RESEARCH & DEVELOPMENT

Chip Seal Construction Variability and Its Impact on Performance

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16. Abstract

This report presents the findings from a field and laboratory experimental program that was designed to assess the amount and nature of any construction variability and the impact of any such variability on the performance of chip seal treatments. The research approach involved the construction of three double-seal test sections in Rowan, Moore, and Caswell Counties, respectively, by two contractors and three different construction crews, and the sampling of chip seal specimens obtained from these test sections. Granite 78M and No. 14 aggregate and CRS-2L emulsion were used in the construction. The aggregate application rate (AAR) and emulsion application rate (EAR) were determined using the ignition oven test, and aggregate loss and bleeding were evaluated using the third-scale model mobile load simulator (MMLS3) test. In addition, the research team evaluated the effects of the quality of the emulsion on chip seal performance by measuring the sprayability and drain-out of the fresh emulsion using the three-step shear test in a rotational viscometer and the high temperature binder performance of the residue using the multiple stress creep and recovery (MSCR) test in a dynamic shear rheometer.

The main findings from this study are: (1) the AARs and EARs that were measured from all three field sections constructed by three different construction crews were significantly lower than the targeted design application rates; (2) although the individual application rates were much lower than the targeted application rates, the constructed chip seals did not exhibit significant performance problems in the field based on the condition survey performed eight months after construction because the lower than targeted EARs and AARs seemed to have canceled out the negative effects of having less than adequate amounts of aggregate and emulsion; (3) the MSCR test results were correlated with the amount of bleeding observed from the MMLS3 testing of the chip seal specimens; and (4) a performance-related specification framework that provides guidance for test procedures that can help identify construction variability issues as well as a chip seal best practices document and quality assurance training programs were developed for the NCDOT's future use.

17. Key Words
Chip seal, application rate, aggregate loss, bleeding, performance, MSCR, MMLS3, EPG

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EXECUTIVE SUMMARY

Research Objectives

The overall objectives of this research are to:

1. Identify the sources of construction and materials variability in chip seal construction.
2. Determine the range of the variability in contracted chip seal construction and the impact of the variability on the performance of chip seals.
3. Develop a comprehensive synthesis of best practices for chip seal construction.
4. Develop guidelines for a chip seal certification and quality assurance (QA) program.

Research Methodology

The methodology employed for this research includes field experimentation and analysis as well as laboratory tests of extracted field samples. The research approach involved the construction of three double-seal test sections in Rowan, Moore, and Caswell Counties, respectively, followed by the sampling of chip seal specimens from these sections for performance testing by the North Carolina State University (NCSU) research team to assess the amount and nature of any construction variability and the impact of any such variability on the performance of the chip seal treatments. Two contractors and three construction crews constructed the chip seal sections.

The materials utilized for all the field sections were granite 78M and granite #14, each with CRS-2L emulsion. The granite aggregate used for each field chip seal construction project was obtained from aggregate sources typically used by the bituminous paving crew in each Division where the construction would take place. The double seals constructed in Rowan and Caswell Counties consisted of a bottom seal made with granite 78M and a top seal made with granite #14. Both layers of the double seal constructed in Moore County were made with granite 78M.

The NCSU research team conducted ignition oven tests using chip seal samples obtained from the constructed field test sections on Vialit plates to determine the material application rates. Using the resultant test data, the research team compared the measured material application rates and the targeted design application rates to quantify the construction variability for each field section. The team also conducted third-scale model mobile load simulator (MMLS3) tests using the chip seal specimens obtained from the field sections to investigate the impact of the observed variability on the aggregate loss and bleeding resistance of the chip seal treatment.

In order to assess the effects of the application rates, the research team evaluated the effects of the emulsion material properties on the chip seal performance. The test procedures that were utilized to assess the materials' performance are included in the emulsion performance-graded (EPG) specifications, developed by the NCSU research team under NCHRP Project 9-50 and fully detailed in NCHRP Report 837. Key test procedures that the research team utilized in this NCDOT project include the multiple stress creep and recovery (MSCR) test that uses a dynamic shear rheometer as well as sprayability and drain-out tests that use a rotational viscometer in accordance with the EPG specifications.

A performance-related specification (PRS) framework for chip seal construction that the NCSU research team developed under NCHRP Project 10-82A was refined in this NCDOT study. These specifications recommend that extracted Vialit test samples should be used to measure rate variability and to assess aggregate loss. Also, the ‘performance uniformity coefficient’ (PUC), which is an indicator of the uniformity of the aggregate gradation, should be employed as a pass/fail criterion during regular quality control testing of quarry material. Survey results coupled with engineering judgment were able to provide guidance for preliminary pay adjustment factors based on aggregate loss. The NCSU research team also determined preliminary ‘percent within limits’ values for each ‘acceptance quality characteristic’ (AQC) to discern whether a lot warrants full pay (AQC > 90), partial pay (60 < AQC < 90), or no pay (AQC < 60) for chip seal treatments. The preliminary pay adjustment factors require further consideration and NCDOT input. This PRS framework would provide the NCDOT and contractors with test methods and a starting point for identifying construction-related problems in chip seal treatments in the future. The PRS framework also helps to determine the AQCs that can be measured using practical test methods that, in turn, can identify pay factors for chip seal construction.

An extensive review of the literature, findings from past NCDOT projects that had been led by the NCSU research team, laboratory performance data, and field experience all were utilized to develop a construction best practices document to standardize the knowledge needed in order for chip seal construction personnel to construct acceptable chip seal treatments, regardless of the location in the State or the materials used.

The NCSU research team also developed QA training programs for chip seal construction in this study. These programs are intended to standardize the knowledge base of NCDOT inspectors and contractors such that a minimum competency level is demonstrated prior to such personnel taking part in chip seal construction.

The Divisions will be able to use the products of this research to focus on the key factors that impact the performance of chip seal surface treatments. This final report will assist bituminous construction crews in implementing methods to control variability in the field. Importantly, reducing the variability in the construction of chip seal surface treatments will result in a more consistent service life for the treatments and a reduction in the number of costly corrective actions needed for recently treated roadways.

Conclusions

The main conclusions drawn from this research are:

- The material application rates that were measured from the constructed field sections were significantly lower than the targeted design application rates for both the aggregate and emulsion materials applied at all three locations by three different construction crews.
- Although the individual application rates were much lower than the targeted application rates, the constructed chip seals did not exhibit significant performance problems in the field based on the condition survey performed eight months after construction. The reason for this outcome is that the lower than targeted EARs and AARs seemed to have canceled out the negative effects of having less than adequate amounts of aggregate and emulsion.
- The MMLS3 performance test results for the field chip seal samples showed acceptable aggregate retention for all three test sections. However, the chip seal samples from the Rowan County and Caswell County sections exhibited significant bleeding, with the Caswell County section being the worst. It is noted that the Rowan County and Caswell County sections are double seals with granite #14 as the choking layer at the top, whereas both layers in the Moore County section consisted of granite 78M. The under-application of aggregate, combined with the high non-recoverable creep compliance (J_{nr}) values obtained from MSCR tests, likely explains the substantial bleeding observed for the Caswell County section.
- All the emulsions used in this study met the sprayability and drain-out requirements defined in the EPG specifications.
- The MSCR test results for the emulsion residues correlated with the amount of bleeding on the chip seal specimens that were subjected to MMLS3 loading. The binders with lower MSCR J_{nr} values exhibited better resistance to bleeding under MMLS3 loading than binders with higher values, as expected.
- The construction variability test results suggest that test procedures are needed to identify material application rate variability problems in newly constructed sections so that the NCDOT can determine whether or not the failure mechanism for a chip seal treatment is construction-related and requires remedial action by the contracted construction crew. Emulsion testing also should be performed in accordance with the EPG specifications detailed in NCHRP Report 837 to ensure that any observed performance problems are not material-related.
- The chip seal PRS framework, the best construction practices document, and the QA training programs developed in this project should improve the quality of chip seals constructed throughout North Carolina.

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1. INTRODUCTION

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 forefront. In recent years, most agencies have implemented pavement preservation strategies to maximize cost savings for repair operations and to maintain pavements. Pavement preservation treatments are considered sustainable because they improve pavement quality and durability and extend the pavement's service life while reducing energy consumption and greenhouse gas emissions. Chip seals are among the most efficient and cost-effective pavement preservation treatments utilized by state highway agencies to preserve and rejuvenate existing pavements.

Recent mandates by the State Legislature of North Carolina have made chip seals even more important as preservation treatments. The new legislature requires 4,300 lane miles to be covered by pavement preservation treatments in North Carolina. Chip seals would be a large part of the $65 million pavement preservation program that is needed to meet this goal. Another major change in chip seal construction practice is the new directive that prescribes gradual increases in outsourcing chip seal construction from 30% in 2015-2016 fiscal year to 80% by 2017-2018 fiscal year. This increase in the amount of outsourced chip seal construction changes the NCDOT's focus from good construction practices to the development of specifications and quality assurance (QA) programs.

A series of research projects has been funded by the NCDOT for North Carolina State University (NCSU) to investigate various ways to improve chip seal performance by enhancing material specifications, the effectiveness of chip seal construction, and mix design methods and ultimately maximizing the life cycle and cost benefits of each chip seal treatment. The research described herein uses the findings and experience gained from these projects to guide the NCDOT to meet these new challenges and recent legislative mandates. In order to help guide the transition towards a higher percentage of contracted chip seal work performed in North Carolina, a synthesis of chip seal best practices was developed and presented as a comprehensive chip seal construction manual. In addition, both field construction and sampling efforts as well as a laboratory experimental testing plan were employed to identify and quantify the variability associated with chip seal construction and the effect of such variability on the performance of chip seals. The results from the field and laboratory experiments will allow the NCDOT to define tolerance ranges of critical design and construction parameters and acceptable construction practices that are needed to ensure that the contracted work is being completed in a manner that yields satisfactory chip seal performance.

The overall objectives of this research are to:

1. Identify the sources of construction and materials variability in chip seal construction.

2. Determine the range of the variability in contracted chip seal construction and the impact of the variability on the performance of chip seals.
3. Develop a comprehensive synthesis of best practices for chip seal construction.
4. Develop guidelines for a chip seal Certification and QA program.

2. FIELD CONSTRUCTION SUMMARY

2.1. Field Research Overview

The North Carolina State University (NCSU) research team organized the construction of five field sections at each of three construction locations in Rowan, Moore, and Caswell Counties in North Carolina during the field construction effort for this research for a total of 15 field test sections. Two contractors were selected for the construction of the test sections. Contractor A used two different crews to construct the ten (five plus five) sections in Rowan and Caswell Counties, respectively. Contractor B constructed the five sections in Moore County using one crew. It is noted that the five sections in each of the three construction locations were defined only for sampling and monitoring by the research team. That is, each construction crew constructed a single section without knowing that the section actually was divided into five test sections. The research team studied the variability within a single construction crew by investigating the variability found among the five 500-foot chip seal sections that each crew constructed for sampling and monitoring. The research team also studied the variability among the three different construction crews from the two contractors in terms of their practices and work.

The objectives of this field research were to:

- monitor the contractors’ chip seal construction procedures and note any deviations from the recommended chip seal best practices and current NCDOT specifications;
- determine the amount of variability within each chip seal construction project;
- determine the amount of variability for the different contractors’ work; and
- determine the effect of construction variability on pavement performance using laboratory performance tests of field samples as well as field performance monitoring.

2.1.1. Variability within a Project

For each of the three chip seal projects, the research team defined five different sampling and monitoring sections for research purposes. The emulsion type, aggregate type, target material application rates, and construction procedures were kept constant among these five sections constructed at each project location by a single crew to study the variability for that specific construction crew/project.

2.1.2. Variability among Contractors

To study the variability among the contractors in terms of their practice and work, the research team compared the construction variability data acquired from each project to show the impact of the differences in the contractors' practice and work on the measured material application rates and on chip seal performance. The contractors identified by the NCDOT to participate in this research project represented both small and large chip sealing operations. These contractors were asked not to deviate from their normal construction practices for this research.

2.1.3. Construction Day Tasks

On each day of construction, the research team needed approximately one to two hours of traffic control in order to set up the sampling templates prior to the start of construction. The research team also obtained the targeted design emulsion application rates (EARs) and aggregate application rates (AARs) for the day's construction. These targeted application rates were needed for comparison against the measured application rates.

Following construction, the research team extracted chip seal samples from the field sections to determine the measured EARs and AARs for each chip seal location. The team also sampled emulsions from the emulsion spray tanker for performance-related material testing in the laboratory so that the effects of the binder material properties on performance could be taken into account. Testing the material properties would ensure that the asphalt material used in the construction would meet the specified test limits related to the critical performance criteria for chip seals.

The areas of the roadway where the samples were extracted needed to be patched by the contractor on the day of construction, as shown in Figure 1. These patched sampling areas were located in the center of the lane, outside the wheel paths.

Figure 1. Construction crew patching the first chip seal layer following sample extraction and prior to applying the second layer of the double chip seal.

Although sample extraction is destructive in nature, the manual patching process for each 203-mm by 203-mm Vialit test sample extracted proved to be straightforward, even for construction crews with no patching experience. Also, previous construction teams had reported no problems with this process during field research efforts that employed this same extraction and repair method (Kim and Adams 2011).

The research team tried to collect the field data in a manner that would not disrupt the normal operations of the contractor and would avoid biasing the study data. Nonetheless, the research team acknowledges that, despite its best efforts to be discrete and unobtrusive, the construction crews could have tried instinctively to perform better due to the very presence of the researchers.

2.1.4. Field Construction

The field research sections were constructed in Rowan, Moore, and Caswell Counties in North Carolina by different contracted bituminous paving crews. (Specific company names are not given to protect the anonymity of the participants in this research study.) Table 1 shows the construction locations of these test sections. Five double-layer chip seal sections were constructed at each location. Each section was composed of a 50-ft sample extraction area and a 450-ft section monitoring area.

Table 1. Locations and Materials Used in Chip Seal Field Section Construction

Construction Location	Construction Date	Contractor – Crew	Bottom Layer	Top Layer	Emulsion Type
Mt. Tabor Church Rd., Cleveland, NC: **Rowan County**	9/15/16	Contractor A – Crew #1	Granite 78M	Granite #14	CRS-2L
Purvis Farm Rd., Robbins, NC: **Moore County**	10/6/16	Contractor B – Crew #1	Granite 78M	Granite 78M	CRS-2L
Prospect Church Rd., Mebane, NC: **Caswell County**	10/13/16	Contractor A – Crew #2	Granite 78M	Granite #14	CRS-2L

The construction crews targeted the EARs and AARs that are presented in Table 2 through Table 4 for the construction of the double seals.

Table 2. Target Material Application Rates for Rowan County Field Sections

Seal Layer	Target EAR (gal/yd^2)	Target AAR (lb/yd^2)
Bottom	0.3	18
Top	0.2	11

Table 3. Target Material Application Rates for Moore County Field Sections

Seal Layer	Target EAR (gal/yd^2)	Target AAR (lb/yd^2)
Bottom	0.24	26
Top	0.28	26

Table 4. Target Material Application Rates for Caswell County Field Sections

Seal Layer	Target EAR (gal/yd^2)	Target AAR (lb/yd^2)
Bottom	0.3	18
Top	0.25	9

Figure 2 through Figure 4 present photographs of the construction of a field chip seal section by Contractor A.

Figure 2. CRS-2L emulsion application during field chip seal construction.

Figure 3. Granite aggregate application during field chip seal construction.

Figure 4. Compaction during field chip seal construction.

Chip seal samples were obtained from each layer separately by placing Vialit plates on the existing pavement and constructing chip seals over them. The Vialit plates are made of steel and therefore can withstand high temperatures during the ignition oven tests that are used to determine application rates. For the first (bottom) of the two layers in each seal, samples were extracted 15 minutes after the construction crew completed compaction. Prior to the construction of the second (top) layer of the seal, the construction crew manually patched the sampling area of the first layer, as shown in Figure 1. Following the sample extraction and patching of the first layer, the second layer was applied. Chip seal samples on Vialit plates were extracted from the second layer following the same procedure described for the first layer sample extraction. Lastly, after both layers were constructed, samples were extracted on felt that included both layers of the seal for aggregate loss and bleeding performance testing in the laboratory that employed a third-scale model mobile load simulator (MMLS3). After extraction, the samples were placed on wooden boards and moved to well-secured racks on a box truck for transportation to the laboratory.

Figure 5 shows one of the extracted samples that were used in the laboratory to verify the EARs and AARs of both layers of the double seals individually. Figure 6 shows one of the samples used for MMLS3 performance testing.

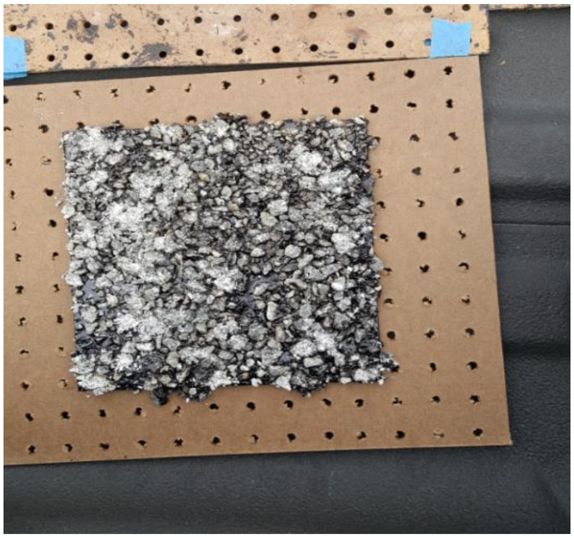

Figure 5. Vialit test sample extracted from a single layer of a chip seal section.

Figure 6. MMLS3 double-seal sample extracted from a chip seal section.

2.2. Field Application Rate Determination Using the Ignition Oven Test

A variety of construction-related issues can cause variability in the EARs and AARs during chip seal construction. These variability problems could have various causes, from operator error to clogged emulsion sprayer nozzles, for example. The NCSU research team had observed problems with material application rates in past field research efforts (Kim and Adams 2011). Therefore, to determine the actual field EARs and AARs for each validation section, the samples that were extracted from the field validation sections underwent ignition oven testing to validate the EARs and AARs used for each field section. The ignition oven tests were carried out in accordance with AASHTO T 308 specifications for asphalt mixtures to determine the amount of asphalt residue that had burned off during the ignition oven test (which then was converted to an emulsion rate using the residual asphalt content for the emulsion) and the amount of aggregate initially applied over the sample area. These measured rates were then compared against the targeted design application rates to determine the amount of rate variability.

Table 5 through Table 7 provide summaries of the results of the rate verification effort and construction variability observed for the samples extracted from each field location. Note that the Vialit test samples were extracted from each of the bottom and top layers of the double seals constructed at each location in order to measure the application rate of each layer separately. Also, MMLS3 specimens (which included both layers of the double seal combined) also were ignition oven tested at the conclusion of the performance testing. Table 5 through Table 7 present the results for the 12 samples extracted from each field location.

Table 5. Target Material Application Rates for Rowan County Field Sections

Seal Layer	**Target EAR (gal/yd^2)**	**Avg. Measured EAR (gal/yd^2)**	**EAR Std. Error**	**% Diff. EAR**	**Target AAR (lb/yd^2)**	**Avg. Measured AAR (lb/yd^2)**	**AAR Std. Error**	**% Diff. AAR**
Bottom	0.30	0.19	0.01	-35.4	18	11.74	0.25	-34.79
Top	0.20	0.17	0.01	-12.9	11	9.57	0.55	-13.0

Table 6. Target Material Application Rates for Moore County Field Sections

Seal Layer	**Target EAR (gal/yd^2)**	**Avg. Measured EAR (gal/yd^2)**	**EAR Std. Error**	**% Diff. EAR**	**Target AAR (lb/yd^2)**	**Avg. Measured AAR (lb/yd^2)**	**AAR Std. Error**	**% Diff. AAR**
Bottom	0.24	0.20	0.01	-16.1	26	15.8	0.7	-39.1
Top	0.28	0.18	0.01	-36.2	26	12.8	0.47	-50.9

Table 7. Target Material Application Rates for Caswell County Field Sections

Seal Layer	**Target EAR (gal/yd^2)**	**Avg. Measured EAR (gal/yd^2)**	**EAR Std. Error**	**% Diff. EAR**	**Target AAR (lb/yd^2)**	**Avg. Measured AAR (lb/yd^2)**	**AAR Std. Error**	**% Diff. AAR**
Bottom	0.30	0.17	0.01	-42.3	18	13.3	0.63	-26.1
Top	0.25	0.19	0.01	-24.6	9	8.82	1.0	-2.0

Table 5 through Table 7 show the ‘percent difference’ between the targeted and measured rates for the field samples to illustrate the variability of the EARs and AARs. The results show that in all cases the percent difference is negative, meaning that the averaged measured rate is lower than the targeted design rate for both the EARs and AARs. Also, the reported standard errors indicate that all the differences between the targeted and measured rates are significant. However, the effect of this rate application inaccuracy on performance could be clouded, because a below-target AAR increases the likelihood of bleeding and lowers the likelihood of aggregate loss, whereas a below-target EAR has the opposite effect (i.e., decreases bleeding potential and increases aggregate loss potential). Therefore, the research team could not accurately predict the impact of this rate inaccuracy on performance because the EAR and AAR trends offset each other.

The results highlight the evidence of construction variability in the three different chip seal sections that were constructed by three different chip seal crews. All of the chip seal test sections exhibited significant under-application of both the aggregate and emulsion materials by 30 percent to 50 percent in some cases. The potential impact of this under-application of both the emulsion and aggregate on the performance of chip seals is discussed later in this report.

2.3. Variability within Each Construction Crew

Five sampling sections were constructed at each of the three locations where each crew constructed chip seals. Table 8 and Table 9 present summaries of the AAR and EAR ranges and standard deviations, respectively, that were found from testing the samples extracted from each of these chip seal sections. Table 8 shows the wide range of AARs that were measured at each location where sections were constructed without varying the targeted AAR at that location. This trend was observed for both the top and bottom layers of the double seals. Likewise, Table 9 shows a wide range of EAR values for the specimens extracted from each location. The standard deviations shown in Table 8 and Table 9 demonstrate that the applied rates are somewhat consistent from section to section throughout a chip seal location. However, although the measured rates are somewhat consistent, Table 5 through Table 7 show that the applied rates vary significantly from the targeted design rates, which is still problematic.

Table 8. AAR Range and Standard Deviation among Samples Extracted from Sections

Location	Seal Layer	Rate Range (psy)	Standard Deviation (psy)
Rowan	Top	5.96	1.64
	Bottom	2.07	0.76
Moore	Top	4.03	1.42
	Bottom	5.92	2.11
Caswell	Top	8.42	2.83
	Bottom	5.14	1.78

Table 9. EAR Range and Standard Deviation among Samples Extracted from Sections

Location	Seal Layer	Rate Range (gsy)	Standard Deviation (gsy)
Rowan	Top	0.06	0.02
	Bottom	0.07	0.03
Moore	Top	0.07	0.02
	Bottom	0.03	0.01
Caswell	Top	0.06	0.02
	Bottom	0.06	0.02

The significant construction variability observed for both the EARs and AARs shown in Table 5 through Table 7 demonstrates that simply checking the initial and final volumes in the emulsion tanker before and after construction is not sufficient for verifying that the correct application rate was applied for the seal. Variation in the application rate can be observed in some spots longitudinally along the length of a section (as evidenced by the range of the rates observed for each location where samples were extracted longitudinally throughout the location) or the variation may be due to clogged sprayer nozzles, for example, which can cause variation in the transverse direction. The pressure in the sprayer nozzle is held constant, and so, the system redistributes the emulsion such that the right volume is output, although not necessarily at the intended distribution locations across the lane. These localized rate variations vary enough from the targeted design rates to cause performance problems. Therefore, it is good practice to identify localized means by which to validate that EARs and AARs are within some reasonable plus/minus range within the targeted design rates.

2.4. Laboratory Performance Testing and Construction Variability Results

This section provides some of the results that were obtained from laboratory performance tests of the double-layer chip seal specimens that were extracted from the field sections after construction.

2.4.1. MMLS3

The MMLS3 test simulates the traffic loading conditions experienced by asphalt surface treatments under real field traffic loading. The MMLS3 applies repeated wheel loads to the asphalt surface at a constant and accelerated rate (990 wheel loads applied every 10 minutes) and causes the surface treatment to respond similarly to the way it would respond in the field. The machine itself consists of a rotating drum that drives a train of buggies across a test sample mounted beneath the machine. The train includes a total of eight buggies, four of which have third-scale wheels (relative to standard dual tire wheels). A maximum of three samples (356-mm length per sample) are secured underneath the MMLS3 for testing at one time. The cumulative sample length of 1,066.8 mm is the effective loading length for the MMLS3. With a wandering width of 177.8 mm, the effective MMLS3 loading area is 19 m^2.

The MMLS3 test method was used in this study to evaluate the aggregate loss and bleeding potential of the samples extracted after field construction. For the aggregate loss tests, the samples were traffic-loaded using the MMLS3 for two hours at 25°C with the sample weight measured before and after traffic loading to determine the amount of aggregate loss. Following the aggregate loss test, the temperature in the MMLS3 temperature chamber was increased to 50°C and the samples were traffic-loaded for three hours to simulate long-term bleeding of the chip seal samples.

The MMLS3 tests of the field-constructed samples provided insight into the aggregate loss and bleeding performance of the double-seal sections. This approach was used to evaluate performance in this project and assess the consequences of the rate inaccuracy found from measuring the actual material application rates in the field.

Table 10 provides a summary of the MMLS3 aggregate loss and bleeding performance test results for the specimens extracted from the field-constructed sections. The performance test results show that none of the tested field samples demonstrated significant aggregate loss, with acceptable aggregate loss being defined as loss of cover aggregate below 10 percent (McHattie 2001).

Table 10. Aggregate Loss and Bleeding of Field-Constructed Samples

Construction Location	**Contractor – Crew**	**Avg. MMLS3 % Aggregate Loss**	**Avg. % Bleeding**
Mt. Tabor Church Rd., Cleveland, NC: **Rowan County**	Contractor A – Crew #1	4.3	72
Purvis Farm Rd., Robbins, NC: **Moore County**	Contractor B – Crew #1	8.9	58
Prospect Church Rd., Mebane, NC: **Caswell County**	Contractor A – Crew #2	6.0	98

Aggregate retention is expected to be good in the double-layer chip seals constructed in this study because two of the three test sections (i.e., in Rowan and Caswell) used #14 aggregate in the top layer as a smaller choking stone. This choking stone is likely to be retained due to its smaller size and increased average embedment when compared with the coarser aggregate that makes up a significant portion of the granite 78M gradation with a nominal maximum aggregate size of 9.5 mm. The Moore County specimens exhibited the most aggregate loss of the three sections. The Moore County sections were the only sections that had granite 78M in the top layer of the double seal, which made it more susceptible to aggregate loss when used in the top layer than the more uniform and smaller #14 granite choking stone.

The MMLS3 test results imply that the under-application of aggregate is more significant than the under-application of emulsion in these sections because, ultimately, the significant under-application of the aggregate contributed to bleeding. These test sections exhibited acceptable aggregate retention overall, but the specimens extracted from the Caswell County sections did exhibit significant bleeding (i.e., 95% of the specimen area bled on average) under MMLS3 loading. This bleeding can be seen clearly in Figure 9 that shows images of a few of the tested specimens that have bled completely. This bleeding under MMLS3 loading indicates that these field sections may be susceptible also to bleeding in the field. *Figure 7* shows the specimens before trafficking and they do not exhibit significant flushing (caused by over-application of emulsion such that the emulsion has flushed the surface prior to being exposed to traffic). Likewise, Figure 8 shows those same specimens after the MMLS3 two-hour aggregate loss test at an intermediate temperature, where no significant bleeding is evident due to short-term traffic loading. However, after three additional hours of MMLS3 traffic loading at 50°C, which simulates long-term high-temperature chip seal performance, the specimen exhibited significant bleeding, as shown in Figure 9.

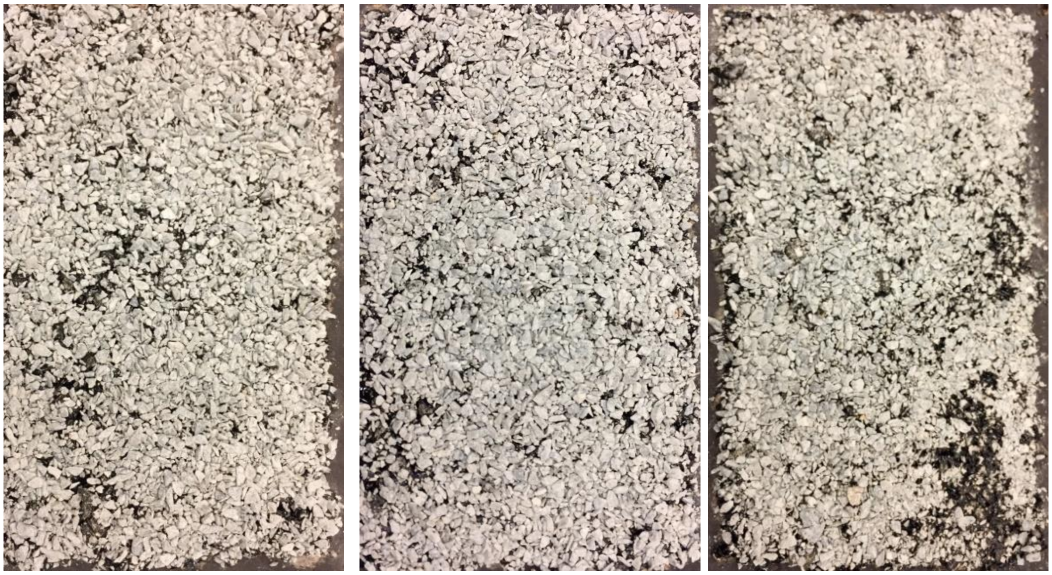

Figure 7. Untrafficked chip seal specimens extracted from Prospect Church Rd. in Caswell County.

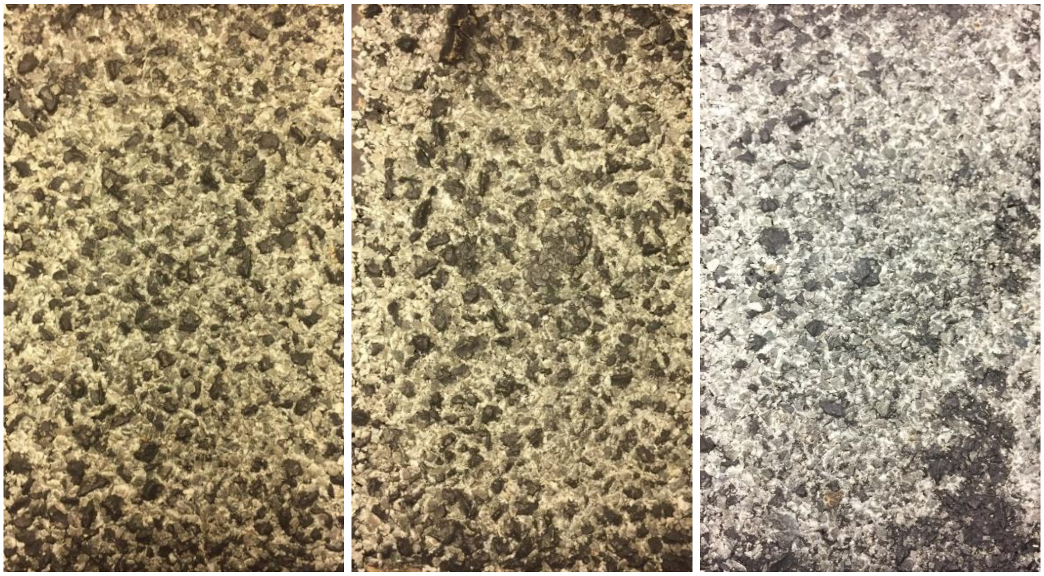

Figure 8. Chip seal specimens extracted from Prospect Church Rd. in Caswell County after MMLS3 aggregate loss testing at 25°C.

Figure 9. Chip seal specimens extracted from Prospect Church Rd. in Caswell County after MMLS3 bleeding testing at 50°C.

To identify the cause of the significant bleeding shown in Figure 9, one must look at both the ignition oven test results for the chip seal mixtures (summarized in Table 7) as well as residual binder material test results to try to identify the mechanisms that caused the performance problems. The ignition oven test results presented in Table 7 reveal that the average EAR for the specimens from the Caswell County section is higher than the targeted design rate. This higher-than-targeted EAR, combined with a measured AAR that is lower than the targeted AAR, contributed to the MMLS3 bleeding shown in Figure 9.

A comparison of the measured application rates and chip seal performance, as evaluated by the MMLS3, indicates that the governing factor for performance is not only the AAR and EAR themselves but also the ratio of those rates to each other. That is, if both the AAR and EAR are lower than the corresponding target rates, the resultant chip seal may not exhibit performance problems due to the cancelling effects. In fact, even though all the sections constructed in this study have AARs and EARs that are lower than the target rates, the MMLS3 test results indicate reasonable performance.

In order to evaluate the combined effects of the AAR and EAR on chip seal performance, the ratio of the AAR to the EAR is calculated and plotted against the percentage of bleeding and percentage of aggregate loss, as shown in Figure 10 and Figure 11, respectively. It is expected that the greater AAR to EAR ratio yields less bleeding and more aggregate loss. This expected trend appears true when the application rates for the top layer are used in the ratio, as shown in Figure 10 (a) for the bleeding results. Figure 10 (b) and (c) respectively indicate that the ratios that are based on the bottom layer application rates and the application rates of both layers together do not exhibit the expected trend. However, Figure 11 shows that the ratio that is based on the application rates of both layers seems to be the best indicator for aggregate loss. These observations suggest that the ratio of the application rates for the top layer is the primary factor for bleeding and that the ratio of the application rates for both layers is important for aggregate loss. The fact that bleeding is a surface distress might explain the reason that the top layer application rates correlate well with bleeding. The penetration into the bottom layer of the aggregate particles that are embedded in the top layer might be the reason for the observation that the application rates for both the top and bottom layers are important for aggregate loss. However, these observations are based on only three AAR-EAR combinations. More systematic research is needed to determine the effects of application rates of different layers in multiple seals on chip seal performance.

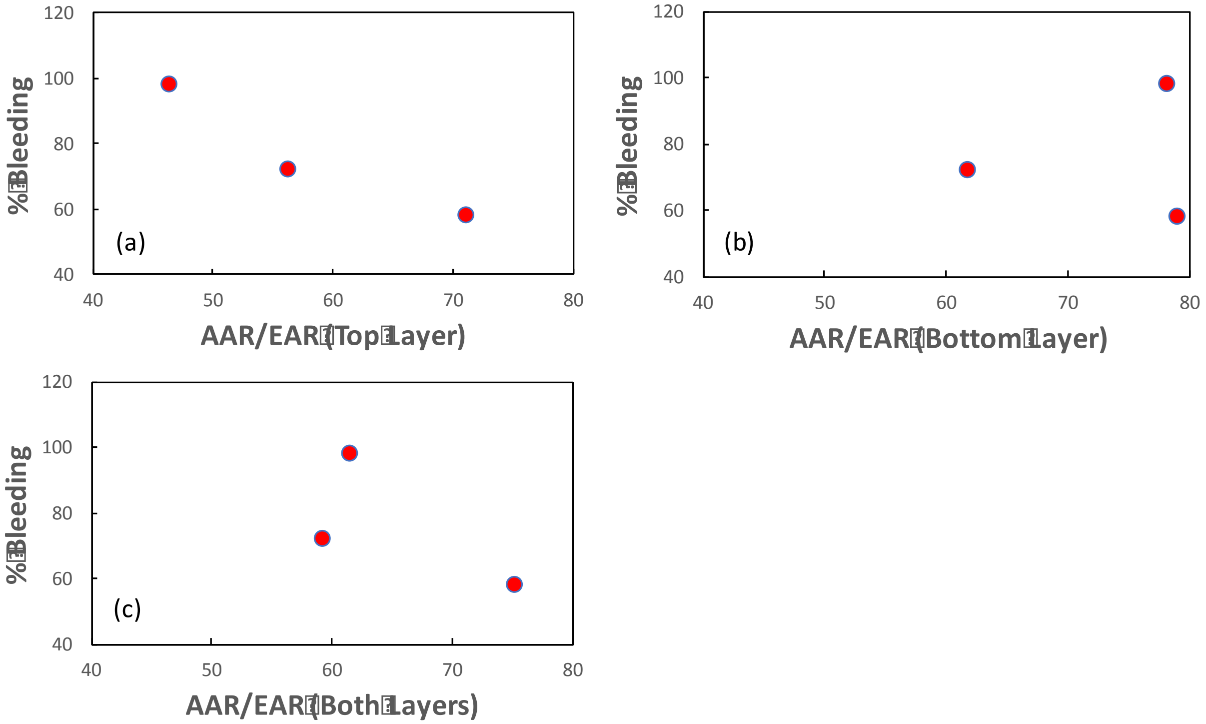

Figure 10. Bleeding as a function of application rate ratio: (a) using rates from the top layer, (b) using rates from the bottom layer, and (c) using rates from both layers.

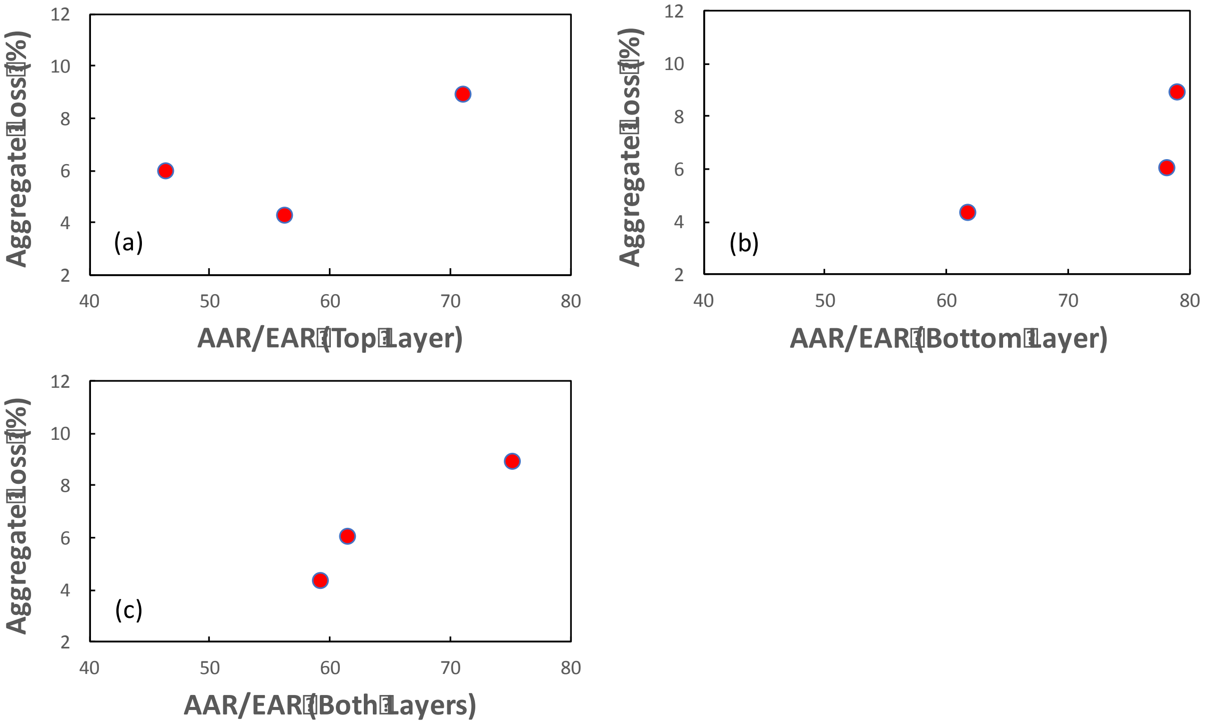

Figure 11. Aggregate loss as a function of application rate ratio: (a) using rates from the top layer, (b) using rates from the bottom layer, and (c) using rates from both layers.

Another factor that affects bleeding and needs further investigation is the performance of the emulsion residue. That is, it is important to understand whether or not the difference between the measured and targeted design application rates fully accounts for the bleeding in isolation. Therefore, the research team investigated the high-temperature performance of the residual binder recovered from the emulsion to see if the material's performance contributed to the poor bleeding resistance in the specimens. The multiple stress creep and recovery (MSCR) test was employed for this material-level performance study; the MSCR test results are presented later in this report.

2.5. Field Performance Monitoring Results

The performance monitoring of the field-constructed sections took place in May 2017, about eight months after construction. During the field monitoring, none of the sections exhibited significant performance problems. The field sections performed better than the samples that were traffic-loaded in the laboratory using the MMLS3, which in the case of the Caswell County samples exhibited significant bleeding. This performance difference between the laboratory and field results was due to differences in the loading conditions between the MMLS3-loaded chip seal samples versus the monitored chip seal field sections. The first reason for this performance difference is that the locations identified for the field construction were low-volume roadways (less than 100 vehicles/day), meaning that the field sections experienced less traffic loading at high temperatures in the field than in the MMLS3 because the MMLS3 applies a constant rate of approximately 1,000 wheel loads every 10 minutes for the entire two-hour test. All of the MMLS3 wheel loads were applied at a consistent high temperature of 50°C, whereas little traffic loading would have taken place on the field sections during peak pavement temperatures. That is, for the field sections, wheel loading during a typical day would not take place at the maximum pavement temperature and therefore would not contribute significantly to bleeding. This difference between MMLS3 loading and field traffic loading is far less pronounced on roadways that have higher traffic volumes than those selected for this study. The field loading conditions under which the test sections experienced significant traffic loading during the summer season more closely replicate the loading that a chip seal experiences under MMLS3 bleeding testing. Another reason for the performance difference between the field and laboratory specimens is the difference in the rate of loading. As noted earlier, the MMLS3 applies 990 wheel loads in 10 minutes, which is a far faster rate than the field sections experienced under low traffic volumes (less than 100 vehicles per day) in the field. This low rate of wheel applications in the field allowed the residual binder in the chip seal field sections more time to recover from stress loading, which led to lower permanent strains in the material and less bleeding in the field compared to laboratory testing. Roadways with higher traffic volumes and faster rates of loading (simulated by MMLS3 testing) have less time for recovery, which therefore increases the permanent strains in the binder material.

Note that although the chip seal test sections did not exhibit bleeding after the first eight months, these sections may still be susceptible to bleeding following the second or third summer, as bleeding may be delayed in the field sections due to the low traffic volumes that these chip seals experienced during short-term field monitoring. The NCSU research team recommends that these field sections should be visited again in the future when they have experienced more field traffic loading at high temperatures. Also, the field sections were constructed after September when the temperature typically is cooler than in, say, July. Moreover, the performance monitoring was conducted in May before the field sections experienced a full summer season when they would be most susceptible to bleeding. Thus, the field monitoring did not include the full effect of summer conditions on field section performance.

2.6. Material Performance Test Results

In addition to evaluating the effects of construction variability on application rates, the research team investigated the material properties of the emulsion used at each construction location in order to assess whether any performance problems that were observed were due to the material properties of the emulsions. The test procedures that were utilized to assess material performance are part of the performance-related emulsion specifications for chip seal treatments, referred to as the ‘emulsion performance-graded’ (EPG) specifications, developed by the NCSU research team under NCHRP Project 9-50 and fully detailed in NCHRP Report 837. Key test procedures that the research team utilized in this NCDOT project include the MSCR test that uses a dynamic shear rheometer (DSR) as well as sprayability and drain-out tests that use a rotational viscometer in accordance with the EPG specifications.

The EPG specifications also include a test for storage stability for fresh emulsions, but this test was not conducted as part of this project due to problems with the test equipment in the research laboratory that did not allow this test to be completed within two weeks of acquisition, which is required for the timely testing of fresh emulsion properties.

The viscosity of the emulsion is critical for acceptable chip seal construction and is characterized by sprayability and drain-out. *Sprayability* is defined as the ability of an emulsion to be sprayed in a uniform thickness across the surface of an existing pavement (Asphalt Institute 2008). An emulsion that is too viscous will result in streaking, spot bleeding, and partial loss of the cover aggregate in the chip seal. For chip seals, the emulsion must be fluid enough so that it can penetrate and fill the surface cracks. *Drain-out* is defined as the ability of an emulsion to resist draining off the pavement surface via gravity after spraying (Bahia et al. 2008). High levels of drain-out lead to premature aggregate loss and reduce the amount of binder that is available for proper aggregate embedment.

The NCSU research team measured sprayability and drain-out in this study using the three-step shear test in accordance with a modification of AASHTO TP 48 that employs a rotational viscometer. This test subjects an emulsion to three successive shear rates to quantify its thixotropic and shear thinning behavior. An initial low shear rate simulates the circulation of the emulsion in a tank, a second step at a high shear rate simulates spraying through a nozzle, and a third step at a low shear rate simulates the flow under gravity once placed. Sprayability is assessed by the viscosity value at the high shear rate. Drain-out is assessed by the viscosity value in the last low-rate shear step. Table 11 presents the three-step shear test limits developed during the NCHRP 9-50 project.

Table 11. Fresh Emulsion Three-Step Shear Test Specification Limits

Test Temperature (°C)	EPG Specification Test	EPG Specification Parameter	Specified Limit
60	Three-Step Shear Test	Sprayability	Maximum 400 cP
		Drain-out	Minimum 50 cP

2.6.1. Constructability: Sprayability and Drain-out Test Results

Figure 12 and Figure 13 present the results of the rotational viscometer tests that measured the sprayability and drain-out material properties, respectively, for the emulsion used at each chip seal construction location. The data presented in Figure 12 show that all the emulsions had measured viscosity values that were below the maximum sprayability threshold of 400 cP during the two required tests, thereby meeting the specification requirement. Likewise, all of the emulsions passed the drain-out minimum threshold of 50 cP, as shown in Figure 13. These results indicate that the viscosity of the emulsions used in this project was such that the emulsions could be sprayed through nozzles effectively (sprayability) without streaking by not exceeding the maximum viscosity threshold, and that drain-out was not observed because the emulsions met the minimum viscosity threshold to resist drain-out.

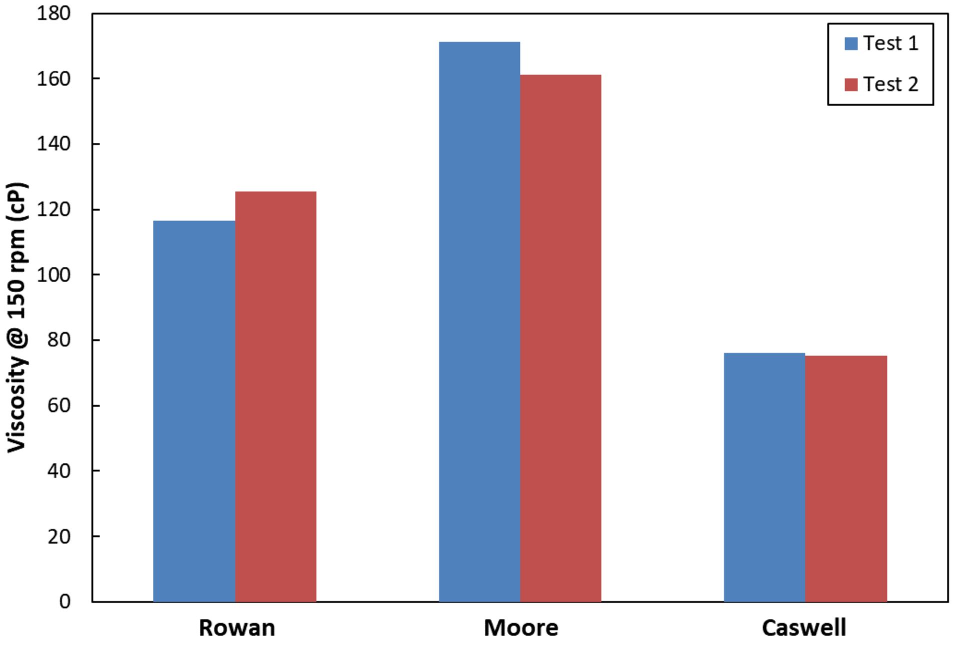

Figure 12. Sprayability results for CRS-2L emulsion samples.

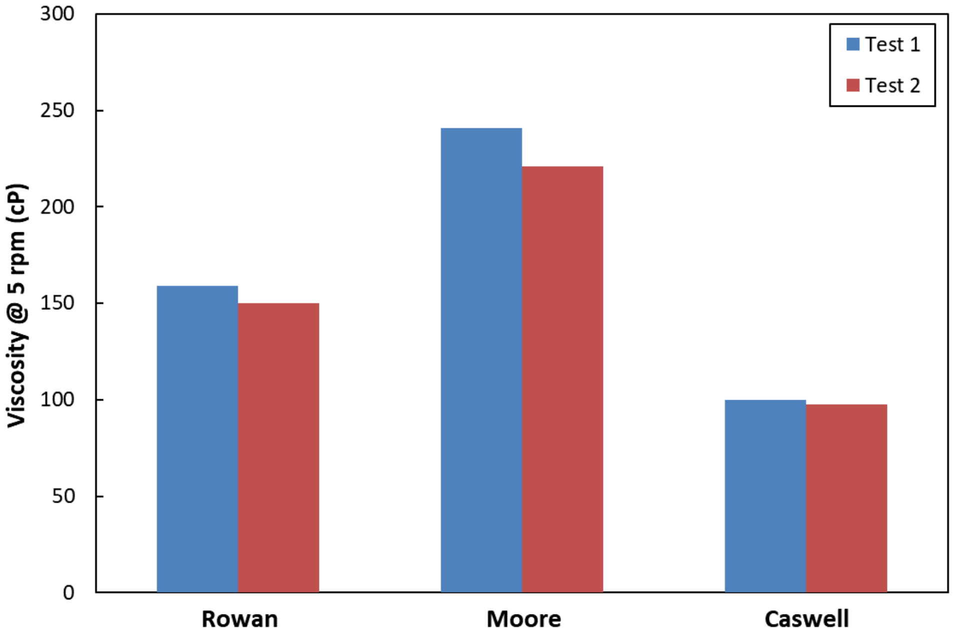

Figure 13. Drain-out results for CRS-2L emulsion samples.

2.6.2. High-Temperature Binder Performance: MSCR Test Results

MSCR testing was conducted using binder residue recovered from the fresh asphalt emulsions that were used during the field construction effort (in accordance with ASTM D7497 Method B). In the EPG specifications, the MSCR test procedure employs a DSR to test residue recovered from emulsions at stress levels of 0.1 kPa^{-1} and 3.2 kPa^{-1}, with the non-recoverable creep compliance (J_{nr}) value measured at the 3.2 kPa^{-1} stress level. The research effort detailed in NCHRP Report 837 found a strong relationship between the measured J_{nr} value at 3.2 kPa^{-1} and bleeding in chip seal mixtures exposed to the seven-day maximum annual pavement surface temperature. The residues recovered from the emulsion materials acquired from each field construction site were tested at the EPG specifications high-temperature performance grade based on North Carolina's climate (defined in the EPG specifications in NCHRP Report 837 as 67°C) to determine the emulsion's susceptibility to bleeding during the summer season after construction, i.e., bleeding that was due to asphalt material performance alone. Figure 14 presents the results of the MSCR tests that show the average J_{nr} values obtained from testing three replicate binder specimens recovered from each emulsion.

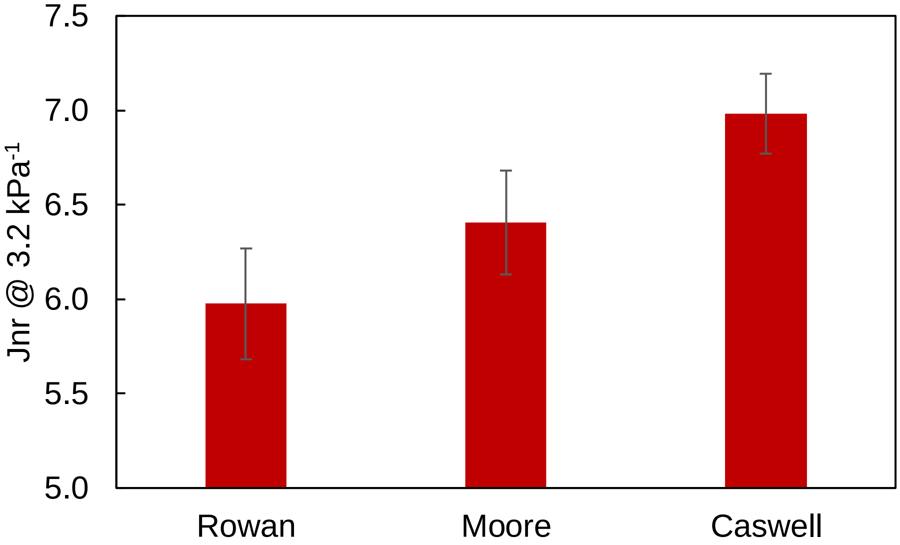

Figure 14. MSCR test results for emulsion residue recovered using ASTM 7497 Method B.

The results presented in Figure 14 indicate that all three emulsions pass the maximum J_{nr} limit of 8.0 kPa^{-1}, as provided in NCHRP Report 837, for the low-volume traffic locations, but do not pass the maximum J_{nr} limit of 5.5 kPa^{-1} for the medium-volume traffic locations. The emulsion used in Caswell County had the greatest likelihood of exhibiting bleeding, because it approached the maximum J_{nr} limit of 8.0 kPa^{-1}. For reference, the higher the J_{nr} value, the more non-recoverable strain the binder exhibits under stress loading. Thus, the binder is less resistant to the accumulation of permanent strain that can lead to bleeding in the field. However, because the MSCR J_{nr} value measured for this emulsion was below the low-volume traffic failure threshold of 8.0 kPa^{-1}, this material still should have performed acceptably in the field in terms of bleeding resistance. However, the Caswell County binder performance is near the critical threshold, which, in theory, leaves less room for error in construction before bleeding problems arise. Likewise, the AARs measured from the ignition oven tests of samples from the Caswell County sections are well below the targeted design rates. This under-application of aggregate, combined with the high J_{nr} value that approaches the failure limit, likely explains the substantial bleeding observed in the MMLS3 test results for Caswell County, as shown in Table 10 and Figure 9. Although all the samples from every section constructed in this research exhibited elevated bleeding potential during performance testing (above 50% bleeding), the binder used in the Caswell County sections had the lowest resistance to bleeding at the material level, which is manifested in the form of the worst bleeding resistance during MMLS3 performance testing.

These findings exemplify the fact that, when explaining the performance problems that a chip seal may exhibit (even when attempting to isolate construction-related performance issues), it is important to look at the chip seal holistically at both the mixture and material levels to fully understand the mechanisms that are causing the demonstrated performance. For these sections, it is possible that, if the measured application rates had been closer to the targeted design rates, the bleeding would not have been as significant, because the MSCR J_{nr} values for the asphalt materials were below the threshold J_{nr} value of 8.0 kPa^{-1} established in the EPG specifications for low-volume traffic roadways.

Also of interest is that the same emulsion supplier supplied the CRS-2L emulsion used in both Rowan and Caswell Counties; yet, Figure 14 shows significant variation between the averaged J_{nr} values obtained from the MSCR tests of the binders recovered from this emulsion that were sampled from the emulsion spray tanker in the field within a few weeks of each other during the Rowan and Caswell County constructions. This finding illuminates the need to test emulsions and recovered residue regularly to identify whether or not a specific batch of emulsion will have performance problems in the field. The EPG specifications (as detailed in NCHRP Report 837) include performance-related testing for grading purposes, but the NCDOT should also consider whether it would be practical to conduct performance-related material tests of the emulsion/binder materials closer to the date of construction to ensure acceptable fresh emulsion and residual asphalt binder performance for the specific batch of asphalt material to be used for chip sealing. By utilizing the test methods provided in the EPG specifications, the NCDOT could help ensure that emulsion/binder quality problems, which in turn cause problems related to bleeding at high temperatures as well as other problems related to storage stability, constructability, etc., are less likely to compromise the quality of specific batches of emulsions used in constructing chip seals.

3. SYNTHESIS OF CHIP SEAL CONSTRUCTION BEST PRACTICES

The objective of the chip seal construction best practices manual is to provide NCDOT personnel with the knowledge necessary to construct a chip seal that provides acceptable service for the design life of the seal. The NCSU research team developed this best practices manual as part of this research at the request of the NCDOT in an effort to provide a consistent guide for contractors that construct chip seals in North Carolina. The best practices manual represents the culmination of years of research conducted by the NCSU research team as well as literature that details best practices for chip sealing worldwide, where applicable.

As one of the deliverables of this research project, a synthesis of these chip seal construction best practices is provided for reference in Appendix A of this report, as the complete best practices manual already has been delivered separately to the Project Steering Committee.

4. A PERFORMANCE-RELATED SPECIFICATION FRAMEWORK FOR CHIP SEAL TREATMENTS TO ADDRESS CONSTRUCTION VARIABILITY ISSUES

The NCSU research team developed a performance-related specification (PRS) framework for chip seal construction under NCHRP Project 10-82A. This PRS framework was further refined in this study. The PRS framework aims to provide guidelines that govern the acceptance or rejection (including appropriate penalty) of a chip seal surface treatment based on whether samples extracted from a defined area (or lot) meet established performance test standards. This framework is intended as a starting point to address the construction variability problems that were observed during this project's research effort as well as during a previous research effort, i.e., the NCDOT HWY-2008-04 project (Kim and Adams 2011).

4.1. Acceptance Quality Characteristics for Chip Seal Treatments

Determining appropriate acceptance quality characteristics (AQCs) and establishing performance relationships were critical steps in developing the performance-related construction specifications framework. The key objective of the research team was to establish relationships between the AQCs and pavement performance of chip seals. In the process of developing these relationships, certain ranges of a particular performance measure could be correlated to the threshold value of the selected AQC. Examples of such correlations were established by collecting and analyzing relevant data through:

- analyzing performance-related trends in historical data obtained from existing projects
- establishing relationships between AQCs and performance measures
- applying engineering judgment and statistical analyses

Once the NCSU research team had established the relationships between the AQCs and performance measures, it could identify methods for measuring the AQCs and determining the limits or thresholds of the AQCs for acceptable levels of performance. General guidelines are provided herein to determine such limits for AQCs based on performance thresholds.

The successful adoption of these construction/acceptance performance-related specifications requires the use of objective test methods that can measure performance-related parameters. The process of specifying such test methods was based on the following concepts:

- minimizing the impact on user delays
- collecting and processing data in a timely manner
- placing emphasis on nondestructive testing techniques

Table 12 details the AQCs that the NCSU research team identified and presents the performance measures (aggregate loss and bleeding) that are related to each AQC, the associated test method, and the specific parameter measured in the field or laboratory for the various AQCs.

Table 12. Overview of Proposed AQCs for Preliminary Performance-Related Specification

Acceptance Quality Characteristics	Related Performance Measure	Proposed Test Method	Test Parameter
Emulsion-Aggregate Adhesive Strength	Aggregate Loss	Vialit Test (Lab)	% Aggregate Loss
Gradation	Aggregate Loss	Gradation Analysis of Vialit Samples (Lab)	Performance Uniformity Coefficient
Emulsion Application Rate (EAR)	Aggregate Loss and Bleeding	Ignition Oven: Vialit Samples	% Difference from Target EAR
Aggregate Application Rate (AAR)	Aggregate Loss and Bleeding	Ignition Oven: Vialit Samples	% Difference from Target AAR

4.1.1. Emulsion-Aggregate Adhesive Bond Strength

Aggregate loss is the primary distress in chip seals at intermediate temperatures. One of the main causes of aggregate loss is the lack of adhesive bond strength between the aggregate and emulsion such that significant cover aggregate is lost upon traffic loading. The adhesive bond between the aggregate and emulsion is a function of the construction practices employed during the chip seal construction. Construction-related factors, such as the time between the application of the aggregate layer onto the emulsion and the first rolling pass, the type of compaction effort applied, the number of roller passes, and the curing time allowed prior to traffic opening, can affect the adhesive bond that is formed (or not formed) between the aggregate and emulsion and thus any aggregate loss observed (Lee and Kim 2008). The Vialit tests of extracted field samples, as proposed in these specifications, directly measures the strength of the adhesive bond that is formed during the construction of a chip seal. This AQC (i.e., bond strength) was determined to be critical to aggregate loss during the NCHRP 9-50 project research (which also was conducted by the NCSU research team and is detailed in NCHRP Report 837).

4.1.2. Gradation

The performance uniformity coefficient (PUC) is a performance indicator of aggregate gradation and gives an indication of the uniformity, or lack thereof, of the aggregate being analyzed. In chip seal surface treatments, aggregate that is more uniform performs better than aggregate particles that are less uniform in terms of aggregate loss and bleeding failure criteria. Thus, the PUC of the aggregate affects the potential bleeding and aggregate loss of the chip seal surface treatment being constructed.

The PUC concept is founded on principles that are based on McLeod's chip seal failure criterion. Essentially, McLeod's premise that 70 percent embedment is the ideal embedment for chip seal surface treatments is implemented in the PUC definition. The PUC is the ratio of the percentage of aggregate particles that pass through a sieve at a given embedment depth (P_{EM}) to the percentage that passes at twice the embedment depth (P_{2EM}) in a sieve analysis curve (McLeod 1971, Lee 2007).

4.1.3. Emulsion and Aggregate Application Rates

The EAR and AAR are both critical to the performance of chip seal surface treatments. Previous findings by the research team indicate that considerable variability often exists between the measured and designed/targeted EARs and AARs in field chip seal construction (Kim and Adams 2011).

The research team found several relationships between the AQCs (see Table 12) and functional performance measures and then developed preliminary limits that require further validation prior to implementation.

4.1.4. Adhesive Bond Strength versus Aggregate Loss

One of the most critical performance measures for a chip seal surface treatment is aggregate loss. The strength of the adhesive bond that forms between the emulsion and aggregate used in chip seal construction is vital to the ability of the chip seal to retain aggregate under field traffic loading. The research team measured the strength of that bond directly by conducting Vialit aggregate loss impact load tests for specimens extracted directly from the constructed field sections. The research team has used this method successfully in numerous past field construction efforts to collect field aggregate loss data (Adams and Kim 2011, Im 2013).

Figure 15 shows the relationship between the Vialit aggregate loss test results and the bitumen bond strength (BBS) values that were measured using a pneumatic adhesive tensile testing instrument (PATTI) to test the emulsions in accordance with AASHTO TP91, *Determining Asphalt Binder Bond Strength by Means of the Bitumen Bond Strength*

Test. The data show that a relationship exists between the Vialit test aggregate loss results and the BBS values for a variety of modified and unmodified emulsion types at different test temperatures, and prove that Vialit test aggregate loss results can be used effectively as an AQC to capture the bond strength between the aggregate and emulsion used in a chip seal.

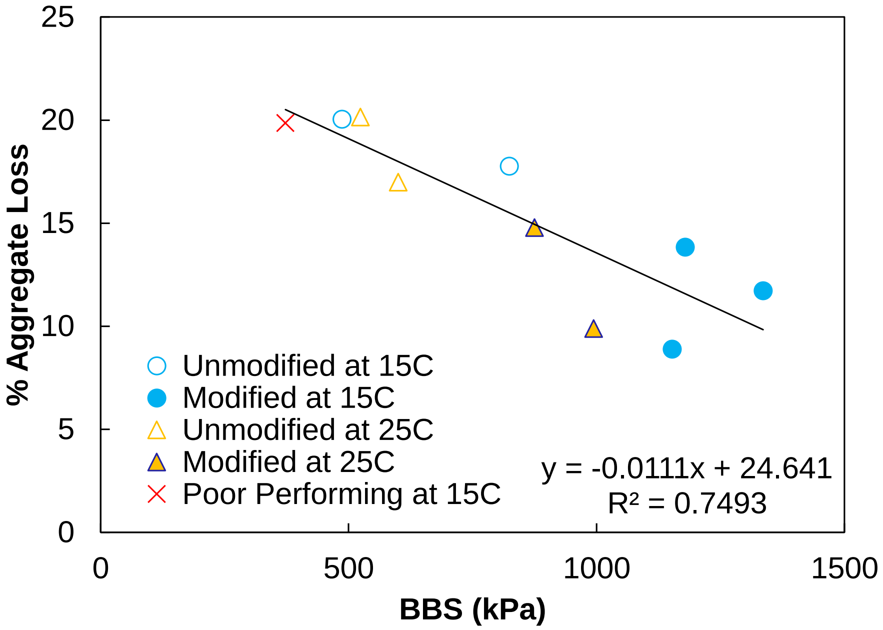

Figure 15. Bond strength vs. Vialit test aggregate loss performance.

The relationship shown in Figure 15 suggests that the BBS value might be a good candidate AQC to characterize a chip seal's resistance to aggregate loss. However, it is noted that the BBS values shown in Figure 15 were obtained using the substrate of the specific aggregate used in the Vialit test. Efforts required to perform BBS tests on a project-specific aggregate substrate suggest that Vialit tests of chip seal samples obtained directly from actual pavements represent a more practical way to determine the aggregate retention for a specific project and to evaluate the adhesive bond strength. Moreover, Vialit tests constitute a more direct measure of the performance characteristic (i.e., aggregate loss) that is related to adhesive bond strength compared to BBS tests. The results presented in Figure 15 show that Vialit aggregate loss tests can be used to differentiate between modified and unmodified emulsions at multiple intermediate temperatures.

4.2. Vialit Test Aggregate Loss Threshold Limit Determination

To determine the Vialit test aggregate loss threshold for the performance-related specifications, limits needed to be derived based on the traffic demand expected for a constructed chip seal section. For example, roadways with higher traffic levels often have higher speed limits, and vehicles are more susceptible to windshield damage due to aggregate loss than is the case for roads with lower traffic levels. Therefore, the acceptable aggregate loss threshold value would be lower (i.e., more restrictive) for roads with higher traffic levels than for roads with lower traffic levels. Conversely, at lower traffic levels, the aggregate loss threshold should be less restrictive than at higher traffic levels. The developed specifications recommend threshold values for three different traffic levels, as defined in Table 13.

Table 13. Traffic Level Definitions for the Performance-Related Specifications

Traffic Level	AADT (vehicles)
Low	< 500
Medium	500 < AADT < 2500
High	2500 – 20000

These traffic levels are consistent with the recommended traffic levels defined in the NCHRP 9-50 project, which proposed performance-related specifications for emulsions used in chip seal treatments (Kim et al. 2016). The NCSU research team recommends 20,000 vehicles as the upper AADT limit for high traffic levels based on a study of high traffic chip seal practice across the United States as well as the research team’s own experience. In California, Colorado, and Montana, for example, chip seals are commonly constructed at AADT counts that can exceed 20,000 vehicles (Gransberg and James 2005). Also, the research team has constructed chip seals at an AADT level above 15,000 vehicles with no reported performance problems (Kim and Im 2015). However, the performance of chip seals constructed for high traffic volumes is heavily dependent on local factors, such as climate, traffic speed, aggregate quality, contractor’s experience, equipment, etc. Therefore, the high traffic upper limit is conservatively set at 20,000 vehicles.

To develop Vialit aggregate loss limits for the specifications, an aggregate loss limit was needed that could differentiate between acceptable and unacceptable mixture performance. Two aggregate loss limits were adopted from earlier research studies that were based on laboratory and field chip seal experiments. The first limit is the maximum allowable aggregate loss limit for the lowest traffic level. The Alaska Department of Transportation (McHattie 2001) defines ‘acceptable’ field aggregate loss as 10 percent or less for any traffic situation where a chip seal is constructed. This 10 percent aggregate loss limit also has been found in previous research to characterize acceptable aggregate loss for MMLS3 testing (Lee 2007, Lee 2009, and Kim and Adams 2011). These earlier research studies found that if a chip seal exhibits 10 percent aggregate loss in the laboratory, it is likely to exhibit significant aggregate loss (based on visual inspections) in the field.

However, these previous research studies also show that Vialit-tested specimens exhibit more aggregate loss than MMLS3-tested specimens when chip seals are constructed and tested under the same conditions. The relationship between MMLS3 test results and Vialit test aggregate loss results was examined in research that is detailed in a previous NCDOT project final report (Kim and Im 2015). In this earlier project, the NCSU researchers found a relationship between the MMLS3 and Vialit mixture test results for both modified and unmodified binders. The mixture specimens that were Vialit-tested and MMLS3-tested for performance were extracted directly from chip seal field sections constructed by an NCDOT chip sealing crew. Table 14 summarizes the relationships observed between the Vialit-tested and MMLS3-tested chip seal samples.

Table 14. Relationship between Vialit and MMLS3 Aggregate Loss Test Results for Chip Seals (Kim and Im 2015)

	Average Vialit Agg. Loss (%)	**Average MMLS3 Agg. Loss (%)**	**Vialit to MMLS3 Ratio**	**MMLS3 Agg. Loss Limit (%)**	**Vialit Agg. Loss Limit (%)**
Modified Emulsions	11	8	1.375	10	10*1.375=**13.75**
Unmodified Emulsions	22	11	2	10	10*2 = **20**

The results presented in Table 14 indicate that, for unmodified emulsions, which often are used in low-volume traffic situations, the Vialit test aggregate loss is double the MMLS3 test aggregate loss. Therefore, based on the 10 percent aggregate loss threshold established for the MMLS3 and the field, the highest allowable equivalent Vialit test aggregate loss is 20 percent. Therefore, a 20 percent maximum aggregate loss threshold is suggested as the low-volume traffic limit for the Vialit test in the current study's performance-related specifications, as this value is roughly equivalent to the 10 percent aggregate loss limit established for the field and MMLS3 wheel loading. Aggregate loss should not exceed this 20 percent Vialit test limit even at the lowest traffic volume that a chip seal experiences, as the windshield damage and reduction in skid resistance associated with excessive aggregate loss beyond this limit would be highly hazardous for vehicles, drivers, pedestrians, etc.

The appropriateness of the 20 percent aggregate loss limit is substantiated by field performance findings. Chip seal sections were constructed using both modified and unmodified emulsions in the same lane at a single construction location to remove all variables except for emulsion type from the field study. The specimens that were Vialit-tested and MMLS3-tested to obtain the data shown in Table 14 were extracted from these same sections so that field versus laboratory aggregate loss could be evaluated. The chip seal section that used modified emulsion did not exhibit any aggregate loss-related problems, and the specimens extracted from the modified field sections had Vialit aggregate loss below 20 percent. The unmodified chip seal section displayed significant aggregate loss in the field, as shown in Figure 16. The specimens extracted from the unmodified field section exhibited Vialit test aggregate loss in the laboratory above 20 percent (as shown in Table 14). This combination of field and laboratory findings supports the 20 percent aggregate loss threshold as an appropriate limit for characterizing aggregate loss for the specifications.

Figure 16. Images of aggregate loss problems observed at the unmodified CRS-2 field section in Durham, NC.

Figure 17 shows the low-volume traffic aggregate loss limit of 20 percent plotted against the aggregate loss percentages for both the modified and unmodified emulsions at two different test temperatures. The figure indicates that both the poor-performing emulsion and the two unmodified emulsions with the lowest bond strength values also show the most aggregate loss and are right at the low traffic threshold of 20 percent aggregate loss. Note that the poor-performing emulsion is an emulsion that was intentionally altered by the emulsion supplier to be poor performing in terms of aggregate retention, but would still meet all current emulsion specifications.

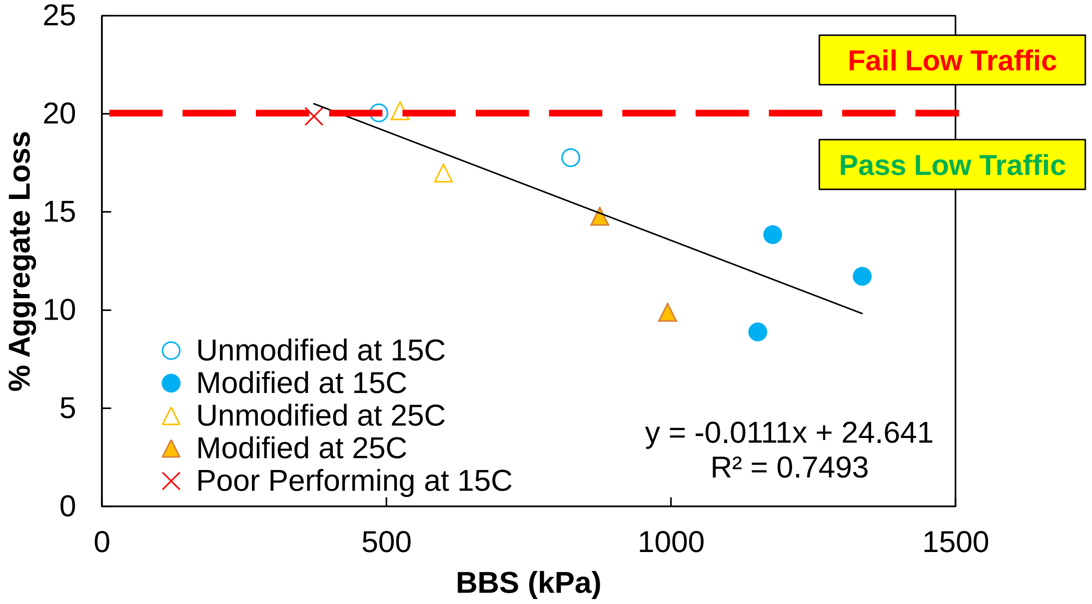

Figure 17. Vialit test aggregate loss plotted against low-volume traffic aggregate loss limit.

The high-volume traffic aggregate loss limit used in the development of the specifications was found through a combination of research findings and results reported in the literature. In the report, *Chip Seals for High Traffic Pavements* (Shuler 1991), Shuler recommends that polymer-modified emulsions should be used in high-volume traffic situations. In addition, Kim and Im (2015) found through field chip seal experiments that modified binders should be used exclusively for chip seal surface treatments in high-volume traffic situations. In the Kim and Im study, single-seal and triple-seal field validation sections were constructed on the same lane of a roadway in North Carolina with an AADT count of 5,000 vehicles (i.e., high traffic). These chip seal sections were visited after the first year of traffic loading for monitoring. The field validation sections clearly showed that the modified binder outperformed the unmodified binder on the same high-volume roadway, as the roadway constructed with modified binder exhibited no performance problems whereas the roadway constructed with unmodified binder had significant aggregate loss.

Therefore, to determine the high-volume traffic performance limit for the specifications, the Vialit test laboratory data presented in Figure 18 were utilized to select the aggregate loss threshold that could distinguish between the modified emulsion, which is known to perform well in high-volume traffic situations, and the unmodified emulsion, which is not recommended for use in high-volume traffic situations. The high-volume traffic aggregate loss limit of 15 percent was selected as the aggregate loss performance threshold that could be used to distinguish modified binders from unmodified binders in terms of performance, as shown in Figure 18.

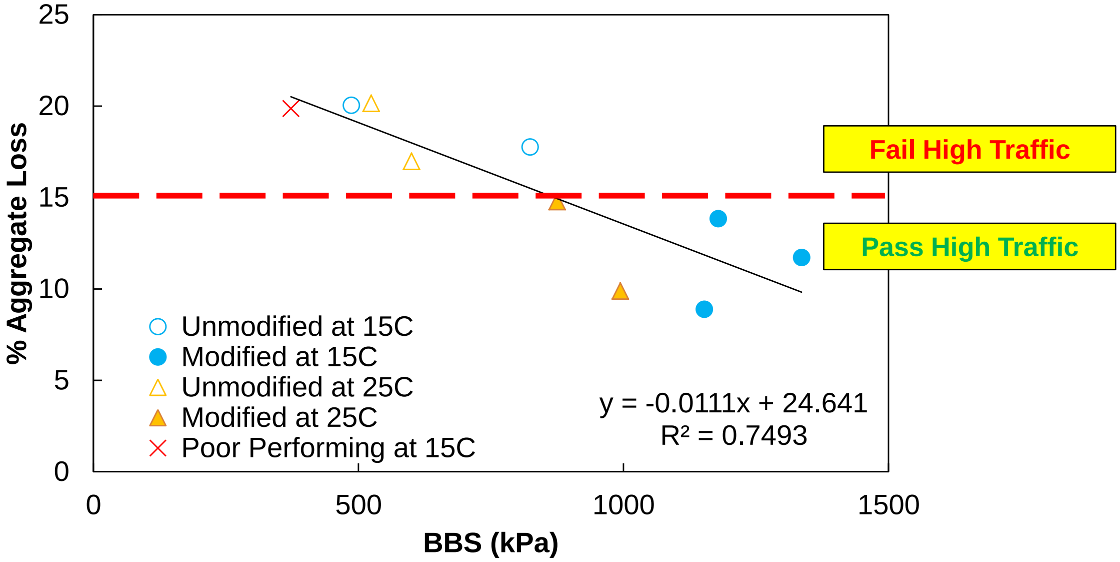

Figure 18. Vialit test aggregate loss plotted against high-volume traffic aggregate loss limit.

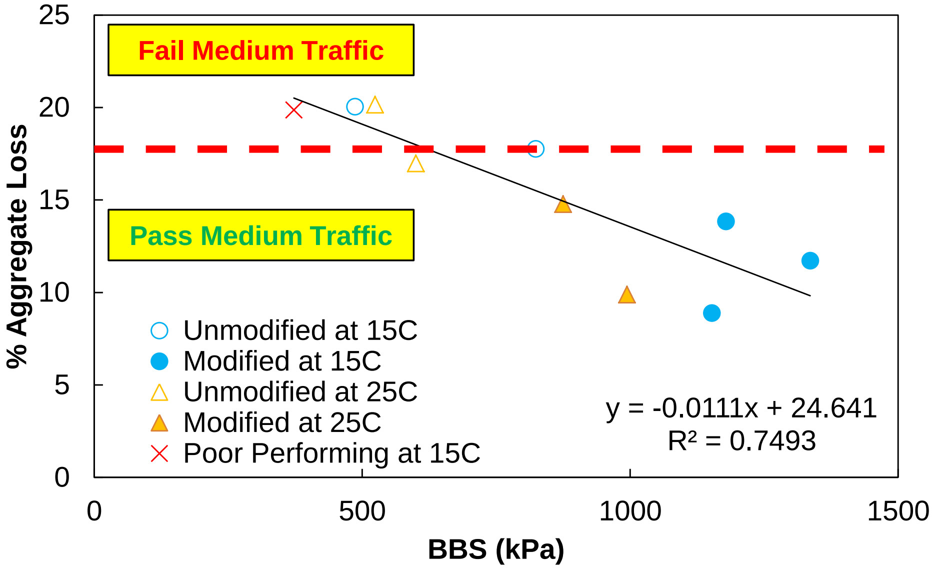

Figure 19. Vialit test aggregate loss plotted against medium-volume traffic aggregate loss limit.

With the aggregate loss threshold limits for low-volume traffic (i.e., 20% aggregate loss) and high-volume traffic (i.e., 15% aggregate loss) established, the research team selected the medium-volume traffic threshold as the average of the low and high limits (i.e., 17.5% aggregate loss). This medium-volume traffic limit is shown in Figure 19 plotted against the Vialit test performance data.

Table 15 summarizes the proposed performance limits for the Vialit aggregate loss AQC according to the traffic level at the chip seal location.

Table 15. Summary of Vialit Test Performance Limits Based on Traffic Level

Traffic Level	AADT	Vialit Aggregate Loss Performance Threshold
Low	< 500	20%
Medium	500 < AADT < 2500	17.5%
High	2500 – 20000	15%

4.3. Relationship between Gradation (Performance Uniformity Coefficient) and Aggregate Loss

Gradation is a significant AQC that is related directly to the performance of chip seal treatments. The AQC parameter that represents the effect of gradation on performance is the PUC. The aggregate PUC gives an indication of the uniformity, or lack thereof, of the aggregate being analyzed. In chip seal surface treatments, gradations that are more uniform perform better than those that are less uniform in terms of aggregate loss and bleeding failure criteria (Lee and Kim 2009, Adams and Kim 2011).

As an AQC that is related directly to aggregate loss, the PUC has been adopted for this project's performance-related specifications. The relationship between the PUC and aggregate loss is shown in Figure 20 for the granite aggregate and in Figure 21 for the lightweight aggregate. Each data point in the figures is the average of nine chip seal specimens that were traffic-loaded using the MMLS3. All of the specimens were fabricated using a single CRS-2L emulsion. The optimum EAR was found to be 0.2 gal/yd^2 and the optimum AAR was found to be 16 lb/yd^2 using a performance-based mix design method (Adams and Kim 2011). Note that these mix design optimum rates are specific to the granite aggregate used in these experiments.

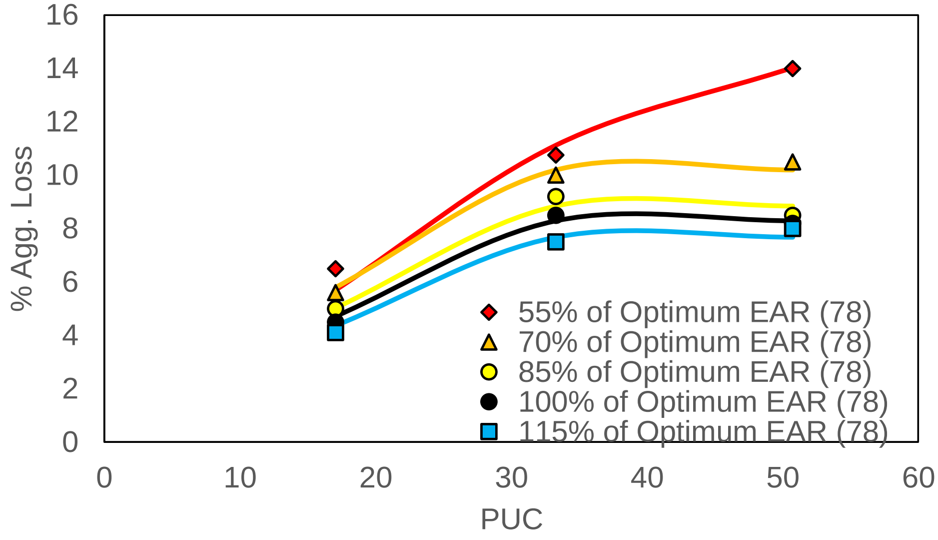

Figure 20. PUC vs. MMLS3 percentage of aggregate loss for granite 78M aggregate.

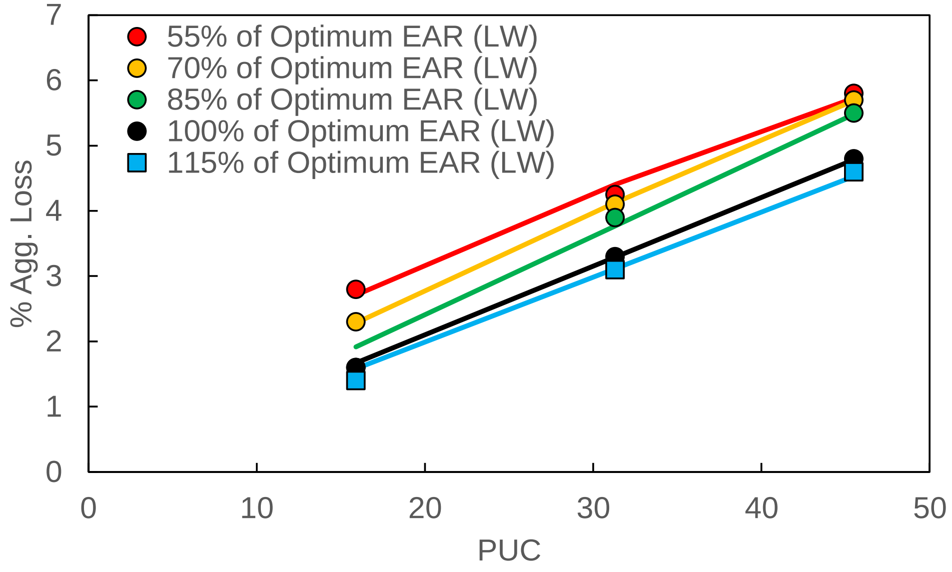

Figure 21. PUC vs. MMLS3 percentage of aggregate loss for lightweight aggregate.

After attempting various models to fit the data, the cumulative distribution form of the skewed logistic function was found to provide a good fit for the relationship between aggregate loss and the PUC for a given EAR. Generalizing the cumulative distribution function for use herein yielded three parameters: (1) the asymptotic value that the aggregate loss approaches at high

PUC values, $\%AggLoss_u$, (2) a location parameter, *a*, and (3) a shape parameter, *b*. Accordingly, the model is defined in Equation (1), and Figure 22 presents the model parameters.

$$\%AggLoss = \%AggLoss_u\left(1+\left(\frac{PUC}{a}\right)^{(\log 2/b)}\right)^{-b/\log 2} \qquad (1)$$

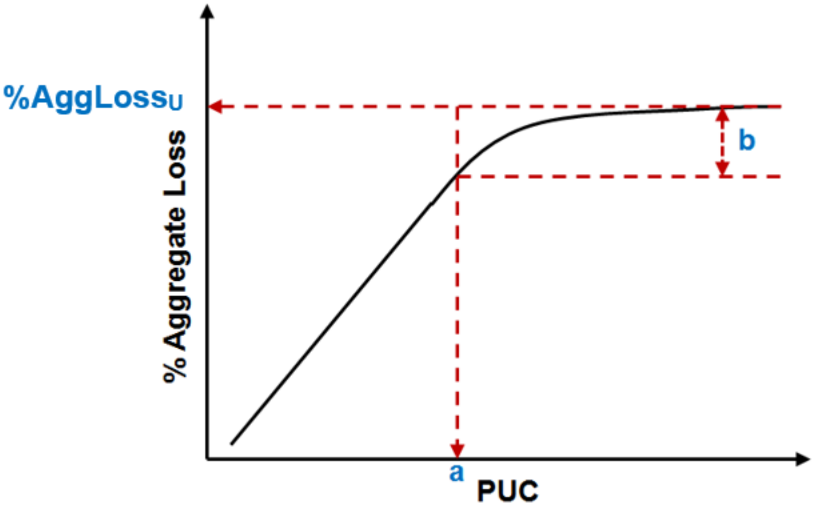

Figure 22. Illustration of the three cumulative distribution function parameters.

Using Equation (1) to predict the percentage of aggregate loss while minimizing error, Figure 20 and Figure 21 show that the model predictions fit the measured data for the PUC and the percentage of aggregate loss for the MMLS3-loaded chip seal specimens for the granite aggregate and lightweight aggregate, respectively.

Figure 20 shows that, as the PUC increases and as the gradation becomes less uniform, the aggregate loss increases. This trend is shown for different EARs as a percentage of the optimum design EAR for the granite 78M aggregate used in these experiments. The data show that at a low PUC value below 20 (i.e., greater aggregate uniformity), decreasing the EAR to below 100 percent of the optimum rate has less effect on the aggregate loss. Conversely, the aggregate loss at PUC values above 50 becomes high at very low EARs.

Figure 21 shows a linear trend for the lightweight aggregate. Also, the magnitude of the aggregate loss is much less for the lightweight aggregate than for the granite 78M at all EARs, even when comparing the aggregate loss percentage at the respective optimum EAR. Even at high PUC values, the aggregate loss percentage is low for the lightweight aggregate, indicating that lightweight aggregate is a better material for chip sealing compared to granite aggregate.

The data shown in Figure 20 and Figure 21 for the two different aggregate types serve as evidence of the appropriateness of the PUC as an effective AQC that relates to aggregate loss performance.

In addition to the lower magnitude of aggregate loss shown in Figure 21, the significantly lower density of the manufactured coarse lightweight aggregate particles (compared to other coarse aggregate such as granite) mitigates the risk of windshield damage, etc. due to aggregate loss. In short, the use of superior materials such as lightweight aggregate is proven to reduce the risk of aggregate loss and damage significantly. Therefore, the use of lightweight aggregate is encouraged in the developed specifications if other performance properties of the lightweight aggregate, such as strength and resistance to abrasion, are satisfactory. Also, the development of an incentive for the use of superior materials is a recommendation for future research.

After using the cumulative distribution model to predict the percentage of aggregate loss from the PUC, appropriate values for the a and b parameters were found such that these parameters could be held constant. Holding a and b constant, the model was used to solve for the $\%AggLoss_u$ parameter, which represents the asymptotic behavior of the PUC versus aggregate loss curves. The $\%AggLoss_u$ parameter is the critical model parameter for the purposes of this analysis because the asymptotic aggregate loss value is the critical performance measure for chip seal treatments in the specifications. In Figure 23, the $\%AggLoss_u$ is plotted as a function of the changing EAR as a percentage of the optimum EAR. This figure shows that the $\%AggLoss_u$ has a relationship with the percentage of the optimum rate such that, as the EAR decreases below the optimum rate, the $\%AggLoss_u$ model parameter (or asymptotic aggregate loss prediction) increases, as expected.

Figure 23, Figure 24, and Figure 25 respectively present the three model parameters, $\%AggLoss_u$, a, and b, plotted as functions of the percentage of the optimum EAR.

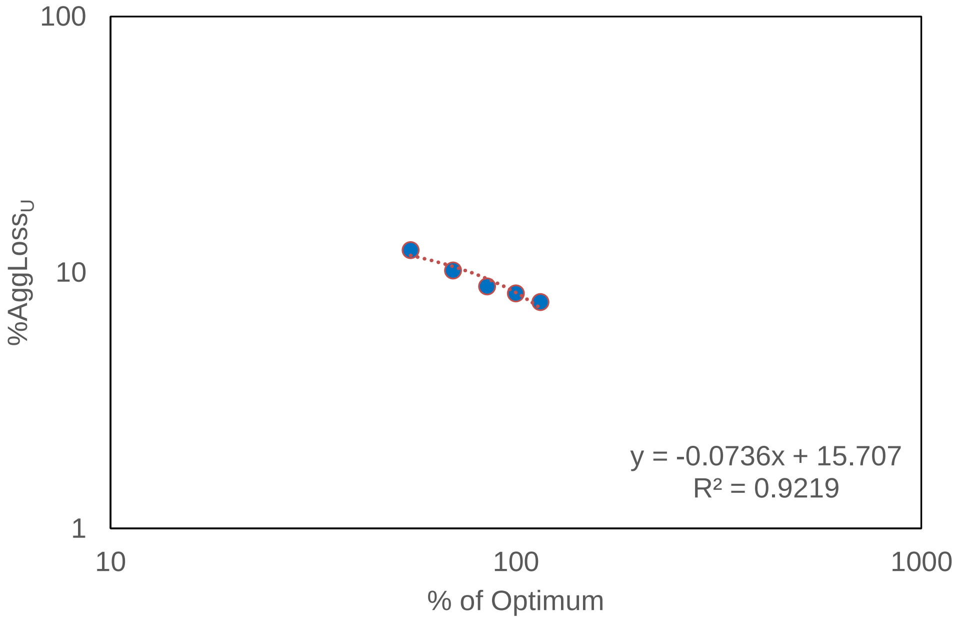

Figure 23. Model parameter *%AggLoss*$_u$ plotted as a function of percentage of optimum EAR.

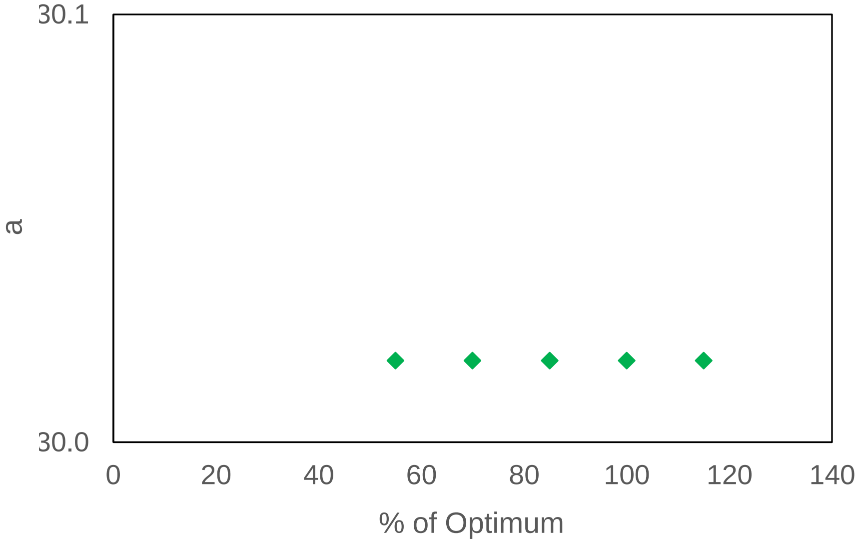

Figure 24. Model parameter *a* plotted as a function of percentage of optimum EAR.

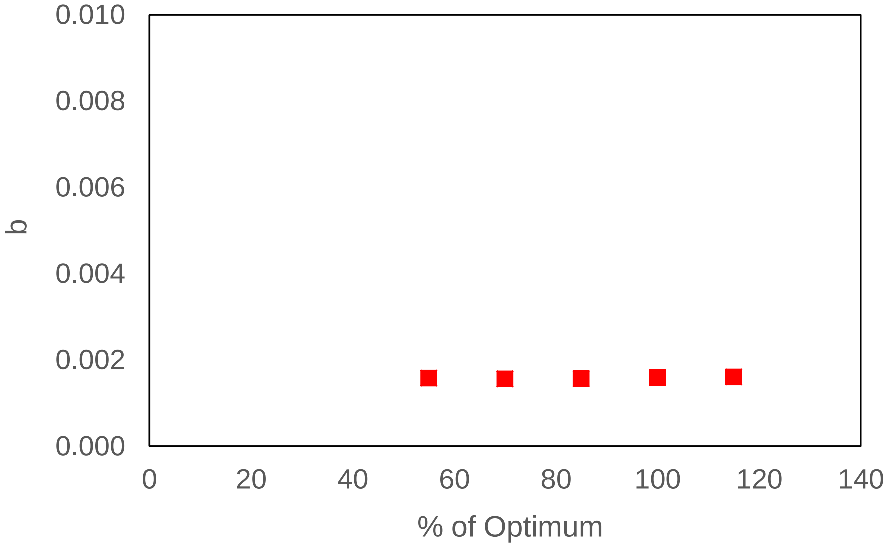

Figure 25. Model parameter *b* plotted as a function of percentage of optimum EAR.

4.3.1. Performance Uniformity Coefficient Threshold Limit Determination

The approach used to determine the PUC threshold limit for the specifications is based on the concept that 100 percent of the optimum EAR (which is based on performance-based mix design) yields the appropriate baseline for aggregate loss. Performance-based mix design has been proven to minimize simultaneously both the potential for aggregate loss and bleeding problems in chip seal mixtures (Adams and Kim 2011). Figure 26 presents the approach used to develop threshold values for the PUC.

The asymptotic aggregate loss for chip seal specimens designed at 100 percent of the optimum EAR and exactly at the optimum AAR of 15.5 lb/yd^2 yields an aggregate loss limit of just above 8 percent, which is slightly below the 10 percent aggregate loss threshold typically used to assess chip seal aggregate loss performance (McHattie 2001). Figure *26* presents a visual representation of this concept. The horizontal dashed line represents the asymptotic percentage of the aggregate loss for 100 percent of the optimum EAR curve. The points at which the curves for the other percentages of the optimum EAR cross this horizontal dashed line reveal the appropriate PUC threshold values for the respective curves. Using this approach, the maximum PUC (or minimum allowable aggregate gradation uniformity) for satisfactory performance is a function of how close the measured EAR is to the optimum EAR. This approach is practical, because a chip seal with an EAR below the optimum EAR requires better, more uniform aggregate to obtain the same aggregate loss/retention results as a seal with an EAR that meets the design requirements. For example, the approach shown in Figure 26 indicates that for the green curve developed for chip seals with a measured EAR at 85 percent of the optimum EAR of 0.2 gal/yd^2, the maximum allowable PUC is approximately 32, whereas the red curve denoting chip seals at 55 percent of the optimum EAR has a more restricted maximum allowable PUC of approximately 24 to indicate acceptable performance.

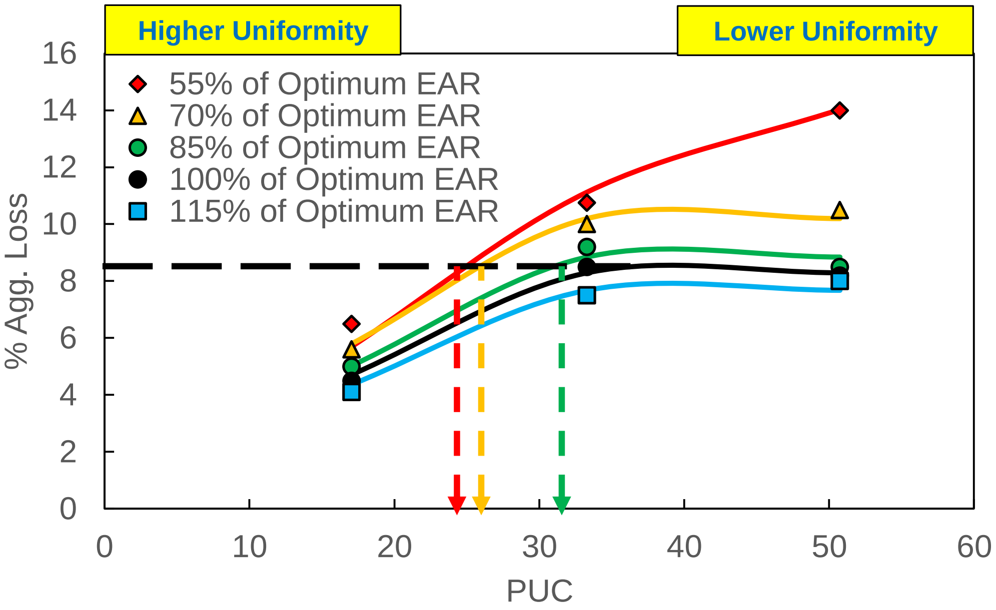

Figure 26. Approach used to develop threshold values for the PUC AQC based on design rates.

Also, the graph presented in Figure 26 indicates the margin for error at various PUC values. If a contractor constructs a chip seal using aggregate that has a PUC below 20, the effect of the EAR is less than if the contractor uses an aggregate with a high PUC that is around 50. With a PUC of approximately 50, if the measured EAR is 70 percent or less of the optimum EAR, aggregate loss problems likely will occur. In the past, the NCSU research team has observed measured field-constructed EAR values that are below the design optimum EAR by over 30 percent for the same aggregate and emulsion materials used in these experiments (Adams and Kim 2011).

Figure 26 also reveals that the sensitivity of the aggregate loss to the PUC parameter (i.e., gradation) is related to the EAR and, more specifically, to how close the measured EAR is to the design optimum EAR. This observation helped to provide threshold values for the aggregate and emulsion utilized in this research; however, more research is needed in the future to establish PUC threshold values that can be verified as appropriate for a wider range of emulsion and aggregate combinations.

4.4. Determining Thresholds and Quality Limits for Acceptance Quality Characteristics

The steps for establishing threshold limits for the AQCs and quality measures are as follows. These steps are applied to actual chip seal field sections constructed in previous NCDOT projects in the next section.

1. Determine relationships between AQCs and performance. The aggregate loss measured from the Vialit test and the gradation effects (represented by the PUC) demonstrate the Vialit test's ability to predict the key performance measures associated with chip seal treatments. Thus, in this project, the relationships between each AQC and performance were established based on Vialit testing and the PUC.
2. Set specification limits. Initial specification limits for the AQCs were determined based on laboratory and field performance data as well as engineering judgement. The research conducted herein provides an example and framework for construction acceptance specifications, although final test limits require refinement and validation prior to implementation.
3. Decide on a quality measure. The recommended quality measure for chip seals was decided as the 'percent within limits' (PWL).
4. Define acceptance quality limits (AQLs). The upper AQL for chip seal treatments is recommended to be a PWL of 90, based on typical AQL values. That is, 90 percent of samples from a lot must pass the AQC specification limit to receive 100 percent pay.
5. Define rejection quality limits (RQL). The RQL is recommended to be a PWL of 60, based on the typical range of RQL values. That is, 60 percent of samples from a lot must pass the specification limit to be eligible for reduced pay.

4.5. Determining 'Percent Within Limits' for Chip Seal Field Demonstration Sections

The PWLs were calculated for chip seal field sections used in previous NCDOT projects that were constructed on roadways at various traffic levels in order to provide a demonstration example of how the PWL concept would work in practice. Table 16 presents the Vialit test aggregate loss results that were used to determine the PWL values. These PWL values were then used to determine whether the contractor for a sample lot would receive full pay, reduced/partial pay, or if the work would be rejected (i.e., no pay for the contractor) in the construction performance-related specification framework.

Table 16. Vialit Test Aggregate Loss PWL Values

Section ID	Traffic Volume	Upper Spec. Limit	Avg. Loss	Std. Dev.	Q	Sample Size	PWL	Pay Conclusion
MD-1	4500	15	11	2.54	1.57	9	95.2	Full Pay
MD-2	4500	15	8.4	1.46	4.52	9	100	Full Pay
MD-3	4500	15	12.2	2.1	1.33	9	91.4	Full Pay
MD-7	4500	15	2.8	0.84	14.52	9	100	Full Pay
MD-8	4500	15	4.2	1.03	10.49	9	100	Full Pay
MD-9	4500	15	1.8	1.4	9.43	9	100	Full Pay
MD-10	1000	17.5	7.3	1.67	6.11	9	100	Full Pay
MD-11	1000	17.5	9.2	3.1	2.68	9	100	Full Pay
MD-12	1000	17.5	13.6	1.75	2.23	9	99.7	Full Pay
MDV-1	2000	17.5	10.2	1.1	6.64	9	100	Full Pay
MDV-2	2000	17.5	16.7	2.7	0.30	9	59.5	<60 Lot Rejected

4.6. Establishment of a Sampling and Measurement Plan

The risks associated with accepting or rejecting a particular lot are related to sample size. The procedure for developing guidelines for a sampling and measurement plan for chip seal treatments is as follows:

1. Determine which party is to perform the acceptance testing. This decision must be agreed upon by the contractor and the NCDOT.

2. Determine the type of acceptance plan to be used. Stratified random sampling, which is a modified version of random sampling commonly used for pavement construction acceptance sampling, is recommended. This type of sampling involves dividing lots into several sublots of equal size (Freeman and Grogan 1998). Random samples are taken from within each sublot with stratification, thus ensuring that the sampling is spread evenly throughout the entire sublot. Freeman and Grogan (1998) outline three rules of stratified random sampling:

    1) An equal number of samples is taken from each sublot.
    2) The sublots are of equal size.
    3) Samples are selected randomly within each sublot.

3. Develop verification sampling and testing procedures. Verification sampling is a standard procedure that is used to verify the accuracy of acceptance test results. The decision whether to use split or independent sampling is dependent on the goals of the particular agency. For this example, it is assumed that the agency or an independent third party will measure the Vialit test

aggregate loss at the recommended sampling frequency for each sublot for verification. In practice, it is appropriate that the agency's verification test methods are used solely for verification and that acceptance methods proposed by the contractor must first be compared to the results of the agency's verification tests.

4. Select an appropriate verification sampling frequency. The verification sampling frequency of the agency should be approximately 10 percent of the acceptance sampling rate of the contractor. In practice, the verification testing frequency is decided for economic, rather than statistical, reasons. Again, this decision must be agreed upon by the agency and the contractor.

5. Determine lot size and sample size. The evaluation of the aggregate loss AQC, for example, involves the extraction of field samples for Vialit aggregate loss testing in a temperature-controlled laboratory environment. Therefore, lots and sublots should be defined logically as segmented lengths of a project. For aggregate loss testing, the recommended lot length is 5,000 feet. Sublot lengths from which stratified random samples are taken are recommended to be 100 feet. The risks associated with sampling depend on the sample size. Based on previous chip seal field research results, nine samples should be taken from each sublot for the Vialit aggregate loss AQC (Kim and Adams 2011). However, in practice, it is not reasonable to take nine samples from each sublot throughout the entire lot, because this effort would be time-consuming and transporting so many samples for laboratory testing would be difficult. Therefore, it is recommended that three sublots should be selected randomly from the lot for sampling. However, individual agencies may increase the number of sublots sampled to minimize risk if sufficient resources and personnel are available.

For the evaluation of the PUC AQC, current agency practices include gradation measurements taken at the aggregate quarry to ensure that the aggregate specified in the chip seal contract meets the gradation requirements. Therefore, because the PUC is determined directly from the aggregate gradation, no field sampling is required. Current quality control checks of gradation should be maintained, and the PUC can be checked using the gradation data.

4.7. Development of Pay Adjustment Factors

Pay adjustment factors are necessary in an acceptance plan for the performance-related specifications. However, establishing pay reduction factors to determine partial pay using typical approaches that are based on the reduction of chip seal service life is not appropriate for performance measures such as aggregate loss, which is the most critical distress for chip seal treatments (Lee 2007). That is, most aggregate loss occurs within the first days and weeks that a chip seal is in service, but aggregate loss early in the life of the seal does not necessarily lead to a reduction in the service life of the seal, as observed in field sections constructed in previous research (Im 2013). Therefore, the NCSU research team obtained the opinion of pavement maintenance practitioners with state highway agencies to provide pay adjustment factor recommendations as a starting point for the development of an acceptance plan for the performance-related specifications. These recommendations should be validated in a rigorous manner prior to implementation.

4.7.1. Vialit Aggregate Loss

The key issue with aggregate loss is the associated vehicular damage (and subsequent claims) that can occur and the resultant public perception of chip seal treatments as an ineffective treatment alternative. Another problem with aggregate loss is that it is one of the leading causes of bleeding (Lawson 2006). Given the established maximum specification thresholds of 20 percent, 17.5 percent, and 15 percent aggregate loss for low, medium, and high traffic levels, respectively, a set of samples for a lot that fails to meet the AQL of 90, but exceeds the RQL of 60, should yield only partial pay for the contractor. In this study, a relationship between aggregate loss and pay factor could not be developed fully based on existing data because quantifying the effect of aggregate loss on bleeding failure, as well as on public perceptions/satisfaction with the quality of the sealing work, is difficult. However, simply as a starting point for these specifications, the research team surveyed pavement maintenance practitioners from state highway agencies to obtain recommendations for reasonable partial pay factors for PWLs ranging from 60 to 90. The survey results were averaged and rounded to the nearest 5 percent. Table 17 presents the survey results as a function of the PWL.

Table 17. Pay factors for Aggregate Loss AQS

PWL Range (%)	**Pay Reduction (%)**
90-100	Full Pay
75-90	25% Pay Reduction
60-75	50% Pay Reduction
0-60	Reject; No Pay

Also, the survey respondents unanimously recommended, and the opinion of the researchers supported, that the contracted party also should be responsible for addressing any vehicle damage claims at no cost to the state highway agency. Thus, the factors listed in Table 17 reflect the recommendations of experienced bituminous supervisors with previous experience overseeing chip sealing operations for state highway agencies and those of the research team. However, final pay reduction factors should be adjusted in accordance with additional research findings and agreed upon by the NCDOT and contractors. Table 17 thus provides examples of how pay/penalty factors could be employed for the aggregate loss AQC based on the demonstrated performance of samples obtained from a lot tested within this performance-related specification framework.

5. REVIEW OF QUALITY CONTROL/QUALITY ASSURANCE CERTIFICATION PROGRAMS

As part of this NCDOT project, the NCSU research team reviewed the quality assurance (QA) programs of two of the states adjacent to North Carolina, i.e., South Carolina and Virginia. This section also provides a table that summarizes the QA certification programs of several other states.

5.1. South Carolina Department of Transportation Certification Program for Pavement Preservation

The current South Carolina Department of Transportation (SCDOT) technician certification policy for pavement preservation work, updated most recently in 2014, is intended to ensure that all SCDOT technicians are properly qualified to test and inspect materials and pavement preservation treatments for the SCDOT. The SCDOT asserts that the certification of technicians is designed to improve the consistency and quality of both laboratory and field test results.

The SCDOT technician field certification program falls under the direction of the SCDOT Technician Certification Board. This board was empowered by the SC State Highway Engineer in April 1994 to investigate and act on all matters, issues, and controversies pertaining to QA programs. Members of the SCDOT Technician Certification Board include the Director of Construction, the Materials and Research Engineer, a representative from the SCDOT's legal section, the District Engineering Administrator, the Chairman of the Pavement Preservation Task Force, the Technician Certification Program Liaison, a representative of the Federal Highway Administration (FHWA), and other chairpersons who lead the Earthwork, Aggregate, and Concrete certification task forces.

SCDOT Technician Certification is required of all personnel who test or inspect construction projects in South Carolina. The certification requirement, as outlined in the SCDOT's 2014 policy, applies to SCDOT personnel, all contractor personnel, and all consulting personnel who perform testing or inspection of SCDOT construction projects or design/build construction projects. The individual technician certification programs and courses are administered by the University of South Carolina and Tri-County Technical College. However, the Pavement Preservation Certification program is offered only at Tri-County Technical College.

Each certification course includes class attendance (mandatory), receipt of a new textbook (even if one was received in the past), and completion of one free examination.

5.1.1. Requirements for Pavement Preservation Certification

The SCDOT Pavement Preservation Certification coursework is intended to provide an overview of pavement preservation construction as well as the testing and inspection of pavement preservation treatments. Following the course, the attendee's competency in the subject area is tested. These courses are not intended to be training courses. Attendees for certification typically include SCDOT, contractor, and consultant personnel who are expected to have sufficient knowledge and experience in the subject matter prior to attending the class and becoming certified. Specifically, the SCDOT requires that each Pavement Preservation Technician Certification applicant has at least six months of documented experience in pavement preservation before attending the course. This experience must be verified via a signed experience form that must be submitted during registration and must include the signature of a person who already holds the certification that the applicant is seeking. The experience form states that the individual has demonstrated to a certified Pavement Preservation Level 1 Asphalt Seal Coat Technician his/her experience in the areas of pavement preservation that are indicated on the signature form. The so-called 'rater', or person who attests that he/she has personally witnessed the qualifications of the applicant, must sign the form for it to be valid. Qualifying areas of experience listed on the form include: monitoring rolling operations, monitoring ambient air and binder temperatures, calculation of binder rates, aggregate rates, and equipment calibration, and familiarity with Sections 406, 407, and 408 of the SCDOT standard specifications. Upon review of the most recent SCDOT standard specifications (last updated in 2007), the NCSU research team found that Sections 406, 407, and 408 cover the materials and construction of single-, double-, and triple-seal treatments, respectively.

The SCDOT Certification Board can waive the six-month experience requirement if the applicant meets certain eligibility requirements and gains an exception from the Certification Board. However, SCDOT personnel are not eligible for the experience waiver. The Pavement Preservation Technician Certification exam is included as part of the training course. The training programs related to pavement preservation offered in South Carolina are summarized in the next section.

5.1.2. Pavement Preservation Training Programs

For pavement preservation inspection/testing technicians, the training programs offered are held only at Tri-County Technical College. These training programs include the following courses: Pavement Preservation Level 1: Asphalt Seal Coats, Pavement Preservation Level 1: Micro/Slurry Seals, and Pavement Preservation Level 1: Concrete Pavements. Each training course takes place over two consecutive days. The first day is a full day from 9 a.m. to 5 p.m., and the second day includes a morning session from 8:30 a.m. to 10:30 a.m. As of September 2015, the fee is $275 per course.

In addition to the fee required for registration in a training course and submission of the signed experience form, each applicant must submit a copy of his/her certification of completion of the Transportation Curriculum Coordination Council (TCCC)/National Highway Institute (NHI) ‘Chip Seal Best Practices’ online course. The online course offerings from the NHI include individual courses that cover topics such as an introduction to pavement preservation, chip seals, fog seals, slurry seals, thin hot mix asphalt overlays, and the selection of the right treatment alternative. The chip seal course, for example, cost $25 per participant in 2016. Topics covered in the one-hour course include project selection, pavement and weather condition requirements, storage, traffic control, construction sequence, aggregate spreading distance, brooming, chip spreading process, distributor preparation, and troubleshooting. Expected outcomes from the online course are that participants should be able to: 1) recognize pavement conditions that are best suited for chip seal treatments, 2) identify ways that proper storage and handling of chip seal materials affect chip seal constructability and performance, 3) describe the construction of a chip seal, 4) identify common problems associated with chip seals and recognize their solutions, and 5) recognize key capabilities and limitations of chip seals. The training draws from the Pavement Preservation Treatment Construction Guide created by the FHWA in partnership with CALTRANS, the National Center for Pavement Preservation, and the TCCC as a resource for agency and industry pavement practitioners. Attendees who pay the course tuition fee and meet the experience and online course completion requirements may take the training course at Tri-County Technical College.

5.2. Virginia Department of Transportation Certification Program for Pavement Preservation

Certification programs are combined for contractors, inspectors, and testing personnel, and are not separated.

5.2.1. Specification Requirements

Special Provision 3-39 in the current Virginia Department of Transportation (VDOT) specifications requires that the Contractor for chip sealing work must have a Certified Surface Treatment Technician present during the placement of surface treatments such as chip seals. Certification is required for any personnel who performs materials acceptance/quality testing or who is required by VDOT specifications to be certified.

5.2.2. Requirements for Technician Certification

Applicants who are seeking to become certified to work with surface treatments can follow either of two processes. The first option is to attend a training course on the topic of surface treatments and then pass a written examination. The surface treatments course costs $200 and is held from

7:30 a.m. to 12:30 p.m. This half-day course covers materials, equipment, placement procedures, and specifications for surface treatment work. The written exam is taken on the same day as the course. The written examination is an open-book test. A candidate must score 70 or above on the written examination to receive a passing score. If an applicant fails the written exam, he/she may retake the part(s) of the exam he/she failed initially. This retake is allowed only one time for each examination. The retake must be completed prior to the end of the calendar year. Once the applicant successfully passes the written examination, the certification is valid for five years; after those five years, an online recertification exam is required. There is no additional cost for recertification.

The second option is that an applicant can seek certification as a ‘self-study student’. This candidate would take the required written examination without attending the full training course. However, the full course fee still applies. If the self-study student fails to pass the examination on the first try, he/she must pay the full course fee for the first attempt and cannot retake the examination without registering for the full course (and again paying the full fee) for certification.

5.3. Nationwide Certification Program for Pavement Preservation

Table 18 provides a summary of the results of an investigation into the QA practices for states that have chip seal programs nationwide. The last row of the table details the NCSU research team’s recommendations for a QA Certification Program for North Carolina.

Table 18. Summary of QA Certification Programs Nationwide

State	Experience Required	Class Length	Exam Required	Passing Score	Fee	Length of Certification	Recertification Requirements	Prerequisites
SC	6 months	1.5 days	Yes	70+ (closed book)	$ 275	5 years	online only	NCCC Online
VA	None	0.5 days	Yes	70+ (open book)	$ 200	5 years	online only	Self-Study Program
GA	No formal technician/contractor certification program. Emulsion Material Testing Certification Only (Sheila Hines, GaDOT).							
TX	No formal certification program. Two types of training offered: 1) Inspector Development Program; and 2) All-day Seal Coat Course (one course for inspectors and a separate course for designers/administrators (Jerry Peterson, TxDOT).							
CA	Contractor's License Program Only. However, a formal technician certification program is under consideration by ISSA (Gary Hicks and Scott Dmytrow).							
IN	No formal certification program. 95% of chip seals constructed in-house by DOT (Todd Shields, InDOT) .							
MN	Formal certification program not yet accepted (Curt Turgeon, MnDOT).							
DE	No formal certification program. Chip seals are constructed in-house by DOT (James Pappas, DelDOT).							
MD	No formal certification program (Woodrow Hood, MDDOT).							
WA	No formal certification program (Tim Rydholm, WSDOT).							
FL	No chip sealing in Florida (Greg Sholar, FDOT).							
NC	**3 mos of chip sealing or 1 mo of related HMA experience**	**1.5 days**	**Yes**	**70+ (closed book)**	**TBD**	**3 years**	**every 3 years (online) and 6 years (on-site)**	**Online course completion**

[a] Transportation Curriculum Coordination Council

6. CONCLUSIONS AND RECOMMENDATIONS

The research described in this report was undertaken to determine whether construction variability issues exist with regard to chip seal treatments and, if so, to identify the effects of variability on pavement performance.

The main conclusions drawn from this research are as follows.

- The material application rates that were measured from the constructed field sections were significantly lower than the targeted design application rates for both the aggregate and emulsion materials applied at all three locations by three different construction crews.
- Although the individual application rates were much lower than the targeted application rates, the constructed chip seals did not exhibit significant performance problems in the field based on the condition survey performed eight months after the construction. The reason for this outcome is that the lower than targeted EARs and AARs seemed to have canceled out the negative effects of having less than adequate amounts of aggregate and emulsion.
- The MMLS3 performance test results for the field chip seal samples showed acceptable aggregate retention for all three test sections. However, the chip seal samples from the Rowan County and Caswell County sections exhibited significant bleeding, with the Caswell County section being the worst. It is noted that the Rowan County and Caswell County sections are double seals with granite #14 as the choking layer at the top, whereas both layers in the Moore County section were made with granite 78M. The under-application of aggregate, combined with the high non-recoverable creep compliance (J_{nr}) values obtained from the MSCR tests, likely explains the substantial bleeding observed in the Caswell County section.
- All the emulsions used in this study met the sprayability and drain-out requirements defined in the EPG specifications.
- The MSCR test results for the emulsion residues correlated with the amount of bleeding on the chip seal specimens that were subjected to MMLS3 loading. The binders with lower MSCR J_{nr} values exhibited better resistance to bleeding under MMLS3 loading than those with higher values, as expected.
- The construction variability test results suggest that test procedures are needed to identify material application rate variability problems in newly constructed sections so that the NCDOT can determine whether or not the failure mechanism for a chip seal treatment is construction-related and requires remedial action by the contracted construction crew. Emulsion testing also should be performed in accordance with the EPG specifications detailed in NCHRP Report 837 to ensure that any observed performance problems are not material-related.

The research conducted in the development of a framework for the construction-related PRS resulted in the following conclusions:

- Vialit testing of extracted field chip seal samples can effectively assess the raveling potential of chip seals for different aggregate types, binder types, design rates, and traffic levels.
- Preliminary PWL values were determined for each AQC to determine if the contractor of a lot will receive full pay (AQC > 90), partial pay (60 < AQC < 90), or no pay (AQC < 60) for chip seal treatments.
- A relationship exists between the aggregate gradation (as represented by the PUC) and the aggregate loss. The PUC can be used to ensure that the aggregate selected for chip sealing meets the gradation requirements that are related to the acceptable performance of chip seals.
- Survey results combined with engineering judgment provided guidance for preliminary pay adjustment factors based on aggregate loss. The preliminary pay adjustment factors require further consideration and NCDOT input.
- The construction-related specification framework recommends that extracted Vialit samples should be used to measure rate variability and to assess aggregate loss and that the PUC, as an indicator of aggregate gradation uniformity, should be used as a pass/fail criterion during regular quality control testing of quarry material.
- Overall, the PRS framework discussed in this report provides procedures that can be used to address construction variability problems that have been observed during chip seal construction efforts in the field.
- The NCSU research team has developed a PRS framework that provides guidance for test procedures that can help identify construction variability problems in the future. These construction specifications are intended to provide practical solutions to help the NCDOT minimize the risk of performance problems in contracted chip seal work.
- The implementation of QA training programs in North Carolina would standardize the knowledge base of NCDOT inspectors and contractors such that a minimum competency level is demonstrated prior to personnel taking part in chip seal construction.
- The chip seal PRS framework, the best construction practices document, and the QA training programs developed in this project should improve the quality of chip seals constructed throughout North Carolina.

The following recommendations are made for future research:

- The performance-related construction specification framework provided in this report should be field-validated by extracting samples from sections statewide and conducting ignition oven and Vialit tests using those samples. Also, the field performance of those sections should be monitored to adjust, as needed, the recommended preliminary threshold values that translate to acceptable performance.

- Additional performance and cost data should be obtained to establish and refine pay adjustment factors based on the percentage of aggregate loss observed from Vialit testing of field samples.
- A sampling and measurement plan should be finalized that measures the critical AQCs that are deemed practical by both the NCDOT and the contracted personnel who typically construct chip seals in the State. The goal of this plan is to strike the appropriate balance between not testing enough, which increases risk to the NCDOT, and testing too rigorously, which causes practical problems in terms of increased costs, traffic closings, and specimen testing time.
- A QA training program should be developed and implemented to standardize the education of personnel who are involved in chip seal construction.

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APPENDIX A SYNTHESIS OF CHIP SEAL CONSTRUCTION BEST PRACTICES

This appendix provides a synthesis of best practices based on the NCSU research team's experience and knowledge that have accumulated over a series of chip seal research projects sponsored by the North Carolina Department of Transportation (NCDOT).

A.1. EFFECTS OF EXISTING CONDITIONS ON PERFORMANCE

A.1.1 Pre-Existing Pavement Surface Conditions

The performance of a chip seal treatment is highly dependent upon the condition of the existing surface onto which the seal is to be constructed. The North Carolina State University (NCSU) research team recommends that, if possible, existing surface problems should be corrected/repaired prior to chip seal construction.

A.1.1.1 *Cracking*

Chip sealing is most effective before transverse or longitudinal cracks become wider than 1/8 inch (3.175 mm). In cases where small cracks are present, chip seals can fill the cracks and prohibit crack propagation up through the pavement surface. However, once the crack exceeds the 1/8-inch width, the residual asphalt is less effective at filling the cracks, and the crack is likely to propagate up through the chip seal within the first year, as observed in various chip seal sections, such as those sections constructed during the NCDOT HWY 2013-03 research project. In cases where significant cracking is present, a crack sealant should be utilized to fill the crack prior to chip sealing. By sealing existing cracks prior to chip sealing, emulsion cannot enter those cracks, and thus, the potential for under-embedment of the aggregate layer is mitigated. As a general rule, cracks should be sealed at least three months prior to chip sealing in order to allow the crack sealant to cure properly (Spray Sealing Guide 2004).

When fatigue cracking is significant or is present in over one-third of the pavement surface (which is a criterion defined by the Federal Highway Administration's Pavement Preservation Emulsion Task Force), a chip seal should not be applied without repairing the existing pavement, as this seal type will not correct the structural problems that are present in the pavement system. Fatigue cracking is an indicator of a weak subgrade and must be corrected prior to any chip sealing. A chip seal, when constructed on a structurally sound existing pavement structure, will effectively reduce moisture infiltration into the subgrade, which will help avoid future subgrade failure.

A.1.1.2 *Potholes and Rutting*

Potholes should be filled and significant rutting should be leveled prior to chip sealing, as these pavement distresses cannot be corrected by chip sealing alone. As a general rule, patching should be completed at least six months prior to chip seal construction (Gransberg et al. 1998).

A.1.1.3 *Bleeding/Flushing*

By constructing a chip seal on an existing surface that has bled/flushed, the friction and skid resistance that have been compromised due to bleeding/flushing can be regained at the surface level. However, the emulsion application rate (EAR) should be lower than that which is typically used on a non-flushed existing surface, as the aggregate applied during the new chip seal construction will embed into the residual asphalt that covers the existing bled surface. This embedment will take place because a flushed pavement surface is often soft and unable to resist aggregate embedment during compaction and traffic loading. The ball penetration test (described later in this appendix) has been proven to be a useful tool for measuring the penetration potential of an existing soft surface. Figure A-1 shows an image of a bled surface.

Figure A-1. Bleeding due to heavy truck traffic and hot weather (Lawson et al. 2007).

Bleeding and flushing typically occur in the wheel path, and thus, care must be taken when applying a chip seal over a flushed surface because the non-flushed areas outside the wheel path will require a different material application rate than the flushed wheel path. In order to accomplish this task, an emulsion distributor with a variable rate spray bar should be used in order to apply less emulsion onto the flushed areas of the road. Care should be taken also to ensure that the aggregate type that is selected to be applied onto a flushed surface can be embedded adequately and retained by the reduced amount of emulsion that is applied to the flushed surface.

A.1.1.4 *Existing Surface Texture*

The texture or roughness of the existing pavement surface on which a chip seal is to be constructed can affect the amount of emulsion that is needed in order to embed the applied aggregate chips. A rough pavement surface will absorb more of the applied emulsion than a smooth surface and may require additional emulsion in order to embed and retain the applied aggregate. The texture of the substrate pavement should be evaluated prior to chip sealing in order to determine whether an adjustment to the design EAR is needed.

Conversely, if the existing surface is flushed, the amount of applied emulsion should be reduced in the bled areas. Bleeding occurs typically in the wheel path and creates non-uniform surface texture transverse to the centerline. Therefore, a distributor with a variable rate spray bar should be utilized to adjust the applied EAR as needed.

A.1.2 Pavement Geometry

A.1.2.1 *Grades and Curves*

Steep grades and super-elevated road curvatures may adversely affect pavement performance due to tractive forces and slow-moving vehicles. Therefore, traffic control should remain in place long enough to allow the emulsion to cure sufficiently to avoid premature aggregate loss in these areas.

A.1.2.2 *Intersections*

Aggregate loss and bleeding can be problems at intersections due to the acceleration, deceleration, and turning that occur near both unsignalized and signalized intersections. Traffic control should remain in place until these areas have cured sufficiently and the bond strength between the asphalt residue and the aggregate is near its maximum value.

A.1.3 Traffic Considerations

A.1.3.1 *Traffic Classes*

Traffic will be categorized in terms of average annual daily traffic (AADT) according to the following classes for roadways to be chip sealed:

- Class I (low traffic) = AADT less than 500 vehicles
- Class II (medium traffic) = AADT 501 to 2500 vehicles
- Class III (high traffic) = AADT greater than 2500 vehicles

A.1.3.2 *Chip Sealing High-Volume Roadways*

It has been demonstrated that chip seals can be constructed successfully on highways with AADT per lane of over 20,000 vehicles without experiencing performance problems such as aggregate loss that can lead to vehicle damage or bleeding. However, when constructing chip seals on high-volume traffic pavements, other factors must be considered. For example, noise increases with increases in traffic volume, traffic speed, and aggregate size on chip-sealed roadways. Therefore, smaller aggregate often is desired for high-volume traffic roadways. However, the margin for error increases as the aggregate size decreases because the amount of emulsion required to reach the target embedment depth for aggregate retention decreases; thus, it is easy to apply too much emulsion and yield subsequent bleeding problems on arterials with high traffic volumes.

Another key consideration for chip sealing on roadways with high traffic volumes is that aggregate with a uniform gradation, at least two crushed faces, high durability (as measured by the Los Angeles Abrasion Test), and low dust proportion should be used. In addition, polymer-modified emulsions are recommended for high-volume traffic situations as these emulsions have performed well consistently in performance evaluations under both field and laboratory traffic loading conditions. Previous research by Im (2013) indicates that, for high-volume traffic roadways, defined as more than 2500 vehicles per day per lane, modified emulsion is required for the sufficient retention of aggregate particles. Research also indicates that modified emulsions provide significantly greater aggregate and bleeding retention capabilities under both laboratory and field traffic loading than unmodified emulsions that performed poorly under identical loading conditions. Also, performance-based mix design should be used to ensure an appropriate design and initial embedment. Lastly, optimal construction practices (e.g., optimized roller types/patterns, a proper traffic opening time, sweeping protocol, etc.), as defined in this document, should be utilized to ensure construction quality.

For best performance at high traffic volumes, the NCSU research team recommends to spray/fog-seal over chip-sealed areas after sweeping and before making permanent pavement markings, but no sooner than 24 hours after final rolling. The emulsion should be diluted to a 50/50 emulsion-to-water ratio at the place of manufacture. The diluted emulsion should be applied at an EAR of 0.06 to 0.12 gal/yd^2. Also, the construction crew should construct a 100-foot test strip for fog seals in order to adjust the application rate as needed. Traffic must not be allowed on the fog seal until it has cured to prevent the emulsion from tracking onto vehicle tires.

A.1.3.3 *Residential*

Chip seals that have been constructed with large aggregate particles are rough and can lead to poor ride quality, lack of friction, and skin abrasions when falls occur. Bicyclists and skaters often complain about chip seals because of the rough surface texture that can cause injury after a fall and that affects ride quality.

A.1.3.4 *Rural*

Areas of chip seals that are subjected to frequent vehicle braking and accelerating can negatively affect chip seal performance. Therefore, rural settings are most ideal for chip seal treatments because traffic tends to flow more consistently with less stopping and starting than in urban settings. Also, because rural traffic volumes tend to be lower than urban traffic volumes, the separation between passing vehicles tends to be greater, resulting in less opportunity for vehicle damage due to dislodged aggregate particles.

A.1.3.5 *Urban*

Urban environments often are considered to be less than ideal for chip seal treatments not only because of high traffic volumes, but also because more turning, decelerating, and accelerating occurs. Although chip seals can be constructed in urban environments with success, the lane closure time required for emulsions to gain sufficient strength to resist the turning, acceleration, and deceleration of vehicles in large volumes is often too long and thus precludes their use.

A.2. MATERIALS SELECTION AND DESIGN

A.2.1 Aggregate Selection

Aggregate particles that interlock after construction, rolling, and early trafficking can provide stability under loading. This interlocked aggregate surface is more resistant to displacement than a looser aggregate surface and thus has less potential for the dislodgement of chips, which, in turn, reduces the potential for vehicle damage and bleeding.

Aggregate with a high nominal maximum aggregate size value requires a higher EAR in order to provide an equivalent embedment percentage when compared to smaller aggregate. This higher EAR allows slightly more room for error during construction with respect to the depth of the chip embedment in the binder. Also, the higher binder application rate provides greater sealing ability.

Aggregate particles that are retained between two adjacent sieve sizes provide the best interlock. The next best are those that occupy the space between three adjacent sieve sizes. These aggregate particle distributions often are described as one- and two-sized aggregate chips, respectively. The reason that one- and two-sized chips perform well is related to the manner in which the chips are embedded in the emulsion. If well-graded aggregate with fines is used, the fine portion of the gradation often enters the emulsion before the coarse portion, which means that the coarse aggregate chips have less binder available for adhesion. The result can be a loss of the coarse portion, thus leading to vehicle damage and bleeding, because the fine portion is inundated with binder.

Aggregate that is selected for chip sealing must not contain leaves, wood, or other deleterious materials. The aggregate material also should be durable and uniform. Table A-1 provides the gradations and quality requirements specified for chip seals. All of the listed passing percentages are by weight. The aggregate size to be used in the chip seal would be provided in the contract/plans. Aggregate retained on the 4.75 mm (No. 4) sieve must be crushed by mechanical means in order to meet the requirements listed in Table A-2.

Table A-1. Chip Seal Aggregate Gradations

Sieve Size	Passing, %
¾”	100
½”	98-100
3/8”	5-30
No. 4	20-45
No. 8	0-15
No. 16	-
No. 30	-
No. 50	-
No. 200	0-0.6

Flakiness index, max. % (FLH T 508)*	25

*In accordance with Federal Lands Highway (FLH) T 508 in the Minnesota DOT seal coat handbook.

Table A-2. Aggregate Fracture and Abrasion Requirements

PROPERTY	CHIP SEAL TRAFFIC CLASS*		
	I	II	III
FRACTURE, 1 FACE, %	70	85	95
FRACTURE, 2 FACES, %	60	80	90
LOS ANGELES ABRASION TEST, MAX. % LOSS, AASHTO T 96	37	35	30

*Class I is less than 500 AADT, II is 501 to 2500 AADT, and III is greater than 2500 AADT.

In high-volume traffic situations or situations where a significant number of heavy vehicles is expected, larger than typical aggregate is recommended for existing soft pavement surfaces (e.g., previously bled/flushed existing chip seal surfaces). These larger aggregate particles are less likely to become totally embedded into the existing pavement surface under heavy truck traffic loading when constructed on soft substrates. Also, larger aggregate particles increase the sealing ability of the chip seal as more emulsion is required to embed these larger chips. However, larger aggregate particles also provide a higher risk of damage if they become dislodged from the seal during or after construction.

A.2.1.1 *Dust Proportion*

The proportion of dust, or the percentage of total aggregate by weight that passes the No. 200 sieve, should not exceed 0.6 percent. A proportion of dust that exceeds this threshold can cause a lack of adhesion of the emulsion to the aggregate during construction, potentially resulting in aggregate loss.

Emulsified asphalts can be produced with the ability to coat aggregate chips that contain small quantities of aggregate that pass the No. 200 sieve. The maximum amount of this fine aggregate depends on the emulsion. For example, medium-setting emulsions can tolerate a higher percentage than most rapid-setting emulsions. This capability is often related to the demulsibility of the emulsion. The greater the demulsibility, the less material passing the No. 200 sieve that can be tolerated before setting and loss of adhesion to the coarse chips occurs.

A.2.1.2 *Moisture Content*

Laboratory testing using the sweep test method (documented in Appendix B of the *Manual for Emulsion Based Chip Seals for Pavement Preservation*) found that aggregate in the saturated surface dry condition provides better adhesion than oven-dried aggregate (Shuler et al. 2011). Most aggregate used for chip seal construction is in a damp condition. However, care should be taken if using aggregate with excess surface moisture beyond the saturated surface dry condition recommended for chip sealing.

A.2.1.3 *Durability*

Aggregate must have enough strength to resist being crushed during construction and trafficking. Breakdown of the aggregate during construction and trafficking could lead to bleeding if significant amounts of coarse particles are reduced to fine particles. Aggregate should meet the durability requirements outlined in Table A-2.

A.2.1.4 *Porosity*

Porous aggregate will absorb more asphalt than non-porous aggregate. Such absorption will negatively affect performance only if the amount of asphalt absorbed into the porous aggregate is not accounted for during the design stage, thus leaving less binder available to hold the chips in place. Porous aggregate in the context of chip seals is defined as aggregate with absorption exceeding 2 percent, as determined using ASTM C127 and ASTM C128. If the aggregate absorption exceeds 2 percent, an adjustment of 0.02 gal/yd^2 of emulsion is recommended (McLeod 1971).

A.2.2 Asphalt Emulsion Selection

Much of the performance of a chip seal is dependent upon the properties of the asphalt emulsion used. The performance properties of the asphalt emulsion during storage and transport and the emulsion application process immediately after opening to traffic and later in the life of the seal are critical to the overall quality of chip seal performance. Performance is related to emulsified asphalt material properties that provide the following characteristics:

- the stability of the emulsion during storage to resist separation and premature breaking;
- the viscosity of the emulsion during and immediately after emulsion application to resist streaking;
- the adhesion of the emulsion to the aggregate under both dry and wet conditions to resist raveling;
- the viscoplasticity of the binder at high temperatures to resist bleeding; and
- the resistance to cohesive fracture in the binder at low temperatures to resist raveling.

The ability of the binder to resist critical chip seal distresses is governed by these properties that can be measured for a wide range of traffic loading and environmental conditions.

Research conducted under the National Cooperative Highway Research Program (NCHRP) 9-50 research project, *Performance-Graded Specifications for Asphaltic Binders Used in Preservation Surface Treatments*, led to a new emulsion performance grading system that captures the critical emulsified asphalt material properties that are related to key chip seal mixture performance measures for use under design climatic and traffic conditions. Based on the NCHRP 9-50 research, NCHRP Report 837 was published, which includes the proposed chip seal specifications and its associated test methods for measuring the critical material properties that are related to chip seal storage, constructability, and ultimately, performance.

A.2.3 Mix Design

Chip seal design methods fall into one of three categories: 1) empirical design based on the experience of the contractor or bituminous supervisor, 2) design based on calculations that employ an equation or algorithm, or 3) performance-based design. The chip seal design process involves the determination of an application rate for an asphalt emulsion given a certain aggregate to be used, with considerations also for the existing pavement surface type and traffic volume.

Designs that are based on equations and algorithms include the earliest known design method from Hanson (1934/35) and more widely used methods developed by McLeod (1971), Kearby (1953), and Austroads (2004). Ideally, chip seals should be designed using a performance-based mix design method along with calibration for local conditions (e.g., climate, traffic, existing pavement conditions, etc.).

One such performance-based mix design method was developed during the NCDOT HWY-2008-04 project (Kim and Adams 2011) and was validated during the NCDOT HWY-2013-03 project (Kim and Adams 2014). This design method uses laser-based volumetric analysis to determine the EAR that is required to embed the specific aggregate to be used in the chip seal such that the chip seal resists both aggregate loss and bleeding under traffic loading. Chip seals designed using this approach perform well in terms of resistance to aggregate loss and bleeding under both laboratory (i.e., using the one-third scale mobile model loading simulator, or MMLS3) and field traffic loading conditions (Kim and Adams 2011). Figure A-2 presents the performance-based mix design framework. In the figure, V_{total}, $V_{aggregate}$, and $V_{emulsion}$ are the total volume, aggregate volume, and emulsion volume, respectively.

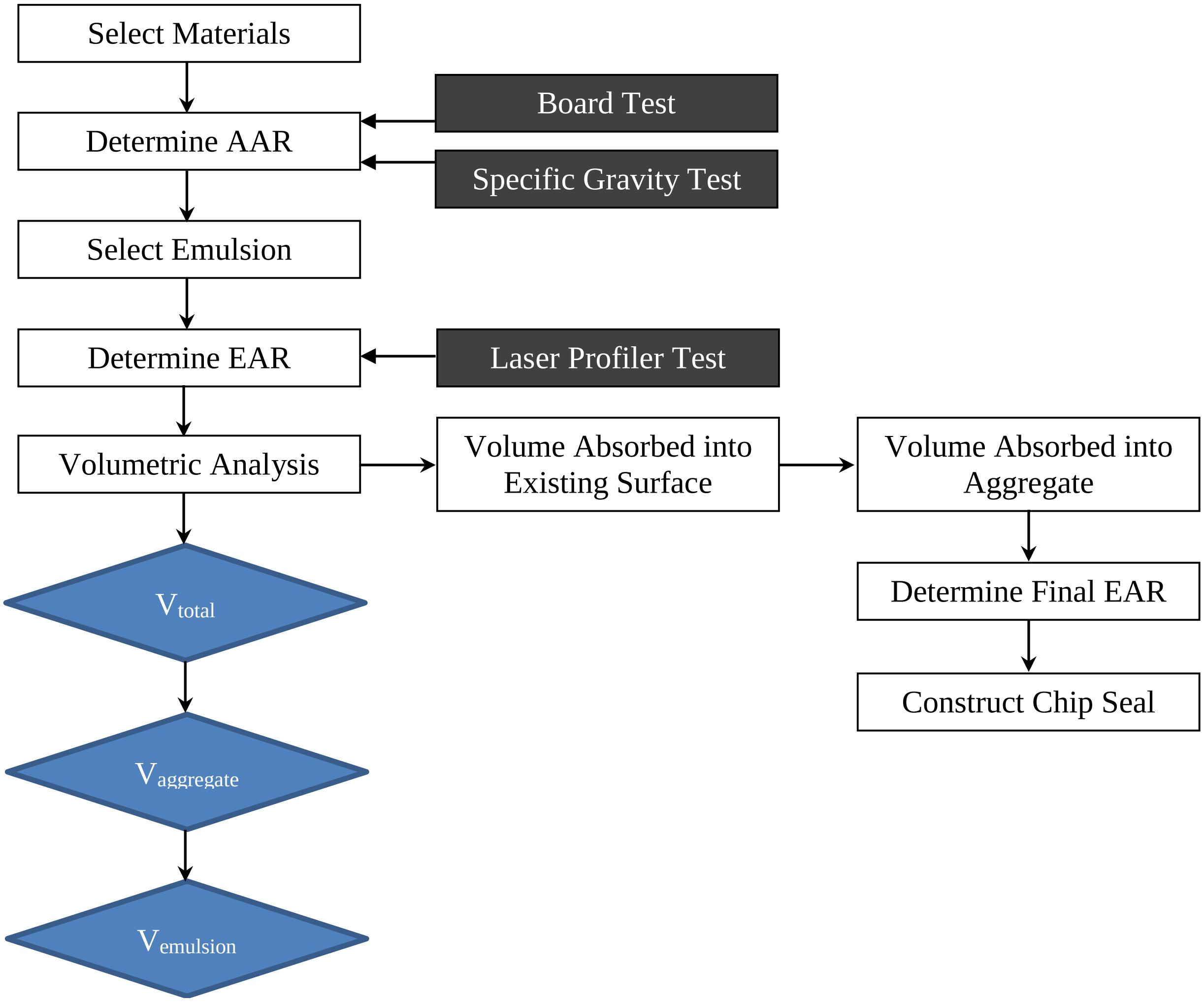

Figure A-2. Performance-based mix design framework.

A.2.3.1 *Design Aggregate Application Rate*

The aggregate application rate (AAR) for each application of a chip seal must be such that the aggregate particles are applied in a tight, uniform manner to provide single-stone coverage per layer. This application is achieved in the performance-based mix design by using a modification of the Kearby board test, which involves spreading aggregate on a 508-mm by 305-mm flat board to achieve the desired uniform single-stone coverage. The AAR (in pounds per square yard) that is required to achieve this single-stone coverage is the design AAR for the chip seal to be constructed using this aggregate. For purposes of volumetric design, the specific gravity of the aggregate is measured using ASTM C127 and C128 for coarse and fine aggregate, respectively.

The proper AAR is critical because insufficient aggregate will not provide the skid resistance that is expected of a surface treatment, and too much aggregate will result in significant aggregate loss and potential injury and vehicle damage and damage claims.

A.2.3.2 *Design Emulsion Application Rate*

The performance-based mix design provides the EAR that is required to obtain 50 percent initial embedment for the specific aggregate to be used in the chip seal. This design method uses a three-dimensional laser profiler to scan the aggregate structure (at 0.3 mm resolution). Then, the subsurface voids are determined for a single-stone aggregate layer by analyzing the three-dimensional data obtained from scanning after the completed modified board test. By using the actual aggregate in its applied state in the laser-based volumetric design, the aggregate size, gradation, flakiness, and average least dimension are all effectively taken into account. This research found that, by determining the EAR that is required to fill the subsurface voids of this aggregate structure, 50 percent initial embedment depth is achieved. The EAR can be adjusted to account for aggregate absorption and the existing pavement surface on which the chip seal is to be constructed.

The EAR must be accurate during construction in order to achieve optimal performance of the chip seal. Too little emulsion will not retain the chips under traffic loading and too much emulsion will lead to bleeding/flushing and loss of skid resistance. The optimal EAR depends on the volume of the voids in the compacted aggregate chip layer, the volume and type of traffic, and the condition of the existing pavement surface.

A.3. PRE-CONSTRUCTION

Before a chip seal can be constructed, certain factors must be known about the pavement upon which the new seal will be placed.

A.3.1 Selecting an Existing Pavement for Chip Sealing

Chip seals are most effective when they are applied to pavements with no significant existing distress, i.e., cracking is minor with widths less than 1/8-inch, rutting is less than 3/8-inch deep, and structural distress is isolated with low severity fatigue. However, when existing distresses are significant, appropriate repairs should be made prior to chip sealing. Chip seals often are used on pavements with significant pre-existing conditions; however, the poorer the condition of the existing substrate pavement, the shorter the life cycle of the new chip seal.

A.3.2 Adjustments for Existing Pavement Substrate Texture

The texture of the substrate pavement must be known prior to chip sealing so that any necessary adjustments can be made to the design EAR. The texture of the substrate can be measured using the three-dimensional laser profiler developed under NCDOT HWY-2013-03, which scans the surface at a resolution of 0.5 mm in directions that are transversal and longitudinal to the traffic direction. The laser scan yields the macrotexture depth and determines the volume of existing surface voids that will be filled by freshly applied emulsion. This method allows for an appropriate adjustment to the EAR to account for the emulsion that will be absorbed into those voids during the emulsion spraying process. Neglecting this ‘lost’ emulsion could result in the under-embedment of the aggregate layer and aggregate loss problems.

A.3.3 Penetration of Chips into Substrate

The substrate pavement should be tested using the ball penetration test to determine if chips are likely to penetrate the substrate pavement after trafficking and to what extent. The ball penetration test, as specified by Transit New Zealand (TNZ) P/17 (New Zealand 2002) involves measuring the penetration of a 19-mm ball bearing into an existing pavement substrate after the ball is struck one time with a Marshall hot mix compaction hammer. In cases where the ball penetration is more than 5 mm, the substrate is deemed to be too soft for a chip seal to be constructed. Substrate softness can lead to deeper embedment of the aggregate than if the surface treatment was constructed on a hard substrate. This deeper embedment of the aggregate increases the likelihood of premature flushing of the surface.

A.3.4 Variability of Pavement Surface

The surface of the existing pavement substrate affects the EAR. If the surface contour varies along the road alignment, the shot rate must change to match these conditions. A map should be provided that indicates the locations where material application rates should change in accordance with the changing substrate conditions. If the variability is found in the longitudinal direction (the direction of traffic), the EAR can simply be adjusted as the emulsion sprayer moves along the roadway. If the variability is in the transverse direction of the roadway (perpendicular to the direction of traffic), variable rate spray bars should be used to apply the emulsion. For example, if the existing surface has bleeding in the wheel path, the EAR would be varied in the transverse direction so that less emulsion is applied in the bled wheel path area than in the non-wheel path area that does not exhibit bleeding.

A.3.5 Pavement Preparation

The substrate pavement must be structurally sound before chip sealing. Areas that show alligator cracking must be patched the full depth of the pavement section using hot mix asphalt before commencing chip seal operations. The surface of these areas should be sprayed with a light application of slow-setting asphalt emulsion diluted 50/50 with water at the recommended rate of 0.10 gallons per square yard or undiluted at the rate of 0.05 gallons per square yard and allowed to cure thoroughly before chip sealing. Failure to apply a fog seal to the surface of the patch may allow the new chip seal binder to be absorbed into the surface of the new patch, thus reducing the amount of binder that is available to retain chips.

The substrate pavement must be cleaned before commencing chip seal operations. Dust and debris on the surface should be removed using power brooms. Power brooms used in urban areas should be of the pick-up type so surface contaminants are not spread onto adjacent properties. Push brooms are sufficient in rural areas when spreading debris onto shoulders or onto adjacent properties so not to cause conflicts with property owners. The surface of the substrate pavement should be damp to dry. A damp surface is acceptable as long as moisture is present only in the surface aggregate voids and is not free moisture between aggregate particles. The appearance of a damp pavement should not be glossy, but should have a dull appearance.

A.4. CONSTRUCTION EQUIPMENT

A.4.1 Emulsion Pressure Distributor

To minimize emulsion application variation from the targeted application rate during construction, the emulsion pressure distributor should have a ground speed control device that interconnects with the emulsified asphalt pump such that the specified application rate can be supplied at any speed. The pressure distributor also should able to maintain the emulsified asphalt at the specified temperature. The spray bar nozzles should produce a uniform triple-lap application fan spray and the shutoff capability should be instantaneous, with no dripping. All nozzles should be oriented at the same angle between 15° and 30° using the wrench supplied by the distributor manufacturer. Each pressure distributor must be capable of maintaining the specified application rate within ±0.015 gal/yd^2.

A.4.2 Aggregate Spreader

For best results, a self-propelled mechanical type of aggregate spreader with computerized spread control should be used to spread the aggregate for a chip seal. The spreader must be capable of distributing the aggregate uniformly to the required width and at the targeted AAR. This self-propelled type of spreader should be mounted on pneumatic-tired wheels.

A.4.3 Rollers

A.4.3.1 *Steel-Wheeled Rollers*

Steel-wheeled rollers can effectively embed aggregate into the emulsion layer, but these rollers often crush the aggregate particles during compaction, which can remove some of the surface texture of the chip seal and reduce skid resistance. Also, any permanent deformation in the wheel paths will not allow these areas to be rolled adequately by a steel-wheeled roller, because the roller cannot conform to the contours of the roadway.

A.4.3.2 *Pneumatic Tire Rollers*

Pneumatic or rubber tire rollers have a tendency to pick up chips due to the propensity of asphalt residue to adhere to rubber tires. However, these types of rollers do not tend to crush coarse aggregate particles as is the case with steel-wheeled rollers.

A.4.3.3 *Combination Rollers*

A combination roller combines the use of a rubber-coated steel wheel drum on the front axle with a single row of rubber tire wheels on the rear axle.

A.4.4 Powered Brooms

Motorized brooms should be employed to control vertical pressure and clean the road surface prior to spraying emulsified asphalt material. Plastic bristle brooms are required to remove loose aggregate after chip sealing, while avoiding damaging the constructed chip seal.

A.5. EQUIPMENT CALIBRATION

Four types of equipment are used for chip sealing: 1) an emulsion pressure distributor, 2) an aggregate (chip) spreader, 3) rollers, and 4) brooms. This document assumes that readers are familiar with these pieces of equipment and their use. However, readers may not be familiar with the calibration of the distributor or chip spreader. Calibration of these pieces of equipment is important to ensure that the quantities of emulsion and aggregate that are applied to the pavement are appropriate and accurate. Although many modern asphalt distributors and aggregate spreaders are computer-controlled, calibration is still needed to 'tell' the computer how much emulsion is actually being applied. So, quantities must be checked prior to spraying emulsion and spreading aggregate and checked against the quantity that the computer (if the distributor is so equipped) indicates is being applied. Once these quantities are verified, the calibrated computer can be utilized for the remainder of the project to confirm the application rates.

A.5.1 Emulsion Pressure Distributor Calibration

The emulsion distributor truck applies asphalt emulsion onto the pavement surface in a uniform manner in both the transversal and longitudinal directions to the centerline of the pavement. The transverse application is uniform only if all the nozzles in the spray bar are the same size, flow at the same rate, are oriented in the same direction, and are the same distance above the pavement.

A.5.1.1 *Nozzle Angle*

The first step in calibrating the distributor is to adjust the spray bar nozzle angles. Each nozzle has a slot cut across the face of the nozzle. When the nozzle is threaded into the spray bar, each slot should be positioned at an angle of approximately 30 degrees to the direction of the spray bar, as shown in Figure A-3.

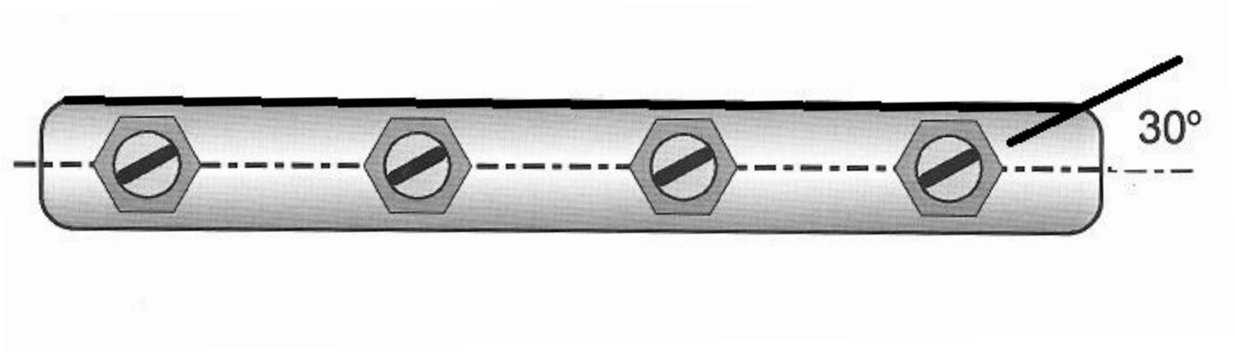

Figure A-3. Nozzle orientation in spray bar (Wood et al. 2006).

The angle of the nozzles should be adjusted using the special wrench supplied by the distributor, as shown in Figure A-4. However, in cases where this wrench is unavailable, a wrench that fits the hexagonal nozzle will suffice, but the angle must be judged visually. The nozzles fitted to the spray bar should be full fan nozzles with the exception of the outer right and left edge nozzles. These nozzles should be half-fan nozzles that are adjusted so that the spray from the nozzle remains to the inside of the spray bar.


Figure A-4. Adjusting nozzle with nozzle wrench.

A.5.1.2 *Spray Bar Height*

The next step in calibrating the distributor is to adjust the spray bar height. If the bar is too high, excess emulsion will form longitudinal ridges on the pavement (sometimes referred to as *roping*). Figure A-5 and Figure A-6 show examples of bar heights that are set too high and too low, respectively.

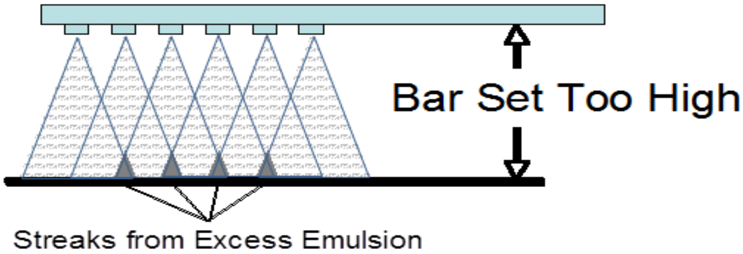

Figure A-5. Streaking resulting from setting the spray bar height too high (Wood et al. 2006).

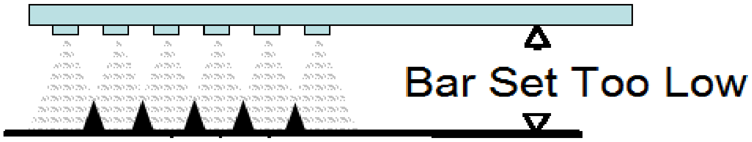

Figure A-6. Streaking resulting from setting the spray bar height too low (Wood et al. 2006).

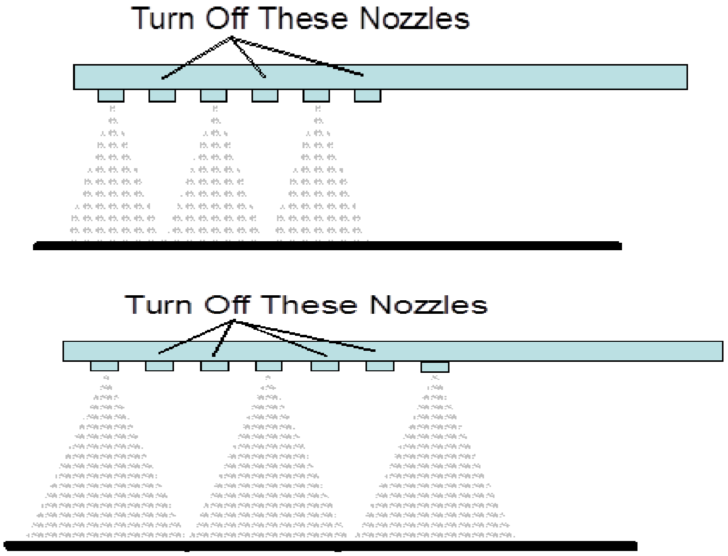

Figure A-7. Examples of turning off spray bar nozzles to achieve even emulsion application (Wood et al. 2006).

Therefore, in order to obtain a uniform, even application of emulsion, the bar must be adjusted to the correct height. The distributor operator should spray emulsion onto the pavement surface for as short an interval as possible while an observer watches where the emulsion hits the pavement from each nozzle that is left open. In some instances, individual nozzles may need to be turned off, as shown in Figure A-7, in order to apply the design EAR properly. Note too that, as the distributor empties during spraying, the bar will rise slightly. However, this rise in height is usually not enough to cause significant streaking that makes it worth adjusting the spray bar.

A.5.1.3 *Transverse Flow Rate*

The nozzle size should be checked by measuring the width of the slot in the nozzle and measuring the orifice diameter. Some nozzles are labeled by the manufacturer, and many manufacturers supply a list of nozzles in the owner's manual that describes which nozzles should be used for various application rates.

However, based on field experience, nozzles of the same apparent size can produce different flow rates. Therefore, all nozzles (i.e., each nozzle to be used for the project) must be checked for flow rate before chip seal operations begin. If the flow rate of any of the nozzles is greater than 10 percent of the average of all the nozzles to be used, these nozzles should be discarded or modified to flow within the 10 percent tolerance.

Determination of uniform lateral flow from the spray bar is determined by collecting a measured volume of emulsion in containers placed under each nozzle. This process is facilitated by using standard 6-inch x 12-inch concrete cylinder molds lined with one-gallon zip-lock freezer bags. The cylinder molds may be reused but the zip-lock bags and their contents should be discarded appropriately (Shuler 1991).

A.5.1.4 *Longitudinal Flow Rate*

The longitudinal flow rate must be measured with all the nozzles inserted in the distributor spray bar. First, the volume of the asphalt emulsion that is in the truck at the time the flow rate measurements are taken must be determined. Although a volume indicator is located at the rear of most modern distributors, typically it is not calibrated in small enough increments to be practical for calibration and should not be used for this purpose. Instead, the dipstick supplied by the distributor should be used as a volume indicator. Prior to spraying the emulsion, an initial volume reading should be taken using the dipstick, as shown in Figure A-8, and then recorded. Then, a minimum length of emulsion spray, 3000 feet by 12 feet, should be sprayed at the design EAR using the gallon per minute pump flow volume and spray truck speed. After the emulsion is applied, a second dipstick reading should be taken and recorded as the end volume. The difference between the initial and end volumes is divided by the area sprayed to determine the EAR that has been applied to the pavement. This value should be compared to that of the distributor computer, if so equipped, to ensure the accuracy of the computer. This calibration effort should be undertaken at the start of each day.

Figure A-8. Recording emulsion distributor tank volume using standard dipstick.

A.5.2 Aggregate Spreader Calibration

A.5.2.1 *Transverse Spread Rate*

Various methods of calibrating the aggregate spreader can be used, and the ASTM D5624 procedure is effective. However, a visual assessment of the lateral distribution of chips is a good place to start the aggregate spreader calibration process because non-uniform distribution often can be observed easily. The uniformity of the 'veil' of the chips that are dropped from the aggregate spreader can be viewed either from the front of the box with the spreader approaching the observer or from behind with the spreader moving away, as shown in Figure A-9. Either position for the observer is adequate for observing the uniformity of the veil of chips as they fall out of the spreader box. Less light coming through the aggregate particles may indicate too many chips, and more light may indicate too few chips. Either instance means that the machine should be stopped, and the gates on the spreader (which contribute to the non-uniformity) should be adjusted for a trial rerun. This procedure allows adjustment to the transverse spread rate. ASTM D5624, *Determining the Transverse Aggregate Spread Rate for Surface Treatment Applications*, is recommended for measuring the amount of aggregate that is being deposited.

Figure A-9. Image depicting a uniform veil of chips observed from behind the aggregate spreader (Wood et al. 2006).

A.5.2.2 *Longitudinal Spread Rate*

Evaluating the quantity of aggregate that is applied after the rate is established is important in order to provide a quantitative baseline for future work. The best evaluation method is to weigh the chip spreader before and after it releases the chips and then calculate the spread rate based on the area covered. However, this method often is not practical. A suitable alternative is to estimate the quantity of the chips that are spread over a known area by weighing each transport truck that supplies the spreader and dividing the estimated weight of the chips spread by the area covered for that load. The following example is taken from the *Manual for Emulsion-based Chip Seals for Pavement Preservation* (Shuler et al. 2011).

Given: Trucks loading the chip spreader are 12-ton capacity tandem dump trucks, on a 12-foot wide pavement, at a 28 pounds per square yard design AAR.

1. Check Truck No. 1
   a. Load = 23,803 lbs
   b. Spreader distance = 213 feet
   c. Rate = 23,803/213 x 12/3 = 27.9 lbs/yd^2
2. Check Truck No. 2
   a. Load = 23,921 lbs
   b. Spreader distance = 211 feet
   c. Rate = 23,921/211 x 12/3 = 28.3 lbs/yd^2
3. Check Truck No. 3
   a. Load = 23,848 lbs
   b. Spreader distance = 213 feet
   c. Rate = 23,848/213 x 12/3 = 28.0 lbs/yd^2
4. Average Rate = (27.9 + 28.3 + 28.0) / 3 = 28.1 lbs/yd^2
5. No adjustment needed because measured rate is within 1 percent of design rate.

This method thus provides a rough estimate of the applied AAR. However, it cannot ensure that variability is not present in the transverse direction along the pavement, so the transverse variability should still be checked.

Moisture on chips must be taken into account when calibrating chip spreaders. No adjustment is needed in the example described above because the measured spread rate is within 0.10 lbs/yd^2 of the design spread rate. However, if the chips had contained as much as 1.02 percent moisture that was not taken into account, the AAR would have been too low.

A.6. CONSTRUCTION OPERATIONS

A.6.1 Environmental Conditions

A.6.1.1 *Ambient Air Temperature*

The minimum ambient air temperature for chip sealing is 15°C (60°F), although temperatures above 21°C (70°F) are recommended for chip seal construction. Ambient air temperatures over

43.3°C (110°F) with sunshine or moderate winds can cause emulsified asphalts to form a ‘skin’ on the surface and may prevent the emulsion beneath the skin to set adequately. Increasing the demulsibility of anionic emulsions helps to remedy this situation in areas where these conditions are common (Shuler 1991).

A.6.1.2 *Windy Conditions*

Wind speeds in excess of 20 mph and transverse to the pavement alignment can disrupt spray fan patterns, thus leading to inconsistent application rates. High winds also can blow asphalt emulsion onto oncoming traffic in two-lane roadways. Therefore, chip seal operations should be avoided under extremely windy conditions.

A.6.1.3 *Rainy Conditions*

Chip seal operations should be avoided under rainy conditions because rainfall could wash away the asphalt emulsion.

A.6.1.4 *Foggy Conditions*

Chip seal construction should be avoided during foggy weather due to low visibility.

A.6.2 Emulsion Application

Prior to construction, the pressure distributor should be calibrated by applying a minimum of 500 gallons of emulsified asphalt onto the roadway and measuring the volume of emulsified asphalt in the distributor using the dipstick supplied by the distributor. Then, the difference between the volumes in the distributor before and after the minimum of 500 gallons is applied is divided by the area of the emulsified asphalt applied. The actual rate applied should be within +/-5 percent of the targeted rate of the chip seal design. After applying the emulsified asphalt, the cover aggregate is applied at the design AAR. If necessary, the AAR can be adjusted so that some emulsified asphalt can be seen between the aggregate chips, but not so much that the aggregate chips adhere to the pneumatic tire rollers. The aggregate in the wheel paths should be visually inspected for proper embedment. Embedment should be 50 percent to 60 percent after rolling. Additional adjustments to the AAR can be made during the project, if needed.

The longitudinal construction joint for a single-layer chip seal must coincide with the painted lane line or the outside edge of the shoulder. The longitudinal construction joint for a double-layer chip seal should have the first layer overlap the painted lane line by 6 inches and the second course should coincide with the original lane line location. A single application chip seal should not have any overlap of the longitudinal construction joint.

Each emulsion application must start and stop on top of 15 lb/yd^2 roofing paper or a similarly dimensioned, equally heavy-crafted paper placed transverse to the centerline of the pavement. The distributor operator should position the spray bar toward the rear of the paper upon take-off so that by the time the bar reaches the pavement the distributor speed is appropriate for the application rate desired. The approximate distance the distributor will travel before reaching the targeted EAR should be calculated at the start of the application. The distributor operator should be instructed to stop spraying when the spray bar has passed over the paper placed at the end of the area to be sprayed.

The temperature of the emulsified asphalt at the time of application must be above 50°C (122°F). Also, it is important to watch for streaking due to clogged spray nozzles during the emulsion application process to ensure a consistent and even layer of applied emulsion at the target EAR.

A.6.3 Aggregate Application

Prior to construction, the aggregate spreader must be calibrated for use in both the transverse and longitudinal directions. First, the lateral spread uniformity should be evaluated by visually observing the flow of aggregate as it exits the spreader box. The spreader must be stopped and the gate openings adjusted if any non-uniformity is observed. ASTM D5624, *Determining the Transverse Aggregate Spread Rate for Surface Treatment Applications*, should be consulted if coarse adjustment is needed for the appropriate gate opening and to determine the flow of the aggregate. Calibration is completed when the actual spread rate matches the targeted design spread rate within +/-10 percent. The longitudinal spread rate is measured using the same procedure by placing one measurement pad directly in front of the spreader at 500-foot intervals for 1,500 feet.

Uniformly moistened aggregate that is damp at the time of placement should be applied immediately (within one minute) after the emulsion has been sprayed. The speed of the spreader should be such that the aggregate chips do not roll prior to compaction. Also, starting and stopping the spreader should be as infrequent as possible. The edges of the aggregate applications should be sharply defined. Previously used aggregate that is swept up may not be returned to the stockpile or spreader for reuse.

Although the mix design is conducted in the laboratory to determine the AAR, adjustments are sometimes needed in the field to ensure that the spreader is applying the appropriate amount of aggregate. The appearance of the aggregate chips can be observed after they have been dropped onto the emulsion, but before rolling. The appearance should be similar to that shown in Figure A-10. Notice that some emulsion is visible between many of the chips, which is desirable, because if emulsion is not visible between the chips (indicating that the AAR is too high), the aggregate particles do not have enough space to reorient after compaction. Conversely, too much emulsion showing through between the aggregate particles indicates an AAR that is too low, which will result in a flushed surface.

Figure A-10. Appearance of aggregate on emulsion prior to rolling.

A.6.4 Optimal Rolling/Compaction Protocol

The initial roller pass should take place as soon as possible, but no longer than two minutes after applying the aggregate. Rolling should proceed in a longitudinal direction at a speed less than or equal to five miles per hour. One pass (or coverage) is defined as the roller moving over the aggregate in one direction. Rolling must be completed quickly enough to embed the aggregate, but before the emulsified asphalt breaks. Rolling should cover the entire width of the treatment area in each pass of the rollers.

A.6.4.1 *Number of Coverages*

The optimal number of roller coverages for chip seals is three. This optimal number of coverages was determined according to aggregate retention test results and aggregate embedment depth measurements obtained by Kim and Lee (2008). Five coverages seem to improve the aggregate retention performance further; however, the extra time needed for the additional two coverages is impractical. For multilayered chip seals, the overarching principle is that one rolling coverage of the layer immediately below the top layer improves the aggregate retention of the top layer (Kim and Lee 2008).

A.6.4.2 *Roller Types and Coverage Pattern*

Use of both the pneumatic tire roller and the combination roller is recommended to improve chip seal performance. With regard to order, rolling should start with the pneumatic tire roller to seat the aggregate effectively (without breaking the coarse aggregate particles). Then, the combination roller is used to produce a smoother, flatter finished texture than could be achieved using the pneumatic tire roller alone (Kim and Lee 2008).

A.6.4.3 *Typical Rolling Distance*

The typical distance to be rolled is 1,000 feet before moving the rolling operation to the next section of the chip seal during construction.

A.6.4.4 *Maximum Rolling Time Allowed*

The time required to roll a chip seal should not exceed five minutes to complete three full coverages of a 1000-foot section. If the seal is not compacted within five minutes, the adhesive bond strength of the seal may not be sufficient, as the emulsion cools and hardens quickly during construction. The rolling time starts the moment the aggregate is applied to the freshly applied chip seal emulsion.

A.6.5 Sweeping

The small quantity of unseated and excess aggregate that remains after rolling and initial trafficking must be swept away no later than one week after chip seal operations have been completed. A power sweeper is preferred, but a vacuum or push broom also is acceptable. Much care is needed for this operation because significant damage to the chip seal can result from harsh sweeping or from sweeping too early in the life of the seal (e.g., on the day of construction before the chip seal has fully cured). Brooms with nylon bristles, not steel, should be utilized for sweeping to avoid dislodging aggregate chips embedded in the seal.

A.7. QUALITY CONTROL

The Contractor should be held responsible for quality control sampling and testing.

A.7.1 Aggregate

A.7.1.1 *Stockpile*

The gradation testing frequency is a minimum of one test per day, or one test per 1,500 tons of material, whichever is greater. If the material is hauled from the production site to a temporary stockpile, then the test should take place at the temporary stockpile. If the results vary from the requirements presented in Table A-1, a price reduction should be applied.

A.7.1.2 *Construction*

The aggregate gradation and quality test results are determined from samples taken directly from the hopper of the aggregate spreader. The testing frequency for gradation should be a minimum of one test per day, or one per 1,500 tons of material, whichever is greater. The testing frequency for quality values, in accordance with Table A-2, is once per source.

A.7.2 Emulsified Asphalt

Only emulsified asphalt from certified or approved sources is allowed for use. The application rate of the emulsified asphalt is verified by dividing the volume of the emulsified asphalt by the area that is chip-sealed each day. The allowable variation is +/- 5 percent of the EAR adjusted from the design quantity. The material certification and quality control test results for each batch of emulsified asphalt used in the project must be recorded. All reports also must include the supplier's name, plant location, emulsion grade, and batch number.

A.8. QUALITY ASSURANCE

The NCDOT is responsible for quality assurance sampling and testing. Samples must be taken randomly by the NCDOT.

A.8.1 Aggregate

A.8.1.1 *Construction*

Sample aggregate should be taken from the aggregate spreader once per day and stored and tested for gradation at the discretion of the NCDOT. If the results vary from the requirements presented in Table A-1, a price reduction can be applied according to a defined Schedule of Price Reduction that should be included in the contract.

A.8.2 Emulsified Asphalt

The first shipment of emulsified asphalt should be sampled; thereafter, one sample for every 50,000 gallons (approximately 200 tons) should be provided for each emulsion type used.

A.9. PERFORMANCE

A.9.1 Less than One Year

The early life of the chip seal is assessed based on aggregate (chip) loss and flushing. Aggregate loss can occur as soon as traffic control is removed and the recently chip-sealed road is reopened to traffic. If this aggregate loss is greater than 10 percent of the chip quantity applied (assuming a one-layer chip seal application), then performance is not acceptable and an investigation regarding the cause should be conducted. Often, early failures of this type are due to higher than appropriate AARs or lower than appropriate EARs, or both. Early aggregate loss also can be due to excess fine aggregate particles or a change in aggregate gradation that was not accounted for by an appropriate change in the EAR. Also, unexpected low temperatures or wet weather as well as removal of traffic control before adequate residue adhesion has developed can cause early chip loss.

Flushing can occur because of an excessively high EAR for the aggregate being used. Streaking can be caused by the spray bar on the asphalt distributor being set either too high or too low. Streaking also can be caused when individual spray nozzles on the emulsion distributor clog. Correction after construction is not possible without the application of another seal.

A.9.2 More than One Year

In the summers following construction, bleeding (and rutting in multilayer seals) can occur in binders with low resistance to permanent deformation under traffic loading. Likewise, as binder hardens and oxidizes, long-term raveling can occur in surface treatments. Visual inspection of the surface treatment is the current method used to evaluate these performance measures in the field.

Texture depth also can be used to evaluate long-term chip seal performance. The Austroads (2006) specification defines the end of design life as the point when the surface texture depth becomes less than 0.035 inch (0.9 mm) for pavements that experience traffic speeds greater than 43 miles per hour.

A.9.3 Warranties

A warranty is a form of guarantee of the integrity and overall quality of a surface treatment constructed by a contractor. The warranty can be used to hold the contractor responsible for any replacement or repair that is required during the effective warranty period (Anderson and Russell 2001). The overall goal of a warranty in the context of this report is to minimize the NCDOT's risk by holding the contractor responsible for any failures and/or defects in the workmanship of the chip seal treatment.

Results from international surveys and surveys conducted in the United States reveal a large discrepancy between the United States and other countries in the use of warranties for chip sealing. Figure A-11 shows that less than 20 percent of the states in the United States require warranties for chip seals. Specifically, chip seal warranty coverage reported in the United States varies from as many as three years (Ohio) to only four weeks (Wyoming). Conversely, almost 90 percent of responding provinces in Canada required warranties, and 100 percent of respondents from Australia, New Zealand, the United Kingdom, and South Africa reported requiring warranties for their chip seals. Most international respondents reported warranty coverage of one year. This length of time is deemed reasonable for North Carolina, as it would protect the NCDOT against construction-related performance problems as well poor short-term performance in terms of aggregate loss and bleeding that often appear during the first year following construction. Therefore, one-year warranties are recommended for contracted chip sealing work.

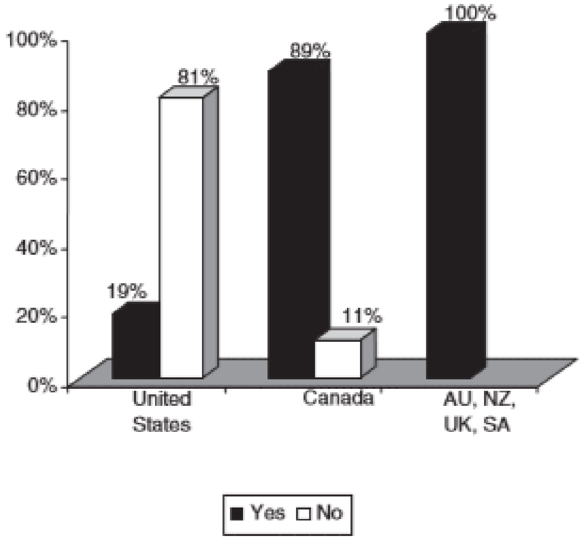

Figure A-11. Proportion of respondents that require warranties for chip seal construction (Gransberg and James 2005).

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