RESEARCH & DEVELOPMENT

Extending the Use of Chip Seals to High Volume Roads by Using Polymer-Modified Emulsions and Optimized Construction Procedures

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16. Abstract

This report presents the findings from a field and laboratory experimental program that is designed to develop guidelines regarding the maximum amount of traffic that modified chip seals can support using improved construction procedures. For the laboratory tests, the evaporation test, bitumen bond strength (BBS) test, and Vialit test are used to investigate the curing and adhesive behavior of unmodified and polymer-modified emulsions. In addition, the third-scale model mobile load simulator (MMLS3) was employed to test for aggregate retention, bleeding, and rutting performance. In order to evaluate the actual chip seal performance in the field, a total of 12 field test sections were constructed on three different traffic volume roads using different materials and seal types. Some of the field samples were extracted from the field test sections and moved to the laboratory for the MMLS3 performance testing. Also, the field sections were monitored to compare the field performance with the laboratory performance.

The main findings from this study are: (1) the laboratory test results indicate that the use of PMEs improves the chip seal performance in all areas, i.e., curing and adhesive behavior, aggregate retention, bleeding, and rutting; (2) strong correlations are found between the bitumen bond strength and the aggregate loss found from the Vialit test; (3) the field observations indicate that SBS-modified emulsion performs the best of all the emulsions, regardless of seal type and traffic volume; (4) 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, and the double seal with CRS-2P emulsion (fog seal application can be considered) is recommended for roads with more than 5,000 ADT or for heavily cracked areas on low-volume roads; and (5) the maximum allowable traffic volume can be estimated for multiple seals using Mean Profile Depth analysis. Finally, different chip seal types and application rates may lead to different maximum allowable traffic volumes. Therefore, further study is recommended to suggest more accurate maximum allowable traffic volumes for chip seals.

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EXECUTIVE SUMMARY

Chip seals are among the most efficient and cost-effective methods utilized by state highway agencies to preserve existing pavements and prolong their service lives. If these benefits of chip seals can be extended to high volume roads, cost savings and increased operational efficiency would be significant. A series of research projects funded by the North Carolina Department of Transportation (NCDOT) has shown various ways to improve chip seal performance, thus extending the use of chip seals to high volume roads. These improvements include the use of: (1) aggregate with uniform gradation, (2) polymer-modified emulsions, (3) optimized rolling protocols, and (4) performance-based mix design.

The objective of this study is to develop guidelines for the amount of heavy traffic that the modified chip seals can support based on the findings from the previous NCDOT projects. Both laboratory experiments and field evaluation were conducted to accomplish the objective.

Two types of aggregate are used for the laboratory 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 in. nominal maximum size of aggregate (NMSA). In order to compare the systematic gradation variations of aggregate sources in terms of performance testing for this research, three gradations are used with varying degrees of gradation uniformity for both lightweight and granite 78M aggregate. Four emulsion types are tested in the laboratory study: HP CRS-2P and SBS CRS-2P produced by Road Science, LLC*TM*, CRS-2L (the three modified emulsions), and CRS-2 (the unmodified emulsion).

The optimal aggregate application rates (AARs) and emulsion application rates (EARs) were determined for 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/yd^2 for the granite 78M aggregate and 7 lb/yd^2 for the lightweight aggregate. For all the specimens of both aggregate types, an EAR of 0.25 gal/yd^2 was applied. All the laboratory chip seal specimens were fabricated using the scaled down chip spreader, ChipSS, and the temperature controlled greenhouse facility.

The laboratory study includes the curing time evaluation and chip seal performance evaluation. The curing times of various emulsions were evaluated using the evaporation test, Pneumatic Adhesion Tension Testing Instrument (PATTI) test, and Vialit test. Chip seal performance characteristics evaluated in the laboratory include aggregate loss and bleeding, which were determined using the third-scale Model Mobile Loading Simulator (MMLS3).

Also, the field sections were monitored to compare the field performance with the laboratory performance. 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.

The construction variables that were used in the field experimental design include:

Emulsion type: CRS-2, CRS-2L, SBS CRS-2P, and FiberMat Type A
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)

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 was used as the top layer as a choking material for the granite 78M aggregate used in the middle layer. A constant EAR and AAR were applied to all the test sections, and the optimal EAR and AAR were decided by the field supervisor.

For the 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 constructed sections were swept after two to three hours of curing, and then the sections were opened to traffic. 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.

The main findings from this study are: (1) the laboratory test results indicate that the use of PMEs improves the chip seal performance in all areas, i.e., curing and adhesive behavior, aggregate retention, bleeding, and rutting; (2) strong correlations are found between the bitumen bond strength and the aggregate loss found from the Vialit test; (3) the field observations indicate that SBS-modified emulsion performs the best of all the emulsions, regardless of seal type and traffic volume; (4) 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, and the double seal with CRS-2P emulsion (fog seal application can be considered) is recommended for roads with more than 5,000 ADT or for heavily cracked areas on low-volume roads; and (5) the maximum allowable traffic volume can be estimated for multiple seals using Mean Profile Depth analysis. Finally, different chip seal types and application rates may lead to different maximum allowable traffic volumes. Therefore, further study is recommended to suggest more accurate maximum allowable traffic volumes for chip seals.

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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 research projects 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 project, 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 project shows that changes in rolling patterns can greatly improve aggregate retention performance. However, the emulsion used in that project 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 projects 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.

The proposed research herein describes a field and laboratory experimental program to develop guidelines regarding the maximum amount of traffic that modified chip seals can support using improved construction procedures.

1.2 Research Objective

The primary objective of the research project is to develop guidelines for the amount of heavy traffic that the modified chip seals can support.

1.3 Research Framework

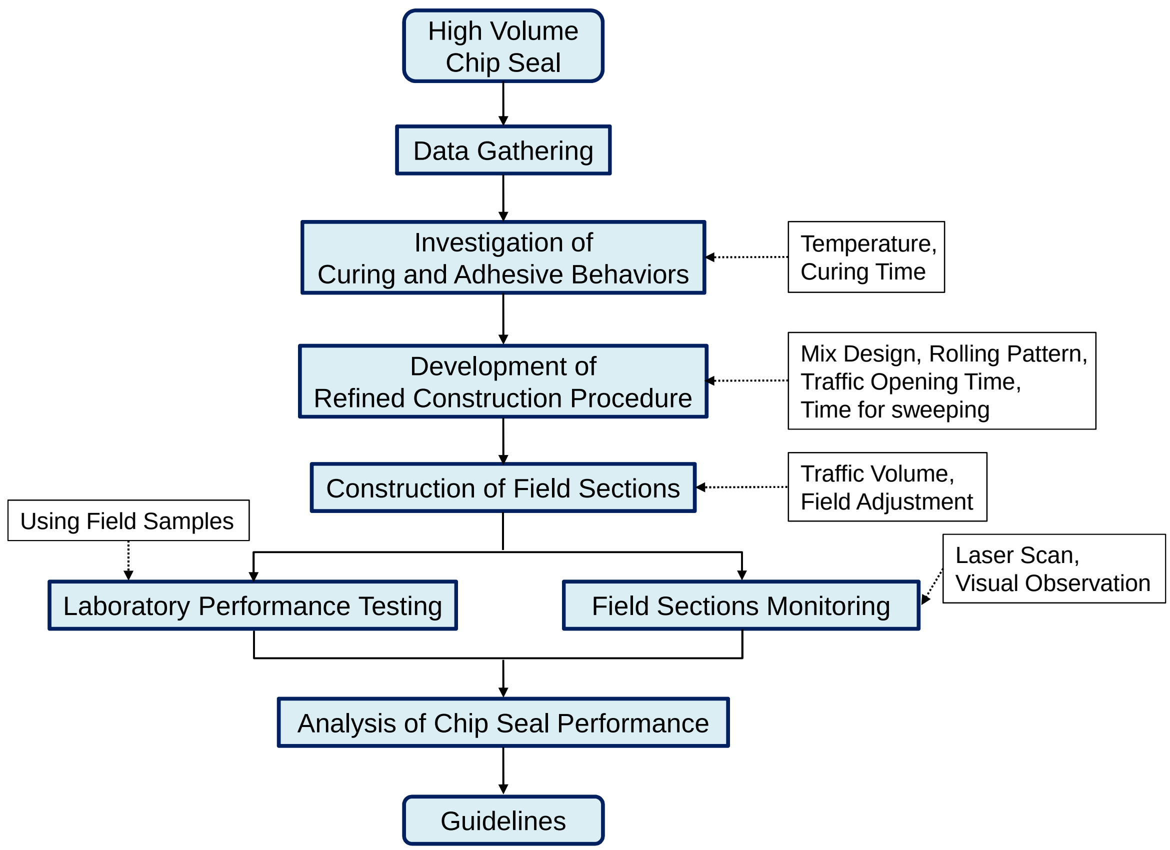


Figure 1 Research framework

1.4 Report Organization

This report is composed of eight chapters. Chapter 1 describes the research needs and objectives. Chapter 2 provides a summary of the literature review of chip seals under high traffic volume. Chapter 3 presents the experimental test program, test procedures, and analysis concepts. Chapter 4 describes the laboratory evaluation of chip seal performance. Chapter 5 provides the field evaluation of chip seal 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 report.

2. LITERATURE REVIEW

2.1 General

The chip seal, also known as surface treatment, seal coat, or surface dressing, 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). Generally, the cationic rapid setting (CRS) type of emulsion is most commonly used in asphalt for chip seals on low volume roads. 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.

2.2 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 PMEs can enhance certain properties of asphalt emulsion. Generally, four types of polymers may be used in PMEs: 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 project 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 2. Also seen in Figure 2, 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.

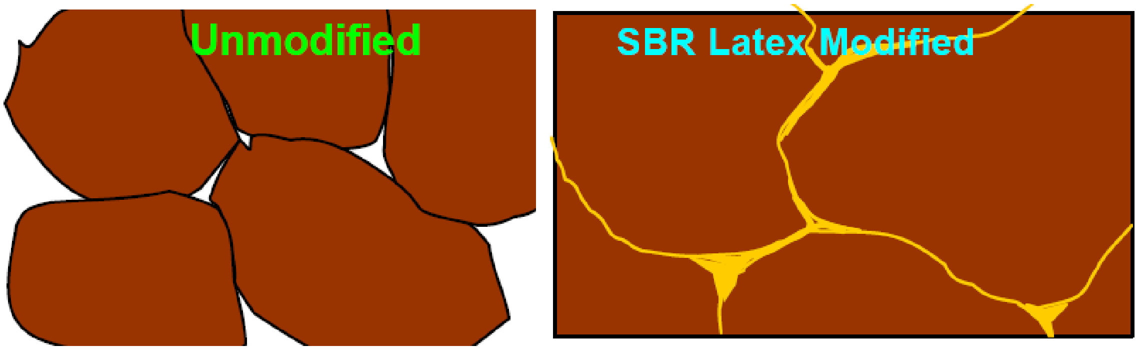


Figure 2 Schematic diagram of fully cured unmodified asphalt and SBR latex polymer-modified asphalt (Takamura 2003)

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.

2.3 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 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 project, 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 projects 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 projects are as follows: the median Pavement Condition Index (PCI) was 75 after 52 months with a significant reduction in cracking; 20% of the projects 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 PMEs 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 PMEs 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 PMEs 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 projects. 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.

2.5 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 HWY-2004-04 project, 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.

2.6 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.

Gransberg and James (2005) 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.

Furthermore, Yazgan and Senadheer (2003) suggested that 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.

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 PMEs, 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 optimal 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 the rolling 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 optimal coverage distribution on the underlying layer of multiple seals (double and triple seals), one coverage of the layer immediately below the top layer improves the aggregate retention performance. Also, delayed rolling after chip spreading negatively affects aggregate retention performance. With regard to rolling pattern, Kim et al. recommended the use of two optimal rolling patterns for chip seal construction. For 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, the type B pattern 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 3 shows the schematic rolling patterns.

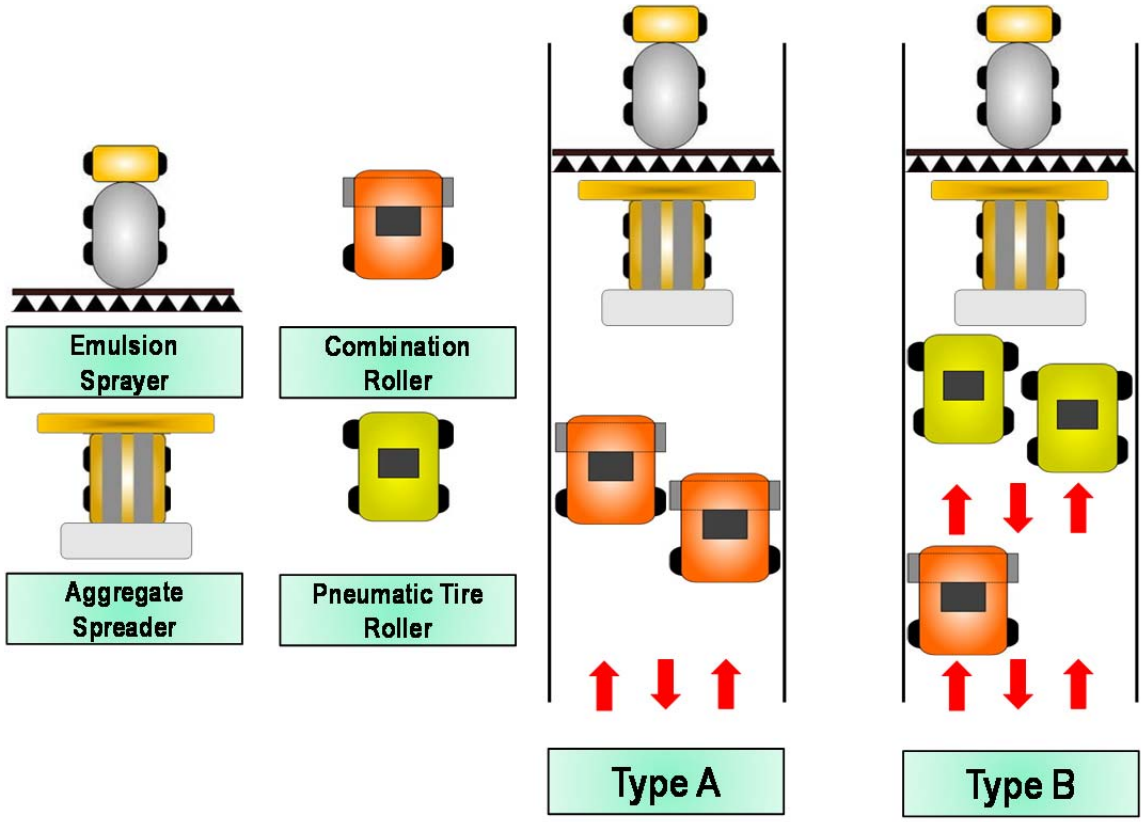


Figure 3 Recommended Rolling patterns (Kim et al. 2008)

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) were found to 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 up to 15,000 ADT comfortably. Also, single-seal construction has been done for 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 chip seal construction on all high-volume roadways. The MNDOT prohibits the use of CRS-2L emulsion (latex-modified) for seal coats because it is not cost-effective. Latex-modified asphalt cures slowly because the latex tends to float to the surface and trap water underneath the latex layer. Also, latex modification requires extra rolling to accelerate curing.

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. 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 4.

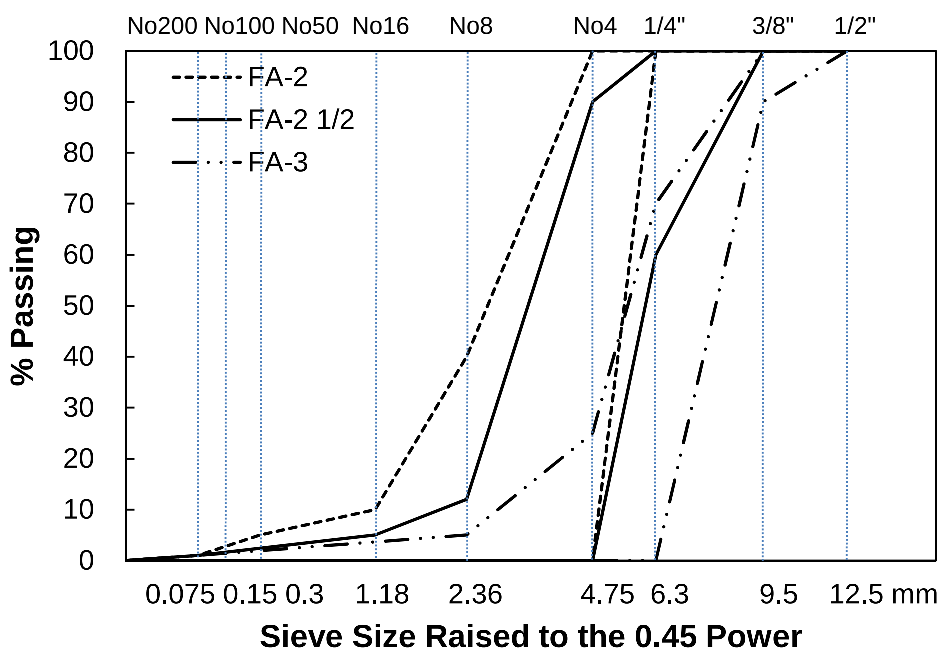


Figure 4 Aggregate particle size gradation in Minnesota: FA-2, FA-2 1/2, and FA-3

Single seals are used exclusively for 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 emulsion with a dilution rate of 50% is applied with rates of 0.07 to 0.12 gal/yd^2 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 of three pneumatic tire rollers is required for a 12-foot lane, and three passes are applied to cover the full paving width. In order to achieve adequate compaction, the roller should be applied continuously to the surface, and below 5 mph is the recommended speed for the rollers.

Sweeping is conducted within 20 minutes after 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 any excess aggregate effectively, mainly from the area outside the wheel path, but also from within 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 typically are used for the sweeping procedure.

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

Table 2 Comparison of Chip Seal Construction Factors

	NCDOT	MNDOT
Traffic Volume	• Single seal: 5,000 ADT • Multiple seal: 15,000 ADT	• Single seal: up to 15,000 ADT • No significant restrictions
Emulsion	• CRS-2L (normally)	• CRS-2P • Fog seal: CSS-1 or CSS-1H
Aggregate	• Granite and Virginia #9 (for choking material) • Less uniformity than MNDOT specifications	• Granite and Virginia #9 (for choking material) • Three uniform gradations with different nominal maximum aggregate sizes • Max. 25% FI
Seal Type	• Multiple seal (normally)	• Normally single seal • Fog seal is applied on chip seals
Compaction	• 3 pneumatic tire rollers and 1 combination roller • Total of 4 coverages	• 3 pneumatic tire rollers • Total of 3 coverages
Sweeping	• 2 – 3 hours after compaction	• After 20 minutes, pilot car leads traffic and sweeper (below 10 mph)

2.7 The Use of Modified Chip Seals for Increased 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 emulsion 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.

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 in. 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 types 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.

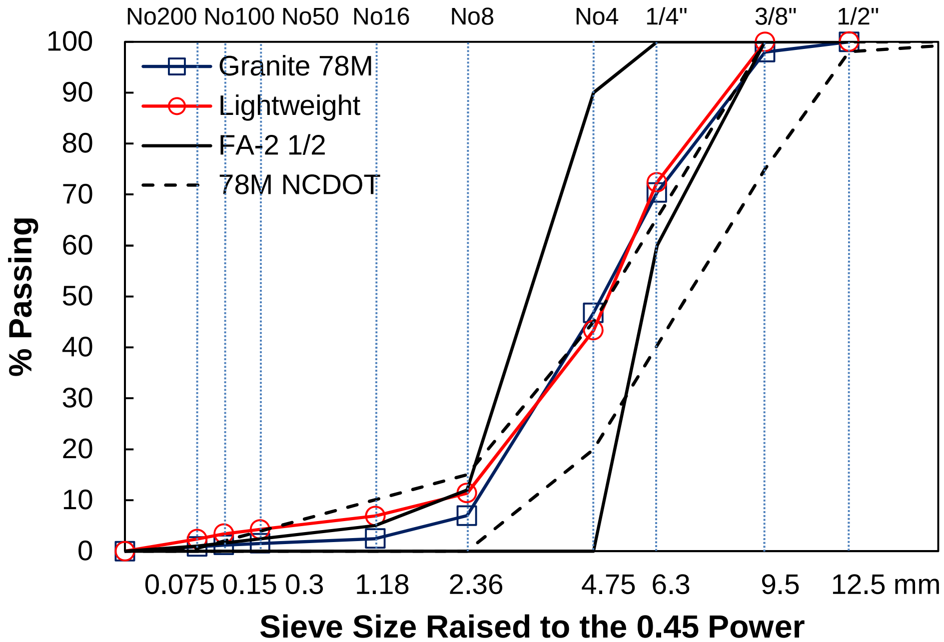


Figure 5 Aggregate particle size gradations

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 Comparison of Aggregate Performance Uniformity Coefficient (PUC) Values

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 for 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. The PUC 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.

$$PUC = \frac{P_{EM}}{P_{2EM}} \tag{1}$$

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 project (NCDOT HWY-2008-04), more uniform gradations (i.e., lower PUC values) led 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

For the performance evaluation of polymer-modified asphalt surface treatments (ASTs) used for this research, Road Science, LLC*TM* has produced two PMEs: 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).

3.1.4 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/yd^2 for the granite 78M aggregate and 7 lb/yd^2 for the lightweight aggregate. For all the specimens of both aggregate types, an EAR of 0.25 gal/yd^2 was applied for the CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions.

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 3 presents the experimental program that has been developed to accomplish the goals of this research project.

Table 3 Experimental Program

Phase	Research Purpose	Factors and Test Methods
1	Investigation of Curing and Adhesive Behaviors	- Temperature and Curing Time - Evaporation Test, PATTI 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 Tests: Aggregate Loss, Bleeding, and Rutting
4-2	Field Section 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).

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, Phase 4-1 and Phase 4-2. In Phase 4-1, 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 projects. In order to compare target application rates and actual application rates, i.e., EARs and AARs from different field sections, the ignition oven test is performed using Vialit samples. Aggregate loss, bleeding, and rutting 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 the use of 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 final report 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 final report 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 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

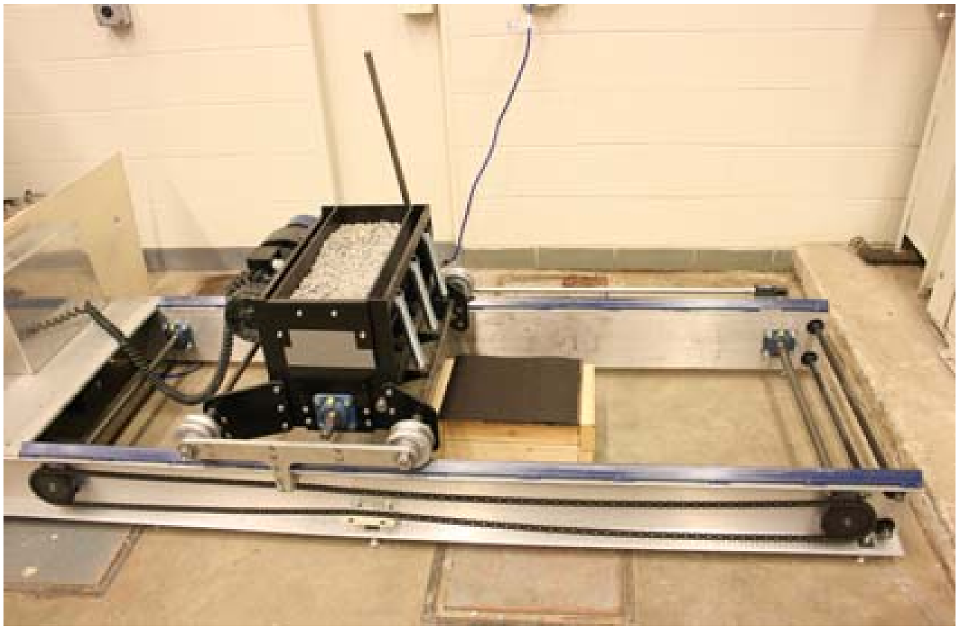


Figure 7 ChipSS

The second control factor that is necessary in carrying out the laboratory testing program is the ability to construct chip seal samples with accurate control over the time variable. Because the emulsion can be sprayed onto felt paper resting on a scale, it is fairly simple to apply the emulsion at a specified rate in the laboratory. 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 the emulsion at a reasonably steady rate. The device, ChipSS, shown in Figure 7, simulates the aggregate spreader that is currently used in field situations. ChipSS is housed in the greenhouse, thus allowing accurate temperature control in producing chip seal samples.

3.4 Experimental Test Methods

Based on the literature review, the NCSU research team has evaluated various chip seal test methods for their effectiveness in accomplishing the research objectives of this study. The selected performance tests for the different performance characteristics are listed in Table 4. 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 4 Test Methods for Chip Seal Performance

Performance Characteristics	Performance Test Methods
Curing and Adhesive Behavior	Evaporation Test, PATTI Test, Vialit Test
Aggregate Retention	MMLS3 Test, Vialit Test
Bleeding	MMLS3 Test
Surface Texture	Laser Profiler, MPD Analysis
Field Application Rates	Ignition Oven Test
Field Performance	Laser Profiler, Visual Observation

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 8 shows evaporation test samples in the 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.

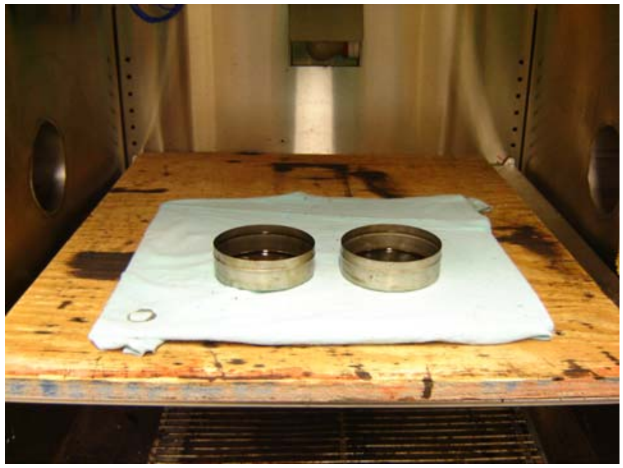
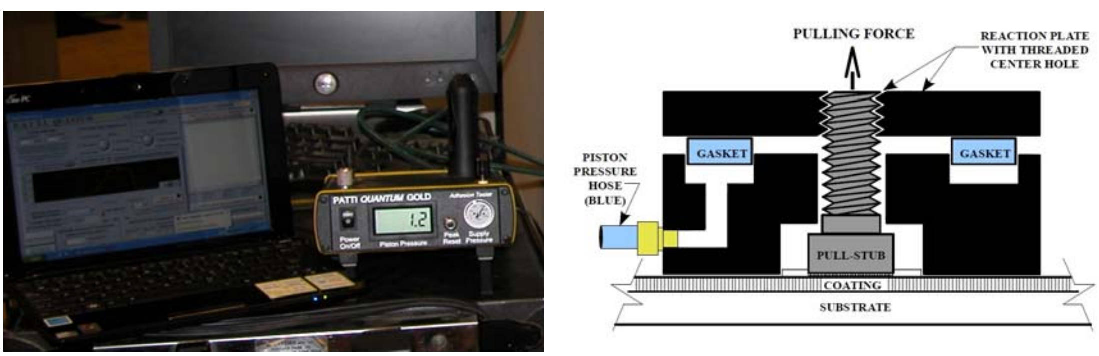


Figure 8 Evaporation test samples in environmental chamber

3.4.2 Pneumatic Adhesion Tension Testing Instrument (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 hot asphalt binders and aggregate surfaces, or between emulsions and aggregate surfaces. The PATTI itself and a schematic representation of the PATTI piston are provided in Figure 9. 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 NCSU research team has modified BBS test procedure so that it can be used also to test the bond strength of emulsions as a function of curing times.



(a) **(b)**

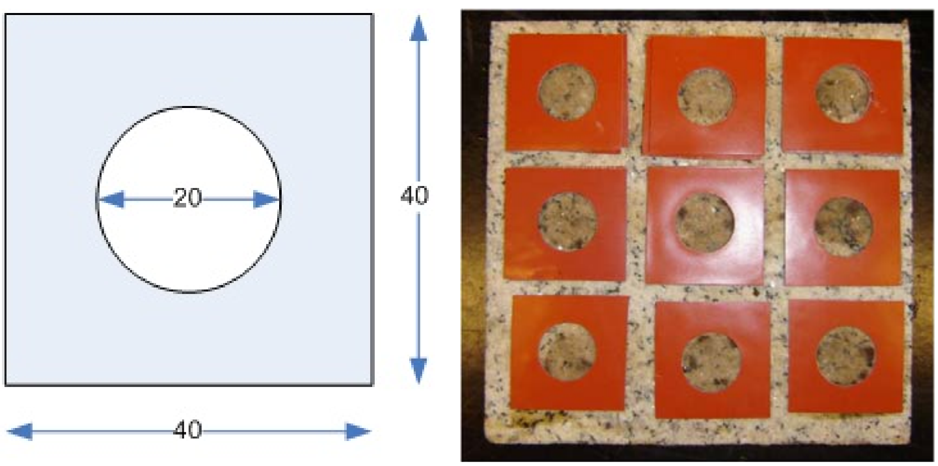
Figure 9 PATTI test: (a) PATTI device and (b) schematic of piston assembly (PATTI manual)

Figure 10 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 10 BBS test setup on aggregate substrate in the environmental chamber: (a) plan view and (b) side view

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 11 shows the mold dimensions and the molds attached to the aggregate substrate



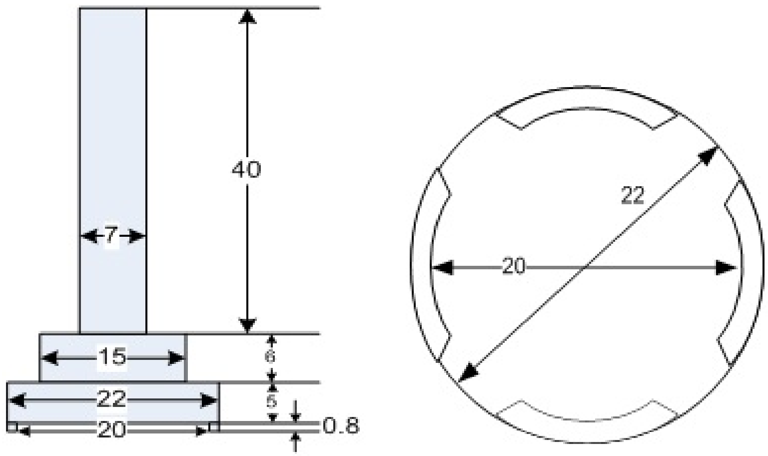
(a) (b)

Figure 11 (a) Mold dimensions (mm) and (b) molds attached 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.

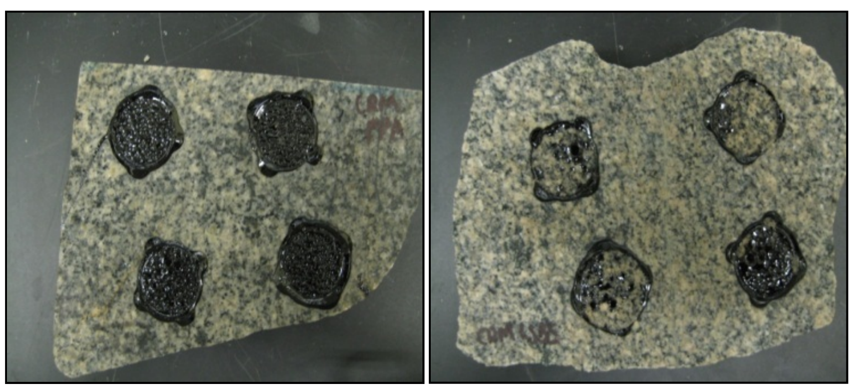
Figure 12 shows that the pull-stubs have 0.8 mm thick rims on the bottom plate and the rim has four gaps. These gaps allow any excess emulsion to flow out of the pull-stub, so the emulsion remains a uniform thickness.



(a) (b)

Figure 12 (a) Dimensions (mm) of pull-stubs: profile view and (b) bottom view (AASHTO-TP 91)

PATTI provides 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 13.



(a) (b)

Figure 13 Failure types; (a) cohesive failure and (b) adhesive failure

In this research, BBS testing 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 NCSU research team modified the BBS procedure 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, the

NCSU research team has 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 5 shows both procedures in detail. In order to maintain the test temperature, Step 4 is conducted in an environmental chamber.

Table 5 Comparison of BBS Procedure and Modified BBS Procedure

Steps	BBS Procedure	Modified BBS Procedure
1	Heat emulsion to 60 ± 2°C.	Heat emulsion to 60 ± 2°C for 1 hour.
2	Attach molds to aggregate substrate, and heat them to an application temperature.	
3	Fill molds with emulsion.	Fill molds with 0.6 ± 0.05 g of emulsion.
4	Cure the sample under controlled conditions for a given curing interval.	
5	Heat pull-stubs to 60 ± 2°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 ± 2°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, typically 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 the 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. Therefore, correction factors are determined for each aggregate type, as shown in Table 6, 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 Equations (2) and (3).

Table 6 Correction Factors for Each Aggregate Type

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

$$W_A = W_{RA} \times C.F. \quad (2)$$

$$W_{RE} = W_O - W_A \quad (3)$$

where

W_A = aggregate weight,
W_{RA} = residual aggregate weight (after burning),
W_{RE} = residual emulsion weight,
W_O = original sample weight, and
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, shown in Figure 14. 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 14 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 15, accelerates wear on the pavement 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 in. × 14 in., and emulsion is applied onto the felt paper in dimensions of 7 in. width and 12 in. length; this 7 in. width is the same width as the MMLS3 wheel path. An actual photograph of the MMLS3 test specimens is shown in Figure 16. The MMLS3 test procedure involves the following steps:

1. Cure the specimens in the temperature chamber at 95°F (35°C) for 12 hours and 35% ± 3% relative humidity, as specified by ASTM D7000 *Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples***.**
2. Weigh the initial specimens.
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 weigh the specimens.
5. Apply MMLS3 loading for 120 minutes, and weigh the specimens 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 15 MMLS3

Figure 16 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 104°F (40°C) testing 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 104°F (40°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 paper, the term *bleeding* is used for both bleeding and flushing.

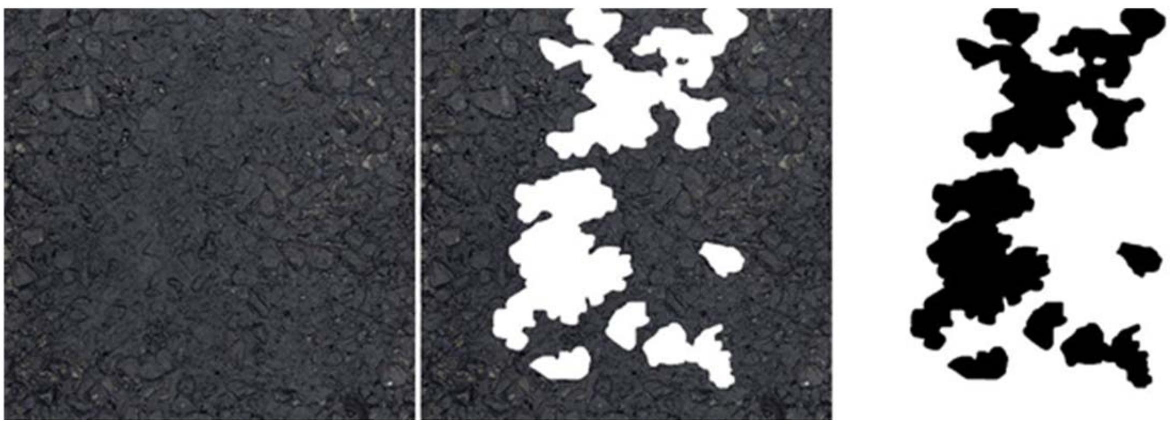
The chip seal samples are placed in the oven at 50°C for three hours prior to four hours of bleeding testing. During the four hours of MMLS3 loading, the test temperature, 50°C, is controlled inside the temperature chamber. This bleeding test process simulates the bleeding of chip seal surfaces during 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). This process is displayed in Figure 17.

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

where

A_{Total} = area of AST specimen (total number of pixels, 10 inches × 10 inches); and
$A_{Bleeding}$ = area of bleeding on AST specimen (sum of pixels obtained from bleeding image).



(a) (b) (c)

Figure 17 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 18 shows the changes in the surface profile due to MMLS3 loading and the resultant humps in a triple seal.

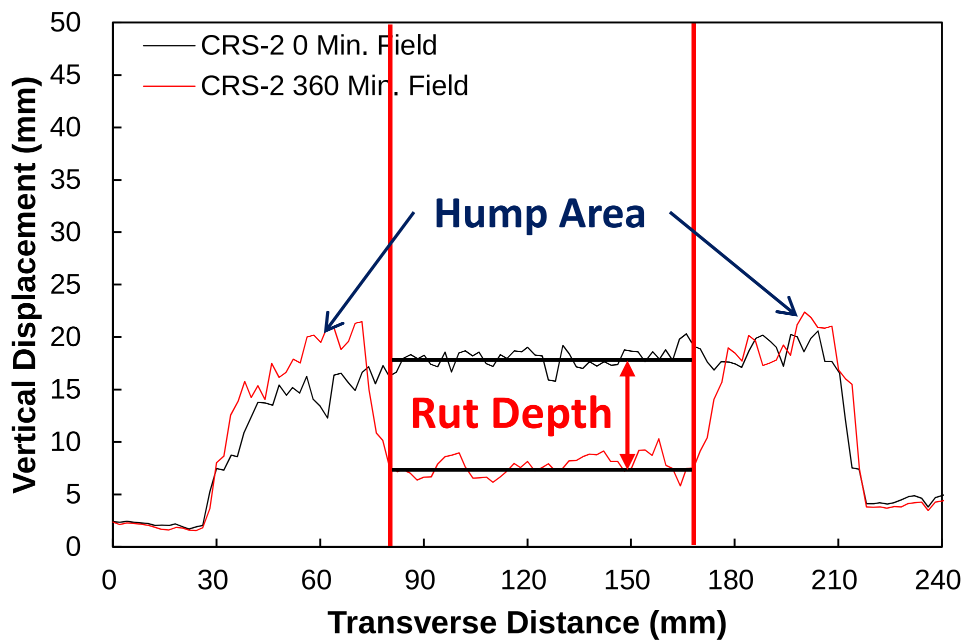


Figure 18 Schematic diagram of a typical cross-section of triple seal

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 19 shows an actual triple seal specimen after six hours of rutting testing.

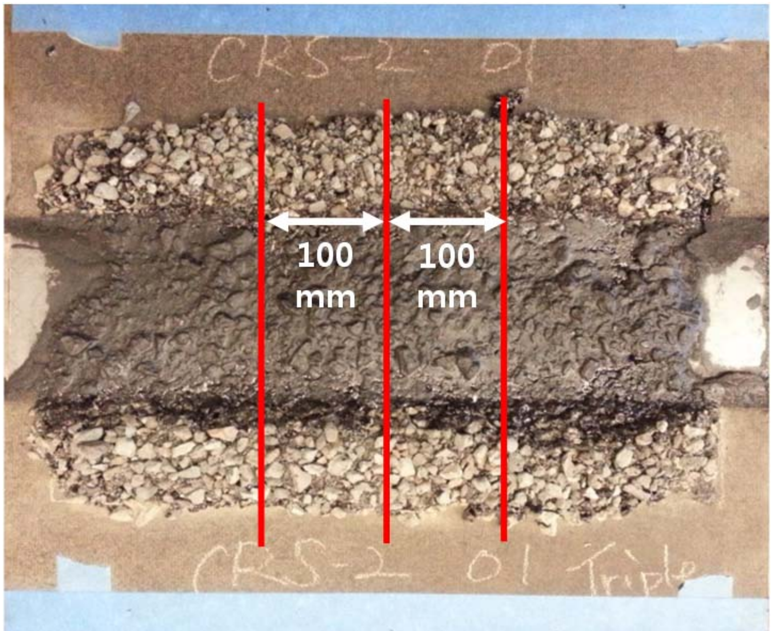


Figure 19 Triple seal specimen after rutting test

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 18 shows the schematic diagram of this method.

3.4.7 Surface Texture Evaluation

3.4.7.1 3-D Laser Profiler

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 20 provides the dimensions and photograph of the portable laser profiler.

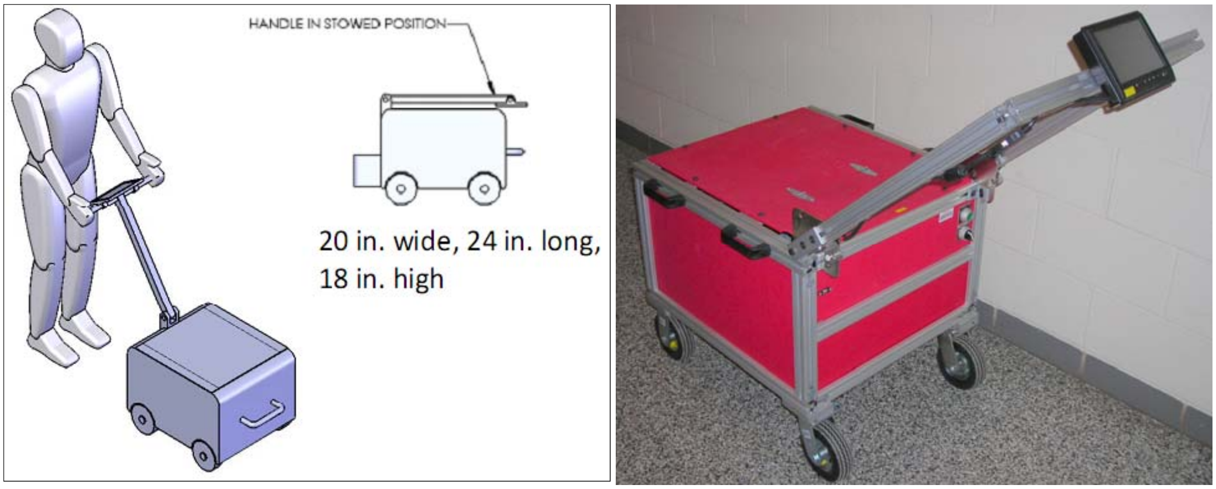


Figure 20 Portable laser profiler

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 research projects. 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).

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

The various chip seal parameters that make up Equation (5) are shown schematically in Figure 21. 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.

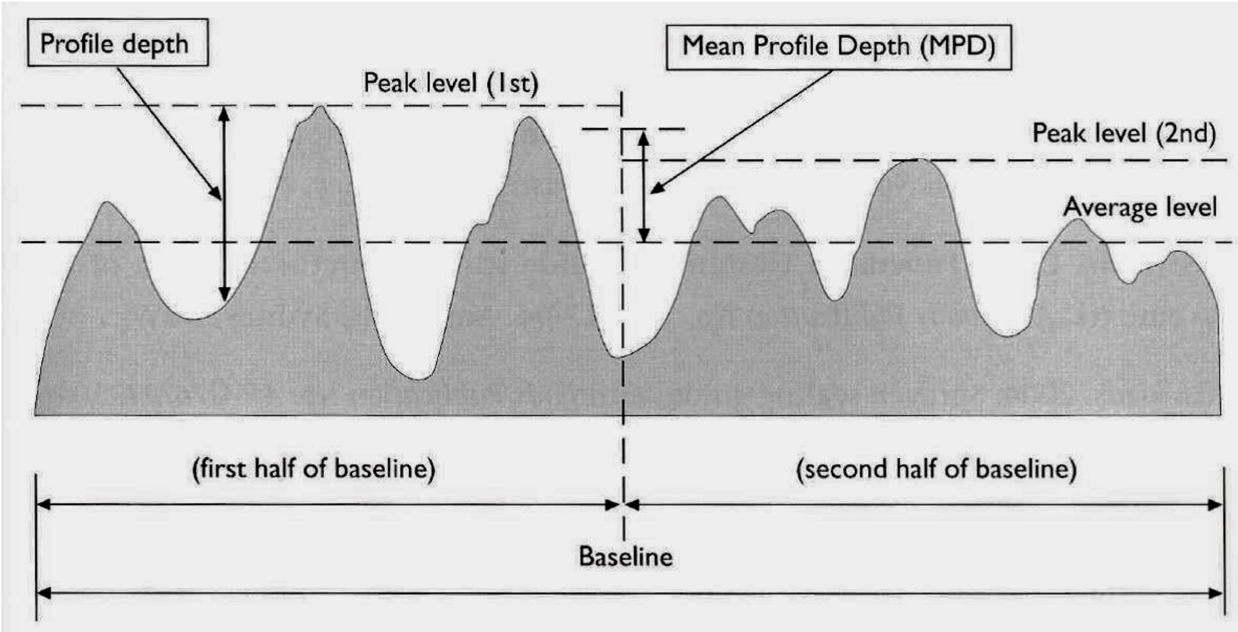


Figure 21 Schematic diagram of mean profile depth determination (Transit New Zealand 2005)

4. LABORATORY EVALUATION OF CHIP SEAL PERFORMANCE

4.1 Curing Time Study

4.1.1 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/yd^2. Figure 22 shows a comparison of the CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions in terms of water loss versus time.

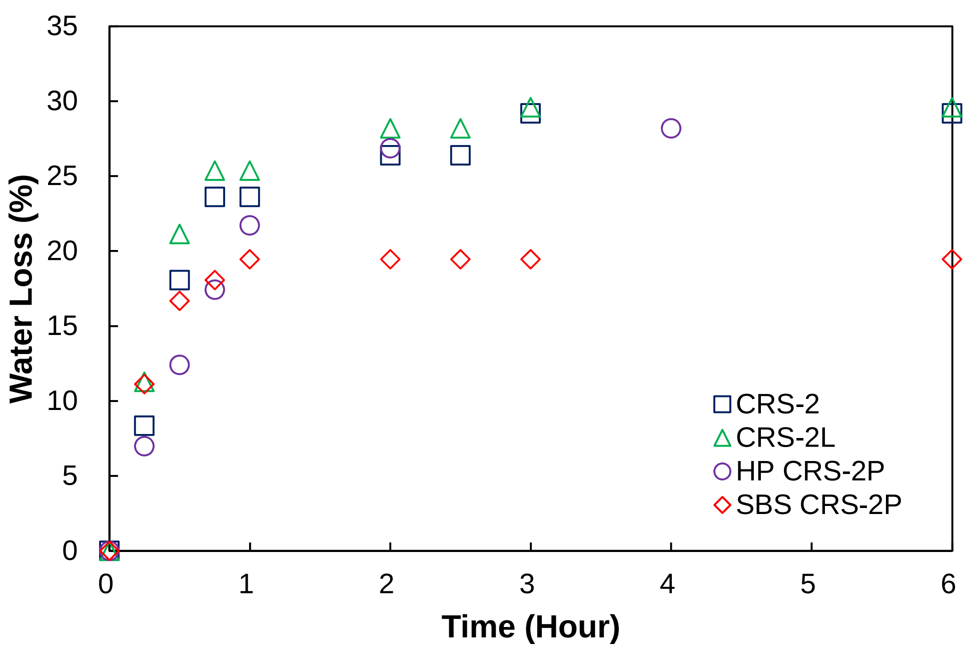


Figure 22 Curing comparison of CRS-2, CRS-2L, HP CRS-2P, and SBS CRS-2P emulsions

Figure 22 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.

4.1.2 PATTI 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 bitumen bond strength (BBS) is determined by PATTI test 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 23 (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 24 (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.

From Figure 23 and Figure 24, as expected, the PMEs 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 PMEs 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 at., 2011). As a result, the contact area of the lightweight aggregate substrate with surface pores is smaller than the standardized area (20mm diameter).

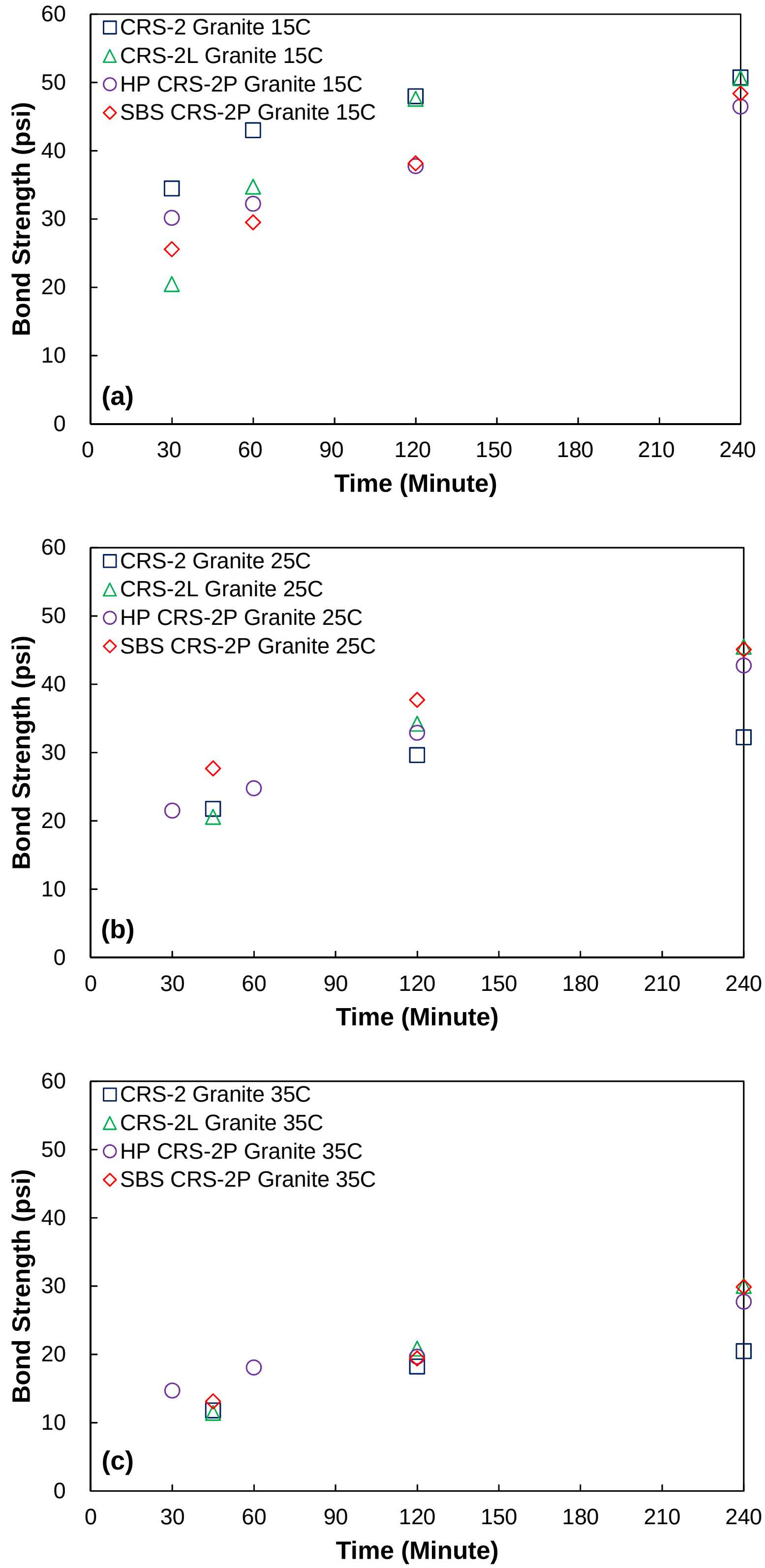


Figure 23 Bond strength versus curing time for granite aggregate types at: (a) 15°C, (b) 25°C, and (c) 35°C

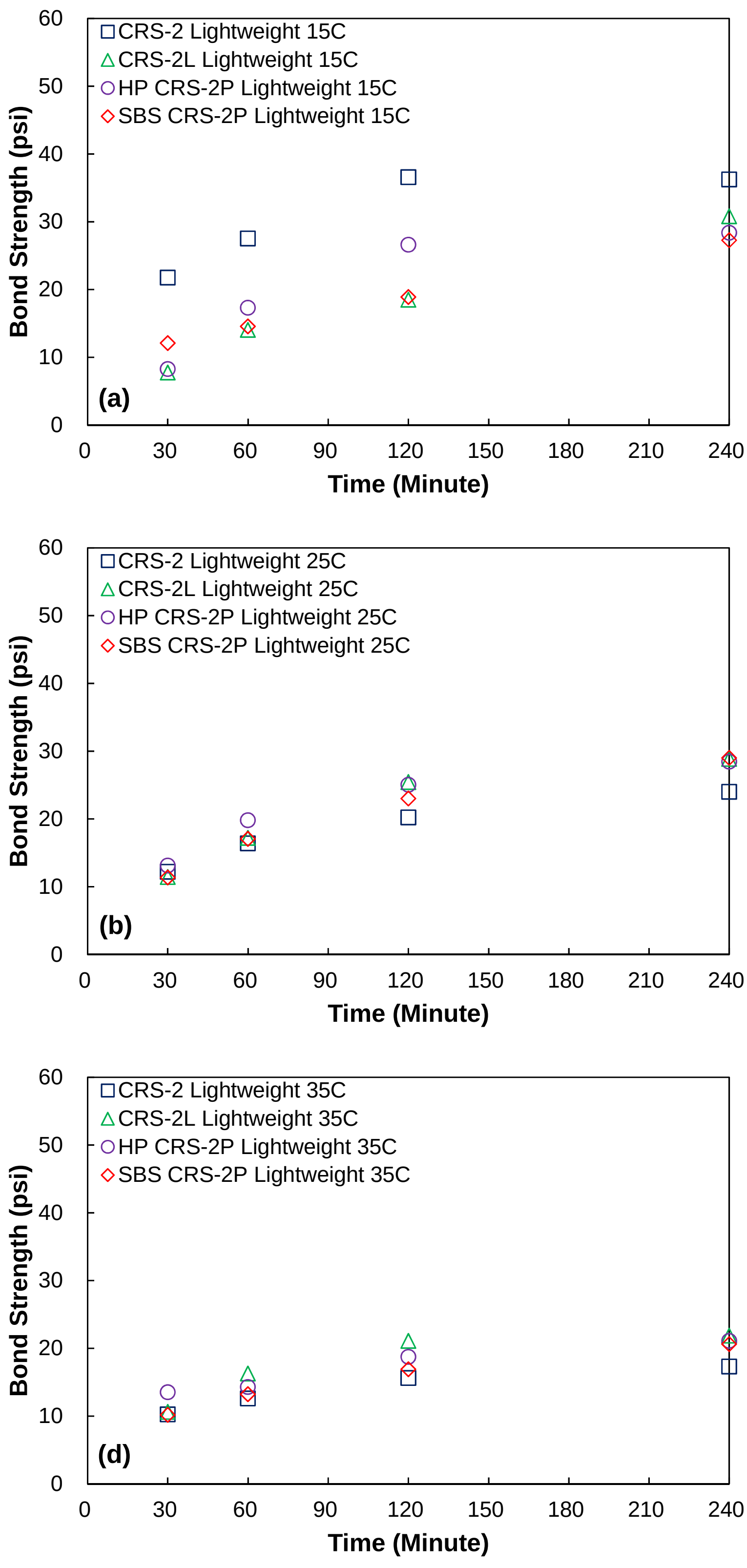


Figure 24 Bond strength versus curing time for lightweight aggregate types at: (a) 15°C, (b) 25°C, and (c) 35°C

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 25 shows the digital images of a color image, grayscale image, and DIP analysis.

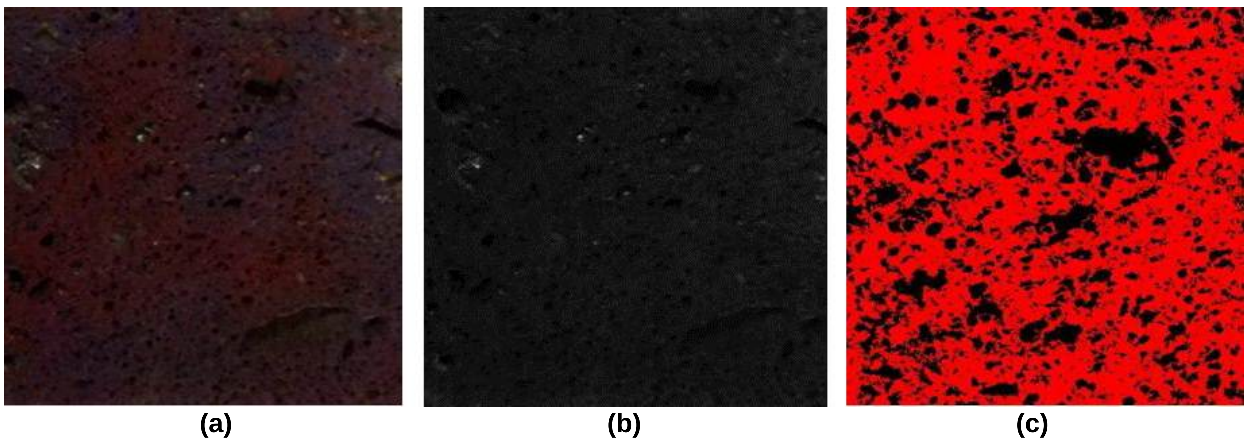


Figure 25 Digital images of lightweight aggregate surface: (a) color, (b) grayscale, and (c) DIP analysis

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.

4.1.3 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/yd^2 for the granite 78M aggregate and 7 lb/yd^2 for the lightweight aggregate. For all the specimens of both aggregate types, an EAR of 0.25 gal/yd^2 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 26 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 26 (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 26 are replotted in Figure 27 to show the effects of different curing temperatures for the same emulsion type in terms of aggregate retention performance.

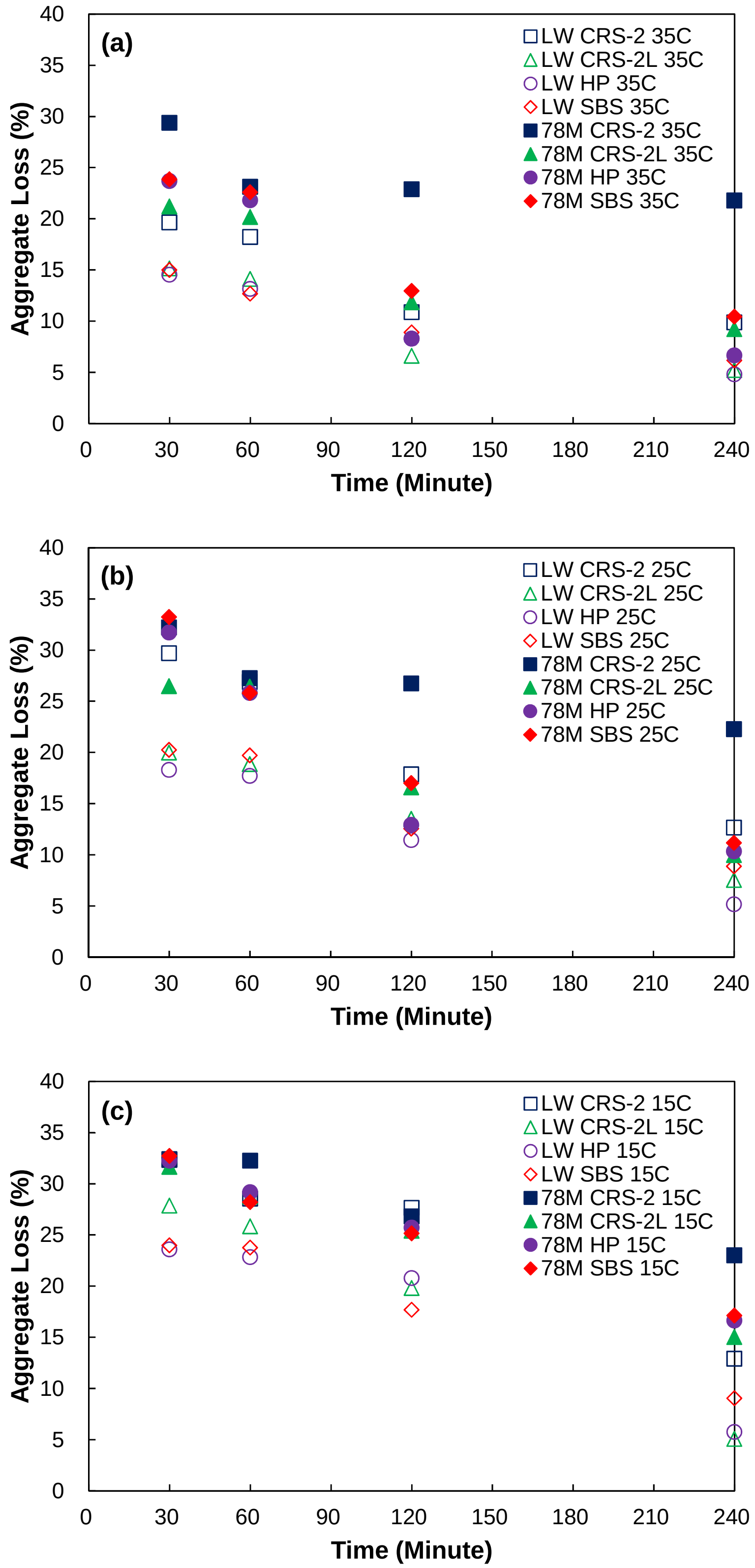


Figure 26 Adhesive behavior at different curing times and at (a) at 35°C, (b) 25°C, and (c) 15°C

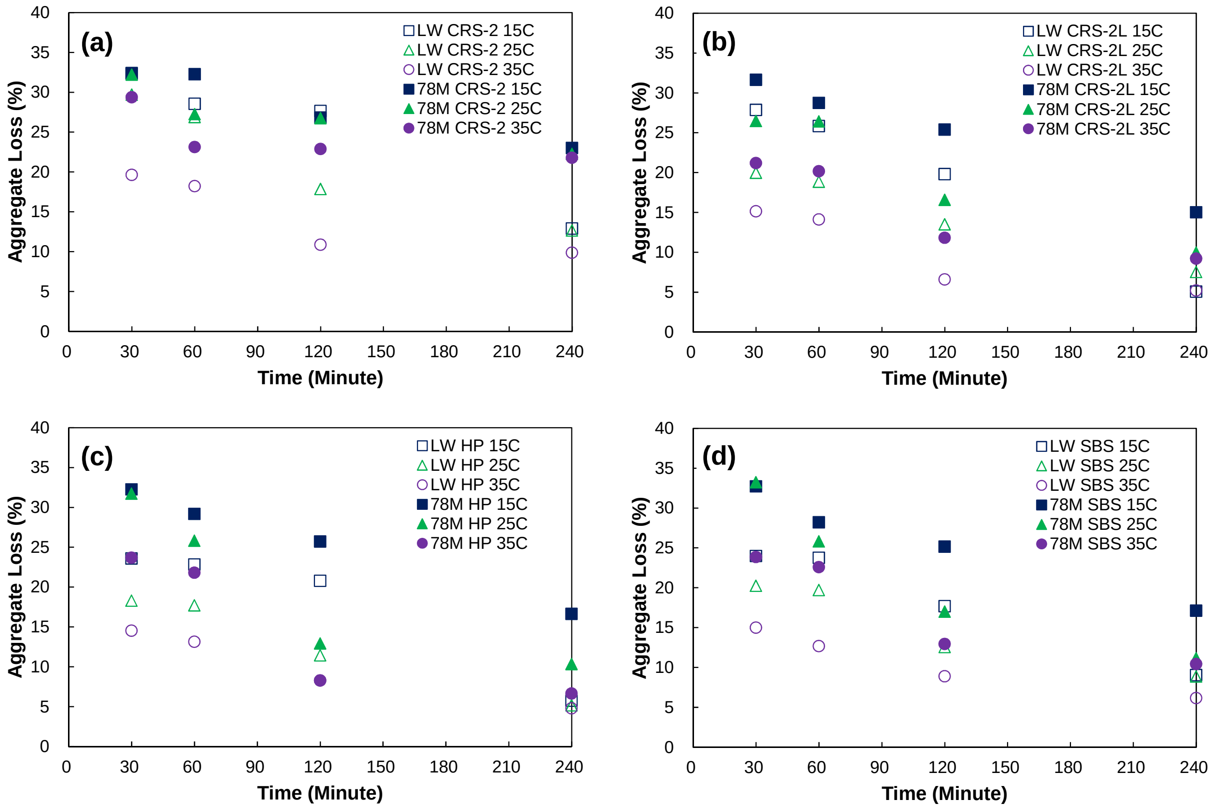


Figure 27 Adhesive behavior at different curing temperatures for: (a) CRS-2, (b) CRS-2L, (c) HP CRS-2P, and (d) SBS CRS-2P

Figure 27 (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.

4.1.4 Correlation between Bitumen Bond Strength and Aggregate Loss by Vialit Testing

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 28 (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 29 (a), (b), and (c) show the correlation between the bond strength and the aggregate loss obtained by the Vialit test for the lightweight aggregate.

Table 7 and Table 8 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.

In Figure 28 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 29 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.

4.2 Chip Seal Performance Tests

4.2.1 Aggregate Loss Test

4.2.1.1 MMLS3 Aggregate Loss Performance Test

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 30 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.

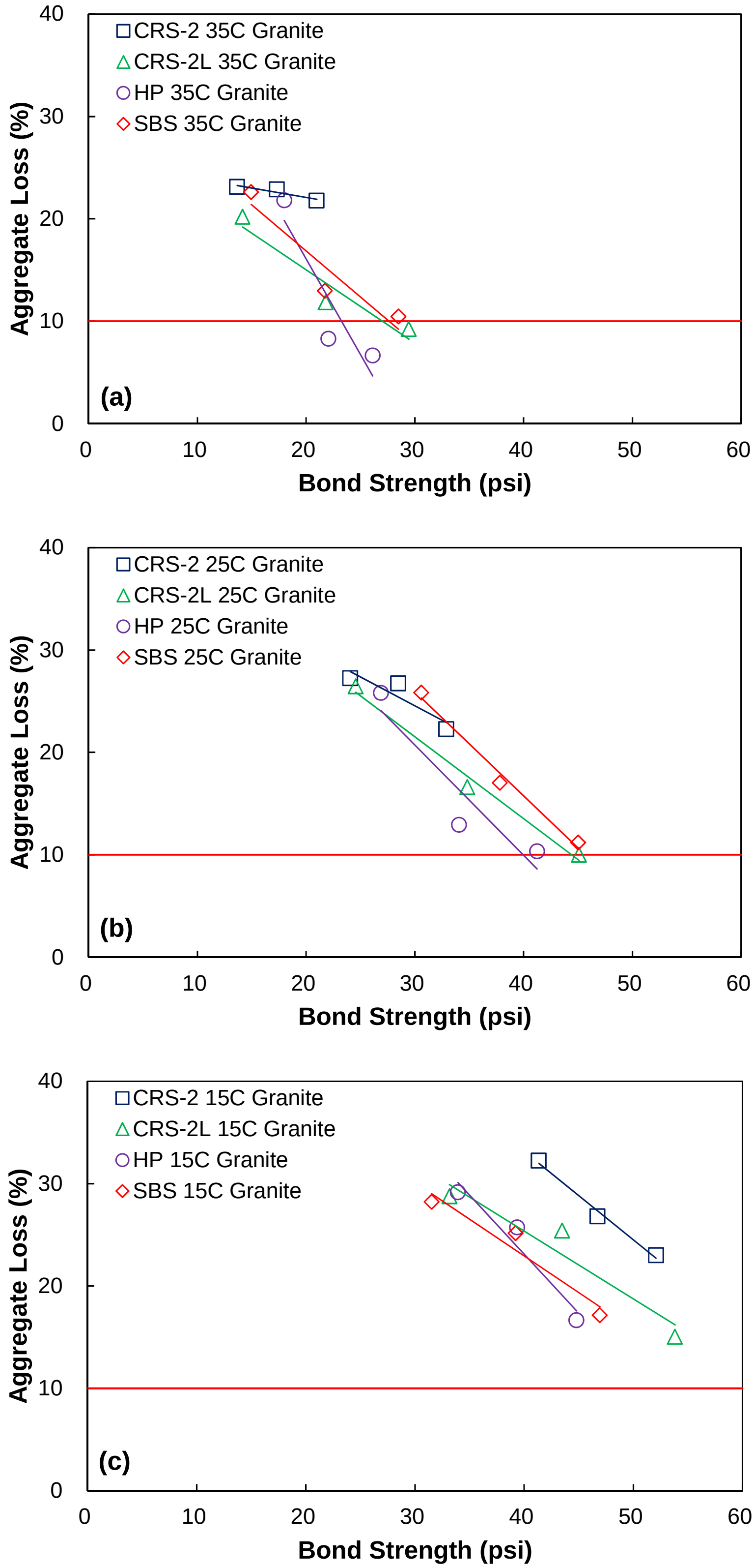


Figure 28 Correlation between bond strength and aggregate loss from Vialit test for granite aggregate at: (a) 35°C, (b) 25°C, and (c) 15°C

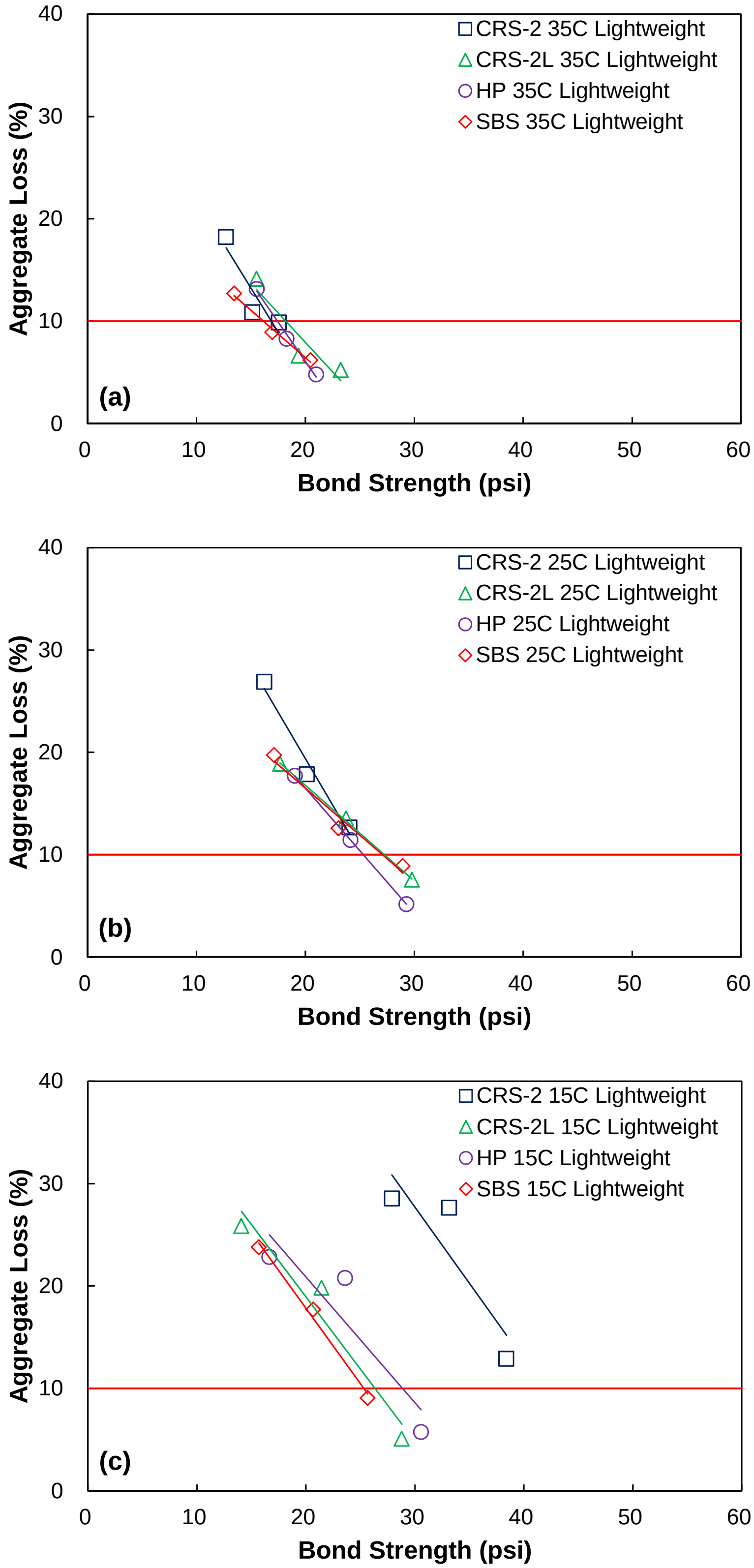


Figure 29 Correlation between bond strength and aggregate loss from Vialit test for lightweight aggregate at: (a) 35°C, (b) 25°C, and (c) 15°C

Table 7 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)	87.6	26.9	23.2	27.6
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)	56.2	44.4	39.8	45.5
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)	67.0	63.5	51.5	57.8

Table 8 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)	16.9	18.3	17.4	16.2
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)	25.2	27.4	25.4	25.8
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)	41.8	25.9	28.8	25.4

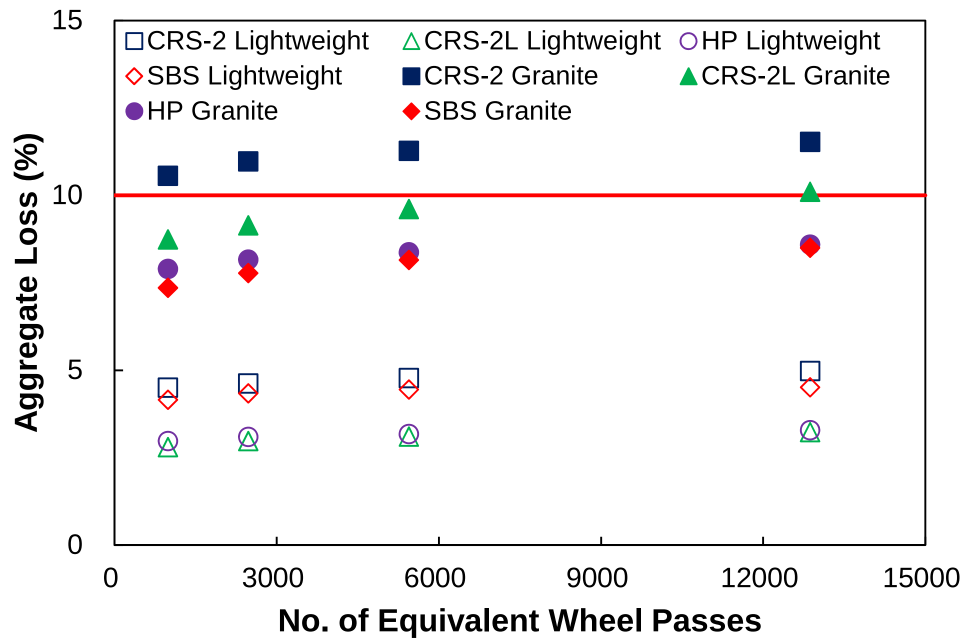


Figure 30 Aggregate loss performance by MMLS3 test

Figure 30 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.

4.2.1.2 Comparison of Aggregate Retention Performance between MMLS3 Test and Vialit Test

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 31 shows the aggregate retention comparison between the MMLS3 test and the Vialit test results.

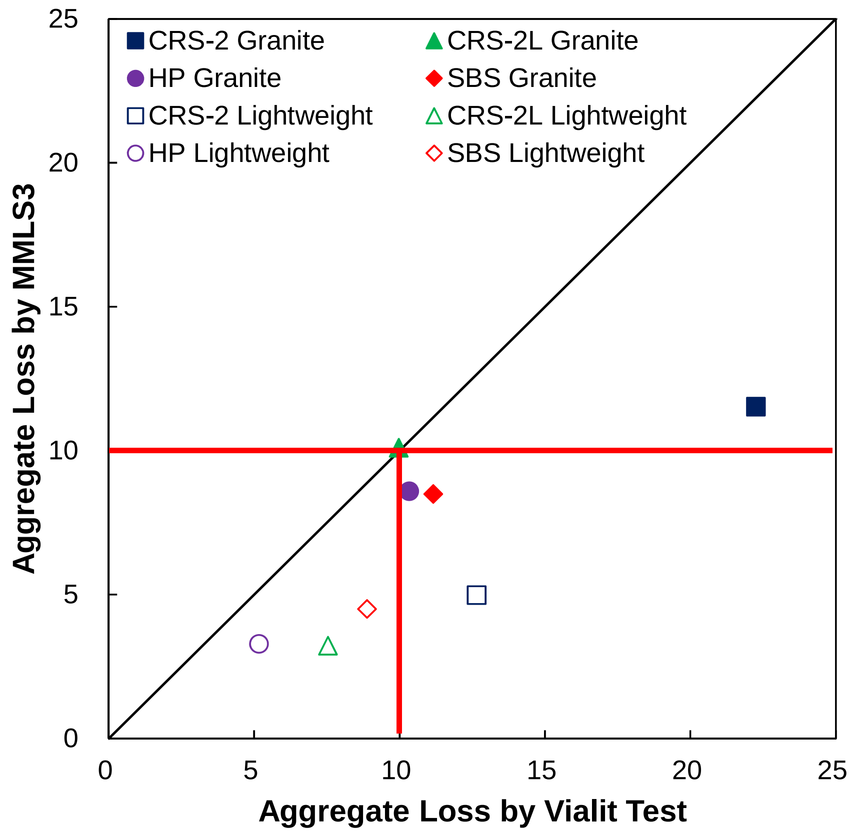


Figure 31 Comparison of aggregate loss between MMLS3 test and Vialit test

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 31 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.

4.2.2 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 32 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.

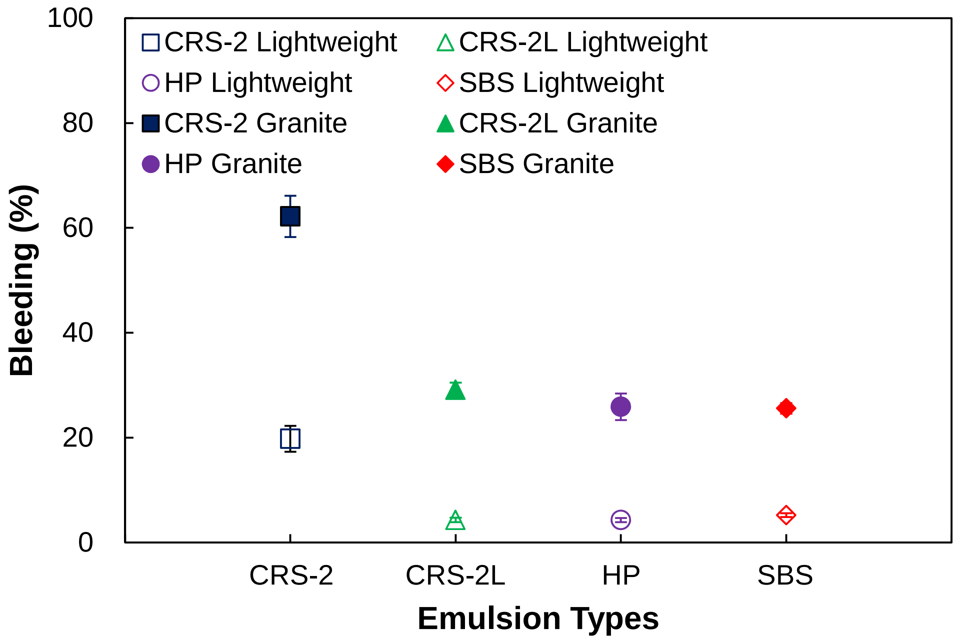


Figure 32 Bleeding performance of different emulsions

Figure 32 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).

5. FIELD EVALUATION OF CHIP SEAL 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.

The construction variables that were used in the field experimental design are shown in Table 9.

Table 9 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)

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 was 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) were used in the field construction. A constant EAR and AAR were applied to all the test sections, and the optimal EAR and AAR were decided by the field supervisor.

For the rolling pattern, type B shown in Figure 3 was selected for the field construction based on the recommendation from the project Steering and Implementation Committee. 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.

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) were targeted for the field construction. The NCDOT engineers were concerned that the CRS-2 emulsion might cause aggregate retention and bleeding problems for high volume roads. Hence, the CRS-2 sections were 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 33 (a), (b), and (c) show the three field sites, respectively, and information about each site.

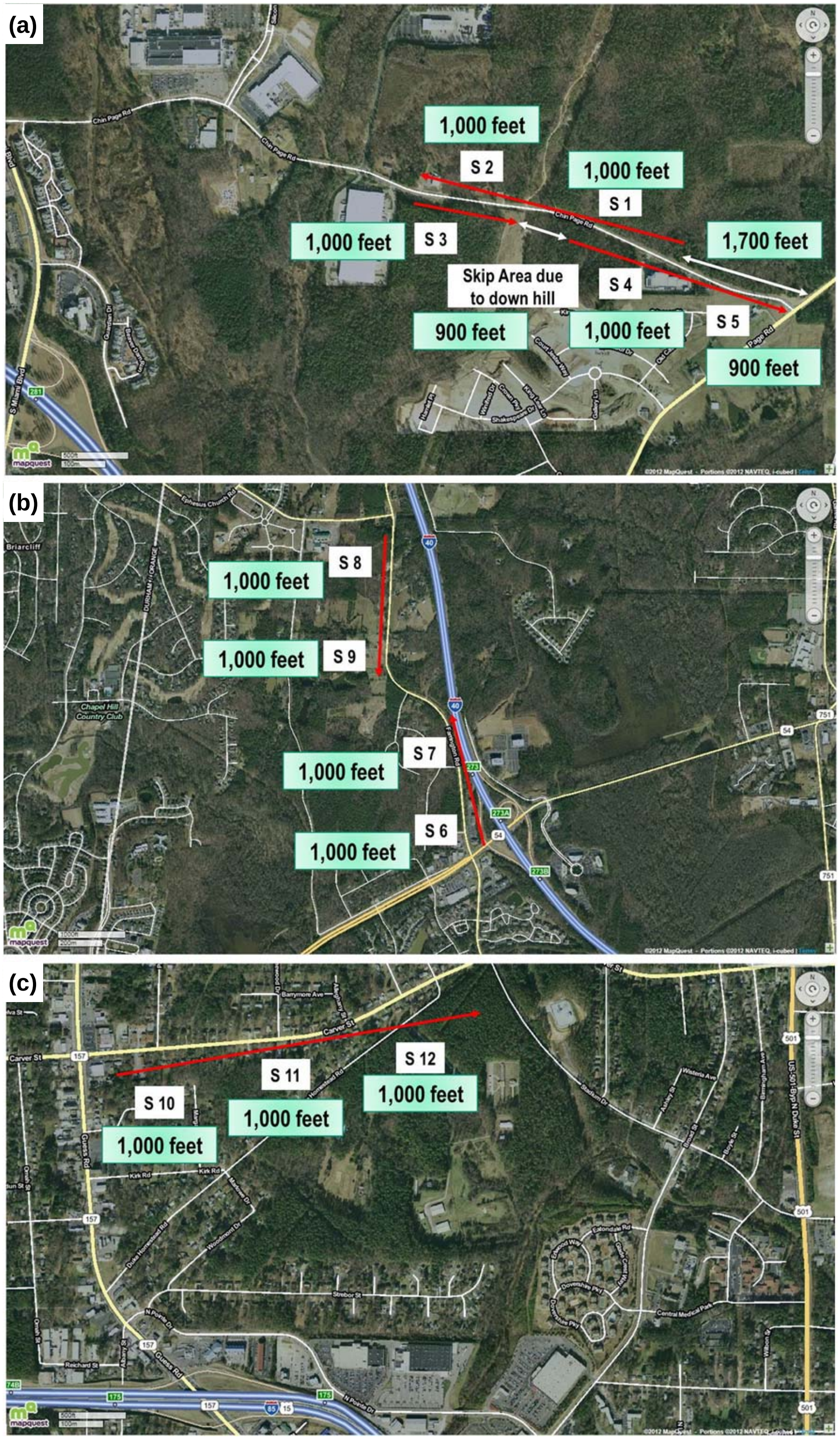


Figure 33 Field construction sites: (a) Chin Page Road (low volume), (b) Farrington Road (medium volume), and (c) Carver Street (high volume)

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 34 shows the test section diagrams.

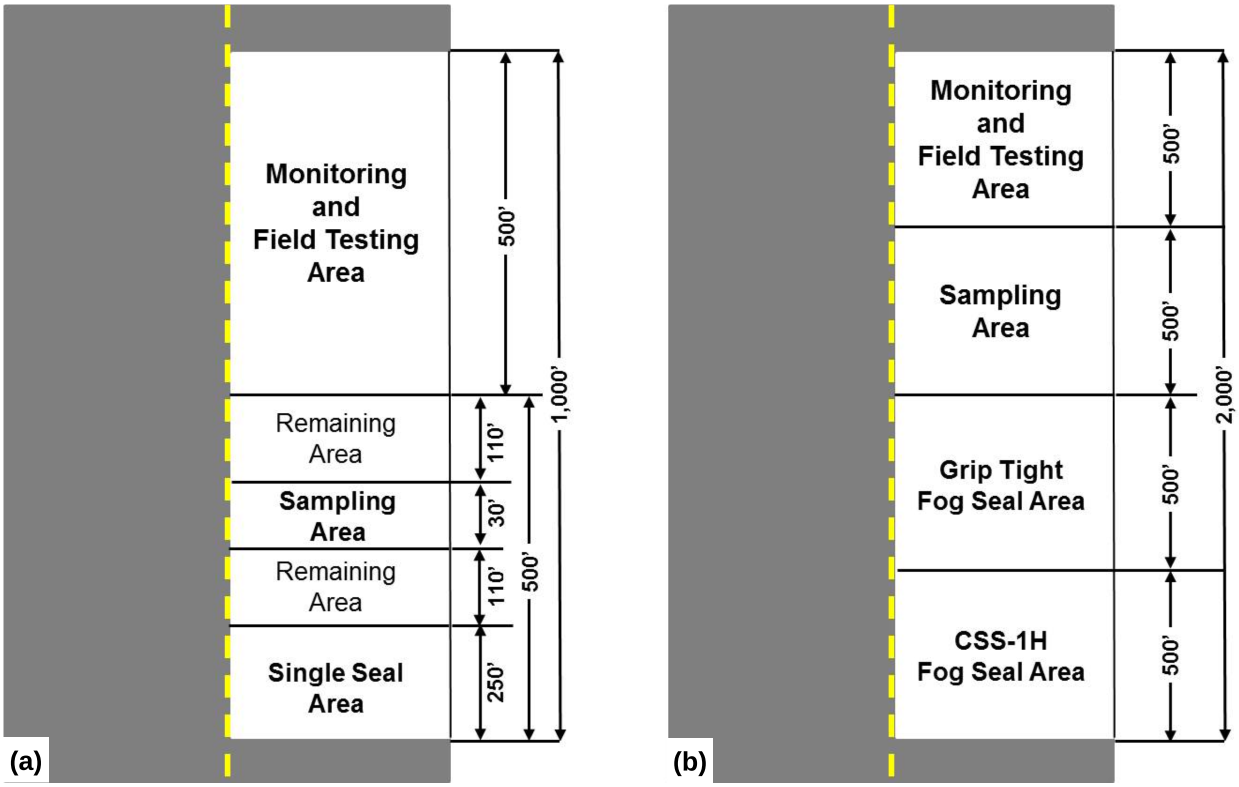


Figure 34 Test section diagram: (a) chip seal section and (b) chip seal with fog seal section

Table 10 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 10 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 Type A	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 Type A	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 Type A	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/yd^2 and AAR of 22 lb/yd^2 (granite 78M) was constructed on the entire section, and the second layer was applied with the EAR of 0.25 gal/yd^2 and AAR of 22 lb/yd^2 (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/yd^2 and AAR of 11 lb/yd^2 (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 35.

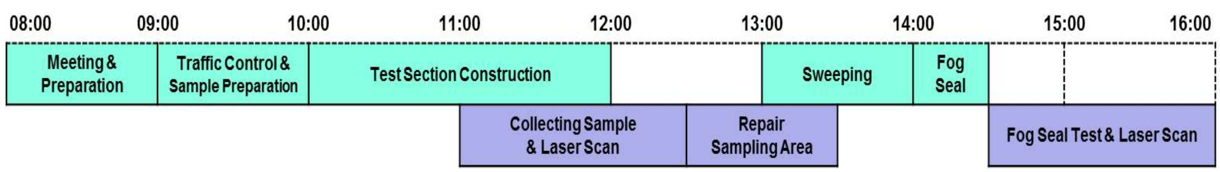


Figure 35 Field construction timeline

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 36 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 results reported in previous quarterly reports, 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 37 shows the laser scanner and the reference points in the field.

Figure 36 Field sampling: (a) Vialit sample template, (b) Vialit samples, (c) MMLS3 sample template, and (d) MMLS3 samples

Figure 37 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/yd^2 (bottom layer), 0.25 gal/yd^2 (second layer), and 0.18 gal/yd^2 (top layer) and AARs of 22 lb/yd^2 (granite 78M, bottom layer), 22 lb/yd^2 (granite 78M, second layer), and 11 lb/yd^2 (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/yd^2 of it was applied, followed by application of the fibers, and then another 0.12 gal/yd^2 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/yd^2 (CRS-2L with fibers) and the AAR of 22 lb/yd^2 (granite 78M) for the bottom layer, and EAR of 0.18 gal/yd^2 (CRS-2L without fibers) and AAR of 11 lb/yd^2 (Virgina #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/yd^2 (CRS-2L with fibers) to 0.20 gal/yd^2 (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/yd^2 (CRS-2L with fibers) and AAR of 22 lb/yd^2 (granite 78M) for the bottom layer, and EAR of 0.15 gal/yd^2 (CRS-2L without fibers) and AAR of 11 lb/yd^2 (Virginia #9) for the top layer. Table 11 shows the construction target application rates.

Table 11 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 38 shows a sample before and after the ignition oven test.

(a) (b)

Figure 38 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/yd^2 and EAR of 0.68 gal/yd^2 were the target rates, and an AAR of 33 lb/yd^2 and EAR of 0.43 gal/yd^2 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 39 (a), (b), and (c) show the actual AARs, EARs, and application ratios for the triple seal sections, respectively. Figure 40 (a), (b), and (c) show the actual AARs, EARs, and application ratios for the double seal sections, respectively. Table 12 presents the field construction conditions and information about each section.

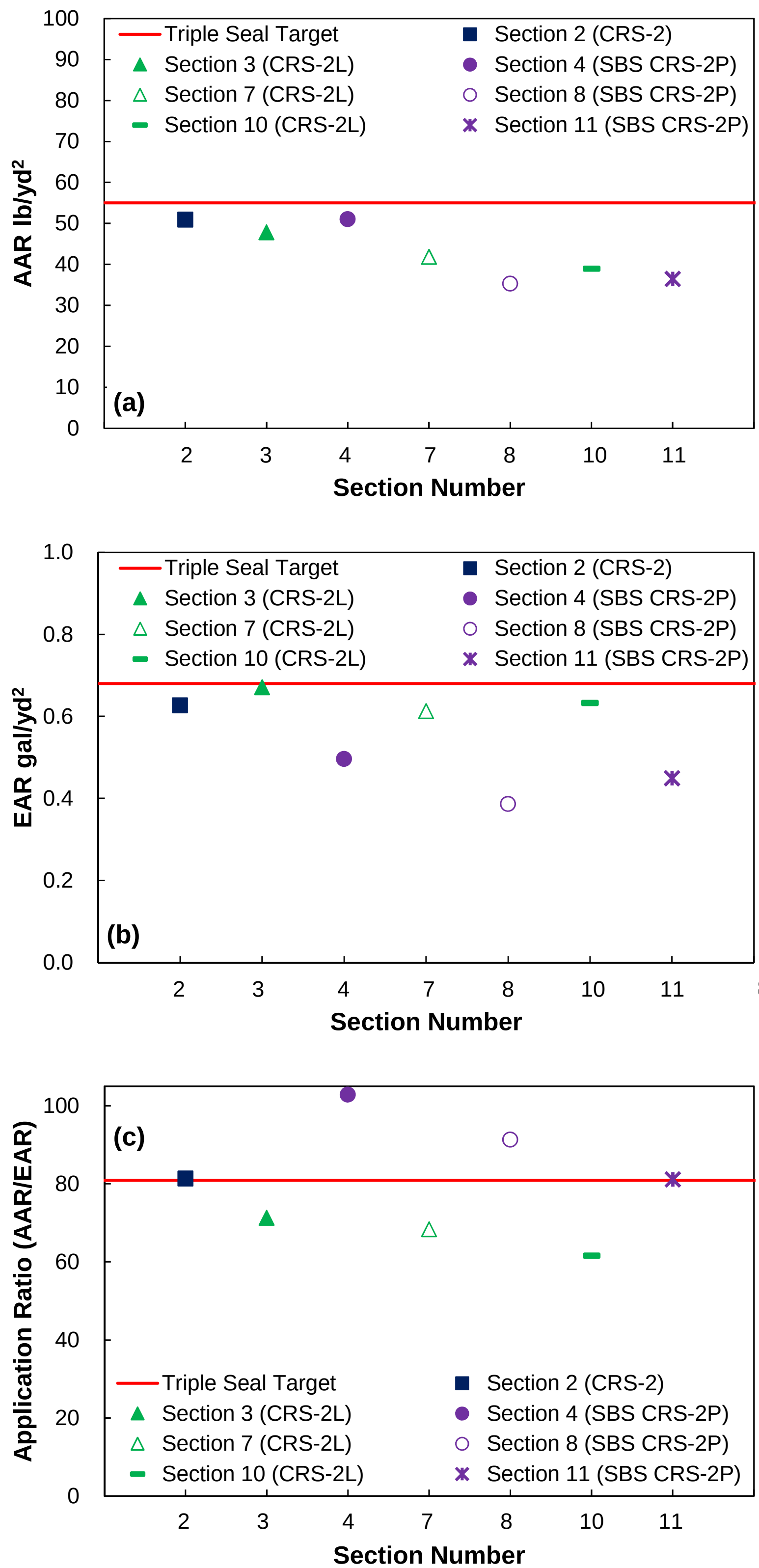


Figure 39 Actual application rates for triple seal sections: (a) AARs, (b) EARs, and (c) application ratios (AAR/EAR)

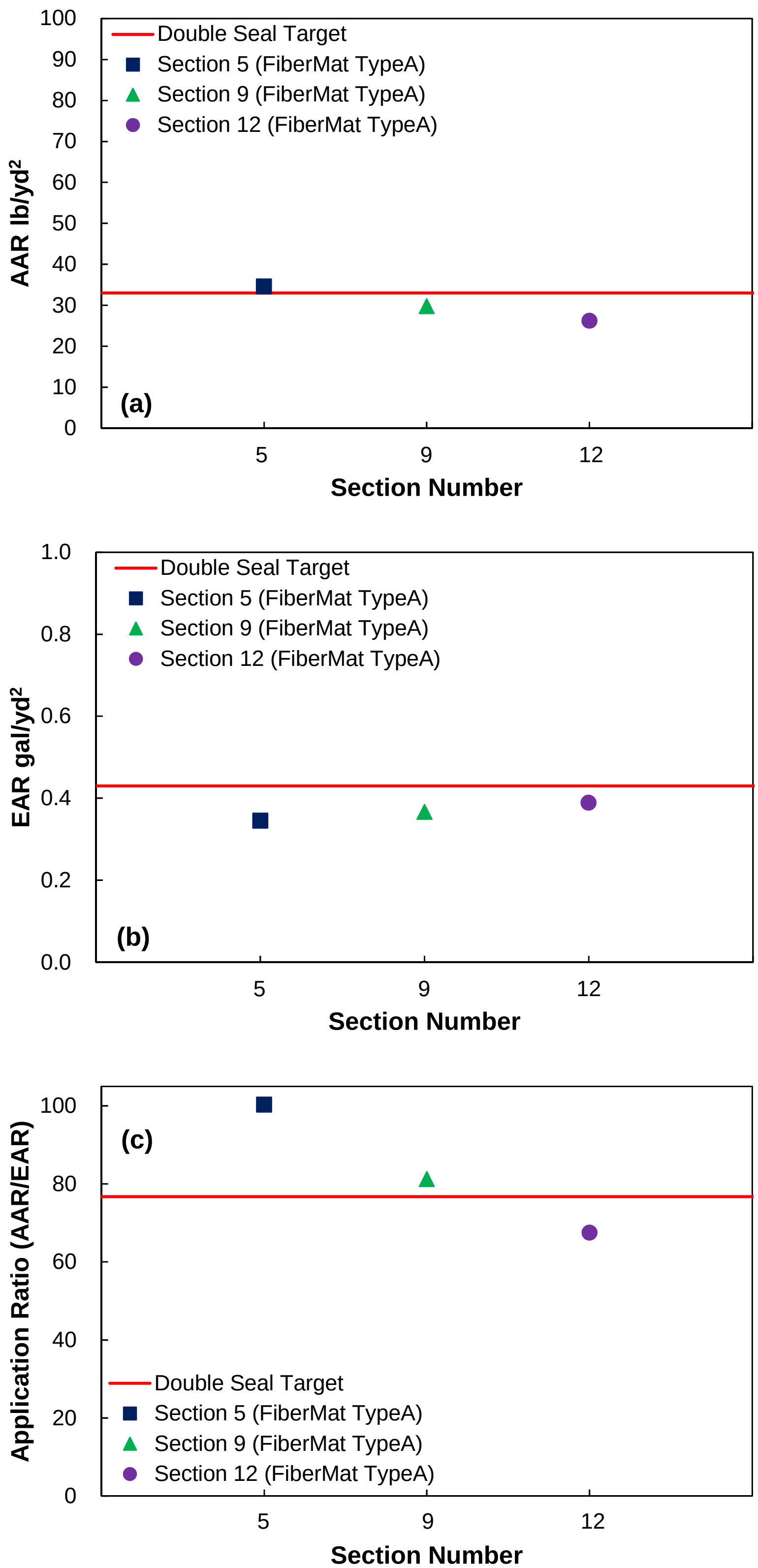


Figure 40 Actual application rates for double seal sections: (a) AARs, (b) EARs, and (c) application ratios (AAR/EAR)

According to the data shown in Figure 39 (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 40 (a) and (b) except for section number 5 (higher AAR and lower EAR). Figure 39 (c) and Figure 40 (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.

In Table 12, 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.

Table 12 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					

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. Figure 41 shows the aggregate loss test results. Each data point represents the percentage of the average cumulative aggregate loss from three specimens.

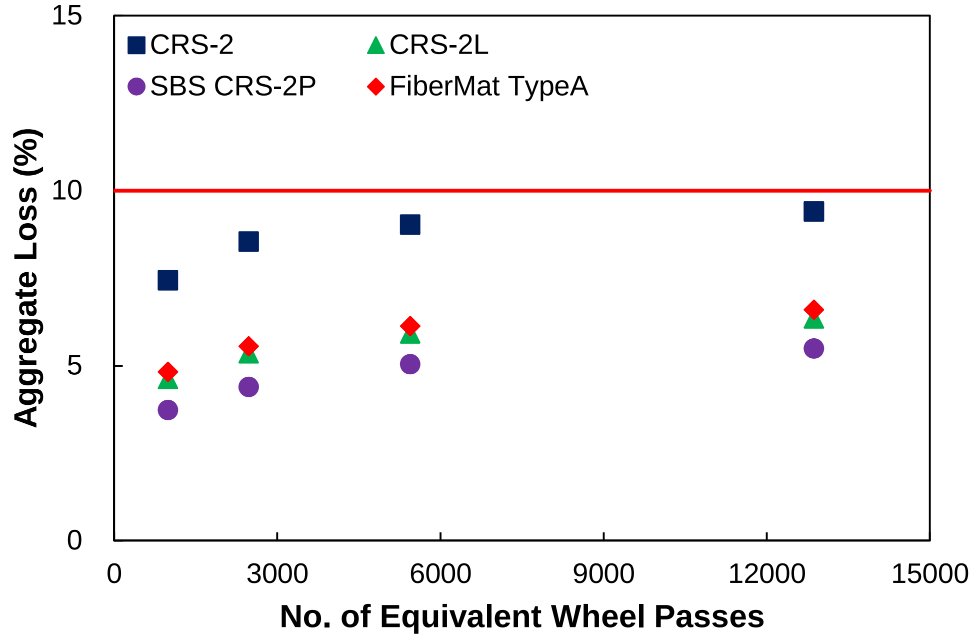


Figure 41 MMLS3 aggregate loss results for field samples

Figure 41 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 41 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. Figure 42 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.

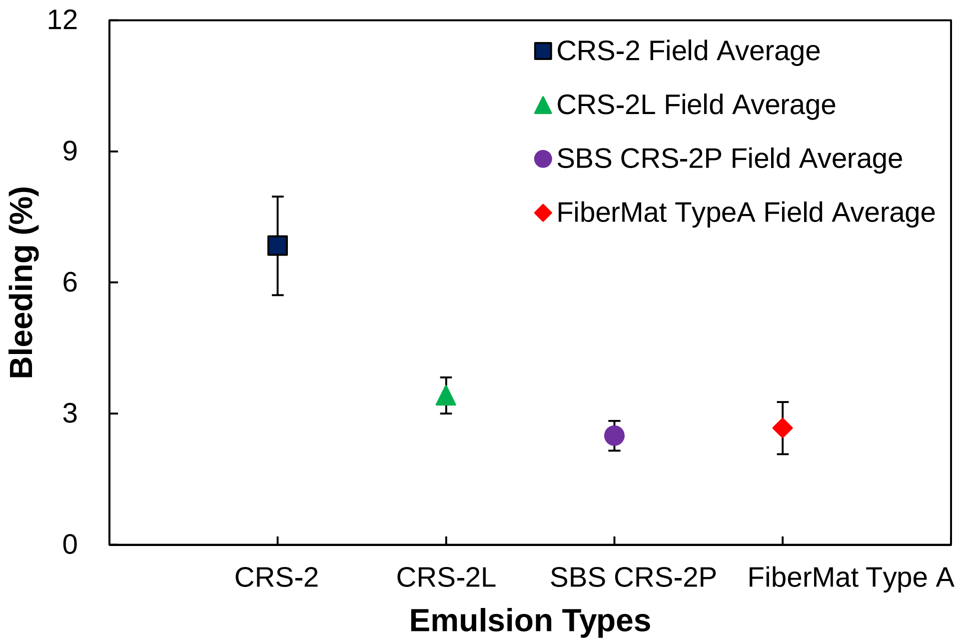


Figure 42 Bleeding analysis for field samples

Figure 42 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 39 and Table 12. 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 43 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 44 in semi-log scale.

Figure 43 and Figure 44 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).

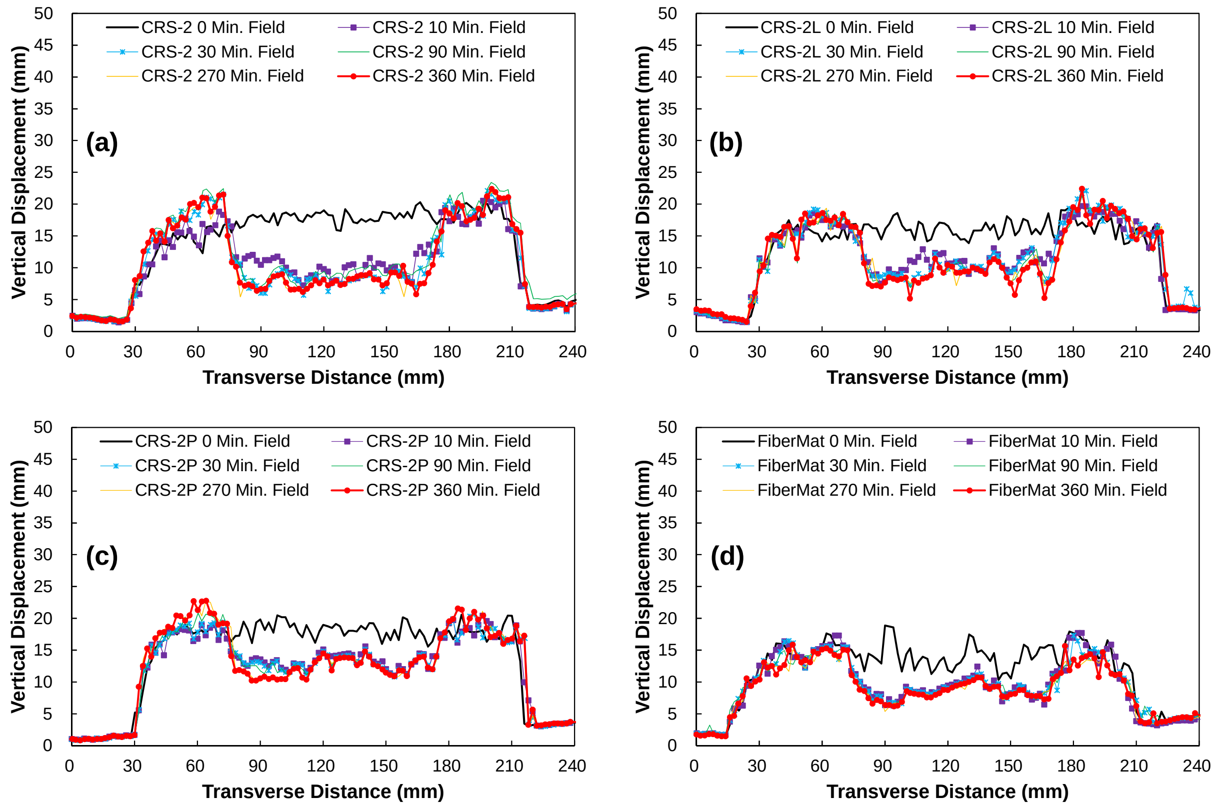


Figure 43 Transversal profiles for field samples: (a) CRS-2, (b) CRS-2L, (c) HP CRS-2P, and (d) SBS CRS-2P emulsions

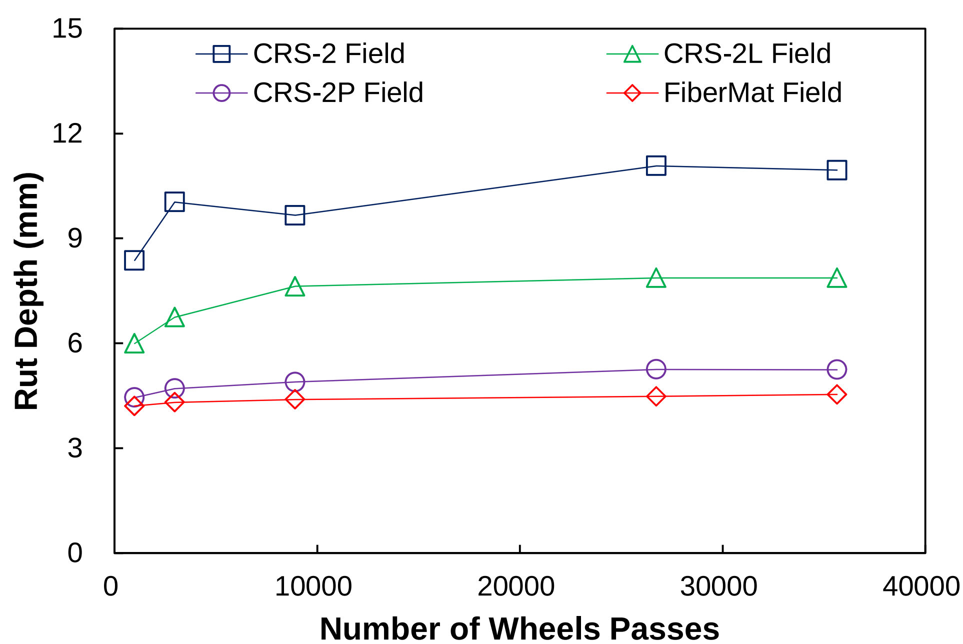


Figure 44 Rut depth growth (semi-log scale)

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 13 presents descriptions of these failure levels, and Figure 45 shows the alligator cracking failure levels.

Table 13 Alligator Cracking Failure Levels (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 ¼ inch wide
Severe	Cracking has progressed so that pieces appear loose with severely spalled edges; cracks are about 3/8 inch to ½ inch wide or greater; potholes may be present.

Light **Moderate** **Severe**

Figure 45 Alligator cracking failure levels (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 14 and Figure 46 explain the failure levels of transverse cracking.

Table 14 Transverse Cracking Failure Levels (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.

Light **Moderate** **Severe**

Figure 46 Transverse cracking failure levels (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 15 presents the rutting failure levels.

Table 15 Rutting Failure Levels (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 16 and Figure 47 describe the raveling failure levels.

Table 16 Raveling Failure Levels (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 47 Raveling failure levels (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 17 and Figure 48 show the bleeding failure levels.

Table 17 Bleeding Failure Levels (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 48 Bleeding failure levels (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 18 explains the failure levels for ride quality.

Table 18 Ride Quality Failure Levels (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.

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 49.

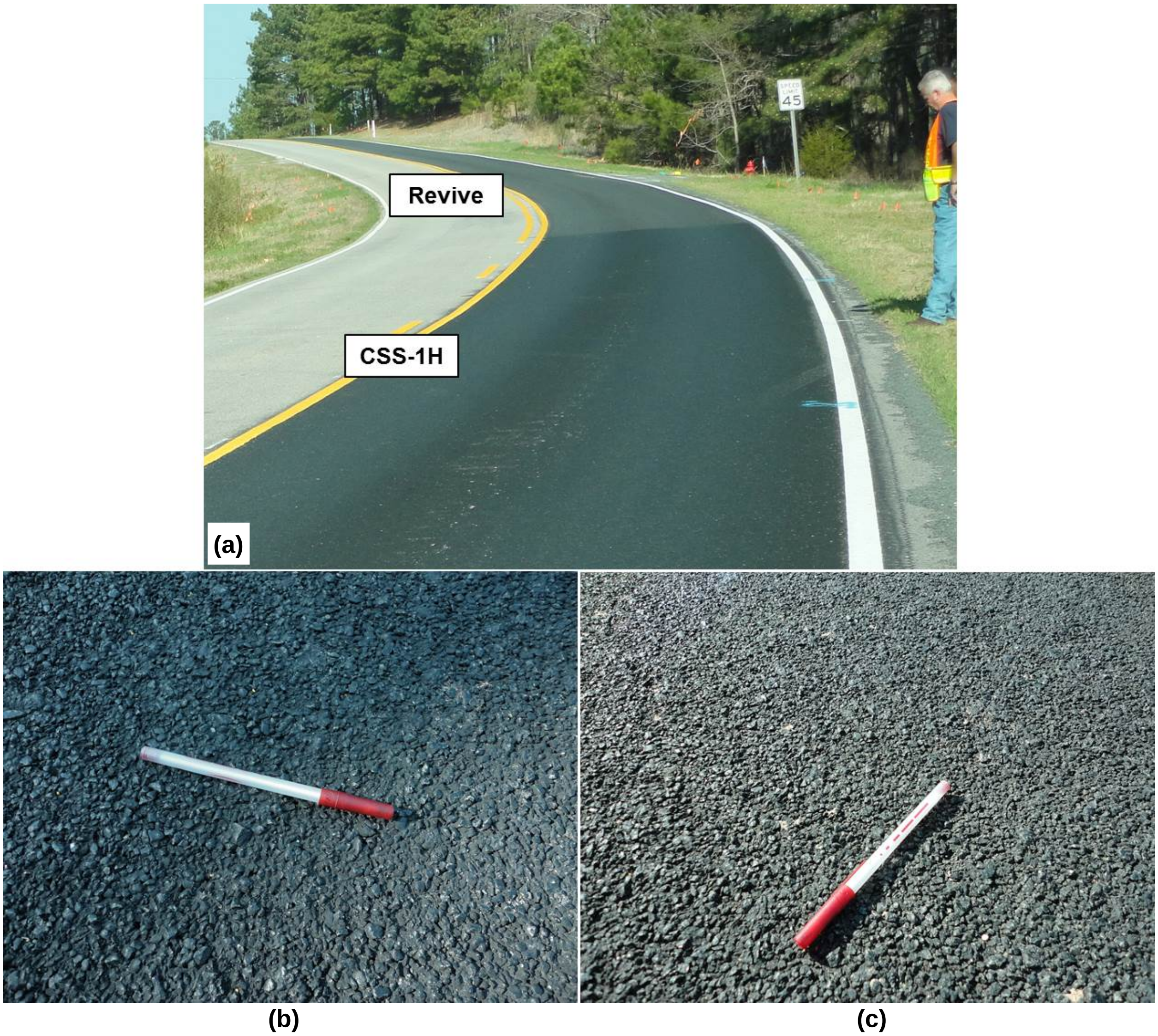
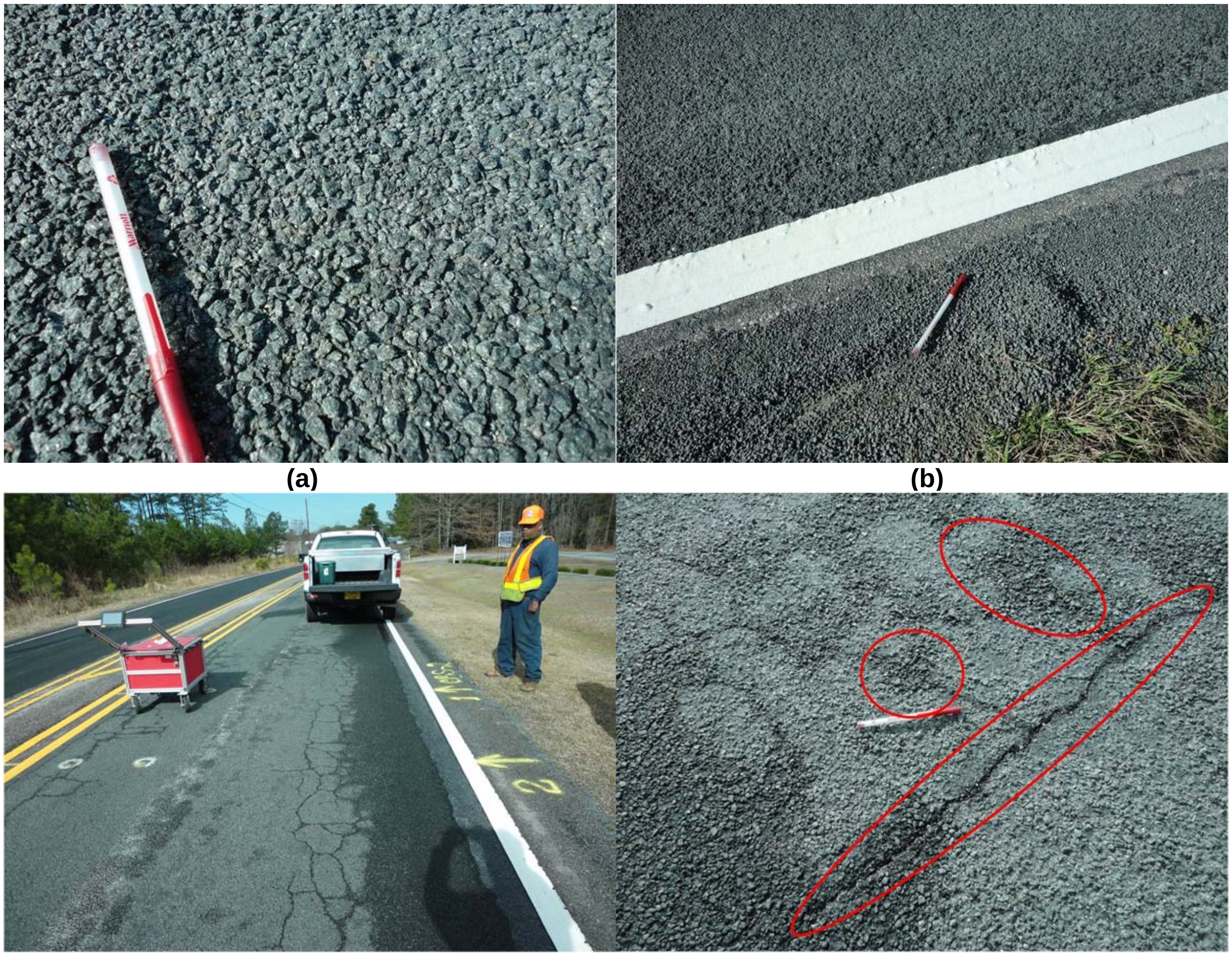


Figure 49 Section 1 (CRS-2 with fog seal): (a) different color appearance between CSS-1H and Revive emulsions, (b) CSS-1H surface texture, and (c) Revive surface texture

Section 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 50 (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 50 (c) and (d) show the cracks on the CRS-2 single-seal section.



(a) (b) (c) (d)

Figure 50 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 choking 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 51 shows the triple seal surface texture and alligator cracks on the single seal.

(a) (b)

Figure 51 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 52.

(a) (b)

Figure 52 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 53 shows the surface texture of the FiberMat Type A section.

Figure 53 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 54 shows the surface textures of the fog seal sections.

(a) (b)

Figure 54 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 55 shows the surface texture of the CRS-2L triple-seal section.

Figure 55 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 56 shows the surface texture of the SBS CRS-2P triple-seal section.

Figure 56 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 57 shows the surface texture of the FiberMat Type A double-seal section.

Figure 57 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 58, Figure 59, and Figure 60 show the different surface textures of this high traffic volume road for these sections.

Figure 58 Section 10 (CRS-2L triple seal)

Figure 59 Section 11 (SBS CRS-2P triple seal)

Figure 60 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 Observations

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 19 shows the findings from the field observations, and Figure 61 shows the field performance ratings.

Table 19 Summary of Field Observations

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
3		CRS-2L	**Single:** Many alligator cracks and three transverse cracks, and aggregate loss	3.5
4		SBS	**Triple:** Performs well	6
5		FiberMat	**Single:** Some alligator cracks	6.5
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	Performs well	8
8		SBS	Performs well	9
9		FiberMat	**Double:** Performs well	7.5
10	High	CRS-2L	Performs well	8
11		SBS	Performs well	7.5
12		FiberMat	**Double:** Performs well	7.5
* Note: *Performs well* indicates no failure on surface.				

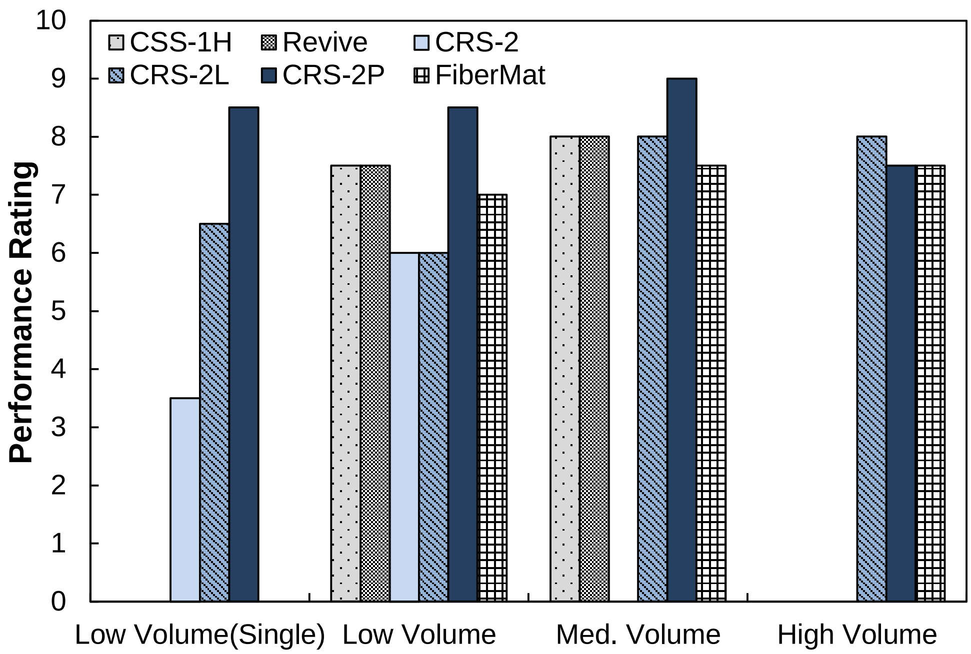


Figure 61 Field performance ratings

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 project), 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 62 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.

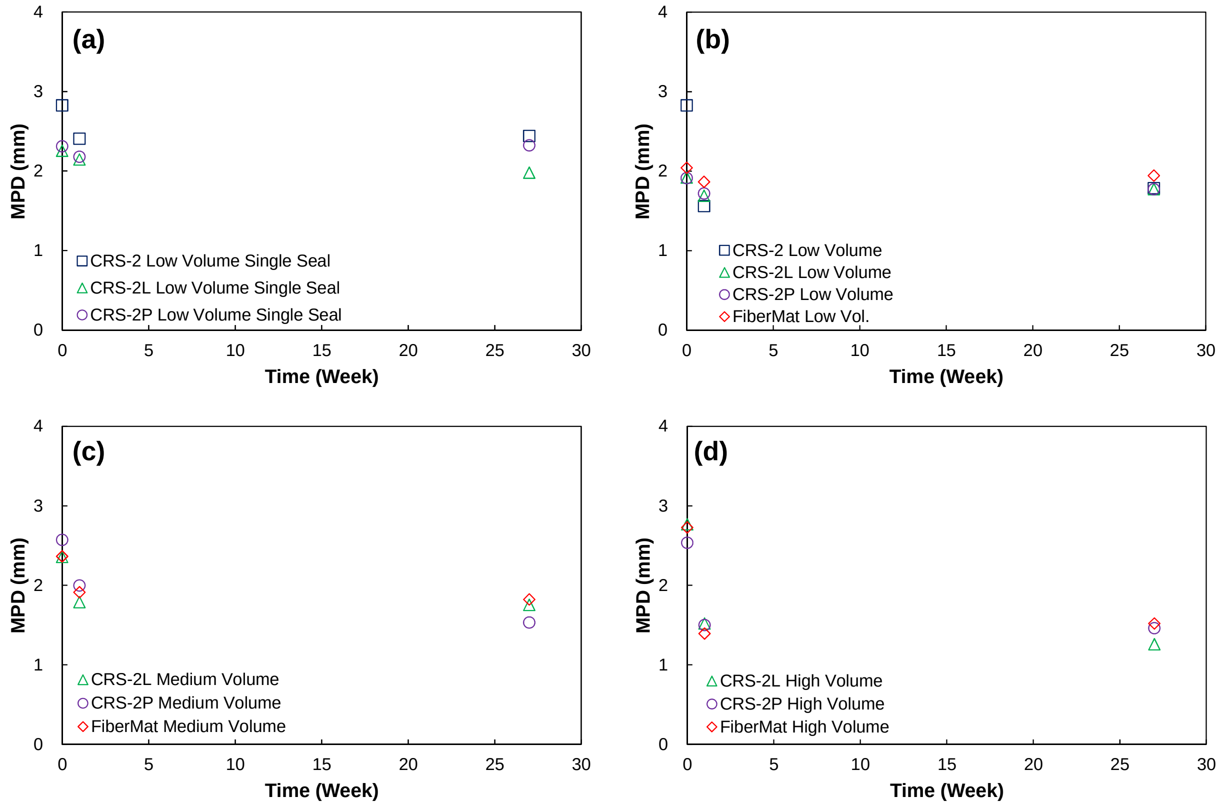


Figure 62 MPD values: (a) single seals on low traffic volume, (b) low traffic volume, (c) medium traffic volume, and (d) high traffic volume sections

Figure 62 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 63 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 20 shows the reduction in MPD calculated from the field MPD data. Figure 64 shows the predicted aggregate loss in the field sections and the aggregate loss results from laboratory tests using the field specimens.

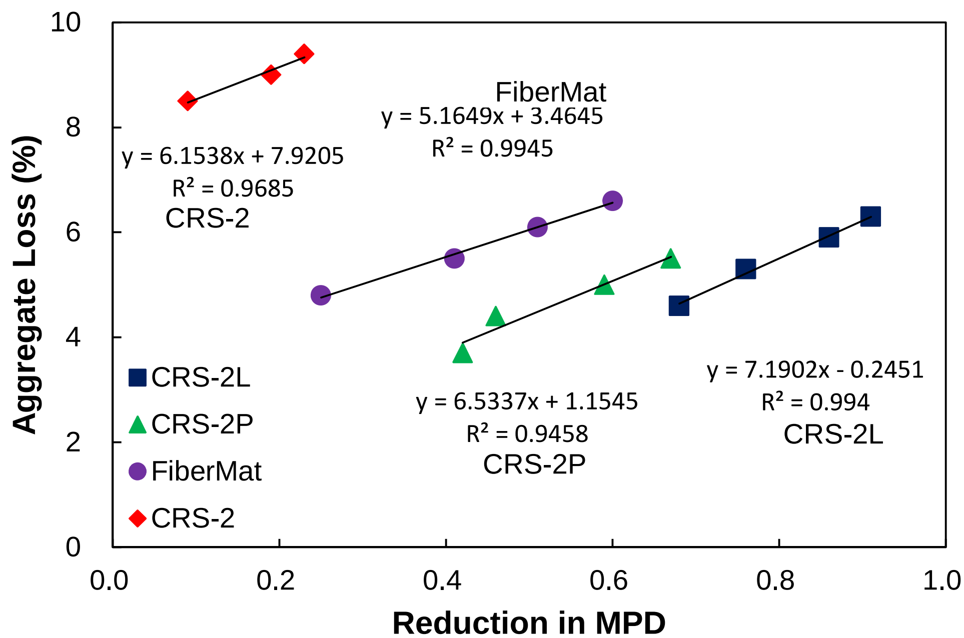


Figure 63 Correlations between aggregate loss and reduction in MPD by MMLS3 test

Table 20 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.

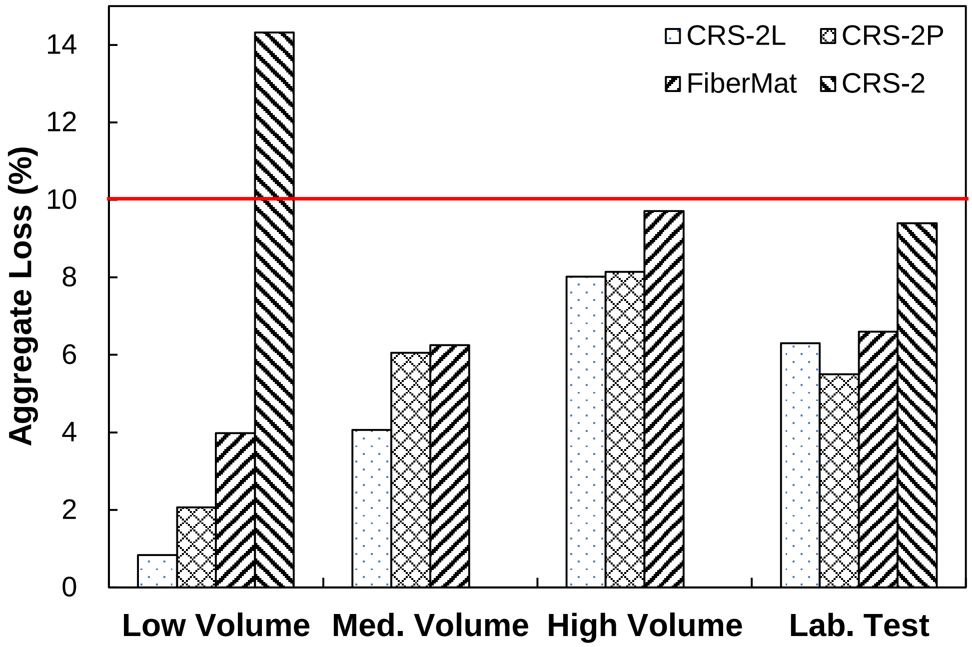


Figure 64 Predicted aggregate loss in field sections

Figure 64 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. This higher MPD value indicates a rougher texture, and the rougher texture means that more excess choking aggregate is retained on the pavement surface. 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 61. 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 Conditions

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 21 shows the original pavement conditions prior to chip seal construction.

Table 21 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.

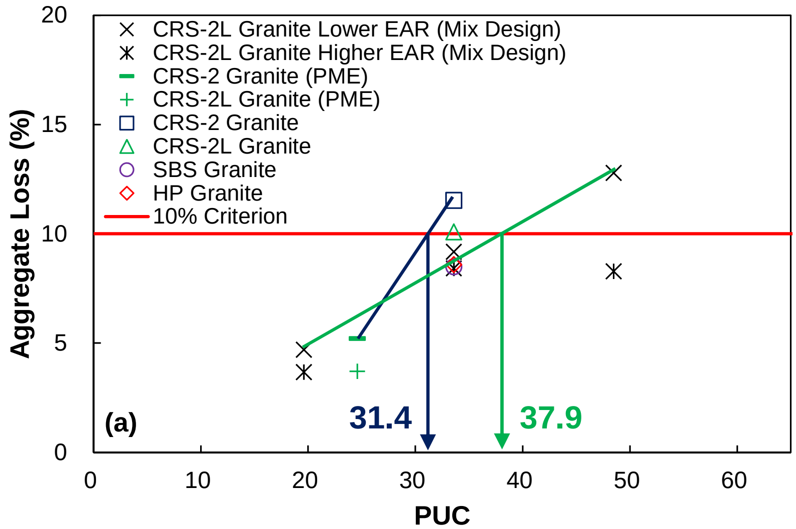
6.2 Materials

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 research projects (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. Table 22 shows detailed information for specimens made with the two aggregate types (granite 78M and lightweight). Figure 65 shows the effects of the PUC for the chip seal performance tests. Figure 65 shows that all the specimens that were made using optimum application rates were used for analysis.

Table 22 Specimen Information for PUC Analysis

Factor	**Mix Design Project** (FHWA/NC/2008-04)	**PME Project** (FHWA/NC/2007-06)	**High Volume Project**
Aggregate Type	Granite 78M		
PUC	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
Aggregate Type	Lightweight		
PUC	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



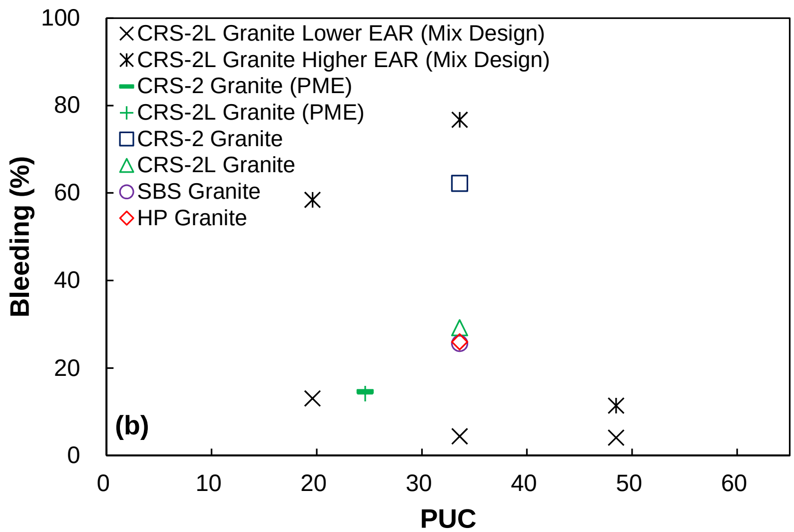


Figure 65 Effect of PUC in performance tests for granite 78M aggregate: (a) aggregate loss and (b) bleeding

Figure 65 (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 65 (b), the specimens made using the higher EAR for the mix design project 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 66 shows the effects of PUCs in chip seal performance tests with the lightweight aggregate. Figure 66 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.

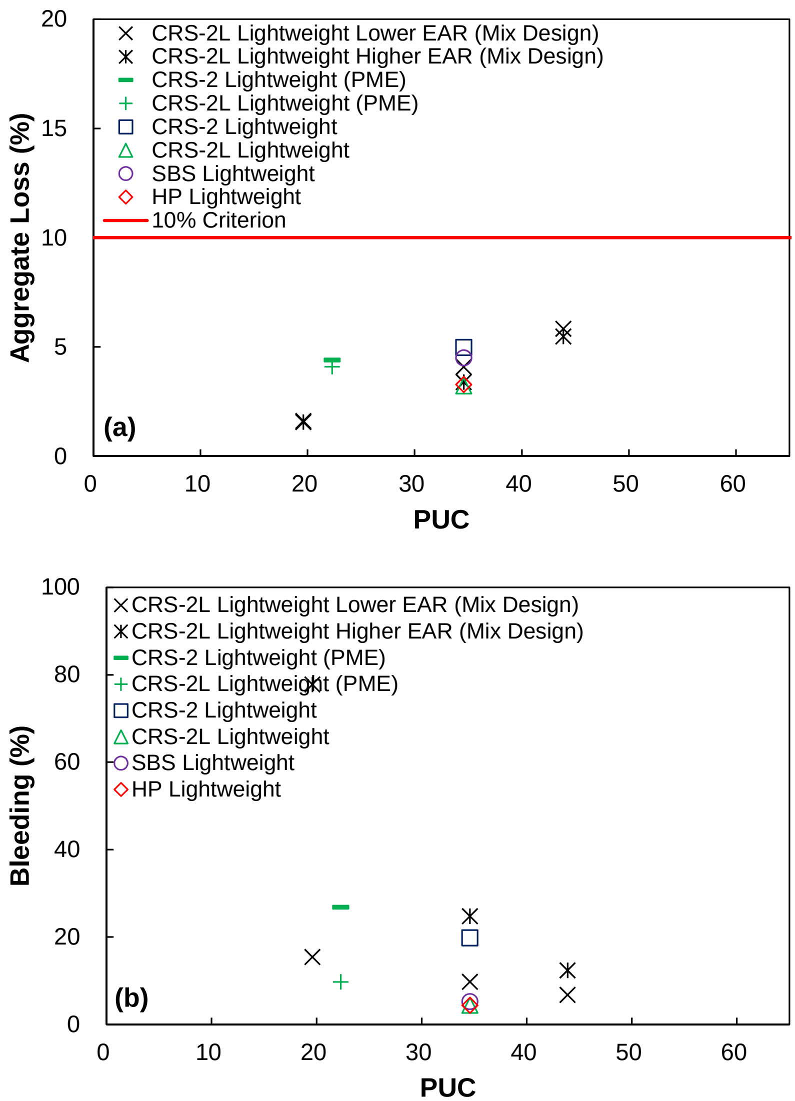


Figure 66 Effect of PUC in performance tests for lightweight aggregate: (a) aggregate loss and (b) bleeding

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 67 shows the comparison of performance test results between single seals and multiple seals.

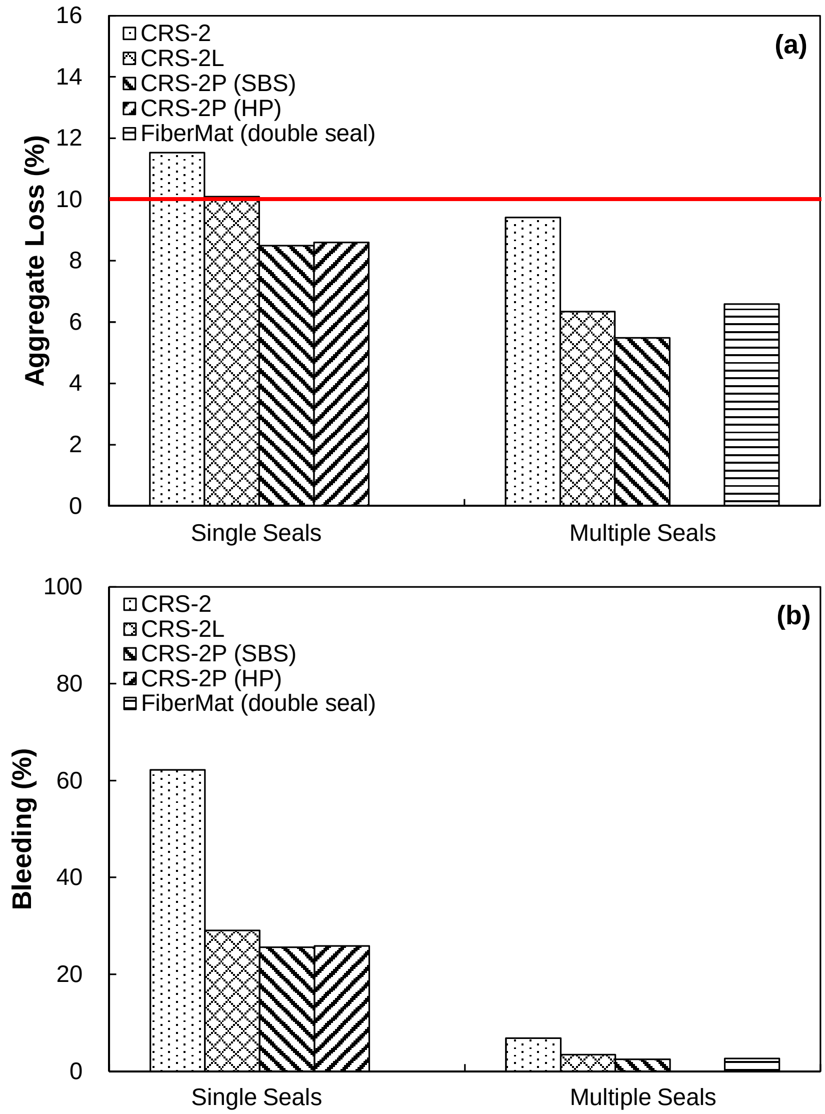


Figure 67 Comparison of performance tests between single seals and multiple seals

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 23 shows the cost information for emulsions used in North Carolina.

Table 23 Emulsion Cost Information (NCDOT 2013)

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

The performance data obtained from this research are compared to the data from previous PME research (FHWA/NC/2007-06). Table 24 shows the application rate information for all the specimens, and Figure 68 through Figure 72 show the comparisons of the performance of emulsions for different conditions. The project 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 projects, the test results cannot be compared directly. Therefore, ratios were calculated based on the non-PME emulsion, and then those results are compared.

Table 24 Application Rate Information

<table>
<tr><th colspan="2">Sample</th><th>AAR (lb/yd^2)</th><th>EAR (gal/yd^2)</th></tr>
<tr><td rowspan="2">Field (PME)</td><td>Granite 78M</td><td>17</td><td>0.35</td></tr>
<tr><td>Lightweight</td><td>9</td><td>0.35</td></tr>
<tr><td rowspan="2">Lab (PME)</td><td>Granite 78M</td><td>17</td><td>0.25</td></tr>
<tr><td>Lightweight</td><td>9</td><td>0.25</td></tr>
<tr><td rowspan="2">Lab (High Vol.)</td><td>Granite 78M</td><td>16</td><td>0.25</td></tr>
<tr><td>Lightweight</td><td>7</td><td>0.25</td></tr>
<tr><td rowspan="2">PME (Double Seal)</td><td>Bottom</td><td>17 (Granite 78M)</td><td>0.25</td></tr>
<tr><td>Top</td><td>9 (Lightweight)</td><td>0.25</td></tr>
<tr><td rowspan="3">PME (Triple Seal)</td><td>Bottom</td><td>17 (Granite 78M)</td><td>0.30</td></tr>
<tr><td>Middle</td><td>17 (Granite 78M)</td><td>0.25</td></tr>
<tr><td>Top</td><td>9 (Lightweight)</td><td>0.20</td></tr>
<tr><td rowspan="2">High Vol. (Field)
(Triple Seal)</td><td>Bottom and Middle</td><td>22 (Granite 78M)</td><td>0.25</td></tr>
<tr><td>Top Layer</td><td>11 (Virginia #9)</td><td>0.18</td></tr>
<tr><td rowspan="3">High Vol. (Lab)
(Triple Seal)</td><td>Bottom</td><td>17 (Granite 78M)</td><td>0.30</td></tr>
<tr><td>Middle</td><td>17 (Granite 78M)</td><td>0.25</td></tr>
<tr><td>Top</td><td>9 (Lightweight)</td><td>0.20</td></tr>
</table>

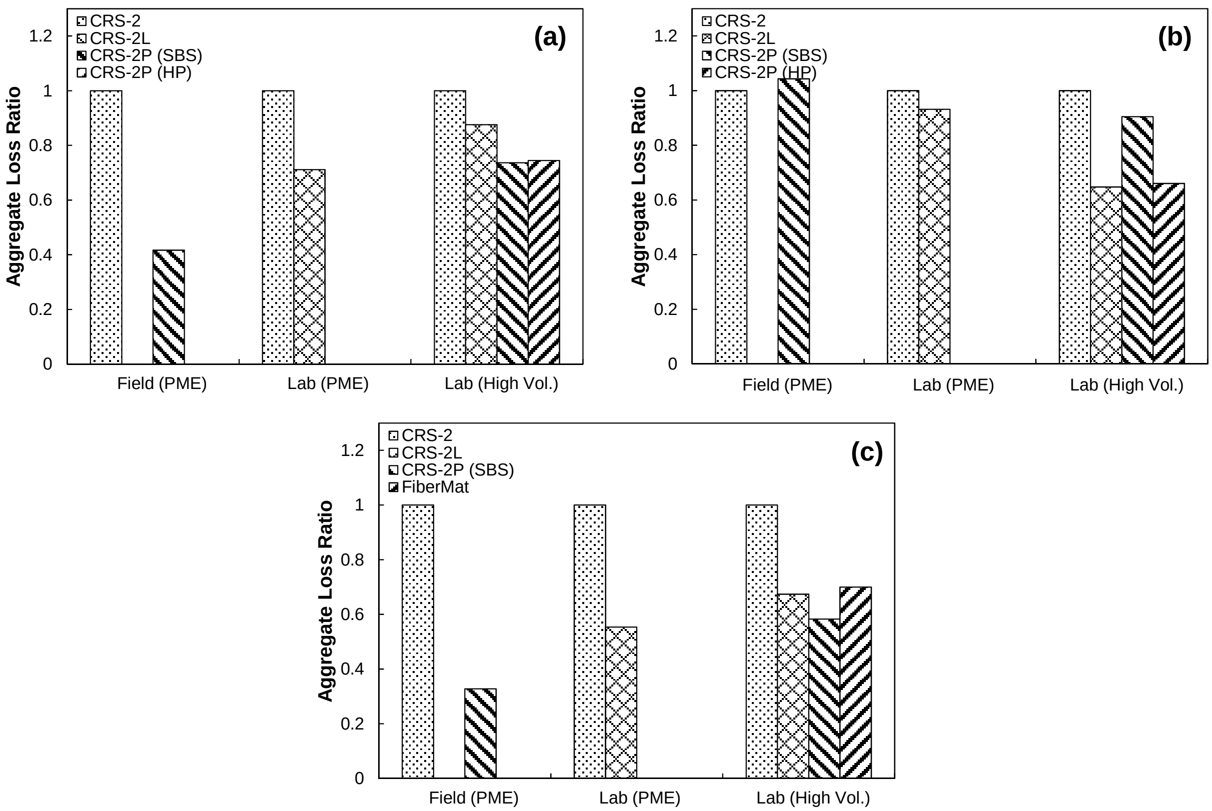


Figure 68 MMLS3 test aggregate retention comparison of different conditions: (a) single seal with granite 78M aggregate, (b) single seal with lightweight aggregate, and (c) multiple seals

Figure 68 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.

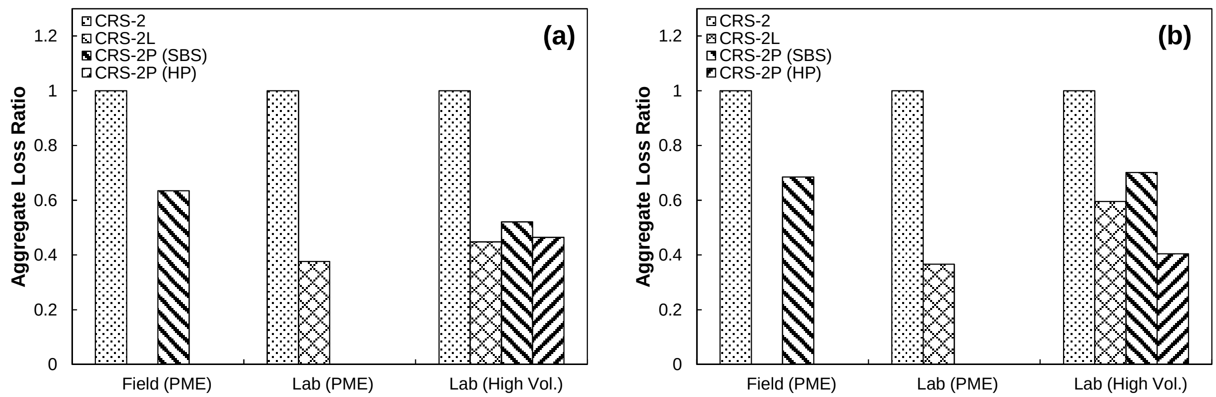


Figure 69 Vialit test aggregate retention comparison of different conditions: single seal with (a) granite 78M aggregate and (b) lightweight aggregate

Figure 69 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.

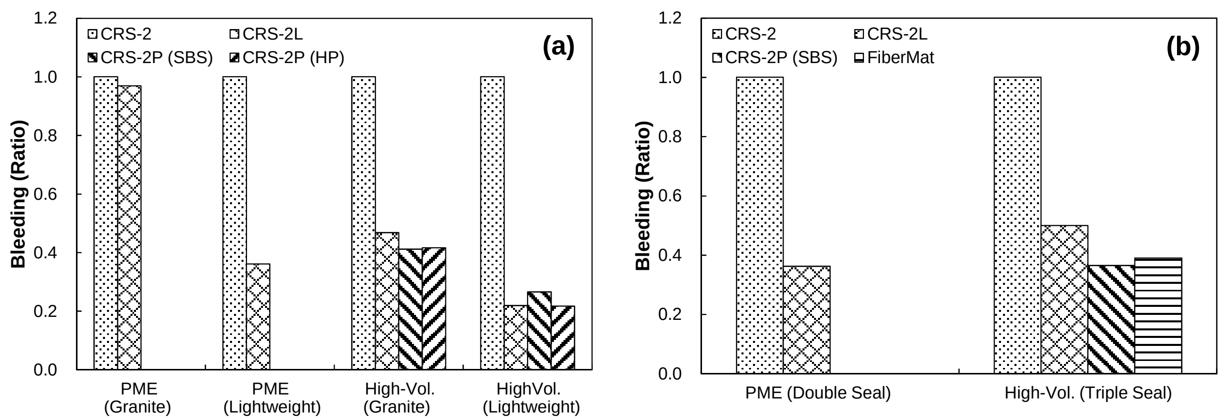


Figure 70 Bleeding resistance comparison of different conditions: (a) single seal and (b) multiple seal

Figure 70 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.

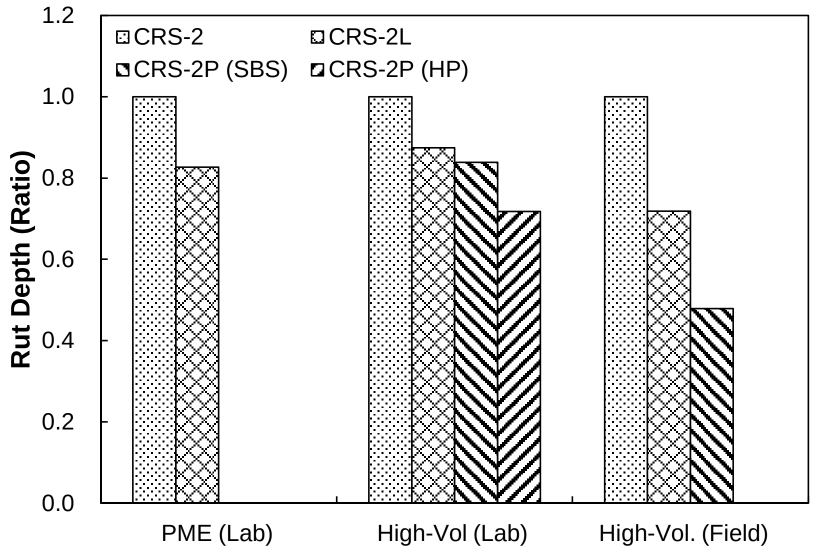


Figure 71 Rutting resistance comparison of different conditions

Figure 71 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.

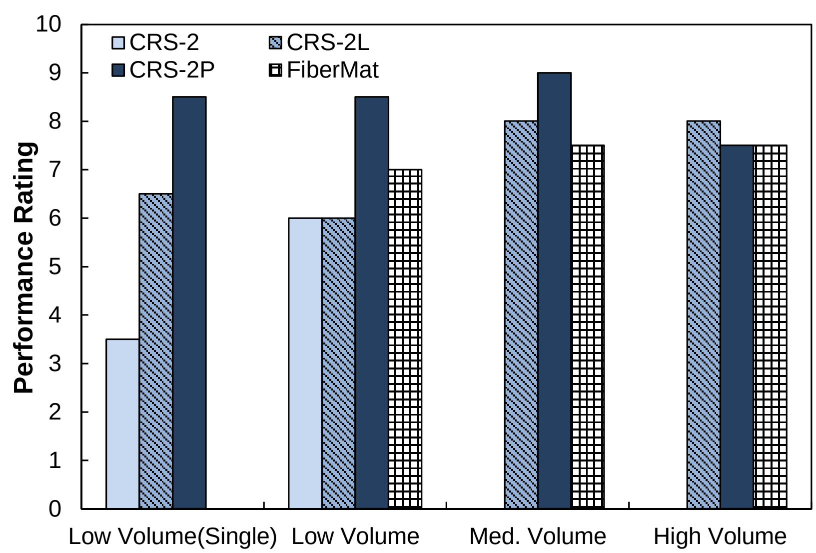


Figure 72 Field performance rating comparison of different conditions

Figure 72 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 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 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 25.

Table 25 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 25 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 26 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.

Table 26 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

Figure 73 (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 73 (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.

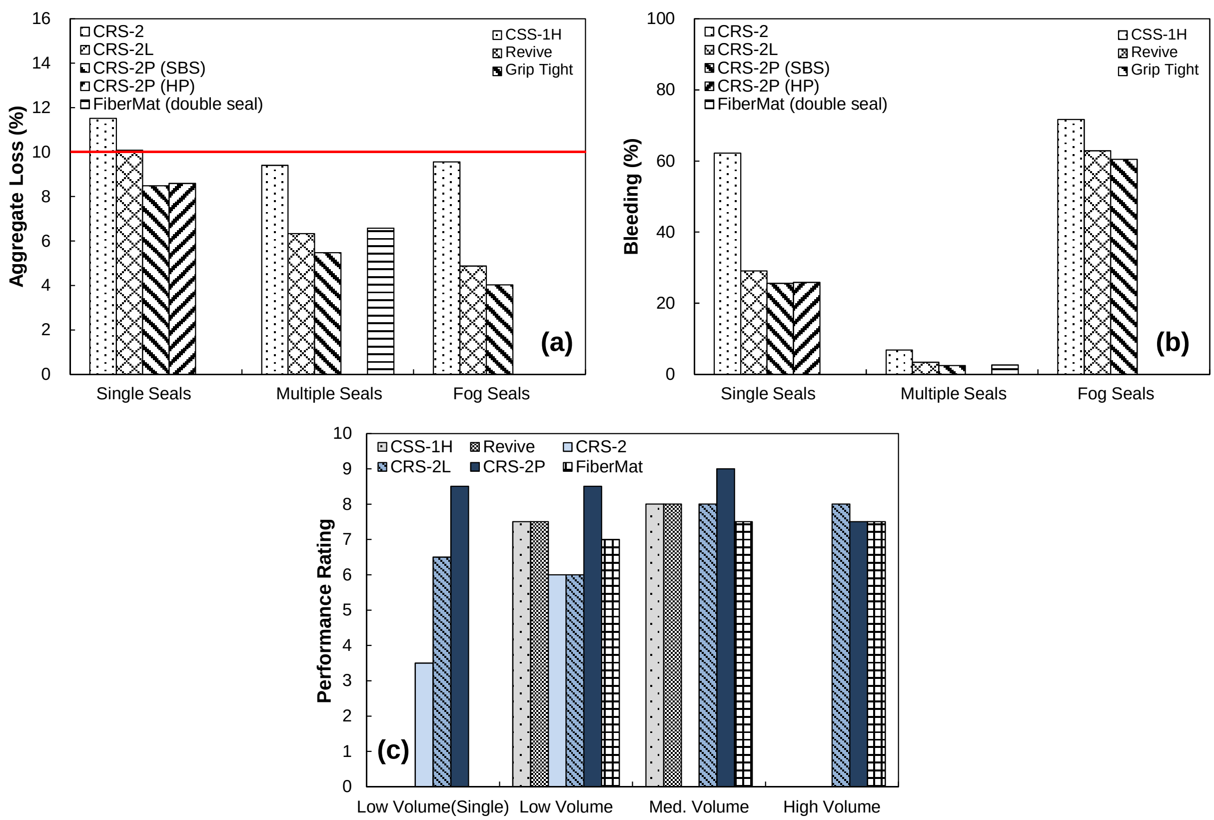


Figure 73 Performance comparisons of different seal types: (a) aggregate retention by MMLS3 testing, (b) bleeding by MMLS3 testing, and (c) field performance ratings

Based on the literature review, cost information, and performance comparisons, two seal types are recommended, depending on traffic volume and pavement conditions. Table 27 shows the recommended seal types.

Table 27 Recommendations for Seal Type

	Single Seal w/ CRS-2P (Fog seal can be considered)	**Double Seal w/ CRS-2P** (Fog seal can be considered)
Recommendations	- Less than 5,000 ADT, or - Pavement condition is good or newly constructed.	- More than 5,000 ADT, or - Heavily cracked roads on low volume
Need Study	- Criteria for pavement condition and in-service life of original pavement	- Maximum allowable traffic volume - Criteria for heavily cracked roads

6.5 Construction Procedures

The information gathered from the literature review and previous research (NCDOT HWY-2006-06 project) 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 project).

Figure 74 shows the construction procedures used in this research and in Minnesota. Figure 74 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.

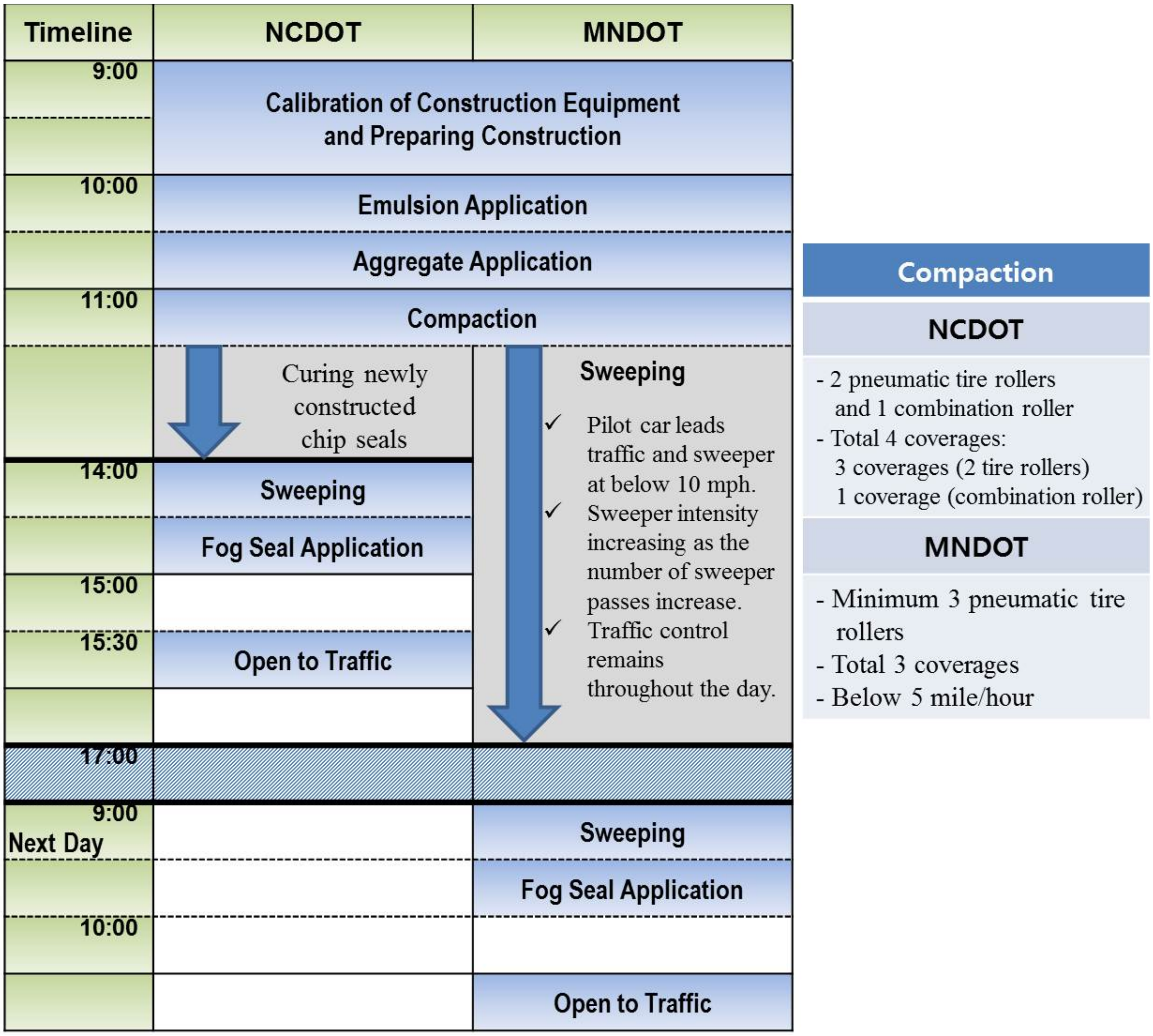


Figure 74 Construction procedure timeline

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 75 shows the MPD analysis that is used to predict the maximum allowable traffic volumes for multiple chip seals with different emulsions.

Figure 75 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 28 presents the estimated maximum allowable traffic volumes.

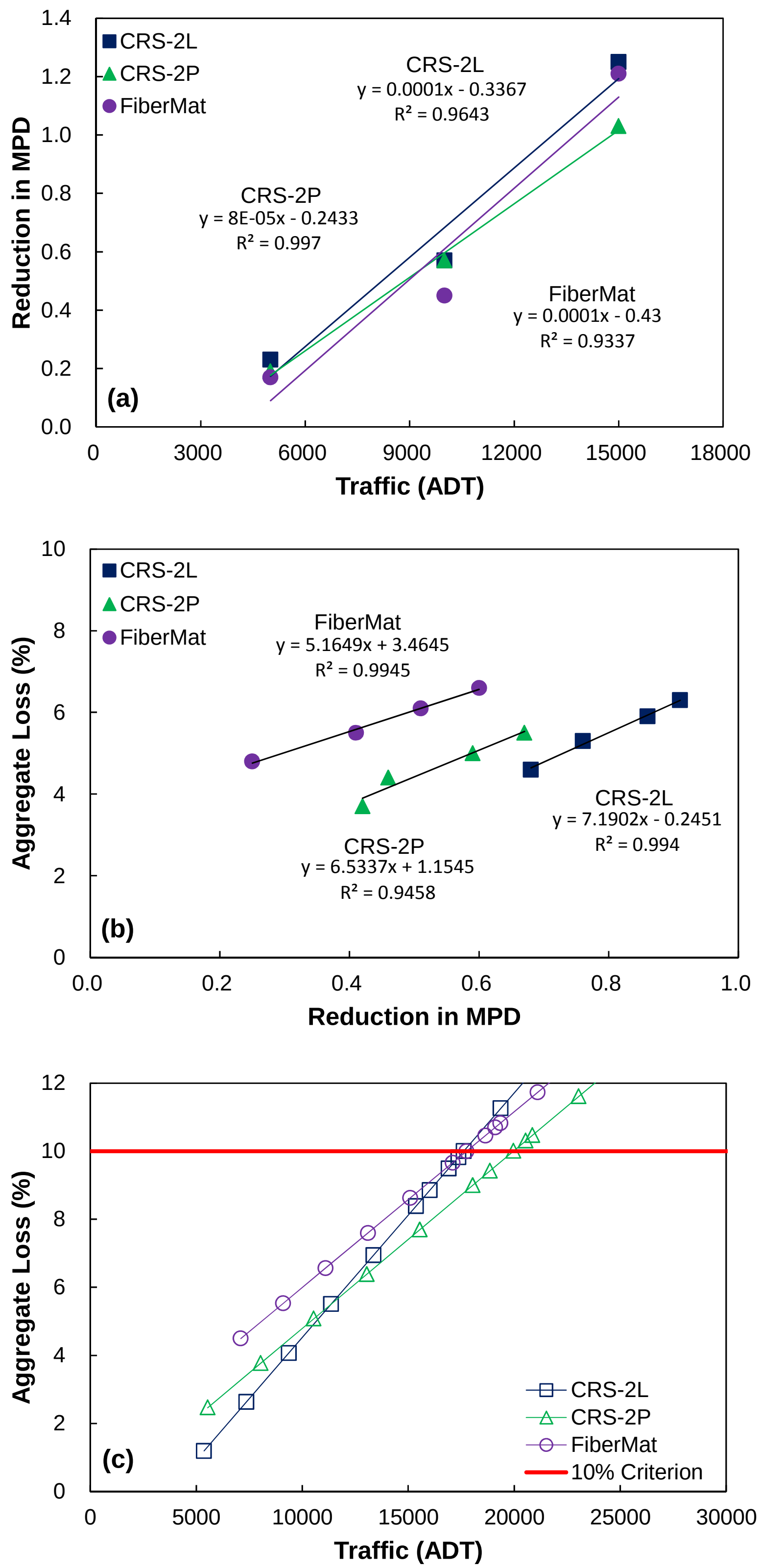


Figure 75 MPD analysis: relationships between (a) MPD and traffic volumes in field, (b) aggregate loss and MPD in laboratory, and (c) aggregate loss and field MPD

Table 28 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.

Table 28 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

7. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

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 PMEs 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 PMEs 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 PMEs 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 PMEs.
- 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 PMEs.
- In summary, all of the test methods used in this study indicate that the PMEs 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 PMEs regarding the performance characteristics

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.
- The existing pavement condition is important for chip seal performance. Chip seals should be applied on roads that are already in relatively good condition without structural failures.
- For single seals with granite 78M aggregate, the maximum PUC value is suggested as 31.4 for non-PMEs and 37.9 for 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 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 or for heavily cracked areas on low-volume roads.
- The maximum allowable traffic volume can be estimated for multiple seals using MPD analysis. 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.

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