitrogen sparge ring but keep nitrogen flowing through the tube to prevent clogging. Then stop the mixer and move the mixer head upward.

6.11 Store the sample in a cool room (25°C). The recovered sample can be used for further testing.

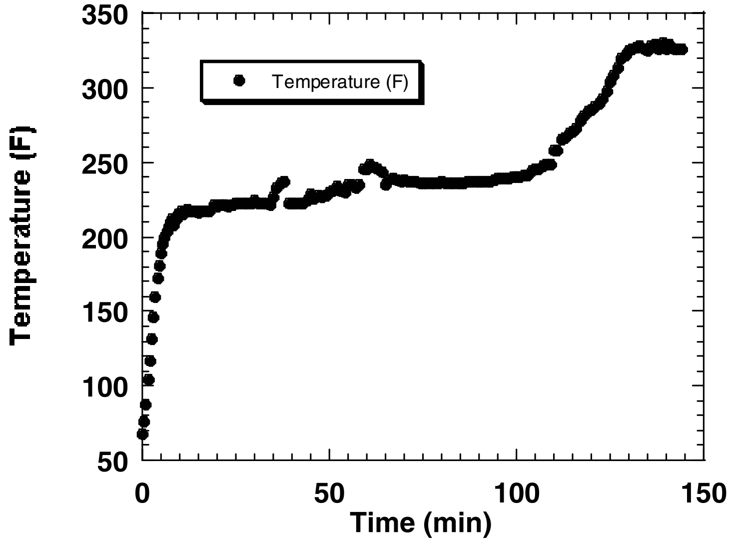

Figure 2. **Temperature evolution of the recovery system.**

Recommended Standard Method of Test for Determining the Strain Sensitivity of Asphalt Emulsion Residue Using Strain Sweeps Performed on a Dynamic Shear Rheometer (DSR)

AASHTO Designation: Txxxx-xx

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1. SCOPE

1.1 This test method covers the determination of strain sensitivity of asphalt residue from a water-based emulsion from changes in the dynamic shear modulus obtained from strain sweeps performed using the dynamic shear rheometer (DSR). This test method is supplementary to AASHTO T 315 and incorporates all of that standard. For this test method, the asphalt binder is the residue obtained by removing the water from a water-based asphalt emulsion.

1.2 This standard is appropriate for unaged material or material aged in accordance with R28.

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2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards:*

- T 315, Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer
- M 320, Performance-Graded Asphalt Binder
- R 28, Accelerated Aging of Asphalt Binder Using a Pressure Aging Vessel (PAV)
- R 29, Grading or Verifying the Performance Grade (PG) of an Asphalt Binder
- T40, Sampling of Bituminous Materials

2.2 *ASTM Standard:*

- E1, Specification for ASTM Thermometers

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3. SUMMARY OF TEST METHOD

3.1 This standard contains the procedure used to measure the complex shear modulus (G*) of asphalt residues from water-based emulsions using a DSR and parallel plate test geometry.

3.2 The standard is suitable for unaged material or material aged in accordance with R28.

3.3 The standard is suitable for use when the emulsion residue is not too stiff to be torqued by the DSR.

4. SIGNIFICANCE AND USE

4.1 The temperature for this test is related to the test temperature experienced by the pavement maintenance treatment in the geographical area for which the asphalt emulsion is to be applied. Typically the maintenance treatment is applied at moderate ambient temperature, and a default temperature of 25ºC can be used for the strain sweep evaluation.

4.2 A plot of dynamic shear modulus G* versus time will be generated and compared as an indication of strain sensitivity of the residue.

4.3 The complex shear modulus is an indication of the stiffness and the resistance of the asphalt residue to deformation under load and also is an indication of the ability of the residue to hold aggregate.

5. APPARATUS

5.1 *Dynamic Shear Rheometer Test System* – Consisting of parallel metal plates, an environmental control system, a loading device, and a control and data acquisition system.

5.2 *Test Plates* – The 8-mm plates are used for this test with a 2-mm gap. The preliminary gap before trimming must be set to achieve an acceptable bulge in the material after trimming.

6. REAGENTS AND MATERIALS

6.1 Varsol or another suitable agent for cleaning the plates.

6.2 Acetone for removal of all remaining residue from the plates.

7. SAMPLE

7.1 The sample is the residue after the water is removed from the water-based asphalt emulsion. The properties of recovered binder may not agree with the base asphalt since other substances have been added to the base binder in the emulsification process.

8. PROCEDURE

8.1 Procedure is as described in AASHTO T 315 using the 8-mm plates with a 2-mm gap.

8.2 Prepare the emulsion residue specimen according to AASHTO T 315.

8.3 Place the sample in the DSR and trim it according to AASHTO T 315.

8.4 Bring the sample and the environmental system to thermal equilibrium according to the manufacturer's directions and AASHTO T 315.

8.5 Perform the strain sweep.

8.6 Use the following parameters for the strain sweeps:

- Intermediate test temperature, with 25ºC being the default temperature.
- For strain sweeps, the DSR is set in oscillation mode for amplitude sweeps.
- DSR is set for auto-stress so that stress will be automatically adjusted to achieve desired strain.
- Frequency is set to 10 radians per second.
- Initial stress is set to the lowest stress that the DSR is capable of applying.
- Strain is set to increment between 1% and 50%, or between 1% and the highest strain that the DSR can achieve with the material being tested. A preliminary test may be needed, especially with stiff residues, to estimate the highest strain percent that can be set for the test.
- Steady shear rate is set to zero and is not used in this test.
- Number of periods is set to 1.
- Number of points is set to 256.
- Number of samples can be between 20 and 30. Determine the number of samples to test at enough points to define the strain sweep curve when plotting G* versus time.
- Strain control sensitivity is set to medium or better.
- Shear strain sequence is set for "up" so that strains are incremented from low to high.
- Time increments are set to linear so that the time increments between measurements are approximately linearly chosen (not logarithmically).
- Delay time is set to 1 s.
- Check that integration time is between 1 and 2 s, and total test time for the strain sweeps is less than 2 min.

8.7 Visually inspect the sample after the test when removing the sample from the plates. Note whether the sample is wholly or partially adhered to the plates, and note whether the sample has a ductile or a brittle break when the plates are pulled apart.

8.8 Generate a plot of dynamic shear modulus versus time. A flat curve indicates a strain-resilient material. A steep curve indicates a strain-sensitive material.

ATTACHMENT

Manual for Emulsion-Based Chip Seals for Pavement Preservation: Research Report

CONTENTS

CHAPTER 1

Introduction

1.1 Background

Emulsion-based chip seals are the most commonly used type of chip seal in the United States for preserving asphalt pavements. The purpose of these preservation treatments is to seal fine cracks in the underlying pavement surface and prevent water intrusion into the base and subgrade. Chip seals are not expected to provide additional structural capacity to the pavement. Benefits are obtained by reducing pavement deterioration before significant distress is exhibited. A large body of research is available on chip-seal design practices (*NCHRP Synthesis 342: Chip Seal Best Practices*), and they were further investigated in this project. However, chip-seal design in the United States has not been developed significantly beyond early work (McLeod 1960, 1969; Epps 1981).

In spite of their apparent benefits, the use of chip seals for pavement preservation in the United States has been hampered by the lack of nationally accepted guidance on their design and construction and appropriate specifications and testing procedures for constituent materials. Therefore, research was needed to develop a manual that identifies factors that influence chip-seal design, construction, and performance and provides guidelines that enable practitioners to improve the opportunity for success when building these systems.

1.2 Project Objectives and Scope

This research was conducted to develop a manual describing the best methods to use for designing and constructing chip seals placed on hot mix asphalt pavements. A significant body of knowledge existed about chip-seal design and construction before this research, much of which is contained in this manual. However, other practices in chip-seal technology have been subjective for many years and are considered an art by some. Therefore, the research conducted in this study focused on elements of chip-seal technology that were subjective or not practiced in the United States. The research presented in this report includes a recommended manual that could replace the subjective or qualitative judgments previously used during chip-seal design and construction with field and laboratory testing, and thus can be used to improve the opportunity for success when building chip seals.

1.3 Organization of the Report

This research report has five chapters. Chapter 1 is the introduction and describes the purpose of the research and the scope of the work. Chapter 2 describes the state of the practice of chip-seal design and construction. Chapter 3 describes the results and analysis of a series of laboratory and field tests. Chapter 4 discusses the application of research findings. The final chapter presents the study conclusions and recommendations. Further elaborations on the research are provided in Appendices A through J, which are not published herein but are available on the TRB website at http://www.trb.org/Main/Blurbs/164090.aspx.

CHAPTER 2

Research Methodology

2.1 Introduction

Research conducted in this project focused on aspects of chip-seal technology that have been qualitative in the past or were based on material properties that did not necessarily relate to chip-seal performance. Quantitative methods were developed to help replace past subjective practices and allow improved prediction of chip-seal behavior in the field. The following issues were addressed in the research through laboratory and field experiments:

- Chip adhesion to emulsion and residue,
- Time required before sweeping and uncontrolled traffic,
- Emulsion consistency in the field,
- Surface texture measurement, and
- Residue recovery and properties.

2.1.1 Chip Seal Definition

Chip seals considered in this research are based on emulsified asphalt binders and natural mineral aggregate chips. The chip seal is constructed by spraying the asphalt emulsion onto the existing asphalt pavement, dropping the aggregate chips into the asphalt emulsion, and embedding the chips in the emulsion using pneumatic-tired rollers. The purposes of the chip seal are to preserve existing asphalt pavement by sealing the surface before cracking occurs or after minor cracks have emerged and to provide additional surface friction.

2.2 Chip Adhesion to Emulsion and Residue

The required adhesive and cohesive strength of the emulsion residue used as the binder in a chip seal directly influences when the chip seal can be opened to traffic after construction. This strength is usually judged subjectively during construction by experienced personnel who decide based on how easily chips can be dislodged from the emulsion. This experience is often gained by trial and error, sometimes leading to vehicle damage when residues that have not gained sufficient strength release chips under traffic loads (Gransberg and James 2005; Shuler 1998). Several tests such as Vialit (Vialit plate shock test), frosted marble (Howard et al. 2009), and the sweep test (Cornet 1999; Barnat 2001; ASTM D7000) attempt to quantify this adhesive behavior and identify when chip seals are ready to accept uncontrolled traffic. However, these tests have shown high variability and have therefore not been widely adopted. One method uses a hand broom to sweep the chips, and the chip seal is judged ready for traffic when the amount of chips dislodged during this procedure is less than 10%. This test is attractive since it uses actual construction materials and with practice could be a means to evaluate adhesion. The sweep test described by ASTM D7000, Standard Test Method for Sweep Test of Bituminous Surface Treatment Samples, appeared to be a reasonable approach to simulating the forces that dislodge aggregate chips from chip seals. This procedure is relatively effective at evaluating differences in adhesive abilities of different emulsions with a single aggregate. This test utilizes a template for specific aggregate gradations to establish the emulsion application rate. While a single emulsion application rate is suitable for relative comparison between emulsions, when aggregate sizes differ, the embedment percentage changes, which affects chip retention. In addition, the test describes a procedure of "hand casting" the aggregates onto the emulsion prior to testing. Attempts to repeatedly place precise amounts of aggregate on test samples during this research proved difficult to replicate. Therefore, the test apparatus was modified so that the exact amount of chips was placed on the test pad each time. To determine if the modified test procedure would be useful to evaluate the adhesive ability of different emulsions and different aggregate chips under varying moisture conditions, a controlled laboratory experiment was conducted.

2.2.1 Experiment Design

Because of variability associated with the manner with which aggregate chips are prepared for testing according to ASTM D7000, a modification to the procedure was made to precisely control how chips are placed on the test pad prior to sweeping. To determine if the modified procedure was an improvement over the ASTM procedure, an experiment was conducted to measure the ability of the modified sweep test to discriminate between four independent variables believed to affect early chip-seal performance. These variables were aggregate source, emulsion type, emulsion cure level, and aggregate chip moisture content.

2.2.1.1 Independent Variables

Independent variables in this experiment are the following:

Aggregate source:	basalt, granite, limestone, alluvial
Emulsion type:	RS-2, RS-2P, CRS-2, CRS-2P, HFRS-2P
Emulsion cure level:	40%, 80%
Aggregate chip moisture content:	dry, saturated surface dry (SSD)

A full-factorial, randomized experiment was designed for each emulsion according to the model shown below (Anderson 1993):

$$Y_{ikl} = \mu + A_i + W_k + M_l + AW_{ik} + AM_{il} + WM_{kl} + AWM_{ikl} + \epsilon_{ikl}$$

Where

Y_{ikl} = chip loss, %;
μ = mean loss, %;
A_i = effect of aggregate i on mean loss;
W_k = effect of water removed k on mean loss;
M_l = effect of aggregate moisture l on mean loss;
AW_{ik}, etc. = effect of interactions on mean loss; and
ϵ_{ikl} = random error for the ith aggregate, kth water removed, and lth replicate.

This experiment design was chosen because results can be easily evaluated using conventional analysis of variance techniques (ANOVA). The experiment was repeated for each emulsion to eliminate potential variability that could be associated with differences in emulsion behavior due to aging.

2.2.2 Materials

A variety of emulsions were selected to represent the range available for construction. These included conventional and polymer modified anionic (RS-2 and RS-2P), high float (HFRS-2P), and cationic types (CRS-2 and CRS-2P). Production of these emulsions using a laboratory emulsion mill in close proximity to the research laboratory was desirable since emulsions have limited shelf life. These factors helped to reduce variability of the emulsion materials. Properties of the emulsions are shown in Table 1.

A variety of aggregates were used to determine if the modified sweep test could discriminate between different mineralogy, shape, and texture. These were a limestone (LSTN) aggregate from Colorado Springs, CO, granite (GRNT) from Pueblo, CO, basalt (BSLT) from Golden, CO, and an alluvial source (ALLV) from Silverthorne, CO. The properties of these materials are presented in Table 2.

2.2.3 Sweep Test Procedure

The test procedure is described in detail in Appendix B. Differences between the procedure conducted in the research and that described by ASTM D7000 include the following:

- 40% initial embedment of the aggregate chips,
- 40% and 80% emulsion moisture loss, and
- Consistent, uniform application of the aggregates to the test pad.

In this procedure, asphalt emulsion is applied to a 15-pound per square yard roofing felt substrate in a circle by means of a steel template with an 11-in. diameter cutout. Emulsified asphalt is screeded level with the template by means of a strike-off rod as shown in Figure 1. Aggregate is then placed mechanically using a dropping apparatus as shown in Figure 2. The

Table 1. Emulsion properties.

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

Table 2. Aggregate properties.

Sieve No. (in.)	Sieve Size (mm)	Passing, %			
		LSTN	GRNT	BSLT	ALLV
3/4	19.0	100	100	100	100
1/2	12.5	100	100	100	100
3/8	9.5	100	99	100	99
5/16	8.0	100	50	79	73
1/4	6.3	48	9	30	33
4	4.75	1	1	1	2
8	2.36	1	1	1	2
16	1.18	1	1	1	2
30	0.60	1	1	1	2
50	0.30	1	1	1	2
100	0.15	1	1	1	2
200	0.075	1	1	1	2
Bulk specific gravity		2.615	2.612	2.773	2.566
Loose unit weight, lbs/cf		78.3	84.0	92.2	86.1
Los Angeles Abrasion Loss, %		26.3	27.8	20.1	22.0
Flakiness Index		33.8	5.8	13.1	10.5

aggregate is then set in place, one stone thick, by means of a compactor as shown in Figure 3. The specimen is then placed in a 160°F oven to allow the emulsified asphalt to cure to 40% moisture loss or 80% moisture loss after which the specimen is removed from the oven. It is then cooled, and any loose particles are removed. The specimen is then swept under the action of a weighted brush which is spun by a planetary motion mixer for 1 min as shown in Figure 4. The specimen is then removed from the machine and brushed by hand to remove all particles that were mechanically dislodged from the specimen surface. The mass loss is then determined, which is expressed as percent loss of the original aggregate mass.

Figure 1. Emulsion strike-off apparatus.

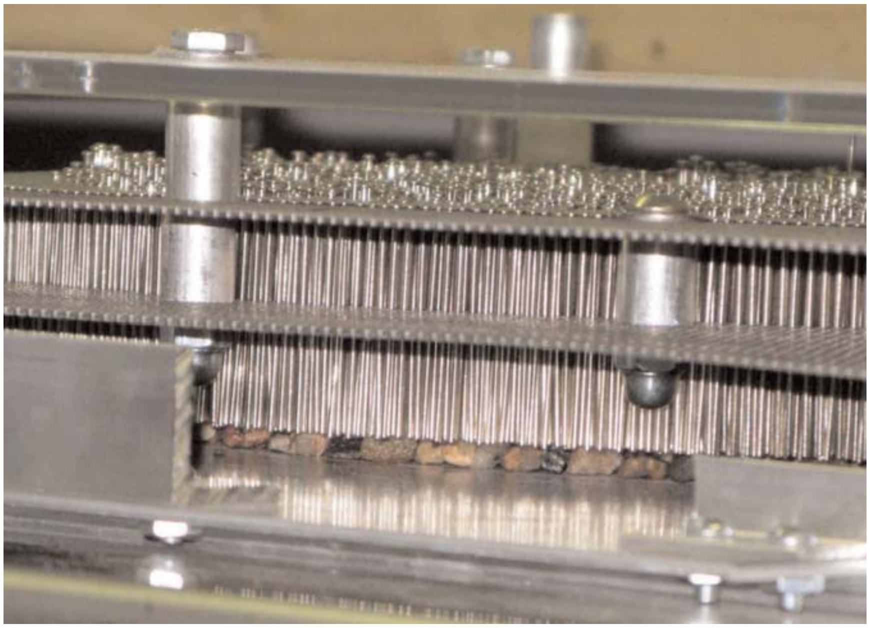

Figure 2. Dropping apparatus placing aggregate on test pad.

2.3 Time Required Before Brooming or Traffic

Determining when the first brooming can be accomplished to remove excess chips or when to open a fresh chip seal to traffic is one of the most subjective decisions that must be made. Releasing traffic too soon can lead to vehicle damage due to flying aggregate particles. Releasing traffic too late can lead to delays and congestion. Also, if light brooming results in damage to the chip seal, the chip seal is often left unbroomed until binder strength increases. However, allowing traffic on the fresh, unswept chip seal can lead to flying chips and potential damage.

The modified sweep test, which measures the relative adhesive strength of emulsions and emulsion residues in the laboratory, was used to evaluate materials from full-scale

Figure 3. Compactor setting aggregates on test pad.

Figure 4. Modified sweep test mixer.

chip seals. The objective of this experiment was to determine if the moisture content of the chip seal in the field affects the ability of the chip seal to withstand brooming and traffic stresses.

2.3.1 Full-Scale Field Tests

Three full-scale chip-seal projects were included in this research. Test pavements were located on County Road 11 near Frederick, Colorado, approximately 30 miles north of Denver, Colorado; the Main Entrance Road in Arches National Park, Utah, approximately 15 miles north of Moab, Utah; and US-101 near Forks, Washington, on the western edge of Olympic National Park.

2.3.2 Moisture Tests

Moisture in a chip seal comes from two sources: the chips and the asphalt emulsion. In addition, on some projects additional moisture may be present in the roadway. If the amount of moisture in the chips and the emulsion is known at the time the chip seal is constructed, the amount of moisture that evaporates after emulsion and chip application can be measured. The objective of this part of the research was to measure the moisture loss in the three chip-seal projects and develop a relationship to chip adhesion.

The amount of moisture remaining in each chip seal was measured and compared with the relative strength of the residue on a scale of 1 (no strength) to 10 (ready for traffic), judged by pulling three chips out of the fresh seal and qualitatively judging dislodgement potential. This qualitative evaluation was conducted after rolling. Moisture remaining in the emulsion was determined by placing plywood pads covered with aluminum foil measuring 24 in. by 24 in. in front of the asphalt distributor prior to spraying with emulsion. The pads were weighed before and after spraying and chipping, and the loss in weight was determined periodically during the day until approximately 95% of the water had evaporated. Figure 5 shows the setup used to measure the tare weight of the apparatus prior to spraying and chipping.

The tared pad was placed in front of the asphalt distributor and chip spreader before chip-seal operations began. After the emulsion and chips were applied to the pavement and tared pad, the pad was removed from the pavement and re-weighed. As moisture evaporated from the pad the weight was recorded and the strength of the emulsion residue was evaluated using the 1 to 10 scale. The resulting relationship between emulsion strength and moisture loss was developed.

2.4 Emulsion Consistency in the Field

The consistency of the emulsion is an important factor that influences performance of the chip seal. An emulsion with viscosity too low may not have the ability to hold chips in place or could flow off the pavement. An emulsion with viscosity

Figure 5. Moisture test pads prior to spraying/chipping.

too high could be difficult to spray evenly or may not have the wetting ability needed to coat chips. Emulsions are often tested at the point of manufacture and a certificate of compliance is issued by the manufacturer indicating compliance to state, local, ASTM, or AASHTO specifications. However, because changes to physical properties of emulsions used for chip seals can occur during transportation, a means of measuring the consistency of the emulsion at the construction site is desirable. Some highway agencies have portable laboratories capable of conducting viscosity tests in the field (Santi 2009). However, most agencies do not have laboratories or trained personnel to conduct such tests. Therefore, a simple method of verifying the ability of the emulsion to be used as a chip-seal binder was identified in this research.

2.4.1 Full-Scale Field Tests

Two simple methods for measuring the consistency of asphalt emulsions in the field were evaluated. One method based on a procedure developed by Wyoming DOT (Morgenstern 2008) requires a Wagner Part #0153165 funnel, wind protection, 16-ounce plastic cups, thermometer, and a stop watch. The other method was a falling cylinder viscometer which was found to be cumbersome to operate and time consuming to clean and not appropriate for use in the field.

The first tests were conducted at the Arches site using the Wagner funnel with a 4 mm orifice. However, the emulsion required over 90 s to empty the funnel. This resulted in large differences between test results because the emulsion viscosity increased as the temperature decreased, increasing the time to empty the Wagner cup. Therefore, the orifice was drilled out to increase the diameter until the cup emptied in approximately 60 s or less. This process was repeated for the Frederick, CO, and Forks field tests.

The test proved simple to conduct, low cost, and required a simple apparatus. Although this test would require more development to be used for determining specification compliance in the field, the test will help a field inspector rapidly determine the suitability of an emulsion upon delivery to the construction site.

2.5 Pavement Texture Testing

Adjusting the emulsion spray rate to compensate for differences in pavement surface texture is one of the most subjective adjustments made during chip-seal construction.

Except for the sand patch test used in South Africa and Australia/New Zealand (Austroads 2006, South African Roads Agency 2007), adjustments in the United States are made using judgment based on past experience. The objective of this experiment was to provide a more quantitative method for evaluating pavement texture and adjustment of emulsion application rate.

Macrotexture is the texture type that is relevant to chip seals. Macrotexture is surface roughness that is caused by the mixture properties of an asphalt concrete surface or by the finishing/texturing method of a portland cement concrete surface (Hall et al. 2006).

Previous work has indicated that either the sand patch test (ASTM E 965) or the circular texture meter (CT meter) profile (ASTM E 2157) can be used to effectively evaluate pavement macrotexture (Abe et al. 2001, Hall et al. 2006, Hanson and Prowell 2004). Both of these measurements are easily performed in the field, but traffic control is needed during these measurements. The sand patch test has been used for texture measurement because it requires inexpensive equipment that is easy to obtain, and it provides acceptable measurements (Austroads 2006, South African Roads Agency 2007). However, conducting the test is slow and exposes personnel to traffic, and results are influenced by wind and moisture.

The CT meter evaluation of surface macrotexture can be made more quickly than sand patch testing and therefore exposes the technician to less traffic and accident risk. Also, the CT meter measurements do not depend upon operator skill. Figure 6 shows the interior of the CT meter, which faces the pavement when taking measurements.

2.5.1 Laboratory Texture Testing

One part of this research involved testing three slabs of varying surface texture. These test slabs provided a range of textures for evaluating three texture measurement techniques. The slabs were fabricated to simulate three surfaces ranging from very rough, simulating a highly raveled and pocked surface, to very smooth, simulating a very flushed surface.

The slabs were cast over asphalt pavements using a very low viscosity self-consolidating concrete. The self-consolidating concrete was used to make the texture specimens because of the concrete's ability to flow into the smallest voids in the surface of the asphalt pavements. This created texture test specimens that mimicked the texture of the three pavement surfaces. Texture of the three slabs was measured using sand patch, CT Meter, and the Aggregate Imaging System (AIMS).

2.5.1.1 Sand Patch Test

The sand patch test (ASTM E 965) is a volumetric technique for determining the average depth of pavement surface macrotexture. A known volume of small particles (either sieved sand or small glass beads) is poured onto the pavement surface and spread evenly into a circle using a spreading tool. Four diameters of the circle are measured and an average profile depth is calculated from the known material volume and the averaged circle area. This depth is reported as the mean texture depth (MTD). The method provides an average depth value and is insensitive to pavement microtexture characteristics.

The CT meter test method (ASTM E 2157) is used to measure and analyze pavement macrotexture profiles with

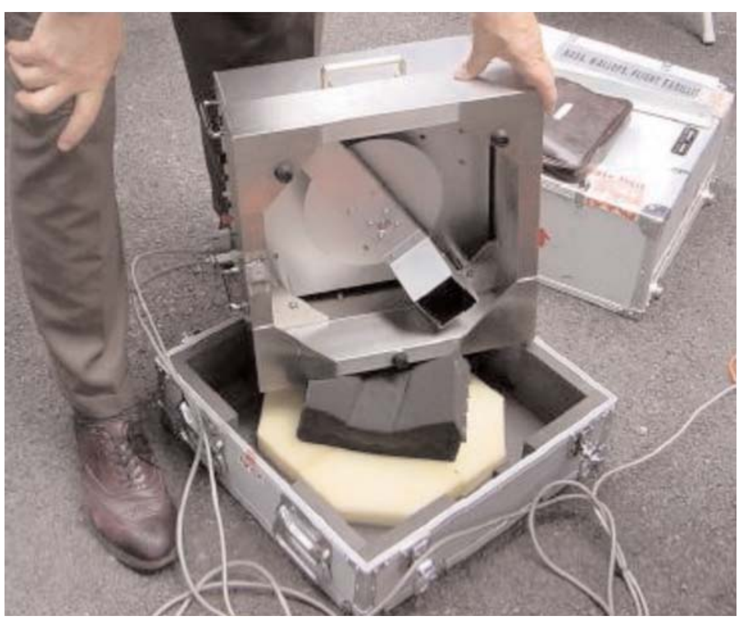

Figure 6. CT meter.

a laser displacement sensor. The laser sensor is mounted on an arm which follows a circular track of 284 mm (11.2 in.) diameter. Depth profiles are measured at a sample spacing of 0.87 mm, and the data are "segmented into eight 111.5 mm (4.39 in.) arcs of 128 samples each" (ASTM E 2157). A mean profile depth (MPD) is calculated for each segment, and an average MPD is then calculated for the entire circular profile.

2.5.1.2 AIMS

The AIMS was created to quantitatively describe the characteristics of aggregates (Masad 2005). The system consists of a camera mounted above a table with several lighting arrangements. Using AIMS, coarse aggregate is characterized by particle shape, angularity, and texture. Samples of coarse aggregate are placed on the AIMS table under the camera and lighted from above, below, or both, and camera images are used to quantify the aggregate characteristics. Analyzing macrotexture of coarse aggregates can be compared to measuring macrotexture of a pavement surface.

Using AIMS, microtexture or macrotexture of coarse aggregate surfaces can be quantified using wavelet analysis of a grayscale digital photo. Camera focal length can be adjusted depending on whether macrotexture or microtexture is of interest. Using AIMS, depth measurements were generated every 1 mm for four scanlines of 100 mm length each, 20 mm apart, and in two perpendicular directions, for a total of eight scanlines per test slab. The total of eight scanlines at 100 mm length each was chosen to be similar to the eight segments of the CT meter profile. The two sets of four scanlines each were taken in perpendicular directions to account for directional differences in pavement texture. This arrangement could be used to estimate directional differences in texture, which is texture in the direction of traffic versus texture perpendicular to the direction of traffic. Profiles were generated for the scanlines and analyzed in a procedure similar to the CT meter analysis (ASTM E 1845). A mean profile depth, MPD, was calculated from the AIMS data for each of the three test slabs.

2.6 Residue Recovery Methods and Properties

The performance grading (PG) asphalt binder grading system (Asphalt Institute, SP-1) is widely used as the specification for grading and selecting asphalt binders. The PG specification was developed for use in hot mix asphalt concrete (HMAC) pavement layers. However, the PG system is not applicable to classifying and choosing binders for use in pavement chip seals. Chip seals differ from full-depth HMAC layers in construction methods, structural functions, behavioral responses, distress types, and effects of environmental exposure. Therefore, the binder grading system, surface performance grading (SPG), was first suggested to classify emulsion residues or hot-applied binders for use in chip seals (Epps et al. 2001, Barcena et al. 2002). This grading system utilizes the same test methods as the PG system, but applies limits on test parameters that are consistent with the mechanics of chip seals rather than hot mix asphalt.

An emulsion residue specification requires a standardized emulsion residue recovery method that produces a material representative of the emulsion residue in situ. Currently, emulsion residues are recovered by distillation (ASTM D 6997) that exposes the material to high temperatures and may destroy or change any polymer networks present in modified emulsion residues.

This section describes the experiment used to compare emulsion residue recovery methods, characterizes the emulsion residues by both the PG and SPG grading systems and some additional tests, and recommends an emulsion residue recovery method and emulsion residue specification.

2.6.1 The Surface Performance-Graded Specification

The tests used in the SPG grading system are conducted with standard PG testing equipment and the analyses are performance-based and consistent with chip-seal design, construction, behavior, in-service performance, and associated distresses (Epps et al. 2001, Barcena et al. 2002). Field validation of the initial SPG system was completed in Texas (Walubita et al. 2005, Walubita et al. 2004) and resulted in the proposed three SPG grades shown in Table 3.

2.6.2 Residue Recovery Experiment

The standard PG system (Asphalt Institute, SP-1) and the modified SPG system (Epps et al. 2001, Barcena et al. 2002, Walubita et al. 2005, Walubita et al. 2004) were both used to grade all base binders and corresponding recovered emulsion residues in this experiment.

2.6.2.1 Materials

Eight emulsions were included in this research, five of which, identified as emulsions 1 through 5, were laboratory prepared. The other three emulsions were obtained from the full-scale test pavements in Utah Arches National Park; Frederick, Colorado, CR-11; and Forks, Washington, US-101. Table 4 lists the types of emulsions and, when known, the PG grades of the base binders as reported by the supplier.

Table 3. Criteria for SPG grades for emulsion residues (Walubita et al. 2005, Walubita et al. 2004).

	Surface Performance Grade*											
	SPG 58				**SPG 61**				**SPG 64**			
	–10	**–16**	**–22**	**–28**	**–10**	**–16**	**–22**	**–28**	**–10**	**–16**	**–22**	**–28**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<58				<61				<64			
Minimum Surface Pavement Design Temperature, °C	≥10	≥16	≥22	≥28	≥10	≥16	≥22	≥28	≥10	≥16	≥22	≥28
Original Binder												
Viscosity ASTM D 4402 Maximum: 0.15 Pa·s; Minimum: 0.10 Pa·s Test Temperature, °C	≤205				≤205				≤205			
Dynamic Shear, AASHTO TP5 $\frac{G^*}{Sin\,\delta}$, minimum: 0.65 kPa Test Temperature @10 rad/s, °C	58				61				64			
PAV Residue (AASHTO PP1)												
PAV Aging Temperature, °C	90				100				100			
Creep Stiffness, AASHTO TP1 S, Maximum: 500 MPa m-value, minimum: 0.240 Test Temperature @ 8 s, °C	–10	–16	–22	–28	–10	–16	–22	–28	–10	–16	–22	–28

**The table presents only three SPG grades as an example, but the grades are unlimited and can be extended in both directions of the temperature spectrum using $3^{o}C$ and $6^{o}C$ increments. For illustration, SPG 58–10 indicates a material suitable for construction in an environment from $58^{o}C$ to $-10^{o}C$.*

Table 4. Binders and PG and SPG grades.

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

2.6.2.2 Emulsion Residue Recovery Methods

Hot oven (with nitrogen blanket) and stirred can (with nitrogen purge) emulsion residue recovery (SCERR) methods were used to extract the water from the emulsions and to supply dewatered residue for the material properties testing. A third residue recovery method known as "warm oven" or "low temperature evaporative technique" (Kadrmas 2008, Hanz et al. 2009) was also compared with the hot oven and stirred can techniques (Prapaitrakul et al. 2009).

2.6.2.3 Laboratory Tests

Rheology Tests. Binder characterization tests utilized the same equipment and some of the same tests as specified in the PG system (Asphalt Institute, SP-1), but with different limiting criteria and test conditions as shown in Table 4.

All of the binders in this experiment were aged using the pressure aging vessel (PAV), as described in the PG grading system (Asphalt Institute, SP-1). Rolling thin film oven (RTFO) aging was not used because emulsion binders are not exposed to this type of heating in chip-seal construction. Unaged binder was tested at the high temperature that is the critical condition for early strength development in the chip seals. PAV aged binder was used in the bending beam rheometer (BBR) to simulate long-term in-service aging that may cause failure at cold temperatures for chip seals. PAV aging simulates approximately the first hot and cold seasons of a chip seal, which is when most chip-seal failures occur (Epps et al. 2001, Barcena et al. 2002).

Strain Sweep Tests. Strain sweep tests using a dynamic shear rheometer have been correlated to the chip-seal sweep test, ASTM D 7000 (Kucharek 2007). Therefore, strain sweep information collected in this research supplements the SPG system for evaluating strain tolerance and resistance to raveling of emulsion residues during curing and at early ages.

The strain sweeps were conducted using a dynamic shear rheometer (DSR) at 25°C with 8 mm plates and 2 mm gap on both unaged and PAV aged material to show the change in the complex modulus (G*) with increasing strain. Test results are affected by how the test is performed and by the parameters input into the DSR. The DSR is continually oscillating during strain sweep testing. Input to the DSR requested strains of 1% to 50%, and the strain sweeps were initiated at 1%. A 10 min period was allowed after mounting the sample and before testing started for thermal equilibrium to occur. An angular loading frequency of 10 radians/second and a linear loading sequence with time was applied. A delay time of 1 s after the load (strain) was incremented but before the measurements were taken was chosen, and 20 to 30 strain measurements were taken during each test. The test time for each strain sweep was approximately 1 to 2 min (after thermal equilibrium).

Chemical Tests. Gel permeation chromatography (GPC) was performed on each recovered residue to determine if all of the water had been removed during the residue recovery process. Presence or absence of a peak at a time of 35 to 37.5 min on the GPC chromatogram indicates the presence or absence of water in the residue.

Fourier transform infrared (FT-IR) spectroscopy was performed on the residues from the five laboratory emulsions to obtain an indication of whether the recovery methods caused oxidation of the materials. The infrared spectra were plotted, and then the area under the wavenumber band from 1,820 to 1,650 cm^{-1} was integrated to determine the carbonyl area, which is carbonyl used to represent the extent of oxidation in the materials (Epps et al. 2001, Prapraitrakul et al. 2009, Woo et al. 2006).

2.7 Estimating Chip Embedment Depth During Construction

Embedment depth is usually determined during construction by pulling several chips out of the binder and visually estimating the amount of the chip embedment in the binder. Because it is generally difficult to accurately assess chip embedment using this procedure, two methods based on the sand patch test were developed to provide a quantitative measure of embedment depth: the constant volume method and the constant diameter method.

Both methods were developed using the LSTN and GRNT aggregates from the laboratory sweep test experiment. These aggregates were used because they represent a range of flakiness from a high of approximately 34% for the limestone to a low of 6% for the granite.

2.7.1 Constant Volume Method

The objective of this experiment was to determine if the diameter of a constant volume of glass beads spread in a circular shape onto the surface of a new chip seal could be used to estimate the embedment of chips in the binder.

The aggregate chips (LSTN and GRNT) were oriented on their widest faces so that the average particle heights were their average least dimensions. Embedment percentage was determined for each specimen based on the aggregate average least dimension, weight-to-volume relationships of the materials, and the diameter of the glass bead circle from equation 1.

The texture depth (T) is the average distance the aggregate chip is exposed above the surface of the asphalt (or ALD – Embedment depth) as shown in Figure 7.

Figure 7. Embedment depth by constant volume model.

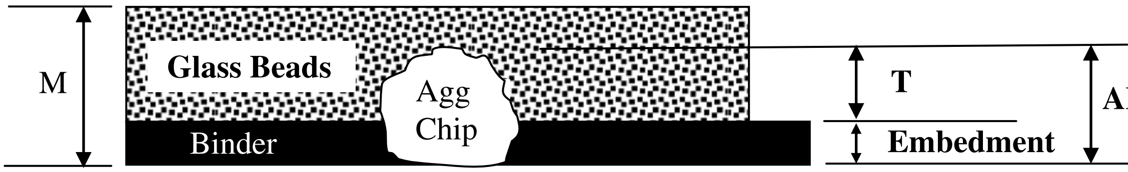

Figure 8. Embedment depth by constant diameter model.

$$T = \frac{\text{volume of beads between the binder surface and the top of the chip}}{\text{area of glass bead circle (A)}}$$

Volume of beads between binder surface and the top of the chip, $V_{bb} = W_{bb}/\gamma_b$

Where
W_{bb} = weight of beads between binder surface and top of chip and
γ_b = unit weight of beads

So

$$T = (W_{bb}/\gamma_b * A)$$

Since

$$\text{Embedment, \%} = 100 * (ALD - T)/ALD$$

$$\text{Embedment, \%} = 100 * \{ALD - [W_{bb}/(\gamma_b * A)]\}/ALD \qquad (1)$$

This relationship assumes the volume of glass beads is spread over the chip seal up to the peak of each particle such that the glass beads follow the profile of the particle peaks. Therefore, the average height of the glass beads on the chip seal is equivalent to the void height that would be seen between equal-height particles of a chip seal that is built with exactly one-sized aggregate.

Equation 1 can be used to calculate the percent embedment of a chip seal for a known volume of glass beads spread in a circle of a measured diameter. This procedure was used for limestone and granite aggregates, and the results were compared with the actual embedment depths to determine if the procedure yields appropriate results.

2.7.2 Constant Diameter Method

This method uses a constant diameter mold and measures the amount of glass beads necessary to fill the mold above the chip seal. Constant diameter chip-seal specimens were covered with glass beads until the peaks of the largest chips were completely submerged in glass beads. A mold was used to confine the glass beads to a constant diameter. By subtracting the volume of beads above the average particle height from the total volume of glass beads used, the volume of beads below the average particle height can be determined. Figure 8 represents the apparatus used in this experiment.

To determine embedment percent, the chip-seal specimen is placed in the mold, and the mold is filled with glass beads to the top of the mold. The total mass of beads which fills the space above the specimen is determined and its volume is calculated using its density. Knowing the average height of the chip-seal aggregate, the volume of glass beads between the top of the mold and the top of the average particle is calculated from the following:

$$\text{Volume of beads above chips to top of mold, } V_{ba}\text{, mm}^3 = (M - ALD) * A$$

Where:
M = mold height, mm,
ALD = average particle height, mm, and
A = mold cross-sectional area, mm^2.

The volume of beads between the chips is determined by subtracting V_{ba} from the total volume of beads to fill the mold. This value is used to determine the distance the chips extend above the binder.

$$\text{Volume of beads between the chips, } V_{bb}\text{, mm}^3 = V_{bt} - V_{ba}$$

Where:
V_{bt} = total volume of beads to fill the mold, cm^3 = $(W_{bt}/\gamma_b) - V_{ba}$,
W_{bt} = weight of beads to fill mold, gm, and
γ_b = unit weight of beads, gm/cm^3.

Percent embedment is calculated as follows:

$$\text{Embedment depth, \%} = [ALD - (V_{bb}/A)]/ALD. \qquad (2)$$

CHAPTER 3

Results and Analysis

This chapter describes the results of the laboratory and field studies conducted during this project that were used to develop the "Manual for Emulsion-Based Chip Seals for Pavement Preservation" provided with this report. Details of the laboratory and field testing are provided in the Appendices.

3.1 Sweep Test

Chip loss measured after the sweep test is shown in Figures 9 through 12 for each of the dry, SSD, 40% and 80% moisture loss test conditions. Results of ANOVA shown in Table 5 and the Newman-Keuls (Anderson and McLean 1993) multiple comparison test in Table 6 indicate statistically significant differences between the 40% and 80% moisture loss test specimens for all five emulsions. Chip loss with dry aggregates averaged approximately 70% and 15% at 40% and 80% moisture loss, respectively. Chip loss for SSD aggregates averaged approximately 65% and 10% moisture loss, also respectively.

The sweep test indicates a statistically significant difference in chip loss between aggregates that were dry when embedded in the emulsion and those that were in the SSD condition when embedded. The Newman-Keuls multiple range comparison from Table 6 indicates that dry aggregate has significantly higher loss than SSD aggregates except when the CRS-2 emulsion is the binder used because damp aggregates allow the emulsion to wick into the aggregate pores and provide improved adhesion and cohesion properties.

There are statistically significant differences in chip loss between the emulsions. The RS-2P showed aggregate loss similar to the other emulsions at 40% moisture loss with either dry or SSD chips but higher chip loss at 80% moisture loss with either dry or SSD chips. The CRS-2P performed similarly to the other emulsions under all conditions except at 80% moisture loss with SSD chips, where it showed less aggregate loss than the other binders except the HFRS-2P.

The particle charge on the emulsion appears to have little effect on chip loss at 40% moisture loss as shown in Figures 10 and 11. That is, the anionic RS-2 adheres equally well to the limestone as to the granite and basalt, and the cationic CRS-2 adheres equally well to all of the aggregates. Some difference may be significant with respect to the polymer modified RS-2P, where adhesion appears much better on the limestone. However, in general, the anionic emulsions do not appear to have a greater affinity to limestone, and the cationic do not appear to have a greater affinity to the granite nor basalt. Table 6 shows an opposite trend for the CRS-2P, which adhered better to the limestone (25% loss) than the granite (38% loss) at $\alpha = 0.05$. Also, the basalt had the least chip loss and the alluvial had the most loss regardless of the emulsion. This indicates that factors other than surface chemistry affect adhesion.

3.2 Field Moisture Tests

The results of this experiment indicate that chip adhesion reaches the point where significant force is required to dislodge the chip at approximately 75% to 85% moisture loss. At that time sweeping can commence and traffic can be allowed to travel on the new surface. Figures 13, 14, and 15 show the relationship between chip-seal binder strength and moisture loss for each test pavement. The chip-seal binder strength was judged subjectively by pulling three chips out of the emulsion and rating the relative strength with respect to how difficult the chips were to pull out of the emulsion residue on a scale of 1 (no strength) to 10 (ready for traffic). This qualitative rating was made after rolling.

3.3 Laboratory Sweep Test for Field Materials

The sweep test was conducted for aggregates and emulsions obtained from the three field test pavements. Aggregates were tested using two moisture contents and a range of moisture loss percentages. Results are presented in Table 7,

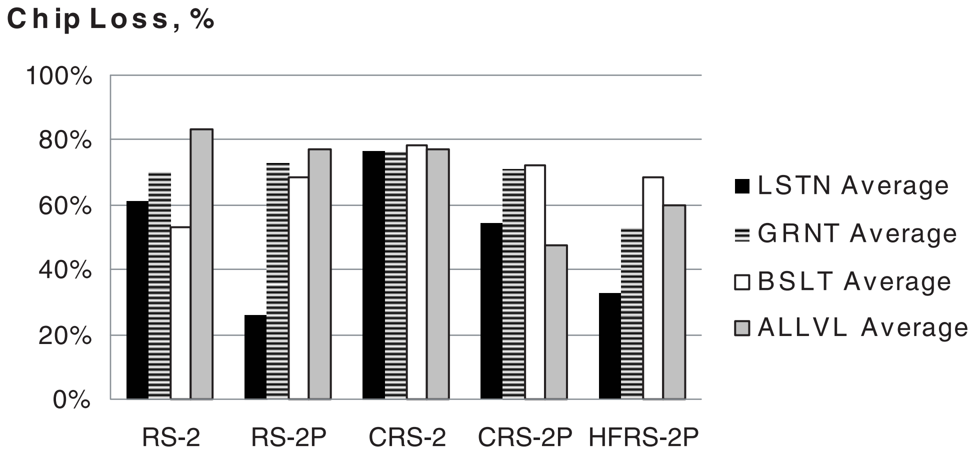

Figure 9. Sweep test results for dry chips at 40% cure.

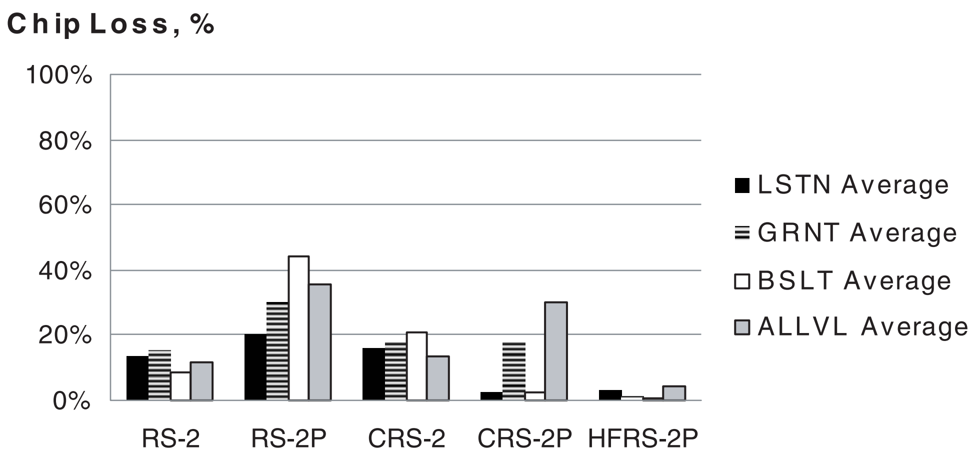

Figure 10. Sweep test results for dry chips at 80% cure.

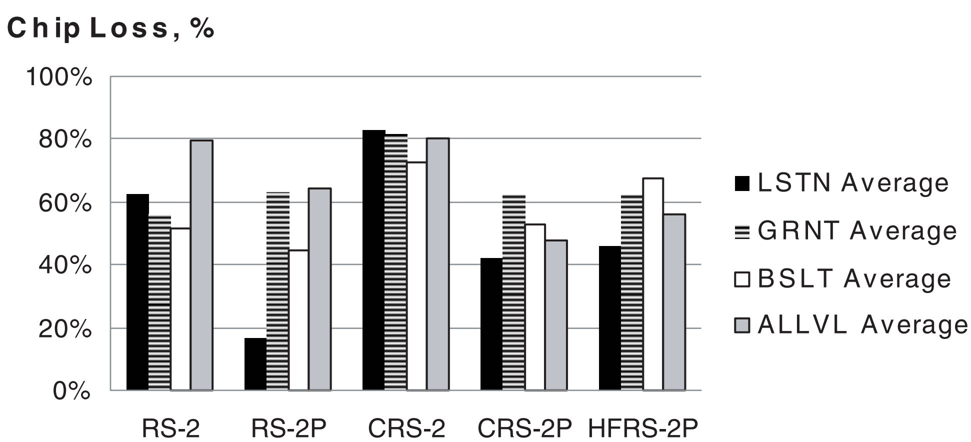

Figure 11. Sweep test results for SSD chips at 40% cure.

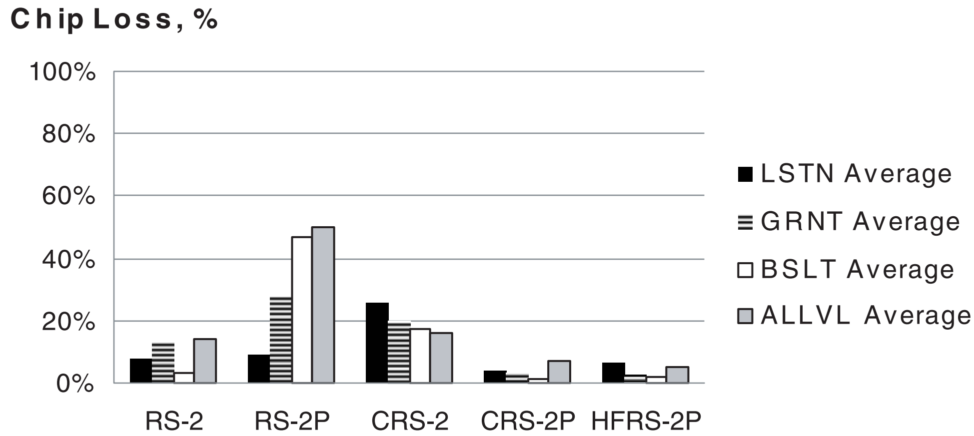

Figure 12. Sweep test results for SSD chips at 80% cure.

Table 5. Results of ANOVA for laboratory sweep tests.

Variable Tested	Alpha Level for Significant Differences				
	RS-2	RS-2P	CRS-2	CRS-2P	HFRS-2P
aggregate	<0.0001*	<0.0001*	0.3887	0.0049*	<0.0001*
moisture	0.0169*	0.0220*	0.1597	0.0003*	0.0335*
cure	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
agg x ** moist	0.2468	0.3618	0.0994	0.7574	0.5873
agg x cure	0.0001*	0.0020*	0.3927	0.0005*	0.0032*
moist x cure	0.5425	0.0136*	1.0000	0.9546	0.6490
agg x moist x cure	0.1064	0.2088	0.8805	0.0114*	0.2366

* Statistical significance at $\alpha = 0.05$ or less
**x indicates the interaction effect of the variables shown on the mean chip loss

Table 6. Results of Student Newman-Keuls multiple comparison test for aggregate.

Aggregate	Emulsion				
	RS-2	RS-2P	CRS-2	CRS-2P	HFRS-2P
ALL	A*(47)**	A(57)	A(50)	A (38)	A (44)
GRN	B(39)	A(51)	A(49)	AB (33)	AB (37)
LS	B(36)	A(51)	A(47)	AB (32)	B (28)
BST	C(29)	B(18)	A(47)	B (25)	B (25)

*Letters indicate different levels of statistical significance in chip loss average at $\alpha = 0.05$ for the different aggregates and the same emulsion. For example, there is a significant difference in chip loss between the alluvial (ALL) and the granite (GRN) for the RS-2 (47% vs. 39%), but not for the RS-2P (57% vs. 51%).
**Numbers in parentheses are the average percent chip loss after the sweep test

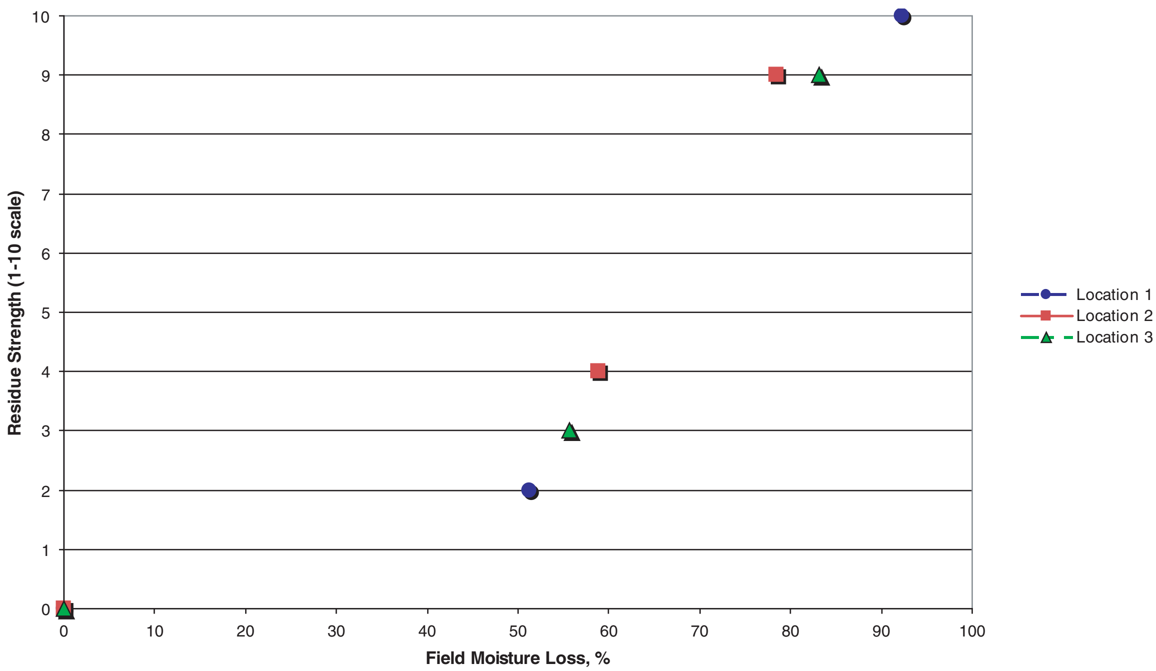

Figure 13. Residue strength versus emulsion moisture at Arches National Park, UT.

and the relationship between moisture loss and chip loss is shown in Figure 16. At approximately 85% moisture loss, residue strength increased to the point where chips could not be dislodged during the test. This suggests that a relationship exists between the laboratory sweep test and actual residue strength in the field as a function of moisture content of the chip-seal system.

The results show little difference between the dry and SSD aggregate conditions with respect to chip loss. The regression equations for both moisture conditions were similar, and location had little effect. However, there appears to be a strong relationship between chip-seal moisture loss and chip loss. Therefore, the moisture content of the chip-seal system (i.e., the moisture of the emulsion and the moisture of the

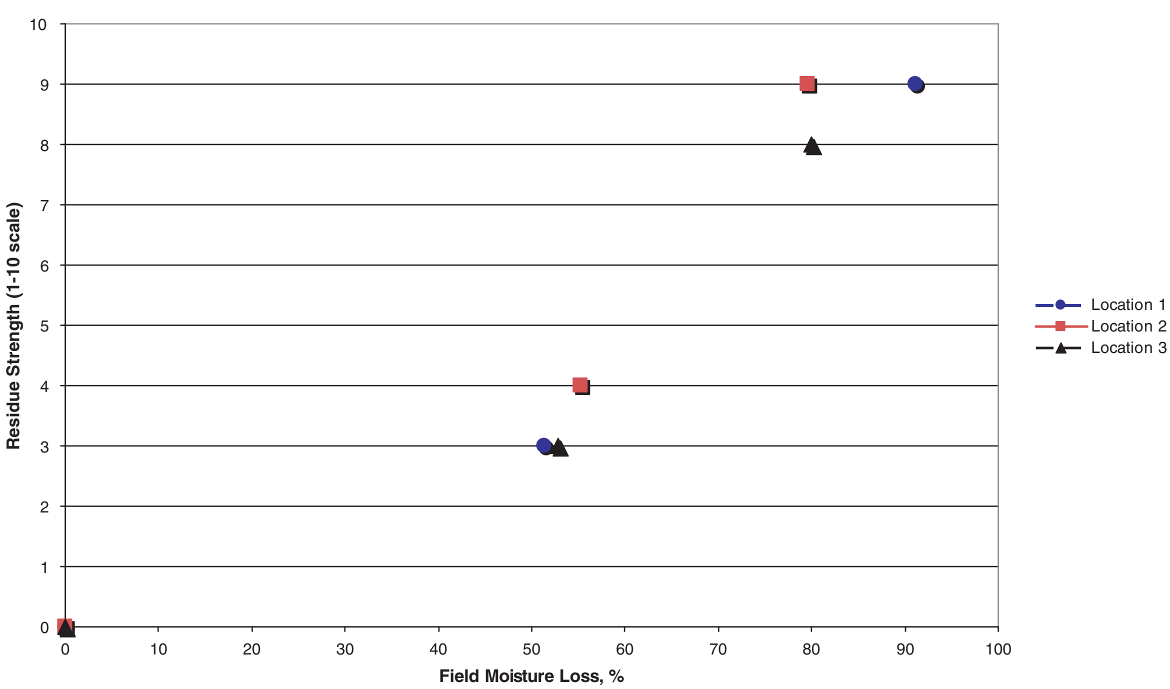

Figure 14. Residue strength versus emulsion moisture for CR-11, Frederick, CO.

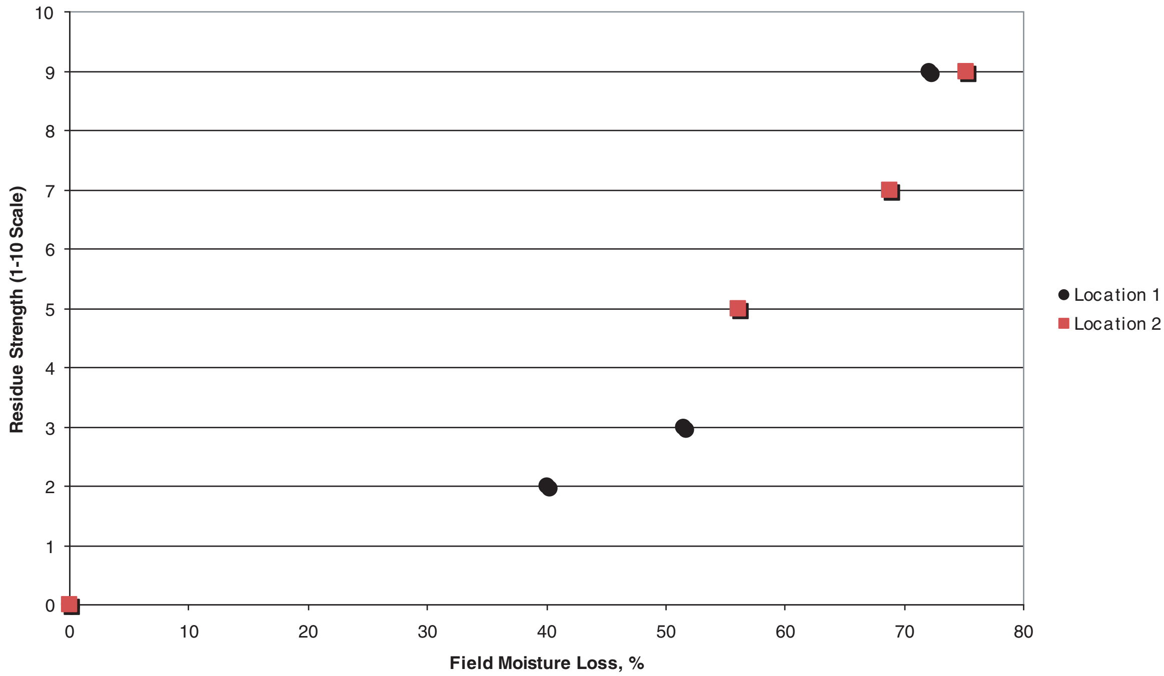

Figure 15. Residue strength versus emulsion moisture at US-101, Forks, WA.

chips) could be used to determine when the chip seal has developed enough adhesive strength to resist the stresses of sweeping and uncontrolled traffic.

3.4 Emulsion Consistency in the Field

Results of the tests at Arches National Park, CR-11–Frederick, and US-101–Forks are shown in Figures 17 and 18 for the 6-mm and 7.5-mm orifices, respectively. Arches testing did not include the 7.5-mm orifice.

The emulsion consistency at all three test sites was considered acceptable for constructing chip seals, i.e., it remained on the pavement surface and did not flow off but was not so viscous as to prevent wetting of the aggregate chips. Based on this observation, Wagner cup flow times of 20 to 70 s at emulsion temperatures of 85 to 150°F for a 6-mm orifice or 10 to 60 s at emulsion temperatures of 85 to 140°F for the 7.5-mm orifice may be appropriate for use as a guide for evaluating emulsion flow.

A correlation between Wagner cup flow time and Saybolt viscosity was developed by Wyoming DOT (Morgenstern

Table 7. Chip loss for test pavement materials.

Site	Aggregate Moisture	Chip-Seal Moisture Loss, %	Avg. Sweep Test Chip Loss, %
Arches	Dry	41.0	32.3
Arches	Dry	84.0	0.05
Frederick	Dry	45.9	39.3
Frederick	Dry	81.6	0.00
Forks	Dry	40.6	68.2
Forks	Dry	75.7	0.05
Arches	SSD	38.9	63.3
Arches	SSD	80.3	0.21
Frederick	SSD	41.6	40.6
Frederick	SSD	81.6	0.04
Forks	SSD	42.9	47.6
Forks	SSD	71.3	0.41

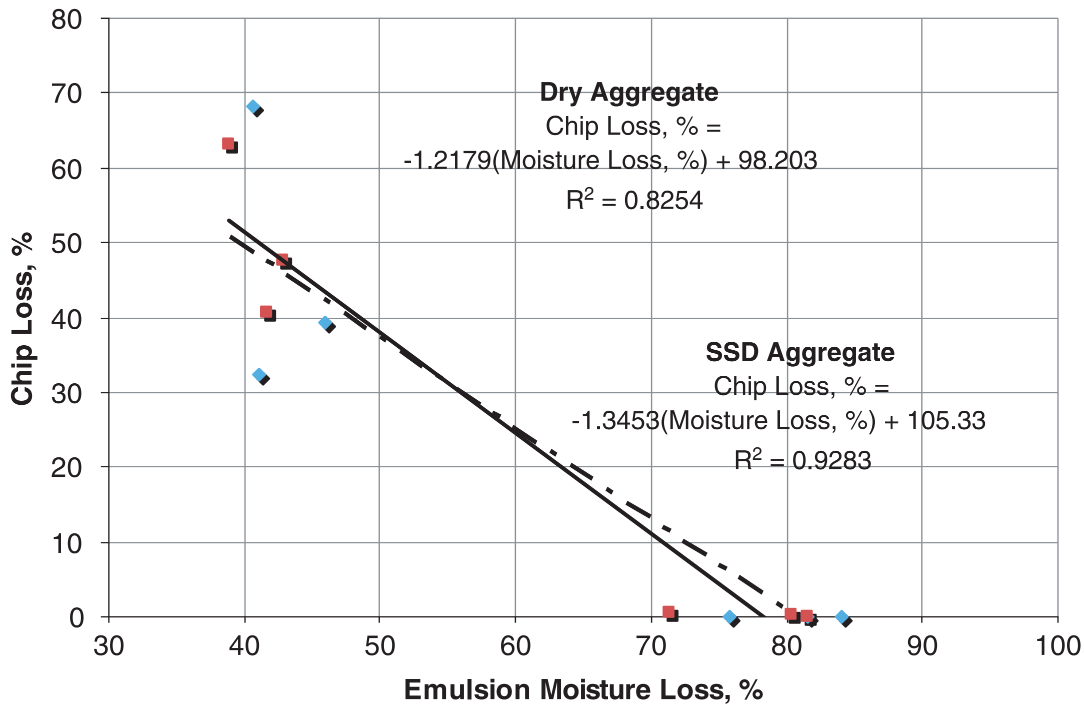

Figure 16. Chip loss versus emulsion moisture loss.

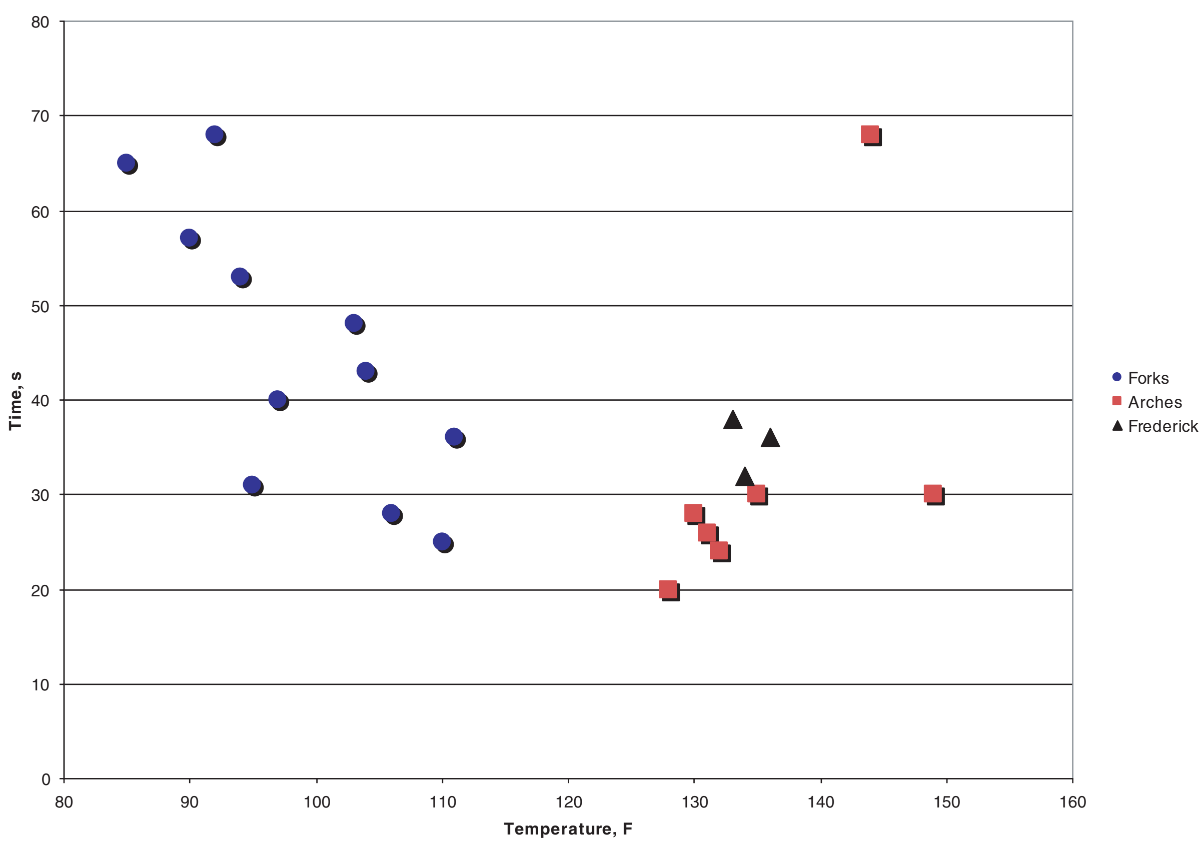

Figure 17. Field flow time for 6-mm orifice Wagner cup.

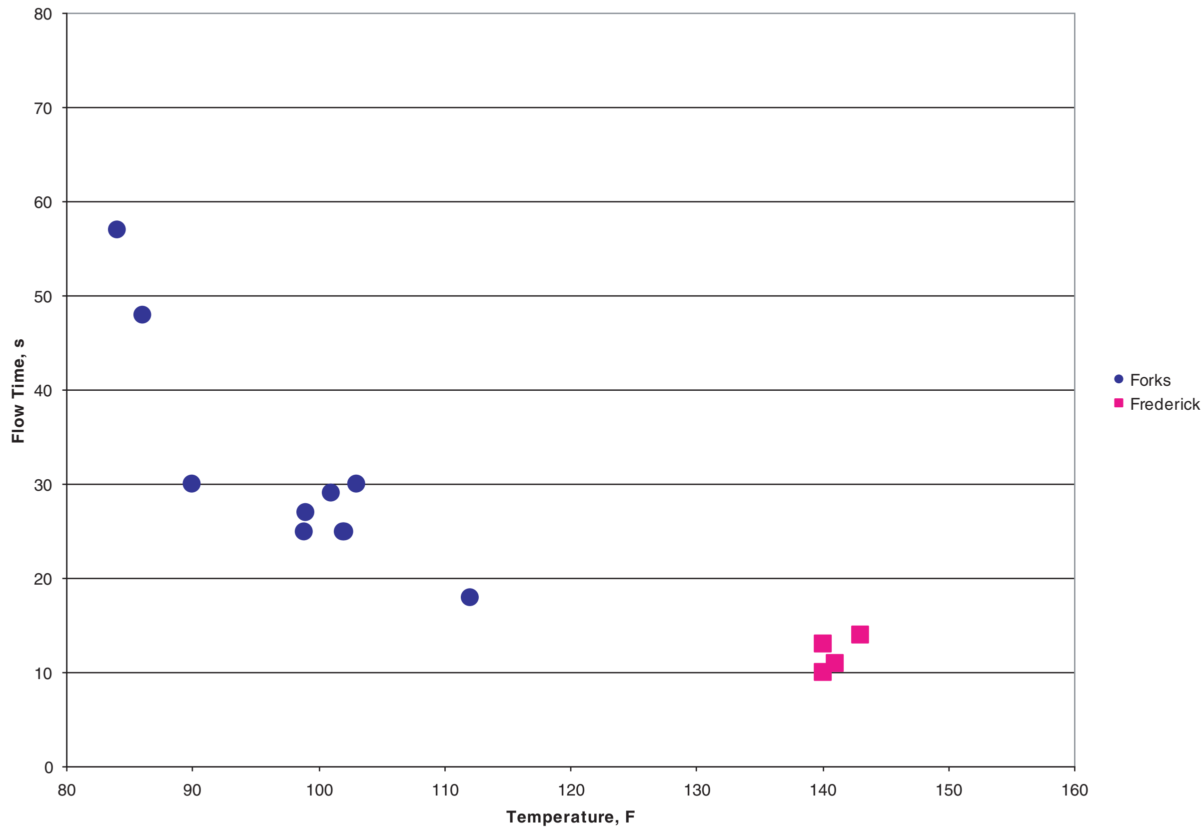

Figure 18. Field flow time for 7.5-mm orifice Wagner cup.

2008) and is presented in Figure 19 for a CRS-2P. Similar curves could be developed at different temperatures.

3.5 Pavement Texture Measurement

Texture of three concrete texture slabs was measured in the laboratory using the sand patch test, the CT meter, and the AIMS apparatus. Texture measurements were also made on the test pavements at Arches–Utah; Frederick, Colorado; and Forks, Washington. Multiple measurements of within-wheel path and between-wheel path textures were made on each project; an average texture depth at each measurement location was calculated.

3.5.1 Laboratory Texture Measurements

The results of texture measurements for the laboratory texture slabs using the sand patch, CT meter, and AIMS test methods are shown in Figure 20. Both the CT meter and AIMS test methods correlate fairly well to the sand patch test. Further testing using the CT meter and sand patch were made at each of the three field test sites.

3.5.2 Field Texture Measurements

Texture measurements for the three field test sites and the three laboratory test slabs are shown in Figure 21. Textures ranged from 0.1 mm for one of the test slabs to nearly 3 mm at the Arches site. Linear regression using all data resulted in an R^2 of 0.96 with slope of 0.96 and intercept of 0.14 indicating nearly a one-to-one relationship between sand patch and CT meter texture measurements when laboratory and field data are combined.

3.6 Residue Recovery Methods and Properties

Rheological Properties

At the high temperatures, the base binders in every case exhibited lower $G^*/\sin\delta$ than did the recovered residues, possibly due to stiffening and aging of the residues during either the emulsification process or the residue recovery process. The BBR test results indicated that the base binders and the recovered emulsion residues had similar cold temperature properties, probably due to deterioration of the polymer additive structure over time and with aging (Woo et al. 2006).

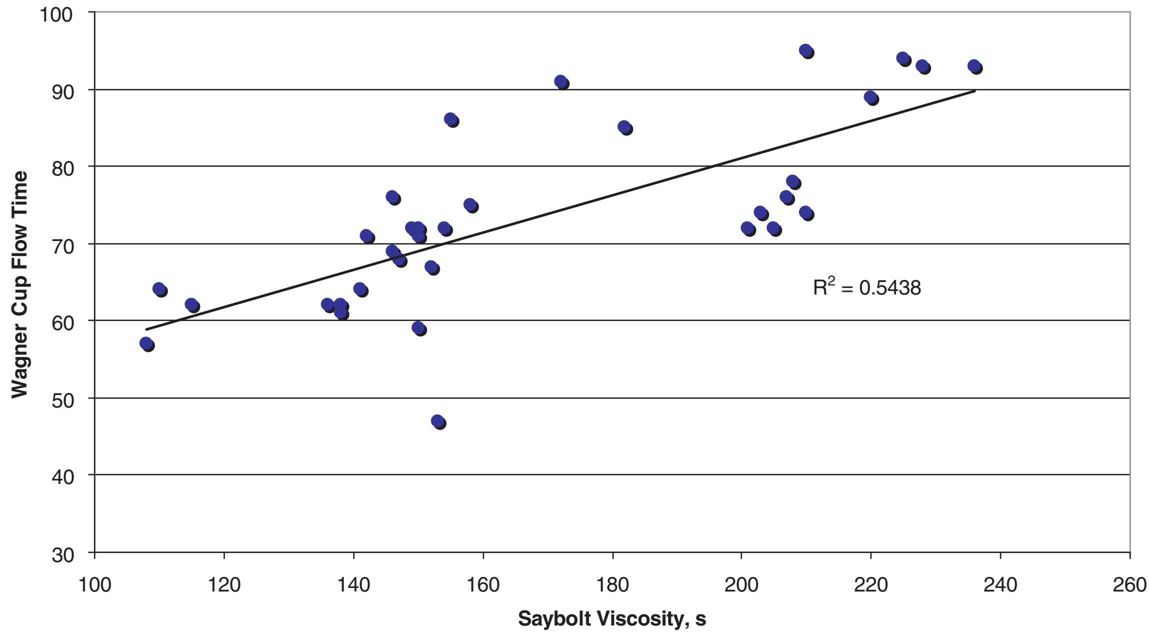

Figure 19. Saybolt viscosity versus Wagner cup flow time (Morgenstern 2008).

All of the materials met the PG (G*sin δ) criterion at the SP-1 specified intermediate temperatures.

PG and SPG Grading

Both PG and SPG grades were determined for all of the base binders and recovered residues, and the results are shown in Table 4. Interpolation was used to determine the continuous grades. In general, the PG and SPG grades were consistent for the base binder and the residues from both recovery methods. However, examination of the continuous grades indicated that the base binder grades were slightly different from the grades of the recovered residues. The SPG system resulted in a higher continuous grade at both the high and the low temperature ends than the continuous grade with the PG system. The average differences in the high and low tempera-

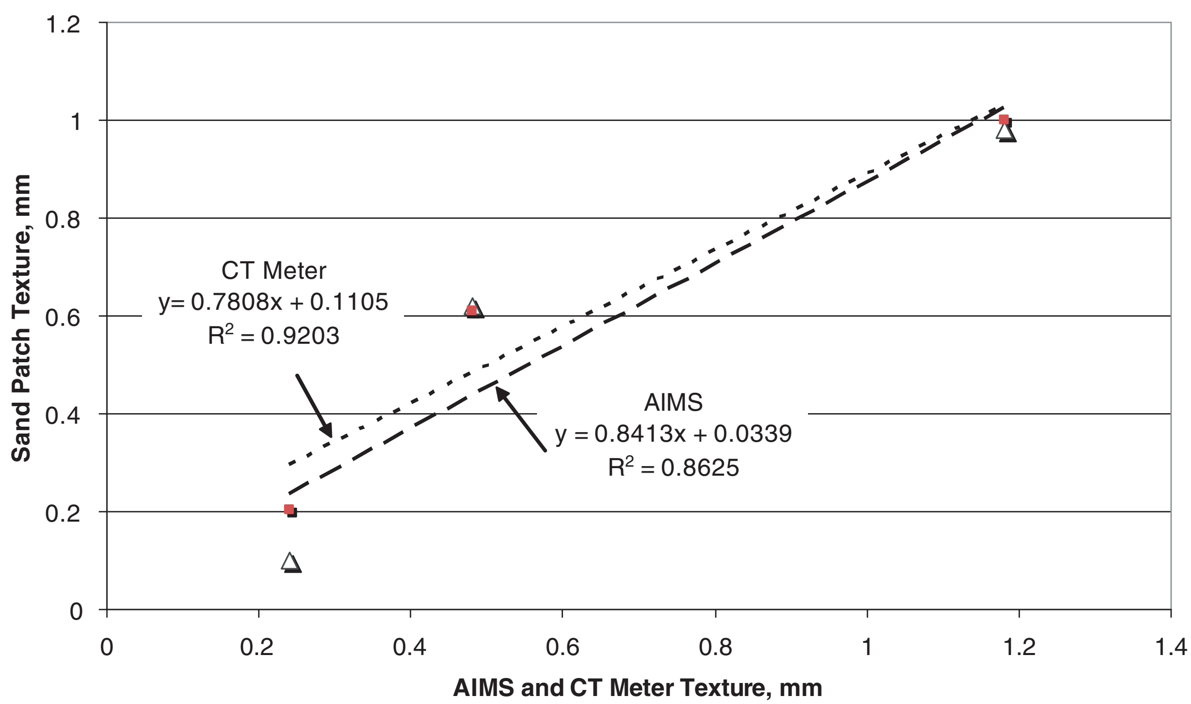

Figure 20. Laboratory test slab texture by sand patch and AIMS.

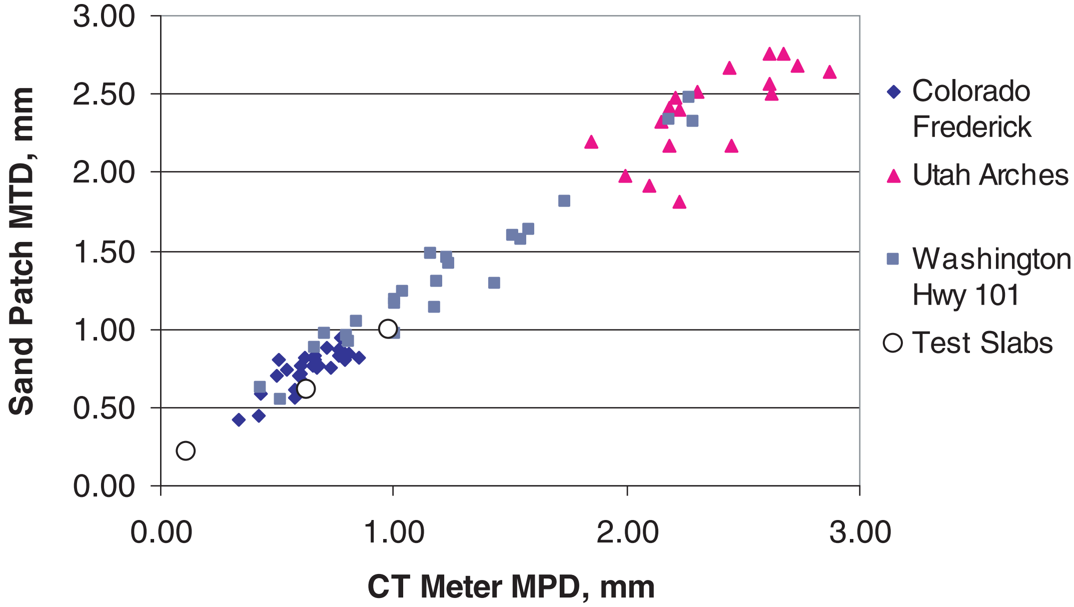

Figure 21. CT meter versus sand patch texture.

ture continuous grades (SPG minus PG) were +3.6° C and +11.3° C, respectively.

Chemical Properties

The GPC chromatograms for all of the residues from both of the recovery processes indicated that water was absent from the recovered emulsion residues and had therefore been completely removed from the emulsions during the recovery procedures.

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

Statistical Analyses Summary

The rheological data collected with the DSR and the BBR were analyzed statistically to determine if there were statistical differences between the emulsions and between the recovery methods. ANOVA and Tukey's honestly significant differences (HSD) multiple comparison techniques with a level of confidence of $\alpha = 0.05$ were used in all of the analyses.

When comparing the DSR data by recovery method, the analysis results statistically grouped the recovery methods of stirred can and hot oven together, and the base binder ("no recovery") was grouped separately for the emulsions with base binders available (1 through 5). Both recovered residues were stiffer, with larger values of G*, than the base binders, but not stiff enough to change the high-temperature PG grade for emulsions 1 through 5 as shown in Table 8. With smaller temperature increments, the high-temperature SPG grade did change to a larger value for four of emulsions 1 through 5.

Analysis of the BBR measurements showed that the recovery procedure (with base binders included as "no recovery") did not affect the response variables S or m-value of the recovered residues. This result seems to indicate that after PAV aging, the polymers and additives no longer have an effect on stiffness properties.

The spectroscopic data were also analyzed statistically using ANOVA and Tukey's HSD multiple comparison techniques for a level of confidence of $\alpha = 0.05$. Statistical analyses of carbonyl areas did not differentiate the recovery methods. The base binders and the recovered residues were statistically different, but the two recovery methods were similar to each other in terms of oxidative effects.

Strain Sweep Results

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

Review of the plots of G* versus strain percentage indicate that the magnitudes of the G* and strain values and the shapes and rates of change of the curves can be used to compare

Table 8. Strain sweep test results.

Emulsion	Recovery	UNAGED G_i* (Pa, at 1% γ)	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*	AGED G_i* (Pa, at 1% γ)	% γ at $0.98G_i$*	% γ at $0.90G_i$*	% γ at $0.80G_i$*	% γ at $0.50G_i$*
1	base	241,120	21.23	34.74	n/a	987,120	4.95	10.88	12.67*	n/a
1	stirred can	326,460	19.20	31.22	n/a	883,620	5.01	11.86	14.15*	n/a
1	hot oven	337,500	19.79	32.67	60.06*	844,030	5.53	11.46	14.82*	n/a
2	base	248,290	25.72	6.18	84.03*	1,448,300	3.93	7.31	8.62*	n/a
2	stirred can	298,170	22.17	38.31	n/a	1,948,300	2.77	5.29	6.40*	n/a
2	hot oven	318,660	21.32	36.98	63.37*	1,385,600	4.33	7.68	9.01*	n/a
3	base	747,630	14.84	16.71	n/a	3,329,800	2.31	n/a	n/a	n/a
3	stirred can	825,740	13.26	15.13	n/a	2,811,300	3.62	n/a	n/a	n/a
3	hot oven	813,970	13.64	15.35	n/a	3,163,400	2.14	n/a	n/a	n/a
4	base	219,060	25.41	44.14	n/a	954,040	5.24	10.92	13.11*	n/a
4	stirred can	289,860	20.77	34.51	n/a	905,480	5.58	11.27	13.82*	n/a
4	hot oven	257,750	24.35	34.26	n/a	778,100	4.84	11.11	16.10*	n/a
5	base	266,850	22.03	38.45	n/a	1,260,200	4.92	8.81*	9.91*	n/a
5	stirred can	297,360	17.79	31.46	67.95*	765,620	5.18	10.76	16.35*	n/a
5	hot oven	286,680	17.27	30.57	70.53*	801,740	3.96	10.38	15.54	n/a
6 – UT	stirred can	1,182,300	9.18	10.56*	n/a	2,486,600	2.45	4.46	n/a	n/a
6 – UT	hot oven	1,203,200	9.21*	10.37*	n/a	2,886,400	3.33	3.84*	n/a	n/a
7 - CO	stirred can	440,260	18.16	28.36	45.86*	1,235,400	3.36	8.41	10.11	n/a
7 - CO	hot oven	444,800	17.92	28.20	45.42*	1,198,900	3.06	7.51	10.36	n/a

* Max DSR stress was reached; n/a = test didn't run that far

materials and characterize strain tolerance. For comparison, the strain sweep data from the stirred can recovery residues for aged and unaged materials are shown in Figure 22.

Materials with high strain tolerance exhibit slow deterioration of G* with increasing strain level, indicating that the material maintains stiffness and holds together under repeated and increasing loads. Emulsions 1, 2, 4, and 5 in the unaged state exhibited this behavior and were visibly more adhesive and elastic when handled in the laboratory. After PAV aging, some materials exhibit less strain tolerance and develop a steep decrease in G* with increasing strain. Emulsions 2, 3, and Utah Arches are examples of this type of behavior. These materials were very stiff and broke off of the test plates in a brittle manner after the strain sweep testing was completed.

An asphalt binder must develop enough stiffness (G*) to be able to carry vehicle loads before the chip-sealed pavement is broomed or opened to traffic. The amount of moisture remaining in the chip seal has been shown to relate to binder strength development. This moisture level could be correlated with G* from strain sweep testing to determine a minimum G* for traffic bearing capacity.

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

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

Hanz et al. (2009) found that stiffer emulsion residues after PAV aging are difficult to induce 50% G_i* and even 90% G_i* in strain sweep testing. Most of the unaged and only a few of the PAV aged materials reached 80% G_i*, as shown in Table 8, and none reached 50% G_i*. It is possible that intermediate reductions in G_i* could be used to characterize behavior of the fully cured residues when 50% or 90% G_i* cannot be attained.

Besides differing in the rate at which G* decreased with increasing strain, the materials differed in their original stiffness, G_i*, and the rate of change of G_i* between the unaged and

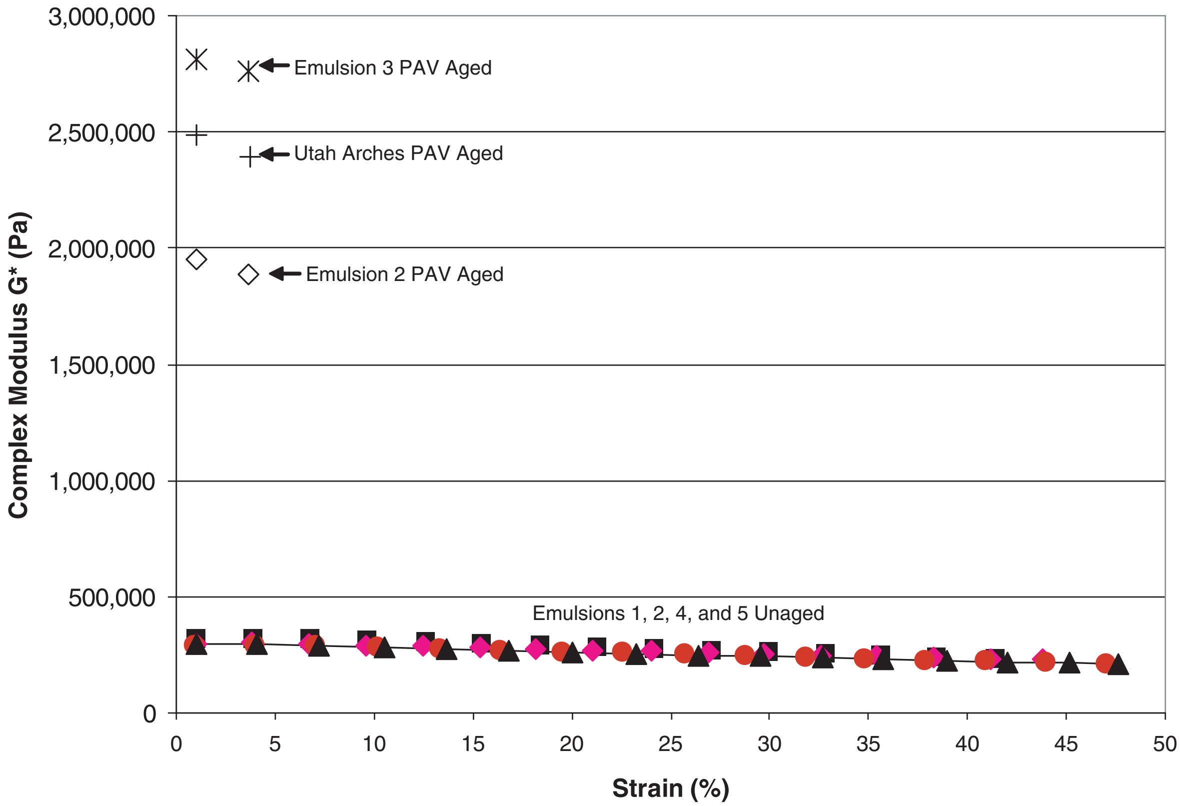

Figure 22. G* versus shear strain from stirred can recovery method.

the PAV aged states as shown in Table 8. The stiffest material in the unaged state was Emulsion residue 6, a latex-modified, rapid-setting emulsion. The stiffest material in the aged state was the Emulsion 3 residue, a rapid-setting unmodified emulsion. G* increased the most from the unaged to the aged state for the Emulsion 3 residue. It was followed by the Emulsion 2 residue, also a rapid-setting unmodified emulsion, and then by the Emulsion 6 residue. Residues for polymer modified Emulsions 1, 4, 5, and 7 increased in G* and exhibited aged behavior after the PAV aging, but not by as much as the residues for Emulsions 2, 3, and 6. Also, for Emulsions 1, 4, and 5, the base binder increased in G* considerably more than the recovered residue did, possibly indicating that either the emulsification process or the residue recovery process reduced the susceptibility of these materials to the PAV aging process.

Based on the results of the strain sweep testing, Emulsions 1, 2, 4, 5, and 7 would be expected to resist raveling due to their high strain tolerances. Emulsions 3 and 6, which had very stiff unaged residues, would be expected to resist flushing and also might be able to be opened to traffic earlier. However, these emulsions became more brittle with aging and could therefore exhibit raveling with age.

A comparison between the emulsion residues used at the three field tests and those recommended by the SPG criteria are shown in Table 9. In all three cases the materials used were higher temperature grades than the SPG recommended criteria, and in the case of Washington and Utah, lower temperature grades, as well.

The proposed emulsion residue criteria shown in Table 10 are based on those originally proposed in previous research

Table 9. Recommended SPG temperature ranges (°C).

Field Site	SPG Recommendation	Actual Material Used
Forks, WA	52–12	67–15
Arches NP, Utah	61–12	79–15
Frederick, CO	58–24	76–18

Table 10. Proposed emulsion residue criteria.

	Performance Grade*											
	SPG 61				SPG 64				SPG 70			
	–12	**–18**	**–24**	**–30**	**–12**	**–18**	**–24**	**–30**	**–12**	**–18**	**–24**	**–30**
Average 7-day Maximum Surface Pavement Design Temperature, °C	<61				<64				<70			
Minimum Surface Pavement Design Temperature, °C	>–12	>–18	>–24	>–30	>–12	>–18	>–24	>–30	>–12	>–18	>–24	>–30
Original Binder												
Dynamic Shear, AASHTO TP5 $\frac{G^*}{Sin\ \delta}$, Minimum: 0.65 kPa Test temperature @10 rad/s, °C	61				64				70			
Shear Strain Sweep % strain @ $0.8G_i^*$, Minimum: 25 Test Temperature @10 rad/s linear loading from 1–50% strain, 1 s delay time with measurement of 20–30 increments, °C	25				25				25			
PAV Residue (AASHTO PP1)												
PAV Aging Temperature, °C	100				100				100			
Creep Stiffness, AASHTO TP1 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8 s, °C	–12	–18	–24	–30	–12	–18	–24	–30	–12	–18	–24	–30
Shear Strain Sweep G_i^*, Maximum: 2.5 MPa Test Temperature @10 rad/s linear loading at 1% strain and 1 s delay time, °C	25				25				25			

*This table presents only three SPG grades as an example, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3°C and 6°C increments for the high temperature and low temperature grades, respectively.

shown in Table 3, including equivalent testing and performance thresholds for parameters measured in the dynamic shear rheometer and bending beam rheometer for unaged, high-temperature and aged, low-temperature properties, respectively. Additional testing and performance thresholds were added based on strain sweep testing conducted as part of this project and other research (Hanz et al. 2010) and the significantly different performance of Emulsion 3 and the Utah Arches emulsion. The thresholds provided for the DSR and BBR parameters are based on validation with Texas field test sections adjusted for climates in Utah and Colorado.

3.7 Estimating Embedment in the Field

Embedment depth is usually determined during construction by pulling several chips out of the binder and visually estimating the amount of embedment. This practice is problematic even if chips have a very low flakiness index because it is difficult to assess quantitatively with any precision. Therefore, two methods based on the sand patch test were developed to estimate embedment depth: the constant volume method and the constant diameter method.

3.7.1 Constant Volume Method

Glass beads were spread out in a circle on top of chips embedded to 20% and 80% of the chip average least dimension. The diameter of the circle was compared with the theoretical diameter that should result based on weight-to-volume characteristics of the materials presented in Section 2.7.1. Results of this experiment are shown in Figure 23.

At 20% embedment, the measured diameters are reasonably close to the theoretical diameters. However, at 82% embedment, the measured diameters are significantly less than the calculated values.

At 20% embedment, voids are deep, requiring many beads, and the procedure of spreading the beads from particle peak to peak contributes less to error than it does at higher embedment percentages when the amount of beads between the aggregate voids is relatively less. At 80% embedment, many particles were fully covered by asphalt, making it impossible to spread the glass beads between these aggregates.

Test results indicate this procedure to be useful when chip-seal particle embedments are closer to 50% or not submerged and chips have low flakiness index.

3.7.2 Constant Diameter Method

This method of estimating embedment depth used a mold of constant diameter in which glass beads were poured on top of the aggregate chips and the volume measured. Using weight-to-volume relationships for the materials, the volume of glass beads required to fill the mold was calculated as a function of the aggregate embedment depth. A comparison between the calculated volume of glass beads required to fill the mold and the actual volume measured for the limestone and granite aggregates embedded to 20% and 82% is shown in Figure 24.

At 20% embedment, measured values deviate 10% from the theoretical values. At 82% embedment, the deviation is less at 5% from theoretical. Deviations were similar for the limestone and the granite at both levels of embedment.

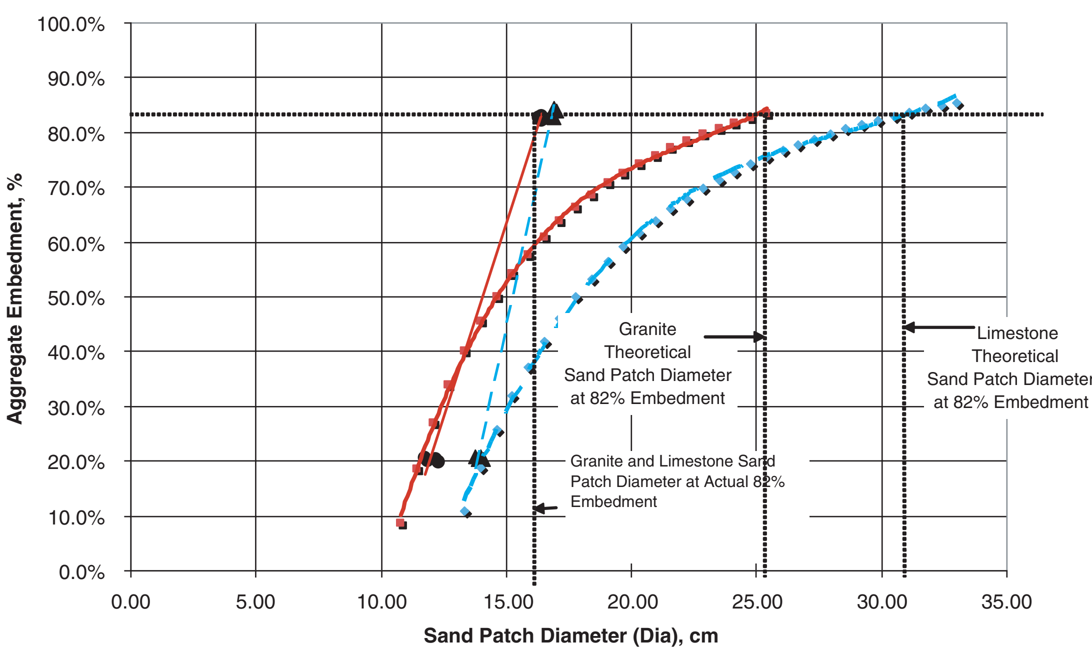

Figure 23. Comparison of calculated to measured embedment depth.

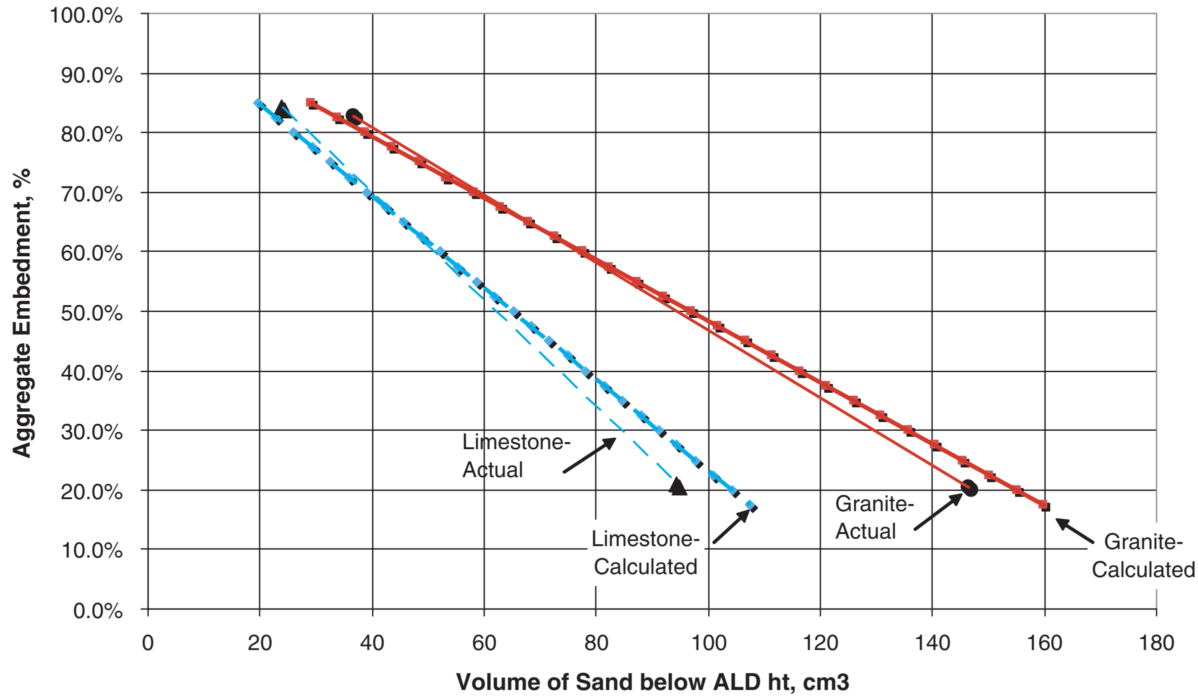

Figure 24. Embedment depth from constant diameter method.

CHAPTER 4

Practical Application of the Research

Five new products were identified in this research to improve the design and construction of chip seals. This chapter describes these products and their application.

4.1 Modified Sweep Test and Critical Moisture Contents

This test provides a method to determine the timing for chip-seal brooming and opening to uncontrolled traffic. The test determines the moisture content of the chip seal, which corresponds to adhesion needed to retain chips under traffic loads. The moisture content of the chip seal can be monitored during construction to determine when the desired moisture content is reached. This moisture content ranged from about 15% to 25% of the total chip-seal moisture. A description of the test method is provided in the appendix to the manual.

Results of the modified sweep test indicated that an aggregate in the saturated surface dry condition provides better adhesion than dry aggregates. This finding suggests that chip-seal aggregates be moistened prior to construction.

4.2 Field Consistency Test

A Wagner cup viscometer was used in this research to measure the consistency of emulsions.

By conducting the test at a variety of temperatures in the laboratory, a temperature versus flow time relationship can be produced. Flow in the field can then be measured and compared with laboratory results to determine actual viscosity at the field temperature. The test method is described in the appendix to the manual.

4.3 Pavement Texture

A direct correlation between the sand patch test and the CT meter indicates that pavement texture measurements can be made with the CT meter and used as a substitute for the sand patch test results in the design process. This texture measurement can then be used to adjust emulsion spray rates during construction. Recommended adjustments are provided in the manual.

4.4 Residue Recovery and Desirable Properties

The SCERR method is recommended for obtaining emulsion residues for use in tests proposed for measuring physical properties. Proposed emulsion residue criteria are listed in Table 10. The test method is provided in the appendix to the manual.

4.5 Measuring Aggregate Embedment in the Field

Two methods for measuring aggregate embedment in the field have been developed. The constant volume method is a simple method, using a constant volume of glass beads spread on the pavement surface in a circle. By measuring the diameter of the circle, the embedment of the aggregate can be estimated. However, this procedure becomes less accurate at embedment over 50%. An alternative procedure, the constant diameter method, can be used to estimate embedment up to 80%. These test methods are provided in the appendix to the manual.

CHAPTER 5

Conclusions and Recommendations

5.1 Conclusions

This report documents laboratory testing and field evaluation of several new procedures suitable for use by highway agencies, consultants, contractors, and others involved in the design and construction of chip seals. These new procedures were developed to add objective measurement capability to some of the largely subjective judgments made during chip-seal design and construction.

A laboratory test that simulates the sweeping action of rotary brooms during chip-seal construction was developed. This test simulates the shear forces applied by brooms and uncontrolled traffic to fresh chip seals, and can be used to predict the time required before brooms or uncontrolled traffic can be allowed on the surface of the chip seal. The test indicated the following:

- The moisture content at which 90% of the aggregate chips are retained during the sweep test is the "critical moisture content" corresponding to very high residue adhesive strength at which traffic could be allowed onto the chip-seal sections.
- Significantly higher chip loss was measured for sweep test specimens fabricated with dry aggregates than with saturated surface dry aggregates.
- No significant difference in chip loss was measured either at 40% or 80% moisture loss between cationic and anionic emulsions used with either calcareous or siliceous aggregates.

The Wagner cup viscometer for measuring the consistency of paints was successfully adapted to measuring viscosity of emulsions. The test is inexpensive, field portable, repeatable, simple to operate, and can be correlated to laboratory tests.

An adjustment to the emulsion spray quantity should be made to account for pavement surface texture. This process is often done subjectively or measured using the sand patch test in other countries. Although the sand patch test can measure texture effectively, the CT meter and AIMS apparatus were found to be faster and provide very similar results.

Extensive testing was done to evaluate new methods of emulsion residue recovery. The methods included hot oven (with nitrogen blanket), stirred can (with nitrogen purge), and warm oven. Residues recovered using these methods were tested using the Superpave PG test methods and chemical analysis to determine which recovery technique mimicked the base asphalts closest and resulted in the least amount of water remaining in the samples. These tests indicated that the SCERR method is rapid and provides a good simulation of the base asphalt material properties. Also, recovered emulsion residues were shown to be different from their base binders at high temperatures before PAV aging, but similar to the base binders at cold temperatures after PAV aging.

The residues obtained from the emulsions used in the three field test sites were characterized using the Superpave PG binder tests. The result of this work is a performance-based criterion for chip-seal residues. Initially, this SPG criterion was calibrated using field test sections in Texas. However, results of this research indicated that adjustments to the original criteria should be made to accommodate other climates. Therefore, characterization of residues should be done by evaluating the complex shear modulus, G^*, over a range of shear strains to evaluate strain resistance. These results could be used to predict when emulsion-based chip seals will develop resistance to raveling and enough stiffness to be opened to traffic, both in newly constructed chip seals and after weathering and aging.

5.2 Recommendations

The findings of this project were based on a significant amount of field and laboratory measurement. However, additional studies would help improve upon these findings and the recommendations. Such studies may include the following:

- Further sweep testing with other sources of aggregate and emulsion to verify the validity of the test as a means of measuring chip adhesion.
- Evaluation of grayscale photography and image analysis for quantifying macrotexture of pavement surfaces (Pidwerbesky et al. 2009) to possibly provide a viable and relatively inexpensive alternative to the sand patch test and the CT meter measurements.
- Monitoring the performance of the three test sites constructed as part of this research to provide additional validation for setting thresholds in the proposed SPG specification.

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APPENDIX A THROUGH APPENDIX J

Appendices A through J of the contractor's final report for NCHRP Project 14-17 are available on the TRB website at http://www.trb.org/Main/Blurbs/164090.aspx.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation