

ABSTRACT

IM, JEONG HYUK. Performance Evaluation of Chip Seals for High-Volume Roads Using Polymer-Modified Emulsions and Optimized Construction Procedures. (Under the direction of Dr. Y. Richard Kim.)

This dissertation presents research to develop guidelines for chip seals under high-volume traffic. It examines the characteristics of asphalt surface treatments (ASTs) that include their material properties (curing and adhesive behavior) as well as their laboratory performance (aggregate retention, bleeding, rutting, skid resistance, and surface texture) and field performance (visual observation and surface texture). The curing and adhesive behavior of ASTs is evaluated using the evaporation test, bitumen bond strength test, and Vialit test. Laboratory performance is investigated using the third-scale model mobile load simulator test, Vialit test, and laser profiler. Field performance is evaluated using the laser profiler and visual observations based on the NCDOT Pavement Condition Survey Manual.

This study also uses laboratory performance tests to evaluate the benefits of polymer-modified emulsions in ASTs. Refined AST construction procedures are developed based on previous research results and information gleaned from a literature review. Based on this information, a total of 12 field test sections are constructed for three traffic volumes (5,000, 10,000, and 15,000 ADT). In order to evaluate the performance of the ASTs constructed in the field, samples are extracted after construction and then tested in the laboratory. The field test sections are monitored periodically (on the day of construction and before and after the first winter) to evaluate the actual performance of ASTs in the field in terms of traffic volume.

Fog seals are also evaluated in this study as a means of reducing potential aggregate loss problems of ASTs in high traffic volume roadways. Curing behaviors of unmodified and polymer-modified emulsions are investigated using laboratory tests. These tests include the evaporation test and two newly developed *in-situ* test methods, rolling ball test and damping test.

Guidelines for chip seals under high-volume traffic are developed based on the determined performance characteristics of ASTs in both the laboratory and the field, and the field monitoring results. However, a few additional factors that affect chip seal construction, e.g., the condition of old pavement, performance uniformity coefficient analysis, and maximum allowable traffic volume, should be studied in more depth and are recommended for future research. Also, this research develops a method to predict aggregate loss in the field using mean profile depth (MPD) analysis, which employs the aggregate loss results and the MPDs obtained from both the laboratory tests and the field monitoring. The results of the predictions are similar to field performance ratings, but further research is needed to verify the predictions.

Performance Evaluation of Chip Seals for High Volume Roads Using Polymer-Modified Emulsions and Optimized Construction Procedures

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DEDICATION

To my family,

I would like to dedicate my dissertation work to my parents and sister.

There is no doubt in my mind that without their continued encouragement, support, and love,

I could not achieve this work.

I also wish to express special feeling of gratitude to my wife, Hyeseung Lee,

and my son, Jayden Jaegyun Im.

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The LORD your God is with you, he is mighty to save.

He will take great delight in you, he will quiet you with his love, he will rejoice over you

with singing. Zephaniah 3:17

BIOGRAPHY

Jeong Hyuk Im was born in Seoul, Korea on March 1, 1977. He received his Bachelor's degree and Master's degree in Civil Engineering in 2003 and 2005 from Kyunghee University in Korea, respectively. After graduation he worked as an engineer at Daehan Consultants for one year and then worked as a researcher at the Korea Expressway Corporation Research Institute (KECRI) for two years. In 2009 he then moved to North Carolina State University to pursue his Ph.D. degree in Civil Engineering.

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1. INTRODUCTION

1.1 Research Needs and Significance

As the general performance of roadways in the United States has deteriorated over time, an increased interest in preventive maintenance and rehabilitation has come to the fore. Without appropriate preventive maintenance over the course of a pavement's life cycle, the cost to restore the pavement more than quadruples. Chip seals are among the most efficient and cost-effective methods utilized by state highway agencies to preserve and rejuvenate existing pavements. For example, in North Carolina, although approximately 8% of roadway pavement expenditures are spent on surface treatment construction, that percentage constitutes about 50% of the miles paved. Thus, it becomes imperative for agencies to optimize the use of these treatments in terms of prolonged service life, decreased life cycle costs, increased operational efficiency, and enhanced safety.

A series of researches funded by the NCDOT has shown various ways to improve chip seal performance. These improvements include the use of: (1) lightweight aggregate with uniform gradation, (2) polymer-modified emulsions (PMEs), and (3) optimized rolling protocols. Specifically, the findings from the HWY-2007-06 research, Performance-Based Analysis of Polymer-Modified Emulsions in Bituminous Surface Treatments, clearly indicate a significant improvement in the performance of chip seals constructed with PMEs, and that the curing behavior of these modified chip seals is quite different from that of unmodified chip seals.

With the increased levels of effectiveness that PMEs provide, as compared to their unmodified counterparts, the use of chip seals on high-volume roads is now feasible and provides some of the same benefits that chip seals have been shown to provide for low-volume roads. NCDOT Road Maintenance Supervisors have already begun constructing chip seals for higher volumes than have been used successfully in the past. This capability is

increasingly important as traffic levels steadily increase and state budgets decrease. The economic benefits of using chip seals on high-volume roads is that they extend the life of the pavement and thus maximize the funds that were initially invested into the road construction. This extension of the pavement life in turn delays the time by which major rehabilitation or complete reconstruction would be necessary, thus stretching state tax dollars further on high-volume roads where major rehabilitation and reconstruction are very costly.

Moreover, the HWY-2006-06 research shows that changes in rolling patterns can greatly improve aggregate retention performance. However, the emulsion used in that research was CRS-2 emulsion, not PME. The very different curing and adhesive behavior of PME demands that the construction procedure must be optimized for the modified chip seals in order to maximize the benefits of polymer modification. The respective findings from these two researches strongly suggest that by using PMEs and by optimizing the construction procedures for modified chip seals, chip seals can indeed be used for roads that have a higher traffic volume than unmodified chip seals can handle.

One of the primary concerns regarding the use of chip seals in high-volume roads is the presence of loose stone. A fog seal, which is an emulsified product placed on top of a chip seal, is designed to mitigate this problem by 'locking down' the top layer of stone. The Asphalt Emulsion Manufacturers Association (AEMA) defines a fog seal as "a light spray application of diluted asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces" (AEMA 2004). Other states have employed fog seals in their respective chip seal operations and, most recently, the Federal Highway Administration (FHWA) and the Foundation for Pavement Preservation have co-sponsored a research that evaluates the sprayed application of polymer surface seals. The research results show that such sealants add new asphalt to seal the surface, and rejuvenators soften age-hardened asphalt to restore the desired mechanical properties of the mixture in the upper 3/8 inch to 1/2 inch of the pavement surface (King et al. 2007). Other studies (Wood et al. 2006, Jahren et al. 2007) also report the advantages of fog seals, including their low cost, ease of construction, and desirable black appearance, to name a few. A few reported

disadvantages include the delay in opening to traffic and reduction in skid resistance (Jahren et al. 2007).

At this time, the NCDOT rarely uses fog seals in conjunction with its chip seal operations. Recognizing the significant proportion of chip seal pavements in the NC highway network and that the main problem with the chip seal is loose stone, it is deemed important to investigate the potential of fog seals as a cost-effective method to improve the performance of chip seals. This dissertation herein describes a research effort based on field and laboratory experimental program to develop guidelines regarding the maximum amount of traffic that modified chip seals can support using improved construction procedures and fog seals.

1.2 Research Objectives

The primary objectives of the research are:

- to optimize construction procedures for polymer-modified chip seals;
- to determine optimal fog seal application rates for chip seals commonly used in North Carolina;
- to compare the aggregate loss and skid resistance of chip seals with and without fog seals; and
- to develop guidelines for the amount of heavy traffic that the modified chip seals can support.

1.3 Dissertation Organization

This dissertation is composed of eight chapters. Chapter 1 describes the research needs and objectives. The literature review of modified chip seal and fog seal applications are summarized in Chapter 2. In Chapter 3, experimental test program, test procedures, and analysis concepts are described. Chapter 4 describes the laboratory evaluation of the asphalt surface treatments (ASTs) performance. Chapter 5 provides the field evaluation of ASTs performance including the field section information. Chapter 6 suggests the guideline for

chip seals under high traffic volume. Chapter 7 offers conclusions and recommendations for further research. Chapter 8 lists references cited in this dissertation.

2. LITERATURE REVIEW

2.1 General

For the asphalt surface treatments (ASTs), there are several terms, such as chip seal, seal coat, surface treatment, bituminous surface treatment, spray seal (Austria), and surface dressing (United Kingdom). In the North Carolina Department of Transportation (NCDOT) specification, the term of ASTs is used officially.

The chip seal offers significant advantages, primarily as an economical and efficient means to provide skid resistance and fast construction. Generally, the cationic rapid setting (CRS) type of emulsion is the most commonly used asphalt for chip seals on low-volume roads. Chip seals have proved to be cost effective due to their low initial costs in comparison with thin asphalt overlays and due to other factors that affect treatment selection decisions where the structural capacity of the existing pavement is sufficient to sustain its existing loads (Gransberg 2006).

Due to the low-cost maintenance benefits of chip seals, SHAs would like to extend their use to include roadways with traffic volumes that are higher than those currently used. For high-volume roads, PMEs can be used in the chip seal design because the polymer modification decreases the pavement's susceptibility to changes in temperature, increases adhesion to reduce aggregate loss, and allows the road to be opened to traffic earlier than would otherwise be the case. Together, all of these benefits have led to the increased use of PMEs by the chip seal industry.

The major concern with chip seals is aggregate loss. Other states have employed fog seals in their respective chip seal operations as a means of locking down the top layer of stone in the chip seal. Several studies report the advantages of a fog seal, including low cost, ease of construction, and a desirable black appearance, to name a few. However, a few disadvantages, including delay in opening to traffic and reduction in skid resistance, have also been reported.

2.2 Distresses in ASTs

In order to ensure satisfactory performance of AST over its design life, the performance is primarily governed by these distresses. In the same manner, for a sufficient fog seal performance, the fog seal should not be applied on chip seal road that exhibit severe distress. That is, it is important to find severe distresses on chip seal pavement and to remedy them prior to the application of new AST or fog seal.

In ASTs, the general failure types are summarized as follows; streaking, flushing/bleeding, and aggregate loss. The streaking is explained by the debonding of the existing surface and the new AST and caused by the failure to apply asphalt emulsion uniformly. In the AST industry, the terms of bleeding and flushing are used commonly. Simply, problems by the spread of hot emulsion are called bleeding, and by an excess of emulsion are called flushing. However, two failure types show the same behavior that is reducing the skid resistance of pavement surface (McLeod 1969, Gransberg 2005). There are some causes of aggregate loss of ASTs, such as excessive aggregate application, poor traffic control during construction, inadequate embedment of the aggregate particles into the emulsion, poor aggregate gradation qualities, and dusty aggregate (Shuler 1990, Gransberg 2005). Based on these causes, the aggregate loss mainly occurs during initial traffic passes. Skid resistance can be one of the parameters for a new AST because AST provides old pavement surface with an increase in skid resistance (Gransberg 2005).

2.3 Emulsion Properties

In the early 1900's, asphalt emulsions were created to apply for dust control and spray applications. Since asphalt emulsions have many advantages, today the use of asphalt emulsions are increasing. For the variety of field conditions, physical properties of emulsions can be changed. For example, emulsions can be charged positively or negatively for compatibility with aggregates. In order to improve emulsion properties, various modifiers, such as polymer, latex, filler, anti-strip, and stabilizer, can be added to basic emulsions. In addition, emulsions are representative eco-friendly product in paving industry.

The asphalt emulsion can be said a dispersed asphalt in water and consists of asphalt (40 to 75%), water (25 to 60%), emulsifier (0.1 to 2.5 %), and minor component. These physical components give a few advantages, such as low viscosity (easy application), lower required temperature for both application and storage, and less sensitivity to application on damp surfaces (Maintenance Technical Advisory Guide, TAG 2003).

According to the Asphalt Emulsion Manufacturers Association (AEMA) brochure, the emulsion is classified by their ionic charge so that asphalt emulsions are divided into three categories: anionic, cationic and nonionic. The name of emulsion begins with a “C” or no “C”. Letter “C” means a cationic emulsion, and no “C” is normally an anionic or nonionic emulsion, but the nonionic emulsion is used rarely. The emulsion charge is important for compatibility with aggregates. In North Carolina, cationic emulsion is proper for AST design.

Set time, which is also called as flocculation and coalescence, of emulsion is designated by second letter. The letter presents the speed with an emulsion breaking after contacting the aggregate surface. There are four terms, such as RS (Rapid Set), MS (Medium Set), SS (Slow Set), and QS (Quick Set). RS emulsions are not stable and break quickly when they are contacted with aggregate. It is hard or impossible for RS emulsions to mix with aggregate so that they are usually employed for spray application, such as chip seal. In order to improve adhesion and open traffic early, a polymer can be added. MS emulsions are made for mixing with course aggregate not fine aggregate. Based on the design, MS emulsions have workability during a few months. SS emulsions are designed for fine aggregate. They are the most stable so that the emulsions can allow sufficient mixing time and extend workability. In order to reduce their viscosity, SS emulsions can be diluted with water so they can be applied for tack coats and fog seals. QS emulsions are also made for fine aggregate. Their breaking time is faster than SS emulsions so they can allow faster traffic opening. QS emulsions are generally used for micro-surfacing and slurry seals. HF is placed preceding a letter of setting time and indicates a high float emulsion, which is passed the float test (AASHTO T-50 or ASTM D-139). After HF emulsions are cured, gel-type structure is formed in the asphalt residue. It makes HF emulsions to improve their performance in a wider temperature range and to be applied to dusty aggregate. They can be

used for chip seals and cold mixes. Next letter for setting time, a “1” or “2” is placed to indicate emulsion viscosity. “1” is lower viscosity emulsions, and “2” is higher viscosity emulsions. In some cases, emulsions may have the letter “h” or “S” in the last part of name. The letter “h” means that the emulsion is made by a harder asphalt base (Wood et al. 2006). In order to indicate the use of polymer modifier in emulsions, “P” or “L” can be added in the last part of name. “P” and “L” mean polymer and latex modified emulsions respectively.

2.4 Polymer-Modified Emulsion

2.4.1 *Modified Emulsion Properties*

The adhesion of the emulsion to the aggregate in a chip seal system is strongly associated with the performance and service life of the chip seal. Wood et al. (2006) explain that PME's can enhance certain properties of asphalt emulsion. Generally, four types of polymers may be used in PME's: natural latex, synthetic latex, styrene butadiene rubber (SBR) and styrene butadiene styrene (SBS) polymers. Typically, approximately 2.5% to 3% polymer, by weight, is added to the emulsion. When polymer is added to the emulsion, several benefits emerge: e.g., early aggregate retention raises the softening point of the base asphalt, the chip seal is better protected, and fewer materials are wasted.

Bolander et al. (1999) summarized their analysis and supporting test information used to determine and evaluate the factors behind chip seal failure and then discussed the lessons learned. In this research, two types of emulsion were used: HFRS-2 (anionic high float rapid set emulsion) and HFRS-P1 (anionic high float rapid set emulsion modified with polymer). Severe potholes developed where the HFRS-2 was used, i.e., without polymer modification or a low-temperature additive, during the first winter. Bolander et al. found that failure resulted from interacting factors, including a dust coating on the chips, an incompatibility of the emulsion and chips, cold and wet weather, and a nearly impervious base course. Five important factors were found from this research to affect bituminous surface treatment (BST) performance: (1) adequate and accurate quality control, (2) a drain in the base course under a

BST, (3) weather and dust on the aggregate, (4) an emulsion's breaking and curing times, and (5) the compatibility between the asphalt emulsion and the aggregate.

Takamura (2003) presents the properties of asphalt emulsion modified with SBR latex. SBR latex was designed for asphalt modification to create a polymer film in the presence of residual water, without coagulum, thus promoting early strength development. The SBR latex polymer remains in the aqueous phase and naturally changes to a honeycomb structure surrounding asphalt droplets. The finer the polymer structure, the more definitive is the improvement in asphalt rheology. The latex particles in the emulsion spontaneously transform to a continuous polymer film that coats the asphalt particles after water evaporates from the emulsion, as shown in Figure 1. Also seen in Figure 1, the unmodified residue asphalt would normally fracture through the asphalt/droplet boundaries, but because SBR latex film is highly flexible, the SBR latex film surrounding these droplets reduces excess stress through elastic deformation without causing permanent deformation to the bulk asphalt phase. This microscopic polymer mechanism is the reason for significantly improved fatigue resistance of the emulsion residue that is modified by the cationic SBR latex.



Figure 1 Schematic diagram of fully cured unmodified asphalt and SBR latex polymer-modified asphalt (Takamura 2003)

Gransberg (2006) correlated individual chip seal performance ratings with reported construction practices and found a number of strong correlations. The ambient air temperature specification was commonly higher (average of 60°F (15°C)) for those

respondents who reported *excellent* or *good* chip seal performance. For the best performance of a fresh new chip seal, the newly sealed road must undergo an average wait period of 28 hours prior to allowing full-speed traffic on the new surface.

Holleran et al. (2006) studied the difference in curing times between bitumen or cut-back seals in chip seal construction. Curing time is often associated with the notion that water must evaporate or the seals must dry to gain initial strength. Many factors that affect the curing characteristics of an emulsion are associated with the physical form and chemical composition of the emulsion. These factors have a significant effect on the initial seal strength. Holleran et al. measured the curing rates under a range of conditions, including humidity and temperature. They recommended that emulsion curing be controlled under poor conditions such as high humidity and cool temperatures to optimize performance.

2.4.2 *Modified Emulsion Types*

The two main types of modifiers used for emulsions are plastomers and elastomers. Plastomers exhibit quick early strength under loading but cannot exhibit strain without brittle failure. Plastomers include low density polyethylene (LDPE) and ethylene vinyl acetate (EVA) (Stroup-Gardner and Newcomb 1995). Elastomers resist permanent deformation because they are rubber-like and can stretch and regain their original strength once the load is removed. Some examples of elastomers that are most commonly used are SBR, which is a synthetic rubber, and SBS, which is a thermoplastic rubber.

The use of emulsions is highly popular because emulsions do not require a hot mix set-up, they have a low sensitivity to temperature changes, and they are not likely to be hazardous to the construction crew. Aside from these benefits, most sources agree that the use of PME binder also provides benefits to the binder after modification. Most scientific sources are also in agreement that the best and most effective concentration of polymers is one that allows for the formation of a continuous polymer, and 3% to 5% is a generally advisable application rate for polymers (Voth 2006, Stroup-Gardner and Newcomb 1995). Aside from these benefits that are generally agreed upon, it seems that no real understanding of the best dosage rate or recommended concentration exists for polymer modification. As

Voth points out in his preliminary report (2006), a considerable amount of information is available, but no real consensus has been reached. This dilemma may be due to the fact that the dosage rates are maintained as a kind of ‘secret recipe’ by the companies that manufacture emulsions.

2.4.3 Polymer-Modified Emulsion Performance

Coyne (1988) researched PME chip seals. A modified version of the Vialit ball drop test and the surface abrasion test were used for this study. The modified Vialit ball drop test was used to evaluate the setting characteristics of the seal coat. The durability of the seal coat was evaluated using the surface abrasion test that was selected to assess the effects of traffic on aggregate retention. The surface abrasion test had been used by Caltrans for many years to evaluate the abrasive action of traffic on asphalt concrete mixtures. Coyne found from the modified Vialit ball drop test that PME improves aggregate retention under cold temperatures. The surface abrasion test revealed that the binder type and amount of binder, moisture conditioning, and test temperature all affect the durability of the chip seal.

Shuler (1991) investigated the causes of dislodgement of chip seal coats on high traffic volume pavement; the application of chip seals generally had been limited to low traffic volume roads because their cost-effectiveness for high-volume roads and the amount of vehicle damage from loose aggregate were both unknown factors at that time. For this research, the cationic-type CRS-2S modified emulsion that uses a styrene block copolymer and special processing was used to construct six experimental test sections. The experimental chip seals were constructed on a paved road with an AADT count of 38,000. No vehicle damage claims resulted from these experimental test sections, which supports the potential use and effectiveness of chip seal applications.

Serfass et al. (1992) researched the utilization and evaluation of SBS-modified asphalt for aggregate surface treatments. When SBS is added to the emulsion, the emulsion exhibits improved cohesion and reduced thermal susceptibility, which in turn leads to less aggregate dislodgement and better resistance to bleeding. However, very high SBS rates (up

to 5%) indicate some degree of failure in the form of aggregate loss due to early trafficking before the emulsion has had time to form enough viscosity.

Janisch (1995) researched the construction of a chip seal with improved quality, because the MNDOT had received complaints (leading to some claims) about poor performing chip seals. The Janisch study includes an examination of the current MNDOT specifications and an investigation into the performance of chip seals designed according to Asphalt Institute MS-19, *A Basic Asphalt Emulsion Manual*, which was used by the Strategic Highway Research Program (SHRP). Five factors were examined in this study: application rate, sweep time, aggregate type, gradation, and binder type. Field test sections were constructed and monitored over subsequent years to evaluate their performance.

Temple et al. (2002) performed a five-year field performance study of 1995-1996 chip seal and micro-surfacing researches using a summary of data generated by the Louisiana Department of Transportation and Development's Pavement Management Group. For this study, four performance indicators were involved: the International Roughness Index (IRI), crack analysis, rut depth, and ground-penetrating radar thickness. The pavement conditions were rated annually from the point of pretreatment until spring of 2001. Observations from the chip seal researches are as follows: the median Pavement Condition Index (PCI) was 75 after 52 months with a significant reduction in cracking; 20% of the researches showed moderate to heavy bleeding; rutting was not evident; and measurements for skid resistance indicated very good performance. The equivalent annual cost (EAC) of the chip seal was nearly 27 cents a year when five years was the anticipated service life.

One of the most prevalent failures of chip seals is aggregate loss that occurs from traffic loading. One of the benefits of using PME for chip seals is that PMEs mitigate such aggregate loss. Takamura (2003) compared the aggregate retention performance of unmodified emulsion and PME (3% cationic SBR latex). He used the brush test that was developed to reduce problems associated with loose aggregate in chip seal operations. He conducted the brush test using eight different aggregate types after five hours of curing at 95°F (35°C). A comparison of the unmodified emulsion and the emulsion modified with

SBR latex shows that the SBR latex-modified asphalt emulsion provides faster strength development, with above 80% aggregate retention, than the unmodified emulsion.

Kuennen (2005) also describes the benefits of PME for chip seals. Polymer modifiers generally enhance the bond between the aggregate and binder and therefore are commonly used as the binder modifiers. The typical price of polymer-modified binders is higher than that of unmodified emulsions by about 30 percent. However, a benefit of PME is that they reduce bleeding and flushing in warm weather due to enhanced binder stiffness.

Khattak et al. (2007) evaluated and compared binder-aggregate adhesion and the mechanistic characteristics of polymer-modified asphalt mixtures at low temperatures. The lap-shear test and environmental scanning electron microscope (ESEM) *in situ* tensile test were used to test the adhesion and fracture morphology of neat and modified binders. The indirect tensile (IDT) strength test and IDT cyclic load test were used to obtain the mechanistic properties. The lap-shear strength and toughness energy values changed as functions of temperature and polymer concentration. The ESEM *in situ* tensile test results indicate that modified binders exhibit improved adhesion properties and have more and longer asphalt fibrils relative to the neat asphalt. The improvements in binder-aggregate adhesion at low temperatures stem from the enhancement of the mechanistic properties. Also, Khattak et al. found that the plastic deformation rates of the modified mixtures are lower than for the neat ones and are related to the lap-shear strength and toughness energy.

Lawson et al. (2007) identified maintenance solutions for bleeding and flushed asphalt pavements surfaced with seal coats or surface treatments. The terms *bleeding* and *flushing* are both used, although the basic mechanism that underlies both terms is the same, referring to the excess asphalt binder that fills the voids between aggregate particles. The key factor of bleeding is that the binder is in liquid form. Numerous factors converge to create both bleeding and flushed pavements; these factors involve aggregate type, binder type, traffic conditions, environmental conditions, and construction variables. Bleeding requires immediate maintenance, such as removing the damaged asphalt and rebuilding the pavement seal. In contrast, flushed asphalt pavements are not a maintenance problem. To treat flushed pavement, a new textured surface is constructed over the flushed pavement. The PME

surface provides an improved seal coat and surface treatment performance that makes bleeding and flushing problems less common.

In the summer of 1998, the Minnesota Department of Transportation (MNDOT) built a test site to test different types of chip seals and to compare and estimate the performance of a PME (CRS-2P) and unmodified emulsion. The PME showed a dramatic improvement in early aggregate retention performance. So, the MNDOT began to recommend the use of PME on any roadway with an annual average daily traffic (AADT) count of more than 500. The MNDOT currently requires CRS-2P for all its chip seal researches. Also, the MNDOT recommends sweeping no earlier than the next morning following construction, because even this slight delay dramatically reduces the number of claims for vehicle damage caused by flying loose aggregate particles. The use of PME has almost completely eliminated the bleeding of chip seals due to an increase in the softening point of the binder. Therefore, the binder application rate for the PME could be increased by as much as 15% over the unmodified emulsion without fear of bleeding. Based on these improved performance results and advantages, the use of PME for chip seals in Minnesota has increased dramatically, from 8% in 1999 to more than 50% in 2005 (Wood et al. 2007).

Janisch's study (1995), which was mentioned before, led to changes in the current MNDOT bituminous seal coat specifications. The MNDOT bituminous seal coat specification (2356 bituminous seal coat) that was revised in 2008 lastly suggests that the use of the CRS-2P emulsion produced by using polymer modified base asphalt only. The use of latex modification is prohibited for seal coat. Based on the personal discussion with Mr. Thomas Wood by email (2013), the latex modification cures slower as latex tend to float up to surface and trap water underneath latex layer so extra rolling is required to accelerate curing if latex modification is used.

Kim et al. (2009) compared the aggregate retention performance of non-PME (CRS-2) and PMEs (CRS-2L and CRS-2P). The MMLS3 test, FOT, Vialit test, the bleeding test, and the rutting test were performed on both laboratory and field fabricated samples under different temperature conditions. The benefits of using PME in chip seal construction were supported in this study. The CRS-2L emulsion manifests a reduction in the amount of

aggregate loss during early curing times, less curing time needed to obtain the desired adhesion, and the ability to allow traffic on the newly constructed road safely and sooner. Also, the CRS-2L emulsion improves the aggregate retention performance at low temperatures. The CRS-2L emulsion tested by the Vialit test meets the criterion of 10% maximum allowable aggregate loss by Alaska specifications at -20°C and 5°C. Based on the results from the bleeding performance tests and visual observation, the PME improves the bleeding resistance regardless of chip seal types. The PME has a benefit for the significant rutting resistance against the traffic loading. Specially, the PME provides a benefit of the rutting resistance at the high temperatures (54°C). The PME is cost effective in life cycle cost analysis on condition that PME service lives is 2 years longer than that of non-PME chip seal road although PMEs cost typically about 30% more than non-polymer modified emulsions.

2.4.4 Curing and Adhesive Behavior of Polymer-Modified Emulsions

Proper curing and adhesion are critical to the performance of chip seals. The curing time needed in chip seal construction is an issue of concern for high traffic volume roads, because the length of the curing time determines the duration of the traffic closures that cause delays. The adhesive behavior between the emulsion and the aggregate is likewise important to chip seal performance. To construct well performing chip seals, it is important not to allow other factors to contribute to poor adhesive behavior. For example, if the aggregates used for construction are too dusty, the adhesion between the aggregate and emulsion will not be strong due to the amount of fines that would limit the bonding ability of the two materials. Because PME has stronger adhesive strength than unmodified emulsion, it is less susceptible to issues caused by dusty aggregate and, therefore, is recommended for use in chip seal construction.

One way to increase adhesive strength in a treated pavement surface is to construct a fog seal on top of the chip seal layer to ensure that the chips are held in place and that flying aggregate cannot cause windshield damage. The California Chip Seal Association (CCSA 2005) suggests that too many small chips in the gradation can prevent the larger chips from

reaching the emulsion and thus could lead to the loss of the larger chips. Therefore, as seen in the NCDOT FHWA/NC/2005-15 research, the gradation of the aggregate is important to adhesion.

Furthermore, the CCSA suggests that premature failure of chip seals is associated with poor binder quality, which is consistent with the experience of field supervisors at the NCDOT. The CCSA suggests the use of a modified emulsion that is less brittle at low temperatures and stiff at high temperatures. Also, the material should be adhesive and durable at all temperatures. These characteristics help protect the chip seal against not only elevated summer temperatures where bleeding could occur, but also against cold winter temperatures where cracking could occur, as well as the loss of aggregate due to weak adhesion.

Adhesion has also been found to be directly related to the compatibility of the aggregate and the emulsion, and not just the emulsion characteristics alone. Therefore, compatibility should be determined so as not to negate the improved adhesive benefits that stem from the PME used in chip seal construction.

2.5 Construction Procedures Used for Modified Chip Seals at High Traffic Volumes

With regard to the construction of chip seals on high-volume roads, Schuler (1991) reports that the construction guidelines summarized in the NCHRP Chip Seal Best Practices (Gransberg and James 2005) and shown in Table 1 improve chip seal performance.

Table 1 Best Practices for Constructing High Volume Chip Seals (Gransberg and James 2005)

Practice	Reason
Reduce excess aggregate	Increases sweeping proficiency
Reduce aggregate size	Larger aggregate causes more damage
Use double chip seals	Smaller aggregate is in contact with tires
Use lightweight aggregate	Lower specific gravity causes less damage
Use choke stone	Locks in larger aggregate
Use fog coat	Improves embedment
Precoat aggregate	Improves adhesion
Use polymer modifiers	Improves adhesion
Allow traffic on chip seal	Vehicles provide additional embedment
Control traffic speed on chip seal	Reduces whip-off

Table 1 shows that in addition to the use of PME to improve adhesive performance, other valuable construction methods exist that can benefit the performance of chip seals at high volumes, such as the use of lightweight aggregate or a reduction in aggregate size. From the literature review (Shuler 1990) it is found that sweeping is also an essential aspect of chip seal construction at high volumes. Sweeping becomes even more essential for high speeds. It is recommended that the road surface is swept before being opened to traffic after construction.

It is also found that chip seals perform well on high-volume roads when used as a preventive maintenance tool on roads where the distress level is determined to be moderate, at worst, and where the pavement condition rating is used as the threshold to determine when a pavement needs to be surfaced using a chip seal treatment (Gransberg and James 2005).

Furthermore, at high traffic volumes the adhesion and bond between the aggregate and emulsion become even more pivotal. It is suggested that aggregate-binder compatibility is tested in a laboratory setting before construction even begins to ensure that the compatibility is strong enough for proper bonding (Yazgan and Senadheer 2003).

Temperature is also an essential factor of adhesion and subsequent chip seal performance. If the pavement temperature is too low during the emulsion application period of construction, poor bonding between the aggregate and emulsion may be evident. This situation is remedied either by constructing the pavement within an appropriate temperature range, or using low temperature PME's, such as those tested and developed by Road Science, LLC. The Road Science research team constructed a chip seal on a day in March when the temperature was below 50°F, which is below the temperature suggested in chip seal construction guidelines. For this construction, the Stylink Low Temperature Emulsion Seal Coat, specially developed by Road Science, was used. The Road Science team reported proper curing and adhesion even at these low temperatures (Road Science 2009).

Road Science has developed additional equipment to help address the importance of the time that elapses between spraying the emulsion and spreading the aggregate during chip seal construction. Effectively, by controlling and limiting the time between the emulsion being sprayed and the aggregate being spread, Road Science is able to ensure that the bonding between the aggregate and emulsion is not hindered by cold emulsion that has cooled during the time gap. The justification behind the development of such a machine is that this time gap between spraying and spreading is even more critical at high volumes and high speeds because poor aggregate retention is more likely to endanger drivers and damage windshields at high speeds.

Kim et al. (2008) suggest optimum rolling patterns in chip seal construction based on the results from aggregate retention performance tests and visual observation. They recommend the use of both the pneumatic roller and combination roller to improve chip seal performance. With regard to order, rolling should start with the pneumatic tire roller and finish with the combination roller to produce a smooth surface. The optimal number of coverages for both single- and double-seal construction is three. Five coverages seem to improve the aggregate retention performance, but extra time is needed to perform five coverages. For the optimal coverage distribution on the underlying layer of multiple seals (double and triple seals), one rolling coverage of the layer immediately below the top layer improves the aggregate retention performance. Also, a delayed rolling time after chip

spreading affects aggregate retention performance. Based on the findings, two optimum rolling patterns are recommended for chip seal construction. According to the type A rolling pattern, two combination rollers with three coverages are used to compact the entire lane width. For the type B rolling pattern, two pneumatic tire rollers are used to apply three coverages to the entire lane width, and then the combination roller, as a third roller, is employed to apply an additional coverage on the section. The advantage of type B is that it allows more coverages (four coverages in type B versus three coverages in type A) within the same amount of rolling time. In addition, type B can fully capture the ability of both the pneumatic tire roller that rolls the uneven surface of the existing pavement and the combination roller that provides a smooth surface. Figure 2 shows the schematic rolling patterns.

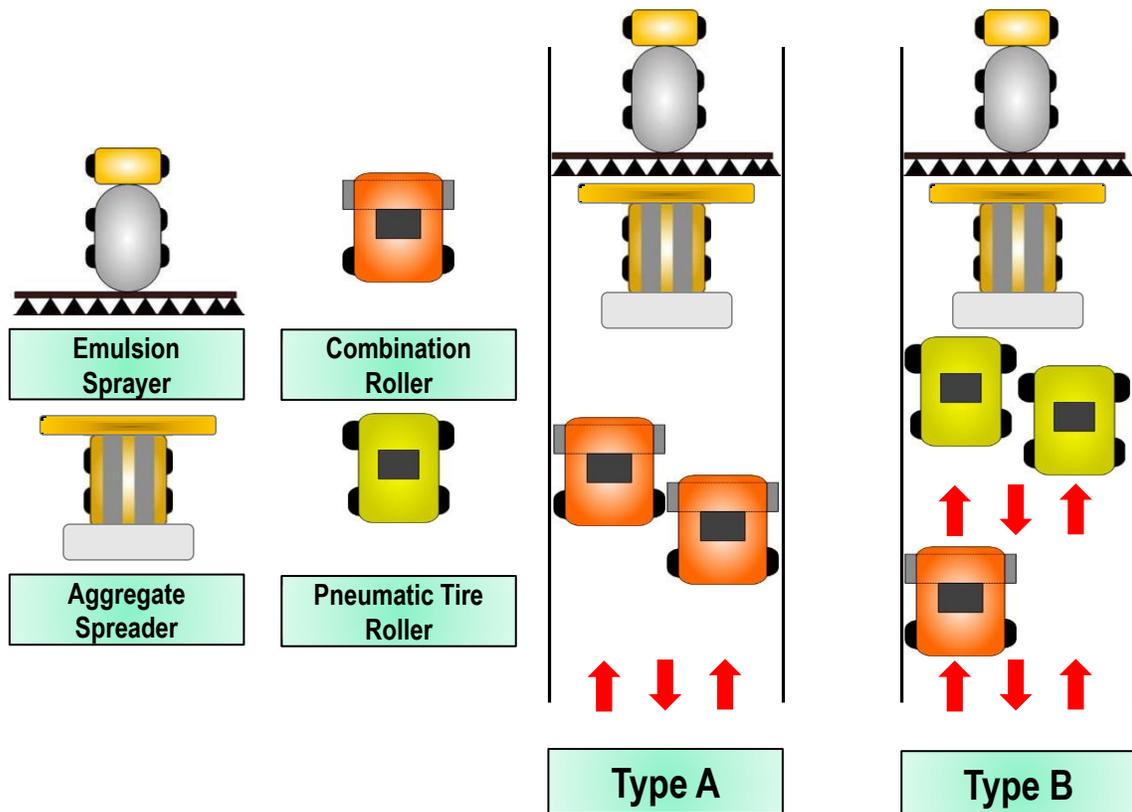


Figure 2 Rolling patterns

Aggregate gradation is one of the most important factors that affect chip seal performance. The performance uniformity coefficient (PUC) can be used to compare the effects of different aggregate gradations. The closer the PUC is to zero, the more uniform is the gradation of the aggregate source. In the Kim et al. (2011) study, three different gradations of both granite 78M and lightweight aggregate were used to make specimens, and then MMLS3 aggregate loss and bleeding tests were conducted. Based on the test results, more uniform gradations (i.e., low PUC values) lead to better performance (i.e., less aggregate loss and bleeding) than less uniform gradations (i.e., high PUC values) (Kim et al. 2011).

The Minnesota DOT (MNDOT) is one of the most expert agencies in seal coat construction. Its publication, *Minnesota Seal Coat Handbook 2006*, includes bituminous seal coat specifications. The following summary of the use of modified chip seals on high-volume roadways is based on these specifications (Section 2356 Bituminous Seal Coat), which were revised most recently in 2008, and based also on personal email discussions with Mr. Thomas J. Wood, Research Project Supervisor at the MNDOT

First of all, traffic volume is an important issue in chip seal construction. In Minnesota, single seals can be constructed comfortably up to 15,000 ADT. Also, single-seal construction is scheduled on roads with 30,000 ADT. Currently, the MNDOT does not have restrictions on traffic level for single-seal construction. In order to achieve good performance, chip seals typically are constructed on new hot mix asphalt (HMA) pavement no more than four to five years after HMA pavement construction.

The MNDOT specifications recommend only CRS-2P emulsion, which is produced with polymer-modified base asphalt, for high-volume chip seal construction. CRS-2P emulsion is used for all high-volume roadways, whereas CRS-2L emulsion (latex-modified) is not allowed. Latex-modified asphalt cures slowly because latex tends to float to the surface and trap water underneath the latex layer. Extra rolling is required to accelerate curing if latex modification is used; therefore, it is not cost-effective and the MNDOT prohibits its use for seal coats.

For seal coat construction, the use of quality aggregate is important. Sound and durable particles of crushed stone or gravel typically are used. The MNDOT specifications recommend the use of clean, uniform-sized aggregate particles that are free from wood, bark, roots and other deleterious materials. In order to measure the flatness of the aggregate particles used in chip seals, the so-called *flakiness index* (FI) is employed. The MNDOT specifies the use of aggregate with a maximum 25% FI and average 12% FI. Lightweight aggregate is not used in Minnesota because single seals are commonly used for seal coats. The gradations of FA-2, FA-2 1/2, and FA-3 are commonly used for chip seal treatments in Minnesota; these gradations are plotted in Figure 3.

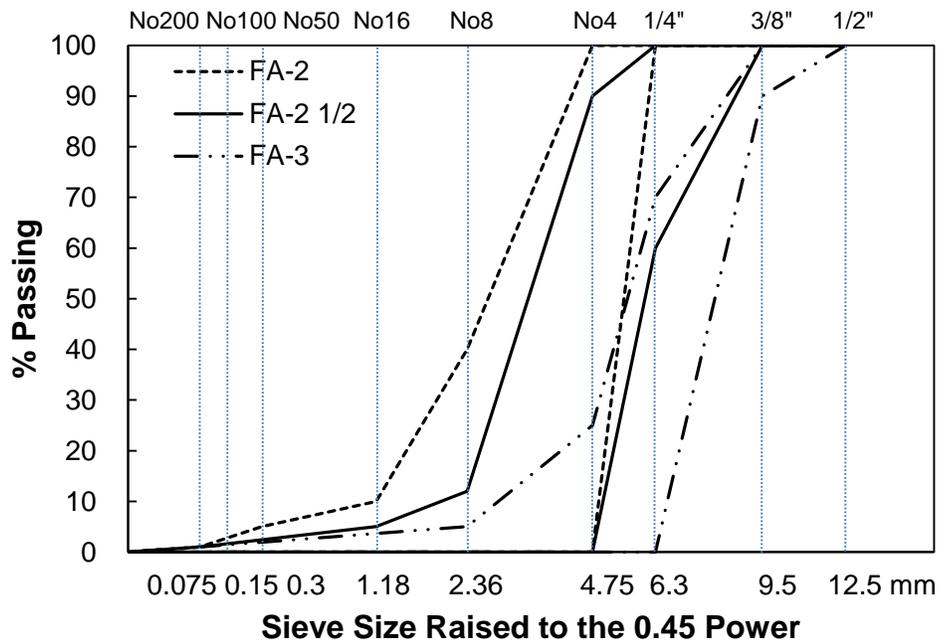


Figure 3 Aggregate particle size gradation in Minnesota: FA-2, FA-2 1/2, and FA-3

The single seal is used exclusively in seal coats even for high-volume roadways, and a fog seal is applied on all chip seals the next day after the sweeping procedure. In general, diluted CSS-1 or CSS-1h emulsions with a dilution rate of 50% are applied with rates of 0.07 to 0.12 gal/yd² (0.32 to 0.54 L/m²) for chip seals.

However, double seals can be used on heavily cracked roads. Because double seals are more susceptible to bleeding with choking stone (Virginia #9) on the surface, the emulsion application rate (EAR) of the second layer should be cut down sufficiently. If a single seal cannot achieve its design specifications properly, then second and third layers of aggregate can be added to the seal to attain the desired performance.

In chip seal construction, several different types of rollers are used; these include the pneumatic tire roller, steel wheel roller, vibratory steel wheel roller, rubber-coated vibrating drum roller, and combination roller. Currently, the MNDOT specifications recommend only pneumatic tire rollers in chip seal construction. A minimum number of three pneumatic tire rollers is required for a 12-foot lane, and three passes are applied for the full paving width. In order to achieve adequate compaction, the roller should be applied to the surface continuously, and below 5 mph is the recommended speed for the rollers.

Sweeping is conducted within 20 minutes of compaction. After 20 minutes, a pilot car traveling below 10 mph leads traffic across the fresh seal, and a sweeper (at a low-sweep intensity setting) follows the pilot car and traffic. This process that combines the use of the pilot car and sweeper continues with the sweeper's intensity increasing as the number of sweep passes increases. The early, slow (below 10 mph) traffic helps to embed and reorient the aggregate particles of the chip seals. Also, early light sweeping removes excess aggregate effectively, mainly from the area outside the wheel path, but also from the wheel path. Traffic control remains in place throughout the day of construction. The final sweep is applied the next morning. Up to three brooms are commonly used for the sweeping procedure.

The construction procedure for modified chip seals in Minnesota indicates a few differences from the chip seal construction procedure used by the NCDOT. Table 2 presents a comparison of chip seal construction factors between the NCDOT and the MNDOT.

Table 2 Comparison of Chip Seal Construction Factors

	NCDOT	MNDOT
Traffic Volume	<ul style="list-style-type: none"> • Single seal: 5,000 ADT • Multiple seal: 15,000 ADT 	<ul style="list-style-type: none"> • Single seal: up to 15,000 ADT • No real restrictions
Emulsion	<ul style="list-style-type: none"> • CRS-2L (normally) 	<ul style="list-style-type: none"> • CRS-2P • Fog seal: CSS-1 or CSS-1h
Aggregate	<ul style="list-style-type: none"> • Granite and Virginia #9 (for choking material) • Less uniformity than MNDOT specifications 	<ul style="list-style-type: none"> • Granite and Virginia #9 (for choking material) • Three uniform gradations with different nominal maximum aggregate sizes • Max. 25% FI
Seal Type	<ul style="list-style-type: none"> • Normally multiple seals 	<ul style="list-style-type: none"> • Normally single seal • Fog seal is applied on chip seals
Compaction	<ul style="list-style-type: none"> • 3 pneumatic tire rollers and 1 combination roller • Total 4 coverages 	<ul style="list-style-type: none"> • 3 pneumatic tire rollers • Total 3 coverages
Sweeping	<ul style="list-style-type: none"> • 2 – 3 hours after compaction 	<ul style="list-style-type: none"> • After 20 minutes, pilot car leads traffic and sweeper below 10 mph

2.6 The Use of Modified Chip Seals for Increased Traffic Volume Roads

2.6.1 Modified Chip Seals for Higher Traffic Volume Roads

At one time, the prevailing assumption was that chip seal surface treatments are not adequate for high-volume roads. Now, with an improved understanding of the mechanics behind chip seal performance, as well as improved material alternatives and construction procedures, chip seal surface treatments are considered a viable option if designed and constructed properly, even on high-volume roads.

For example, the Washington State DOT has been using chip seals successfully on the deck of the Tacoma Narrows Bridge for years. This particular bridge has an ADT count of 178,000. Additionally, Caltrans (the California Department of Transportation) uses chip seals on I-5 and I-80, which are high-volume roadways, and has not had major issues with them (Kuennen 2005).

Specifically, the CCSA provides guidelines for designing and constructing chip seals that perform well on high-volume roads. To ensure chip retention early in the life of the chip seal, the CCSA suggests using polymer-modified emulsion and waiting for appropriate climate conditions. It also suggests that fog seals can be used to hold chips in place at high traffic levels when necessary.

Schuler (1990) reports that chip seals used on high traffic volume roads in excess of 5,000 vehicles per day experience an average performance life of six to seven years, with some chip seals lasting much longer. His study goes on to describe reasons for chip seal failures on high-volume roads and details the methods used to overcome those problems. Specifically, Shuler describes a method for predicting the potential adhesive ability of chip seal emulsions by using a modified Vialit testing procedure.

In the NCHRP Chip Seal Best Practices (Gransberg and James 2005), it is noted that California, Colorado, and Montana regularly construct chip seals on roads with ADT counts that exceed 20,000 vehicles. It is reported that these chip seals perform either *good* or *excellent* under these traffic conditions. Texas also has had success constructing chip seals on high-volume roads. It is noted that the chip seals that perform well tend to be polymer-modified seals. As stated previously, PME has better adhesion than unmodified emulsion, which helps the retention of aggregate at high traffic volumes and speeds (Kuennen 2005).

Gransberg and James (2005) report that in South Dakota chip seals using unmodified polymer perform poorly in high-volume/high-speed road applications. Aggregate retention was found to be the problem associated with most of the seal failures, with broken windshields cited in many cases. The South Dakota DOT then embarked on a research effort to determine the specific factors that could improve the performance of chip seal surface treatments on high-volume roadways. In this study, twelve chip seal designs were used to compare high-volume chip seal sections using modified and unmodified emulsion. The results of the study, reported in a January 2002 Transportation Research Board presentation on the *Evaluation of Chip Seals on High-Speed Roadways*, suggest that “polymer-modified binders are the key to successful chip seals on South Dakota’s interstate-type, high-speed pavements” (Wade et al. 2001). In short, Wade et al. found that performance was enhanced

on high-volume roads by using PME. As previously mentioned, they reported adhesive benefits as the main factors behind the improved performance.

Zaniewski and Mamlouk (1996) report that some agencies use PME in the design of chip seals, particularly on high-volume roadways, because the polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, and allows the road to be opened to traffic earlier than would ordinarily occur.

2.6.2 Fog Seal Application

2.6.2.1 Fog Seal General

Fog seals have been used as an effective means of preserving pavements for many years. Fog seals are a method to ‘lock in’ aggregate by placing a light application of a diluted asphalt emulsion over a chip seal. To achieve this seal, the fog seal emulsion must fill the voids in the surface of the existing pavement. The fog seal emulsion also must have sufficiently low viscosity so as not to break before it penetrates the surface voids of the chip seal pavement during the fog seal application. A slow-setting emulsion that is properly diluted with water is used for a fog seal. An improperly diluted emulsion may not adequately penetrate the chip seal voids, resulting in excess asphalt on the surface of the pavement after the emulsion breaks, which can result in a slippery surface (California DOT 2003). Fog seals should not be used when a pavement has poor surface texture, large cracks, rutting, shoving, structural deficiencies or low friction numbers (King et al. 2007).

The purpose of the fog seal is to improve aggregate retention and extend the service life of the pavement by increasing the pavement’s impermeability to water and air. Also, small cracks can be sealed by a fog seal application (Wood et al. 2006). For a proper fog seal application, the existing pavement surface must be clean and dry. As part of a new chip seal application, the fog seal should be applied immediately after sweeping. To be effective, fog seals need to form a cohesive film once the water evaporates from the emulsion. This cohesive film does not form properly at temperatures lower than the minimum air

temperature of around 60°F. Therefore, the fog seal application process should not begin when the air temperature is below 60°F or if there is a possibility of precipitation (Wood et al. 2006). Also, environmental factors (i.e., high temperature, humidity, and wind) affect the length of time the fog seal emulsion takes to break (FHWA 2003).

The Minnesota DOT (MnDOT) has had success with fog seals on new chip seals (Wood et al. 2006). In the MnDOT road researches, the fog seal controlled dust, locked down the chips, and created a black surface. The fog seal reduced the likelihood of shelling and also protected the chip seal against snow plow damage. The black surface serves to improve visibility and public acceptance. Wood et al. summarize the benefits of fog seals as follows:

- The traveling public thinks it is driving on a new HMA surface rather than a chip seal.
- The emulsion is diluted, which yields a very low viscosity that allows most, if not all, of the additional asphalt binder to fill the chip voids increasing embedment by up to 15 percent with no bleeding.
- The fog seal reseals any chips that may have partially broken loose during sweeping operations.
- Darkening the pavement surface with a light application of asphalt emulsion allows the pavement surface temperature to rise. The subsequent softening of the binder allows the chips to orient to their least dimension more quickly. This factor is very important in Minnesota where late season chip seal researches are more susceptible to failure due to colder weather conditions.
- Fog sealing can provide a designer with a chance for a “re-do” of a chip seal application. If, after traffic has driven on the surface, it appears that embedment is low, an engineer can add additional binder to the chip seal by increasing the fog seal amount. In some cases, the amount of fog seal emulsion applied increased to over 0.20 gal/yd² (0.91 L/m²).
- When a fog seal is applied, a reduced amount of paint is necessary to make pavement markings visible on the surface.

- The low cost (i.e., average cost of a fog seal is \$0.18–\$0.80/yd² (\$0.22 - \$0.97/m²)) and ease of construction add to the benefits of fog seals.

Despite their advantages, however, fog seals have a few disadvantages as well. These problems include the fact that traffic cannot be allowed on a road with a new fog seal until the binder has cured completely, which can take 6 to 8 hours depending on weather conditions. Also, the fog seals may have low friction numbers until the binder wears off from the surface of the aggregate that contacts the vehicle tire (Jahren et al. 2007).

When fog sealing chip seals, proper embedment of the aggregate particles requires a given volume of emulsion – whether that emulsion is applied before or after the aggregate is spread. Chip seal designs should be adjusted by reducing the initial shot rate accordingly (King et al. 2007).

Nikornpon et al. (2005) describe a procedure for estimating the fog seal EAR. A one-liter can of diluted emulsion (usually 1:1 dilution rate) is poured evenly on an area of one square meter, i.e., a diluted EAR of 1 liter/m². The EAR is reduced if the emulsion is not absorbed into the surface after 2 to 3 minutes and is repeated until the approximate EAR is found. If, after the first test, the surface appears to be able to absorb more emulsion, the EAR is increased and tested over a new 1 m² area. The process is repeated until the approximate EAR is found. This same procedure can be followed using gallons and square yards (yd²) to determine the EAR in US customary units.

The AEMA (2004) offers a guide for fog seal applications. This guide shows suggested EARs for the fog seal, as seen in Table 3. The objective of the fog seal is to apply a uniform coverage of emulsion and seal the pavement pores, small cracks, and voids against water and weathering. If an emulsion is over applied, a light cover of clean, fine sand may be applied onto the uncured fog seal at the rate of 6 to 10 lb/yd² (3.3 to 5.4 kg/m²) to provide a safe, skid-resistant surface. Then, one pass of a pneumatic tire roller should be made to firmly embed this light dusting of sand. The fog seal should be allowed to cure completely before opening the roadway to traffic. Traffic control is necessary during the application process to protect the freshly sprayed emulsion until it is overlaid or cured to a safe condition.

The normal EAR used by the MnDOT ranges from 0.06 to 0.12 gal/yd² (0.27 to 0.54 L/m²) of diluted CSS-1h (cationic slow-setting) emulsion, depending on the size of the chips used. A higher rate of application is used for coarse chips, and a lower rate is used as the chips become finer. Minnesota requires a dilution rate of one part emulsion (Wood et al. 2006).

Table 3 Suggested Application Rates for Fog Seals (AEMA 2004)

Rate of Dilution	Type of Surface to Be Fog Sealed	
	Dense Surface Low Absorption gal/yd ² (L/m ²)	Open Surface High Absorption gal/yd ² (L/m ²)
% Emulsion (emulsion + water)		
Net residual asphalt desired	0.01 to 0.03 (0.05 to 0.14)	0.03 to 0.05 (0.14 to 0.23)
50% (1+1)	0.03 to 0.11 (0.14 to 0.05)	0.09 to 0.23 (0.41 to 1.04)
40% (2+3)	0.04 to 0.13 (0.18 to 0.59)	0.12 to 0.30 (0.54 to 1.36)
25% (1+3)	0.06 to 0.21 (0.27 to 0.95)	0.19 to 0.47 (0.86 to 2.13)
20% (1+4)	0.08 to 0.25 (0.36 to 1.13)	0.24 to 0.59 (1.09 to 2.67)
16.7% (1+5)	0.09 to 0.31 (0.41 to 1.40)	too high
14.3% (1+6)	0.12 to 0.41 (0.54 to 1.86)	too high
12.5% (1+7)	0.13 to 0.47 (0.59 to 2.13)	too high

Estakhri et al. (1991) studied the effectiveness of fog seals for bituminous pavement surface treatments, i.e., chip seals. They employed two experimental programs: laboratory and field evaluations. For the laboratory study, Estakhri et al. conducted Vialit testing to determine appropriate fog seal EARs to improve the aggregate retention performance of the chip seal. For the Vialit tests, the chip seal samples were fabricated using a binder application rate that was less than the optimal rate so that the aggregate was embedded into the asphalt to approximately 20 percent. MS-1 asphalt emulsion that was diluted with water at a 1:1 ratio was applied to the chip seal sample. Four different residual binder rates were employed for this study: 0.00, 0.05, 0.10, and 0.20 gal/yd² (0.00, 0.23, 0.45, and 0.91 L/m²). From the

Vialit test results, the fog seal applied at the residual asphalt application rate of 0.10 gal/yd² (0.45 L/m²) showed significant improvement in aggregate retention.

For the field test part of the Estakhri et al. study, four test roads under low traffic volume were constructed and evaluated to determine the effectiveness of fog seals at improving aggregate retention. Each fog seal was applied before the first winter after the chip seal was constructed. To compare a fog seal with a non-fog seal, a portion of each chip seal was not fog sealed. The aggregate loss, determined from close-up photographs, was used to evaluate performance. The performance evaluations were made after the first winter that the fog seal was applied and again after the second winter. The fog seal sections showed significantly less aggregate loss (i.e., better aggregate retention) than the sections that were not fog sealed. A large amount of aggregate loss occurred in the non-fog sealed sections, particularly between the wheel paths, over the first winter.

The preliminary literature review on fog seals reveals that the criteria used to evaluate fog seal performance focus on aggregate loss. The aggregate loss performance of the fog seal application process can be evaluated using various laboratory test methods, including the Vialit test and the sweep test (ASTM D 7000) (Barnat 2001, Yazgan 2004). However, each of these methods applies a different form of mechanical energy to assess the aggregate-binder bond interaction; and neither of these methods simulates the mechanical force imparted on the pavement by traffic wheel loading. To alleviate this shortcoming, a performance-based AST test method was developed and tested as part of the FHWA/NC/2005-15 research (Kim and Lee 2005). This accelerated test method uses the MMLS3, which is a scaled-down unidirectional vehicle load simulator that uses a continuous loop for trafficking. The wheels travel at a speed of about 5,500 wheel applications per hour, thus allowing an accelerated evaluation of pavement performance under more realistic loading conditions than that of other available AST tests.

In addition to existing AST test methods, such as the Vialit test and the flip-over test (FOT), the NCSU research team has developed several other AST performance test methods, including: a digital imaging technique to evaluate bleeding, the modified sand patch test, a digital imaging technique for examining cross-sections of epoxy-reinforced chip seal samples,

and a laser surface profiling system to determine the aggregate exposure depth (Kim and Lee 2008). These test methods are designed to be applicable under both laboratory and field conditions, with the exception of the digital imaging technique, which is applicable to laboratory samples only. Some of these methods are reviewed briefly in the following sections.

Based on the literature review, the pros and cons of fog seal application can be revealed as seen in Table 4.

Table 4 Pros and Cons of Fog Seal Application

Pros	Cons
<ul style="list-style-type: none"> • Cost-effective method • Ease of construction • Extension the service life of the pavement • Desirable black appearance 	<ul style="list-style-type: none"> • Long curing time (delayed traffic opening) • Reduction of skid resistance

2.6.2.2 Review of Existing Fog Seal Guidelines

One of important goals of this research is to develop a fog seal application guideline for use in North Carolina. As a result of the literature review of fog seals, the three appropriate guidelines has been found to consult for this work: *Fog Seal Guidelines* (for California), the *Minnesota Seal Coat Handbook 2006*, and *Fog Seal Application* (for the FHWA), as well as other studies on the topic.

Fog Seal Guidelines (State of California Department of Transportation)

Asphalt emulsion and water typically are used in the construction of fog seals. In some cases, the emulsions are made for special purposes, but the primary types used are CSS-1h and SS-1h. Asphalt emulsions contain up to 43% water, but must be diluted further before use to reduce their viscosity. Typically, the recommended dilution rate is 50% (1:1). Typical EARs for diluted emulsions range from 0.15 to 1.0 L/m² (0.03 to 0.22 gal/yd²)

depending on the surface conditions (see Table 5). To estimate the optimal EAR, a method that uses a one-liter can is employed, as follows. Take a one-liter can of diluted emulsion and pour it evenly over an area about 1 m². If the emulsion is not absorbed into the surface, decrease the amount and apply to a new 1 m² area. If the surface looks as though it will absorb more emulsion, increase the amount and apply over a new 1 m² area. Repeat the trials until the approximate EAR is found. This procedure for estimating the fog seal EAR is noted also in Nikornpon et al. (2005). The fog seal guidelines are discussed in Maintenance Technical Advisory Guide (TAG) (California DOT 2003).

Table 5 AEMA Recommendations for Application Rates

% Original Emulsion	Dilution Rate	Tight Surface*		Open Surface**	
		(L/m ²)	(gal/yd ²)	(L/m ²)	(gal/yd ²)
50	1:1	0.15 – 0.5	0.03 – 0.11	0.4 – 1.0	0.09 – 0.22

*A tight surface is of low absorbance and is relatively smooth.

** An open surface is relatively porous and absorbent with open voids.

To be effective, fog seals need to break quickly and cure completely. To achieve this behavior, an asphalt film must form properly. Thus, warm weather conditions with little to no chance of rain are necessary, and fog seals should not be applied when the atmospheric temperature is below 10°C (50°F) and the pavement temperature is below 15°C (50°F). Furthermore, the pavement surface must be clean and dry before applying the fog seal. After applying the fog seal, the curing time will vary depending on the weather and surface conditions. Under ideal conditions, traffic should not be allowed on the roadway for at least two hours and only after acceptable skid test (CT 342) values, over 0.30, are achieved. To allow early opening to traffic, sand blotters may be used at approximately 1 kg/m².

Minnesota Seal Coat Handbook 2006 (Minnesota Department of Transportation)

The *Minnesota Seal Coat Handbook 2006* has been used extensively in Minnesota and has served as a model for other states and jurisdictions around the United States. This

handbook also includes several advances in the seal coating process, and fog seals in particular are discussed in Chapter 5. According to this handbook, fog seals are used commonly to ensure the retention of stone and to add service life to the pavement by increasing its impermeability to water and air.

The normal EAR range is from 0.06 to 0.12 gal/yd² (0.27 to 0.54 L/m²) of diluted CSS-1h emulsion, depending on the size of the chips used. A higher rate of application is used for coarse chips, and a lower rate is used as the chips become fine. Like the California guideline, the Minnesota handbook also requires warm conditions with little to no chance of rain to ensure successful applications. It suggests that the air temperature is below 60°F.

Fog Seal Application (Federal Highway Administration)

Fog Seal Application is one of a series of documents created to guide state and local highway maintenance and inspection staff in the use of innovative pavement preventive maintenance processes. Because this document is not a complex paper but a simple checklist, it is easier to apply in actual field construction than some of the other fog seal guidelines.

Asphalt emulsion and water are the main materials used for fog seals, but this checklist does not mention specific emulsions or dilution rates. To determine the appropriate EAR, the one-liter can method is used. The steps of this method are the same as those outlined in the *Fog Seal Guidelines* used by the California DOT. The FHWA checklist recommends that fog seals should be applied when the minimum surface and air temperature requirements have been met (default 15°C, 59°F). Table 6 summarizes these three primary guidelines for fog seals.

Table 6 Summary of Guidelines Used for Fog Seals

Index	Fog Seal Guidelines (for California)	Minnesota Seal Coat Handbook 2006	Fog Seal Application (for the FHWA)
Type of Emulsions	CSS-1h and SS-1h	-	CSS-1h
Application Rate	Recommendation of AEMA	-	0.06-0.12 gal/yd ² (0.27 to 0.54 L/m ²)
Estimating Application Rate	1 Liter Can Method	1 Liter Can Method	-
Curing Time	At least 2 hours	-	-
Skid Resistance	At lease 0.30 (by CT 342)	-	-
Applying Sand	Yes	Yes	-

Note: Blank cells indicate no mention in the guidelines.

2.6.2.3 Factors Affecting Fog Seal Performance

Emulsion Properties

The materials used in fog seals typically are slow- or medium-setting emulsions diluted with water to produce a low viscosity that will not allow the emulsion to break before penetrating the voids in the pavement. Standard emulsions are cationic CSS-1 or CSS-1h and anionic SS-1, SS-1h, or MS-2 (although MS is slowly being replaced by better products) (TxAPA 2006).

In the *Minnesota Seal Coat Handbook*, three grades, cationic, anionic, and nonionic, are used to classify emulsions based on the electrical charge of the emulsifier surrounding the asphalt particles. For pavement construction and maintenance, only two classifications, cationic and anionic, are used. In order to prevent failure, cationic emulsions must be used with negatively charged aggregate, and anionic emulsions must be used with positively charged aggregate.

Emulsions also can be classified according to setting speed. After being applied in the field, emulsifiers begin to attract to aggregate surfaces that are oppositely charged, and then the asphalt particles settle to the bottom of the emulsion. The terms RS, MS, QS, and SS

stand for rapid-setting, medium-setting, quick-setting and slow-setting, respectively. The quick-setting designations have been introduced for emulsions that are intermediate in reactivity between the MS and SS designations (James 2006).

The viscosity of an emulsion affects its ability to penetrate the voids within the chip seal, and, therefore, viscosity is one of the most important properties of emulsion. Emulsions are classified by the numbers 1 and 2. The number 1 indicates emulsions with lower viscosity and more fluid, and the number 2 indicates emulsions with higher viscosity and less fluid. In some cases, emulsion designations may have the letter “h” added to the name, which indicates that the emulsion is made using a hard asphalt base (Wood et al. 2006). The detail information was mentioned in section 2.3.

In order to improve certain emulsion properties, polymer-modified emulsions (PMEs) are used in chip seal and fog seal construction. Polymer modification brings some advantages, such as a decrease in the emulsion’s susceptibility to temperature, an increase in adhesion of the emulsion, and allowing the road to be opened to traffic earlier than is the case when unmodified emulsions are used. Due to the ability of PMEs to enhance pavement performance, their use by the chip seal industry has increased in recent years.

Emulsion Curing Time

The curing time of an emulsion can affect the overall performance of the fog seal. In order to find the appropriate curing time for emulsions, the first step is to understand the curing procedure, shown in Figure 4. The curing process takes two steps, i.e., breaking and curing. The breaking process is when the emulsion changes from a dispersed form to an asphalt form, and curing is water evaporation from the emulsion.

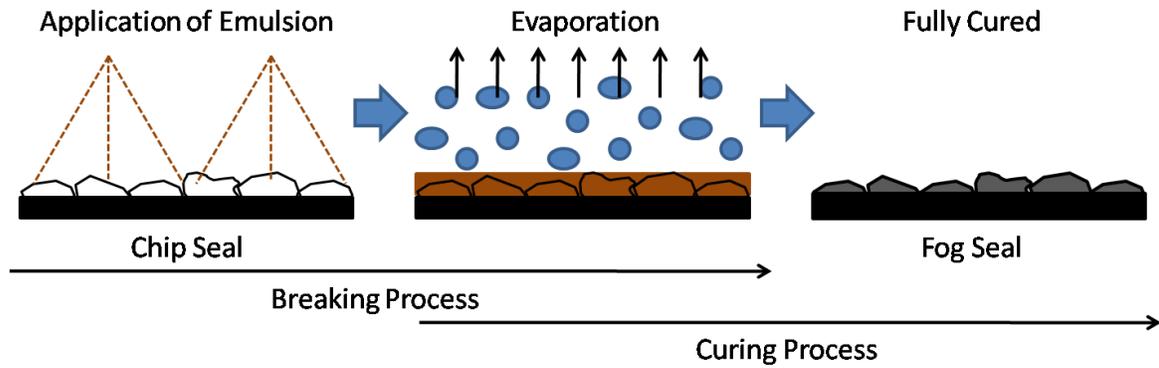


Figure 4 Emulsion curing procedure

Emulsion Application Rates

Proper EARs depend on the size of the air voids, size of the aggregate, and porosity. The EAR plays an important role in emulsion curing time and fog seal performance. A low fog seal EAR, for example, can lead to a short curing time, but it can also cause poor performance of the fog seal. Hence, it is necessary to determine proper fog seal EARs prior to fog seal construction. Nikornpon et al. (2005) recommend the AEMA's application rate (see Table 5), and in the case of TxAPA (2006), a few specific rates are recommended, depending on the aggregate grade: 0.08 – 0.10 gal/yd² (0.36 – 0.45 L/m²) for Grade 5, 0.01 – 0.12 gal/yd² (0.05 – 0.54 L/m²) for Grade 4, and 0.12 – 0.14 gal/yd² (0.54 – 0.63 L/m²) for Grade 3. Two studies (Jahren et al. 2007, Wood et al. 2006) do not provide a specific fog seal EAR.

3. TEST PROCEDURES AND ANALYSIS CONCEPTS

3.1 Materials

3.1.1 Aggregate

Two types of aggregate are used for this study, based on the most common usage for chip seal construction in North Carolina: a 78M graded granite aggregate and a lightweight aggregate with 3/8 inch nominal maximum size of aggregate (NMSA). In order to verify the gradation of the two aggregate stockpiles, dry sieve analysis was conducted in accordance with ASTM C 117. Figure 5 shows the gradations of the two aggregate types plotted on the 0.45 power chart. For comparison, the gradations of the chip seal aggregate specified by the NCDOT and MNDOT are plotted as well. In Minnesota, the gradations of FA-2, FA-2 1/2, and FA-3 are commonly used for chip seal treatments, but the FA-2 1/2 gradation is plotted because it covers the two aggregate gradations used in this research.

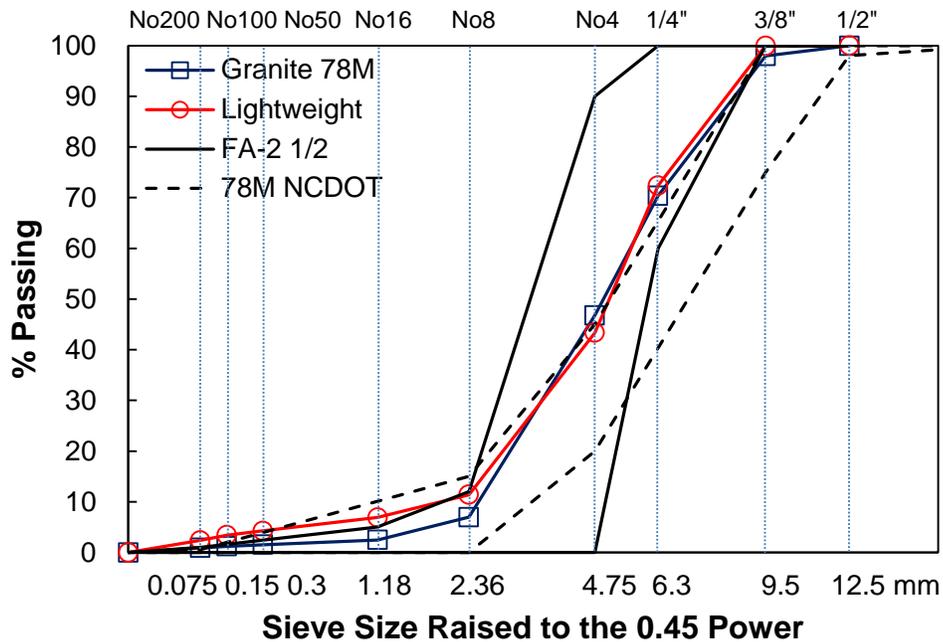


Figure 5 Aggregate particle size gradations

Figure 5 shows that the NCDOT specifications recommend less uniform gradation than the MNDOT specifications. The granite 78M and lightweight gradations that are used in this study have similar gradations, but the lightweight aggregate includes more fine aggregate.

3.1.2 Aggregate Performance Uniformity Coefficient (PUC)

Aggregate gradation is one of the most important factors that affect the performance of chip seal surface treatments. The literature and field surveys emphasize the importance of uniform-sized aggregate particles in chip seal construction. The *Minnesota Seal Coat Handbook* recommends single-sized aggregate as the best seal coat gradation for good performance (Wood et al. 2006). Gransberg and James (2005) also suggest single-sized aggregate with less than 2% fine passing the No. 200 sieve as an ideal aggregate source. McLeod (1960) proved that using (close to) one size of aggregate, even it may cause higher initial construction costs, leads to good performance and is an economical option in surface treatments.

In order to indicate the uniformity of chip seal aggregate particles, Lee and Kim developed the concept of the performance uniformity coefficient (PUC) (Lee and Kim 2009). The PUC combines the uniformity coefficient (UC) concept and McLeod's failure criteria for chip seals and is employed as a performance indicator of chip seals by representing the uniformity of the aggregate source that is used in chip seal surface treatments. In Equation (1), the PUC is expressed as the ratio of the percentage passing at a given embedment depth (E) of median particle size (M) to the percentage passing at twice the embedment depth of the median particle size in a sieve analysis curve.

$$PUC = \frac{P_{EM}}{P_{2EM}} \quad (1)$$

where

P_{EM} = percentage passing at a given embedment depth (E) of median particle size (M) in sieve analysis curve; and

P_{2EM} = percentage passing at twice the embedment depth of median particle size in sieve analysis curve.

The closer the PUC is to zero, the more uniform is the gradation of the aggregate source. In the previous mix design research (NCDOT HWY-2008-04), more uniform gradations (i.e., lower PUC values) lead to better performance than less uniform gradations (i.e., higher PUC values) in terms of characteristics such as aggregate retention and resistance to bleeding. In order to compare the systematic gradation variations of aggregate sources in terms of performance testing for this research, three gradations are used: A gradation (lowest PUC value), B gradation (natural gradation), and C gradation (highest PUC value) for both lightweight and granite 78M aggregate.

3.1.3 *Emulsion Type*

3.1.3.1 *Emulsion for Chip Seals*

For the performance evaluation of polymer-modified asphalt surface treatments (ASTs) used for this research, Road Science, LLCTM has produced two PME: HP CRS-2P and SBS CRS-2P. In order to compare the emulsion properties of both of these PMEs with an unmodified emulsion, CRS-2 emulsion was selected as the unmodified emulsion because it best matches the surface charge of the granite and lightweight aggregate types that are commonly used in North Carolina. In addition, CRS-2L, which is an SBR latex-modified emulsion, was selected as another modified emulsion to be used for comparative purposes due to its popular usage in North Carolina. Thus, four emulsion types are tested in this comparative study: HP CRS-2P, SBS CRS-2P, CRS-2L (the three modified emulsions), and CRS-2 (the unmodified emulsion).

3.1.3.2 *Emulsion for Fog Seals*

The CSS-1h (cationic slow-setting) and SS-1h (slow-setting) types of emulsions are commonly used in fog seal applications (California DOT 2003). For the granite and lightweight aggregates commonly used in North Carolina, the CSS-1h emulsion best matches the surface charge of these aggregates. From the literature review, it was also found that the Minnesota DOT uses PME for its fog seals. Specially-diluted CRS-2Pd (cationic rapid-

setting, polymer-modified) emulsion has replaced SS-1h/CSS-1h emulsion as the MnDOT's standard for fog sealing, and essentially serves as their control emulsion. The emulsion is diluted by the manufacturer as 3 parts emulsion to 1 part water for a specified residue content of 51% (King et al. 2007). During the early stages of its research, the CRS-2Pd emulsion was considered for fog seal performance testing, but the use of the emulsion decided against the idea based on information obtained from Mr. Thomas Wood, who is conducting a study of chip seals and fog seals for the MnDOT. He advised the NCSU research team that CSS-1h emulsion typically is used for fog seals because the hard-based asphalt is less sticky than other types of emulsion. The CRS-2Pd emulsion is used only on shoulders, rumble strips, and older recreational trails for fog seals because it stays sticky longer than other types, and live traffic could pull chips out of the fresh chip seal. Some suppliers have tried to dilute CRS-2L (cationic rapid-setting, latex-modified), which is not polymer-modified but latex-modified, but this method has not been successful.

From this information regarding emulsion types, the CSS-1h emulsion is selected as an unmodified emulsion type. The CQS-1h (cationic quick-setting) emulsion also is selected as an unmodified emulsion type. This emulsion has a minimum binder content of 57% and is rarely used for fog seals; it is mainly used as a polymer-modified (latex) version of a slurry seal. In order to compare unmodified emulsions and PMEs, both Grip-Tight, produced by Hammaker East, Ltd., and ReviveTM, produced by Road Science, LLCTM, have been selected for the fog seal study. The Grip-Tight emulsion is a highly polymerized asphalt emulsion that is specially designed for fog seal and flush coat applications. The best feature of this emulsion is that it allows for a short curing time, i.e., early traffic opening time. According to information provided by the manufacturer, traffic could be back on the road within 15 minutes of application. The ReviveTM emulsion is a quick-setting fog seal emulsion that is specially designed to break and cure significantly faster than traditional fog seal emulsions. The main advantage of this emulsion is similar to that of Grip-Tight. The emulsion company states that ReviveTM takes only 30 to 45 minutes to break and cure before the road can be opened to traffic.

From the literature review it is found that the range of typical application rates for fog seal emulsions, which are diluted with water, is from 0.03 to 0.22 gal/yd² (0.14 to 1.00 L/m²). In this research, the fog seal EARs are considered when the fog seal is applied on the chip seal surface, which has a rougher surface texture than typical asphalt pavement. A few representative fog seal EARs were selected through the curing time study, and then they were used for the fog seal performance tests. The fog seal EARs were determined and adjusted depending on the test method.

3.1.4 Type of Chip Seal

For the Vialit test and MMLS3 test (aggregate loss and bleeding tests), single-seal specimens were fabricated for both aggregate types (granite 78M and lightweight). The optimal aggregate application rates (AARs) and emulsion application rates (EARs) were determined for these single seals based on an earlier chip seal mix design study (NCDOT HWY-2008-04). All the specimens were fabricated with AARs of 16 lb/yd² (8.7 kg/m²) for the granite 78M aggregate and 7 lb/yd² (3.8 kg/m²) for the lightweight aggregate. For all the specimens of both aggregate types, an EAR of 0.25 gal/yd² (1.13 L/m²) was applied for the CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions.

In order to investigate rutting performance, triple-seal specimens were fabricated based on the previous PME study (NCDOT HWY-2007-06). All the triple-seal specimens were composed of granite 78M, granite 78M, and lightweight aggregate for the bottom, middle, and top layers, respectively. The AARs for the triple seals are 17 lb/yd² (9.2 kg/m²), 17 lb/yd² (9.2 kg/m²) and 9 lb/yd² (4.9 kg/m²) for the bottom (granite 78M), middle (granite 78M), and top (lightweight) layers, respectively. The EARs are 0.30 gal/yd² (1.36 L/m²), 0.25 gal/yd² (1.13 L/m²), and 0.20 gal/yd² (0.91 L/m²) for the bottom, middle, and top layers, respectively.

For the fog seal study, representative chip seal samples must be fabricated for fog seal performance testing because the fog seal EARs can be varied depending on the texture of existing pavement. In this research, one type of chip seal texture has been created using 0.25 gal/yd² (1.13 L/m²) of CRS-2L emulsion and 10 lb/yd² (5.4 kg/m²) of lightweight aggregate,

as recommended from the HWY-2008-03 research. It is acknowledged that additional chip seal textures should be tested for further research.

3.2 Experimental Program

According to previous research and examples found in the literature, chip seals constructed using PMEs exhibit improved initial and long-term performance (i.e., aggregate loss and bleeding resistance), extend the service life of pavements, and reduce expenses for pavement maintenance. Because chip seals with PMEs exhibit these good performance properties, the possibility of using them on high-volume roads should be explored. In order to do so, it is important to develop construction guidelines that incorporate chip seal structure types, optimized construction procedures, and the maximum traffic volumes for polymer-modified chip seals. Table 7 presents the experimental program that has been developed to accomplish the goals of this research.

Table 7 Experimental Program

Phase	Research Purpose	Factors and Test Methods
1	Investigation of Curing and Adhesive Behaviors	- Temperature and Curing Time - Evaporation Test, BBS Test, and Vialit Test
2	Development of Refined Construction Procedure	Mix Design (EAR, AAR, Material Types and Properties, and Chip Seal Structure), Rolling Pattern, Traffic Opening Time, Time for Sweeping
3	Construction of Field Sections	Traffic Volume and Field Adjustment
4-1	Laboratory Performance Testing	- MMLS3: Aggregate Loss, Bleeding, and Rutting - Skid Resistance: British Pendulum Test - Surface Texture: Laser Profiler (MPD Analysis)
4-2	Field Sections Monitoring	Laser Scan and Visual Observation
5	Analysis of Chip Seal Performance	Curing and Adhesive Behaviors and Performance Properties for both Laboratory and Field Specimens
6	Guidelines	Construction Procedures and Maximum Traffic Volume

Phase 1 is designed to investigate the basic mechanisms, i.e., curing and adhesive behavior, which govern the aggregate retention performance of chip seals. These two mechanisms are evaluated as a function of temperature and time using a well-controlled laboratory experimental program.

In Phase 2, the information gathered from the literature review and Phase 1 is used to develop several refined construction procedures for modified chip seals and a field experimental program to evaluate performance improvements. The refined construction procedures are developed by optimizing the following construction factors: (1) mix design (i.e., EAR, AAR, material types and properties, and chip seal structures), (2) the time interval between spraying the emulsion and spreading the aggregate, and between spreading the aggregate and rolling, (3) rolling patterns, (4) traffic opening time, and (5) time for sweeping. For the mix design, the findings from the previous chip seal mix design study (NCDOT HWY-2008-04) and the performance-based PME study (NCDOT HWY-2007-06) are used to develop a few candidate parameters for the mix design; these factors include EAR, AAR, material types and properties, and chip seal structure. Two to three candidate rolling patterns have been developed from the findings of the previous rolling study (NCDOT HWY-2006-06).

The fog seal application is considered in Phase 2 because fog seals are among the most effective methods to improve the performance of chip seals. A tentative experimental program has been developed based on the findings from the literature review. Two target parameters have been identified as important variables for the satisfactory performance of fog seals and for their specifications. These parameters are the fog seal EAR and curing time. The fog seal EAR is affected by surface voids, surface absorption, and emulsion type. The curing time is affected by the dilution rate, application rate, and curing temperature. These two target parameters affect several performance characteristics of fog seals. The fog seal EAR affects the surface texture depth and, thus, aggregate loss and skid resistance. The curing time, which is determined by the curing rate of the emulsion, is related to performance because the speed at which the emulsion cures helps determine when the roadway can be opened to traffic.

Phase 3 is designed for the construction of the chip seals on actual roadways using the refined construction procedures developed in Phase 2. The field construction days, locations, and variables were confirmed during the pre-construction meeting and in consideration of field conditions (i.e., weather, traffic volume, traffic control, and material supply).

Phase 4 is separated into two phases, such as phase 4-1 and 4-2. In phase 4-1, both the laboratory samples fabricated in laboratory and the field samples extracted from the field sections are tested in the laboratory using performance test methods, including the Vialit test and MMLS3 test that have been used successfully in previous chip seal research researches. For the curing time study, the evaporation test, BBS test, and Vialit test are performed under different conditions. The fog seal field tests, i.e., the damping test and rolling ball test, are evaluated in the laboratory in order to apply them for field construction. In order to compare between target application rates and actual application rates, i.e., EARs and AARs from the different field sections, the ignition oven test is performed using Vialit samples. Aggregate loss, bleeding, and rutting performance are evaluated using the MMLS3 test. In Phase 4-2, the performance of the chip seals in the field sections is monitored for comparison with the laboratory performance tests using a laser scan and/or visual observation. Because the aggregate loss of chip seals normally occurs after the first winter, the field section monitoring is performed at several times (i.e., after construction, before winter, and after winter).

In Phase 5, the adhesion relationships developed in Phase 1, the findings from the laboratory tests in Phase 4-1, and the performance observations from the field sections in Phase 4-2 are used to develop construction and traffic volume guidelines for PME chip seals. These guidelines include recommendations for: (1) optimized construction procedures for PME chip seals, including the timing of the various steps involved in chip seal construction (i.e., aggregate spreading, rolling, traffic opening, and sweeping and rolling patterns), and (2) the maximum traffic volumes that PME chip seals constructed with different materials can accommodate using the optimized construction procedures.

For Phase 6, the dissertation documents the findings from the literature review and the findings from the field and laboratory testing program, and provides the construction guidelines for PME chip seals. The dissertation also summarizes the recommendations for

optimized construction procedures for PME chip seals and the maximum traffic volumes that PME chip seals can accommodate.

3.3 Sample Fabrication

3.3.1 *Sample Fabrication Facility*

In order to eliminate temperature as a variable in fabricating and testing fog seal and chip seal specimens in the laboratory, it is important to be able to control the temperature throughout the entire process. Such control is vital because it ensures that each sample is subjected to nearly identical temperatures during the fabrication, curing, and testing processes. Pivotal to achieving this level of temperature control is a closed facility that can host the fabrication process. The NCSU research team has constructed such a facility, a 16 ft. by 8 ft. greenhouse made of wood and polycarbonate glass. This greenhouse, pictured in Figure 6, ensures a relatively consistent temperature for the specimens during fabrication.



Figure 6 Greenhouse for temperature control

The fog seal study requires performance testing of fog seal samples using various fog seal EARs for different chip seal samples. However, performance testing of fog seal field sections is too costly, if not impossible, within the time and resources allotted in this research. Therefore, a laboratory device that can fabricate fog seal and chip seal samples with accurate EARs and consistency is important for the success of this research. Because emulsion can be sprayed onto a felt disk or chip seal sample resting on a scale, it is fairly simple to apply the emulsion at a specified rate in the laboratory. Figure 7 shows an emulsion spraying procedure that employs a paint gun. The difficulty lies in spreading the aggregate in a realistic and consistent manner. The NCSU research team has designed an experimental chip seal spreader that automatically spreads aggregate on emulsion at a reasonably steady rate. The device, ChipSS, shown Figure 8, simulates the aggregate spreader that is currently used in field situations. ChipSS currently is housed in the greenhouse, thus allowing accurate temperature control in producing chip seal and fog seal samples.



Figure 7 Emulsion spraying procedure

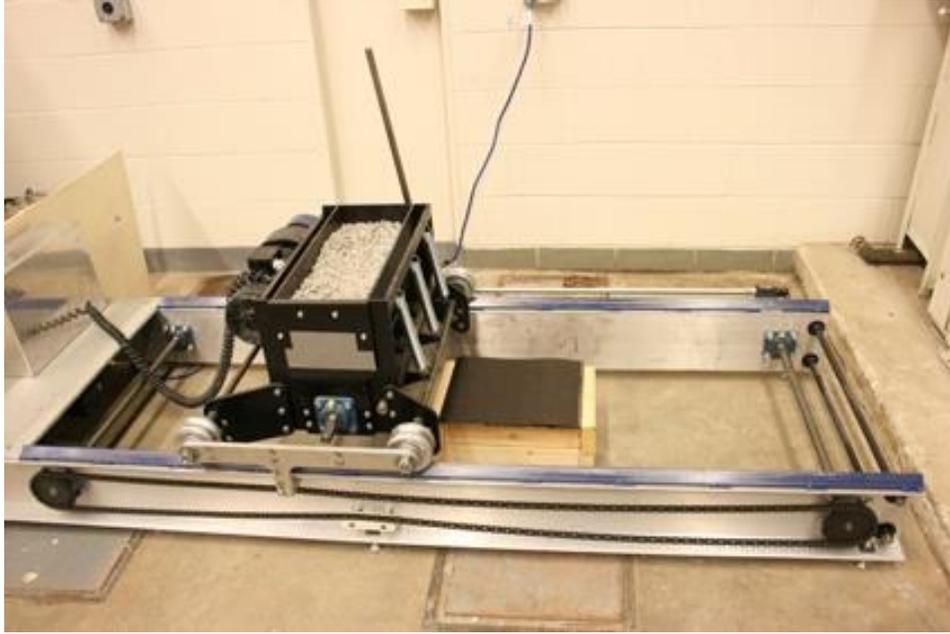


Figure 8 ChipSS

3.4 Experimental Test Methods

Based on the literature review, various ASTs test methods have been evaluated for their effectiveness in accomplishing the research objectives of this study. The selected performance tests for different performance characteristics are listed in Table 8. The results from these tests will be analyzed and compared to determine the performance properties of chip seals that consist of different materials at different conditions.

Table 8 Test Methods for Performance Properties

Performance Characteristics	Performance Test Methods
Curing and Adhesive Behavior	Evaporation Test, BBS Test, Vialit Test, Rolling Ball Test, Damping Test
Aggregate Retention	MMLS3 Test, Vialit Test, Photo-record (Field)
Bleeding and Rutting	MMLS3 Test
Skid Resistance	BPT
Surface Texture	Laser Profiler, MPD Analysis
Field Application Rates	Ignition Oven Test
Field Performance	Visual Survey, Laser Profiler

3.4.1 *Evaporation Test*

It is important to determine the curing time that is required for the respective emulsions to reach their asymptotic percentage of water loss (% water loss), that is, the point at which no more water loss occurs. This determination allows a direct comparison of the curing characteristics of the four test emulsions. For these evaporation tests, the emulsions are prepared and placed in small cans of 90 mm diameter each. All of the emulsion samples are exposed to the same conditions in the environmental chamber. Figure 9 shows evaporation test samples in the environmental chamber.

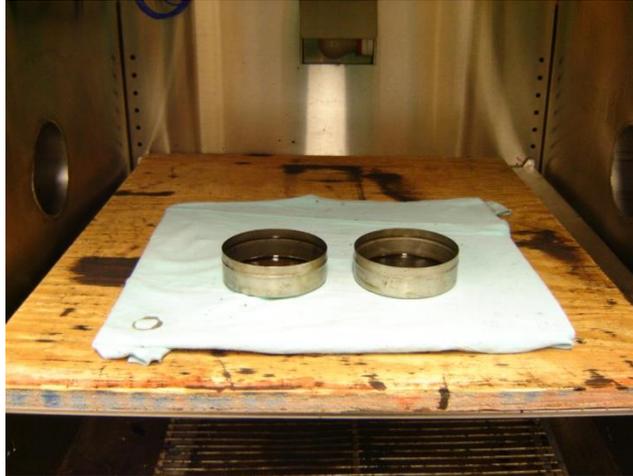


Figure 9 Evaporation test samples in environmental chamber

The evaporation test procedure involves the following steps:

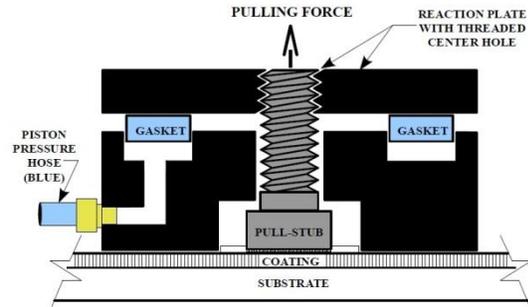
- 1) Heat the test emulsion at 60°C for 2 hours.
- 2) Place the cans in the oven at the test temperature for 1 hour.
- 3) Place the cans on the scale.
- 4) Pour the emulsion into the cans.
- 5) Place the specimens in the environmental chamber at the test temperature.
- 6) Measure the weight of the specimens periodically.

3.4.2 BBS Test (PATTI Test)

The PATTI test is an adhesion test developed by the National Institute of Standards and Technology and is typically used in the paint industry. This test is standardized in ASTM D 4541: *Pull-Off Strength of Coatings Using Portable Adhesion*. In the pavement field, PATTI can be used to measure the bond strength between the hot asphalt binders and aggregate surfaces, or between the emulsions and aggregate surfaces. The PATTI itself and a schematic representation of the PATTI piston are provided in Figure 10. The AASHTO-TP 91 was developed for asphalt binders and emulsions using the PATTI device and is called the bitumen bond strength (BBS) test. The BBS test procedure has been modified so that it can be used also to test the bond strength of emulsions as a function of curing times.



(a)



(b)

Figure 10 PATTI test; (a) PATTI device and (b) schematic of piston assembly (PATTI Manual)

Figure 11 shows the BBS test set up. After preparing the test materials, all procedures are conducted in an environmental chamber because the test temperature plays a vital role in the emulsion curing.



(a)



(b)

Figure 11 PATTI samples in environmental chamber for: (a) emulsion and (b) fog seal emulsion

In order to fabricate emulsion specimens on an aggregate substrate surface, a silicone mold that is approximately 400 mm × 400 mm with a 20 mm diameter hole is used. The mold has no backing and is used to contain the emulsion on the aggregate substrate during curing. Figure 12 shows the mold dimensions and the molds attached to the aggregate substrate.

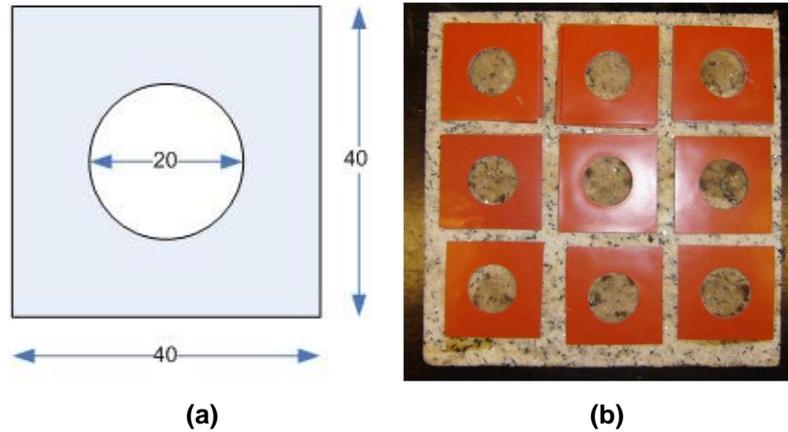


Figure 12 Molds: (a) dimensions (mm) and (b) attached molds to aggregate substrate

Precut granite substrate is used for BBS testing. In order to prevent the possibility of eccentric loading during testing, the granite substrate must be uniformly flat. Hence, the substrate is polished using a 280-grit silicon carbide material to remove saw marks and to ensure a consistent surface roughness. Prior to testing, the substrate should be cleaned using an ultrasonic cleaner filled with distilled water for 60 minutes at 60°C. Residual particles on the substrate surface can affect the bond strength of the emulsion, so this cleaning procedure is essential for the proper implementation of the BBS test.

Pull-stubs made of stainless steel are used. To ensure good adhesion between the emulsion, pull-stubs, and substrate, the pull-stubs should be firmly pressed down into the aggregate substrate. Figure 13 shows that the pull-stubs have 0.8 mm thick rims on the bottom plate and the rim has four gaps. These gaps allow any excess emulsion to flow out of the pull-stub, so the emulsion remains a uniform thickness. According to previous studies, the bond strength can be affected by the thickness of the emulsion film and curing of the emulsion. However, it is difficult to control the film thickness of fog seal emulsions, which are diluted with water, because the volume of fog seal emulsions changes significantly depending on the curing time. Thus, in order to keep the fog seal emulsion film thickness constant, 13.5 kg of dead weight is applied for 10 seconds when adhering 1/2inch (12.7 mm) pull-stubs onto the substrate. Although the BBS test procedure suggests using 20 mm pull-stubs, such pull-stubs cannot be applied to film that is thinner than 0.8 mm.

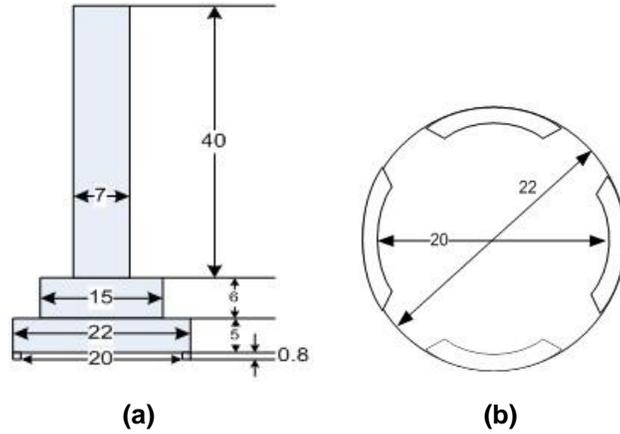


Figure 13 Dimensions (mm) of pull-stub: (a) profile view and (b) bottom view (AASHTO-TP 91)

PATTI provides the maximum pull-off tensile strength by converting air pressure to tensile strength. In general, when a failed surface on the substrate has asphalt remaining on it, the type of failure is referred to as *cohesive failure*. When little to no asphalt remains on the substrate, the type of failure is referred to as *adhesive failure*. Examples of cohesive and adhesive failures are provided in Figure 14.

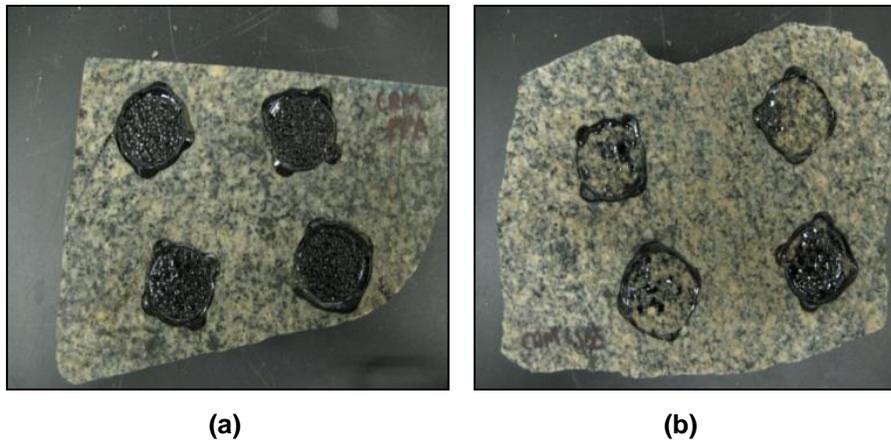


Figure 14 Failure types: (a) cohesive failure and (b) adhesive failure.

In this study, the BBS test is used to compare the adhesive behavior of each emulsion as a function of different curing times and temperatures. In other words, the most important factor in the BBS test is not bond strength itself, but the change in bond strength as a function

of curing time. In the fog seal research (HWY-2010-02), the BBS procedure was modified so that it applies to fog seal emulsions, which are very sensitive to curing time due to the fact that they are prepared by diluting them with water. That is, the amount of water evaporation is higher than that of a normal emulsion. From the fog seal BBS test results, it has been found that the modified BBS procedure works well. The only difference between the BBS procedure and the modified BBS procedure is the testing time. In the BBS procedure, once the pull-stubs are affixed, one hour is required to allow the samples to acclimate to the testing conditions. Therefore, when the BBS test is conducted for two hours of curing time, the actual test is performed at three hours of curing time. This additional one hour not only can affect the bond strength but it also can be a major variable in determining the emulsion curing rates, because any significant change in the curing rate of the emulsion normally occurs during the early part of the test. Therefore, the modified BBS test procedure is used for analysis of the adhesive behavior of each emulsion. Table 9 shows both procedures in detail. In order to maintain the test temperature, Step 4 and 8 are conducted in an environmental chamber.

Table 9 Comparison of BBS Procedure and Modified BBS Procedure

Steps	BBS Procedure	Modified BBS Procedure
1	Heat emulsion to $60 \pm 2^{\circ}\text{C}$.	
2	Attach molds to aggregate substrate, and heat them to an application temperature.	
3	Fill molds with 0.4 ± 0.05 g of emulsion and 0.6 ± 0.05 g of fog seal emulsion.	
4	Cure the sample under controlled conditions for a given curing interval.	
5	Heat pull-stubs to $60 \pm 2^{\circ}\text{C}$.	
6	After removing samples from the chamber, remove molds and place the pull-stubs on the emulsion.	In the chamber, remove molds and place the pull-stubs on the emulsion.
7	Return the testing assembly to the oven at $25 \pm 2^{\circ}\text{C}$ for 1 hour.	Wait 10 minutes.
8	Conduct the test.	Conduct the test.

3.4.3 Ignition Oven Test

The ignition oven test, which is specified in ASTM D 6307, commonly is used to calculate the weight of residual aggregate and emulsion by burning samples in an ignition furnace. Because the application rates of the aggregate and the emulsion affect the performance properties of chip seal surface treatments, it is necessary to know the actual application rates used in field construction. The actual application rates can be calculated from field samples using the ignition oven test results. The mass of the aggregate can be affected by the pyrolytic action that occurs during the ignition oven test. Correction factors are determined for each aggregate type, as shown in Table 10, and applied for the calculation of the actual application rates of the field samples. The actual application rates for the aggregate and emulsion are calculated by Equation (2) and (3).

Table 10 Correction Factors for Each Aggregate Type

Type of Aggregate	Correction Factor (%)
Granite 78M	0.26
Lightweight	0.27

$$W_A = W_{RA} \times C.F. \tag{2}$$

$$W_{RE} = W_O - W_A \tag{3}$$

where

W_A = Aggregate weight

W_{RA} = Residual aggregate weight (after burning)

W_{RE} = Residual Emulsion Weight

W_O = Original sample weight

C.F. = Correction factor

3.4.4 *Flip-Over Test*

The flip-over test (FOT) is the part of the sweep test procedure (ASTM D7000) that measures the amount of excess aggregate on the specimen. It is used to simulate the sweeping process on a chip seal surface one day after new chip seal construction. At the end of the curing time, the specimen is turned vertically upright and any loose aggregate particles are removed by lightly brushing the specimen. The specimen is weighed before and after the FOT to determine the amount of excess aggregate on the specimen.

3.4.5 *Vialit Test*

The Vialit test was developed by the French Public Works Research Group and is standardized in BS EN 12272-3. This test method is an indicator of aggregate retention for chip seals using the Vialit testing apparatus, as shown in Figure 15. A stainless steel ball is dropped three times from a height of 19.7 inches onto an inverted chip seal tray. The percentage of aggregate loss after three ball drops is used to evaluate the aggregate retention of the specimen.



Figure 15 Vialit test apparatus

3.4.6 Third Scale Model Mobile Load Simulator (MMLS3) Performance Test

3.4.6.1 Aggregate Loss Test

Testing with the MMLS3 is a relatively new technique developed by the NCSU research team. This test targets both aggregate loss and bleeding. The MMLS3, shown in Figure 16, accelerates wear on the pavements and allows researchers to simulate years of damage in mere days. Chip seal samples must be fabricated for MMLS3 testing. To this end, asphalt felt papers are cut to 12 inches \times 14 inches, and emulsion is applied onto the felt paper in dimensions of 7 inches width and 12 inches length; this 7 inches width is the same width as the MMLS3 wheel path. An actual photograph of the MMLS3 test specimens is shown in Figure 17. The MMLS3 test procedure involves the following steps:

- 1) Curing the specimens in the MMLS3 temperature chamber at 95°F (35°C) for 12 hours and $35 \pm 3\%$ relative humidity, as specified by the ASTM D7000 *Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples*.
- 2) Weight the initial specimen.
- 3) Condition the temperature of the specimens to 77°F (25°C) for 3 hours for the aggregate retention test.
- 4) Apply MMLS3 loading for 10 minutes, which is the time required for the MMLS3 to complete one wandering cycle, and then weight the specimen.
- 5) Apply MMLS3 loading for 120 minutes, and weight the specimen periodically.
- 6) Condition the specimens to 122°F (50°C) for 3 hours for the bleeding test.
- 7) Apply MMLS3 loading for 4 hours at 122°F (50°C).
- 8) Scan the surface of the specimens.
- 9) Conduct the bleeding analysis.

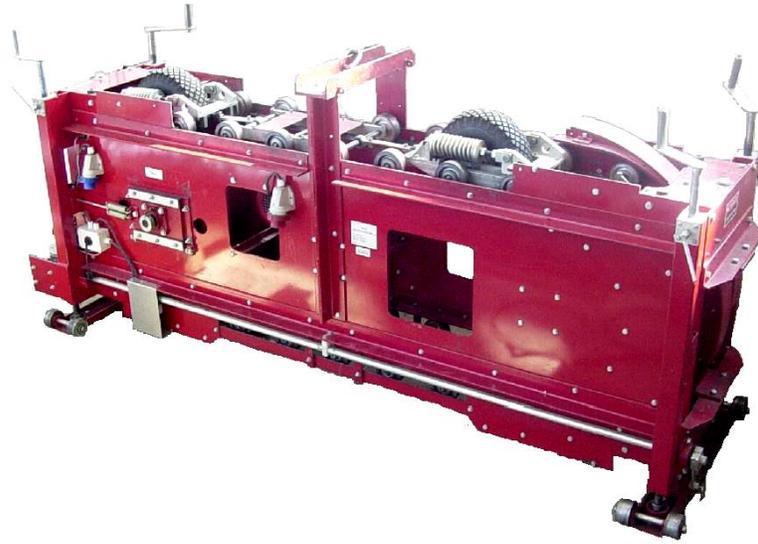


Figure 16 MMLS3



Figure 17 MMLS3 test specimens before loading

Including the specimen fabrication time, this MMLS3 procedure takes one week to

complete. The following information can be obtained at the end of the testing:

- Percentage of aggregate loss as a function of the number of load cycles
- Percentage of bleeding area
- Rutting profiles after 77°F (25°C) testing and after 104°F (40°C) testing
- Skid resistance (i.e., the British Pendulum Number, or BPN) after as a function of the number of load cycles
- Visual observation of the specimen surface after 77°F (25°C) testing to check for cracking
- Visual observation of the specimen surface after 122°F (50°C) testing to check for bleeding

3.4.6.2 Bleeding Analysis

Once the aggregate loss testing is completed, the bleeding tests are performed. In the AST industry, the terms *bleeding* and *flushing* refer to the spread of hot emulsion and an excess of emulsion, respectively. However, because both of these failure types can reduce skid resistance, they show similar failures. Therefore, in this research, the term *bleeding* is used for both bleeding and flushing.

The AST samples are placed in the oven at 50°C for three hours prior to four hours of bleeding testing. During the four hours of MMLS3 loading, the test temperature, 50°C, is controlled inside the temperature chamber. This bleeding test process simulates the bleeding of AST surfaces during the summer.

In order to quantify the bleeding area of the chip seal specimens, the specimens are scanned using a Hewlett Packard digital scanner (HP Scanjet 4850) as a color BMP file with a resolution of 200 dpi. The digital image is cut down to 10 in. × 10 in. to 1,400 pixels in width and 1,400 pixels in height to maintain consistency for the size of the image pixels. This size also covers the width of the MMLS3 wheel path. The contour of the bleeding area is drawn on the digital images using Adobe Photoshop CS4, and the bleeding area is calculated using Equation (4).

$$Bleeding (\%) = \frac{A_{Bleeding}}{A_{Total}} \times 100 \quad (4)$$

where

A_{Total} = area of AST specimen (total number of pixels, 7 × 7 inches); and

$A_{Bleeding}$ = area of bleeding on AST specimen (sum of pixels obtained from bleeding image)

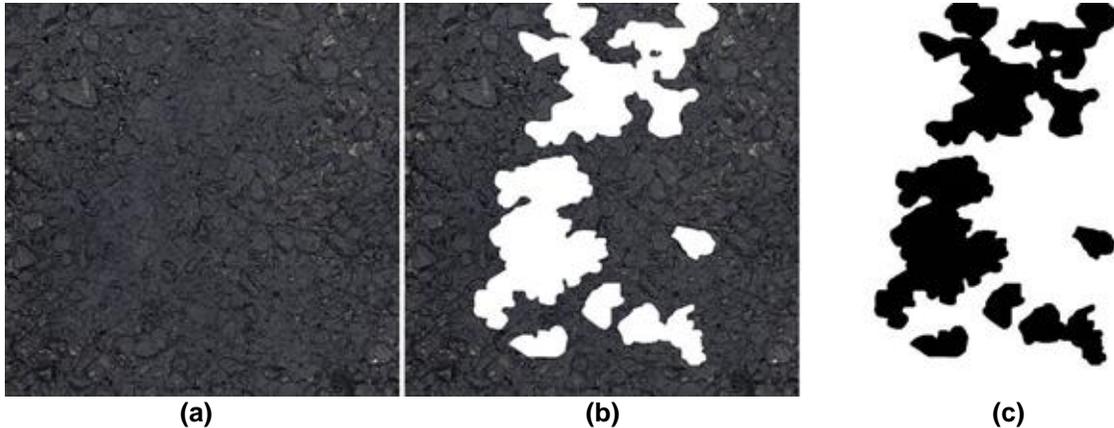


Figure 18 Example of bleeding analysis (SBS CRS-2P with granite 78M aggregate): (a) sample after bleeding test, (b) sample applied bleeding area, and (c) bleeding area

3.4.6.3 Rutting Test

A multiple seal is one of the most commonly used ASTs for high-volume roadways. In general, the multiple seal is comprised of two or three layers, and each layer is constructed by applications of emulsion and aggregate in the same manner as for single seal construction. A well-constructed multiple seal can extend the service life of a pavement longer than a single seal can do. Currently, multiple chip seals are being constructed in North Carolina using both PME (CRS-2L) and CRS-2 emulsions and granite 78M aggregate. In order to reduce aggregate loss, Virginia #9 (or lightweight aggregate) is recommended for the top layer.

In this research, the field test sections were constructed as seven sections of triple seal (granite 78M, granite 78M, and Virginia #9 aggregate used for the bottom, middle, and top

layers, respectively) and three sections of double seal (granite 78M and Virginia #9 aggregate used for the bottom and top layers, respectively). The double seal sections use only the FiberMat Type A emulsion; therefore, it is not possible to compare the triple seal with the double seal directly.

The MMLS3 can be used to test for rutting in chip seal specimens in terms of emulsion type. The rutting test protocol was developed at NCSU (Kim et al. 2005) and involves the following steps:

- 1) Condition the temperature of the specimens to 122°F (50°C) for 3 hours for the rutting test.
- 2) Condition the temperature chamber to 122°F (50°C).
- 3) Apply MMLS3 loading for 6 hours, and measure the profile of the specimens periodically (10, 30, 90, 270, and 360 minutes).

In general, *rutting* (i.e., permanent deformation) is defined as the accumulation of permanent deformation that is not recovered after the traffic load is applied to the pavement. There are two main causes of rutting in pavement. The first cause is the consolidation of the pavement under traffic loading, and the second cause is the lateral movement of the asphalt concrete. These two behaviors can occur separately or simultaneously. Lateral movement occurs in the upper portion of the pavement as a result of shear failure. The chip seal specimens made from both field and laboratory samples are not wide enough (the width of the specimens is only 7 in.) to produce the lateral support to the material under loading. As a result, the lateral movement of the material causes humps (raised areas) outside of the trafficked area. Figure 19 shows the changes in the surface profile due to MMLS3 loading and the resultant humps in a triple seal.

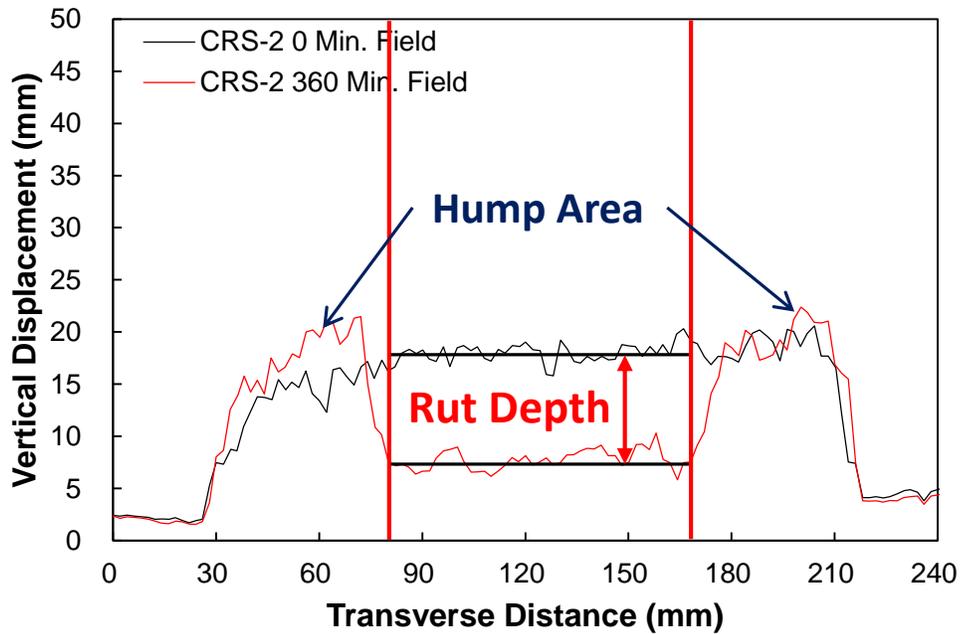


Figure 19 Schematic diagram of a typical cross-section of triple seal

In order to evaluate the rutting behavior of the chip seal specimens, the rut depth is measured periodically (10, 30, 90, 270, and 360 minutes) by the laser profiler during the six-hour tests. The transversal profile is measured three times in the middle of specimen, and 100 mm in both directions from the middle line. Figure 20 shows an actual triple seal specimen after six hours of rutting testing.

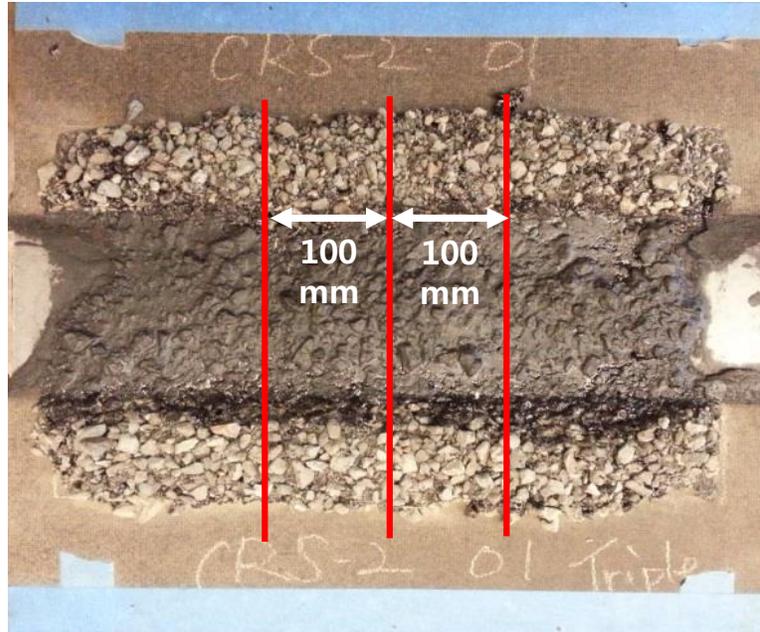


Figure 20 Triple seal specimen after rutting test

In this study, the rut depth is calculated without including the hump area; that is, the rut depth is defined as the difference in surface elevations before and after loading within the wheel path. First, the transversal surface profile measurements obtained from the wheel path area are averaged to determine the original surface elevation. The same method is applied to the surface profiles obtained from the specimens trafficked for 10, 30, 90, 270, and 360 minutes during the entire rutting test. The rut depth is determined from the difference between the average of the profiles at zero traffic time and the average of the profiles from a certain traffic loading time. Figure 19 shows the schematic diagram of this method.

3.4.7 Surface Texture Evaluation

3.4.7.1 Laser Profiler Test

The three-dimensional (3-D) laser profiler, which has been used in previous research, originally included a 3-D line laser capable of scanning an area 97 mm wide and 1,727 mm long during each pass. However, its unwieldy size caused some problems in the field.

Therefore, the NCSU research team developed a portable 3-D laser profiler that can be used both in the field and in the laboratory. In order to analyze the pavement surface texture, only the data obtained from within the wheel path are needed, rather than the entire lane width. After conducting sensitivity analysis, which was conducted also in previous research (HWY-2009-01), approximately 280 mm was determined as the width of the wheel path. The portable laser profiler design includes the following features: XY Gantry robot, encoders, GPS, PC (Windows XP compatible), external USB interface, rubber wheels, touch screen LCD, stowaway handle, carrying handles, graphical user interface (GUI), rechargeable battery, and AC power. The portable laser profiler weighs approximately 100 lbs, and the scan time, although variable, takes about five minutes to complete, which is faster than the previously used Selcom RoLine FP1000 line laser. Figure 21 provides the dimensions and photograph of portable laser profiler.



Figure 21 Portable laser profiler

3.4.7.2 Mean Profile Depth Analysis

The mean profile depth (MPD) is a parameter that represents the exposed texture depth of a pavement surface, and has been used especially for chip seal surface analysis in some of NCSU's researches. The MPD is inversely related to the embedment depth; that is,

as the EAR increases (as applied on a given single aggregate layer), the MPD decreases, and when the EAR is decreased for a given aggregate structure, the MPD will increase. Equation (5) is the definition of MPD given in Transit New Zealand (2005).

$$MPD = \frac{Peak\ level\ (1st) + Peak\ level\ (2nd)}{2} - Average\ level \quad (5)$$

The various chip seal parameters that make up Equation (5) are shown schematically in Figure 22. In the diagram, the MPD clearly indicates the roughness (i.e., macro-surface texture) and aggregate exposure depth of the chip seal. Roughness is an important factor because it provides the skid resistance and friction needed for vehicles to brake adequately. The aggregate exposure depth is important because it is a function of the aggregate embedment depth, which is the most important factor that controls the aggregate loss and bleeding performance of chip seals. A low MPD value indicates the likelihood of bleeding and skid resistance problems. A high MPD value after construction indicates the possibility of excessive aggregate loss and, therefore, bleeding due to aggregate loss. Therefore, a medium MPD value is desirable for optimal performance.

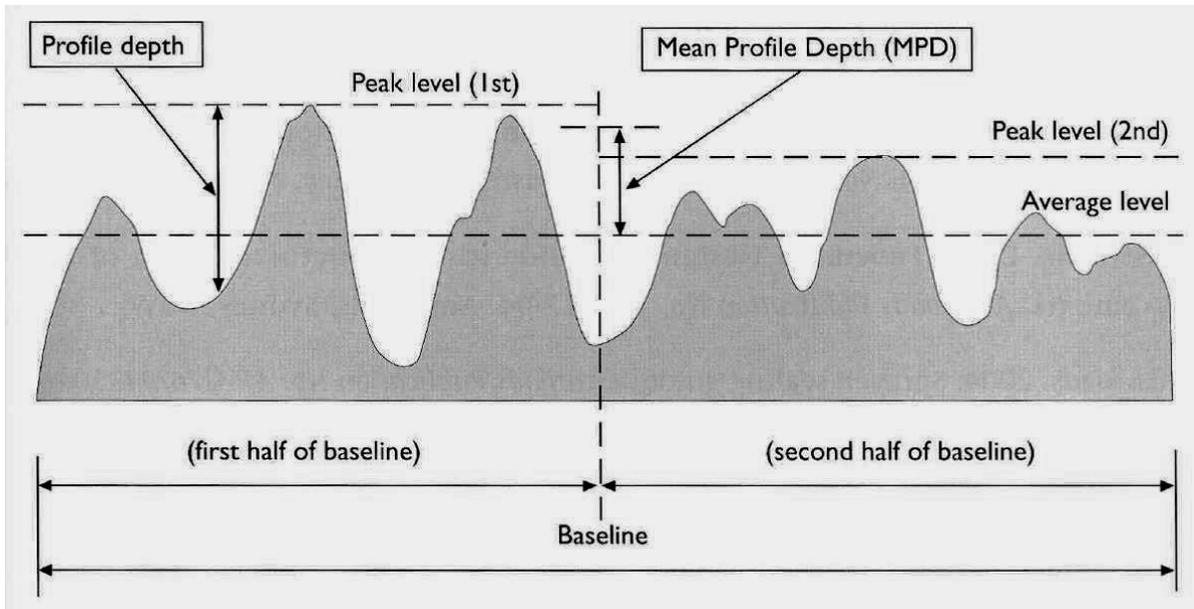


Figure 22 Schematic diagram of MPD determination (Transit New Zealand 2005)

3.4.7.3 Skid Resistance Test

A major advantage of chip seals is the increase in skid resistance that they provide. The textural depth created by chip seals allows for improved contact and adhesion between a vehicle's tires and the road surface, thereby increasing road safety. However, a fog seal on top of a chip seal surface decreases the skid resistance, especially when too much emulsion is applied. It is, therefore, important to include skid resistance as one of the performance characteristics of fog seals. Two testing subsets are available for determining a pavement's skid resistance – textural and drag testing.

As part of the FHWA/NC/2005-15 research, a comprehensive review of these two skid resistance test methods was conducted. This review included not only the technical soundness of the test method, but also the equipment availability, ease of the test procedure, and the quality of its performance in previous research. Although textural test methods are simpler in nature than drag test methods, more reliable results can be obtained from drag testing whereby the skid resistance of a pavement surface can be measured directly. The review concluded that the locked-wheel skid test (LWST) and BPT are the most reliable

means of measuring the skid resistance of the surface treatment.

The LWST is used extensively to measure pavement friction in accordance with ASTM E 274 *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. Once water is sprayed onto the test pavement as 10 to 18 inches (250 to 450 mm) in front of the tester axes through the centerline of the wheel, the wheel is locked for 1 second, and the frictional force is measured. At this point, the operational speed is restricted to between 40 mph and 60 mph. According to the LWST procedure, the skid number (SN) is calculated by dividing the horizontal force by the vertical load and then multiplying by 100 to obtain a whole number. The range for SNs is between 0 and 100.

The BPT is widely used for laboratory skid resistance testing and is specified by ASTM E 303 *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. A pendulum swings across the pavement or sample surface, and then the height the pendulum traveled is measured by a drag pointer on the device. The drag pointer indicates the British pendulum number (BPN), and the average BPN is calculated from four swings of the pendulum for each test surface. The range for BPNs is from 0 to 140. Figure 23 shows the LWST and BPT apparatus.



Figure 23 Equipment for the: (a) LWST and (b) BPT

Because the LWST cannot be performed in the laboratory, the relationship between

the SNs obtained from the LWST and the BPNs obtained from the BPT is helpful to know. During the FHWA/NC/2005-15 research, Mr. Jerry Blackwelder, with the help of the NCSU research team, conducted BPT and LWST tests for about a dozen surface treatment researches in the fall of 2004. The resultant data were used to develop the relationship between the SN and BPN so that BPNs measured from laboratory experiments could be converted to SNs in the field. This relationship can be seen in Figure 24.

In this research, the BPT is used to determine the skid resistance of fog seals with varying rates of emulsion. In addition, the textural test method, which is based on laser profiling, is used to develop the relationship between the aggregate exposure depth and the skid resistance.

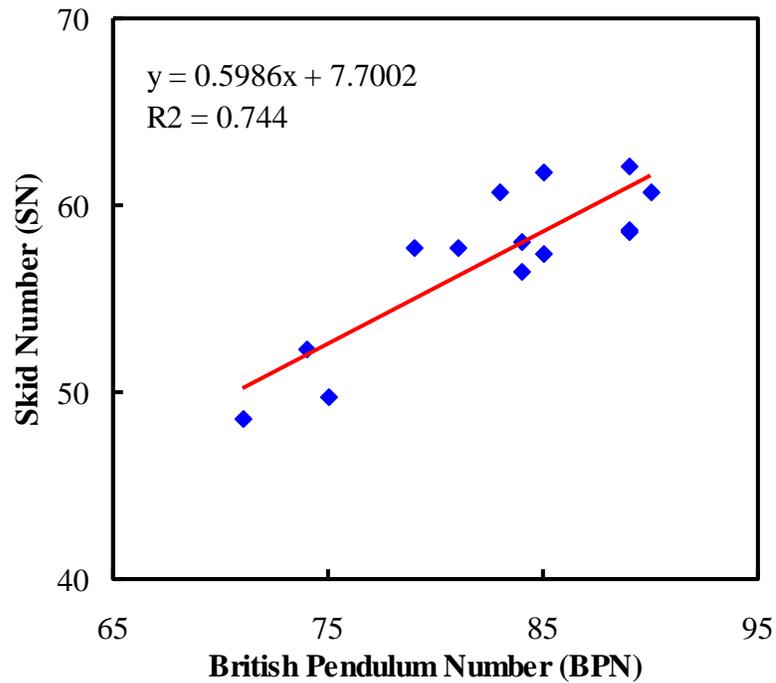


Figure 24 Correlation between average BPN and average SN

3.4.8 Fog Seal Field Test Evaluation

3.4.8.1 Rolling Ball Test

Field test methods should be simple so that they can be implemented quickly, and field test equipment should be portable for use in the field. The rolling ball test meets these criteria, whereby a ball is rolled across an emulsified surface. This method is standardized in ASTM D 3121: *Standard Test Method for Tack of Pressure-Sensitive Adhesives by Rolling Ball*. Specifically, in order to determine the viscosity of an emulsion, a steel ball is released from the top of an incline such that it rolls onto a horizontal surface that is applied with emulsion. The viscosity is determined by measuring the distance that the ball travels across the emulsified surface before stopping. This method was developed for materials that are more adhesive than fog seal emulsion, so the size of the equipment and samples had been modified in order for the test setup to be suitable for testing fog seal emulsion.

In the ASTM standard specifications, the inclined ball stand is 65 mm in height and its angle is 21°30'. However, when the specified equipment size was used to test the viscosity of the fog seal emulsion, the traveling distance of the ball was too long to capture within the range of the equipment setup. Therefore, the height of the inclined ball stand has been changed to 15 mm, and the equipment size has been modified to 320 mm long and 50 mm wide, as determined by running a few trial tests. In order to maintain a level surface during curing and testing, a steel plate was used for the horizontal portion of the test setup, and an asphalt felt disk, which is normally used for chip seal laboratory samples, was attached to the steel plate. Four walls were constructed around the steel plate to prevent the fog seal emulsion from flowing off the plate. Figure 25 shows the modified rolling ball test equipment and emulsion samples.



Figure 25 Rolling ball test: (a) side view and (b) plane view

During this testing, when the ball passed the end of the emulsion sample, its distance was recorded as 300 mm. The rolling ball test procedure is as follows:

- 1) Prepare the emulsion by diluting it with water.
- 2) Prepare the sample mold that is 320 mm long and 50 mm wide.
- 3) Heat the fog seal emulsion to $60 \pm 2^\circ\text{C}$, and heat the sample mold to 30°C .
- 4) Fill the molds with fog seal emulsion, and keep the steel plate level.
- 5) Cure the samples for a specified amount of time.
- 6) Release the ball from the ball stand three times for one condition.
- 7) Measure the distance in millimeters.

3.4.8.2 Damping Test

The damping test has been developed based on a concept introduced by *Road Science LLC* that is the test method for tracking emulsion and aggregate. Briefly, the purpose of this test method is to indicate, under standard conditions, the propensity of a fog seal emulsion to track or peel under traffic loading when applied at a specified application rate after a specified curing time using a wheel tracking device over the chip seal specimen. As stated previously, field test methods should be simple in design, and the test equipment should be portable for use in the field. Thus, the damping test method has been developed for use in the

field. One kilogram of dead weight was applied to the emulsion samples for 15 seconds instead of using a wheel tracking device, and absorbent pads were used between the emulsion samples and dead weight to enable visible results that serve to verify the curing status of the fog seal emulsions. In addition, the digital image processing (DIP) technique was utilized to express the visible results numerically.

As an initial attempt, filter paper that is used in the gyratory compactor for asphalt mix design was used in the testing, but the paper tore easily in many cases. In order to prevent such damage, cotton cloth also was tested, but no standard specifications are available to suggest a specific type of cloth for the damping test. For these reasons, the idea of using filter paper or cotton cloth was discarded, and an idea of use absorbent pads that normally are used for cleaning spills on land and water was found. Specifically, absorbent pads that are classified as standard melt-blown pads and produced by Chemtex, Inc. were selected for this test. The pads are 100% polypropylene, and their absorbent capacity is 36 gallons per bale, which is equivalent to 0.18 gallon per piece. The size of one piece of absorbent pad is 15 inches wide and 19 inches long. One piece was cut into separate pieces five centimeters by five centimeters, and then used for the damping test.

In order to select an appropriate dead weight and application time, 1kg, 3kg, and 5 kg of dead weight were applied on emulsion samples for 10, 15, 60, 180, and 300 seconds. In many cases, the heavier weights and longer times damaged the absorbent pads. As a result of the trial tests, one kilogram of dead weight and 15 seconds were selected as the application criteria. The damping test device can be seen in Figure 26.

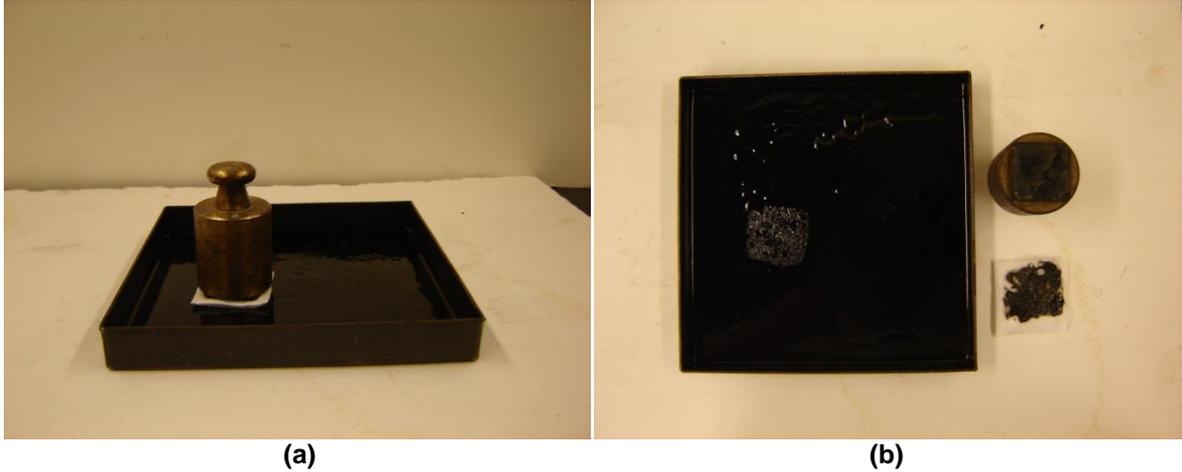


Figure 26 Damping test: (a) applied dead weight and (b) after testing

The damping test was conducted in an environmental chamber to maintain the temperature during curing and testing. The steps for the damping test are:

- 1) Prepare the emulsion by diluting it with water.
- 2) Prepare 5 cm by 5 cm absorbent pads.
- 3) Heat the fog seal emulsion to $60 \pm 2^\circ\text{C}$, and heat the Vialit plates to 30°C .
- 4) Fill the molds with fog seal emulsion, and keep the samples level.
- 5) Cure the samples for a specified amount of time.
- 6) Place the absorbent pads onto the emulsion samples.
- 7) Place 1 kg of dead weight onto the absorbent pads for 15 seconds in the environmental chamber.
- 8) Detach the absorbent pads from the emulsion samples.
- 9) Analyze the stained pads using DIP.

The curing rates for the fog seal emulsions can be quantified employing DIP. During the damping test, the absorbent pad is stained by the emulsion, and then the pad's surface is scanned using a Hewlett Packard digital scanner (HP Scanjet 4850) as a color BMP file with a resolution of 200 dpi. The digital image then is converted from a color scale to an 8-bit grayscale that consists of a single plane of pixels. Each pixel is encoded using a single number representing grayscale intensity values (GIVs) from 0 to 225. The grayscale image

was cut down to 3.51 cm by 3.51 cm to 276 pixels in width and 276 pixels in height to maintain consistency for the size of the image pixels.

Figure 27 shows that the absorbent pads used for the damping test contain one or two holes in them as a result of the production process of the pads. In addition, even emulsion cured for 24 hours produces only a small amount of stain on the pads. Thus, acknowledging the holes in the pads and the small amount of stain on the pads is important in the analysis of the stained areas. The technique called *thresholding* in DIP was incorporated into this analysis using National Instruments Vision Assistant (NIVA) 7.0. The thresholding procedure is conducted by setting all the pixels that belong to the threshold interval to 1, and setting all the other pixels in the digital image to zero. After finding a critical threshold value, MATLAB[®] R2007a is utilized for the analysis of the stained areas. The value of 190 is set in the program as a threshold value, and then a grayscale image with GIVs ranging from 0 to 255 is converted into a binary image (black and white), which means a GIV of 0 or 1. The number or percentage of stained pixels can be calculated by adding together all the pixels with a GIV of 0 or 1.

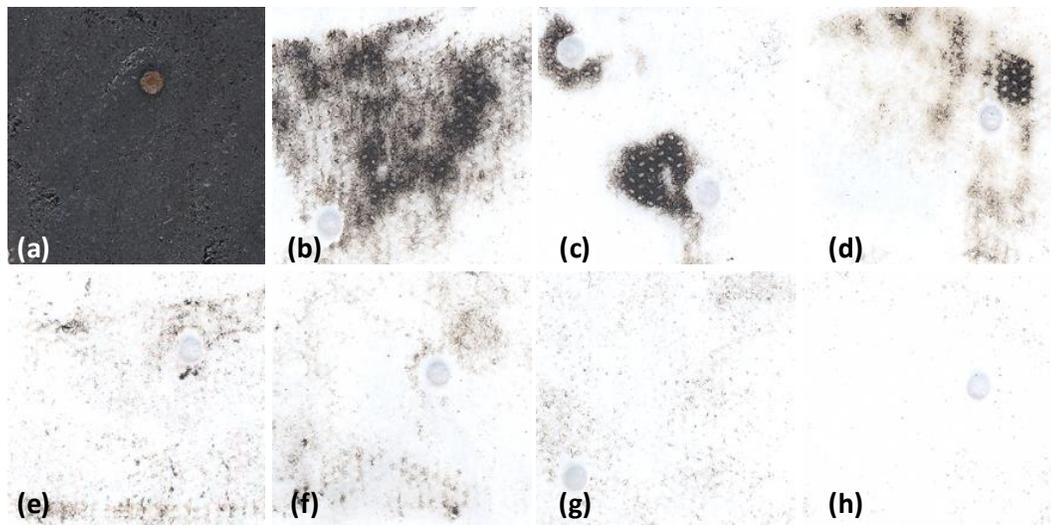


Figure 27 Examples of stained pads for damping test at 30°C: (a) 100%, (b) 44.1%, (c) 10.5%, (d) 6.5%, (e) 3.5%, (f) 2.4%, (g) 1.5%, and (h) 0.1%

4. LABORATORY EVALUATION OF AST PERFORMANCE

4.1 Chip Seal Performance

4.1.1 *Curing Time Study*

4.1.1.1 *Evaporation Test*

The evaporation test is used to help determine the emulsion curing time, and the NCSU research team conducted this test at curing temperature of 35°C. The testing was conducted to determine the curing time required for each test emulsion to reach its asymptotic percentage of water loss, that is, the point at which no more water loss occurs. This determination allows for a direct comparison of the curing characteristics of all four emulsions: CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P. For the tests, all four emulsions were exposed to the same conditions; i.e., each was placed in a 90 mm diameter container and subjected to the same EAR of 0.25 gal/yd² (1.13 L/m²). Figure 28 shows a comparison of the CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions in terms of water loss versus time.

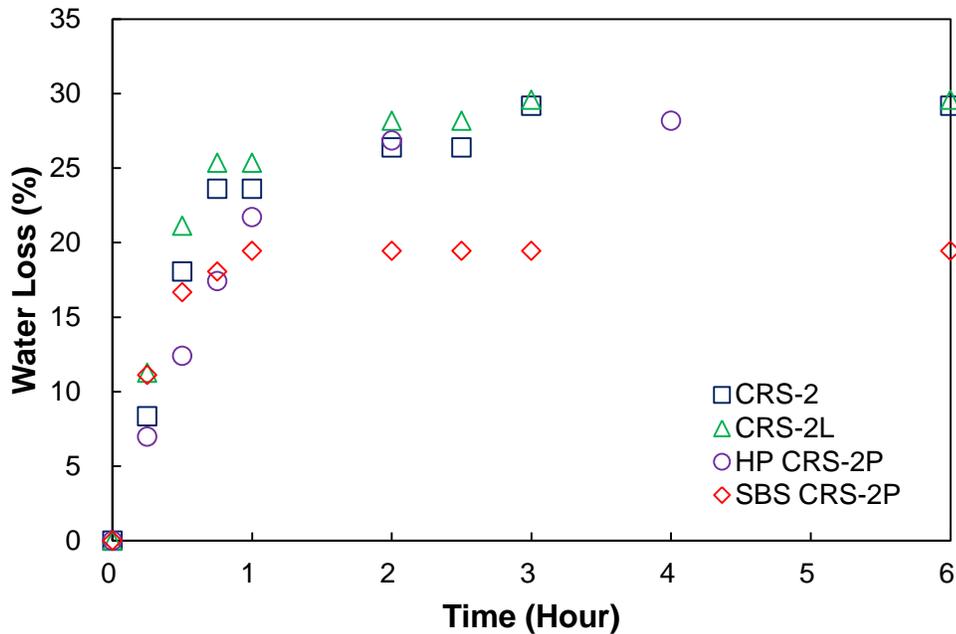


Figure 28 Curing comparison of CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions

Figure 28 indicates that the SBS CRS-2P emulsion reaches its asymptotic final percentage of water loss (curing) the fastest of all the emulsion types. It reaches its asymptotic curing value in approximately an hour, and the HP CRS-2P emulsion reaches its asymptotic curing value in two hours. Both the CRS-2 and CRS-2L emulsions reach their asymptotic curing values at around three hours. Thus, in this test, the SBS CRS-2P emulsion cures about two times faster than the HP CRS-2P emulsion and about three times faster than the CRS-2 and CRS-2L emulsions.

4.1.1.2 BBS Test

The bond strength of emulsions is one of the most important factors that are needed to understand the curing and adhesive behavior of chip seals. The bond strength is determined at different curing times and temperatures. The BBS test was employed for this purpose and conducted with all the emulsion types and aggregate types under the same condition. The CRS-2 emulsion was used as the unmodified emulsion, and the CRS-2L, SBS CRS-2P, and HP CRS-2P emulsions were employed as PMEs. The granite and lightweight rocks were

prepared as aggregate substrates by cutting and sanding. The BBS test was planned to conduct at three curing times (45, 120, and 240 minutes), and a few specimens were tested at three curing times. However, in order to capture the early bond strength, the BBS test was performed at four curing times (30, 60, 120, and 240 minutes) for both lightweight and granite aggregate substrates at three curing temperatures (15°C, 25°C, and 35°C). All the BBS tests were conducted in an environmental chamber to maintain the temperature during curing and testing. Three replicates were tested for each temperature and application rate combination.

Figure 29 (a), (b), and (c) show the bond strength values at different curing times (30, 45, 60, 120, and 240 minutes) using all the emulsions and granite aggregate types at 35°C, 25°C, and 15°C. Figure 30 (a), (b), and (c) show the bond strength values at different curing times (30, 45, 60, 120, and 240 minutes) using all the emulsions and lightweight aggregate types at 35°C, 25°C, and 15°C.

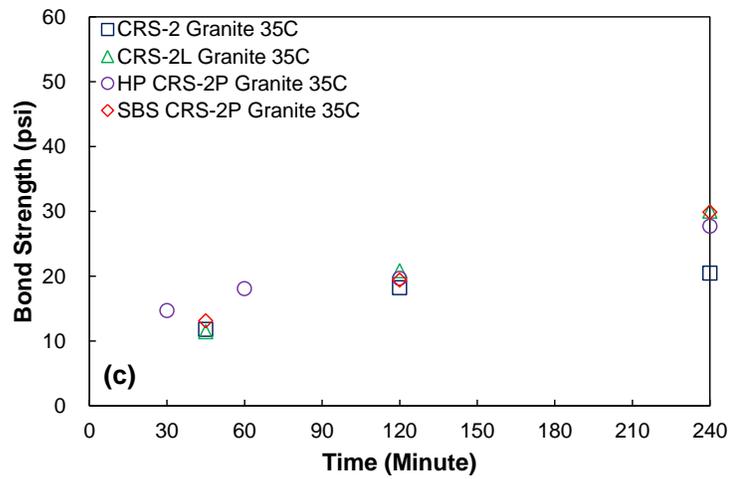
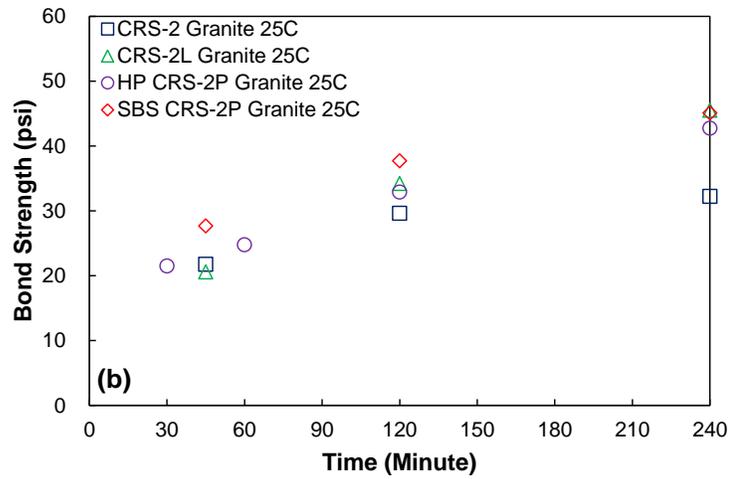
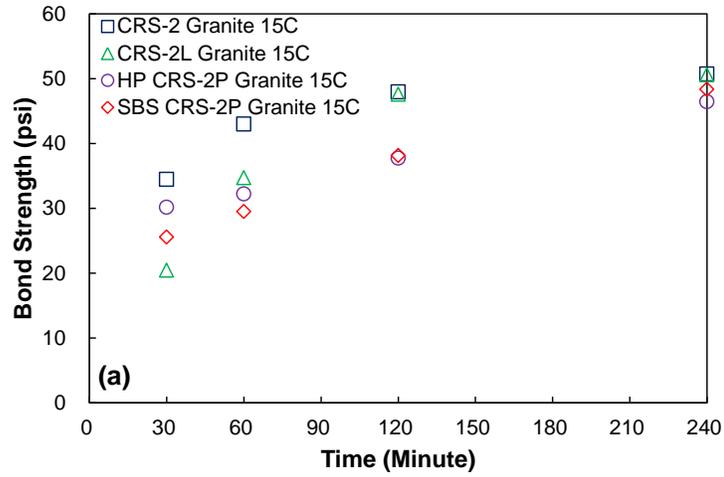


Figure 29 Bond strength versus curing time for granite aggregate types at: (a) 15°C, (b) 25°C, and (c) 35°C

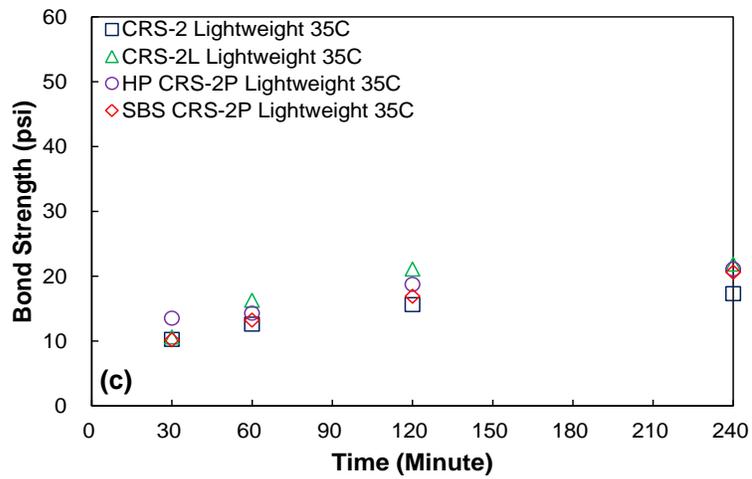
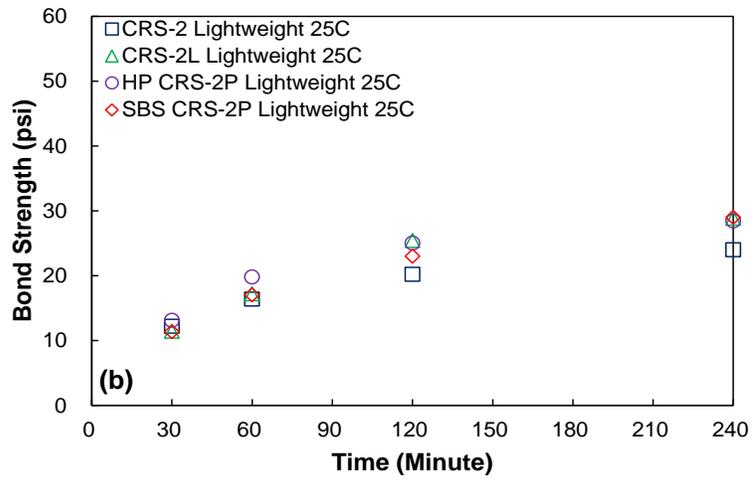
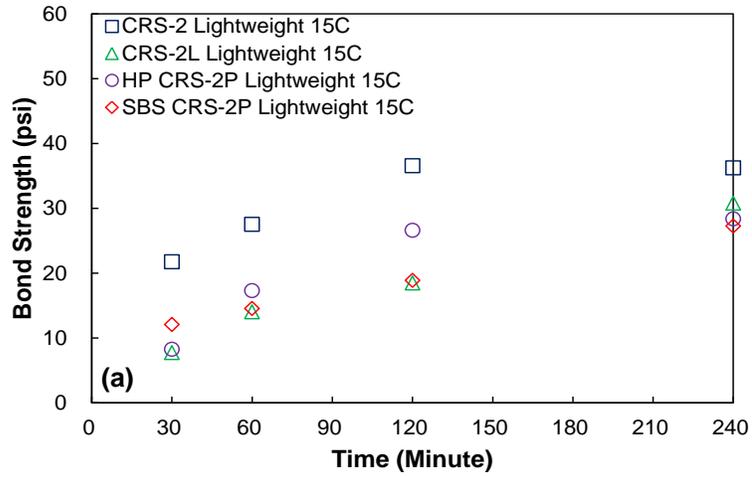


Figure 30 Bond strength versus curing time for lightweight aggregate types at: (a) 15°C, (b) 25°C, and (c) 35°C

From Figure 29 and Figure 30, as expected, the PME's show better bond strength than the CRS-2 emulsion at 35°C and 25°C, even though there is not much difference in the bond strength values at 35°C. In contrast, at 15°C, the PME's show less bond strength than the CRS-2 emulsion. The behavior of the CRS-2 emulsion was not expected, so the CRS-2 and SBS CRS-2P emulsions were tested again at 15°C in order to eliminate the possibility of mistakes in the test procedure. The results of these tests indicate that the bond strength values are similar to the previous results at the different curing temperatures, which suggests that no mistakes or errors in the test protocol were made in the BBS testing.

This unexpected behavior at 15°C seems to be related to the contact area between the pull-off stubs and aggregate substrate, and to be dependent on the test temperature. The test temperature may affect the viscosity of the emulsion, and the viscosity will then affect the penetration of the emulsion into the voids in the aggregate substrate. For the BBS test, it is important to maintain the same contact areas in order to compare the bond strength values directly, because a smaller contact area produces less bond strength when the same load is applied to the specimen. The porosity of the aggregate substrate can affect the bond strength because air can be trapped in the surface voids when the emulsion is poured (Moraes et al., 2011). As a result, the contact area of the lightweight aggregate substrate with surface pores is smaller than the standardized area (20mm diameter).

In order to measure the actual contact area, the digital image processing (DIP) technique that is used for bleeding analysis was applied. The lightweight aggregate substrates were scanned using a Hewlett Packard digital scanner (HP Scanjet 4850) as a color 'bit map' (BMP) file with a resolution of 200 dpi. The digital image then was converted from a color scale to an 8-bit grayscale that consists of a single plane of pixels. Each pixel was encoded using a single number that represents a grayscale intensity value (GIV) from 0 to 225. The technique called *thresholding* in DIP was incorporated into this analysis using National Instruments Vision Assistant (NIVA) 7.0. The threshold procedure was conducted by setting all the pixels that belong to the threshold interval to one, and setting all the other pixels in the digital image to zero. Figure 31 shows the digital images of a color image, grayscale image, and DIP analysis.

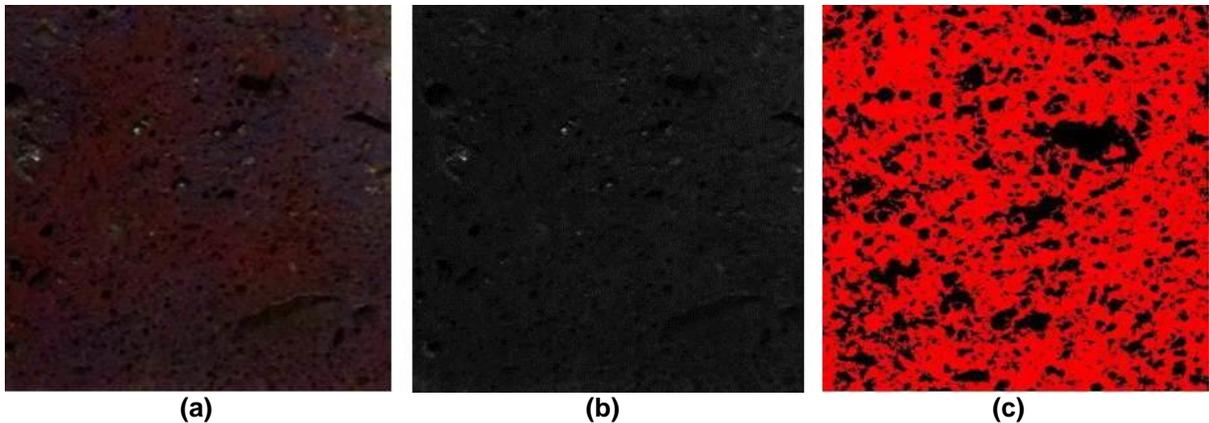


Figure 31 Digital images of lightweight aggregate surface: (a) color, (b) grayscale, and (c) DIP analysis

As a result of the DIP analysis, 65.9% of the lightweight aggregate surface was determined to be an actual contact area. The BBS values were recalculated using the actual contact area, and the results were analyzed. However, even though the modified BBS values of the lightweight aggregate samples increased, the actual contact area, 65.0%, cannot be employed for different test temperatures and emulsion types because the viscosity of emulsions differs, depending on the temperature and emulsion type, and the different viscosities can affect the contact area between the pull-off stubs and aggregate substrate. Based on these findings, the research team decided that the comparison of the BBS values should be done within the same aggregate substrate types.

4.1.1.3 Vialit Test

The Vialit test was performed to determine the adhesive behavior of the seal specimens at different curing times and at different curing temperatures to evaluate their aggregate retention performance. The test procedure involves fabricating single-seal specimens that are then placed in the oven at a certain curing temperature for specified curing times that are determined based on the results of the curing by weight tests for each emulsion. Four replicates were fabricated for each condition to assure confidence in the resultant data. All the specimens were fabricated with AARs of 16 lb/yd² (8.7 kg/m²) for the granite 78M aggregate and 7 lb/yd² (3.8 kg/m²) for the lightweight aggregate. For all the specimens of

both aggregate types, an EAR of 0.25 gal/yd² (1.13 L/m²) was applied for the CRS-2, CRS-2L, SBS CRS-2P, and HP CRS-2P emulsions.

In the field, chip seals used to be constructed at various temperatures except winter season. For instance, the Minnesota Seal Coat Handbook (2006) recommends pavement and air temperatures to be 15.5°C or higher, and the Maintenance Technical Advisory Guide (2003) suggests 10°C as the lowest temperature. Therefore, the NCSU research team decided to investigate the effects of aggregate retention performance at temperatures lower than 25°C even though the research proposal suggests only 25°C and 35°C as curing temperatures. According to the evaporation test results, all four test emulsions cure within four hours; therefore, the NCSU research team decided to use four hours as the maximum curing time. The Vialit test was conducted for both lightweight and granite 78M aggregate specimens at four curing times (30, 60, 120, and 240 minutes) and three curing temperatures (15°C, 25°C, and 35°C), and testing included the sweep process. Figure 32 shows the Vialit test results as percentages of aggregate loss at the different curing times for all four emulsion types and both aggregate types at 15°C, 25°C, and 35°C.

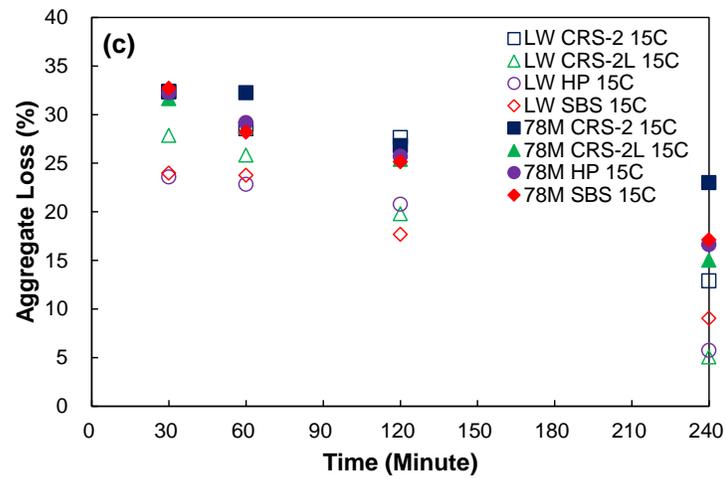
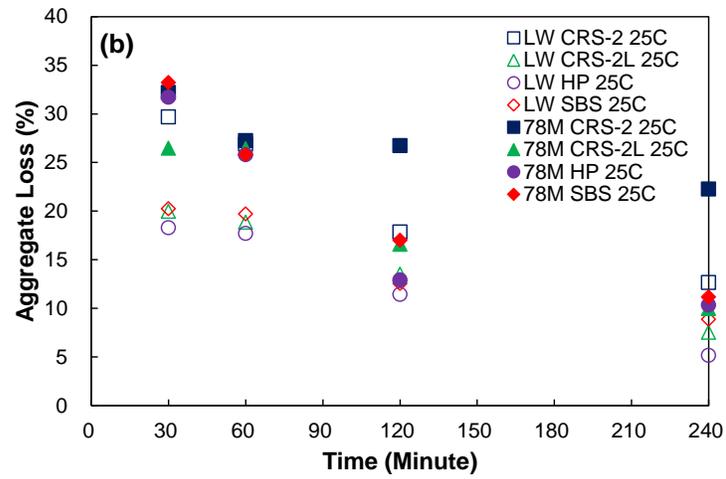
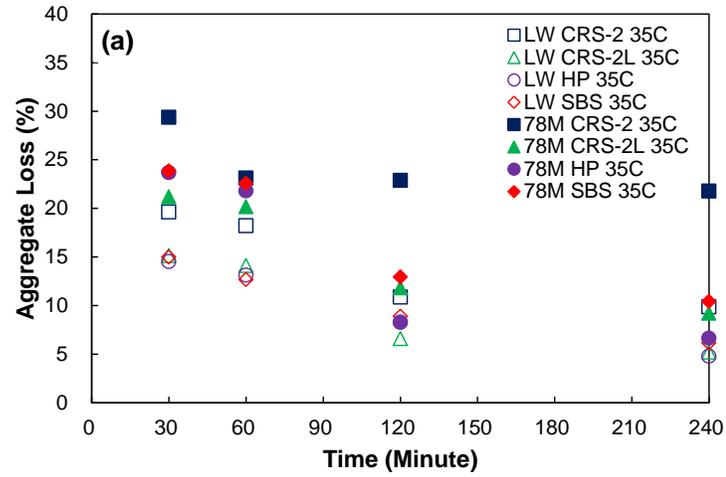


Figure 32 Adhesive behavior at different curing times and at (a) at 35°C, (b) 25°C, and (c) 15°C

Figure 32 (a), (b), and (c) show that the granite 78M aggregate specimens are more prone to aggregate loss than the lightweight aggregate specimens at all curing temperatures. As expected, the CRS-2 unmodified emulsion always shows the worst aggregate retention performance (more aggregate loss) at the same temperatures for both aggregate types. As for the PMEs, the SBS CRS-2P emulsion shows slightly more aggregate loss at four hours of curing than the CRS-2L and HP CRS-2P emulsions, but the aggregate retention performance of the three PMEs does not differ significantly.

The data in Figure 32 are replotted in Figure 33 to show the effects of different curing temperatures for the same emulsion type in terms of aggregate retention performance.

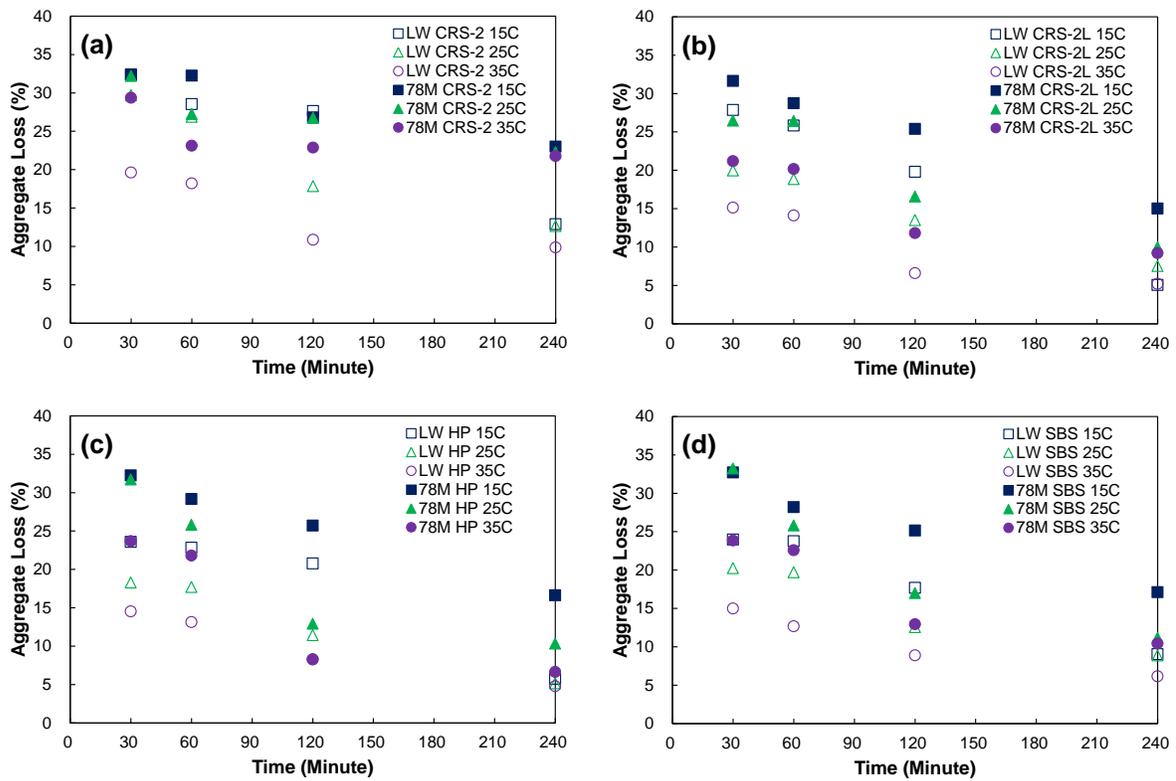


Figure 33 Adhesive behavior at different curing temperatures for: (a) CRS-2, (b) CRS-2L, (c) HP CRS-2P, and (d) SBS CRS-2P

Figure 33 (a), (b), (c), and (d) show that low curing temperatures cause more aggregate loss for both the lightweight and granite 78M aggregate than the high curing

temperatures. The reason for this result is that at the higher temperatures the emulsion is more fluid, and this emulsion state allows the aggregate particles to be reoriented in a manner that maximizes the embedment depth in the compaction state and improves aggregate retention. As expected, a direct relationship is found between the curing temperature and aggregate loss results, regardless of emulsion type.

At four hours of curing, the lightweight aggregate specimens show similar aggregate retention performance for each emulsion type, regardless of curing temperature. However, the granite 78M aggregate specimens cured at 15°C show more aggregate loss than the specimens cured at 25°C and 35°C, except for the CRS-2 emulsion specimens, which present similar aggregate retention performance for each curing temperature. These findings suggest that the curing temperature of 15°C is too low for the Vialit specimens made of granite aggregate to be completely cured within four hours. For field construction, warm weather is necessary for chip seals to achieve sufficient aggregate retention performance.

4.1.1.4 Correlation between BBS and Aggregate Loss by Vialit Test

In order to understand the aggregate retention performance of chip seals, the basic mechanisms, i.e., curing and adhesive behavior, have been evaluated as a function of temperature and time by performing the BBS and Vialit tests. Both test results suggest the aggregate retention performance of the different emulsion and aggregate types, but comprehensive analysis of the bond strength and aggregate loss plays a vital role in validating the effects of both properties on the aggregate retention performance.

A correlation between bond strength and aggregate loss has been established by comparing the bond strength obtained by the BBS test to the aggregate loss measured by the Vialit test at different curing temperatures (15°C, 25°C, and 35°C) and curing times (60, 120, and 240 minutes).

Figure 34 (a), (b), and (c) show the correlation between the bond strength and the aggregate loss obtained by the Vialit test for the granite aggregate. Figure 35 (a), (b), and (c) show the correlation between the bond strength and the aggregate loss obtained by the Vialit test for the lightweight aggregate.

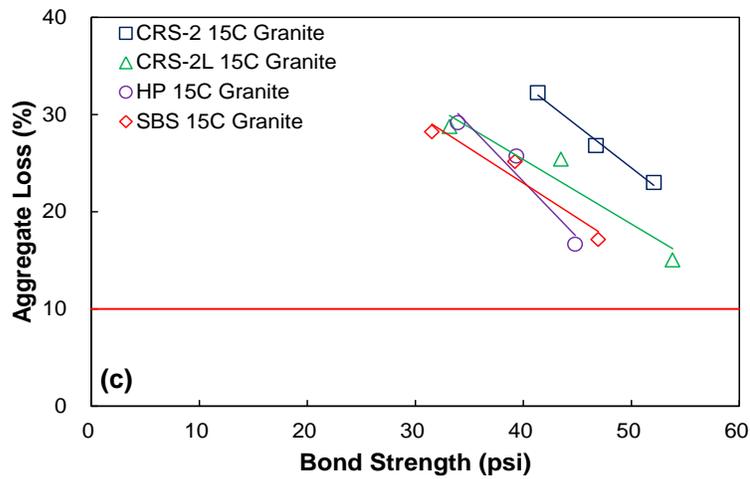
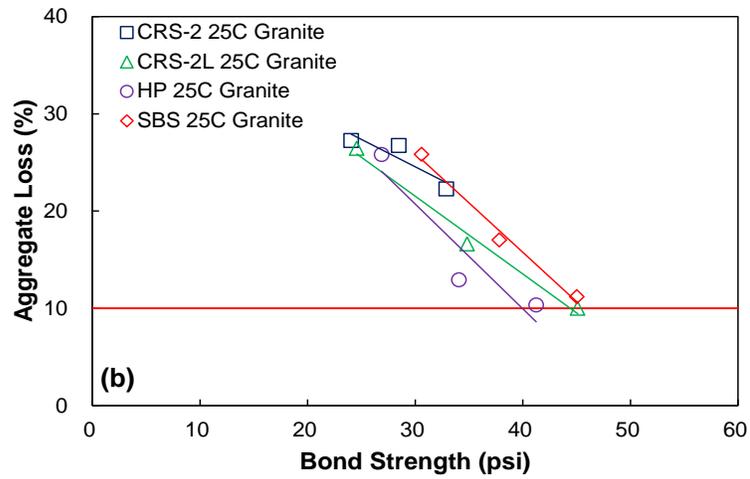
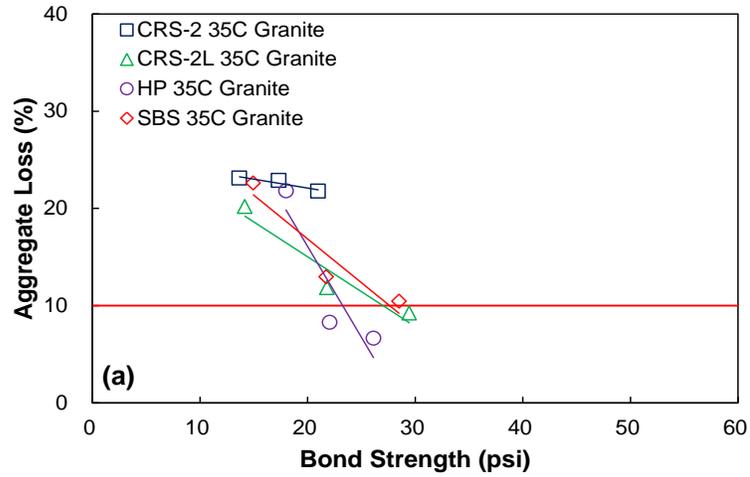


Figure 34 Correlation between bond strength and aggregate loss from Vialit test for granite aggregate at: (a) 35°C, (b) 25°C, and (c) 15°C

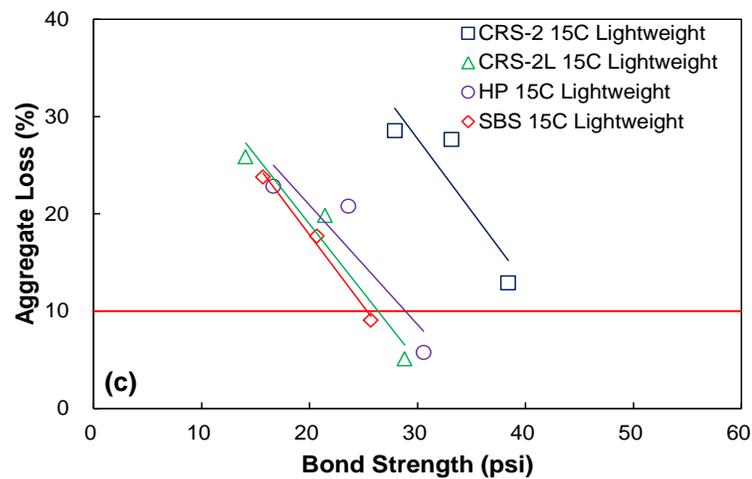
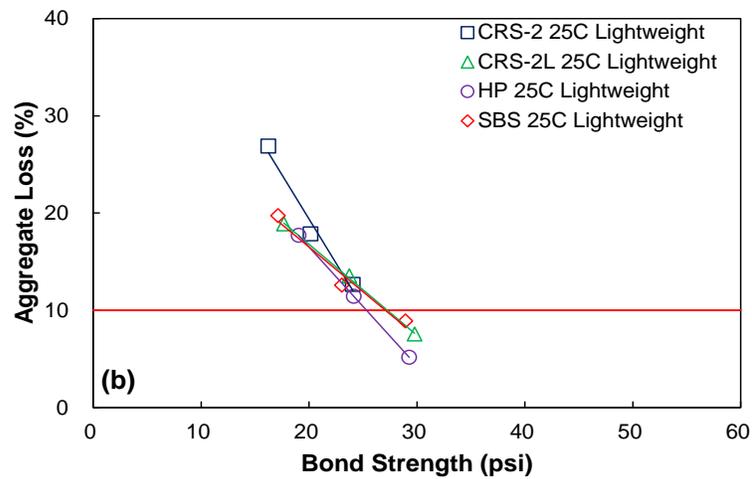
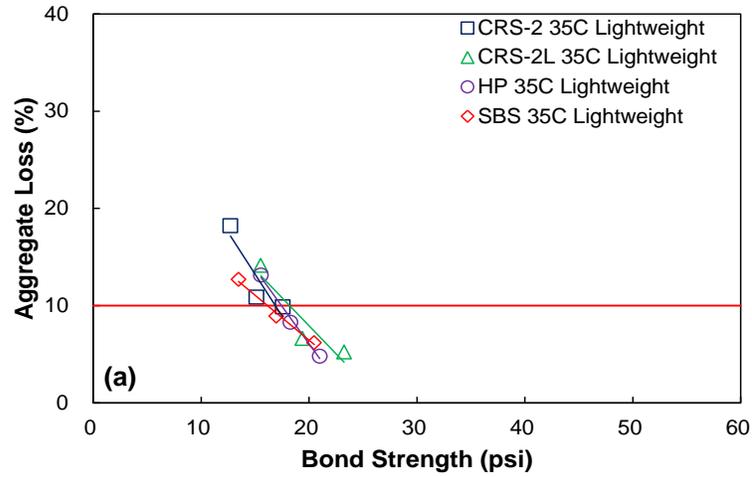


Figure 35 Correlation between bond strength and aggregate loss from Vialit test for lightweight aggregate at: (a) 35°C, (b) 25°C, and (c) 15°C

Table 11 and Table 12 show the potential BBS limits as obtained from using the linear model that determines the correlation between the BBS and aggregate loss for the granite aggregate and for the lightweight aggregate, respectively.

Table 11 Potential BBS Limit Obtained from Linear Model Using the Correlation between BBS and Aggregate Loss for Granite Aggregate

Emulsions		CRS-2	CRS-2L	HP CRS-2P	SBS CRS-2P
35 °C	Linear Model	y = -0.0018x + 0.258	y = -0.0072x + 0.294	y = -0.0187x + 0.534	y = -0.009x + 0.349
	BBS Limit psi (kPa)	87.6 (604.0)	26.9 (185.5)	23.2 (160.0)	27.6 (190.3)
25 °C	Linear Model	y = -0.0056x + 0.415	y = -0.008x + 0.456	y = -0.0108x + 0.530	y = -0.0102x + 0.564
	BBS Limit psi (kPa)	56.2 (387.5)	44.4 (306.1)	39.8 (274.4)	45.5 (313.7)
15 °C	Linear Model	y = -0.0086x + 0.676	y = -0.0066x + 0.519	y = -0.0115x + 0.692	y = -0.0072x + 0.517
	BBS Limit psi (kPa)	67.0 (462.0)	63.5 (437.8)	51.5 (355.1)	57.8 (398.5)

Table 12 Potential BBS Limit Obtained from Linear Model Using the Correlation between BBS and Aggregate Loss for Lightweight Aggregate

Emulsions		CRS-2	CRS-2L	HP CRS-2P	SBS CRS-2P
35 °C	Linear Model	y = -0.0172x + 0.390	y = -0.0115x + 0.310	y = -0.0153x + 0.367	y = -0.0093x + 0.250
	BBS Limit psi (kPa)	16.9 (116.5)	18.3 (126.2)	17.4 (120.0)	16.2 (111.7)
25 °C	Linear Model	y = -0.0181x + 0.557	y = -0.0093x + 0.355	y = -0.0122x + 0.410	y = -0.0103x + 0.366
	BBS Limit psi (kPa)	25.2 (173.8)	27.4 (188.9)	25.4 (175.1)	25.8 (177.9)
15 °C	Linear Model	y = -0.0149x + 0.723	y = -0.0147x + 0.480	y = -0.0123x + 0.454	y = -0.0147x + 0.473
	BBS Limit psi (kPa)	41.8 (288.2)	25.9 (178.6)	28.8 (198.6)	25.4 (175.1)

In Figure 34 for the granite aggregate, the CRS-2 emulsion specimens are always over the limit of 10% aggregate loss as measured by the Vialit tests. Also, all emulsion specimens at 15°C are over the limit. It can be said that the CRS-2 emulsion with the granite aggregate and all emulsions types with the granite aggregate at 15°C do not exhibit sufficient aggregate retention performance within four hours. In Figure 35 for the lightweight aggregate, the CRS-2 emulsion specimens at 15°C and 25°C are over the limit. Based on the relationship, the lightweight aggregate shows better aggregate retention performance and curing behavior, but the bond strength values of the lightweight aggregate are lower than those of the granite aggregate due to the smaller actual contact area between aggregate surface and emulsion.

4.1.2 *Chip Seal Performance Test*

4.1.2.1 *Aggregate Retention Performance*

The MMLS3 aggregate retention tests and bleeding tests were conducted with the CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsion samples. For the aggregate retention tests, all samples were cured at 35°C for 24 hours and tested at 25°C, which is the MMLS3 testing protocol. Six replicates were fabricated for each of the four emulsion types: CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P. After the aggregate retention tests, those same samples were used for the bleeding tests. Figure 36 shows the results of the aggregate loss tests for the granite 78M and lightweight aggregates, respectively. Each data point represents the percentage of the average cumulative aggregate loss for the different conditions.

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in aggregate retention performance between the CRS-2 emulsion and the PMEs. Table 13 summarizes the results of the statistical analysis for the emulsion types. The p-values of the HP CRS-2P and SBS CRS-2P emulsions with the granite 78M aggregate are less than 0.05. Thus, the MMLS3 test results indicate that these two emulsion types (HP

CRS-2P and SBS CRS-2P) with the granite 78M aggregate differ statistically from the CRS-2 emulsion in terms of aggregate retention performance.

Table 13 Results of Statistical Analysis for Emulsion Types: Aggregate Retention Performance of Laboratory Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
Granite 78M aggregate							
CRS-2	11.5	1.5	1.2	0.50			
CRS-2L	10.1	8.5	2.9	1.19	1.11	0.146	Accept H ₀
HP CRS-2P	8.6	11.7	3.4	1.40	1.98	0.048	Reject H ₀
SBS CRS-2P	8.5	13.7	3.7	1.51	1.91	0.049	Reject H ₀
Lightweight Aggregate							
CRS-2	5.0	10.2	3.2	1.31			
CRS-2L	3.2	0.2	0.5	0.20	1.32	0.121	Accept H ₀
HP CRS-2P	3.3	4.7	2.2	0.88	1.07	0.156	Accept H ₀
SBS CRS-2P	4.5	2.0	1.4	0.58	0.33	0.375	Accept H ₀

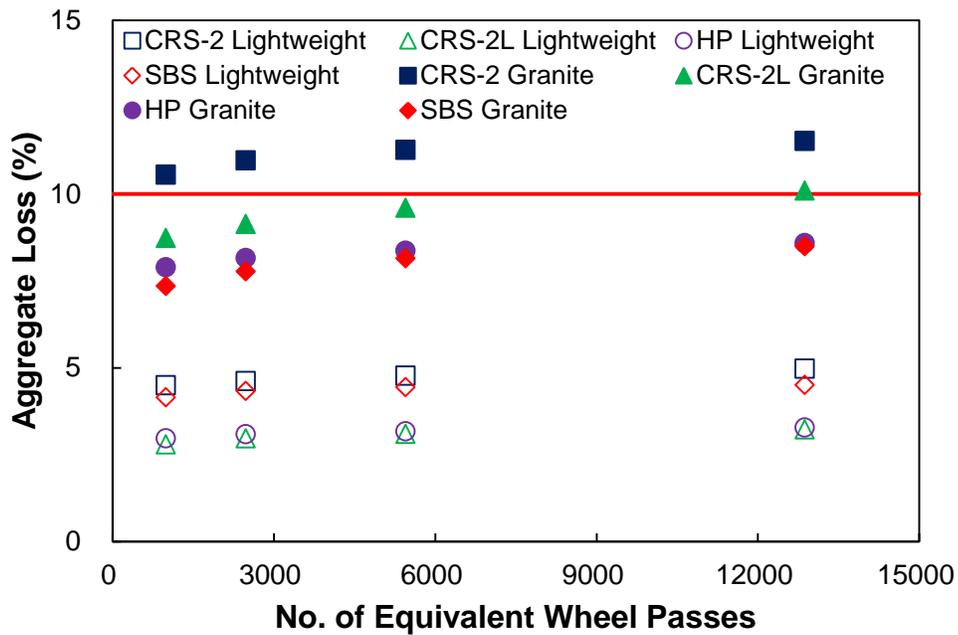


Figure 36 Aggregate loss performance by MMLS3 test

Figure 36 also shows that the CRS-2 unmodified emulsion samples perform the worst of all the emulsion types; in particular, the samples of CRS-2 emulsion with the granite 78M aggregate show approximately 12% aggregate loss after MMLS3 loading. This result can be considered to be a failure of chip seal performance according to the maximum allowable aggregate loss (10%) criterion established by the Alaska Department of Transportation. The other three emulsion types used with the granite 78M aggregate and all four emulsion types used with the lightweight aggregate meet the criterion. Specifically, the samples made with lightweight aggregate show aggregate loss below 5% after MMLS3 loading, regardless of emulsion type.

The Vialit test was performed to evaluate the aggregate retention behavior at different curing times and temperatures in the curing time study. Based on the curing time study results, all the emulsions can be considered to be cured after four hours; therefore, the aggregate loss results of the Vialit test at four hours curing time can be compared to the aggregate loss results of the MMLS3 test. Because the MMLS3 aggregate loss test protocol suggests 25°C as the test temperature, only the Vialit test data tested at 25°C are used for the comparison of aggregate retention performance. Figure 37 shows the aggregate retention comparison between the MMLS3 test and the Vialit test results.

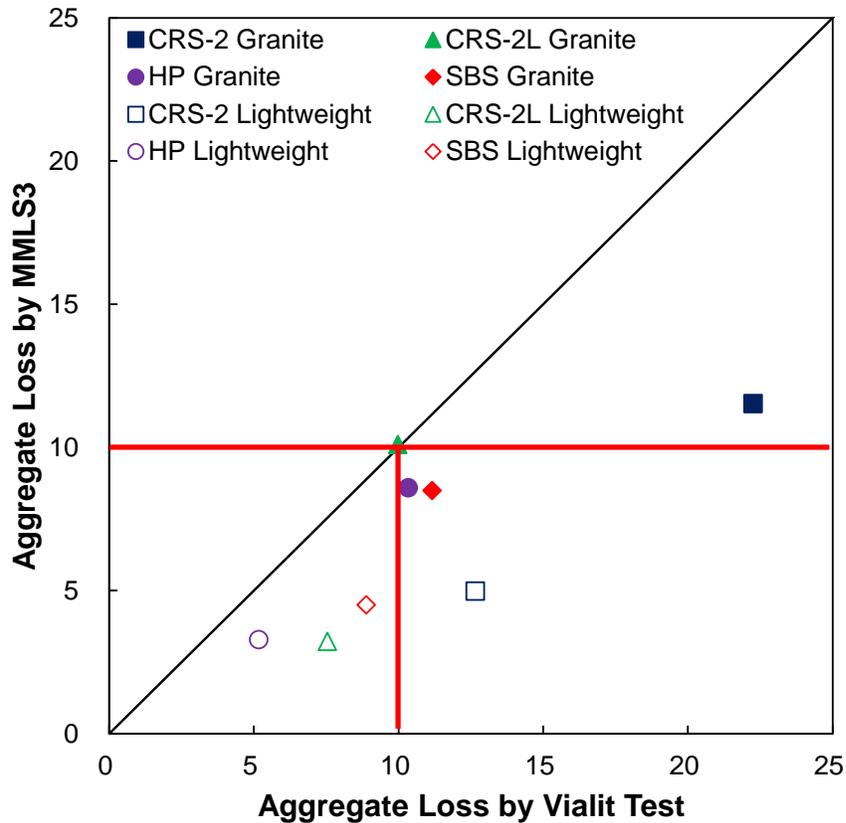


Figure 37 Comparison of aggregate loss between MMLS3 test and Vialit test

Because the mechanism that causes aggregate loss from the chip seal specimens is different between the MMLS3 test and the Vialit test, it is not possible to compare aggregate retention performance directly. For example, in order to simulate traffic loading, both the MMLS3 tire loading and the Vialit test's steel ball drop mechanisms are employed. The MMLS3 test can simulate actual traffic loading better than the Vialit test, but the MMLS3 test is conducted using only cured specimens, which are cured during 24 hours at 35°C. In other words, it is not possible to investigate the aggregate retention performance as a function of curing time using MMLS3. However, the Vialit test can be performed at different curing times and is a very simple test method; thus, the Vialit test can be employed for both aggregate loss testing and the curing study.

Figure 37 indicates that all the specimens tested by the Vialit method show more aggregate loss than those tested by the MMLS3 test. This result may be due to the self-weight of the aggregate particles, because the Vialit test protocol involves the impact of the steel ball on a specimen that has been flipped over. In particular, the CRS-2 specimens indicate a greater variation in the aggregate loss results between the MMLS3 test and the Vialit test; i.e., the Vialit test aggregate loss is two times higher than the MMLS3 test aggregate loss. However, both test results show a similar aggregate retention performance trend. The PMEs show better aggregate retention performance, and the SBS CRS-2P emulsion in particular shows slightly more aggregate loss than the other modified emulsions, even though the difference is not significant.

4.1.2.2 Bleeding Performance

The specimens used for the MMLS3 aggregate loss testing also were used for the bleeding tests. The samples were conditioned in the MMLS3 chamber for three hours at a temperature of 50°C, and then MMLS3 loading was applied for four hours at the same temperature. This test protocol was developed to simulate the bleeding of chip seal surfaces during the summer. After the tests, the specimens were scanned, and the digital images were analyzed to present numerical values for the bleeding areas on the specimen surface. Figure 38 shows the bleeding performance of the four emulsion types, CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P, for the granite 78M and lightweight aggregates, respectively.

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in bleeding performance between the CRS-2 emulsion and the PMEs. Table 14 summarizes the results of the statistical analysis for the emulsion types. The p-values of all the emulsions with both aggregate types are less than 0.05. Thus, statistical differences in bleeding performance are evident between the PMEs and the CRS-2 emulsion.

Table 14 Results of Statistical Analysis for Emulsion Types: Bleeding Performance of Laboratory Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
Granite 78M aggregate							
CRS-2	62.2	92.4	9.6	3.9			
CRS-2L	29.1	11.5	3.4	1.4	7.95	0.0002	Reject H _o
HP CRS-2P	25.9	38.4	6.2	2.5	7.78	0.00003	Reject H _o
SBS CRS-2P	25.6	10.1	3.2	1.3	8.86	0.0001	Reject H _o
Lightweight Aggregate							
CRS-2	19.8	36.8	6.1	2.5			
CRS-2L	4.3	1.0	1.0	0.4	6.17	0.0016	Reject H _o
HP CRS-2P	19.8	36.8	1.0	0.4	6.19	0.0016	Reject H _o
SBS CRS-2P	19.8	36.8	1.0	0.4	5.80	0.0021	Reject H _o

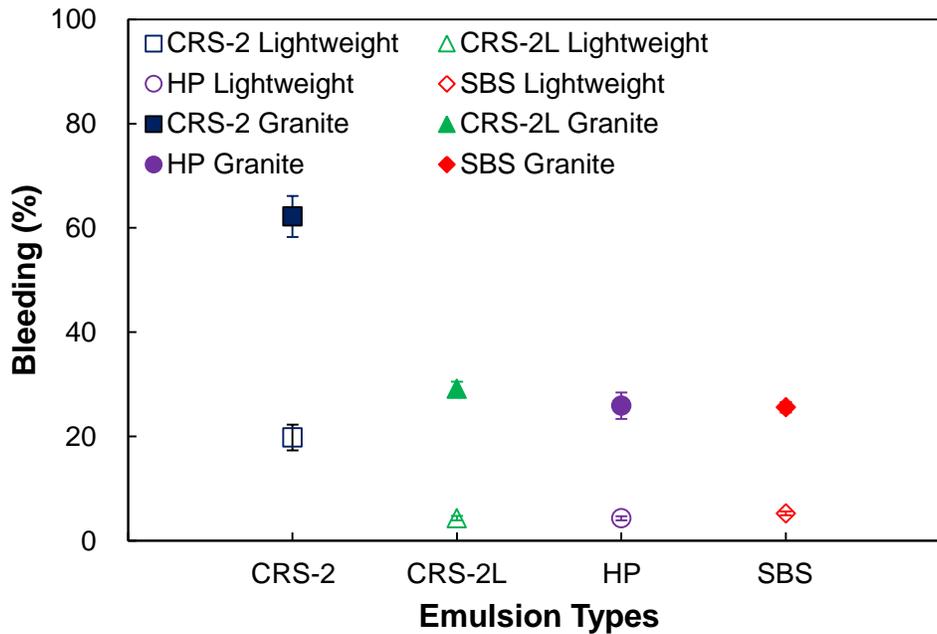


Figure 38 Bleeding performance of different emulsions

Figure 38 indicates that the lightweight aggregate shows better bleeding resistance than the granite 78M aggregate, and shows also that the unmodified emulsion, CRS-2, performs the worst in terms of bleeding for all emulsion types. In particular, the combination

of the CRS-2 emulsion and granite 78M aggregate corresponds to the worst performance (least bleeding resistance/most bleeding).

4.1.2.3 Rutting Performance

In order to investigate rutting performance, triple-seal specimens were fabricated based on the previous PME study (NCDOT HWY-2007-06). All the triple-seal specimens were composed of granite 78M, granite 78M, and lightweight aggregate for the bottom, middle, and top layers, respectively. The AARs for the triple seals are 17 lb/yd² (9.2 kg/m²) 17 lb/yd² (9.2 kg/m²) and 9 lb/yd² (4.9 kg/m²) for the bottom (granite 78M), middle (granite 78M), and top (lightweight) layers, respectively. The EARs are 0.30 gal/yd² (1.36 L/m²), 0.25gal/yd² (1.13 L/m²), and 0.20 gal/yd² (0.91 L/m²) for the bottom, middle, and top layers, respectively.

The transversal profiles were measured at 0, 10, 30, 90, 270, and 360 minutes during the entire test period. Based on the profiles, the trafficked area was obtained for each specimen, and the rut depth was determined from the difference between the average of the profiles at zero traffic time and the average of the profiles from a certain traffic loading time. Figure 39 shows the transversal profiles as a function of MMLS3 loading time for all specimens.

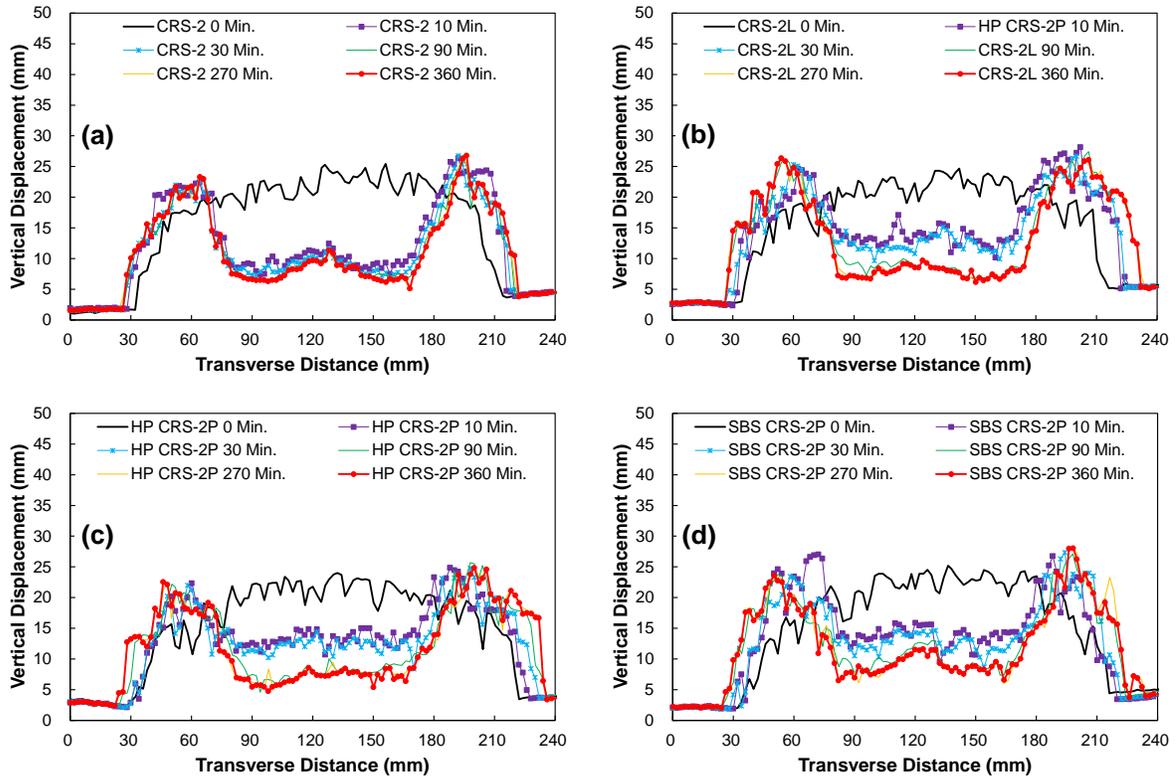


Figure 39 Transversal profiles for all emulsion types: (a) CRS-2, (b) CRS-2L, (c) HP CRS-2P, and (d) SBS CRS-2P emulsions

Figure 39 illustrates that the height of the humps outside of the trafficked area increases with loading time. The rut depth of the CRS-2 specimen grows faster than for the other emulsion samples. In order to compare the rut depths of all the triple-seal specimens, the calculated rut depths of all the specimens are determined as a function of the number of wheel passes, as shown in Figure 40 in semi-log scale.

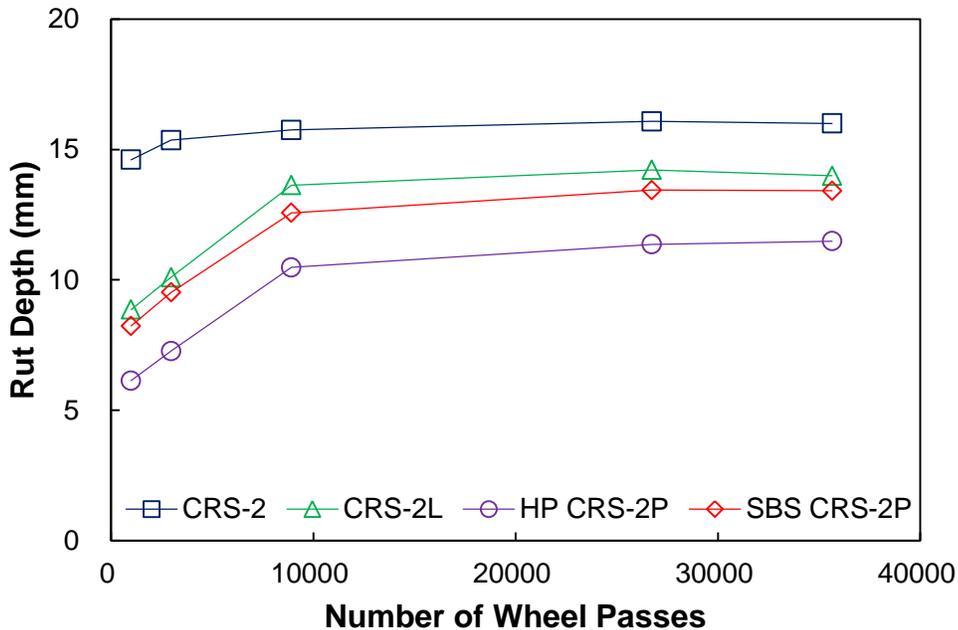


Figure 40 Rut depth growth (semi-log scale)

Figure 39 and Figure 40 indicate that the CRS-2 unmodified specimen shows the poorest resistance to rutting. In particular, the CRS-2 specimen reaches its final rut depth after only 30 minutes of traffic loading (2,970 wheel passes). In contrast, the rut depths of the other emulsion specimens reach their final rut depths after 90 minutes of traffic loading (89,100 wheel passes). The HP CRS-2P emulsion exhibits the best resistance to rutting among all the PME specimens, but the trend of rut depth development is very similar to the other PME specimens.

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in rutting performance between the CRS-2 emulsion and the PMEs. Table 15 summarizes the results of the statistical analysis for the emulsion types. The p-values of the HP CRS-2P and SBS CRS-2P emulsions are less than 0.05. Thus, these two emulsion types (HP CRS-2P and SBS CRS-2P) show statistical differences in rutting performance in comparison to the CRS-2 emulsion.

Table 15 Results of Statistical Analysis for Emulsion Types: Rutting Performance of Laboratory Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
CRS-2	16.0	0.95	0.98	0.56			
CRS-2L	14.0	0.72	0.85	0.49	2.69	0.055	Accept H _o
HP CRS-2P	11.5	0.58	0.19	0.11	6.31	0.003	Reject H _o
SBS CRS-2P	13.4	0.04	0.77	0.44	4.49	0.046	Reject H _o

4.2 Fog Seal Performance

4.2.1 Fog Seal Curing Time Study

4.2.1.1 Emulsion Property Test

A simple water compatibility test and residual asphalt content test were conducted to better understand the compatibility between water and emulsion and the amount of residual asphalt of the study emulsions.

The simple water compatibility test procedure is to pour diluted emulsion (approximately 1 liter) through a pre-wetted 150 µm sieve, and the amount of retained material on the sieve is weighed. If more than 1% by weight of material is retained on the sieve, the water is not compatible with the emulsion, and the spray jets may become clogged. Incompatible water may be treated with 0.5% to 1.0% of a compatible emulsifier solution (*Fog Seal Guidelines for California*). This test has been conducted using distilled water and study emulsions and obtained 0.3% retained material. Based on this test, no water treatment is necessary for this study.

The residual asphalt content tests were conducted based on ASTM D 244. The CSS-1h and CQS-1h emulsion were diluted with water using a dilution rate of 50 percent. The ReviveTM emulsion is used in the field with a dilution ratio of 60% of emulsion to 40% of water, which is recommended by the emulsion manufacturer. The Grip-Tight is produced in ready use in the field without the diluting process recommended by the emulsion

manufacturer. However, it was found that the Grip-Tight emulsion had been produced with more than typical asphalt residue due to cold weather. So, for the tests, the Grip-Tight emulsion had to be diluted by 45% asphalt residue. Because this research is interested only in each emulsion's properties, the same dilution rates should be applied to each emulsion type. However, because it is more important to find an emulsion that shows better performance when it is used on a typical chip seal surface, the optimized dilution rates recommended by the emulsion manufacturer were applied to each emulsion during this research.

Three samples were fabricated for each test, and the samples were weighed after complete curing. Table 16 presents the test results for the simple water compatibility test and the residual asphalt content test.

Table 16 Material Properties of Study Emulsions

Property Test	Type of Emulsion			
	CSS-1h	CQS-1h	Revive TM	Grip-Tight
Simple Water Compatibility Test	0.3 %	0.2 %	0.3 %	0.3 %
Residual Asphalt Content Test	31.4 %	32.5 %	38.5 %	62.7 %

4.2.1.2 Evaporation Test

The evaporation test is used to help determine the emulsion curing time, and it has been conducted at several EARs and temperatures. As explained in section 3.4.1, the evaporation test has been conducted at three temperatures, 20°C, 30°C, and 40°C, each of which has eight fog seal application rates, 0.02, 0.06, 0.09, 0.12, 0.16, 0.19, 0.23, and 0.26 gal/yd² (0.09, 0.27, 0.41, 0.54, 0.72, 0.86, 1.04, and 1.18 L/m²). The test temperatures were determined to range between 20°C and 40°C, based on monthly normal high temperatures between March and October for North Carolina cities. The fog seal EARs range from 0.02 to 0.26 gal/yd² (0.09 to 1.18 L/m²) based on AEMA recommendations and the literature review. For the test, all four study emulsions, such as CSS-1h, CQS-1h, ReviveTM, and Grip-Tight,

were used, and two replicates were prepared for each condition. The curing time is determined when the percentage of water loss is less than 10% based on asymptotic trends of all the emulsions.

Figure 41 shows the results of the evaporation tests for the CSS-1h and CQS-1h emulsions with representative EARs of 0.06, 0.12, 0.19, and 0.26 gal/yd² (0.27, 0.54, 0.86, and 1.18 L/m²), and at 20°C, 30°C, and 40°C. From these tests, CSS-1h and CQS-1h emulsions have similar curing time trends, but the CSS-1h emulsion shows a little shorter curing time than the CQS-1h emulsion. Based on this finding, the CSS-1h emulsion is used as the representative unmodified emulsion type for the evaporation test.

In order to understand the curing time trends of each emulsion for different curing temperatures, Figure 42 shows the results of the evaporation tests for each emulsion at three different temperatures. Figure 43 shows the curing time trends for different emulsion types.

It has been informed that there are a few sections constructed recently by fog seal application using the Grip-Tight emulsion in North Carolina. A few sections in North Carolina have been constructed recently for fog seal application using the Grip-Tight emulsion. For the construction, 0.12 gal/yd² (0.54 L/m²) of Grip-Tight emulsion was applied in the field, and traffic was opened approximately 1 hour later. Based on this information and the curing time trends for all emulsions, the evaporation tests for 0.12 gal/yd² (0.54 L/m²) of fog seal emulsion for all types of emulsions are compared in Figure 44.

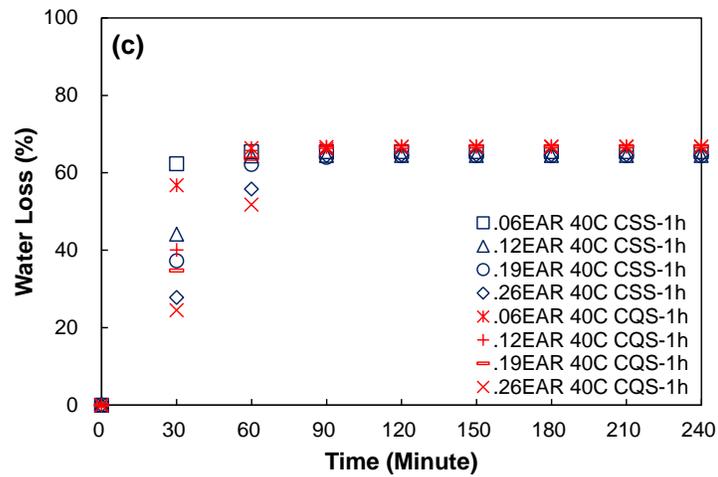
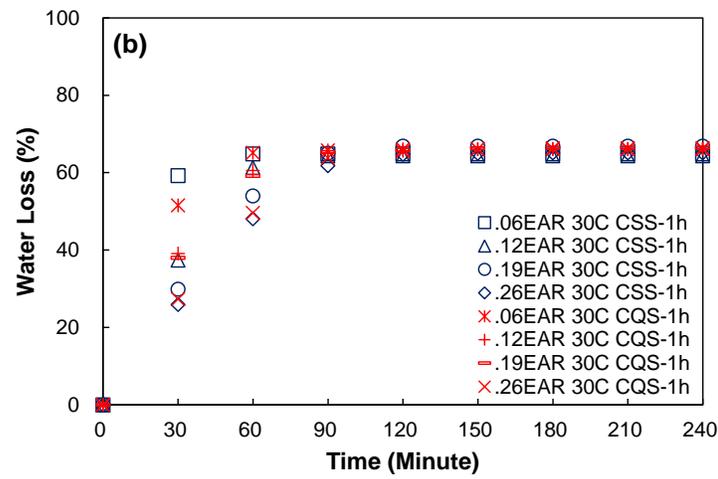
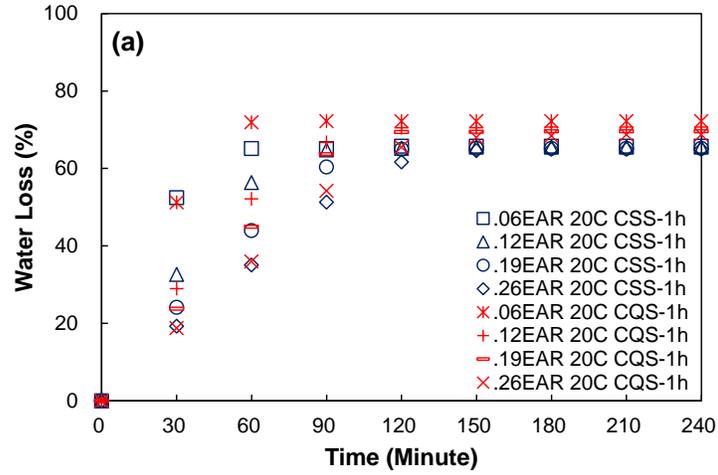


Figure 41 Evaporation test results for CSS-1h and CQS-1h emulsions of 0.06, 0.12, 0.19, and 0.26 gal/yd² (0.27, 0.54, 0.86, and 1.18 L/m²) at: (a) 20°C, (b) 30°C, and (c) 40°C

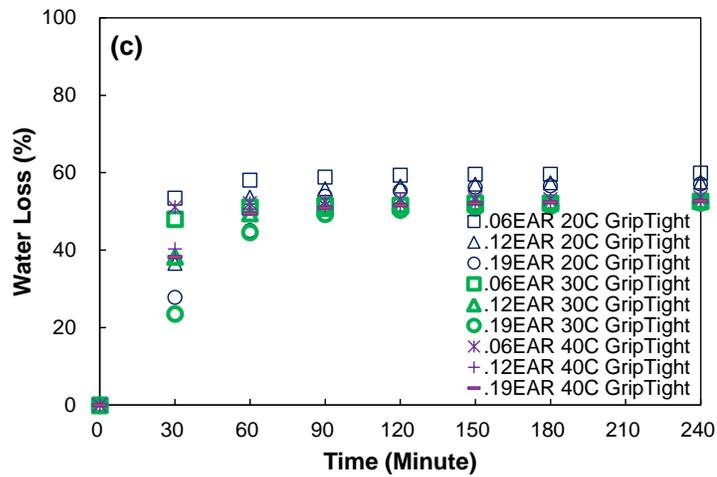
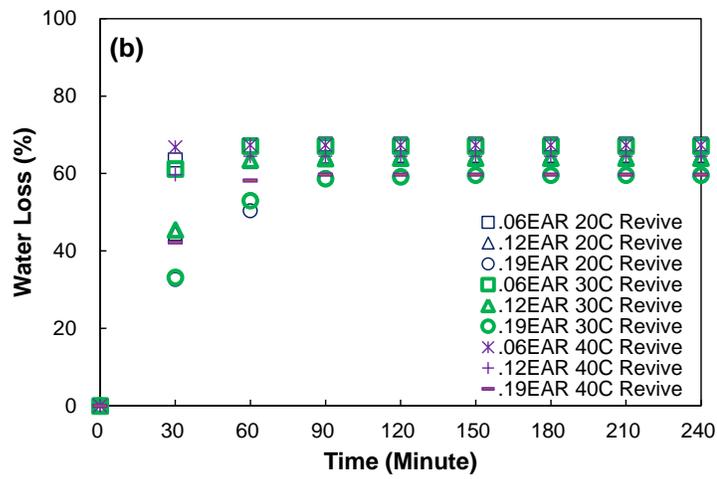
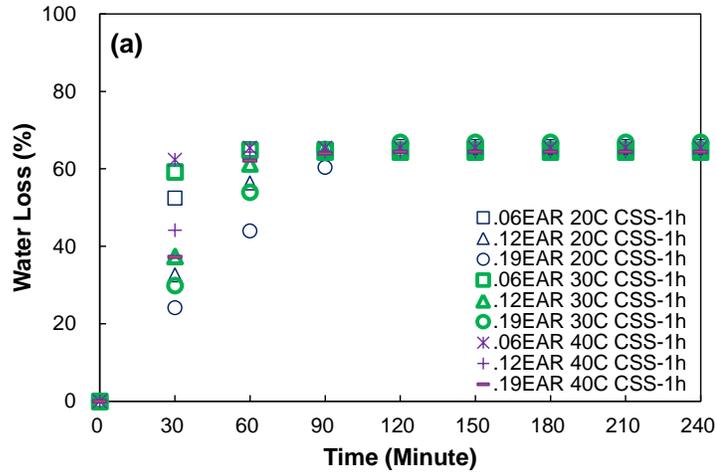


Figure 42 Evaporation test results at all temperatures for 0.06, 0.12, and 0.19 gal/yd² (0.27, 0.54, and 0.86 L/m²) of: (a) CSS-1h, (b) Revive™, and (c) Grip-Tight emulsions

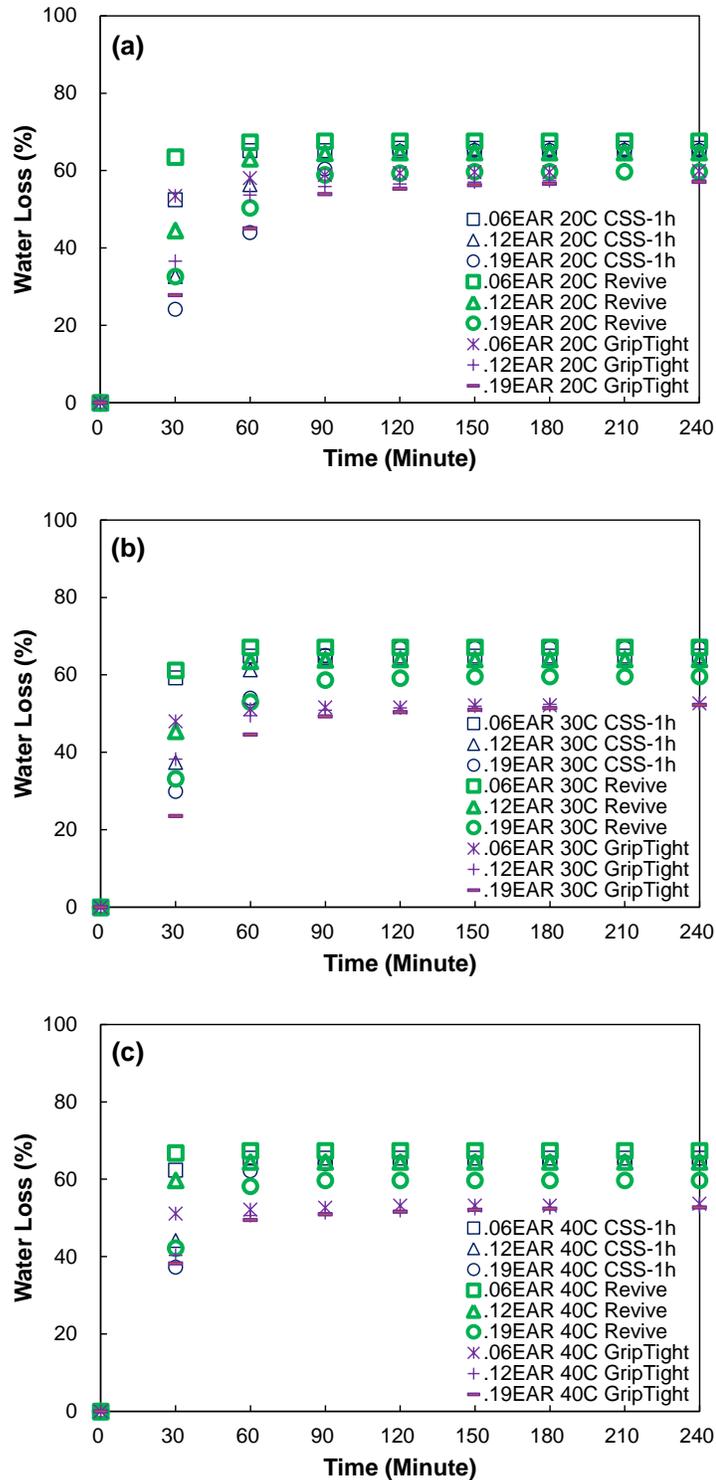


Figure 43 Evaporation test results for CSS-1h, ReviveTM, and Grip-Tight emulsions of 0.06, 0.12, and 0.19 gal/yd² (0.27, 0.54, and 0.86 L/m²) at: (a) 20°C, (b) 30°C, and (c) 40°C

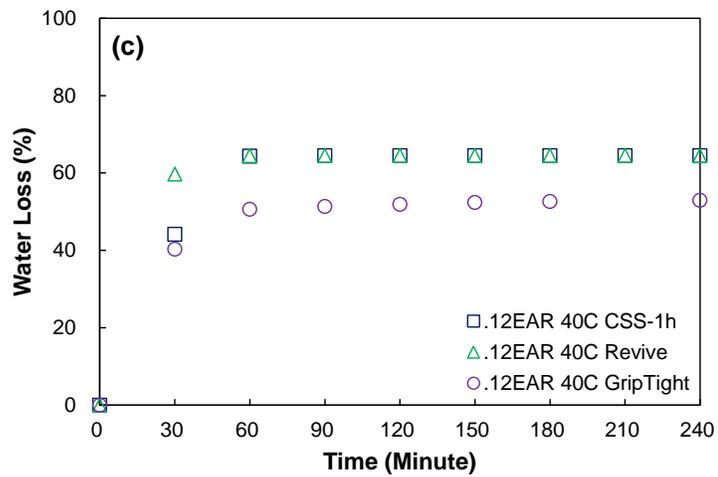
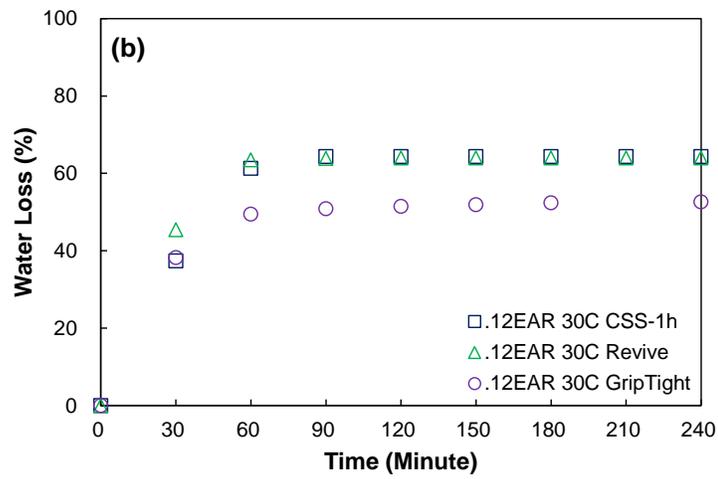
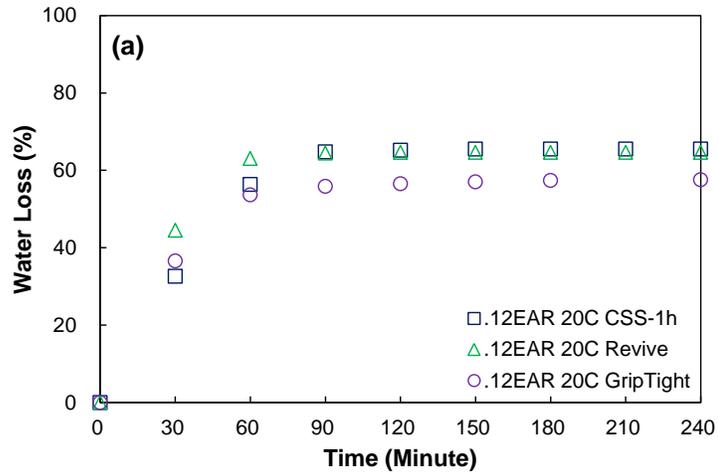


Figure 44 Evaporation test results for CSS-1h, ReviveTM, and Grip-Tight emulsions of 0.12 gal/yd² (0.54 L/m²) at: (a) 20°C, (b) 30°C, and (c) 40°C

Figure 42 indicates that all three types of emulsions show the shorter curing time once the samples are placed at a higher temperature. Most samples can reach their asymptotic percentage of water loss within 1.5 hours, except the CSS-1h emulsion samples with a high EAR (0.19 gal/yd² (0.86 L/m²)) tested at 20°C.

Figure 43 shows similar curing time trends for the ReviveTM and Grip-Tight emulsions at all three temperatures, but CSS-1h emulsion shows a little longer curing time. The curing times vary between each emulsion, especially at 20°C.

Figure 44 shows emulsion samples that were tested with an EAR of 0.12 gal/yd² (0.54 L/m²) at three temperatures. These results show that most samples tested at 30 and 40°C reach their asymptotic percentage of water loss within one hour. Table 17 presents details regarding curing time values in terms of temperature for each emulsion.

As previously mentioned, the curing times for each sample are determined when the percentage of water loss is less than 10% based on asymptotic trends of all emulsions. Table 17 presents the determined curing times for all emulsion types and fog seal EARs.

Table 17 Curing Times for the CSS-1h, CQS-1h, ReviveTM, and Grip-Tight Emulsions

EARs (gal/yd ²)	Curing Time (Minutes)											
	20°C				30°C				40°C			
	CSS-1h	CQS-1h	Revive	Grip-Tight	CSS-1h	CQS-1h	Revive	Grip-Tight	CSS-1h	CQS-1h	Revive	Grip-Tight
0.02	60	90	60	60	60	60	60	60	60	60	60	60
0.06	90	90	60	60	60	90	90	60	60	60	60	60
0.09	90	90	60	60	90	90	90	60	60	90	60	60
0.12	90	120	90	90	90	90	90	90	90	90	60	60
0.16	120	120	90	90	90	90	90	90	90	90	60	60
0.19	120	120	90	90	90	90	90	90	90	90	90	60
0.23	120	150	120	120	120	120	120	90	90	120	90	60
0.26	120	150	120	120	120	120	120	90	90	120	90	60

Table 17 also shows that the modified emulsions (ReviveTM and Grip-Tight) show the shorter curing times than the unmodified emulsions (CSS-1h and CQS-1h). Most samples cure within 1.5 hour, except the CSS-1h and the CQS-1h emulsion samples with high EAR (more than 0.19 gal/yd² (0.86 L/m²)) tested at 20°C and the PME samples tested using high EAR (0.23 and 0.26 gal/yd² (1.04 and 1.18 L/m²)) and the lowest curing temperature (20°C).

As previously stated, emulsion consists of asphalt and water, and must be further diluted with water for the fog seal construction to reduce its viscosity. Typically, unmodified emulsions are diluted with water using a dilution rate of 50%, but each modified emulsion has a specific dilution rate recommended by manufacturer. For instance, the ReviveTM emulsion is used in the field with a dilution ratio of 60% of emulsion to 40% of water, and the Grip-Tight emulsion is recommended for use with 45% of asphalt residue. For the ReviveTM emulsion, dilution process should be carried out in the field or emulsion plant before construction, but the Grip-Tight emulsion can be employed in the field without the dilution process. The large amount of asphalt residue may affect the emulsion curing times even without considering emulsion properties. Therefore, it is necessary to check the difference in curing times between the recommended and other dilution rates.

The evaporation tests using the same asphalt residue for each emulsion has conducted. For this test, the CSS-1h, ReviveTM, and Grip-Tight emulsions were selected, and EARs of 0.06, 0.12, and 0.19 gal/yd² (0.27, 0.54, and 0.86 L/m²) were applied at 30°C. These three emulsions were diluted prior to testing using the same dilution rate of 33% asphalt residue. Figure 45 and Table 18 present all the test data, and Figure 46 shows the results for an EAR of 0.12 gal/yd² (0.54 L/m²).

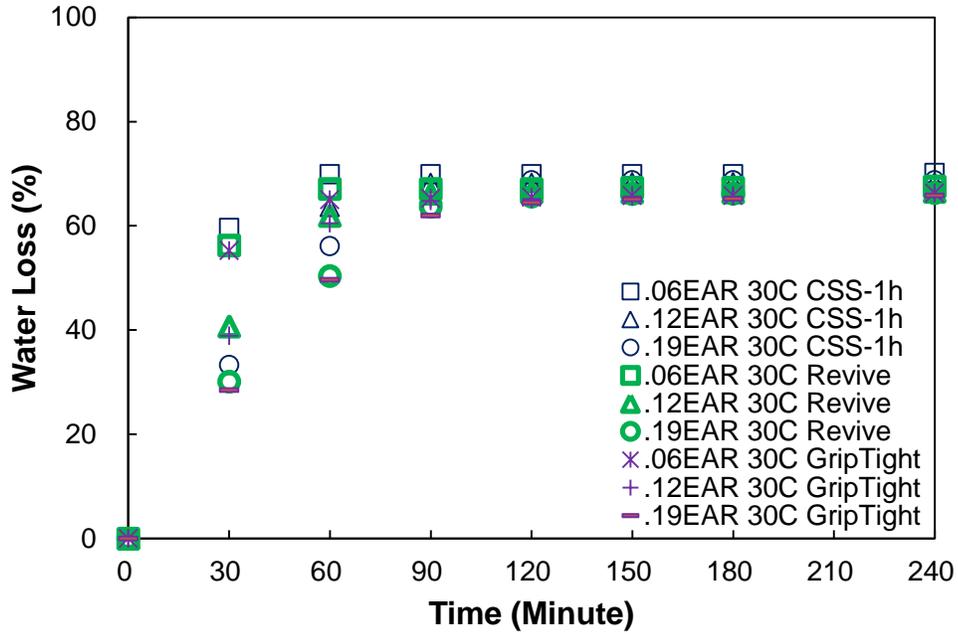


Figure 45 Evaporation test results for CSS-1h, Revive™, and Grip-Tight emulsions with same asphalt residue

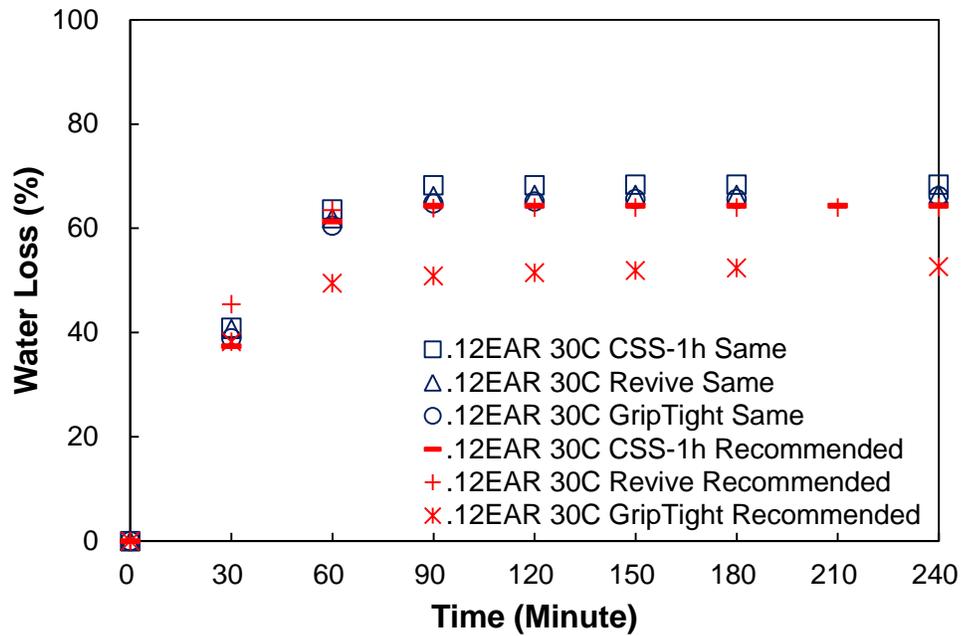


Figure 46 Evaporation test results with 0.12 gal/yd² (0.54 L/m²) of CSS-1h, Revive™, and Grip-Tight emulsions for comparison same asphalt residue and recommended dilution rate

Table 18 Curing Times for the CSS-1h, ReviveTM, and Grip-Tight Emulsions at 30°C

EARs (gal/yd ²)	Curing Time (Minutes)					
	Recommended Dilution Rate			Same Asphalt Residue		
	CSS-1h	Revive	Grip-Tight	CSS-1h	Revive	Grip-Tight
0.02	60	60	60	-	-	-
0.06	60	90	60	60	90	60
0.09	90	90	60	-	-	-
0.12	90	90	90	90	90	90
0.16	90	90	90	-	-	-
0.19	90	90	90	120	120	120
0.23	120	120	90	-	-	-
0.26	120	120	90	-	-	-

Figure 45, Figure 46, and Table 18 indicate that the curing times for a lower EAR (0.06 gal/yd² (0.27 L/m²)) of the same asphalt residue samples are lengthened for all emulsion types, but the curing times for high EARs (0.12 and 0.19 gal/yd² (0.54 and 0.86 L/m²)) of the same asphalt residue samples are the same as for the recommended dilution rate samples.

4.2.1.3 BBS Test

A granite substrate was used for the BBS tests conducted during this research. All the BBS tests were conducted in an environmental chamber to maintain the temperature during curing and testing. Three replicates were tested for each temperature and application rate combination.

When considering the results of the evaporation tests for the four types of emulsions, the curing times determined from the evaporation tests may not yield sufficient information to determine the minimum recommended curing times for fog seal emulsions. The evaporation test considers only how fast water would evaporate from an emulsions by measuring the weight of the emulsion, so it does not capture the advantages of modified fog

seal emulsions, such as higher adhesive strength values than unmodified emulsions. Consequently, the BBS test can help determine the minimum curing times for fog seal emulsions in addition to the curing times determined from the evaporation tests.

The BBS tests were conducted at different curing times and selected EARs based on the evaporation test results. The BBS test were conducted at times of 30, 60, 90, 120, 180 minutes, and 1 day, at EARs of 0.06, 0.12, 0.19, and 0.25 gal/yd² (0.27, 0.54, 0.86, and 1.13 L/m²), and at temperatures of 25°C, 30°C, and 35°C for the four emulsion types, CSS-1h, CQS-1h, ReviveTM, and Grip-Tight. However, during the BBS tests, a problem was detected that the bond strength values at EARs of 0.06 and 0.12 gal/yd² (0.27 and 0.54 L/m²) were erroneous because the volume of the emulsion was not enough to fill the gap between the pull-stub and the substrate. Thus, only the BBS data for EARs of 0.19 and 0.25 gal/yd² (0.86 and 1.13 L/m²) are used for comparison.

Figure 47 presents all the bond strength values of all emulsion types with EARs of 0.19 and 0.25 gal/yd² (0.86 and 1.13 L/m²) at each temperature, 25°C, 30°C, and 35°C.

Table 19 and Table 20 present the bond strength values for all three study emulsions with the two application rates at the three curing times, and also present the percentage of bond strength as determined by dividing the bond strength values at different curing times by the full bond strength, which is determined at 24 hours.

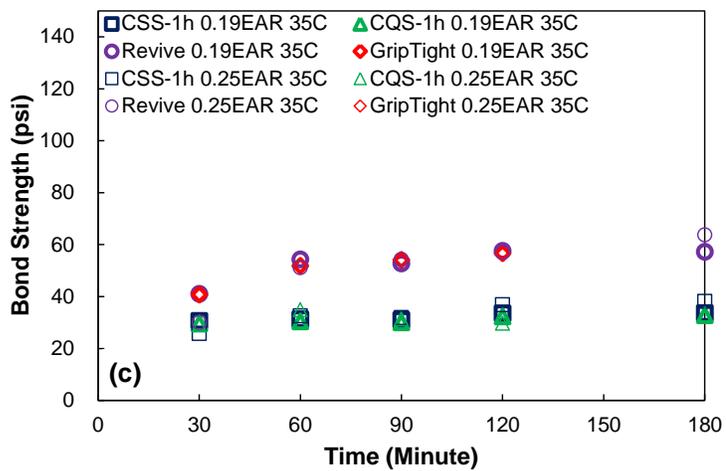
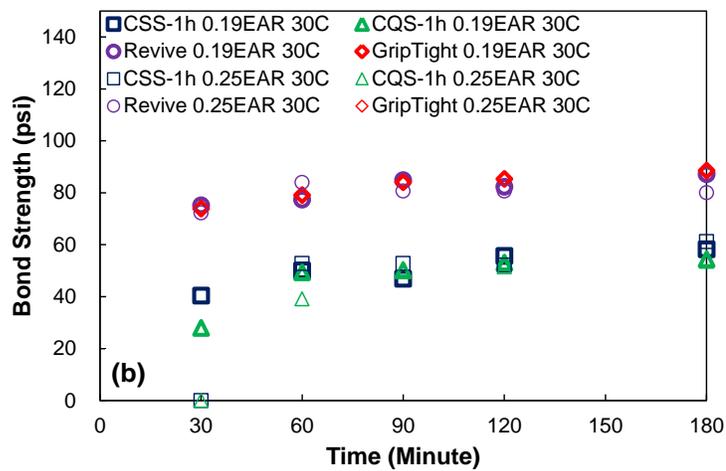
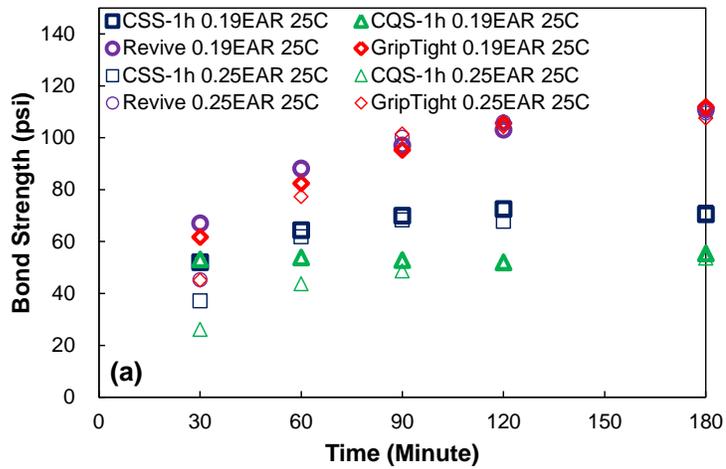


Figure 47 BBS test results at all EARs and emulsions at: (a) 25°C, (b) 30°C, and (c) 35°C

Table 19 Bond Strength Values for CSS-1h, CQS-1h, and Revive™ Emulsions

Tem. °C	EARs gal/yd ²	Emulsion Types	Bond Strength (psi, (kPa)) at Curing Time (Minutes)					
			30	60	90	120	180	1 day
25	0.19	CSS-1h	52.1(359)	64.4(444)	69.9(482)	72.5(500)	70.5(486)	75.8(523)
		CQS-1h	53.1(366)	53.7(370)	52.7(363)	51.9(358)	55.3(381)	55.7(384)
		Revive	67.0(462)	88.1(607)	97.1(669)	103.1(711)	110.9(765)	121.3(836)
		GripTight	61.7(425)	82.3(567)	95.3(657)	105.6(728)	111.7(770)	122.8(847)
	0.25	CSS-1h	37.1(256)	61.8(426)	68.3(471)	67.7(467)	71.2(491)	73.1(504)
		CQS-1h	26.1(180)	43.6(301)	48.6(335)	52.5(362)	53.5(369)	56.2(387)
		Revive	45.2(312)	87.5(603)	100.2(691)	106.0(731)	109.4(754)	120.6(832)
		GripTight	45.0(310)	77.2(532)	101.4(699)	104.2(718)	107.5(741)	119.1(821)
30	0.19	CSS-1h	40.4(279)	50.1(345)	46.9(323)	55.6(383)	58.2(401)	55.3(381)
		CQS-1h	27.9(192)	49.3(340)	50.1(345)	53.0(365)	54.3(374)	55.6(383)
		Revive	75.1(518)	77.4(534)	84.9(585)	82.3(567)	87.2(601)	88.5(610)
		GripTight	73.8(509)	79.0(545)	83.9(578)	85.2(587)	88.5(610)	87.8(605)
	0.25	CSS-1h	0.0	52.7(363)	52.7(363)	52.1(359)	61.2(422)	59.55(411)
		CQS-1h	0.0	39.1(270)	50.8(350)	51.4(354)	53.5(369)	59.2(408)
	Revive	72.2(498)	83.9(578)	80.7(556)	80.7(556)	80.0(552)	98.2(677)	
35	0.19	CSS-1h	30.6(211)	31.3(216)	31.0(214)	33.6(232)	33.6(232)	33.2(229)
		CQS-1h	29.7(205)	30.3(209)	30.0(207)	32.3(223)	32.7(225)	35.2(243)
		Revive	41.0(283)	54.3(374)	52.8(364)	57.6(397)	57.3(395)	64.7(446)
		GripTight	25.8(178)	51.7(356)	54.0(372)	56.6(390)	-	67.3(464)
	0.25	CSS-1h	25.8(178)	32.6(225)	31.9(220)	36.8(254)	38.1(263)	39.4(272)
		CQS-1h	29.0(200)	34.9(241)	31.3(216)	29.7(205)	32.7(225)	35.7(246)
	Revive	30.0(207)	51.1(352)	54.3(374)	57.0(393)	63.8(440)	64.4(444)	

Table 20 Percentages of Full Bond Strength for CSS-1h, CQS-1h, and ReviveTM Emulsions

Temp. °C	EARs, gal/yd ²	Emulsion Types	Bond Strength (%) at Curing Time (Minutes)					
			30	60	90	120	180	1 day
25	0.19	CSS-1h	69	85	92	96	93	100
		CQS-1h	95	97	95	93	99	100
		Revive TM	55	73	80	85	91	100
		Grip Tight	50	67	78	86	91	100
	0.25	CSS-1h	51	85	93	93	97	100
		CQS-1h	46	78	86	93	95	100
		Revive TM	38	73	83	88	91	100
		Grip Tight	38	65	85	87	90	100
30	0.19	CSS-1h	73	91	85	101	105	100
		CQS-1h	50	89	90	95	98	100
		Revive TM	85	88	96	93	99	100
		Grip Tight	84	90	96	97	101	100
	0.25	CSS-1h	0	89	89	87	103	100
		CQS-1h	0	66	86	87	90	100
		Revive TM	74	85	82	82	81	100
35	0.19	CSS-1h	99	101	100	108	102	100
		CQS-1h	84	86	85	92	93	100
		Revive TM	63	84	82	89	88	100
		Grip Tight	60	77	80	84	-	100
	0.25	CSS-1h	65	93	81	93	97	100
		CQS-1h	81	98	88	83	92	100
		Revive TM	47	79	84	88	99	100

The following observations can be made from Figure 47, Table 19, and Table 20:

- Figure 47 indicates that the differences in EARs do not affect the bond strength of the study emulsions after 1 hour, except for the CQS-1h emulsion, whereas the EAR does affect the bond strength after 1.5 hours.

- The bond strength develops more quickly in the CSS-1h and ReviveTM emulsions than in the CQS-1h emulsion. After 1 hour, the bond strength of ReviveTM is greater than that of the CSS-1h and CQS-1h emulsions, indicating the ability of ReviveTM to gain strength early and quickly.
- Most of the bond strength gain is achieved in the first hour for the CSS-1h and ReviveTM emulsions and after 1.5 hours for the CQS-1h emulsion.
- The final bond strength values of the CSS-1h and CQS-1h emulsions are similar, except the 25°C results that show greater bond strength of the CSS-1h emulsion, and that the bond strength of the ReviveTM emulsion is much greater than that of the other two emulsions.
- The full bond strength of ReviveTM emulsion can be achieved in 1.5 hours. The curing time based on the bond strength is 0.5 hour shorter than that determined from the evaporation test.

4.2.2 Fog Seal Field Test

4.2.2.1 Rolling Ball Test

The field viscosity test has identified as a means to determine the appropriate traffic opening time for fog seals in the field. An *in situ* test may be necessary because fog seal emulsions are very sensitive to the environment. In the previous report, the Wagner flow cup test was suggested as a field viscosity test for the emulsions, but a trial test revealed that it was not suitable for fog seal emulsions. As mentioned before, the volume of fog seal emulsions is changeable depending on curing time, so it is difficult to obtain a certain amount of cured emulsion.

Rolling ball tests were conducted at different curing times and selected EARs based on previous testing, i.e., the evaporation test and the PATTI test. The rolling ball tests were conducted at times of 15, 30, 45, 60, 90, 120, 180, 240 minutes, and 1 day, at EARs of 0.06 and 0.12 gal/yd² (0.27 and 0.54 L/m²), and at temperatures of 25°C and 30°C for the three

emulsion types, CSS-1h, ReviveTM, and Grip-Tight. Figure 48 and Table 21 show the rolling ball test results. In Table 21, the shaded cells indicate the curing time of each condition.

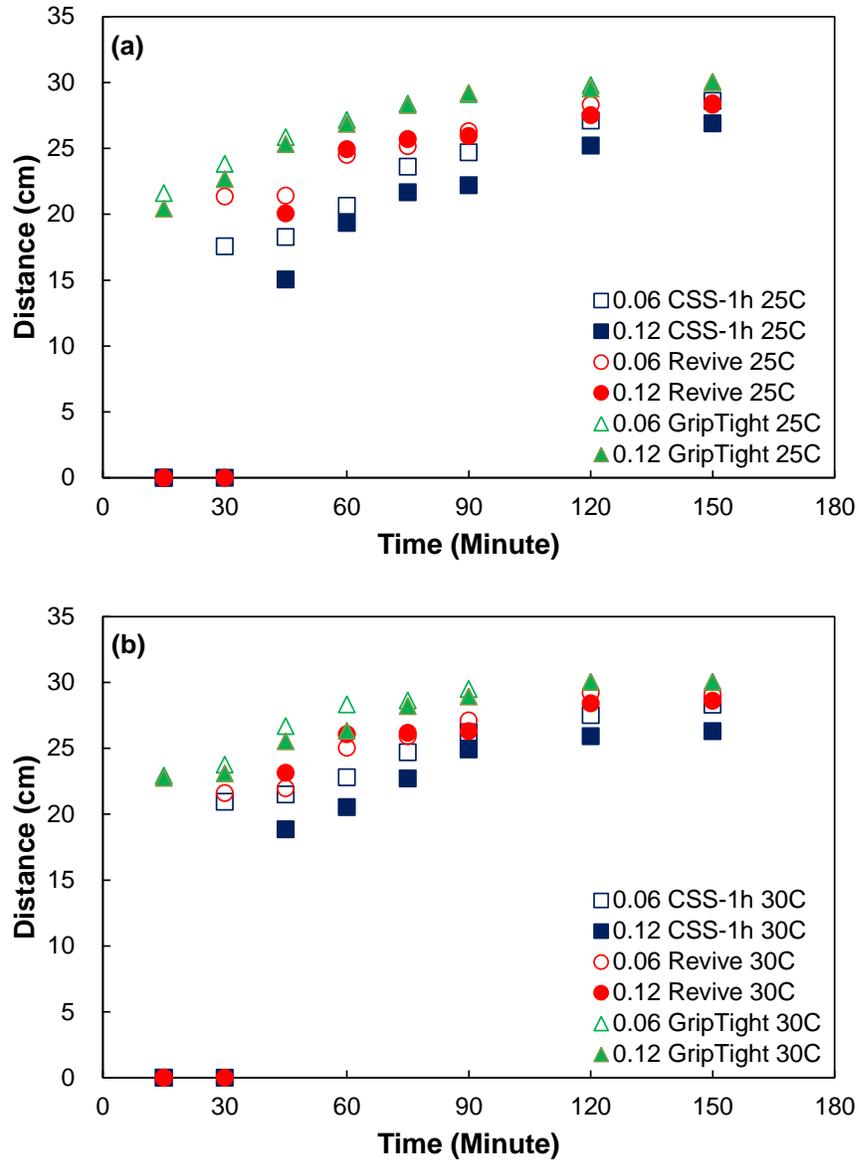


Figure 48 Rolling ball test for CSS-1h, ReviveTM, and Grip-Tight emulsions with 0.06 and 0.12 gal/yd² (0.27 and 0.54 L/m²) at: (a) 25°C and (b) 30°C

Table 21 Rolling Ball Test for CSS-1h, ReviveTM, and Grip-Tight Emulsions with 0.06 and 0.12 gal/yd² (0.27 and 0.54 L/m²) at 25°C and 30°C

Time (Minute)	CSS-1h				Revive TM				Grip-Tight				
	30°C		25°C		30°C		25°C		30°C		25°C		
	0.06	0.12	0.06	0.12	0.06	0.12	0.06	0.12	0.06	0.12	0.06	0.12	
	(gal/yd ²)												
15	-	-	-	-	-	-	-	-	-	22.9	22.7	21.6	20.4
30	20.9	-	17.6	-	21.6	-	21.3	-	23.7	23.1	23.8	22.6	
45	21.5	18.8	18.3	15.0	22.0	23.1	21.4	20.1	26.7	25.5	25.8	25.3	
60	22.8	20.5	20.6	19.3	25.0	26.1	24.5	24.9	28.3	26.3	27.1	26.8	
75	24.7	22.7	23.6	21.7	25.9	26.2	25.2	25.7	28.6	28.2	28.4	28.3	
90	26.2	24.9	24.7	22.2	27.1	26.3	26.3	25.9	29.5	28.9	29.1	29.2	
120	27.5	25.9	27.1	25.2	29.2	28.4	28.3	27.5	30.0	30.0	29.8	29.5	
150	28.3	26.3	28.6	26.9	29.1	28.6	28.4	28.3	30.0	30.0	30.0	30.0	
1 day	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	

The following observations can be made from Figure 48 and Table 21:

- The Grip-Tight emulsion can be tested from 0.25 hour for all conditions, which suggests that the curing rate of the Grip-Tight is faster than that of the other emulsion types.
- At the both temperatures, 25°C and 30°C, the Grip-Tight emulsion provides the longest distance in the rolling test, and the CSS-1h emulsion shows the shortest distance.
- After 1.5 hours, the Grip-Tight and ReviveTM emulsions reach their asymptotic distances.
- When considering all the distances reached by all the samples for each condition, 25 cm can be suggested as a critical distance.
- Based on this critical distance, the Grip-Tight and ReviveTM emulsions can be cured within one hour, but the curing times of the CSS-1h emulsion are longer than 1.25

hours. In particular, the CSS-1h emulsion tested at 25°C with an EAR of 0.12 gal/yd² (0.54 L/m²) can be considered cured after two hours.

4.2.2.2 Damping Test

As stated previously, field test methods should be simple in design, and the test equipment should be portable for use in the field. Thus, the damping test has been developed as a method for field application. One kilogram of dead weight is applied to the emulsion samples for 15 seconds instead of using a wheel tracking device, and absorbent pads are used between the emulsion samples and one kilogram of dead weight to produce visible results that can verify the curing status of the fog seal emulsions. The DIP technique also is utilized to express the visible results numerically.

The damping tests were conducted at different curing times and selected EARs based on previous test results (the evaporation test and the PATTI test results). The damping tests were performed at times of 15, 30, 45, 60, 75, 90, 105, 120, 150, 180 minutes, and 1 day, at EARs of 0.06, 0.12, and 0.19 gal/yd² (0.27, 0.54, and 0.86 L/m²), and at 30°C for the four emulsion types, CSS-1h, CQS-1h, ReviveTM, and Grip-Tight. Table 22 shows the percentage of stained pixels after DIP analysis of damping test results.

Table 22 Percentage of Stained Pixels for Damping Test for All Study Emulsions at 30°C

Time (Min.)	Percentage of Stained Pixels											
	CSS-1h			CQS-1h			Revive			Grip-Tight		
	0.06	0.12	0.19	0.06	0.12	0.19	0.06	0.12	0.19	0.06	0.12	0.19
	(gal/yd ²)											
15	-	-	-	-	-	-	-	-	-	98.9	-	-
30	-	-	-	-	-	-	-	-	-	52.2	-	-
45	-	-	-	-	-	-	8.7	-	-	0.0	65.1	-
60	33.8	-	-	25.9	-	-	0.1	96.4	-	0.0	0.0	97.3
75	1.3	83.5	-	3.2	99.9	-	0.1	10.5	100.0	-	-	30.0
90	1.9	4.0	98.2	2.1	65.7	99.6	0.1	0.1	44.1	-	-	0.0
105	0.9	3.5	7.1	1.1	3.4	6.5	0.1	0.0	0.1	-	-	-
120	0.5	1.3	0.9	1.6	2.4	1.4	0.1	0.0	0.0	-	-	-
150	0.7	0.9	0.9	1.5	0.6	1.3	-	-	-	-	-	-
180	1.7	1.9	1.0	2.1	0.5	0.2	-	-	-	-	-	-
1 day	1.2	1.6	0.7	0.6	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0

When comparing the data from Table 22 and the digital image samples shown in Figure 27 (Section 3.4.8.2), the five percentages of stained pixels can be suggested as a critical value to determine emulsion curing time.

The shaded cells in Table 22 and Table 23 indicate the curing times for each condition. Overall, the Grip-Tight emulsion shows the best results, i.e., a low number of stained pixels, and the ReviveTM emulsion performs better than the CSS-1h and CQS-1h emulsions. In order to evaluate the temperature sensitivity of the damping test, the Grip-Tight emulsion was tested at 25°C, and the data were compared against the data obtained from the 30°C test. Table 23 shows the percentage of stained pixels after DIP analysis of the damping test results for the Grip-Tight emulsion at 25°C and 35°C. It shows that the curing time for the Grip-Tight emulsion tested at 25°C is 15 minutes shorter than the 30°C data, but the

Grip-Tight emulsion shows the best results among the four emulsion types even though the other emulsions were tested at 30°C.

Table 23 Percentage of Stained Pixels for Grip-Tight Emulsion at 25°C and 30°C

Time (Minute)	Percentage of Stained Pixels					
	Grip-Tight at 30°C			Grip-Tight at 25°C		
	0.06 gal/yd ²	0.12 gal/yd ²	0.19 gal/yd ²	0.06 gal/yd ²	0.12 gal/yd ²	0.19 gal/yd ²
15	98.9	-	-	-	-	-
30	52.2	-	-	-	-	-
45	0.0	65.1	-	86.5	-	-
60	0.0	0.0	97.3	4.2	77.5	-
75	-	-	30.0	0.0	0.7	94.3
90	-	-	0.0	-	0.0	79.5
105	-	-	-	-	-	0.1
120	-	-	-	-	-	0.0
1 day	0.0	0.0	0.0	0.0	0.0	0.0

4.2.2.3 Verification of Fog Seal Field Tests

A correlation between bond strength and curing behavior has been established by comparing the bond strength values obtained by the BBS test to the distance measured by the rolling ball test, and the stained pixels obtained by the damping test at 30°C and different curing times (30, 45, 60, 75, 90, 120, and 150 minutes). Figure 49 (a) shows the correlation between the bond strength and the rolling distance from the rolling ball test, and Figure 49 (b), (c), and (d) show the correlation between the bond strength and the percentage of stained pixels by the damping test.

The correlations presented in Figure 49 (a) through (d) allow the verification of the curing time criteria suggested from the curing time study. Because bond strength is a fundamental material property, the bond strength values that are required to meet the

empirical criteria for full curing, that is, the critical values of rolling distance and percentage of stained pixels that have been determined from the rolling ball test and the damping test respectively, should be the same for each of the two tests. In Figure 49 (a), the bond strength values for the CSS-1h emulsion that are needed to meet the rolling ball curing criterion of 25 cm are around 49 psi (337.8 kPa) and 51 psi (351.6 kPa) for EARs of 0.06 and 0.12 gal/yd² (0.272 and 0.543 L/m²), respectively. Figure 49 (b) shows that the 5% stained area criterion for the damping test yields bond strength values very close to the values obtained from the rolling ball test. A similar observation can be made using the data from the Revive emulsion; i.e., the bond strength values (around 79 psi (544.7 kPa)) that are needed to meet the rolling distance criterion are close to those obtained from the damping test (between 78 and 82 psi (537.8 and 565.4 kPa)). For Grip-Tight emulsion, the bond strength values (around 76 psi (524.0 kPa)) that are needed to meet the rolling distance criterion are close to those obtained from the damping test (between 77 and 79 psi (530.9 and 544.7 kPa)). These comparisons suggest that the critical distance of 25 cm for the rolling ball test and critical percentage of stained pixels of 5% for the damping test are the criteria that can be used to help determine whether fog seal emulsions are cured properly or not.

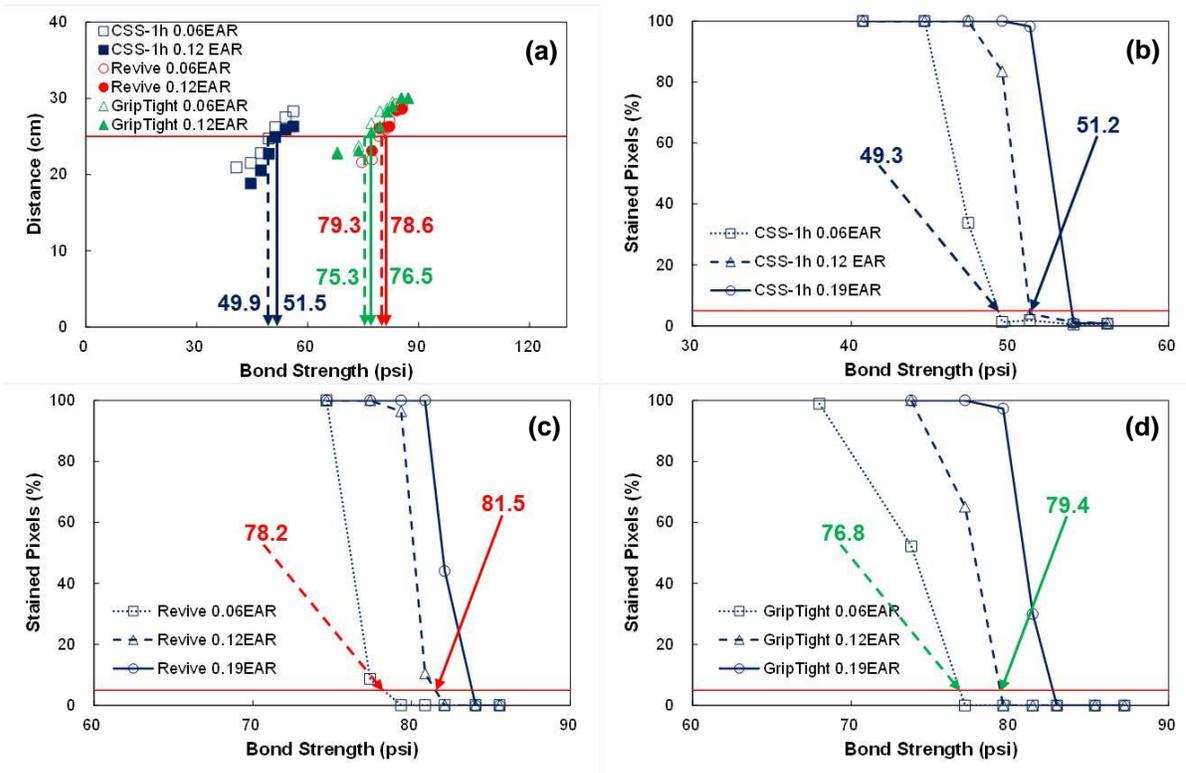


Figure 49 Comparison between BBS test and field tests at 30°C: (a) damping test, (b) rolling ball test for CSS-1h, (c) rolling ball test for Revive, and (d) rolling ball test for Grip-Tight

4.2.3 Fog Seal Performance Test

4.2.3.1 Aggregate Retention Performance

The Vialit test was performed before starting the other tests to verify and select representative fog seal EARs, and was conducted based on the method used in the Estakhri study. The test procedure is that chip seal samples are placed at 77°F for 24 hours for curing and, after fog sealing, the samples are cured at 140°F for 24 hours. EARs of 0.02, 0.06, 0.09, 0.12, 0.16, 0.19, 0.23, and 0.26 gal/yd² (0.09, 0.27, 0.41, 0.54, 0.72, 1.04, and 1.18 L/m²) were used for the CSS-1h and CQS-1h emulsions. In order to fabricate the chip seal samples, an aggregate application rate (AAR) of 10 lb/yd² (5.4 kg/m²) for the lightweight aggregate and an EAR of 0.25 gal/yd² (1.13 L/m²) for the CRS-2L emulsion were applied. These rates

are recommended in the previous chip seal mix design study (Kim and Adams 2011). From these Vialit tests, almost 0% of aggregate loss for all samples was found. Table 24 presents the aggregate loss results from the Vialit tests.

Table 24 Aggregate Loss from the Vialit Tests Using CSS-1h and CQS-1h Emulsions

Loss of Aggregate (%)	Application Rate (gal/yd ²)							
	0.02	0.06	0.09	0.12	0.16	0.19	0.23	0.26
CSS-1h	0.5	0.2	0	0	0	0	0	0
CQS-1h	0.4	0.2	0	0	0	0	0	0

After finding that the Vialit test could not properly test aggregate loss for fog seal samples, the MMLS3 aggregate loss test was performed to verify aggregate loss for fog seal samples. Based on the curing time study, the fog seal emulsion types (CSS-1h, ReviveTM, and Grip-Tight) and EARs (0.08, 0.12, and 0.16 gal/yd² (0.36, 0.54, and 0.72 L/m²)) were selected, and chip seal samples were fabricated in accordance with a previous research (HWY-2008-04). For the chip seal samples, 0.25 gal/yd² (1.13 L/m²) of CRS-2L emulsion and 10 lb/yd² (5.4 kg/m²) of lightweight aggregate were used.

The MMLS3 test procedure is described in section 3.4.6. For aggregate loss testing, the MMLS3 is loaded for 160 minutes at 25°C. Chip seal specimens were fabricated, and then subjected to 10 minutes of MMLS3 loading, which is the time it takes for the MMLS3 to wander across the whole 7-inch width of the specimens. After the fog seal was applied to the loaded chip seal specimens, the specimens again were subjected to MMLS3 loading. Measurements of the specimens were taken for weight, surface texture, and skid resistance at 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15,840 MMLS3 wheel passes). These times can be converted to the number of wheel passes because the MMLS3 applies repeated wheel loads to the specimen surface at a consistent and accelerated rate (990 wheel loads applied every 10 minutes). Figure 50 shows the aggregate loss performance of the fog seal samples.

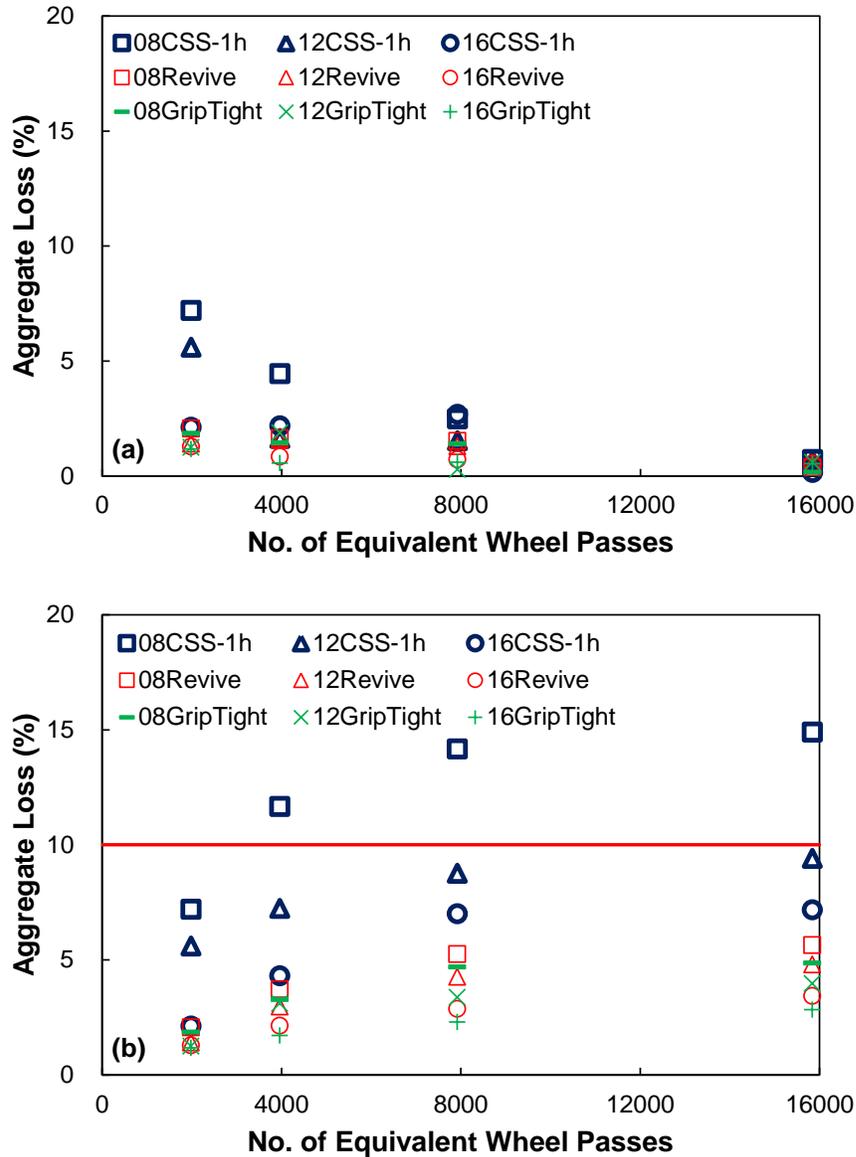


Figure 50 Aggregate loss performance of fog seal specimens: (a) aggregate loss and (b) cumulative aggregate loss

Figure 50 shows that fog seal samples that contain CSS-1h emulsion perform the worst of all the emulsion types; in particular, the samples with an EAR of 0.08 gal/yd² (0.36 L/m²) show approximately 15 % aggregate loss after MMLS3 loading. However, the samples that are applied with ReviveTM and Grip-Tight emulsions show less than 5 % aggregate loss.

The most aggregate loss occurs during the initial stages of testing, and low EARs induce more aggregate loss for all conditions. Overall, the fog seal samples with Grip-Tight emulsion perform the best in terms of aggregate retention performance.

4.2.3.2 Bleeding Performance

The fog seal test specimens used for the MMLS3 aggregate loss testing also were used for the bleeding tests. After the tests, specimens were scanned, and the digital images were analyzed to present numerical values for the bleeding areas on the specimen surface.

Figure 51 shows the bleeding performance of CSS-1h, ReviveTM, and Grip-Tight emulsions as a function of EARs, i.e., 0.08, 0.12, and 0.16 gal/yd² (0.36, 0.54, and 0.72 L/m²).

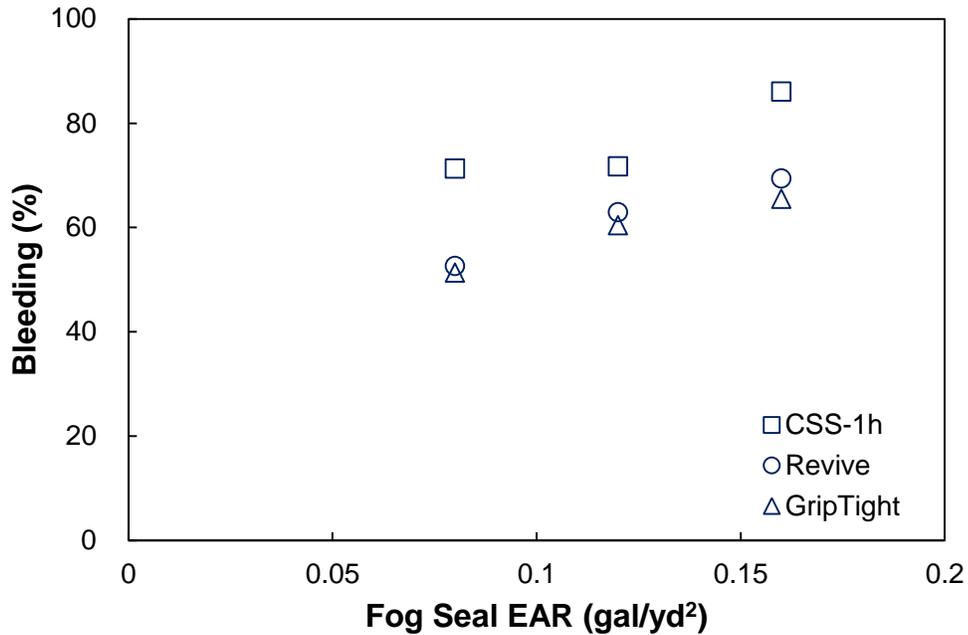


Figure 51 Bleeding test results for CSS-1h, ReviveTM, and Grip-Tight emulsions

Figure 51 shows that higher EARs correspond to more bleeding areas for all emulsion types. The ReviveTM and Grip-Tight emulsions show a similar bleeding trend to each other, whereas the CSS-1h emulsion presents higher bleeding percentages in every case. In

particular, the EAR of 0.16 gal/yd² (0.72 L/m²) for CSS-1h corresponds to the worst performance (least bleeding resistance/most bleeding). This result relates to the skid resistance results. That is, a high bleeding percentage corresponds to a reduction in skid resistance.

4.2.3.3 Mean Profile Depth (MPD) Analysis

The fog seal specimen surface was able to be scanned at 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15,840 MMLS3 wheel passes) during the MMLS3 aggregate loss performance testing. These laser scan data can be calculated to MPD values, as described in section 3.4.7.2. Figure 52 and Figure 53 show the MPD values as a function of the number of wheel passes. Table 25 presents all of the MPD values.

Table 25 MPD Values

Specimens (EARs and Name)	Applied Loading Time (Minutes)							
	0 (Chip Seal)	10 (Chip Seal)	10 (990)	20 (1980)	40 (3960)	80 (7920)	160 (15840)	400 (396000)
0.08 CSS-1h	2.88	2.92	3.39	2.60	2.43	2.26	2.16	1.84
0.12 CSS-1h	2.85	2.93	3.66	2.95	2.53	2.33	2.16	1.52
0.16 CSS-1h	3.11	2.78	3.76	2.65	2.41	2.15	2.02	1.39
0.08 Revive TM	3.00	2.87	4.47	2.62	2.31	2.23	2.07	2.06
0.12 Revive TM	3.07	2.72	4.75	2.42	2.21	2.11	2.00	1.78
0.16 Revive TM	3.10	2.67	5.12	2.56	2.43	2.21	2.18	1.53
0.08 GripTight	3.10	2.59	4.54	2.67	2.27	2.08	1.97	1.77
0.12 GripTight	3.13	2.72	5.52	3.05	2.33	2.04	1.86	1.44
0.16 GripTight	3.15	2.94	5.50	3.30	2.73	2.38	2.17	1.51

* The numbers in parenthesis indicate the number of wheel passes.

** The shaded column lists the MPD values obtained from the bleeding test samples.

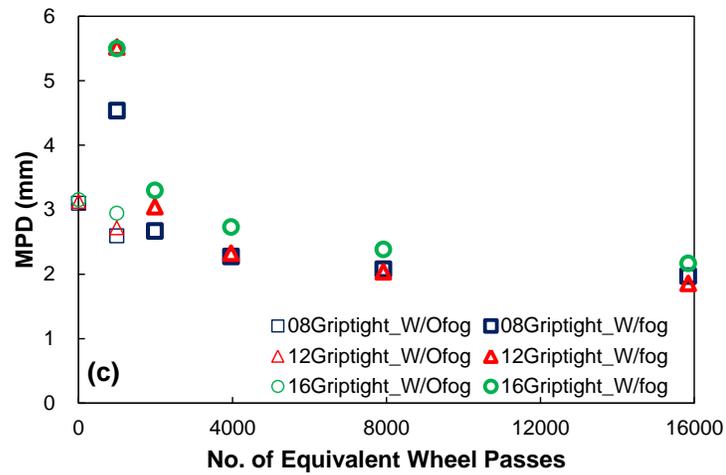
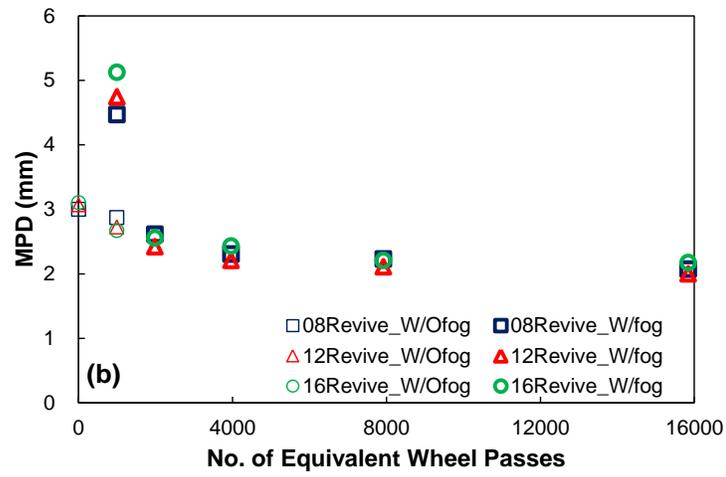
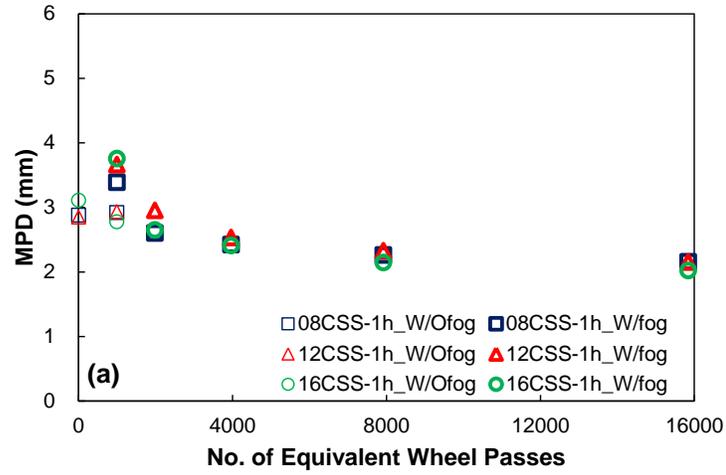


Figure 52 MPD vs. No. of wheel passes for: (a) CSS-1h, (b) Revive™, and (c) Grip-Tight

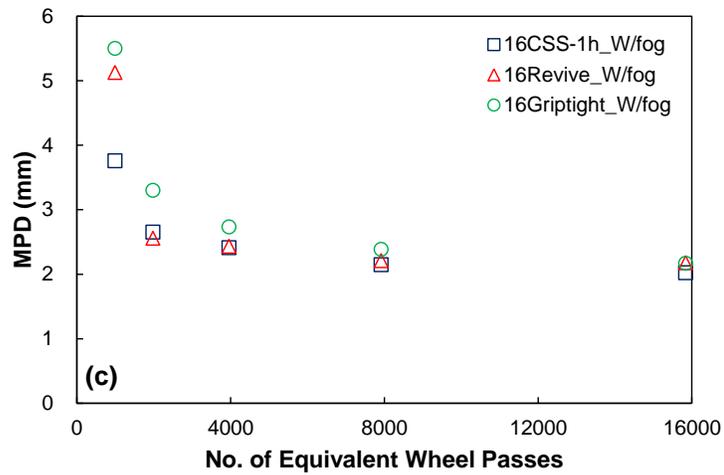
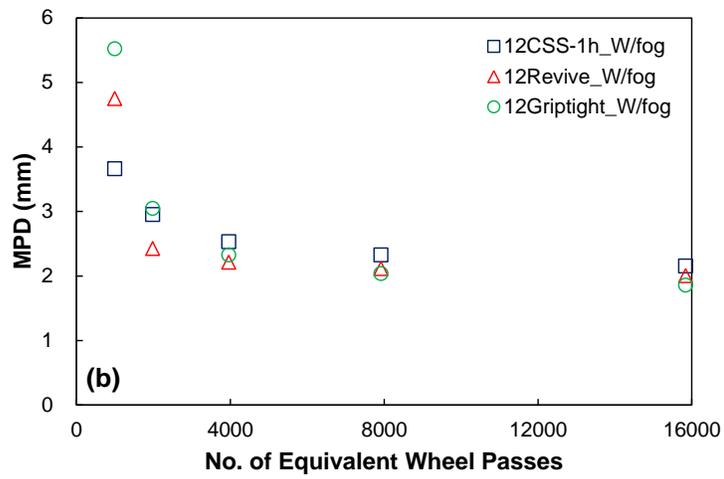
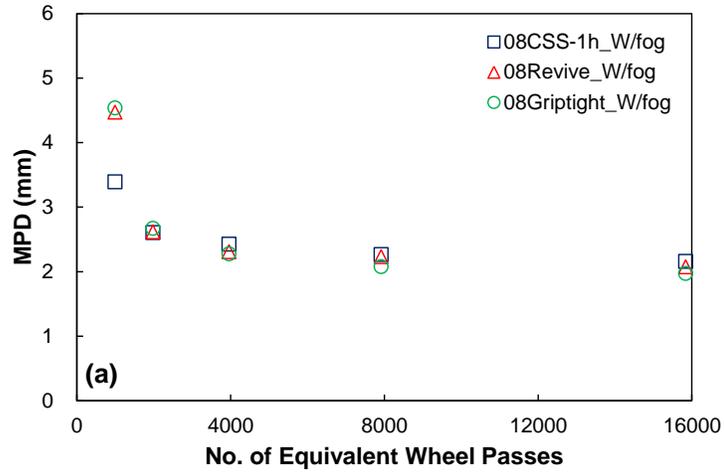


Figure 53 MPD vs. No. of wheel passes for: (a) 0.08 (0.36), (b) 0.12 (0.54), and (c) 0.16 (0.72) gal/yd² (L/m²) of EARs

Figure 52, Figure 53, and Table 25 show that fog sealing increases the MPD values temporarily. However, after traffic loading for 10 minutes, the MPD values decrease to the MPD values of the samples that have not been fog sealed, i.e., the chip seal samples. The reason for this decrease is that applied emulsion can create a rough surface texture once the emulsion is completely cured, but this surface texture can be smoothed easily by traffic loading. Also, the Grip-Tight and ReviveTM emulsions have more asphalt residue than the CSS-1h emulsion, which suggests that emulsions containing more asphalt residue lead to a rougher surface texture than those that do not contain a high level of asphalt residue. For example, the MPD values of Grip-Tight and ReviveTM emulsions are higher than those of CSS-1h emulsion. When comparing overall MPD values as a function of wheel passes, the MPD values decrease significantly within 40 minutes (3,960 MMLS3 wheel passes), but after that amount of time, the change in MPD values is small. Another finding is that the MPD values of each EAR are similar to each other, although their initial MPD values may differ.

4.2.3.4 Skid Resistance Test

The British Pendulum Test (BPT) was performed on fog seal specimen surfaces for 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15840 MMLS3 wheel passes) during the MMLS3 aggregate loss performance testing. The resultant BPN data were converted to SNs, as described in section 3.4.7.3. After aggregate loss performance testing, all of the specimens were subjected to MMLS3 loading for the bleeding test, and BPT was performed on the bleeding test samples. Table 26 presents all of the SNs acquired from BPT results, and Figure 54 shows the SN for the three emulsion types (CSS-1h, ReviveTM, and Grip-Tight).

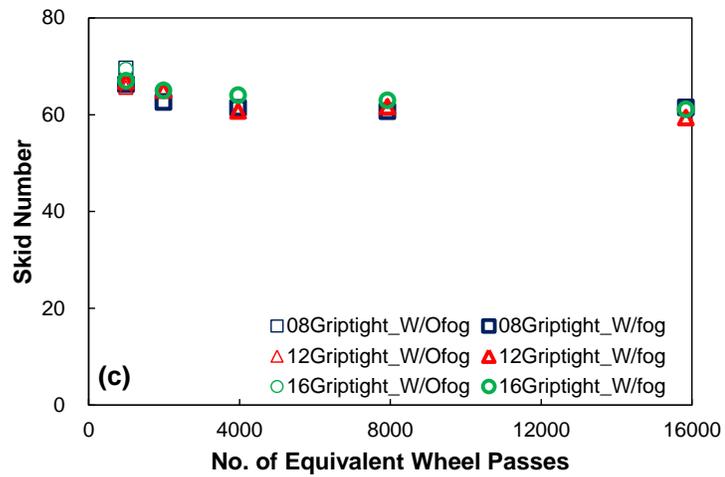
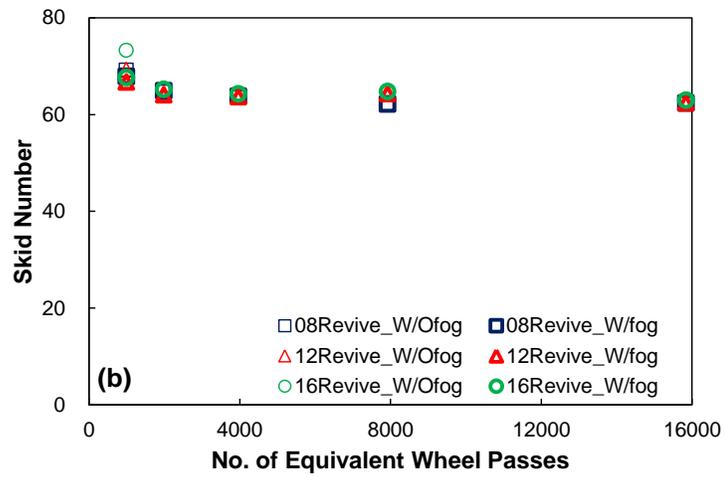
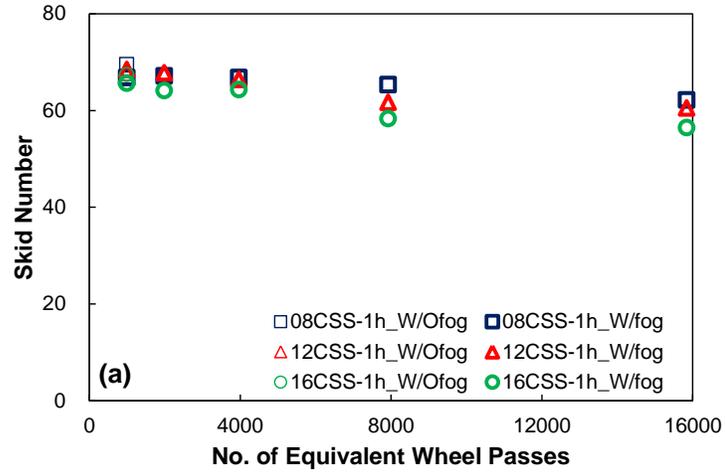


Figure 54 Skid number vs. No. of wheel passes for: (a) CSS-1h, (b) Revive™, and (c) Grip-Tight emulsions

Table 26 Skid Number from BPT

Specimens (EARs and Name)	Skid Number						
	10 min. (Chip Seal)	10 min. (990)	20 min. (1980)	40 min. (3960)	80 min. (7920)	160 min. (15840)	400 min. (396000)
0.08 CSS-1h	70	67	67	67	65	62	58
0.12 CSS-1h	68	68	68	66	62	61	56
0.16 CSS-1h	67	66	64	64	58	56	38
0.08 Revive TM	69	68	65	64	62	62	58
0.12 Revive TM	69	67	64	64	64	62	56
0.16 Revive TM	73	68	65	64	65	63	54
0.08 GripTight	70	66	63	61	61	61	58
0.12 GripTight	66	67	65	61	62	59	57
0.16 GripTight	69	67	65	64	63	61	53

* The numbers in parenthesis indicate the number of wheel passes.

** The shaded column lists the SNs obtained from the bleeding test samples.

From the literature reviews, it is found that the application of fog seal normally reduces the skid resistance of pavement surface. However, Figure 54 does not show a significant reduction in skid resistance between the chip seal and fog seal surface. Table 26 indicates that, after the bleeding test, the skid resistance of most samples does not decrease much, except in the one case with a high EAR (0.16 gal/yd² (0.72 L/m²)) for CSS-1h emulsion. Of course, the skid resistances of fog seal samples is slightly less than that of chip seal samples, but the SNs of fog seal samples are much higher than North Carolina requirement for surface skid resistance (SN 37). This finding suggests that the use of chip seal recommended by the chip seal mix design research (HWY-2008-04) for fog seal construction is adequate and does not cause skid resistance problems.

5. FIELD EVALUATION OF AST PERFORMANCE

5.1 Development of Refined Construction Procedure

The information gathered in literature review, investigation of curing and adhesive behaviors, and previous researches (NCDOT HWY-2006-06, 2007-06, and 2008-04) has been used to develop several refined construction procedures for modified chip seal and a field experimental program to evaluate performance improvement. The refined construction procedures for modified chip seals have been developed by optimizing the following construction factors: (1) mix design, i.e., the emulsion application rate (EAR) and aggregate application rate (AAR), (2) the time interval between spraying the emulsion and spreading the aggregate, (3) the time interval between spreading the aggregate and rolling, (4) rolling patterns, (5) traffic opening time, and (6) time for sweeping.

The objectives of the field construction are:

- to evaluate the aggregate retention performance of the chip seal pavements,
- to obtain field samples immediately after construction,
- to test the samples in the laboratory for aggregate retention performance, and
- to monitor field sections for the performance of the chip seal pavements.

At the pre-construction meeting for the high-volume chip seal field construction, the construction variables that had been proposed in the previous meeting were confirmed for application in the field testing. Table 27 shows the variables.

Table 27 Field Construction Variables

Variables	Decision
Seal Type	Triple Seal
Emulsion Type	CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A
Mix Design	Optimal EAR and AAR
Rolling Pattern	Type B
Sweeping Schedule	After Curing for 2 to 3 Hours
Fog Seal	Revive and CSS-1h on CRS-2 and CRS-2L Sections
Traffic Volume	Low (~ 5,000 ADT), Medium (~ 10,000 ADT), and High (~ 15,000 ADT)
Number of Samples	15 MMLS3 (low volume) and 3 Vialit (medium and high volumes)

At the meeting, the triple seal was selected because it is a commonly used seal type that is used for high-volume roads nationally. The Virginia #9 aggregate will be used as the top layer as a choking material for the granite 78M aggregate used in the middle layer. This approach has been reported successful in reducing the aggregate loss and improve the visual appearance of the chip seal.

Four emulsion types (CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A) will be used in the field construction. A constant EAR and AAR will be applied to all the test sections, and the optimal EAR and AAR were decided by the field supervisor.

For the rolling pattern, type A and type B shown in Figure 2 were suggested at the meeting based on previous research (NCDOT HWY-2006-06), and type B was selected for the field construction. For type B, two pneumatic tire rollers are used to apply three coverages to the entire lane width, and then the combination roller, as a third roller, is employed to apply an additional coverage on the section. The advantage of type B is that it allows more coverages (four coverages in type B versus three coverages in type A) within the same amount of rolling time. In addition, type B can fully capture the ability of both the pneumatic tire roller that rolls the uneven surface of the existing pavement and the combination roller that provides a smooth surface. The schematic rolling patterns can be seen in the literature review section (Figure 2).

In general, sweeping before opening to traffic is recommended because loose stones can cause serious damage to vehicles on high-volume roads. Hence, it was decided that the constructed section should be swept after two to three hours of curing, and then the section will be opened to traffic.

Fog seals are one of several effective ways to improve chip seal pavements. Two sections, one constructed with CRS-2 emulsion and one with CRS-2L emulsion, have been selected to study the curing and retention performance of fog seals on top of chip seals. For the field tests, the CSS-1H and Revive emulsions were selected as an unmodified emulsion and a PME, respectively.

In order to compare the effects of different traffic volumes on chip seal performance, three traffic volumes, low (less than 5,000 ADT), medium (5,000 – 10,000 ADT), and high (10,000 – 15,000 ADT) will be targeted for the field construction. It was stated at the meeting that the CRS-2 emulsion causes aggregate retention and bleeding problems for high-volume roads. Hence, it was proposed that the CRS-2 sections will be constructed for low traffic volumes only. Based on existing pavement conditions and other variables, Chin Page Road (SR 1969), Farrington Road (SR 1110), and Carver Street (SR 1407) in Durham County were selected as roadways for field sections with low (5,000 ADT), medium (10,000 ADT), and high (15,000 ADT) traffic volumes, respectively. Based on discussions held at a few meetings at the field sites, the test section lengths and locations were determined because similar existing pavement conditions and a longitudinal slope would play a vital role in the comparison of performance among all the test sections. Figure 55 (a), (b), and (c) show the three field sites, respectively, and information about each site.

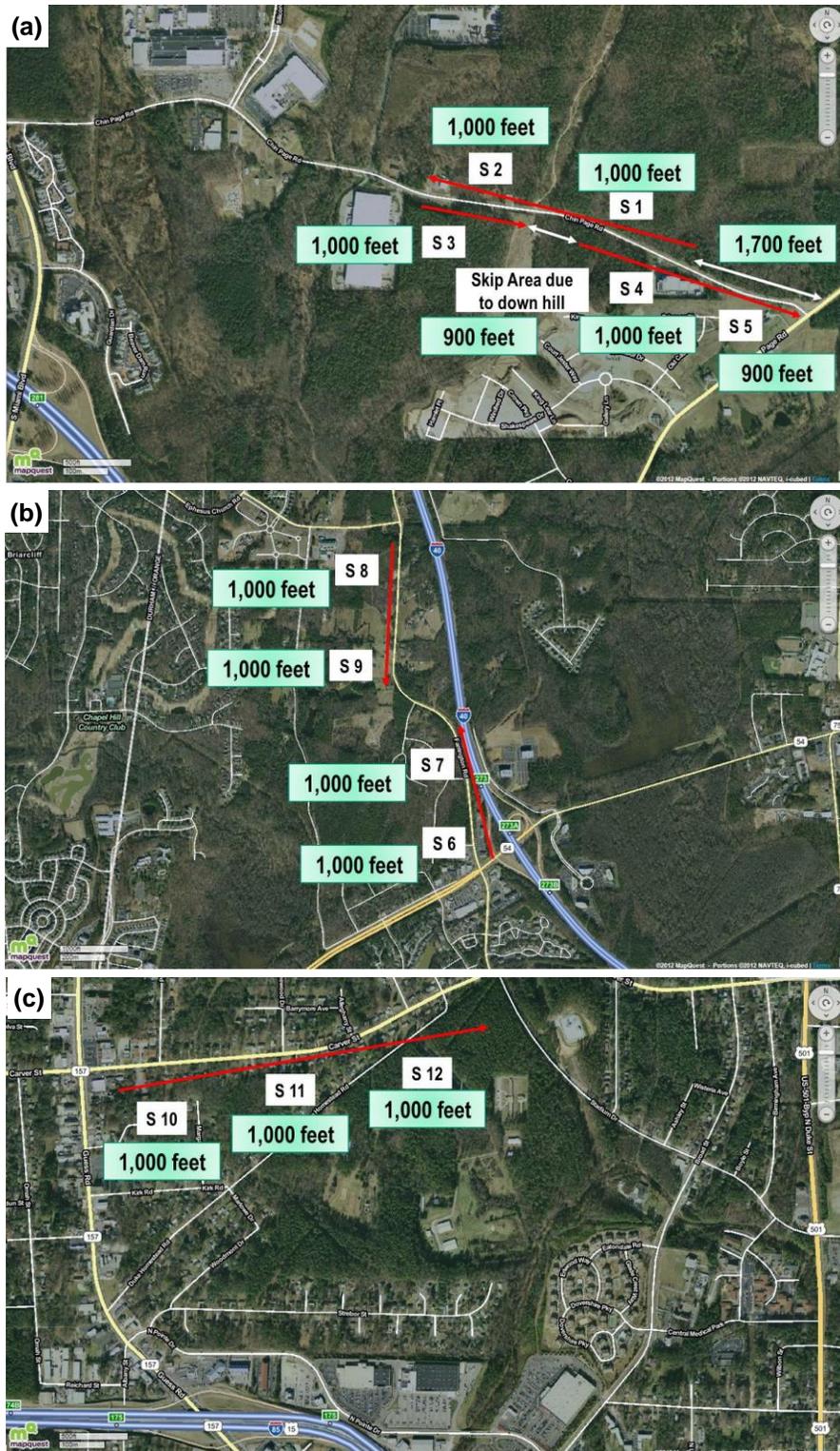


Figure 55 Field construction sites: (a) Chin Page Road (low volume), (b) Farrington Road (medium volume), and (c) Carver Street (high volume)

In order to ensure a sufficient test length that can accommodate the monitoring, field testing, and sampling of each section, each section was decided to be 1,000 feet long. Figure 56 shows the test section diagrams.

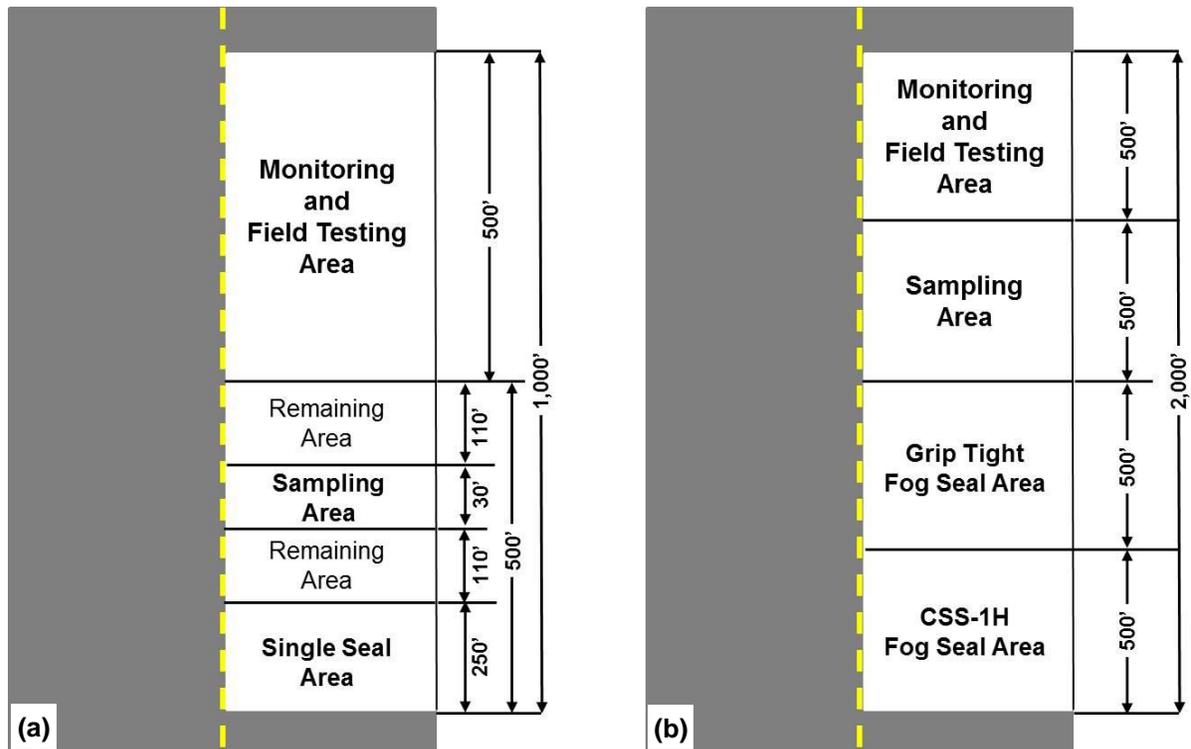


Figure 56 Test section diagram: (a) chip seal section and (b) chip seal with fog seal section

Table 28 shows information that includes the location, pavement condition rating, resurfaced year, section number, traffic volume, emulsion type, section type, section length, field sample, and field test for all the construction sections.

Table 28 Field Section Information

Location	Traffic Volume	Condition Rating 2010	Resurfaced	Section Number	Emulsion	Type and Length (feet)	Sampling	Testing
Chin Page Road	Low < 5K ADT	91.7	2005	1	CRS-2 (Fog Seal)	CSS-1h (500), Revive (500)	None	Fog seal tests
				2	CRS-2	Triple (800), Single (200)	Triple (MMLS3) Single (Vialit)	Laser scan
				3	CRS-2L	Triple (800), Single (200)	Triple (MMLS3) Single (Vialit)	Laser scan
				4	SBS CRS- 2P	Triple (800), Single (200)	Triple (MMLS3) Single (Vialit)	Laser scan
				5	FiberMat	Double (900)	Double(MMLS3)	Laser scan
Farrington Road	Medium 5K < <10K ADT	85.1	2004	6	CRS-2L (Fog Seal)	CSS-1h (500), Revive (500)	None	Fog seal tests
				7	CRS-2L	Triple (1,000)	Vialit	Laser scan
				8	SBS CRS- 2P	Triple (1,000)	Vialit	Laser scan
				9	FiberMat	Double (1,000)	Vialit	Laser scan
Carver Street	High 10K < <15K ADT	93.4	2003	10	CRS-2L	Triple (1,000)	Vialit	Laser scan
				11	SBS CRS- 2P	Triple (1,000)	Vialit	Laser scan
				12	FiberMat	Double (1,000)	Vialit	Laser scan

5.2 Construction of Field Section Using Different Construction Procedures

5.2.1 *Field Construction Timeline*

At the pre-construction meeting for the high-volume chip seals, September 24th, 25th, 26th, and 27th were proposed as construction dates for the three sections of the high-volume road (SR 1407, Carver Street), four sections of the medium-volume road (SR 1110, Farrington Road), two sections of the low-volume road, and three sections of the low-volume road (SR 1969, Chin Page Road), respectively. All the test sites are located in Durham County.

After preparing the field sites, which included calibrating the equipment, traffic control, and sample template preparation, the bottom layer of the chip seal with the EAR of 0.25 gal/yd² (1.13 L/m²) and AAR of 22 lb/yd² (11.9 kg/m²) (granite 78M) was constructed on the entire section, and the second layer was applied with the EAR of 0.25 gal/yd² (1.13 L/m²) and AAR of 22 lb/yd² (11.9 kg/m²) (granite 78M), except the single seal area, which is located at the end of the section. Finally, the top layer with the EAR of 0.18 gal/yd² (0.81 L/m²) and AAR of 11 lb/yd² (6.0 kg/m²) (Virginia #9) was constructed on the double seal area. One important component of the test protocol was to create a sweeping schedule for the high-volume chip seal construction because loose aggregates can cause serious damage to vehicles, especially on high-volume roads. Based on Shuler's recommendation, sweeping was planned for three hours after construction (Shuler 1990). For the fog seal performance validation, two sections (CRS-2 on the low-volume road and CRS-2L on the medium-volume road) were selected, and the fog seal was constructed after sweeping with CSS-1h and Revive emulsions. The construction timeline is displayed in Figure 57.

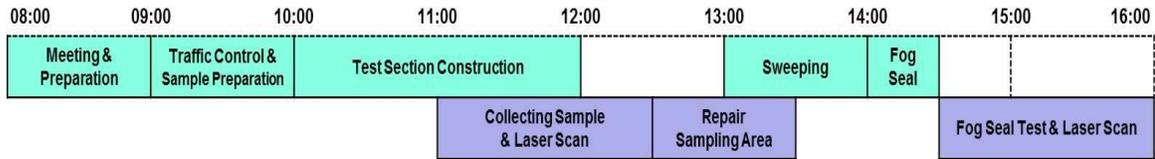


Figure 57 Field construction timeline

5.2.2 Field Sampling and Testing

In order to compare the actual application rates of the emulsions and aggregates, two Vialit samples were extracted from both the high and medium volume roads per section, and for the laboratory testing, 15 MMLS3 samples were taken from the low-volume road per section. Sampling was undertaken after one hour of curing to prevent damage to the field samples. The sides of the sampling area were cleaned to patch the damaged area effectively, and then the samples were placed on wood boards and transported to a box truck. Figure 58 shows the field sampling for the Vialit and MMLS3 samples.

The monitoring of the chip seal pavement will be performed until early 2013. According to the literature review, the aggregate loss of chip seals occurs during the first winter season, so it is important to know the initial condition of the chip seal pavements in order to compare their performance. In order to monitor the performance of the chip seals, the pavement surface will be scanned before and after the sweeping procedure on the monitored area. The laser scanning and visual observation should be performed before and after the winter of 2013. As reference points for this future work, two nails have been driven into the pavement surface, and the scanning area has been marked on the pavement surface. Figure 59 shows the laser scanner and the reference points in the field.



Figure 58 Field sampling: (a) Vialit sample template, (b) Vialit samples, (c) MMLS3 sample template, and (d) MMLS3 samples



Figure 59 Laser scanning in the field

5.2.3 Construction Target Rates

All the CRS-2, CRS-2L, and SBS CRS-2P emulsion sections for the three traffic volumes (low, medium, and high) were constructed according to the following application rates: EARs of 0.25 gal/yd² (1.13 L/m²) (bottom layer), 0.25 gal/yd² (1.13 L/m²) (second layer), and 0.18 gal/yd² (0.81 L/m²) (top layer) and AARs of 22 lb/yd² (11.9 kg/m²) (granite 78M, bottom layer), 22 lb/yd² (11.9 kg/m²) (granite 78M, second layer), and 11 lb/yd² (6.0 kg/m²) (Virginia #9, top layer). The application rates of the emulsion and seal type were changed for the FiberMat sections because FiberMat generally is applied as a single seal treatment. However, the NCDOT bituminous supervisor in charge of construction had reservations about applying FiberMat as a single seal, so CRS-2L emulsion with Virginia #9 aggregate were used to cover the FiberMat single seal. The CRS-2L emulsion was used for the FiberMat construction, and 0.12 gal/yd² (0.54 L/m²) of it was applied, followed by application of the fibers, and then another 0.12 gal/yd² (0.54 L/m²) of CRS-2L emulsion was applied to cover the fibers. As a result, the FiberMat sections for all traffic volumes (low, medium, and high) were constructed as double seals with the following application rates: EAR of 0.24 gal/yd² (1.09 L/m²) (CRS-2L with fibers) and the AAR of 22 lb/yd² (11.9 kg/m²) (granite 78M) for the bottom layer, and EAR of 0.18 gal/yd² (0.81 L/m²) (CRS-2L without fibers) and AAR of 11 lb/yd² (6.0 kg/m²) (Virginia #9) for the top layer. During the construction of the 200 feet of single seal on low-volume sections, the FiberMat distributor changed the EAR from 0.12 gal/yd² (0.54 L/m²) (CRS-2L with fibers) to 0.20 gal/yd² (0.91 L/m²) (CRS-2L with fibers) without consulting the NCDOT or the NCSU research team. The NCDOT Bituminous Supervisor and the NCSU research team believed that this revised rate would definitely cause bleeding based on visual inspection and made the necessary adjustment for that part of the section. In summary, the single seal was changed to a double seal with the following application rates: EAR of 0.40 gal/yd² (1.81 L/m²) (CRS-2L with fibers) and AAR of 22 lb/yd² (11.9 kg/m²) (granite 78M) for the bottom layer, and EAR of 0.15 gal/yd² (0.68 L/m²) (CRS-2L without fibers) and AAR of 11 lb/yd² (6.0 kg/m²) (Virginia #9) for the top layer. Table 29 shows the construction target application rates.

Table 29 Construction Target Application Rates

Section Number	Seal Type	EAR (gal/yd ²)	AAR (lb/yd ²)
1 – 4, 6 – 8, 10 – 11	Triple	0.25/0.25/0.18 (Bottom/Second/Top)	22/22/11 (Granite/Granite/Virginia#9)
5, 9, 12	Double	0.24/0.18 (Bottom/Top)	22/11 (Granite/Virginia#9)

5.3 Field Application Rates (Ignition Oven Test)

For the MMLS3 performance test, field samples were obtained from the low traffic volume sections for the different emulsion types (CRS-2, CRS-2L, CRS-2P, and FiberMat Type A). In order to compare the performance of chip seal samples obtained from the field, it is necessary to know the actual EARs and AARs for the field samples, even though the target rates are already known. The ignition oven test is used for this purpose. Figure 60 shows a sample before and after the ignition oven test.



Figure 60 Ignition oven test sample: (a) before test and (b) after test

For the ignition oven test, three Vialit or MMLS3 samples, which were obtained from all the field sections except the fog seal sections (section numbers 1 and 6), were used to determine the actual EARs and AARs used in the field construction. The MMLS3 aggregate loss tests were conducted using field samples for all the emulsion types (CRS-2, CRS-2L,

CRS-2P, and FiberMat Type A), which were obtained from the low-volume sections. The aggregate loss was calculated using the actual EARs and AARs of the tested samples.

As mentioned before, seven sections (section numbers 2, 3, 4, 7, 8, 10, and 11) were constructed as triple seal sections, three sections (section numbers 5, 9, and 12) were constructed as double seal sections, and two sections (section numbers 1 and 6) were applied fog seals. It is not possible to know the actual AARs and EARs for each layer (bottom, middle, and top) with field samples, so the sum of the AARs and EARs for each layer was used to verify the actual rates. For the triple seals, an AAR of 55 lb/yd² (29.8 kg/m²) and EAR of 0.68 gal/yd² (3.08 L/m²) were the target rates, and an AAR of 33 lb/yd² (17.9 kg/m²) and EAR of 0.43 gal/yd² (1.95 L/m²) were the target rates for the double seals. After determining the actual AARs and EARs, the application ratio (AAR divided by EAR) was obtained to compare each section's conditions. Figure 61 (a), (b), and (c) show the actual AARs, EARs, and application ratios for the triple seal sections, respectively. Figure 62 (a), (b), and (c) show the actual AARs, EARs, and application ratios for the double seal sections, respectively. Table 30 presents the field construction conditions and information about each section.

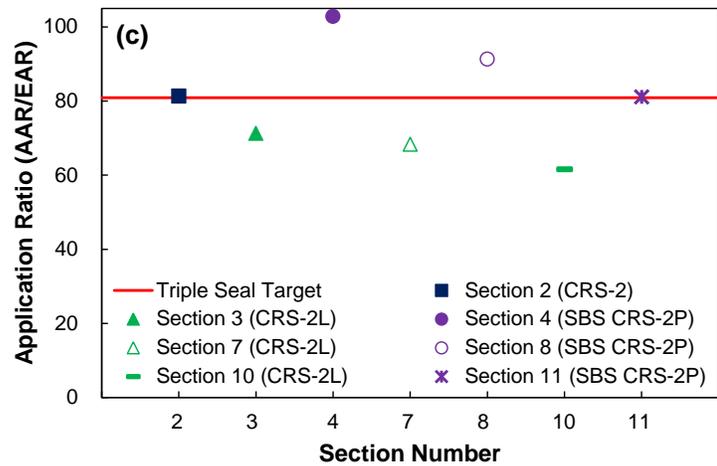
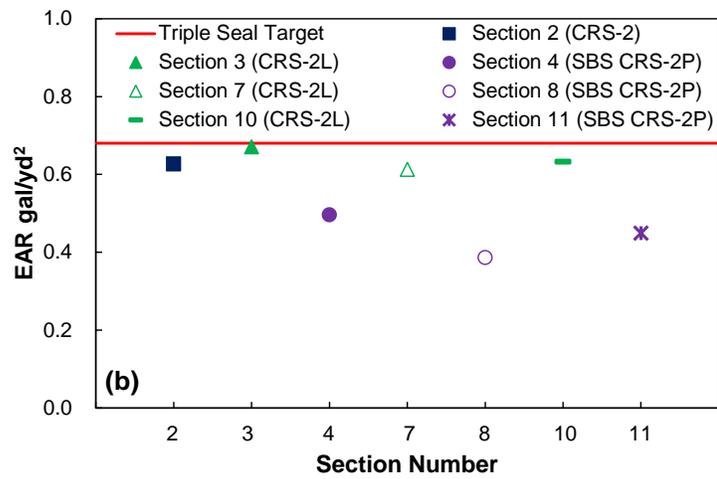
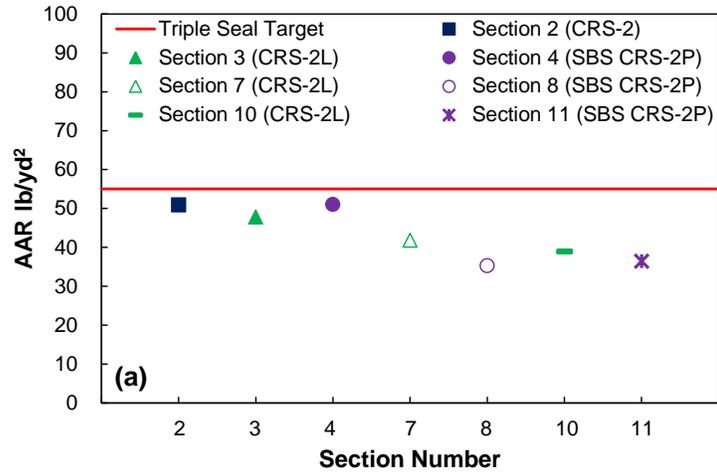


Figure 61 Actual application rates for triple-seal sections: (a) AARs, (b) EARs, and (c) application ratios (AAR/EAR)

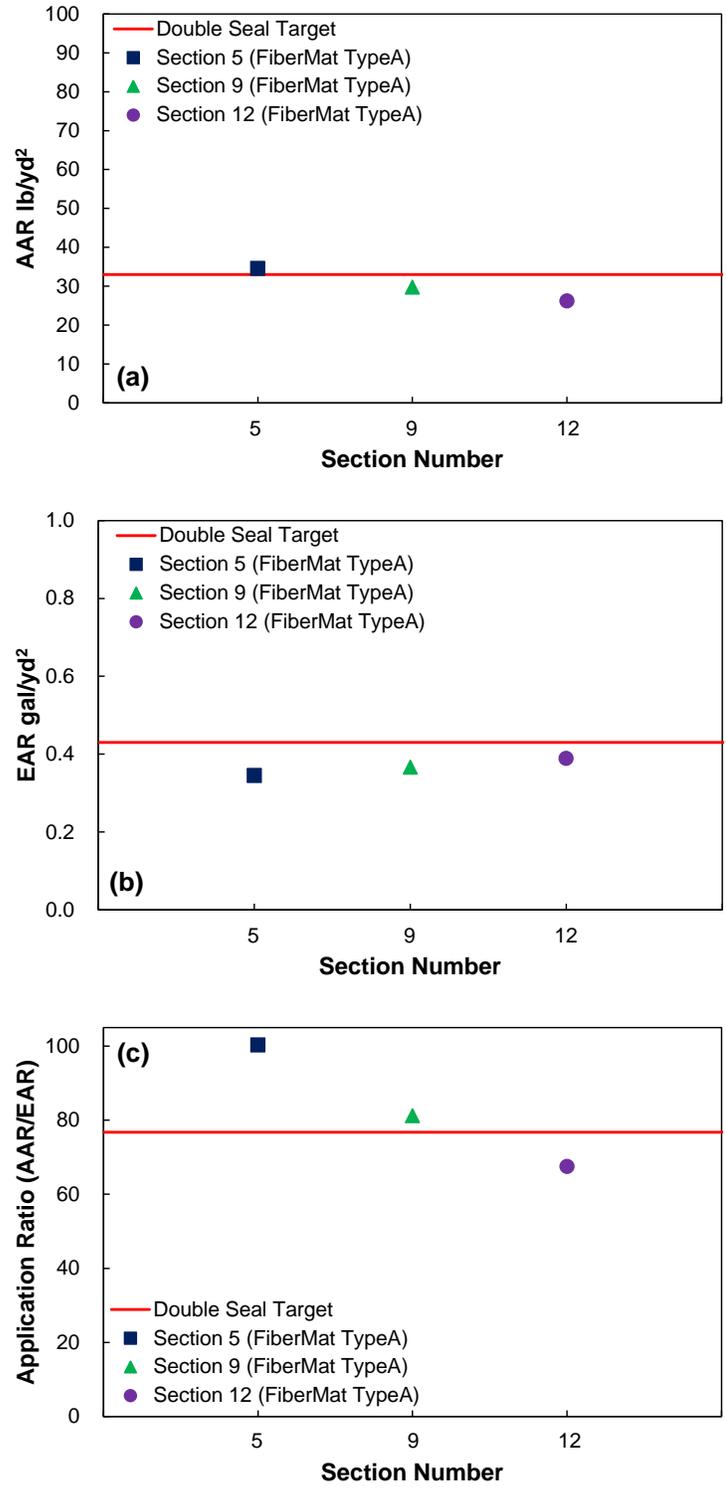


Figure 62 Actual application rates for double-seal sections: (a) AARs, (b) EARs, and (c) application ratios (AAR/EAR)

According to the data shown in Figure 61 (a) and (b), the AARs and EARs that were actually applied to triple chip seal sections are lower than the target rate for all the emulsion types. The same observation can be made for the double seal sections in Figure 62 (a) and (b) except for section number 5 (higher AAR and lower EAR). Figure 61 (c) and Figure 62 (c) show the AAR/EAR application ratio for each section. From the figures, it is seen that almost all the sections do not meet the target application ratio; this finding confirms the presence of wide and unpredictable variations in application rates during field construction.

Table 30 Field Construction Conditions

Section Number	Traffic Volume	Field Condition	Type		
			Emulsion	Seal Type	Aggregate Type*
2	Low (<5K ADT)	Dry	CRS-2	Triple	G/G/V
3		Wet	CRS-2L	Triple	G/G/V
4		Dry	SBS CRS-2P	Triple	G/G/V
5		Dry	FiberMat Type A	Double	G/V
7	Medium (<10K ADT)	Wet	CRS-2L	Triple	G/G/V
8		Dry	SBS CRS-2P	Triple	G/G/V
9		Dry	FiberMat Type A	Double	G/V
10	High (<15K ADT)	Wet	CRS-2L	Triple	G/G/V
11		Dry	SBS CRS-2P	Triple	G/G/V
12		Wet	FiberMat Type A	Double	G/V

Note: *G - Granite 78M aggregate, V - Virginia #9 aggregate

In Table 30, the field condition is described as a dry or a wet condition. The dry condition indicates that the AAR/EAR ratio of a given section is higher than its target ratio. Because the ratio is calculated by the AAR divided by the EAR, a dry section with a high application ratio indicates that more aggregate is applied based on the amount of emulsion that is applied. In contrast, the wet condition indicates a lower AAR/EAR ratio than the target ratio, and less aggregate is applied based on the amount of emulsion that is applied.

5.4 Chip Seal Performance Tests on Field Samples

5.4.1 Aggregate Loss Test

The MMLS3 aggregate retention tests and bleeding tests were conducted using field samples obtained from the low traffic volume sections. The emulsion types are CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A.

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in aggregate retention performance between the CRS-2 emulsion and the PMEs. Table 31 summarizes the results of the statistical analysis for the emulsion types. The p-values of all the emulsion types are less than 0.05. Thus, the MMLS3 test results indicate that the field samples constructed with the PMEs differ statistically in terms of aggregate retention performance compared to those made of the CRS-2 emulsion.

Table 31 Results of Statistical Analysis for Emulsion Types: Aggregate Retention Performance of Field Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
CRS-2	9.4	0.03	0.2	0.095			
CRS-2L	6.3	1.39	1.2	0.680	4.47	0.023	Reject H _o
SBS CRS-2P	5.5	6.78	2.6	1.302	3.00	0.029	Reject H _o
FiberMat	6.6	1.98	1.4	0.813	3.45	0.037	Reject H _o

Figure 63 shows the aggregate loss test results. Each data point represents the percentage of the average cumulative aggregate loss from three specimens.

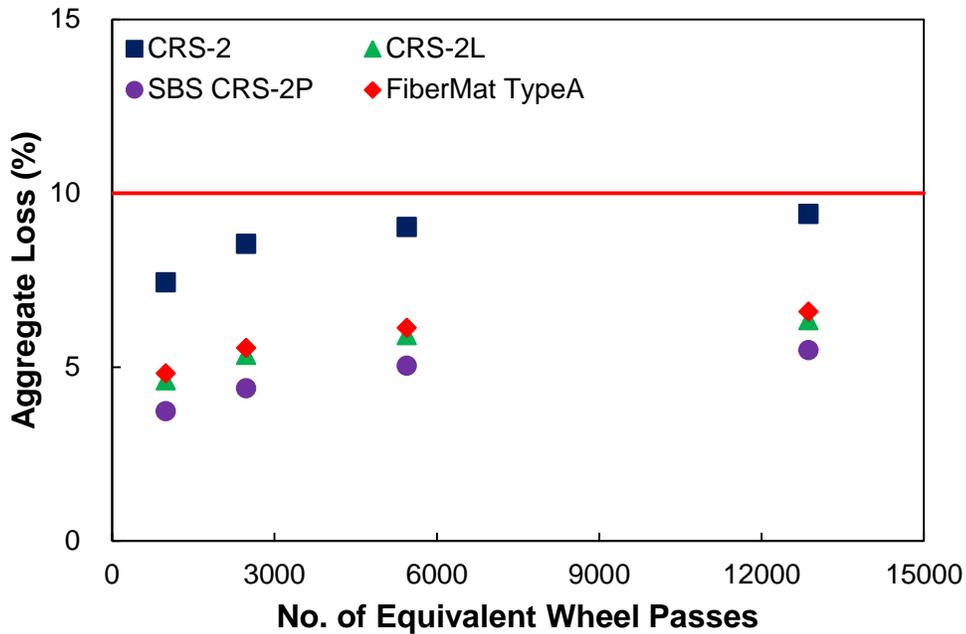


Figure 63 MMLS3 aggregate loss results for field samples

Figure 63 indicates that the CRS-2 samples show the worst aggregate retention performance, whereas the SBS CRS-2P samples perform the best of all the emulsion types. The proper interpretation of the results shown in Figure 63 requires a careful consideration of the field sample conditions, because the dry condition tends to cause more aggregate loss than the wet condition. Based on the ignition oven tests, the CRS-2, SBS CRS-2P, and FiberMat Type A emulsion samples indicate the dry condition, and only the CRS-2L emulsion samples indicate the wet condition. In spite of the dry condition of the field samples, the SBS CRS-2P samples still show the best aggregate retention performance. Another important finding from the MMLS3 aggregate loss tests is that all the field samples meet the criterion of 10% aggregate loss. Therefore, the test results clearly show that the use of Virginia #9 aggregate as a top layer is effective in reducing aggregate loss in chip seals.

5.4.2 Bleeding Test

The specimens used for the MMLS3 aggregate loss tests typically are used for the bleeding tests, but in this case, the specimens must be burned after the aggregate loss test to

calculate the amount of aggregate loss. Thus, only some of the specimens used for the MMLS3 aggregate loss test (three replicates per emulsion type) were used for the bleeding tests. The samples were conditioned in the MMLS3 chamber for three hours at 50°C, and then MMLS3 loading was applied for four hours at the same temperature. This test protocol was developed to simulate the bleeding of chip seal surfaces during the summer. After the tests, the specimens were scanned, and the digital images were analyzed to present numerical values for the bleeding areas on the specimen surface.

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in bleeding performance between the CRS-2 emulsion and the PMEs. Table 32 summarizes the results of the statistical analysis for the emulsion types. The p-values of all the emulsion types are higher than 0.05. Thus, the bleeding performance of the field samples does not differ statistically between the PMEs and the CRS-2 emulsion.

Table 32 Results of Statistical Analysis for Emulsion Types: Bleeding Performance of Field Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
CRS-2	6.8	2.55	1.6	1.129			
CRS-2L	3.4	0.51	0.7	0.412	2.84	0.215	Accept H _o
SBS CRS-2P	2.5	0.35	0.6	0.340	3.68	0.169	Accept H _o
FiberMat	2.7	1.07	1.0	0.596	3.26	0.082	Accept H _o

Figure 64 shows the bleeding performance of the field samples obtained from the low traffic volume sections. The emulsion types are CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A.

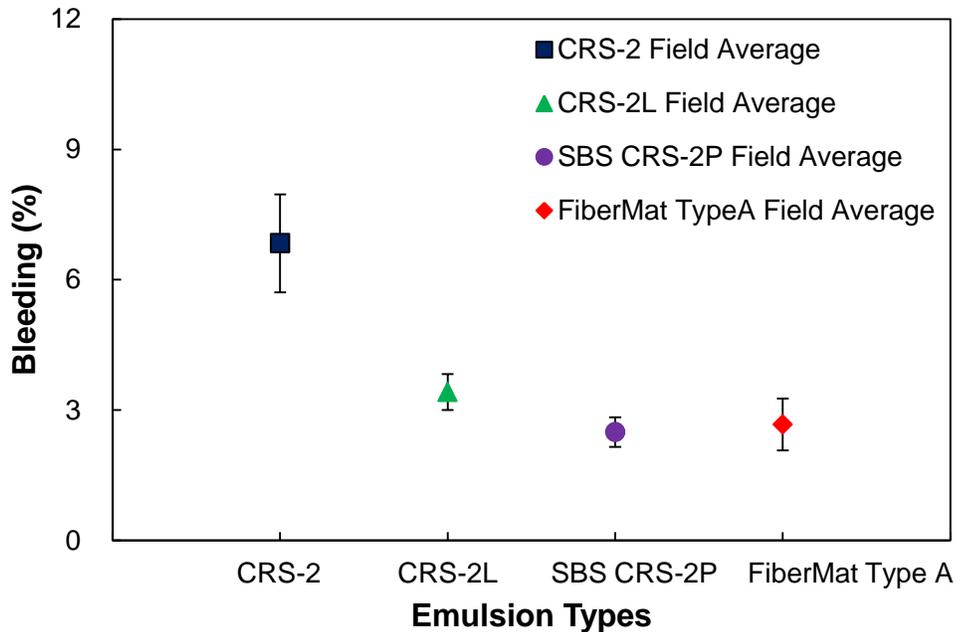


Figure 64 Bleeding analysis for field samples

Figure 64 indicates that the CRS-2 emulsion samples exhibit the least resistance to bleeding, and the SBS CRS-2P emulsion samples exhibit the most resistance to bleeding for all emulsion types. For the bleeding analysis, the field condition (dry or wet) should be considered. A slightly higher bleeding shown in CRS-2L might be due to the wet condition of the CRS-2L section (section 3) as shown in Figure 61 and Table 30. It is noted that the bleeding test results for all the emulsion types are very low, almost the same as the laboratory test results for the combination of the PME and the lightweight aggregate. That is, all the field samples, even the CRS-2 emulsion samples, show strong resistance to bleeding.

5.4.3 Rutting Test

Figure 65 shows the transversal profiles as a function of MMLS3 loading times for all specimens (CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A emulsions). In order to compare the rut depths of the triple seal and double seal specimens, the calculated rut depths of all the specimens are determined as a function of the number of wheel passes, shown in Figure 66 in semi-log scale.

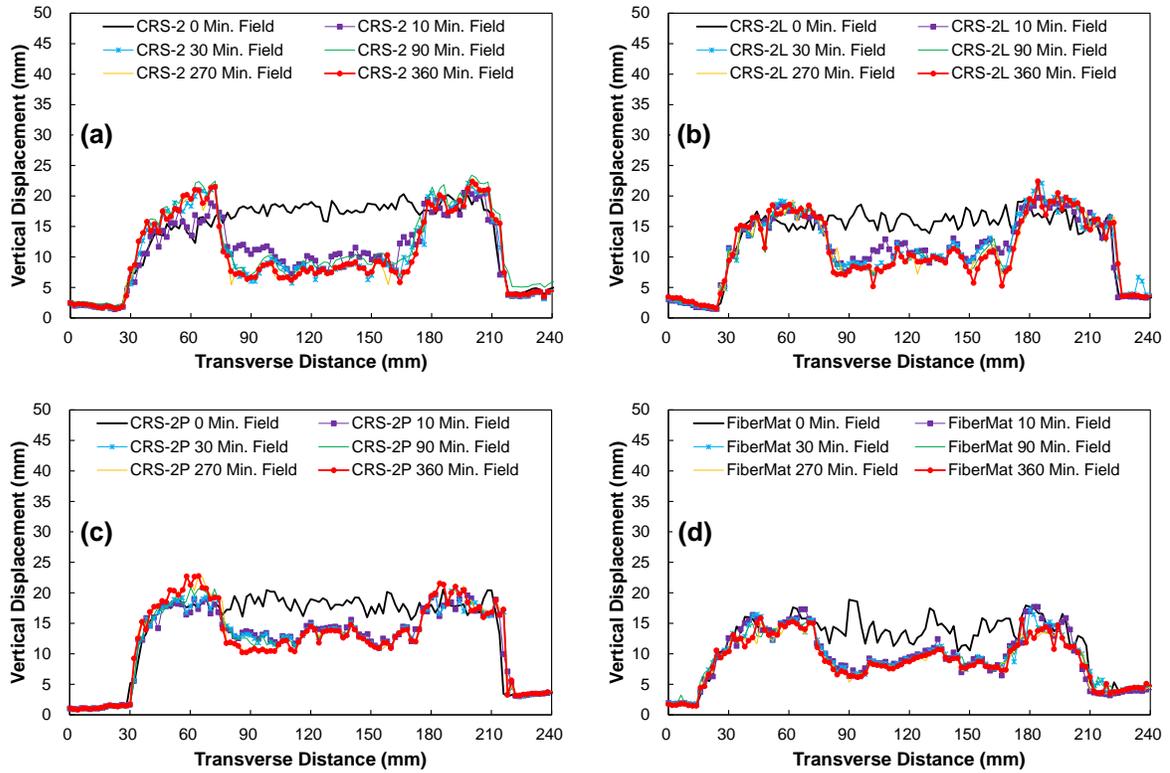


Figure 65 Transversal profiles for field samples: (a) CRS-2, (b) CRS-2L, (c) HP CRS-2P, and (d) SBS CRS-2P emulsions

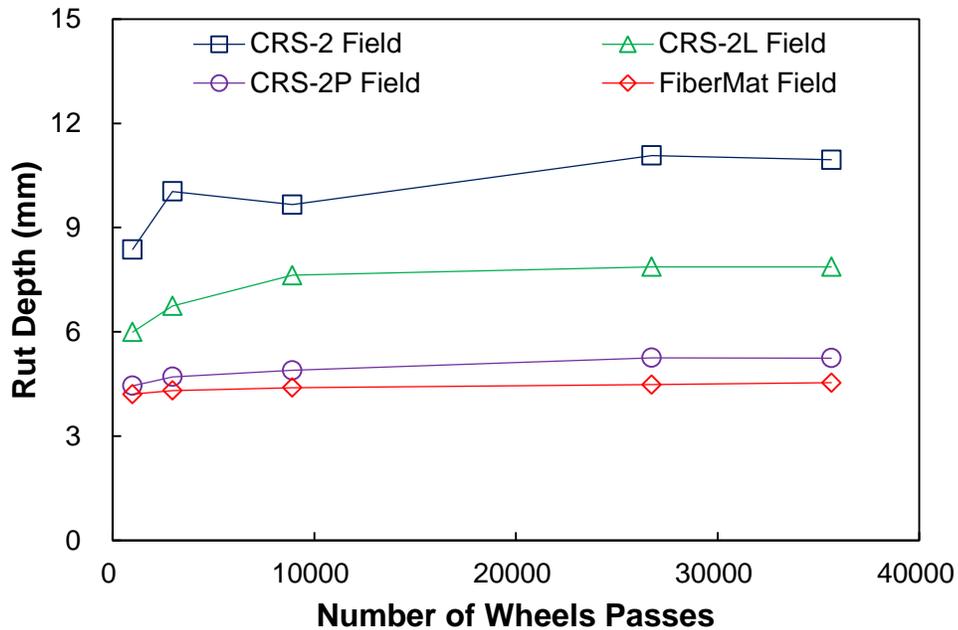


Figure 66 Rut depth growth (semi-log scale)

Figure 65 and Figure 66 illustrate that the CRS-2 sample shows the poorest resistance to rutting, and the SBS CRS-2P sample exhibits the best resistance to rutting among the triple seal samples. Although the FiberMat Type A sample resists rutting better than the SBS CRS-2P sample, it is not possible to compare them directly due to the different seal types (triple vs. double seals).

A t-test with significant levels of 0.05 was performed to evaluate the statistical differences in rutting performance between the CRS-2 emulsion and the PMEs. Table 33 summarizes the results of the statistical analysis for the emulsion types. The p-values of all the emulsion types are less than 0.05. Thus, the rutting performance of the field samples differs statistically between the PMEs and the CRS-2 emulsion.

Table 33 Results of Statistical Analysis for Emulsion Types: Rutting Performance of Field Samples

Emulsion Type	Mean	Variance	Std. Dev.	Error	t-test	p-value	Conclusion
CRS-2	11.0	0.30	0.54	0.314			
CRS-2L	7.9	0.31	0.55	0.319	6.85	0.0024	Reject H _o
SBS CRS-2P	5.2	2.85	1.69	0.976	5.57	0.0308	Reject H _o
FiberMat	4.5	0.21	0.46	0.265	15.55	0.0001	Reject H _o

5.5 Field Section Monitoring

For this study, all 12 sections were constructed on September 24th, 25th, 26th, and 27th 2012 for three different traffic volumes. All the field sections have been observed visually and scanned using the 3-D laser scanner since the first day of construction. Because aggregate loss, which is one of most common failures, occurs early in the service life after construction, especially during the first winter season, three field section surveys were conducted: on the day of construction, before winter, and after winter. Light sweeping was performed on the day of construction intentionally because of the concern that early sweeping with normal intensity would be too forceful for fresh chip seals and cause more aggregate loss. Thus, the first observation was performed twice, i.e., on the day of construction and a week after construction. The second observation was performed approximately 10 weeks after construction to record the condition of the chip seals before the first winter season. In order to compare the chip seal conditions after the first winter, the third observation was conducted approximately 27 weeks after construction.

5.5.1 *Pavement Distress Conditions for Pavement Condition Survey*

In order to conduct objective analysis of the performance of the test sections, all the test sections were surveyed based on the NCDOT Pavement Condition Survey Manual (NCDOT 2012).

This manual was developed to assist in establishing a uniform level-of-service for maintenance and to reduce government expenditure on all state-maintained roads. All types

of roads, such as HMA, BSTs (including single and multiple seals), and slurry seals (including micro-surface), are included in the survey. The survey manual presents eight different distress types, but six distress types, which are related specifically to BSTs, are considered for these test sections.

5.5.1.1 Alligator Cracking

Alligator cracking, also called fatigue cracking, is one of the most common distress types in asphalt pavement and is caused by repeated traffic loading. The cracks initiate on the wheel path as longitudinal cracking and then propagate in an alligator pattern under further stress. Alligator cracking is measured as three failure levels: light, moderate, and severe. Table 34 presents descriptions of these failure levels, and Figure 67 shows the alligator cracking failure levels.

Table 34 Alligator Cracking Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light	Longitudinal disconnected hairline cracks about 1/8 inch wide running parallel to each other; initially may only be a single crack but could also look like an alligator pattern
Moderate	Longitudinal cracks forming an alligator pattern; cracks may be lightly spalled and are about 1/4 inch wide
Severe	Cracking has progressed so that pieces appear loose with severely spalled edges; cracks are about 3/8 inch to 1/2 inch wide or greater; potholes may be present.



Figure 67 Alligator cracking failure level (NCDOT pavement condition survey manual)

5.5.1.2 Transverse Cracking

Transverse cracking generally is caused by shrinkage due to daily temperature cycling. Transverse cracking occurs perpendicular to the pavement centerline or laydown direction. Block cracking is considered as transverse cracking in the NCDOT pavement condition survey manual. Table 35 and Figure 68 explain the failure levels of transverse cracking.

Table 35 Transverse Cracking Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light	Cracks, usually only transverse, are less than 1/4 inch wide and are not spalled; block pattern may not be visible yet; transverse cracks are usually 10 to 20 feet apart. Cracks have little or no spalling, and joints usually are not bumped up.
Moderate	Block pattern may be visible with blocks of 10 square feet or greater present; cracks are 1/4 inch to 1/2 inch wide; cracks may or may not be spalled; transverse cracks are usually 5 to 20 feet apart; joints may be bumped up 1/2 inch over concrete.
Severe	Cracks may be severely spalled with smaller blocks of 2 to 10 square feet present; cracks are usually greater than 1/2 inch wide; transverse cracks may be 1 to 2 feet apart throughout portions of the surface; cracks may be bumped up more than 1/2 inch.



Figure 68 Transverse cracking failure level (NCDOT pavement condition survey manual)

5.5.1.3 Rutting

Rutting is a surface depression in the wheel path and is caused by consolidation or lateral movement of the materials due to traffic loading. Table 36 presents the rutting failure levels.

Table 36 Rutting Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light	Rutting 1/4 to less than 1/2 inch deep.
Moderate	Rutting 1/2 to less than 1 inch deep.
Severe	Rutting 1 inch deep or greater.

5.5.1.4 Raveling

Raveling is the wearing away of the pavement surface caused by the loss of aggregate particles and loss of asphalt binder. Raveling is measured only for BSTs and slurry seals. Table 37 and Figure 69 describe the raveling failure levels.

Table 37 Raveling Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light	Aggregate loss is not great; small amounts of stripping may be detected; aggregate loss has started to wear away.
Moderate	Some stripping evident; random stripping with small areas (less than one square foot) or strips of aggregate broken away.
Severe	Stripping very evident; aggregate accumulations may be a problem; large sections (greater than one square foot) of stripping with aggregate layer broken away.



Light

Moderate

Severe

Figure 69 Raveling failure level (NCDOT pavement condition survey manual)

5.5.1.5 Bleeding

Bleeding is defined as excess bituminous binder on the pavement surface that may create a shiny, glass-like, reflective surface. Bleeding is usually found on the wheel paths. Table 38 and Figure 70 show the bleeding failure levels.

Table 38 Bleeding Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light	Condition is present on 10% to 25% of the section
Moderate	Condition is present on 26% to 50% of the section
Severe	Condition is present on greater than 50% of the section



Light

Moderate

Severe

Figure 70 Bleeding failure level (NCDOT pavement condition survey manual)

5.5.1.6 Ride Quality

Ride quality is a factor that reflects the degree of pavement roughness based on perceptions of the general public. Ride quality is determined in terms of texture, whether uneven and bumpy or smooth, as well as in terms of the difficulty or ease of maintaining a safe operating speed. In the long-term pavement performance (LTPP) pavement condition survey, the international roughness index (IRI) is used to measure the roughness of the pavement surface. Table 39 explains the failure levels for ride quality.

Table 39 Ride Quality Failure Level (NCDOT Pavement Condition Survey Manual)

Failure Level	Description
Light (Average)	Pavement texture may cause minimum tire noise; isolated cases (up to 1/4 of the section) of bumps and dips; operating speed can be maintained safely.
Moderate (Slightly Rough)	1/4 to 1/2 of the section is uneven and bumpy with dips, rises, and ruts; pavement may be broken and cracked with a resulting increase in tire noise; slight difficulty in maintaining operating speed over section.
Severe (Rough)	Greater than 1/2 of section is uneven and bumpy; rider is frequently jostled; rather large and frequent pavement failures and rough texture may be present, causing a high increase in tire noise and jolts; operating speed cannot be maintained safely.

5.5.2 Visual Observation

The first field observations were made on the day of construction and again a week after construction. All of the chip seal sections appeared to be well-constructed without any problems. For the fog seals, two fog seal emulsions were applied on two sections. The CSS-1h fog seal emulsion was constructed well, but the Revive emulsion was not sprayed evenly on the initial construction area. However, the emulsion sprayer was adjusted, and the remaining area was constructed well. Therefore, well-constructed areas should be monitored for the Revive fog seal sections to prevent construction problems in the field performance investigation.

The second field observation was conducted before the winter season. All of the chip seal sections showed almost the same texture visually. Three single-seal sections on a low traffic volume road also performed well without any problems. It was not possible, however, to distinguish differences among all the chip seal sections visually. The four fog seal sections (two sections on a low traffic volume roadway and two sections on a medium traffic volume roadway) retained more choking materials (Virginia #9 aggregate) on their surfaces; therefore, visually, their surface textures appeared coarser than the other chip seal surfaces.

The third field observation was performed on all sections 27 weeks (a half year) after construction. Because general failures can occur during the first winter season, this third observation plays an important role in analyzing chip seal performance in the field.

5.5.2.1 Low Traffic Volume Sections (Section 1 through Section 5)

The low traffic volume (i.e., below 5,000 ADT) roadway consists of five separate sections, including one fog seal section. The one fog seal section was constructed with two fog seal emulsions (CSS-1h and Revive) on a CRS-2 emulsion triple seal. Three sections (numbers 2, 3, and 4), which were constructed with the CRS-2, CRS-2L, and SBS CRS-2P emulsions have two seal types (triple and single), and one section (FiberMat Type A, section number 5) was constructed as a single seal.



Figure 71 Section 1 (CRS-2 with fog seal): (a) different color appearance between CSS-1h and Revive emulsions, (b) CSS-1h surface texture, and (c) Revive surface texture

Section 1 (CRS-2 triple seal with fog seals made of CSS-1h and Revive emulsions) performed well without any failures. Both fog seals retained more choking aggregate (Virginia #9) than the chip seal sections, so the surface textures of the fog seal sections are the roughest among all the sections. Although the performance investigated by visual observation is the same between the two fog seal types, the CSS-1h fog seal has a more desirable black appearance, as shown in Figure 71.

Section 2 consists of the CRS-2 triple seal and single seal. The CRS-2 triple seal performed well without any failures, but the amount of aggregate loss (whip-off aggregate), which is determined by the pavement surface texture condition and the amount of aggregate on the side of the roadway, is the largest among the triple-seal sections. Figure 72 (a) and (b) show the surface texture of the CRS-2 triple seal and the aggregate loss caused by traffic. The CRS-2 single seal shows many alligator cracks in the longitudinal direction, three transverse cracks, and loss of choking aggregate (Virginia #9). Although the alligator cracks and transverse cracks are not from the new chip seal but from the original HMA pavement or subgrade, the new chip seal (single seal with CRS-2 emulsion) cannot prevent crack propagation. The aggregate loss is determined by the condition of the pavement surface texture and the amount of aggregate on the side of the road. The CRS-2 single seal exhibits the worst performance in terms of aggregate loss. Figure 72 (c) and (d) show the cracks on the CRS-2 single-seal section.

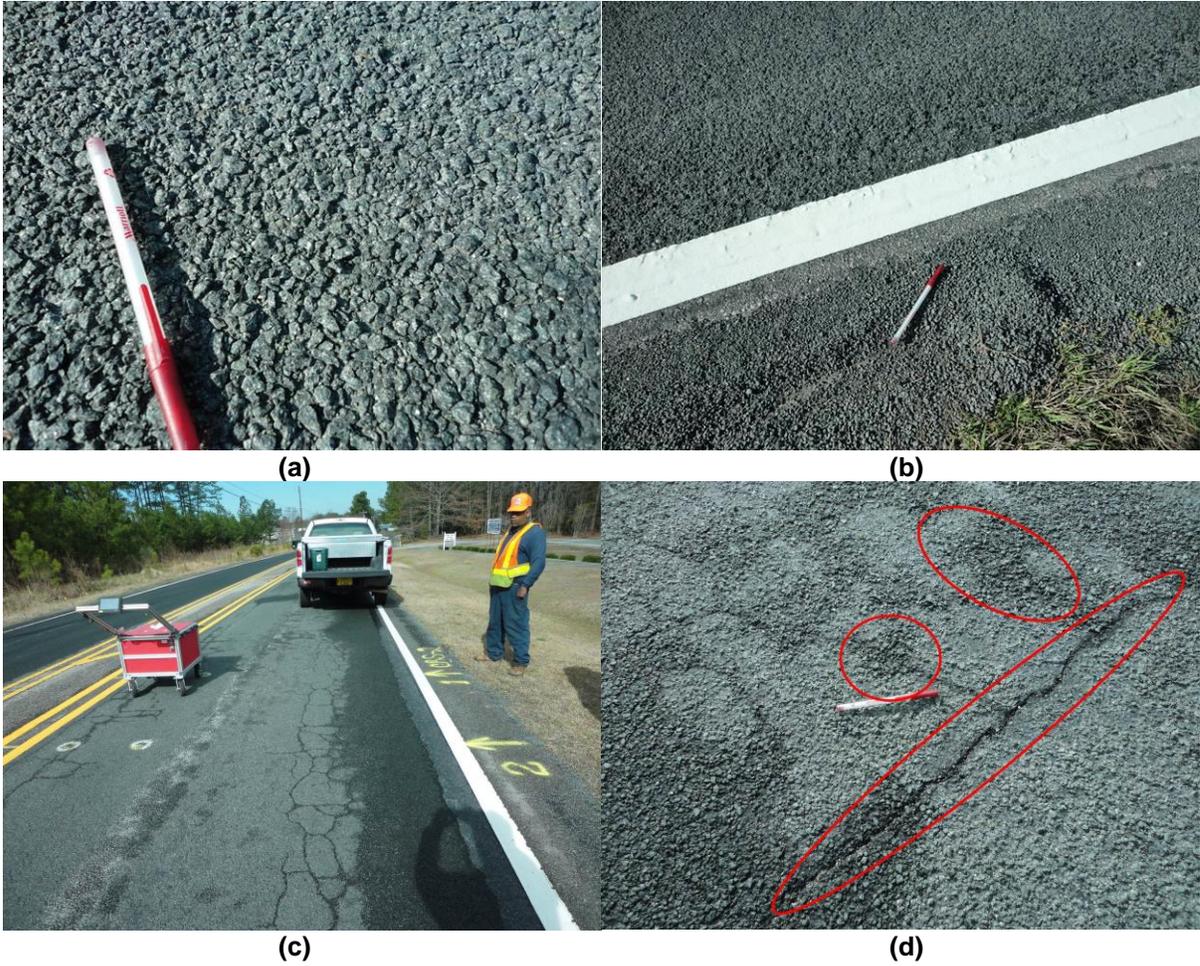


Figure 72 Section 2 (CRS-2): (a) surface texture of triple seal, (b) aggregate loss from triple seal, (c) alligator cracks on single seal, and (d) transverse crack and loss of chocking aggregate on single seal

Section 3 was constructed as a CRS-2L triple seal and single seal. The CRS-2L triple seal performed well without any failure, but the CRS-2L single seal shows some alligator cracks in the longitudinal direction. Figure 73 shows the triple seal surface texture and alligator cracks on the single seal.



Figure 73 Section 3 (CRS-2L): (a) triple seal surface texture and (b) alligator cracks on single seal

Section 4 consists of a SBS CRS-2P triple seal and single seal. The SBS CRS-2P triple seal performs best of all the multiple seal sections, and the SBS CRS-2P single seal performs best of all the single seal sections. In particular, the SBS CRS-2P single seal performs as well as the triple seal in terms of performance ratings. There are some cracks on the original HMA pavement, but the new single seal prevents crack propagation, as shown in Figure 74.



Figure 74 Section 4 (SBS CRS-2P): (a) triple seal surface texture and (b) single seal preventing cracks

Section 5 was constructed as a double seal; the bottom layer was made with FiberMat Type A with granite 78M aggregate, and the top layer was made with CRS-2L emulsion with Virginia #9 aggregate. The FiberMat Type A sections performed well without any failures. Figure 75 shows the surface texture of the FiberMat Type A section.



Figure 75 Section 5 (FiberMat Type A): double seal surface texture

On the low traffic volume road, all the multiple-seal sections (triple and double seals) performed well without any failures, but the sections show some loss of choking materials.

According to the visual investigation, the SBS CRS-2P emulsion section performs best for the triple seals.

Of the single seals, the CRS-2 emulsion section shows the worst performance. Many alligator cracks were observed on the wheel path and three transverse cracks on the pavement. The CRS-2L single-seal section also shows some alligator cracking on the wheel path, but the number of cracks is less than for the CRS-2 single-seal section. The alligator cracking observed from the CRS-2 and CRS-2L single-seal sections was caused not from the new chip seal layers but from the original HMA pavement or subgrade. The SBS CRS-2P single-seal section shows the best performance of the single-seal sections. Some cracking was found on the original HMA pavement, but the SBS CRS-2P single seal prevented crack propagation.

5.5.2.2 Medium Traffic Volume Sections (Section 6 through Section 9)

On the medium traffic volume roadway (5,000 – 10,000 ADT), one fog seal section (CRS-2L triple seal with CSS-1h and Revive fog seals), two triple-seal sections (CRS-2L and SBS CRS-2P), and one double-seal section (FiberMat Type A) were constructed.

Section 6 (CRS-2L triple seal with fog seals of CSS-1h and Revive) performs well and about the same as Section 1 (CRS-2 triple seal with fog seals). Both fog seals retained more choking aggregate (Virginia #9) than the chip seal sections, so their surface textures are the roughest among all the sections. Although the performance investigated by visual observation is the same for both fog seal types, the CSS-1h fog seal has the desirable black appearance. Figure 76 shows the surface textures of the fog seal sections.



Figure 76 Section 6 (CRS-2L triple seal with fog seals): (a) CSS-1h and (b) Revive

Section 7 is the CRS-2L triple-seal section. According to visual observation, Section 7 performs well without any failure. However, the CRS-2L section shows more loss of choking aggregate on the wheel path than the other sections (SBS CRS-2P and FiberMat Type A). This loss of choking materials from the CRS-2L section cannot be considered as a failure of the chip seal because the amount of loss is small without any other failure signs, such as the loss of large aggregate particles, cracking, bleeding, stripping, and so on. However, the amount of loss of choking aggregate (even though it is not possible to quantify the amount precisely) is more than for the other sections on both low- and medium-volume sections. Therefore, the CRS-2L section should be monitored in future. Figure 77 shows the surface texture of the CRS-2L triple-seal section.



Figure 77 Section 7 (CRS-2L): triple seal surface texture

Section 8 (SBS CRS-2P triple seal) shows the best performance for the medium-volume sections. Only a small loss of choking aggregate was found on the section. Figure 78 shows the surface texture of the SBS CRS-2P triple-seal section.



Figure 78 Section 8 (SBS CRS-2P): triple seal surface texture

Section 9 (FiberMat Type A double seal) experienced the loss of a few large stones in the longitudinal direction. The amount of loss of these large stones was not great, however, and the failures were found only in a few spots. From the field investigation, the field construction supervisor noted that this failure can be considered not as the failure of the new

chip seal but a construction failure caused by unevenly distributed emulsion or aggregate. Figure 79 shows the surface texture of the FiberMat Type A double-seal section.



Figure 79 Section 9 (FiberMat Type A): double seal surface texture

Overall, the sections on medium traffic volume roadways, including the fog seal sections, perform well without any cracking, bleeding, and severe aggregate loss. The medium-volume sections perform better than the other sections on the low and high traffic volume roads, but the differences are not significant.

5.5.2.3 High Traffic Volume Sections (Section 10 through Section 12)

Two triple-seal sections, the CRS-2L and the SBS CRS-2P emulsion sections, and one double-seal section, FiberMat Type A, were constructed on a high traffic volume road (10,000 – 15,000 ADT). Figure 80, Figure 81, and Figure 82 show the different surface textures of this high traffic volume road for these sections.



Figure 80 Section 10 (CRS-2L triple seal)



Figure 81 Section 11 (SBS CRS-2P triple seal)



Figure 82 Section 12 (FiberMat Type A double seal)

The sections on the high-volume road also experienced the loss of choking materials, but all three sections (CRS-2L, SBS CRS-2P, and FiberMat Type A) do not show any failure and show similar performance by visual observation. Overall, all three sections perform well without any failure.

5.5.2.4 Summary of Field Observation

The performance of the chip seals was rated on a scale of one to ten by the field construction supervisor based on visual investigation during the field observations. These performance ratings were determined based on several chip seal performance factors, such as aggregate loss, bleeding, surface uniformity, raveling, and cracking. Table 40 shows the findings from the field observation, and Figure 83 shows the field performance ratings.

Table 40 Summary of Field Observation

Sec.	Traffic Volume	Emulsion Type	Findings	Performance Rating
1	Low	CRS-2 (Fog Seal)	CSS-1h: Desirable black surface color Revive: Same performance as CSS-1h - More choking aggregate retained than chip seals	7.5
2		CRS-2	Triple: Performs well	6
			Single: Many alligator cracks and three transverse cracks, and aggregate loss	3.5
3		CRS-2L	Triple: Performs well	6
			Single: Some alligator cracks	6.5
4		SBS	Triple: Performs well	8.5
		Single: Cracks from original pavement, but it was not developed on new seal.	8.5	
5		FiberMat	Double: Performs well	7
6	Medium	CRS-2L (Fog Seal)	CSS-1h: Desirable black surface color Revive: Same performance as CSS-1h - More choking aggregate retained than chip seals	8
7		CRS-2L	Perform Well	8
8		SBS	Perform Well	9
9		FiberMat	Double: Perform Well	7.5
10	High	CRS-2L	Perform Well	8
11		SBS	Perform Well	7.5
12		FiberMat	Double: Perform Well	7.5

* Note: *Performs well* indicates no failures on surface.

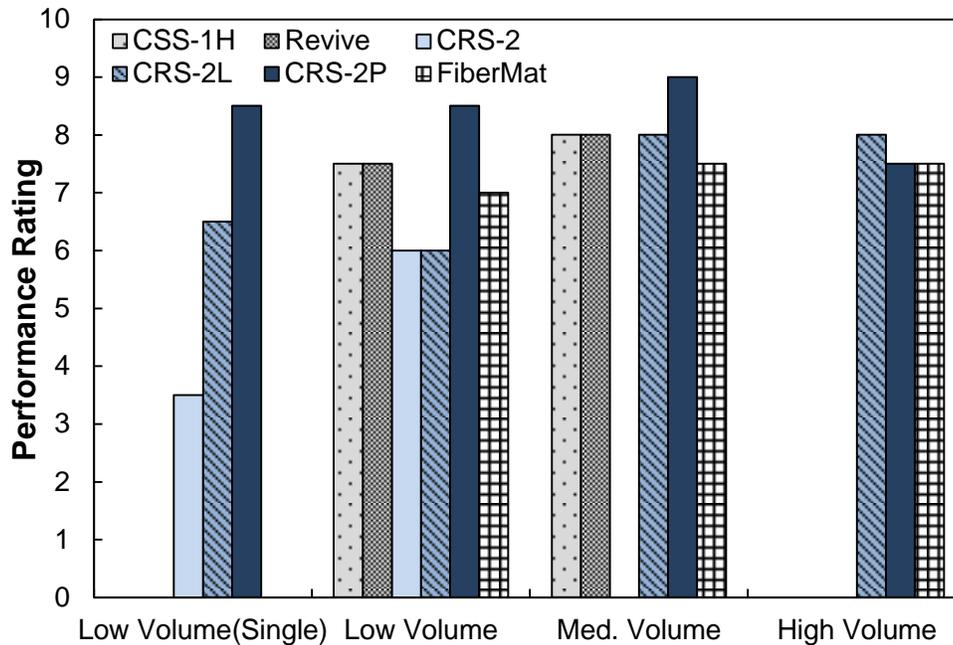


Figure 83 Field performance rating

Overall, all of the sections, excluding the CRS-2 single-seal section, perform well without severe failure. The SBS CRS-2P sections show the best performance regardless of seal type. In particular, the SBS CRS-2P single-seal section performs as well as the triple-seal sections.

5.5.3 MPD Comparison

In order to quantify surface texture roughness as a function of traffic loading, all sections were scanned three times: on the day of construction, at one week, and 27 weeks after construction. From previous research (HWY-2008-04), it is found that the MPD values decrease as a function of traffic loading until the MPD values meet their asymptotic values. The asymptotic MPD values reflect no additional aggregate loss. The MMLS3 aggregate loss test results indicate that all samples made in the laboratory and obtained from the field show asymptotic aggregate loss values without any failure after a certain amount of traffic loading (one hour of loading). However, because the asymptotic MPD values are different depending on traffic volume, aggregate type, and emulsion type, a certain criterion cannot be applied for

chip seal performance; however, it is possible to compare the MPD values within the same section. Therefore, if bleeding failure does not occur on the surface, it can be assumed that the asymptotic value of the MPD indicates good performance (i.e., no severe aggregate loss) of the chip seal. Figure 84 shows the MPD values analyzed from single seals on low traffic volume sections, triple seals on low traffic volume sections, triple seals on medium traffic volume sections, and triple seals on high traffic volume sections as a function of traffic loading.

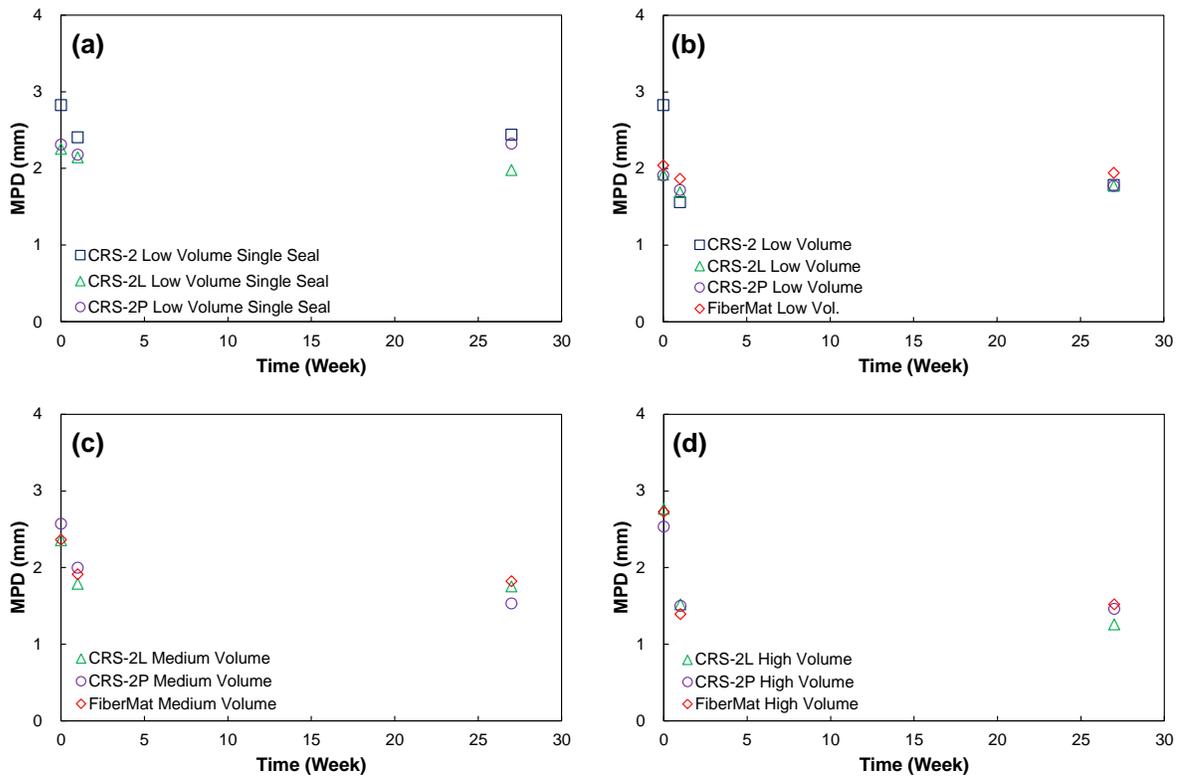


Figure 84 MPD values: (a) single seals on low traffic volume, (b) low traffic volume, (c) medium traffic volume, and (d) high traffic volume sections

Figure 84, indicates that the MPD values decrease significantly from the day of construction to a week after construction. This decrease is due to the early compaction by traffic loading, and the trend is extremely similar to that found from laboratory results. After a week, the MPD values reach their asymptotic values. From the visual observation, none of

the triple-seal sections show any failures, such as cracking, bleeding, and aggregate loss. Therefore, the MPD analysis appears to indicate that all the triple-seal sections perform well. However, the performance ratings indicate that the single-seal sections, except the CRS-2P section, show some failure, i.e., alligator cracking. This observation differs from the MPD analysis. One possibility for the discrepancy may be from the surface condition of the scan locations in the field. The field scans do not show any failure, even on the single-seal sections. In order to evaluate the overall pavement performance conditions, the number of scan locations should be increased in order to represent an entire section.

5.5.4 Prediction of Aggregate Loss in Field Sections

Aggregate loss and bleeding are the two major distresses found in ASTs. Bleeding failure is a long-term distress and can be measured easily by visual survey. However, it is hard to determine the aggregate loss in field ASTs.

In the laboratory, aggregate loss and MPD can be measured using the MMLS3 test. Actual samples (double seal for FiberMat Type A and triple seals for CRS-2L and CRS-2P) were obtained from the field and tested using the MMLS aggregate loss test procedure. In order to compare the field section data, the MPDs were calculated using the laser profile data that were obtained periodically during the aggregate loss tests. The test results indicate that different relationships develop based on aggregate loss as a function of reduction in MPD for the different seal types. Figure 85 shows the correlations between aggregate loss and reduction in MPD obtained from the MMLS3 tests. Based on these relationships, the aggregate loss in the field can be predicted using the reduction in MPD obtained from field sections. Table 41 shows the reduction in MPD calculated from the field MPD data. Figure 86 shows the predicted aggregate loss in the field sections and the aggregate loss results from laboratory tests using the field specimens.

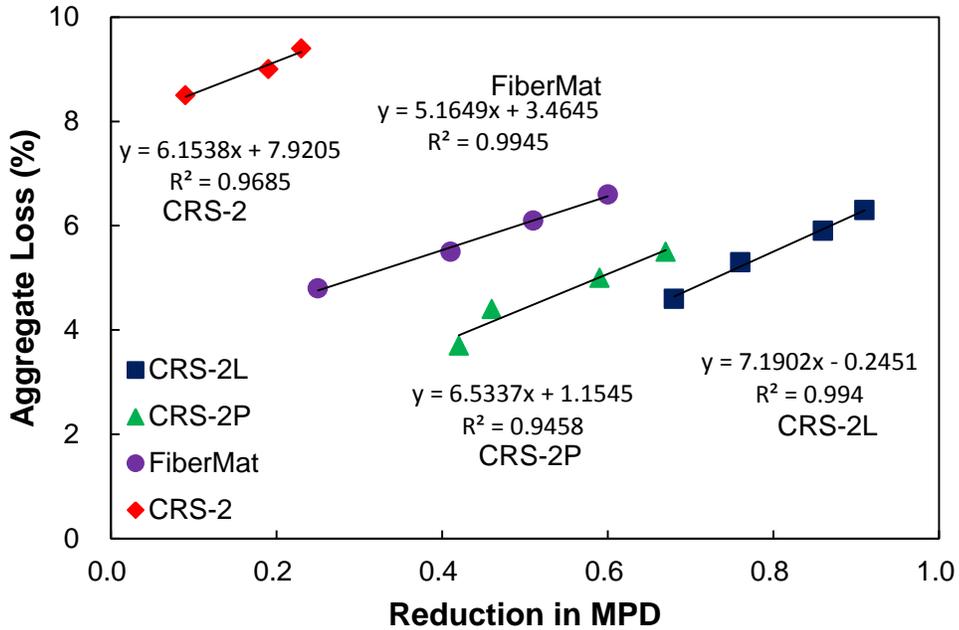


Figure 85 Correlations between aggregate loss and reduction in MPD by MMLS3 test

Table 41 Reduction in MPD from Field Sections

Traffic (ADT)	CRS-2L		CRS-2P		FiberMat		CRS-2	
	1 week	27 weeks	1 week	27 weeks	1 week	27 weeks	1 week	27 weeks
5,000	0.23	0.15	0.19	0.14	0.17	0.1	1.27	1.04
10,000	0.57	0.6	0.57	0.75	0.45	0.54	N.A.	N.A.
15,000	1.25	1.15	1.03	1.07	1.21	1.21	N.A.	N.A.

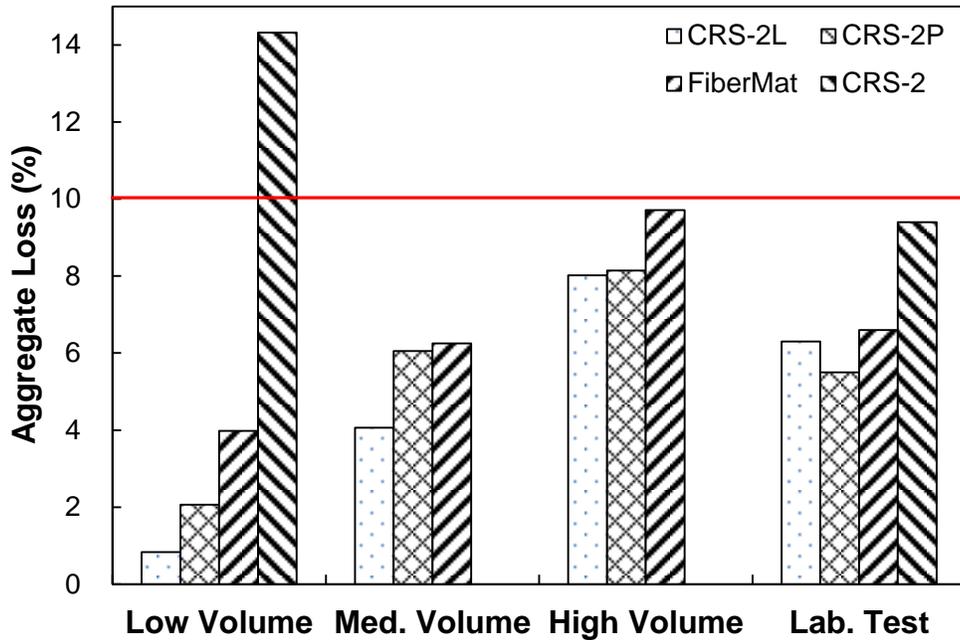


Figure 86 Predicted aggregate loss in field sections

Figure 86, shows that all the field sections, except the CRS-2 emulsion section, meet the 10% criterion. Also, the field sections on the high-volume road show more aggregate loss than those on the low- and medium-volume roads. The interesting point is that the CRS-2 emulsion section indicates greater aggregate loss than the sections with modified emulsions, and the aggregate loss exceeds the 10% aggregate loss criterion for the low-volume road. According to the MPD data obtained from the field, only the CRS-2 emulsion section on the low-volume road shows a higher MPD value after sweeping. The higher MPD value indicates rougher texture, and the rougher texture indicates that more (excess) choking aggregate is retained on the surface of the pavement. When considering the field construction procedure, the intensity of the sweep procedure for this low-volume section was not as strong as for the other sections. That is, the CRS-2 section retained more excess aggregate than the other sections, because the higher MPD value after sweeping is seen for the CRS-2 section only. The MPD value of the CRS-2 single seal constructed on the same section is also higher than for the other single-seal sections. The differences in MPD values after sweeping for the

different emulsion sections are normally within 0.5 mm, whereas the MPD differences seen in the CRS-2 sections (both the single seal and triple seals) are close to 1.0 mm.

The aggregate loss prediction in the field indicates that the sections on high-volume roads show the worst aggregate retention performance (i.e., most aggregate loss). This result is similar to the field performance rating that is shown in Figure 83. However, the low-volume sections present different results between the aggregate loss prediction and the field performance rating. The low-volume sections perform worse than the medium-volume sections in the field performance rating. Currently, the field sections show no significant differences, i.e., no significant failures that can be used to distinguish the performance of the sections. Therefore, in order to verify the aggregate loss predictions, further research is needed; for example, a pavement condition survey and laser scanning in the field sections should be conducted.

6. RECOMMENDED GUIDELINES FOR CHIP SEALS UNDER HIGH-VOLUME TRAFFIC

6.1 Pavement Condition

The condition of the existing pavement plays a vital role in chip seal performance. According to previous studies, chip seals should be constructed on roads that are in relatively good condition (Wood 2006, Gransberg 2005). Chip seals are not a good way to increase the structural capacity of a road but serve as nonstructural treatments that can be applied on existing pavement to prevent deterioration. Therefore, chip seals should be applied to roads under appropriate conditions. It is important that the original pavement does not exhibit severe distresses when chip seals are applied (Gransberg 2006). *Relatively good condition* means that the road should show little distress, i.e., few instances of alligator cracking, transverse cracking, rutting, raveling, bleeding, and so on. If the existing pavement shows severe distress or structural failure (weak base and/or subgrade), the pavement should be repaired before new chip seal treatments are applied. For example, the *Minnesota Seal Coat Handbook 2006* suggests that seal coats should be constructed on pavements under the following conditions: low to moderate block cracking, low to moderate raveling, and low to moderate transverse and longitudinal cracking.

As already indicated, three different roads were selected to evaluate chip seal performance in terms of ADT. Different chip seals, i.e., different materials and structure types, were constructed on those roads. Table 42 shows the original pavement conditions prior to chip seal construction.

Table 42 Pavement Condition

Location	Traffic Volume (ADT)	Condition Rating (2010)	Resurfaced Year	In-Service Life (Year)
Chin Page Rd.	Low (5,000)	91.7	2005	7
Farrington Rd.	Medium (10,000)	85.1	2004	8
Carver St.	High (15,000)	93.4	2003	9

In order to evaluate the performance of the test sections, all the test sections were surveyed based on the NCDOT pavement condition survey manual (NCDOT 2012). This manual has been developed to assist in establishing a uniform level-of-service for maintenance and to reduce government expenditure on all state-maintained roads. All types of roads, such as HMA, BSTs (including single and multiple seals), and slurry seals (including micro-surface), are included in the survey. The survey manual lists eight different distress types, but six distress types, which are related to BSTs, are considered for these test sections.

According to the field test results (pavement performance ratings), the CRS-2 and CRS-2L emulsion single-seal sections perform worse than the CRS-2P single-seal section, as evidenced by alligator cracking problems. This finding suggests that the condition of old pavement is relatively poor and not conducive to single-seal treatment. The best way to determine the condition of a pavement is to suggest a specific value for the condition of the existing pavement that is to be treated with a chip seal. However, there are not sufficient data to suggest such a specific value, so more research is needed. Based on the literature review and field test results, chip seals should be applied to roads that are already in relatively good condition without structural failures.

6.2 Materials

6.2.1 Aggregate

The use of quality aggregate in chip seals is one of the most important factors for good performance. It is recommended to use clean and uniform-sized aggregate particles in

chip seal construction. The PUC concept can be used to control the aggregate gradation (i.e., uniformity). The closer the PUC value is to zero, the more uniform is the gradation of the aggregate source. In previous NCSU chip seal researches (FHWA/NC/2008-04 and FHWA/NC/2007-06) the effects of using different PUC values were evaluated by laboratory performance tests (aggregate loss and bleeding tests). In this study, however, the PUC values are calculated, and then the data are used to analyze the effect of the PUC on chip seal performance. All the data used in the PUC analysis were obtained from single-seal specimens only. Figure 87 shows the effects of the PUC for the chip seal performance tests. Figure 87 shows that all the specimens that were made using optimum application rates were used for analysis. Table 43 shows detailed information for specimens made with the two aggregate types (granite 78M and lightweight).

Table 43 Specimen Information for PUC Analysis

Factor	Mix Design Research (FHWA/NC/2008-04)	PME Research (FHWA/NC/2007-06)	High Volume Research
PUC (Granite 78M)	19.6, 33.6, 48.5	24.6	33.6
AAR (lb/yd ²)	15.1	17	16
EAR (gal/yd ²)	Gradation A: 0.2, 0.25 Gradation B: 0.15, 0.2 Gradation C: 0.1, 0.15	0.25	0.25
PUC (Lightweight)	19.6, 34.6, 43.9	22.3	34.6
AAR (lb/yd ²)	6	9	7
EAR (gal/yd ²)	Gradation A: 0.2, 0.25 Gradation B: 0.15, 0.2 Gradation C: 0.1, 0.15	0.25	0.25

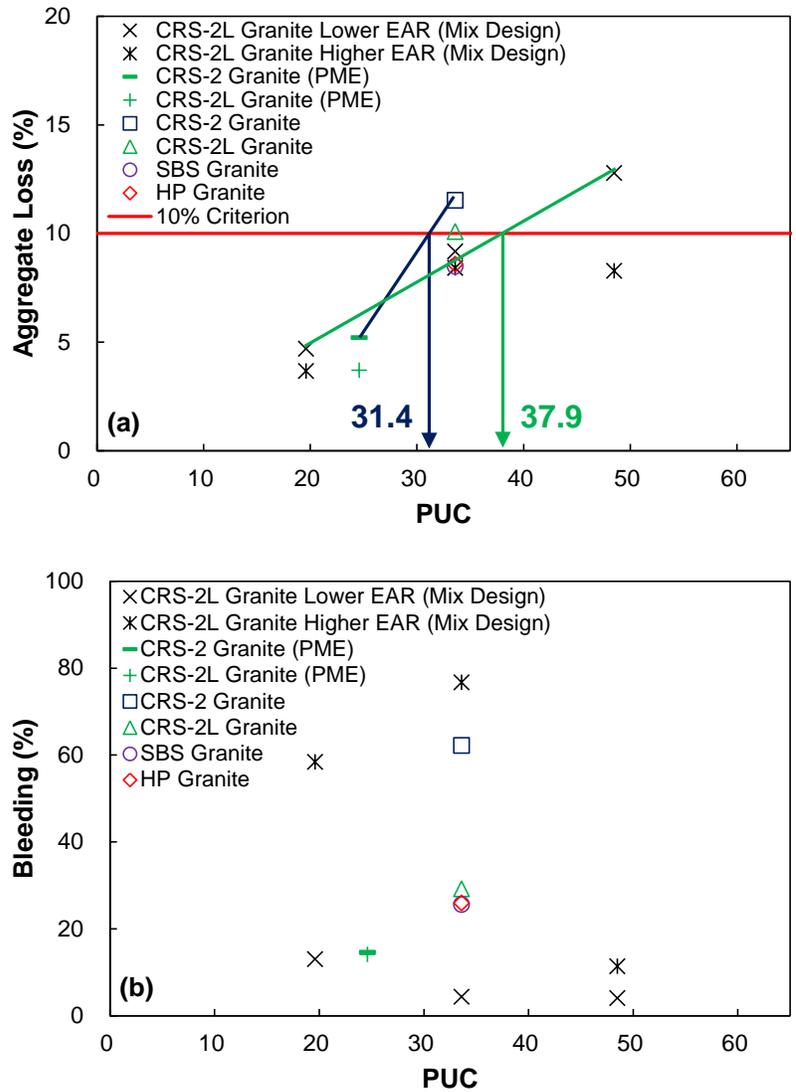


Figure 87 Effect of PUC in performance tests for granite 78M aggregate: (a) aggregate loss and (b) bleeding

Figure 87 (a) indicates that all specimens with low PUC values (19.6 to 24.6) show good aggregate retention performance. With regard to the medium PUC value (33.6), the non-PME specimen exceeds the limit of 10% aggregate loss, whereas the PME specimens meet the limit even though they show more aggregate loss than the specimens with low PUC values. On the high PUC side, the specimens made with the lower EAR are over the limit, but the specimens made with the higher EAR meet the criterion.

According to Figure 87 (b), the specimens made using the higher EAR for the mix design research and the non-PME specimen show the worst bleeding resistance.

Based on PUC analysis for aggregate loss and bleeding, the non-PME emulsion should be used with a PUC below 31.4, and the PME (CRS-2L) can be used with a PUC below 37.9. However, these specific PUC values cannot be recommended strongly because the data points that are needed to develop relationships are insufficient, and the other PME (except the CRS-2L emulsion) specimens were made with only one aggregate. At this point, it is clear that a high PUC value leads to poor performance in chip seals. Therefore, it is important to use well-controlled aggregate sources for chip seal construction. Also, further research into the effects of PUCs in terms of different emulsions should be conducted in order to recommend specific PUC values for chip seals.

Figure 88 shows the effects of PUCs in chip seal performance tests with the lightweight aggregate.

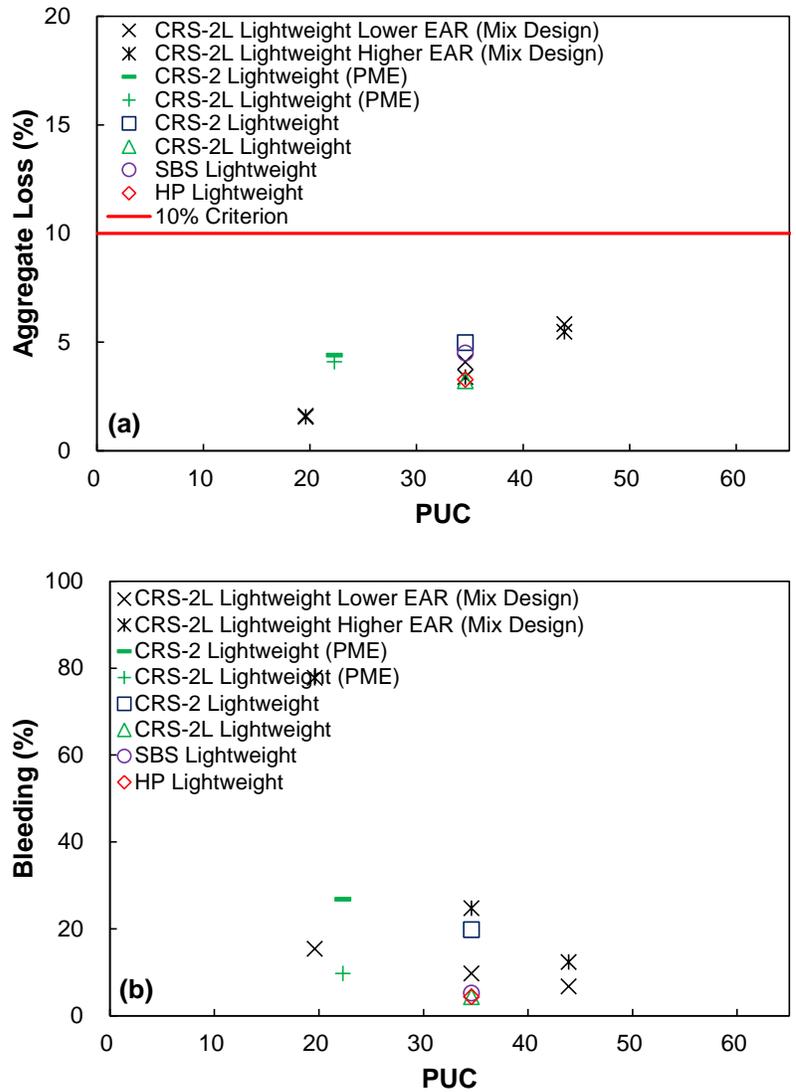


Figure 88 Effect of PUC in performance tests for lightweight aggregate: (a) aggregate loss and (b) bleeding

Figure 88 indicates that different PUC values do not affect the lightweight aggregate as much as the granite 78M aggregate. Overall, all specimens perform well and are resistant to aggregate loss and bleeding. Therefore, if optimal application rates are used in chip seals with lightweight aggregate, the PUC value may not be an important factor.

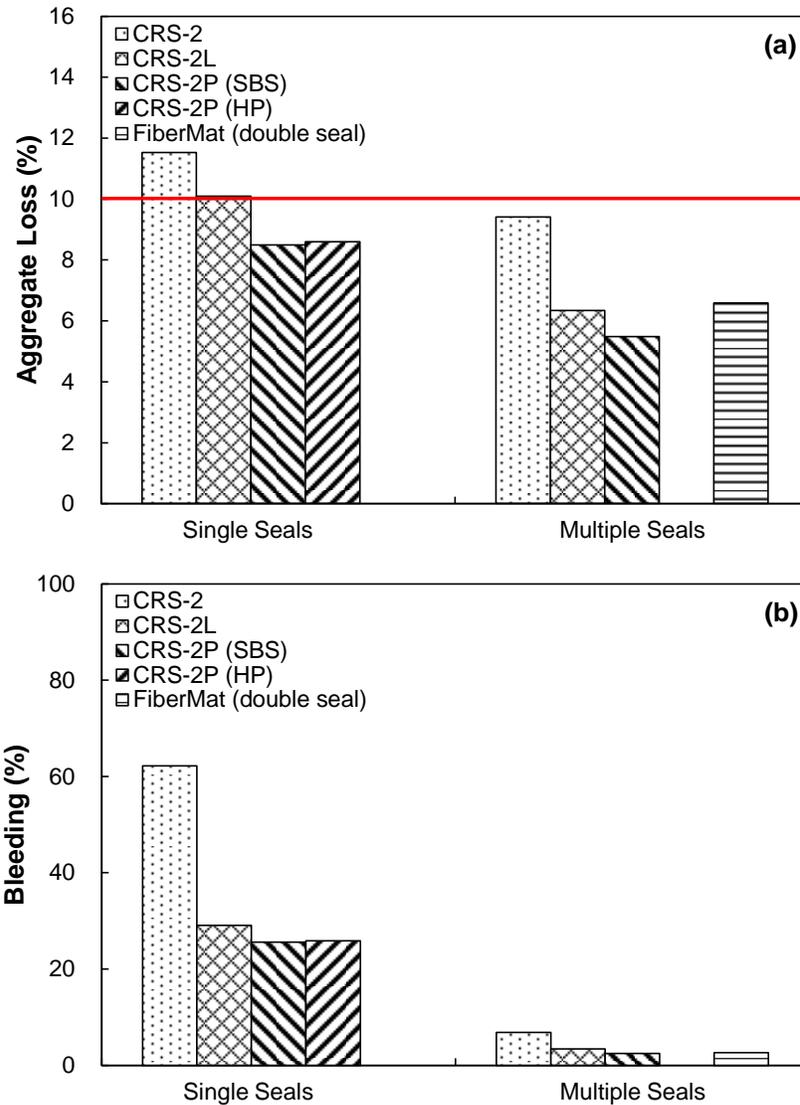


Figure 89 Comparison of performance tests between single seals and multiple seals

PUC analysis should be applied carefully to multiple seals, which have a top layer of choking materials. If choking aggregate, normally Virginia #9, is applied on top of a multiple seal, the PUC of the multiple seal would be different from that of a single seal, and the performance of the multiple seal would be enhanced. Figure 89 shows the comparison of performance test results between single seals and multiple seals.

6.2.2 Emulsion

Based on the literature review and test data obtained from this research, it is clear that PMEs show better performance in terms of aggregate retention and bleeding resistance than the non-PME. With regard to PMEs, currently, the different performance between the CRS-2L and the CRS-2P emulsions is problematic. For example, the MNDOT bituminous seal coat specifications recommend the use of CRS-2P emulsion instead of CRS-2L emulsion because the latex modification of the CRS-2L emulsion leads to slower curing. Specifically, latex tends to float to the surface and trap water underneath the latex layer, so extra rolling is required to accelerate curing if latex modification is used. Also, the cost of the emulsions should be considered prior to chip seal construction if these two types of PME do not exhibit a significant difference in performance. Table 44 shows the cost information for emulsions used in North Carolina.

Table 44 Emulsion Cost Information (NCDOT 2013)

Emulsion	CRS-2	CRS-2L	CRS-2P
Cost (dollar/gallon)	1.78	2.04	2.12

Figure 90 through Figure 94 show the comparisons of the performance of emulsions for different conditions. The data from previous PME research (FHWA/NC/2007-06) are compared with the data obtained from this research. The research names are given in parentheses, and *Field* and *Lab* indicate specimens made in the field and laboratory, respectively. Because different application rates (AARs and EARs) were used for the different researches, the test results cannot be compared directly. Therefore, ratios were calculated based on the non-PME emulsion, and then those results are compared. Table 45 shows the application rate information for all the specimens.

Table 45 Application Rates Information

Sample	AAR (lb/yd²)	EAR (gal/yd²)	
Field (PME)	Granite 78M	17	0.35
	Lightweight	9	0.35
Lab (PME)	Granite 78M	17	0.25
	Lightweight	9	0.25
Lab (High Vol.)	Granite 78M	16	0.25
	Lightweight	7	0.25
PME (Double Seal)	Bottom	17 (Granite 78M)	0.25
	Top	9 (Lightweight)	0.25
PME (Triple Seal)	Bottom	17 (Granite 78M)	0.30
	Middle	17 (Granite 78M)	0.25
	Top	9 (Lightweight)	0.20
High Vol. (Field) (Triple Seal)	Bottom and Middle	22 (Granite 78M)	0.25
	Top Layer	11 (Virginia #9)	0.18
High Vol. (Lab) (Triple Seal)	Bottom	17 (Granite 78M)	0.30
	Middle	17 (Granite 78M)	0.25
	Top	9 (Lightweight)	0.20

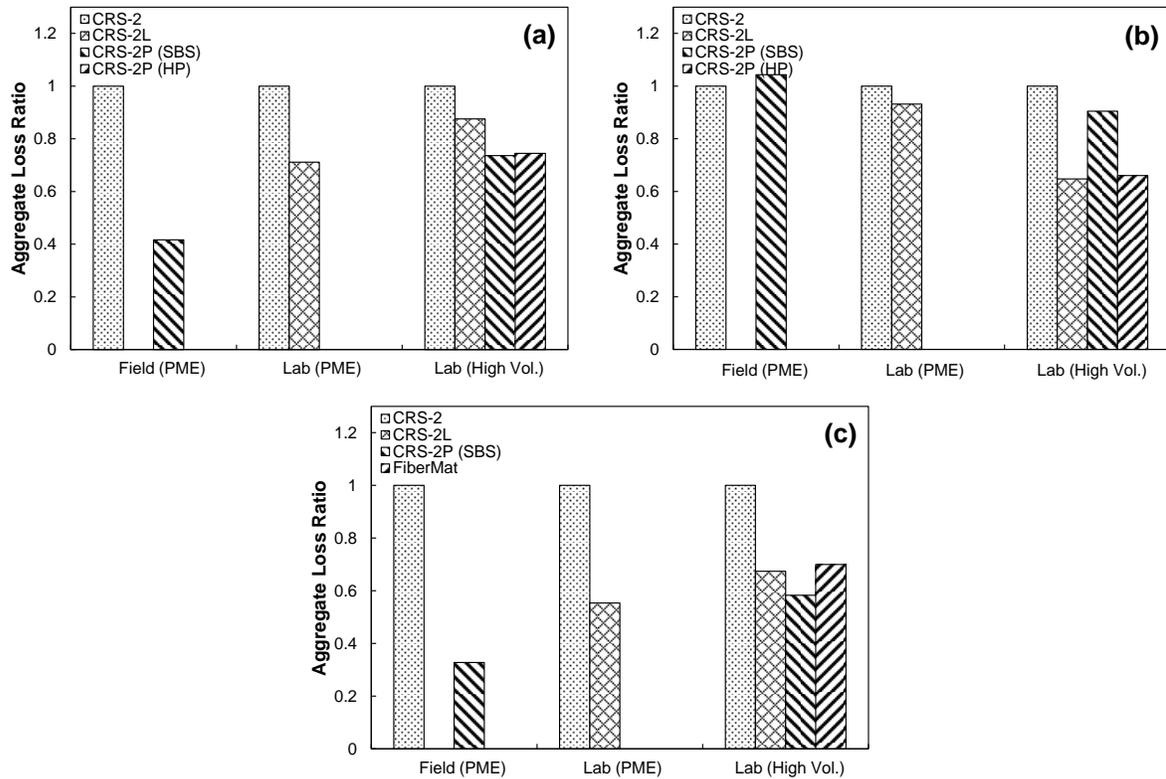


Figure 90 MMLS3 aggregate retention comparison of different conditions: (a) single seal with granite 78M aggregate, (b) single seal with lightweight aggregate, and (c) multiple seals

Figure 90 indicates that the non-PME (CRS-2) always shows the worst aggregate retention performance. With regard to the PMEs, the CRS-2P emulsion performs better than the CRS-2L emulsion except for the lightweight aggregate specimens from the high-volume research. However, the comparison of the aggregate retention performance of lightweight aggregate specimens from the high-volume research indicates negligible differences, because all of the emulsion type specimens show very low (below 5%) aggregate loss.

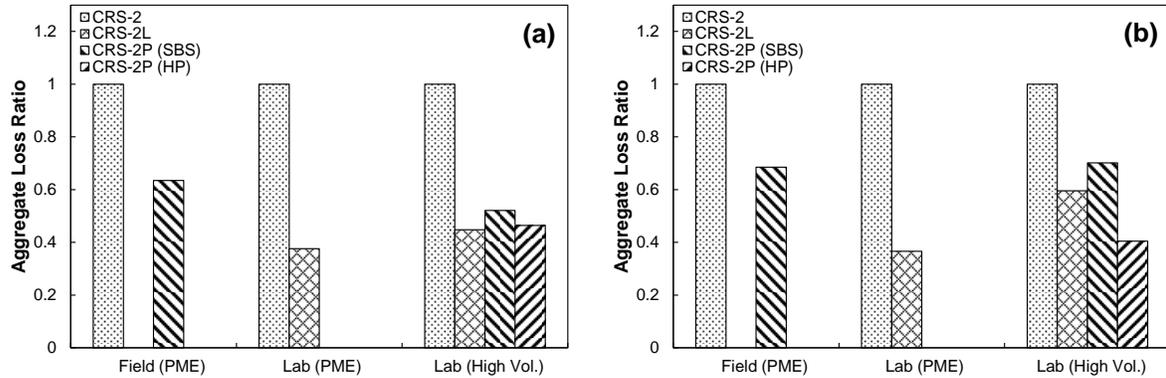


Figure 91 Vialit aggregate retention comparison of different conditions: single seal with (a) granite 78M aggregate and (b) lightweight aggregate

Figure 91 also shows that the non-PME (CRS-2) always performs worse in terms of aggregate retention. The Vialit test results show that the CRS-2L specimens perform better than the CRS-2P specimens, but the difference is not significant.

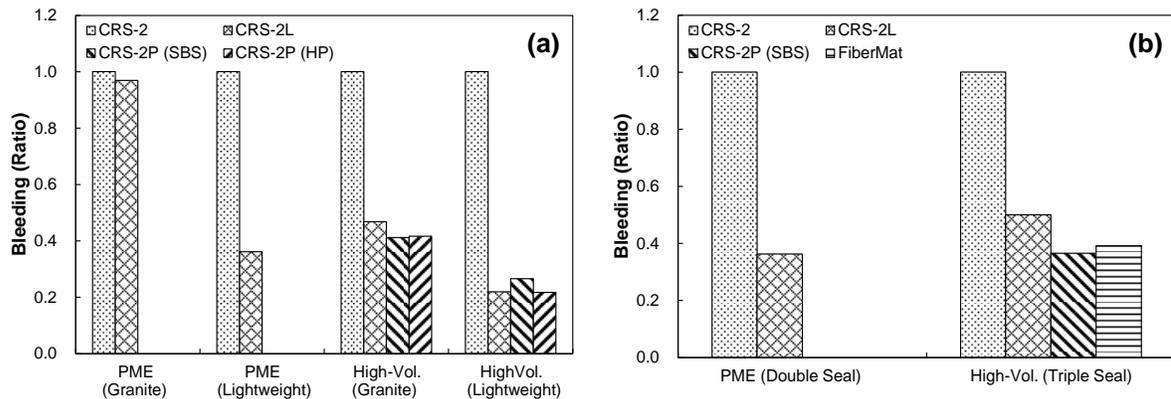


Figure 92 Bleeding resistance comparison of different conditions: (a) single seal and (b) multiple seal

Figure 92 indicates that the non-PME (CRS-2) always performs worse in terms of bleeding. The CRS-2P specimens perform better than the CRS-2L specimens out of all the PME specimens. However, the differences between these PMEs are not significant.

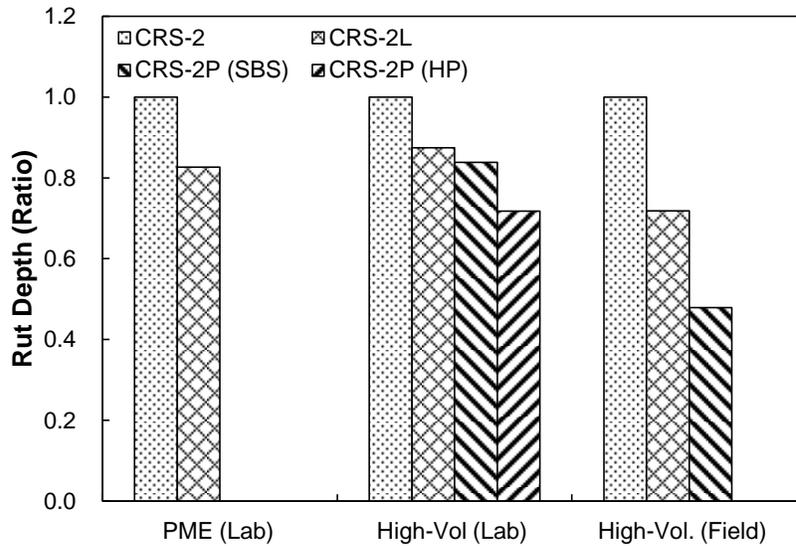


Figure 93 Rutting resistance comparison of different conditions

Figure 93 shows a similar trend to that of the other performance tests (aggregate retention and bleeding). The CRS-2 specimens show the worst rutting resistance, and the CRS-2P specimens perform better than the CRS-2L specimens in terms of rutting resistance. Specially, PME specimens obtained from the field show more distinctive differences in terms of rutting resistance.

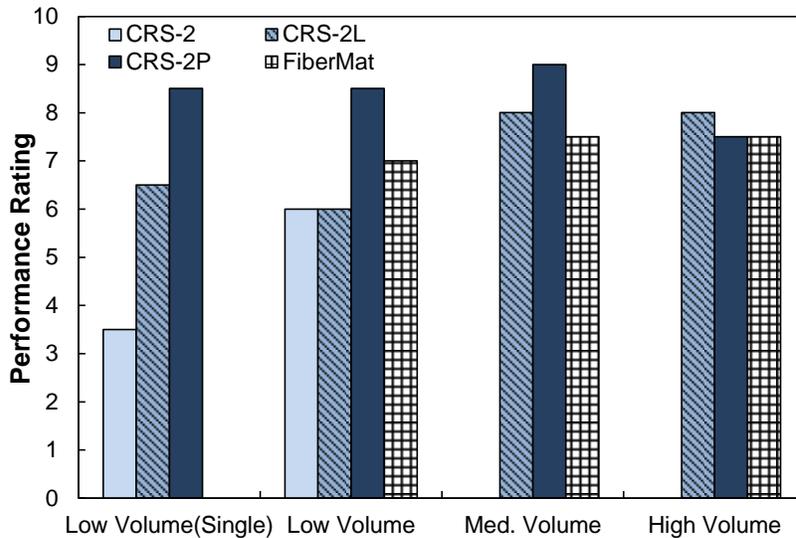


Figure 94 Field performance rating comparison of different conditions

Figure 94 shows the field performance ratings for the different conditions, i.e., traffic volume, seal type, and emulsion type. The CRS-2 emulsion sections clearly show the worst performance ratings. With regard to the PMEs, the CRS-2P sections perform better than the CRS-2L sections. The interesting finding is that the single seal with the CRS-2P emulsion performs better than the triple seals with the CRS-2L emulsion.

Given the findings that are based on the performance test results, the following recommendations for emulsion types are suggested for chip seals.

- The CRS-2 unmodified emulsion is not recommended for single-seal treatment, but can be used as a double seal on low traffic volume road (below 5,000 ADT).
- The CRS-2P emulsion is highly recommended for both single and multiple seals.
- The CRS-2L emulsion can be used, but the CRS-2P emulsion is more effective because it exhibits better performance in both field and laboratory tests and is not much more expensive than the CRS-2L emulsion.

6.3 Weather Conditions

Weather conditions, especially temperature, must be considered prior to chip seal application. Many previous research efforts recommend avoiding cold and wet conditions during chip seal construction. Low temperatures may cause poor adhesion between the emulsion and aggregate. In this research, three curing temperatures (15°C, 25°C, and 35°C) are used to evaluate chip seal performance, and 15°C always shows the worst performance in terms of emulsion curing time and aggregate loss. However, the test data are not sufficient to suggest a specific minimum temperature for chip seal construction. Therefore, based not only on the test data but also on the literature review, potential minimum temperatures are suggested for chip seal construction, as shown in Table 46.

Table 46 Minimum Temperature Information

Literature Name	Minimum Temperature	Note
Chip Seal Best Practices	10°C (50°F)	Air temperature
MNDOT	15.5°C (60°F)	Pavement and air temperature
Caltrans	10°C (55°F)	Pavement temperature
INDOT	4.4°C (40°F) – 15.5°C (60°F)	Aggregate heated to 48.9°C to 65.6°C
Gransberg (2006)	15.5°C (60°F)	Pavement and air temperature

Table 46 shows the recommended minimum temperatures for chip seal construction. Given that warm temperatures are better than high temperatures for the construction of quality chip seals, 15.5°C (60°F) is suggested as a potential minimum temperature for chip seal construction.

6.4 Seal Types

Based on the construction cost information obtained from NCDOT Division 5, different chip seal types (single, double, and triple seals) and fog seals are compared in terms of cost, which includes labor, equipment (rental and own), traffic control, asphalt, aggregate,

and sweeping. During the survey year (2012), only double seals and triple seals were constructed (no single seals). The CRS-2L emulsion and the granite 78M aggregate were commonly employed for the chip seals, and Grip-Tight emulsion was used for the fog seals.

Table 47 Construction Cost Information (NCDOT 2012)

Cost	Triple Seal	Double Seal	Fog Seal	Triple with Fog Seal	Double with Fog Seal
Dollar/yd ²	3.89	2.26	0.47	4.36	2.73
Cost Ratio	1	0.58	0.12	1.12	0.70

Table 47 indicates that the cost of double seals is about half that of triple seals, and the cost of a double seal with a fog seal is 70% of the triple seal cost. The cost of a single seal is not available due to insufficient cost information.

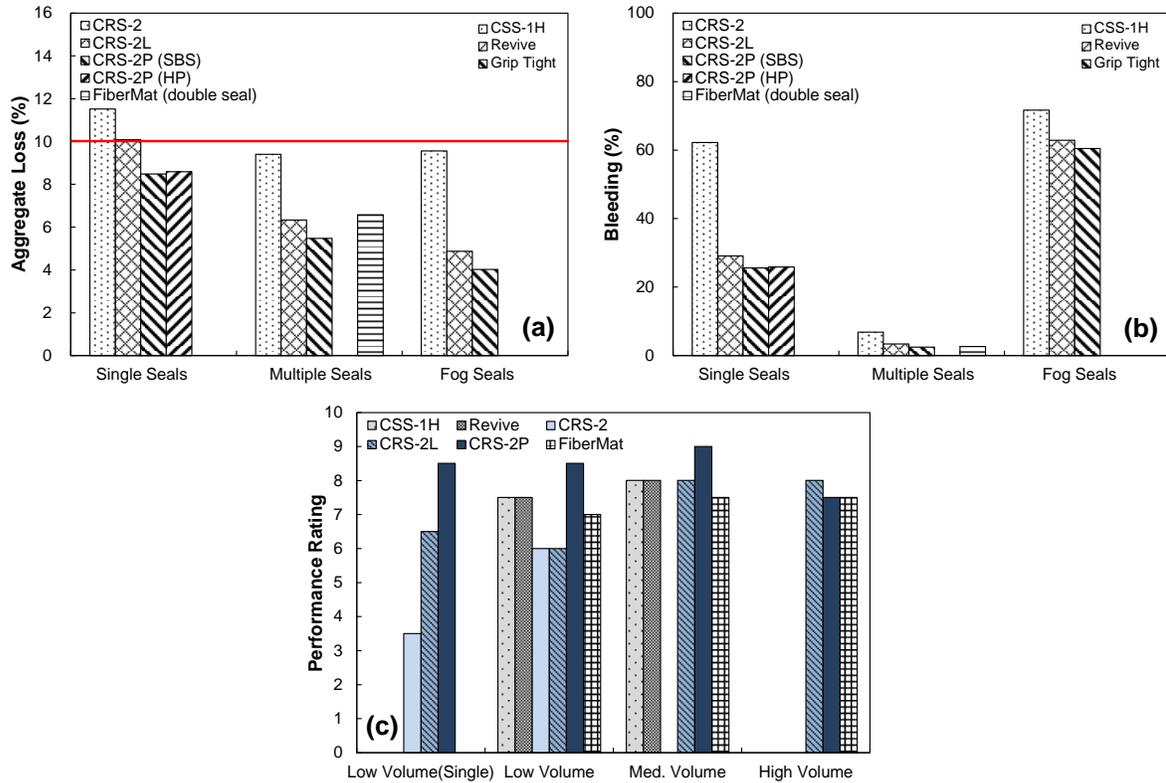


Figure 95 Performance comparisons of different seal types: (a) aggregate retention by MMLS3 test, (b) bleeding by MMLS3 test, and (c) field performance ratings

Figure 95 (a) and (b) indicate that multiple seals show the best performance in terms of aggregate retention and resistance to bleeding. Also, single seals with CRS-2P emulsion perform best in terms of aggregate retention and resistance to bleeding. A fog seal application can enhance the performance of chip seals in terms of reduced aggregate loss, but fog seals may cause bleeding problems due to their high EAR. Figure 95 (c) shows more realistic and reliable performance information obtained from field sections. Overall, single seals show the worst performance, but the interesting finding from the field performance ratings is that the CRS-2P emulsion sections show the best performance. In addition, the single seal with the CRS-2P emulsion performs as well as the multiple seals with the CRS-2P emulsion. Also, fog seal applications enhance performance in the field sections. Bleeding problems were not observed from the field survey.

Based on the literature review, cost information, and performance comparisons, two seal types are recommended, depending on traffic volume and pavement conditions. Table 48 shows the recommended seal types.

Table 48 Recommendation of Seal Type

Seal Types	Single Seal w/ CRS-2P (Fog Seal can be considered)	Double Seal w/ CRS-2P (Fog Seal can be considered)
Recommendation	- Less than 5,000ADT, or - Pavement condition is good or newly constructed.	- Top layer: choking material - More than 5,000ADT, or - Heavily cracked roads on low volume
Need Study	- Criteria in pavement condition and in-service life of original pavement	- Maximum allowable traffic volume - Criteria in heavily cracked roads
Fog Seal	Fog seal application is recommended if the CRS-2L emulsion is used instead of the CRS-2P emulsion.	

6.5 Construction Procedures

The information gathered from the literature review and previous research (NCDOT HWY-2006-06) is used to develop several refined construction procedures. The main points of the developed construction procedures are as follows.

- 1) Emulsion spreading, aggregate spreading and compaction are conducted as soon as each procedure is completed.
- 2) Sweeping is applied two to three hours after compaction.
- 3) Traffic is allowed after the sweeping procedure.
- 4) Fog seals are applied on the same day.
- 5) Compaction is applied according to the method recommended from previous research (NCDOT HWY-2006-06)

Figure 96 shows the construction procedures used in this research and in Minnesota.

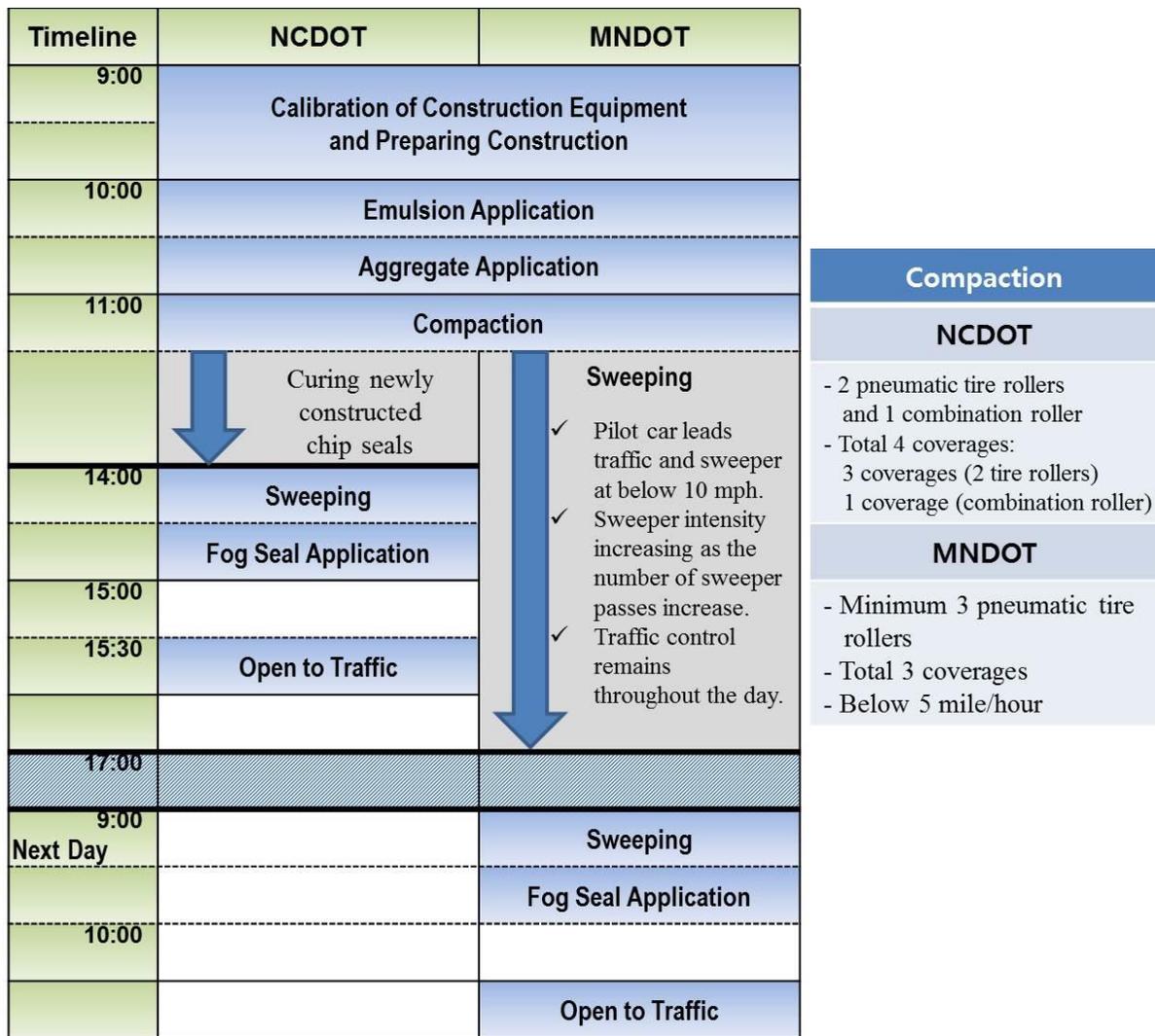


Figure 96 Construction procedure timeline

Figure 96 shows that the NCDOT construction procedure needs one day for construction, including the fog seal application, but the road should be closed during construction. The MNDOT construction procedure takes two days for construction, but the road closing time is less than in the NCDOT procedure. Also, traffic speeds should not exceed 10 mile/hour throughout construction.

6.6 Traffic Volume

Normally, chip seals are constructed on rural roads with low traffic volume as a surface treatment. However, with the increased levels of effectiveness that PMEs provide, as compared to their unmodified counterparts, the use of chip seals on high-volume roads is now feasible and provides some of the same benefits that chip seals have been shown to provide for low-volume roads. In other words, as the quality of the materials and construction procedures (i.e., use of PMEs, controlled aggregate sources, and refined construction procedures) is enhanced, the maximum allowable traffic volume in chip seals can be increased.

The major concern in predicting or evaluating chip seal performance in the field is that there are no methods that can produce quantitative values of performance in the field. The critical parameters of chip seal performance are aggregate loss and bleeding. Bleeding can be measured by visual observation and pictures of the pavement surface, but aggregate retention performance cannot be measured in the field. The only parameter that can be measured in the field is pavement surface texture. This measurement can be taken by a laser profiler, and then the profiles can be calculated as MPD values. With the field MPDs obtained under different conditions, such as different types of emulsion and traffic volumes, relationships between the field MPDs and traffic volumes can be developed. Also, MPDs can be obtained as a function of the percentage of aggregate loss in laboratory tests. Based on the laboratory aggregate loss test results, relationships between the laboratory MPDs and aggregate loss can be obtained. Finally, relationships between aggregate loss and traffic volume are developed to predict the maximum allowable traffic volumes in the field, based on the 10% aggregate loss criterion.

Because the CRS-2 emulsion single seal was constructed only on a low-volume road in the field, the CRS-2 emulsion and single seal cannot be used to develop the relationships for the prediction of aggregate loss in the field. Figure 97 shows the MPD analysis that is used to predict the maximum allowable traffic volumes for multiple chip seals with different emulsions.

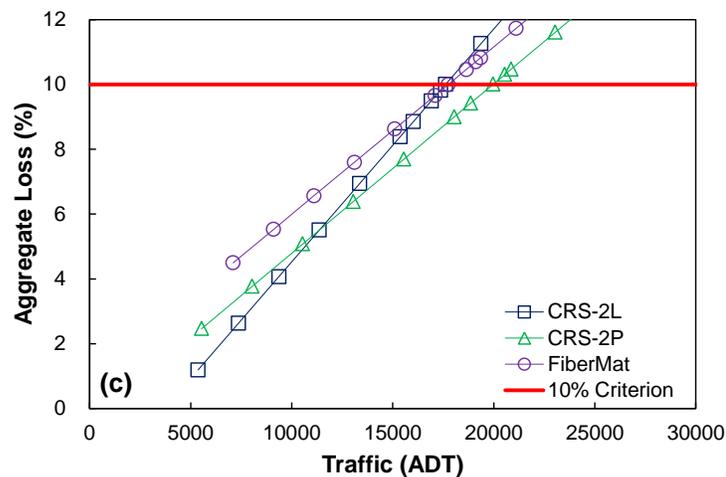
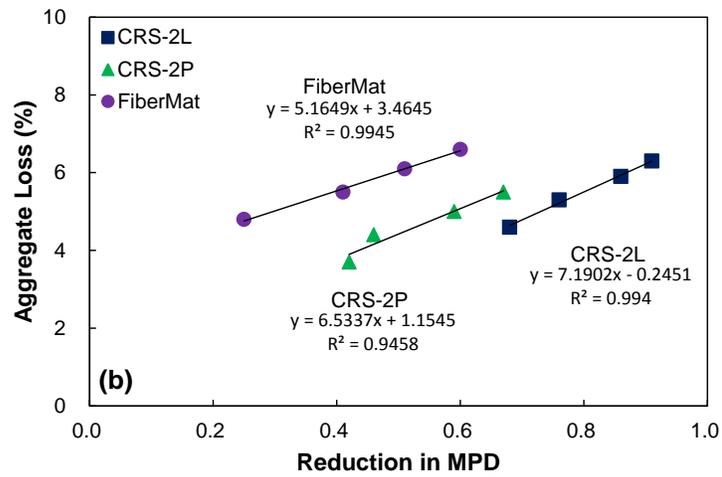
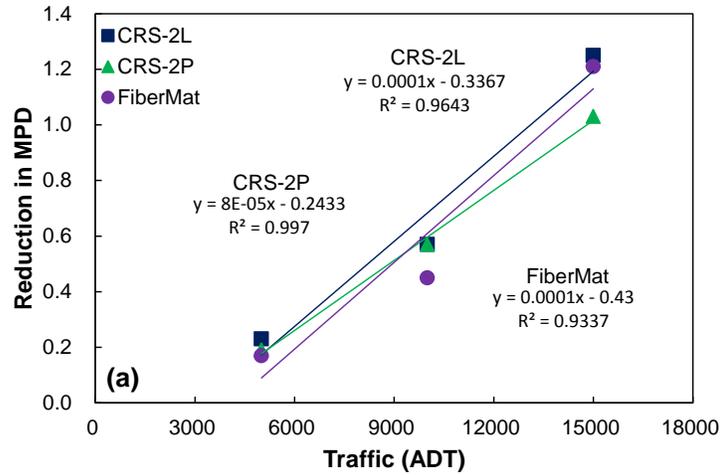


Figure 97 MPD analysis: relationships between (a) MPD and traffic volumes in field, (b) aggregate loss and MPD in laboratory, and (c) aggregate loss and field MPD

Figure 97 shows the maximum allowable traffic volumes for triple seals with the CRS-2L and the CRS-2P emulsions. The maximum allowable traffic volumes for double seals with FiberMat Type A can be estimated based on the 10% aggregate loss criterion. Table 49 presents the estimated maximum allowable traffic volumes.

Table 49 Estimated Maximum Traffic Volume for Multiple Seals

Sample Type	Maximum Traffic Volume (ADT)
CRS-2L (Triple Seal)	17,617
CRS-2P (Triple Seal)	19,966
FiberMat (Double Seal)	17,750

Table 49 shows that the triple seal with the CRS-2P emulsion can be constructed up to 20,000 ADT, and the triple seal with the CRS-2L emulsion and the double seal with the FiberMat Type A emulsion can be applied below 18,000 (approximately) ADT. That is, the CRS-2P emulsion can be used with a higher maximum allowable traffic volume than the CRS-2L and the FiberMat Type A emulsions. Given the performance test results and field performance ratings, the estimated maximum traffic volumes are reasonable results. However, the MPD analysis is not sufficient to apply it to actual chip seal construction because these maximum allowable traffic volumes are suitable for specific chip seal types (i.e., the applied application rates and types used in this research). The use of different chip seal types and application rates may lead to different maximum allowable traffic volumes. Therefore, further study is needed to suggest additional accurate maximum allowable traffic volumes for chip seals.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Conclusions

This research presents an evaluation of the performance of polymer-modified ASTs and fog seals in order to develop and suggest guidelines for chip seals under high-volume traffic. The curing time study was performed to investigate the curing and adhesive behavior of the emulsions, and AST performance testing was conducted in the laboratory to evaluate chip seal performance.

A refined construction procedure for chip seals under high-volume traffic was developed based on previous research efforts. Then, field test sections were constructed based on the gathered information, i.e., emulsion properties, chip seal performance characteristics, and the refined construction procedure.

The performance of actual chip seals was evaluated by laboratory performance tests using the field samples, and field section monitoring was performed by the laser profiler and visual survey to develop guidelines for chip seals under high-volume traffic. The guidelines can be an effective means to construct quality chip seals on high-volume traffic roadways.

7.1.1 Evaluation of Chip Seal Performance

In order to evaluate the performance of polymer-modified ASTs, four emulsion types (CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P) and two aggregate types (granite 78M and lightweight) were used to fabricate chip seal specimens for laboratory tests in this research. All the specimens were tested for adhesive behavior, aggregate retention performance, and bleeding performance using the evaporation test, Vialit test, and MMLS3 test under different temperature and/or curing time conditions. Based on the test data, the following conclusions are drawn to support the benefits of using PME in ASTs.

- According to the evaporation test results, the SBS CRS-2P emulsion cures the fastest (within an hour), and the HP CRS-2P emulsion cures within two hours. The CRS-2 and the CRS-2L emulsions cure within approximately three hours.
- The PMEs show better bond strength than the CRS-2 unmodified emulsion, but the difference is not significant at a low curing temperature (15°C).
- Based on the Vialit test results, the adhesion development of all four emulsion types is very sensitive with regard to curing time and temperature.
- At high curing temperatures, aggregate retention develops quickly. Although the CRS-2 unmodified emulsion shows a similar development trend to the aggregate retention performance of the PMEs, the difference in aggregate loss between the CRS-2 emulsion and the PMEs is significant after two hours of curing.
- The PMEs cure faster than the CRS-2 unmodified emulsion at all curing temperatures, and all four emulsions cure faster at higher curing temperatures.
- Overall, the CRS-2 unmodified emulsion shows the worst aggregate retention performance (most aggregate loss) at all curing times and temperatures. The SBS CRS-2P emulsion shows slightly more aggregate loss at four hours of curing time than the CRS-2L and HP CRS-2P emulsions, but the aggregate retention performance of the three PMEs does not differ significantly.
- The lightweight aggregate specimens show better aggregate retention performance than the granite 78M specimens for all emulsion types.
- The curing temperature of 15°C is too low for the Vialit specimens made of granite aggregate to cure completely within four hours. Therefore, for field construction, warm weather is necessary for the sufficient aggregate retention performance of chip seals.
- Based on the curing time and temperature study that employs the evaporation test and the Vialit test, the use of PMEs in chip seals provides a shorter curing time and better aggregate retention performance than unmodified emulsions. Also, a high curing temperature (i.e., warm weather conditions in the field) plays a vital role in improving chip seal performance.

- Correlations between bond strength and aggregate loss that are found from the Vialit test results can be established for different emulsions, aggregates, and curing temperatures. The correlations suggest potential BBS limits based on the 10% aggregate loss criterion for the different conditions. Overall, the BBS limits of the PME's are lower than those of the CRS-2 emulsion.
- From the MMLS3 aggregate loss performance test results, the samples of CRS-2 unmodified emulsion with the granite 78M aggregate show the worst aggregate retention performance and exceed the aggregate loss criterion (10%) established by the Alaska Department of Transportation. However, the three modified emulsion types with the granite 78M aggregate and all four emulsion types with the lightweight aggregate meet the criterion. Specifically, the samples made with lightweight aggregate show aggregate loss below 5% after MMLS3 loading, regardless of emulsion type.
- The MMLS3 test and Vialit test results can be compared even though the two test methods use different mechanisms to induce the aggregate loss in chip seal samples. Both sets of test results show a similar aggregate retention performance trend; that is, the PME's show better aggregate retention performance than the unmodified emulsion. The HP CRS-2P emulsion shows the best aggregate retention performance according to both sets of test results, but there is no significant difference among the PME's.
- The bleeding test analysis also shows that the CRS-2 unmodified emulsion performs the worst among all emulsion types. In particular, the combination of the CRS-2 emulsion and granite 78M aggregate corresponds to the worst performance (least bleeding resistance/most bleeding). The HP CRS-2P and SBS CRS-2P emulsions show the most bleeding resistance, but there is no significant difference among the PME's.
- In summary, all of the test methods used in this study indicate that the PME's show better performance in all areas (adhesive behavior, aggregate retention, and

bleeding) than the CRS-2 unmodified emulsion. However, there is no significant difference among the PME's regarding the performance characteristics.

7.1.2 Evaluation of Fog Seal Performance

The fog seal study presents information regarding the effectiveness of fog seals and application guidelines for fog seals applied to chip seal surface. The curing time study reveals the curing properties of the study emulsions and determines approximate curing times. Also, the fog seal performance test results suggest appropriate fog seal EARs and fog seal effectiveness characteristics, such as reduced aggregate loss, and sufficient skid resistance. Ultimately, this study can lead to the recommendation of a certain fog seal emulsion type and EAR for good pavement surface performance. However, only one type of chip seal texture was employed for this research (i.e., the one recommended by the chip seal mix design research). Therefore, additional research into different chip seal surface textures is necessary to learn more about the application of fog seals on various chip seal surfaces.

The following findings can be drawn from the curing time study:

- When considering the use of unmodified emulsions, the use of CQS-1h emulsion does not offer any advantages over the CSS-1h emulsion.
- The use of modified emulsions improves the emulsion bond strength and decreases the traffic closure period.
- At high temperatures and low EARs, emulsions can cure faster, but low EARs can lead to poor pavement surface performance.
- Bond strength develops more quickly in the ReviveTM emulsion than in the CSS-1h and CQS-1h emulsions, indicating the ability of ReviveTM to gain strength early and quickly.
- The rolling ball test results suggest that the Grip-Tight emulsion is faster than that of the other emulsion types.
- The damping test results suggest that the Grip-Tight emulsion performs the best of all the study emulsions; i.e. it exhibits the lowest number of stained pixels. Also,

the damping test results suggest that the ReviveTM emulsion performs better than the CSS-1h and CQS-1h emulsions.

- Overall, modified emulsions show more effective emulsion curing rates than unmodified emulsions. When comparing the properties of the two emulsions, the Grip-Tight emulsion performs better than ReviveTM emulsion, but the difference between them is not significant.
- For field applications, the emulsion diluting process is not necessary for the Grip-Tight emulsion.

The following findings can be drawn from the fog seal performance study:

- The Vialit test is not effective for fog seal performance tests.
- Fog seal samples that are applied with CSS-1h emulsion exhibit the most aggregate loss (i.e., the worst aggregate retention performance), especially at the lowest EAR (0.08 gal/yd² (0.36 L/m²)), showing approximately 15 % of aggregate loss after MMLS3 loading. Whereas, the samples applied by ReviveTM and Grip-Tight emulsions show below 5 % of aggregate loss.
- Overall, the fog seal samples that are applied with the Grip-Tight emulsion exhibit the least aggregate loss (i.e., the best aggregate retention performance).
- Fog sealing increases the MPD values of samples temporarily, but after traffic loading, the MPD values decrease to those of samples that have been fog sealed (i.e., chip seal samples).
- When comparing overall MPD values as a function of wheel passes, the MPD values decrease significantly within 40 minutes (3,960 MMLS3 wheel passes), but after that amount of time, the change in MPD values is small.
- The MPD values for each EAR after 40 minutes of loading are similar to each other, although the initial MPD values may differ.
- The skid resistance test results do not indicate a significant reduction in skid resistance between the chip seal and fog seal surfaces.

- After the bleeding test, the skid resistance of most samples does not decrease much, except one case, i.e., the CSS-1h emulsion with a high EAR (0.16 gal/yd² (0.72 L/m²)).
- The skid numbers for fog seal samples are much higher than the North Carolina requirement for surface skid resistance (SN 37). This finding suggests that the use of chip seal recommended by the chip seal mix design research (HWY-2008-04) for fog seal construction does not cause skid resistance problems.
- High EARs lead to more bleeding areas for all the study emulsion types.
- The ReviveTM and Grip-Tight emulsions show a similar bleeding trend, whereas the CSS-1h emulsion presents higher bleeding percentages in every case.
- The CSS-1h emulsion with an EAR of 0.16 gal/yd² (0.72 L/m²) does not resist bleeding well (i.e., exhibit the worst bleeding resistance). The skid resistance results indicate that a high bleeding percentage corresponds to less skid resistance of surface.

In summary, modified emulsions are better in terms of curing time and performance than unmodified emulsions. Although the difference between the ReviveTM and Grip-Tight emulsions is not significant, in the most cases, the Grip-Tight emulsion exhibits better properties.

7.1.3 Evaluation of Field Tests

For the field tests, four emulsion types (CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A) and two aggregate types (granite 78M for the bottom and middle layers and Virginia #9 for the top layer) were used to construct chip seal sections on roadways. The field specimens were extracted and moved to the laboratory to evaluate the performance of polymer-modified ASTs using the MMLS3. The performance of the field sections also was evaluated by a pavement condition survey and laser scanning. Based on the test data, the following conclusions are drawn to support the benefits of using PMEs in ASTs.

- The MMLS3 aggregate loss performance test results using field samples indicate that the samples of CRS-2 unmodified emulsion show the worst aggregate retention performance, whereas the samples with SBS CRS-2P emulsion show the best aggregate retention performance. However, all the field samples meet the criterion of 10% aggregate loss. Therefore, the test results clearly show that the use of Virginia #9 aggregate as a top layer is effective in reducing aggregate loss in chip seals.
- The bleeding analysis also shows that the CRS-2 unmodified emulsion performs the worst among all emulsion types. However, the bleeding test results for all the emulsion types indicate that the field samples show strong resistance to bleeding (almost the same as the laboratory test results for the PMEs with the lightweight aggregate).
- According to the rutting test results, the PMEs exhibit the best resistance to rutting, and the CRS-2 emulsion specimen attains its final rut depth quickly. The SBS CRS-2P emulsion specimens show the best rutting resistance for the triple seals.
- All of the test methods used in the field tests indicate that the PMEs show better performance in all areas (aggregate retention, bleeding, and rutting properties) than the CRS-2 unmodified emulsion. However, there is no significant difference among the PMEs regarding the performance characteristics.
- The MPD values in the field decrease significantly from the day of construction to one week after construction; this trend is similar to that found in the laboratory test results.
- After a week, the MPD values reach their asymptotic values, which suggests that the field sections perform well without severe failure, such as cracking, bleeding, and aggregate loss.
- Based on the MPDs obtained from both the field sections and laboratory test results, the correlations between aggregate loss and reduction in MPD in the field can be developed to predict the aggregate loss in the field sections.

- The aggregate loss predictions in the field indicate that the sections on high-volume roads show the worst aggregate retention performance. However, the low-volume sections present different results between the aggregate loss predictions and the field performance ratings. This finding may be due to the scanning locations. The scanned areas on low-volume roads do not show any failure, but alligator cracking was found on these same roads. Therefore, it is important to determine proper locations for scanning that are representative of the entire section.
- According to the field pavement condition survey, all the sections, except the CRS-2 emulsion single-seal section, perform well without severe failure. The SBS CRS-2P sections show the best performance regardless of seal type. In particular, the SBS CRS-2P single-seal section performs as well as the triple seals.
- Based on the test data for the laboratory and field specimens, field section monitoring, and literature review, guidelines for chip seals under high traffic volumes can be recommended.

7.1.4 Recommended Guideline

Based on the test data of laboratory and field specimens, the field section monitoring, and the literature reviews, the guideline for chip seals under high traffic volume is recommended.

- The existing pavement condition is important for chip seal performance. Chip seals should not be applied to roads that have structural failures.
- For single seals with granite 78M aggregate, the maximum PUC value is suggested as 31 for ASTs using non-PMEs and 38 for ASTs using PMEs (CRS-2L). However, the PUC values do not affect triple seals with choking aggregate as much as single seals.
- Non-PME (CRS-2) is not recommended for single seals on high traffic volume roads but can be used in double seals on low traffic volume roads (below 5,000 ADT). The CRS-2P emulsion is highly recommended for both single and multiple seals. The CRS-2L emulsion can be used, but the CRS-2P emulsion is more

effective because it shows better performance in both field and laboratory tests and is not much more expensive than the CRS-2L emulsion.

- Given that warm temperatures are better for the construction of quality chip seals, 15.5°C (60°F) is suggested as a potential minimum temperature for chip seal construction.
- Two seal types are recommended for chip seal construction. First, the single seal with CRS-2P emulsion (fog seal application can be considered) is recommended for roads with less than 5,000 ADT or roads in good condition or newly constructed roads. Second, the double seal with CRS-2P emulsion (fog seal application can be considered) is recommended for roads with more than 5,000 ADT. For fog seals, fog seal application is recommended if the CRS-2L emulsion is used instead of the CRS-2P emulsion.
- Refined chip seal construction procedure used in this research can be applied.
- The maximum allowable traffic volume can be estimated for multiple seals using MPD analysis. The triple seal with the CRS-2L emulsion and double seal with the FiberMat Type A emulsion can be constructed on 18,000 ADT roads approximately. The triple seal with the CRS-2P emulsion can be applied on about 20,000 ADT roads. Different chip seal types and application rates may lead to different maximum allowable traffic volumes. Therefore, further study is needed to suggest more accurate maximum allowable traffic volumes for chip seals.
- According to the field performance survey, the single seal with the CRS-2 emulsion should not be constructed on roads that have more than 5,000 ADT. Whereas, the single seal with the CRS-2P and the CRS-2L emulsions can be used on roads that have 5,000 ADT.

7.2 Recommendations for Further Research

7.2.1 Prediction of Aggregate Loss in the Field

Further research is required to extend the findings of the study of aggregate loss prediction in the field. The aggregate loss predictions in the field indicate that high-volume roads show the worst aggregate retention performance (i.e., the most aggregate loss). The prediction results are similar to the field performance ratings. However, the low-volume sections present different results between the aggregate loss predictions and the field performance ratings. The low-volume sections perform worse than the medium-volume sections in the field performance ratings. Currently, the field sections show no significant differences, i.e., no significant failures that can be used to distinguish between the sections in terms of performance. Therefore, in order to verify the aggregate loss predictions, further research is needed; for example, a pavement condition survey and laser scanning of the field sections should be conducted.

7.2.2 Guidelines for Chip Seals

Further research is recommended to improve the recommended guidelines with more specific criteria for chip seals under high-volume traffic. Even though the current research has developed effective guidelines, a few additional factors that affect chip seal construction should be studied in more depth.

Based on the field test results (pavement performance ratings), it is suggested that the condition of old pavements is relatively poor; thus, old pavements are not recommended for single-seal treatment. The best way to determine the condition of a pavement is to suggest a specific value for the condition of the existing pavement that is to be treated with a chip seal. However, there are not sufficient data to suggest such a specific value, so more research is needed.

According to the PUC analysis, unmodified emulsions should be used with a PUC below 31, and the PME (CRS-2L) can be used with a PUC below 38. However, these specific PUC values cannot be recommended strongly because the data points that are needed

to develop relationships are insufficient, and the other PME (i.e., other than the CRS-2L emulsion) specimens were made with only one aggregate. At this point, it is clear that a high PUC value leads to poor performance in chip seals. Therefore, it is important to use well-controlled aggregate sources for chip seal construction. Also, further research into the effects of PUCs in terms of different emulsions should be conducted in order to recommend specific PUC values for chip seals. Furthermore, PUC analysis should be applied carefully to multiple seals, which have a top layer of choking materials. If choking aggregate, normally Virginia #9, is applied on top of a multiple seal, the PUC of the multiple seal would be different from that of a single seal, and the performance of the multiple seal would be enhanced.

According to the MPD analysis for the maximum allowable traffic volume for chip seals, the estimated maximum traffic volumes are reasonable results given the performance test results and field performance ratings. However, this MPD analysis is not sufficient to apply it to actual chip seal construction because these maximum allowable traffic volumes are suitable only for specific chip seal types (i.e., the applied application rates and types used in this research). The use of different chip seal types and application rates may lead to different maximum allowable traffic volumes. Therefore, further study is needed to suggest additional accurate maximum allowable traffic volumes for chip seals.

7.2.3 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is an engineering economic analysis method that can be used to suggest better design for construction, rehabilitation, or preservation by comparing the relative economic benefits of each of these options (FHWA 2004).

In order to improve the recommended guidelines for chip seals under high traffic volume, LCCA can be used to assist in determining economical ways to include pavement conditions, material types, seal types, and maximum traffic volume while considering the performance properties and economic benefits of each factor. Therefore, further study of LCCA is suggested to develop more accurate and effective guidelines for chip seals under high traffic volume.

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