RESEARCH & DEVELOPMENT

Fog Seal Effectiveness for Bituminous Surface Treatments

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Fog Seal Effectiveness for Bituminous Surface Treatments

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16. Abstract

This report presents a laboratory study on the effectiveness of various fog seal materials and the effects of application rates on fog seal curing behaviors. This report is divided into two parts: fog seal emulsion properties and fog seal emulsion applications. In this research, four types of emulsion, including both unmodified and modified emulsions, are used for fog seal testing. The unmodified emulsions are CSS-1h emulsion that is used commonly for fog seal applications and CQS-1h emulsion that is employed for slurry seals. The polymer-modified emulsions (PMEs) are ReviveTM and Grip-Tight and are designed specially for fog seals. The North Carolina State University research team developed the rolling ball test and damping test to verify the fog seal field construction. The curing time studies, which include the evaporation test, PATTI test, rolling ball test, and damping test, have identified some advantages of using PMEs, but ound no advantages for the use of the unmodified CQS-1h emulsion. The curing time study results suggest appropriate emulsion application rates (EARs) and emulsion types, which are verified for fog seal performance tests, such as the third-scale model mobile load simulator (MMLS3) test for aggregate loss and bleeding, mean profile depth (MPD) analysis, and skid resistance testing. The fog seal performance test results also reveal advantages of PMEs. Except in the case of the unmodified CSS-1h emulsion with a high EAR, in general fog seals can improve aggregate retention. High EARs lead to high bleeding percentages and can thereby reduce the skid resistance of the surface. Fog seals in themselves do not provide skid resistance; however, all the skid numbers acquired from conditioned samples satisfy the NCDOT skid resistance requirements. Overall, modified emulsions are better than unmodified emulsions in terms of curing time and performance. Although the difference between the ReviveTM and Grip-Tight emulsions is not significant in most cases, the Grip-Tight emulsion exhibits the better properties. However, only one type of chip seal texture (i.e., that recommended by the chip seal mix design project) is employed for this research. Therefore, additional research into different chip seal surface textures is necessary to show whether fog seals are applicable for other chip seal surfaces.

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1. INTRODUCTION

1.1 Research Needs and Significance

Since 2006, the North Carolina Department of Transportation (NCDOT) has placed greater emphasis on pavement preservation than in previous years. The NCDOT has formally trained field personnel in the importance of ‘placing the right treatment on the right road at the right time.’ One of the most cost-effective preservation treatments is the chip seal. The NCDOT has expanded its chip seal operations and is now paving approximately 3,000 centerline miles annually with its force account labor. In July 2006, the NC General Assembly added a line item to the NCDOT budget that specifically funds ‘System Preservation’. With this emphasis on pavement preservation, further research into preservation treatments is needed, and must include evaluating the effectiveness of placing fog seals on NCDOT chip seals.

One of the primary concerns regarding chip seals is the presence of loose stone. A fog seal, which is an emulsified product placed on top of a chip seal, is designed to mitigate this problem by ‘locking down’ the top layer of stone. The Asphalt Emulsion Manufacturers Association (AEMA) defines a fog seal as “a light spray application of diluted asphalt emulsion used primarily to seal an existing asphalt surface to reduce raveling and enrich dry and weathered surfaces” (AEMA 2004). Other states have employed fog seals in their respective chip seal operations and, most recently, the Federal Highway Administration (FHWA) and the Foundation for Pavement Preservation have co-sponsored a research project that evaluates the sprayed application of polymer surface seals. The research results show that such sealants add new asphalt to seal the surface, and rejuvenators soften age-hardened asphalt to restore the desired mechanical properties of the mixture in the upper 3/8 in. to ½ in. of the pavement surface (King et al. 2007). Other studies (Wood et al. 2006, Jahren et al. 2007) also report the advantages of fog seals, including their low cost, ease of construction, and desirable black appearance, to name a few. A few reported disadvantages include the delay in opening to traffic and reduction in skid resistance (Jahren et al. 2007).

At this time, the NCDOT does not use fog seals in conjunction with its chip seal operations. Recognizing the significant proportion of chip seal pavements in the NC highway network and that the main problem with the chip seal is loose stone, it is deemed important to investigate the potential of fog seals as a cost-effective method to improve the performance of chip seals. This report presents a research effort based on the laboratory and field testing of chip seals with and without fog seals to develop an optimal plan for using fog seals in North Carolina chip seal operations.

1.2 Research Objectives

The primary objectives of the research project are:

- to determine optimal fog seal application rates for chip seals commonly used in North Carolina; and
- to compare the aggregate loss and skid resistance of chip seals with and without fog seals.

1.3 Report Organization

This report is composed of seven chapters. Chapter 1 describes the research needs and objectives. Chapter 2 provides a summary of the literature review of fog seal applications, existing fog seal guidelines, and factors that affect fog seal performance. Chapter 3 presents the experimental test program, test procedures, and analysis concepts. Chapter 4 describes the test materials used in this research. Chapter 5 reports the results of the curing time studies and performance tests. Chapter 6 offers recommendations for proper fog seal emulsion types and application rates, and introduces the fog seal field application plan as a conclusion to this research and suggests further research. Chapter 7 lists references cited in this report.

2. LITERATURE REVIEW

2.1 General

Before discussing the fog seal study, it is critical to understand asphalt surface treatments (ASTs), which are cited officially in the NCDOT specifications. The term, *AST*, covers several types of treatment and terms, including the chip seal, seal coat, surface treatment, bituminous surface treatment, spray seal, and surface dressing. The general failure types of ASTs are streaking, flushing/bleeding, and aggregate loss. Streaking is the debonding between the existing surface and the new AST and is caused by failure to apply the asphalt emulsion uniformly. In the AST industry, the terms *bleeding* and *flushing* are commonly used to describe problems caused by the spread of hot emulsion (bleeding), and by an excess of emulsion (flushing). These two failure types exhibit the same behavior of reducing the skid resistance of a pavement surface (McLeod 1969, Gransberg 2005). AST aggregate loss can be caused by several factors, such as excessive aggregate application, poor traffic control during construction, inadequate embedment of the aggregate particles into the emulsion, poor aggregate gradation qualities, and dusty aggregate (Shuler 1990, Gransberg 2005), and occurs mainly during initial traffic passes. Improved skid resistance due to rough surface texture is considered as one of the benefits of new chip seals (Gransberg 2005).

The specific goal of this fog seal research is to determine the most appropriate fog seal emulsion application rates (EARs) to be applied on top of a chip seal surface to improve its performance. In order for a fog seal to perform well, it should not be applied on a chip-sealed road that exhibits severe distress. Thus, it is important to identify such severe distresses and to remedy them prior to the application of the fog seal onto the chip seal.

2.2 Literature Review of Fog Seals

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

The purpose of the fog seal is to improve aggregate retention and extend the service life of the pavement by increasing the pavement's impermeability to water and air. Also, small cracks can be sealed by a fog seal application (Wood et al. 2006). For a proper fog seal application, the existing pavement surface must be clean and dry. As part of a new chip seal application, the fog seal should be applied immediately after sweeping. To be effective, fog seals need to form a cohesive film once the water evaporates from the emulsion. This cohesive film does not form properly at temperatures lower than the minimum air temperature of around 60°F. Therefore, the fog seal application process should not begin when the air temperature is below 60°F or if there is a possibility of precipitation (Wood et al. 2006). Also, environmental factors (i.e., high temperature, humidity, and wind) affect the length of time the fog seal emulsion takes to break (FHWA 2003).

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

- "The traveling public thinks it is driving on a new HMA surface rather than a chip seal."
- "The emulsion is diluted, which yields a very low viscosity that allows most, if not all, of the additional asphalt binder to fill the chip voids, increasing embedment by up to 15 percent with no bleeding."
- "The fog seal reseals any chips that may have partially broken loose during sweeping operations."
- "Darkening the pavement surface with a light application of asphalt emulsion allows the pavement surface temperature to rise. The subsequent softening of the binder allows the chips to orient to their least dimension more quickly. This factor is very important in Minnesota where late season chip seal projects are more susceptible to failure due to colder weather conditions."
- "Fog sealing can provide a designer with a chance for a 're-do' of a chip seal application. If, after traffic has driven on the surface, it appears that embedment is low, an engineer can add additional binder to the chip seal by increasing the fog seal amount. In some cases, the amount of fog seal emulsion applied increased to over 0.20 gal/yd^2."
- "When a fog seal is applied, a reduced amount of paint is necessary to make pavement markings visible on the surface."
- The low cost (i.e., average cost of a fog seal is \$0.18–\$0.80/yd^2) and ease of construction add to the benefits of fog seals.

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

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

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

The AEMA (2004) offers a guide for fog seal applications. This guide shows suggested EARs for the fog seal, as seen in Table 1. The objective of the fog seal is to apply a uniform coverage of emulsion and seal the pavement pores, small cracks, and voids against water and weathering. If an emulsion is over applied, a light cover of clean, fine sand may be applied onto the uncured fog seal at the rate of 6 to 10 lb/yd^2 to provide a safe, skid-resistant surface. Then, one pass of a pneumatic tire roller should be made to firmly embed this light dusting of sand. The fog seal should be allowed to cure completely before opening the roadway to traffic. Traffic control is necessary during the application process to protect the freshly sprayed emulsion until it is overlaid or cured to a safe condition.

The normal EAR used by the MnDOT ranges from 0.06 to 0.12 gal/yd^2 of diluted CSS-1h (cationic slow-setting) emulsion, depending on the size of the chips used. A higher rate of application is used for coarse chips, and a lower rate is used as the chips become finer. Minnesota requires a dilution rate of one part emulsion (Wood et al. 2006).

Table 1 Suggested Emulsion Application Rates for Fog Seals (AEMA 2004)

Rate of Dilution	**Type of Surface to be Fog Sealed**	
	Dense Surface	**Open Surface**
% Emulsion (emulsion + water)	**Low Absorption (gal/yd^2)**	**High Absorption (gal/yd^2)**
Net residual asphalt desired	0.01 to 0.03	0.03 to 0.05
50% (1+1)	0.03 to 0.11	0.09 to 0.23
40% (2+3)	0.04 to 0.13	0.12 to 0.30
25% (1+3)	0.06 to 0.21	0.19 to 0.47
20% (1+4)	0.08 to 0.25	0.24 to 0.59
16.7% (1+5)	0.09 to 0.31	too high
14.3% (1+6)	0.12 to 0.41	too high
12.5% (1+7)	0.13 to 0.47	too high

Estakhri et al. (1991) studied the effectiveness of fog seals for bituminous pavement surface treatments, i.e., chip seals. They employed two experimental programs: laboratory and field evaluations. For the laboratory study, Estakhri et al. conducted Vialit testing to determine appropriate fog seal EARs to improve the aggregate retention performance of the chip seal. For the Vialit tests, the chip seal samples were fabricated using a binder application rate that was less than the optimal rate so that the aggregate was embedded into the asphalt to approximately 20 percent. MS-1 asphalt emulsion that was diluted with water at a 1:1 ratio was applied to the chip seal sample. Four different residual binder rates were employed for this study: 0.00, 0.05, 0.10, and 0.20 gal/yd^2. From the Vialit test results, the fog seal applied at the residual asphalt application rate of 10 gal/yd^2 showed significant improvement in aggregate retention.
For the field test part of the Estakhri et al. study, four test roads under low traffic volume were constructed and evaluated to determine the effectiveness of fog seals at improving aggregate retention. Each fog seal was applied before the first winter after the chip seal was constructed. To compare a fog seal with a non-fog seal, a portion of each chip seal was not fog sealed. The

aggregate loss, determined from close-up photographs, was used to evaluate performance. The performance evaluations were made after the first winter that the fog seal was applied and again after the second winter. The fog seal sections showed significantly less aggregate loss (i.e., better aggregate retention) than the sections that were not fog sealed. A large amount of aggregate loss occurred in the non-fog sealed sections, particularly between the wheel paths, over the first winter.

The literature review on fog seals reveals that the criteria used to evaluate fog seal performance focus on aggregate loss. The aggregate loss performance of the fog seal application process can be evaluated using various laboratory test methods, including the Vialit test and the sweep test (ASTM D 7000) (Barnat 2001, Yazgan 2004). However, each of these methods applies a different form of mechanical energy to assess the aggregate-binder bond interaction; and neither of these methods simulates the mechanical force imparted on the pavement by traffic wheel loading. To alleviate this shortcoming, a performance-based AST test method was developed and tested as part of the HWY-2004-04 project (Lee et al. 2005). This accelerated test method uses the MMLS3, which is a scaled-down unidirectional vehicle load simulator that uses a continuous loop for trafficking. The wheels travel at a speed of about 5,500 wheel applications per hour, thus allowing an accelerated evaluation of pavement performance under more realistic loading conditions than that of other available AST tests.

In addition to existing AST test methods, such as the Vialit test and the flip-over test (FOT), the NCSU research team has developed several other AST performance test methods, including: a digital imaging technique to evaluate bleeding, the modified sand patch test, a digital imaging technique for examining cross-sections of epoxy-reinforced chip seal samples, and a laser surface profiling system to determine the aggregate exposure depth (Kim and Lee 2008). These test methods are designed to be applicable under both laboratory and field conditions, with the exception of the digital imaging technique, which is applicable to laboratory samples only. Some of these methods are reviewed briefly in the following sections.

Based on the literature review, the advantages and disadvantages of fog seals are presented in Table 2.

Table 2 Advantages and Disadvantages of Fog Seals

Advantages	Disadvantages
• Cost-effectiveness • Ease of construction • Extension of the service life of the pavement • Desirable black appearance	• Long curing time (delayed traffic opening) • Reduction in skid resistance

2.3 Review of Existing Fog Seal Guidelines

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

2.3.1 Fog Seal Guidelines (State of California Department of Transportation)

Fog Seal Guidelines is intended to assist in making better and more informed decisions regarding fog seals and to rejuvenate existing seal practices. This guide details when and how fog seals are to be used by design and field personnel. *Fog Seal Guidelines* notes that fog seals are a method of adding asphalt to an existing pavement surface to improve sealing or waterproofing, prevent further stone loss by holding the aggregate in place, or simply to improve the surface appearance.

Asphalt emulsion and water typically are used in the construction of fog seals. In some cases, the emulsions are made for special purposes, but the primary types used are CSS-1h and SS-1h. Asphalt emulsions contain up to 43% water, but must be diluted further before use to reduce their viscosity. Typically, the recommended dilution rate is 50% (1:1). Typical EARs for diluted emulsions range from 0.15 to 1.0 l/m^2 (0.03 to 0.22 gal/yd^2) depending on the surface conditions (see Table 3). To estimate the optimal EAR, a method that uses a one-liter can is employed, as follows. Take a one-liter can of diluted emulsion and pour it evenly over an area about 1 m^2. If the emulsion is not absorbed into the surface, decrease the amount and apply to a new 1 m^2 area. If the surface looks as though it will absorb more emulsion, increase the amount and apply over a new 1 m^2 area. Repeat the trials until the approximate EAR is found. This procedure for estimating the fog seal EAR is noted also in Nikornpon et al. (2005).

Table 3 AEMA Recommendations for Emulsion Application Rates

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

* A tight surface is of low absorbance and is relatively smooth.
** An open surface is relatively porous and absorbent with open voids.

To be effective, fog seals need to break quickly and cure completely. To achieve this behavior, an asphalt film must form properly. Thus, warm weather conditions with little to no chance of rain are necessary, and fog seals should not be applied when the atmospheric temperature is below 10°C (50°F) and the pavement temperature is below 15°C (50°F). Furthermore, the pavement surface must be clean and dry before applying the fog seal. After applying the fog seal, the curing time will vary depending on the weather and surface conditions. Under ideal conditions, traffic should not be allowed on the roadway for at least two hours and only after acceptable skid test (CT 342) values, over 0.30, are achieved. To allow early opening to traffic, sand blotters may be used at approximately 1 kg/m^2. *Fog Seal Guidelines* are discussed in Chapter 6 of the *Maintenance Technical Advisory Guide (TAG)* (California DOT 2003).

2.3.2 Minnesota Seal Coat Handbook 2006 (Minnesota Department of Transportation)

The *Minnesota Seal Coat Handbook 2006* has been used extensively in Minnesota and has served as a model for other states and jurisdictions around the United States. This handbook also includes several advances in the seal coating process, and fog seals in particular are discussed in

Chapter 5. According to this handbook, fog seals are used commonly to ensure the retention of stone and to add service life to the pavement by increasing its impermeability to water and air.

The normal EAR range is from 0.06 to 0.12 gal/yd^2 of diluted CSS-1h emulsion, depending on the size of the chips used. A higher rate of application is used for coarse chips, and a lower rate is used as the chips become fine. Like the California guideline, the Minnesota handbook also requires warm conditions with little to no chance of rain to ensure successful applications. It suggests that the air temperature is below 60°F.

2.3.3 Fog Seal Application (Federal Highway Administration)

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

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

Table 4 summarizes these three primary guidelines for fog seals.

Table 4 Summary of Guidelines Used for Fog Seals

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

Note: Blank cells indicate no mention in the guidelines.

2.4 Factors that Affect Fog Seal Performance

2.4.1 Emulsion Properties

In the early 1900s, asphalt emulsions were created for dust control and spray applications. They were found to have many advantages, and their usage has increased significantly over time. A particular benefit is that the physical properties of emulsions can be changed according to field conditions. For example, emulsions can be charged positively or negatively in order to be compatible with particular aggregates. Furthermore, various modifiers, such as polymer, latex, filler, anti-stripping, and stabilizers, can be added to basic emulsions to improve their inherent properties. In addition, asphalt emulsions serve as eco-friendly products in the paving industry.

Asphalt emulsion is asphalt dispersed in water and consists of asphalt (40% to 75%), water (25% to 60%), and emulsifier (0.1% to 2.5. These physical components provide a few advantages, such as low viscosity (easy application), low required temperature for both application and storage, and less sensitivity on damp surfaces (California DOT 2003).

Emulsion Classification

Although information regarding emulsion classifications is mentioned in previous paragraphs, it gives only a partial explanation for the designations of emulsion properties. Thus, in this section, emulsion classification is explained comprehensively.

According to the AEMA brochure, emulsions are classified by their ionic charge and thus are divided into three categories: anionic, cationic and nonionic. The emulsion charge is important for compatibility with aggregate. In order to prevent failure, cationic emulsions must be used with negatively charged aggregate, and anionic emulsions must be used with positively charged aggregate. If the name (designation) of the emulsion begins with a "C", then it is a cationic emulsion; otherwise, the designation (no "C") refers normally to an anionic or nonionic emulsion, but nonionic emulsions are used rarely. In North Carolina, the cationic type of emulsion is employed for AST design.

The setting time, which is also called flocculation or coalescence, of emulsions is designated by the second set of letters in the emulsion name. These two letters represent the speed at which the emulsion breaks after contacting the aggregate surface. There are four terms: RS (rapid-setting), MS (medium-setting), SS (slow-setting), and QS (quick-setting) emulsions. RS emulsions are not stable and break quickly when they contact aggregate. It is difficult if not impossible for RS emulsions to mix with aggregate particles, so they are usually employed for spray applications, such as chip seals. MS emulsions are intended for mixing with coarse aggregate rather than fine aggregate. Depending on their design, MS emulsions maintain workability for a few months. SS emulsions are designed for fine aggregate. They are the most stable type of emulsion and allow sufficient mixing time and extend workability. SS emulsions can be diluted with water to reduce their viscosity so they can be applied for tack coats and fog seals. QS emulsions also are made for fine aggregate. Their break time is faster than that of SS emulsions, but slower than that of MS emulsions (James 2006). QS emulsions are generally used for micro-surfacing and slurry seals. In order to improve adhesion and open traffic early, a polymer can be added to these emulsions.

If the letters "HF" precede the set time letter designation, then the emulsion is a 'high float' emulsion, which indicates that it passes the float test (AASHTO T-50 or ASTM D-139). Once HF emulsions are cured, a gel-type structure forms in the asphalt residue, which enables HF emulsions to improve performance over a wider temperature range than other emulsions and to be applied to dusty aggregate. HF emulsions also can be used for chip seals and cold mixes.

The viscosity of an emulsion affects its ability to penetrate the voids within the chip seal, and, therefore, viscosity is one of the most important properties of emulsion. In the emulsion designations, a number, "1" or "2", coming after the setting letters indicates the emulsion's level of viscosity. "1" represents emulsions with low viscosity, and "2" represents emulsions with high viscosity. In some cases, emulsion designations may have the letter "h" in the last part of name. The letter "h" means that the emulsion is made using a 'hard' asphalt base (Wood et al. 2006). In order to improve certain emulsion properties, polymer-modified emulsions (PMEs) are used in chip seal and fog seal construction. Polymer modification brings some advantages, such as a decrease in the emulsion's susceptibility to temperature, an increase in adhesion of the emulsion, and allowing the road to be opened to traffic earlier than is the case when unmodified emulsions are used. Due to the ability of PMEs to enhance pavement performance, their use by the chip seal industry has increased in recent years. In order to indicate the use of a polymer modifier in emulsions, "P" or "L" also can be added to the last part of the name, indicating 'polymer' and 'latex' modified emulsions, respectively.

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

2.4.2 Emulsion Curing Time

The curing time of an emulsion can affect the overall performance of the fog seal. In order to find the appropriate curing time for emulsions, the first step is to understand the curing procedure, shown in Figure 1. The curing process takes two steps, i.e., breaking and curing. The breaking process is when the emulsion changes from a dispersed form to an asphalt form, and curing is water evaporation from the emulsion.

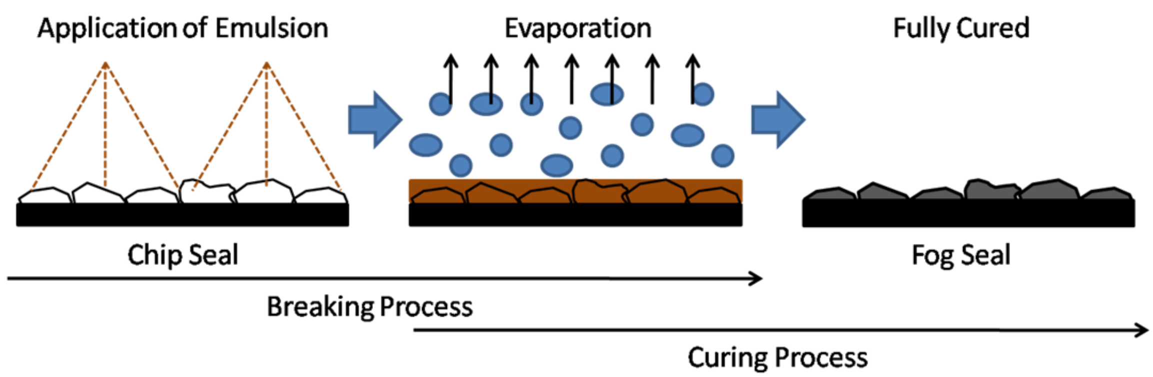


Figure 1 Emulsion curing procedure

2.4.3 Emulsion Application Rate

Proper EARs depend on the size of the air voids, size of the aggregate, and porosity. The EAR plays an important role in emulsion curing time and fog seal performance. A low fog seal EAR, for example, can lead to a short curing time, but it can also cause poor performance of the fog seal. Hence, it is necessary to determine proper fog seal EARs prior to fog seal construction. Nikornpon et al. (2005) recommend the AEMA's application rate (see Table 3), and in the case of TxAPA (2006), a few specific rates are recommended, depending on the aggregate grade: 0.08 – 0.10 gal/yd^2 for Grade 5, 0.01 – 0.12 gal/yd^2 for Grade 4, and 0.12 – 0.14 gal/yd^2 for Grade 3. Two studies (Jahren et al. 2007, Wood et al. 2006) do not provide a specific fog seal EAR.

3. TEST PROCEDURES AND ANALYSIS CONCEPTS

3.1 Sample Fabrication

3.1.1 Sample Fabrication Facility

In order to eliminate temperature as a variable in fabricating and testing fog seal and chip seal specimens in the laboratory, it is important to be able to control the temperature throughout the entire process. Such control is vital because it ensures that each sample is subjected to nearly identical temperatures during the fabrication, curing, and testing processes. Pivotal to achieving this level of temperature control is a closed facility that can host the fabrication process. The NCSU research team has constructed such a facility, a 16 ft. by 8 ft. greenhouse made of wood and polycarbonate glass. This greenhouse, pictured in Figure 2, ensures a relatively consistent temperature for the specimens during fabrication.

Figure 2 Greenhouse for temperature control

This fog seal research requires performance testing of fog seal samples using various fog seal EARs for different chip seal samples. However, performance testing of fog seal field sections is too costly, if not impossible, within the time and resources allotted in this project. Therefore, a laboratory device that can fabricate fog seal and chip seal samples with accurate EARs and consistency is important for the success of this research. Because emulsion can be sprayed onto a felt disk or chip seal sample resting on a scale, it is fairly simple to apply the emulsion at a specified rate in the laboratory. The difficulty lies in spreading the aggregate in a realistic and consistent manner. Figure 3 shows an emulsion spraying procedure that employs a paint gun.


Figure 3 Emulsion spraying procedure

The NCSU research team has designed an experimental chip seal spreader that automatically spreads aggregate on emulsion at a reasonably steady rate. The device, ChipSS, shown in Figure 4, simulates the aggregate spreader that is currently used in field situations. ChipSS currently is housed in the greenhouse, thus allowing accurate temperature control in producing chip seal and fog seal samples.

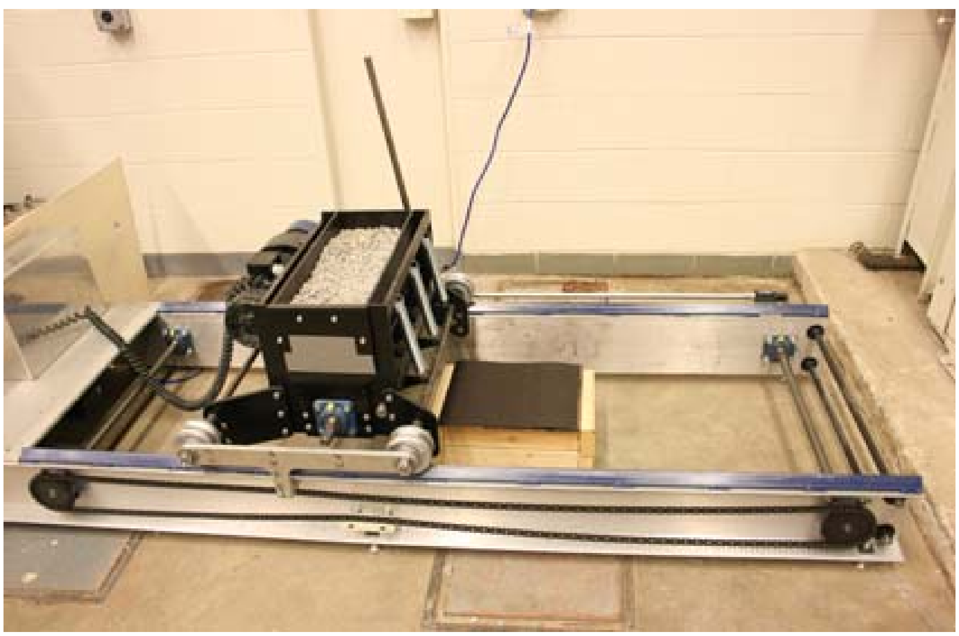


Figure 4 ChipSS

3.2 Development of Experimental Program

3.2.1 Target Parameters

An experimental program has been developed based on the findings from the literature review summarized earlier in the proposal and presented in previous reports. Two target parameters have been identified as important variables for the satisfactory performance of fog seals and for their specifications. These parameters are the fog seal EAR and curing time. Table 5 shows the factors that affect these two target parameters.

Table 5 Target Parameters and Factors that Affect the Target Parameters

Target Parameter	Influential Factors
Fog Seal EAR	Surface Voids Surface Absorption Fog Seal Emulsion Type
Curing Time	Rate of Dilution Fog Seal Rate Temperature

These two target parameters affect several performance characteristics of fog seals. The fog seal EAR affects the surface texture depth and, thus, aggregate loss and skid resistance. The curing time is determined by the curing rate of the emulsion and is related to performance because the speed at which the emulsion cures helps determine when the roadway can be opened to traffic.

3.2.2 Test Methods for Fog Seal Performance

The aggregate loss performance of the fog seal application process can be evaluated using various laboratory test methods, including the Vialit test and the sweep test (ASTM D 7000) (Barnat 2001, Yazgan 2004, and Estakhri et al. 1991). In addition to these existing performance-based AST test methods, the NCSU research team has developed several others, including a digital imaging technique to evaluate bleeding, a modified sand patch test, a digital imaging technique to evaluate cross-sections of epoxy-reinforced chip seal samples, and a laser surface profiling system to determine the aggregate exposure depth (Kim and Lee 2008).

Based on the literature review, the NCSU research team has evaluated various fog seal test methods for their effectiveness in accomplishing the research objectives of this study. The selected performance tests for the different performance characteristics are listed in Table 6. The results from these tests will be analyzed and compared to determine the optimal fog seal EARs and minimum curing times for the various conditions tested.

Table 6 Test Methods for Fog Seal Performance

Performance Characteristics	Performance Test Methods
Aggregate Retention	MMLS3 Test, Vialit Test
Curing Rate	Evaporation Test, PATTI Test, Rolling Ball Test, Damping Test
Skid Resistance	BPT of Specimens Loaded by MMLS3
Surface Texture Depth	Laser Profiler, MPD Analysis

3.2.3 Experimental Design

As explained in Table 2, one of the disadvantages of the fog seal is delayed traffic opening. If the traffic opens before the fog seal emulsion has cured completed, then the road surface will be damaged, which can cause safety issues. The appropriate curing time for fog seal emulsions varies depending on the emulsion type, the pavement surface conditions, and the weather conditions at the time of application. The California DOT (2003) suggests that traffic be kept off the fog seal for at least two hours after application and once acceptable skid test values (CT 342) have been obtained. The specification of the Minnesota DOT (2356 Seal Coat) also states that a fog seal usually cures within two hours under dry conditions and temperatures above 15.5°C (60°F).

In order to make an experimental plan for fog seal performance testing, it is important to understand the fog seal construction procedure. Figure 5 shows the Minnesota DOT construction procedure for seal coats.

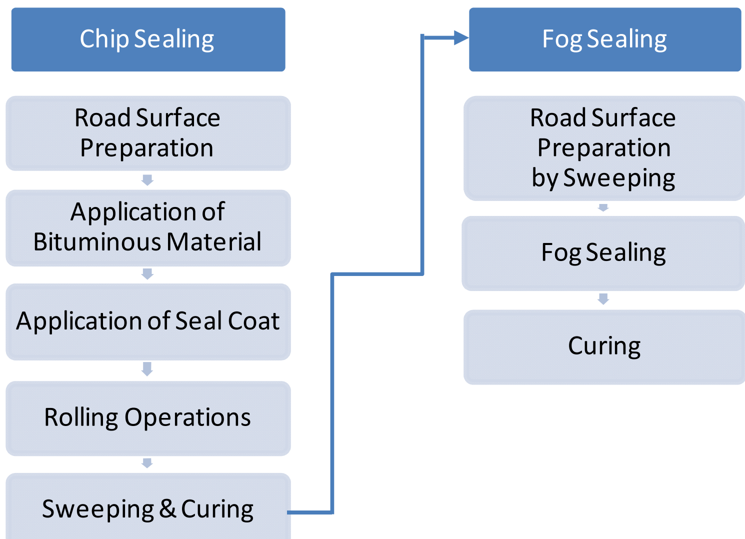


Figure 5 Construction procedure for seal coats (2356, Minnesota DOT)

The first step in the experimental design is to suggest representative fog seal EARs and curing times. These EARs and curing times can be determined from evaporation test results. However, the evaporation test considers only how fast water evaporates from the emulsions by measuring the weight of the emulsion, so it does not capture the advantages of modified fog seal emulsions, such as those that have higher adhesive strength values than unmodified emulsions. Consequently, the so-called *pneumatic adhesion tension testing instrument* (PATTI) test is used to determine the minimum curing times for fog seal emulsions in addition to the curing times determined from the evaporation test.

As mentioned before, the purpose of this research is to create a guideline for the application of fog seals on top of chip seal surfaces. That is, the properties obtained from the fog seal emulsion tests should be applied to chip seal samples and verified. The NCSU research team thus has conducted MMLS3 performance tests on chip seal specimens that have had fog seals applied to their surfaces. Figure 6 shows the plan for the MMLS3 performance testing.

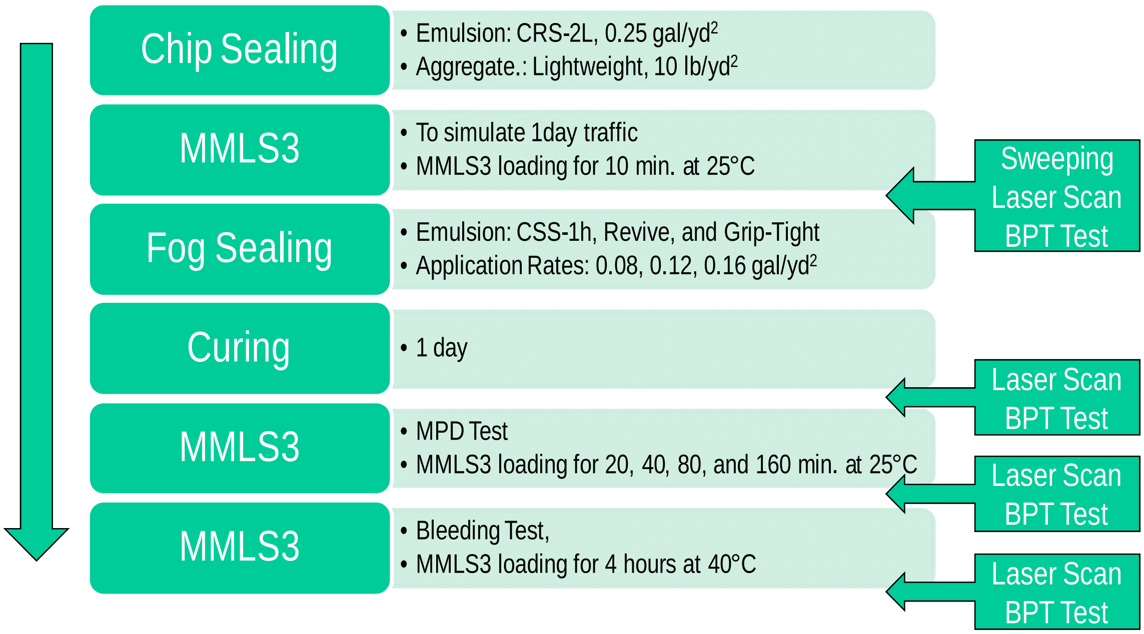


Figure 6 Plan for MMLS3 performance testing

Once the fog seal construction is completed, it is necessary and urgent to determine when the road can be opened for traffic without causing any damage to the pavement. Therefore, field test methods should be simple for fast implementation, and the test equipment should be easily portable. In addition, the test methods must be verified in advance in the laboratory. The rolling ball test and damping test were selected to meet these criteria, and the results were verified in the laboratory for application in the field.

3.3 Curing Time Evaluation

3.3.1 Evaporation Test

It is important to determine the curing time required for the respective emulsions to reach their asymptotic percentage of water loss (% water loss), that is, the point at which no more water loss occurs. This determination allows a direct comparison of the curing characteristics of the test emulsions. For these evaporation tests, fog seal emulsions that are diluted with water are prepared and placed in small cans of 90 mm diameter each. All emulsion samples are exposed to the same conditions in the environmental chamber. The evaporation test samples in the environmental chamber are shown in Figure 7. Figure 8 shows the evaporation test procedure used for this study.

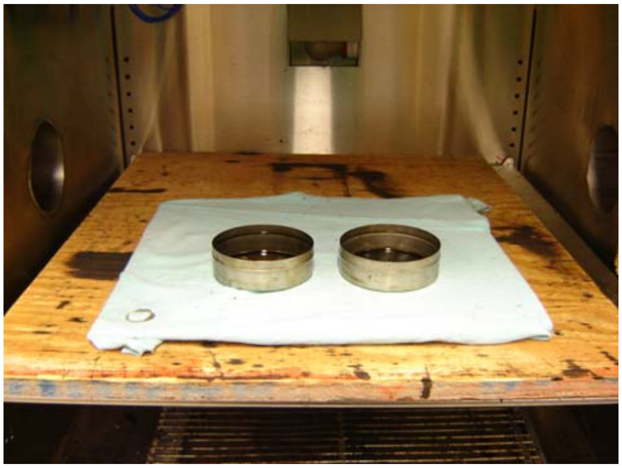


Figure 7 Evaporation test samples in environmental chamber

Place emulsion and water in the oven for 2 hours

↓

Dilute the emulsion with water for 2 to 3 minutes by stirring

↓

Place diluted emulsion in the oven at 122°F (50°C) for 1 hour

↓

Place Vialit plates or cans on the scale

↓

Pour diluted emulsion onto the plates or into the cans

↓

Place samples in the oven at the test temperature

↓

Measure weight of the samples every 30 minutes

Figure 8 Evaporation test procedure

3.3.2 Pneumatic Adhesion Tension Testing Instrument (PATTI) Test

The PATTI test is an adhesion test developed by the National Institute of Standards and Technology and is typically used in the paint industry. This test is standardized in ASTM D 4541: *Pull-Off Strength of Coatings Using Portable Adhesion*. In the pavement field, PATTI can be used to measure the bond strength between the hot asphalt binder and aggregate surface, or between the emulsion and aggregate surface. The PATTI itself and a schematic representation of the PATTI piston are provided in Figure 9. The AASHTO standard for asphalt binders and emulsions is being developed using the PATTI device and is called the bitumen bond strength (BBS) test. The NCSU research team has modified PATTI so that it can be used also to test the bond strength of fog seal emulsions, which are more fluid than typical emulsions. The steps in this procedure are as follows:

1. Prepare fog seal emulsion by diluting it with water.
2. Heat the fog seal emulsion to 60 ±2°C, and heat the substrate to 25 ±2°C.
3. Attach the molds to the substrate.
4. Fill the molds with fog seal emulsion.
5. Cure the samples for a specified amount of time.
6. Heat the pull-stubs to 60 ±2°C.
7. Remove the molds and then adhere the pull-stubs to the substrate in the chamber.
8. Keep the substrate in the chamber at a specified temperature.
9. Conduct the test.

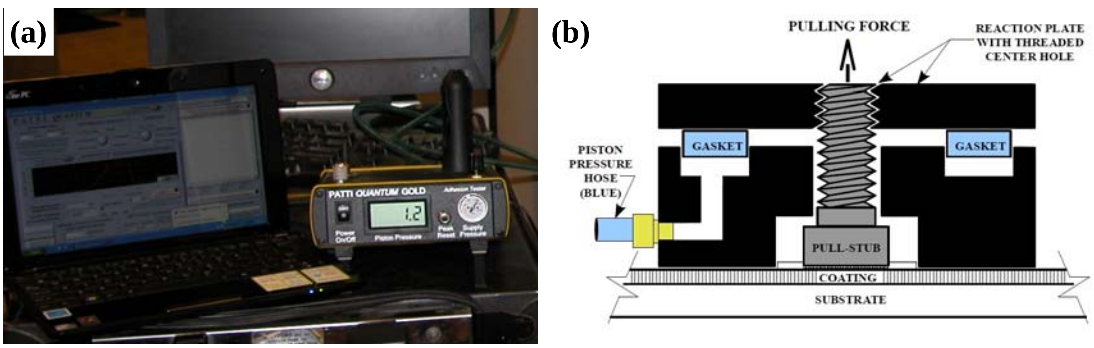


Figure 9 PATTI test; (a) PATTI device and (b) schematic of piston assembly

PATTI provides the maximum pull-off tensile strength by converting air pressure to tensile strength. In general, when a failed surface on the substrate has asphalt remaining on it, the type of failure is referred to as *cohesive failure*. When no asphalt remains on the substrate, the type of failure is referred to as *adhesive failure*. Examples of cohesive and adhesive failure are provided in Figure 10.

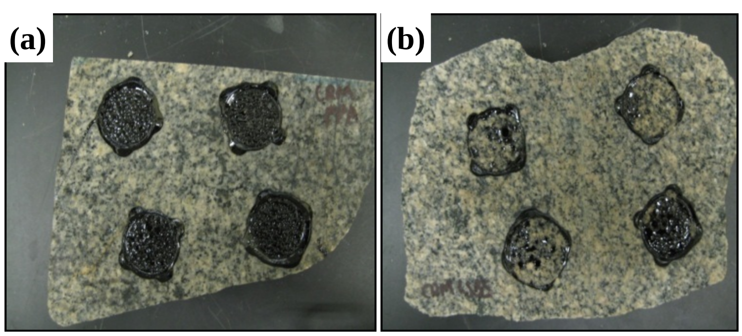


Figure 10 Failure types; (a) cohesive failure and (b) adhesive failure

According to previous studies, the bond strength can be affected by the thickness of the emulsion film and curing of the emulsion. However, it is difficult to control the film thickness of fog seal emulsions, which are diluted with water, because the volume of the emulsion changes significantly depending on the curing time. Thus, in order to keep the film thickness constant, the NCSU research team applied 13.5 kg of dead weight for 10 seconds when adhering 1/2” (12.7 mm) pull-stubs onto the substrate. Although the BBS test procedure suggests using 20 mm pull-stubs, such pull-stubs cannot be applied to film that is thinner than 0.8 mm. Photographs of the PATTI test samples are provided in Figure 11.

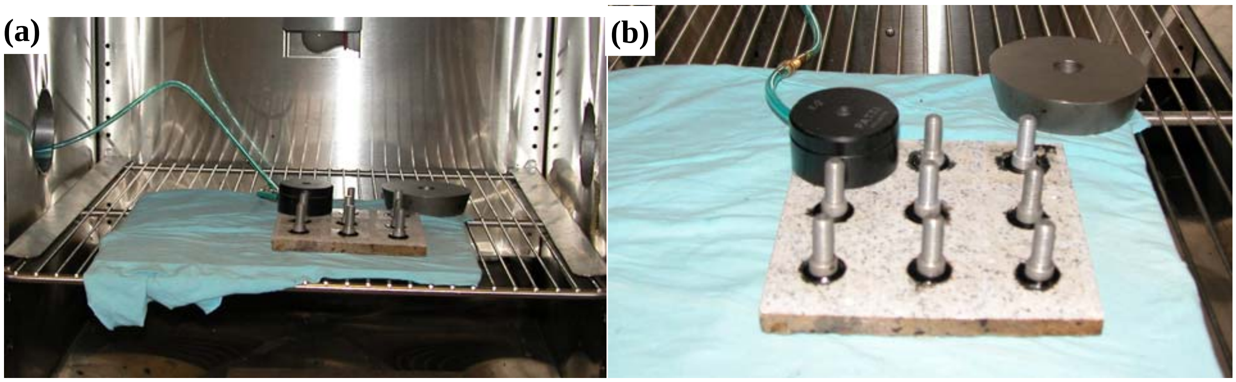


Figure 11 Photographs of PATTI samples; (a) samples in chamber and (b) PATTI test samples

3.3.3 Rolling Ball Test

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

In the ASTM standard specifications, the inclined ball stand is 65 mm in height and its angle is 21°30’. However, when the specified equipment size was used to test the viscosity of the fog seal emulsion, the traveling distance of the ball was too long to capture within the range of the equipment setup. Therefore, the height of the inclined ball stand has been changed to 15 mm, and the equipment size has been modified to 320 mm long and 50 mm wide, as determined by running a few trial tests. In order to maintain a level surface during curing and testing, a steel plate was used for the horizontal portion of the test setup, and an asphalt felt disk, which is normally used for chip seal laboratory samples, was attached to the steel plate. Four walls were constructed around the steel plate to prevent the fog seal emulsion from flowing off the plate. Figure 12 shows the modified rolling ball test equipment and emulsion samples.

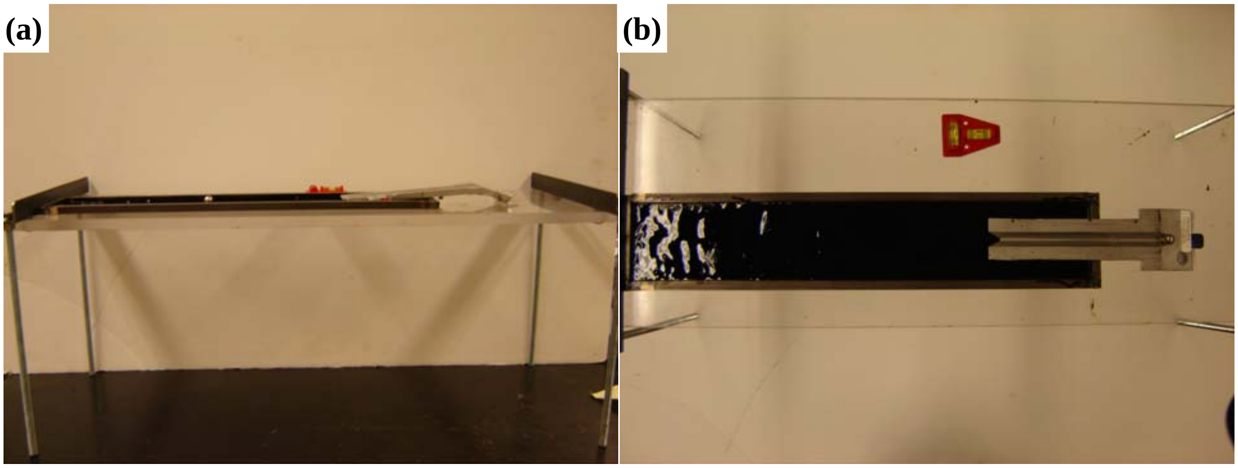


Figure 12 Rolling ball test: (a) side view and (b) plane view:

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

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

3.3.4 Damping Test

In the literature, the Wagner flow cup test is suggested as a field viscosity test for emulsions, but a trial test revealed that it is not suitable for fog seal emulsions because the volume of fog seal emulsions changes depending on curing time. Thus, it is difficult to obtain a certain amount of cured emulsion for the Wagner flow cup test. Hence, the NCSU research team has considered alternative field test methods to the Wagner flow cup test and identified a concept introduced by *Road Science LLC* that is based on the test method for tracking emulsion and aggregate. Briefly, the purpose of this test is to indicate, under standard conditions, the propensity of a fog seal emulsion to track or peel under traffic loading when applied at a specified application rate after a specified curing time using a wheel tracking device over the chip seal specimen. As stated previously, field test methods should be simple in design, and the test equipment should be portable for use in the field. Thus, the NCSU research team has developed a damping test method for field applications. One kilogram of dead weight was applied to the emulsion samples for 15 seconds instead of using a wheel tracking device, and absorbent pads were used between the emulsion samples and dead weight to enable visible results that serve to verify the curing status of the fog seal emulsions. In addition, the digital image processing (DIP) technique was utilized to express the visible results numerically.

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

In order to select an appropriate dead weight and application time, 1 kg, 3 kg, and 5 kg of dead weight were applied on emulsion samples for 10, 15, 60, 180, and 300 seconds. In many cases, the heavier weights and longer times damaged the absorbent pads. As a result of the trial tests, one kilogram of dead weight and 15 seconds were selected as the application criteria. The damping test setup can be seen in Figure 13.

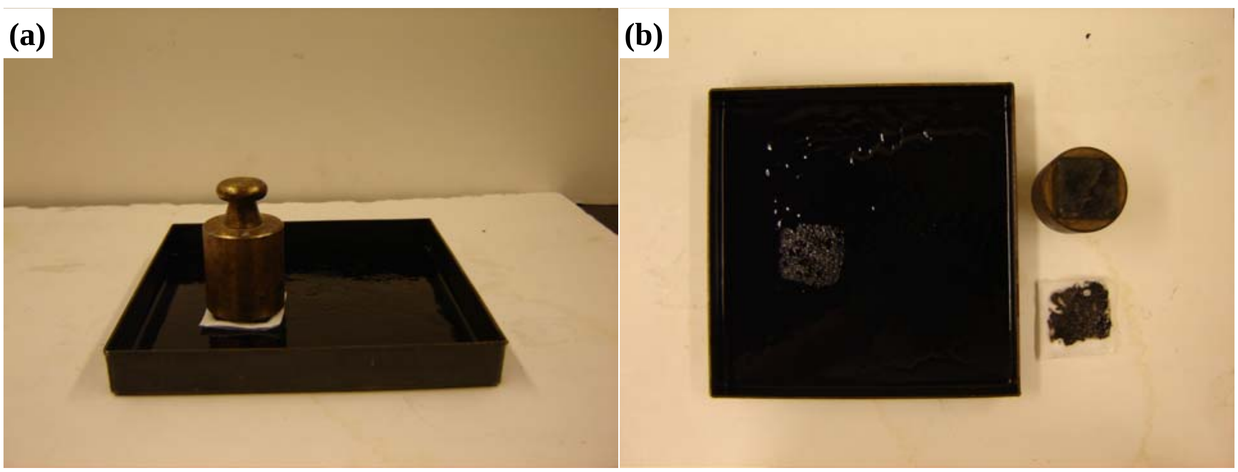


Figure 13 Damping test: (a) applied dead weight and (b) after testing

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

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

The curing rates for the fog seal emulsions can be quantified employing DIP. During the damping test, the absorbent pad is stained by the emulsion, and then the pad's surface is scanned using a Hewlett Packard digital scanner (HP Scanjet 4850) as a color BMP file with a resolution of 200 dpi. The digital image then is converted from a color scale to an 8-bit grayscale that consists of a single plane of pixels. Each pixel is encoded using a single number representing grayscale intensity values (GIVs) from 0 to 225. The grayscale image was cut down to 3.51 cm by 3.51 cm to 276 pixels in width and 276 pixels in height to maintain consistency for the size of the image pixels.

Figure 14 shows that the absorbent pads used for the damping test contain one or two holes in them as a result of the production process of the pads. In addition, even emulsion cured for 24 hours produces only a small amount of stain on the pads. Thus, acknowledging the holes in the pads and the small amount of stain on the pads is important in the analysis of the stained areas. The technique called *thresholding* in DIP was incorporated into this analysis using National Instruments Vision Assistant (NIVA) 7.0. The thresholding procedure is conducted by setting all the pixels that belong to the threshold interval to 1, and setting all the other pixels in the digital image to zero. After finding a critical threshold value, MATLAB®R2007a is utilized for the analysis of the stained areas. The value of 190 is set in the program as a threshold value, and then a grayscale image with GIVs ranging from 0 to 255 is converted into a binary image (black and white), which means a GIV of 0 or 1. The number or percentage of stained pixels can be calculated by adding together all the pixels with a GIV of 0 or 1.

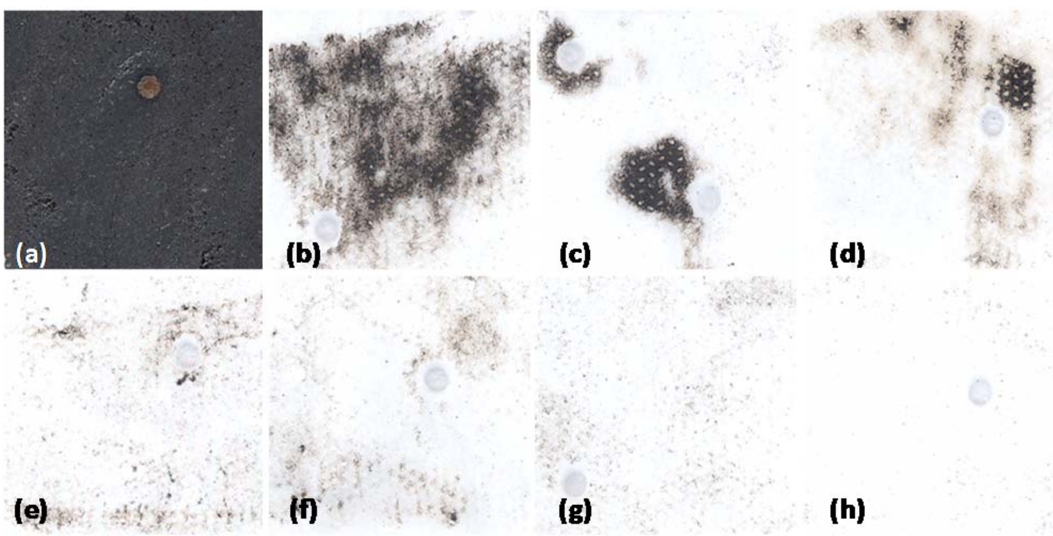


Figure 14 Examples of stained pads for damping test at 30°C: (a) 100%, (b) 44.1%, (c) 10.5%, (d) 6.5%, (e) 3.5%, (f) 2.4%, (g) 1.5%, and (h) 0.1%

3.4 Fog Seal Performance Evaluation

3.4.1 Aggregate Loss Test

3.4.1.1 Flip-Over Test

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

3.4.1.2 Vialit Test

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

Figure 15 Vialit test apparatus

3.4.1.3 Third Scale Model Mobile Load Simulator (MMLS3) Test

Testing with the MMLS3 is a new technique developed by the NCSU research team. This test targets both aggregate loss and bleeding. The MMLS3, shown in Figure 16, accelerates wear on the pavement and allows researchers to simulate years of damage in mere days. Chip seal samples must be fabricated for MMLS3 testing. Based on the size of the modified sweep test specimens, asphalt felt disks are cut down to 12 inches × 14 inches, and emulsion is applied on the felt paper with the dimensions of 7 inches width and 12 inches length, which is the same width as the MMLS3 wheel path. An actual photograph of the MMLS3 test specimens is shown in Figure 17. The advantage of using the modified sweep test specimens is that the aggregate loss can be determined accurately because the weight of the specimen can be measured by first removing the specimen from the bottom plate. The MMLS3 test procedure developed in the

HWY-2004-04 project involves the following steps:

1. Cure the specimens in the MMLS3 temperature chamber at 95°F (35°C) for 12 hours and 35 ± 3% relative humidity, as specified by ASTM D7000 *Standard Test Method for Sweep Test of Bituminous Emulsion Surface Treatment Samples*.
2. Weigh the initial specimen.
3. Condition the temperature of the specimens to 77°F (25°C) for 3 hours for the aggregate retention test.
4. Apply MMLS3 loading for 10 minutes, which is the time required for the MMLS3 to complete one wandering cycle, and then weigh the specimen.
5. Apply MMLS3 loading for 160 minutes, and weigh the specimen periodically.
6. Conduct the British pendulum test (BPT), sand patch and laser tests, visual survey, and transverse profiling.
7. Condition the specimens to 104°F (40°C) for 3 hours for the bleeding test.
8. Apply MMLS3 loading for 4 hours at 104°F (40°C).
9. Weigh the final specimen.
10. Conduct the BPT, laser scanning, and a visual survey.

Figure 16 MMLS3


Figure 17 MMLS3 test specimens before loading

Including the specimen fabrication time, this MMLS3 procedure takes one week to complete. The following information can be obtained at the end of the testing:

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

Representative chip seal specimens used in the MMLS3 testing for aggregate retention tests at 77°F (25°C) and bleeding tests at 122°F (50°C) are shown in Figure 18 after the tests were run**.**

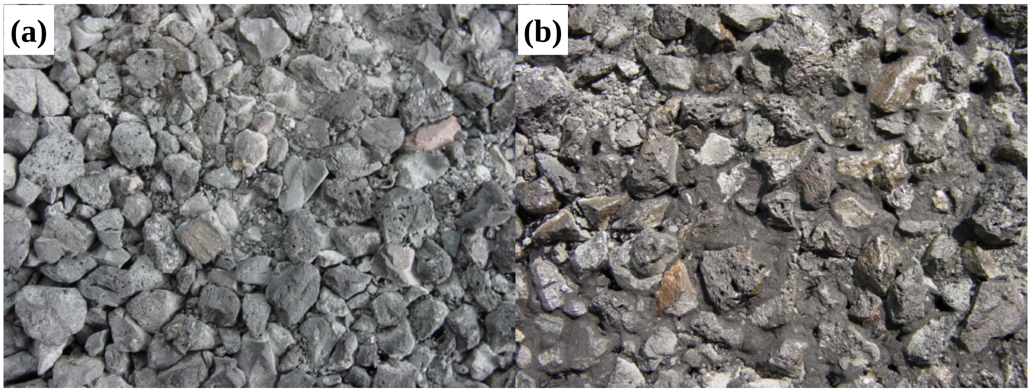


Figure 18 MMLS3 test specimens: (a) after 6,050 wheel load applications at 77°F (25°C); (b) after 11,920 wheel load applications at 25°C followed by 22,070 wheel load applications at 122°F (50°C)

3.4.2 Surface Texture Evaluation

3.4.2.1 Laser Profiler Test

The three-dimensional (3-D) laser profiler, which has been used in previous research, originally included a 3-D line laser capable of scanning an area 97 mm wide and 1,727 mm long during each pass. However, its unwieldy size caused some problems in the field. Therefore, the NCSU research team developed a portable 3-D laser profiler that can be used both in the field and in the laboratory. In order to analyze the pavement surface texture, only the data obtained from within the wheel path are needed, rather than the entire lane width. After conducting sensitivity analysis, which was conducted also in previous research (Research Project No. HWY-2009-01), approximately 280 mm was determined as the width of the wheel path. The portable laser profiler design includes the following features: XY Gantry robot, encoders, GPS, PC (Windows XP compatible), external USB interface, rubber wheels, touch screen LCD, stowaway handle, carrying handles, graphical user interface (GUI), rechargeable battery, and AC power. The portable laser profiler weighs approximately 100 lbs, and the scan time, although variable, takes about five minutes to complete, which is faster than the previously used Selcom RoLine FP1000 line laser. Figure 19 provides the dimensions and a photograph of the portable laser profiler.

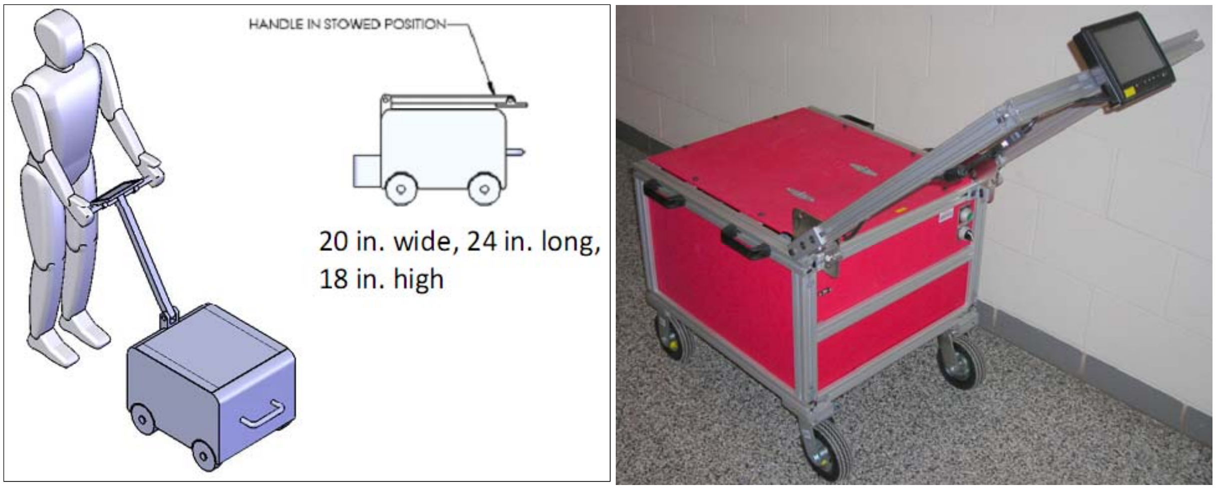


Figure 19 Portable laser profiler

3.4.2.2 Mean Profile Depth Analysis

The mean profile depth (MPD) is a parameter that represents the exposed texture depth of a pavement surface, and has been used especially for chip seal surface analysis in some of NCSU's research projects. The MPD is inversely related to the embedment depth; that is, as the EAR increases (as applied on a given single aggregate layer), the MPD decreases, and when the EAR is decreased for a given aggregate structure, the MPD will increase. Equation (1) is the definition of MPD given in Transit New Zealand (2005).

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

The various chip seal parameters that make up Equation (1) are shown schematically in Figure 20. In the diagram, the MPD clearly indicates the roughness (i.e., macro-surface texture) and aggregate exposure depth of the chip seal. Roughness is an important factor, because it provides the skid resistance and friction needed for vehicles to brake adequately. The aggregate exposure depth is important because it is a function of the aggregate embedment depth, which is the most important factor that controls the aggregate loss and bleeding performance of chip seals. A low MPD value indicates the likelihood of bleeding and skid resistance problems. A high MPD value after construction indicates the possibility of excessive aggregate loss and, therefore, bleeding due to aggregate loss. Therefore, a medium MPD value is desirable for optimal performance.

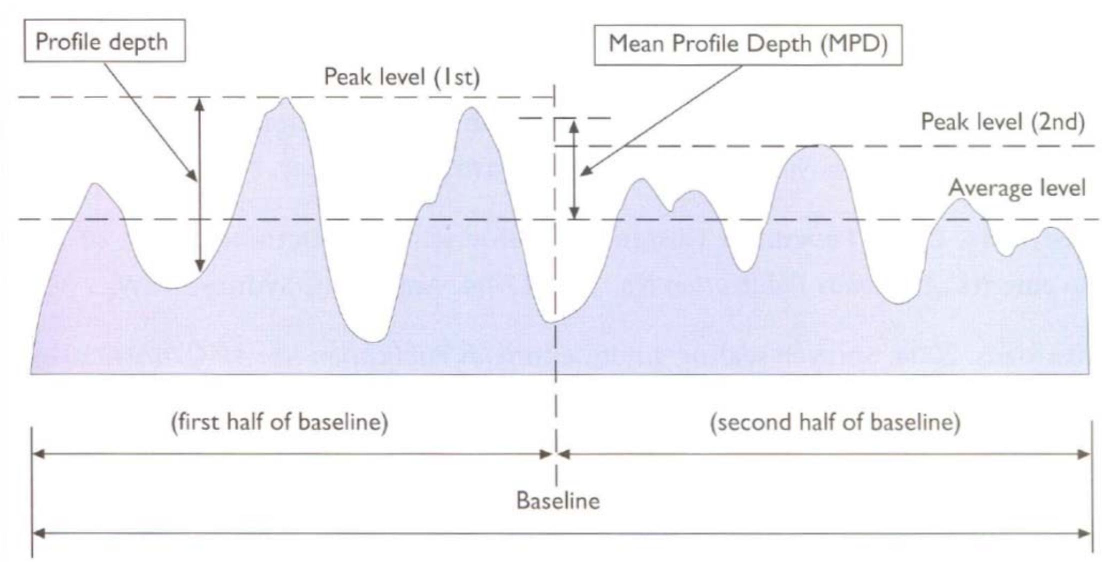


Figure 20 Schematic diagram of mean profile depth determination

3.4.3 Bleeding Analysis

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

The fog seal samples are placed in the oven at 40°C for three hours prior to four hours of bleeding testing. During the four hours of MMLS3 loading, the test temperature, 40°C, is controlled inside the temperature chamber. This bleeding test process simulates the bleeding of fog seal surfaces during the summer.

The bleeding test analysis for chip seal specimens was developed and verified by using DIP results from previous research, but DIP cannot be used for fog seal specimens because the GIVs acquired from digital images of fog seal specimens are not clear enough to distinguish between the bleeding area and unbleeding area. In order to quantify the bleeding area of the fog seal specimens, fog sealed chip seal specimens are scanned using a Hewlett Packard digital scanner (HP Scanjet 4850) as a color BMP file with a resolution of 200 dpi.

The digital image is converted from a color scale to an 8-bit grayscale that consists of a single plane of pixels. Each pixel is encoded using a single number to represent GIVs from 0 to 225. The grayscale image was cut down to 7 inches ×7 inches to 1,400 pixels in width and 1,400 pixels in height to maintain consistency for the size of the image pixels. This size also covers the width of the MMLS3 wheel path. The contour of the bleeding area is drawn on the digital images using Adobe Photoshop CS4, and the bleeding area is calculated using Equation (2).

$$Bleeding\ (\%) = \frac{A_{Bleeding}}{A_{Total}} \times 100 \qquad (2)$$

where

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

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

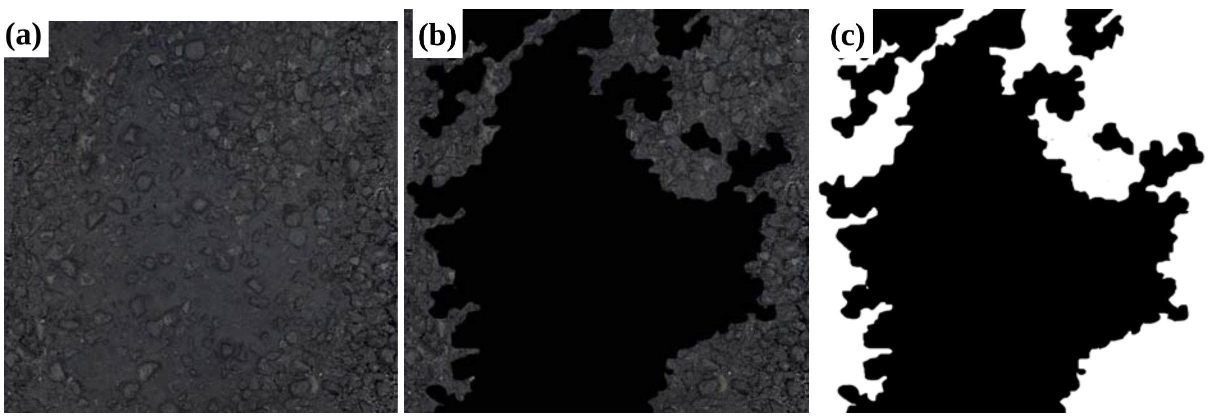


Figure 21 Example of bleeding analysis: (a) sample after bleeding test, (b) sample applied bleeding area, and (c) bleeding area

3.4.4 Skid Resistance Test

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

As part of the HWY-2004-04 project, a comprehensive review of these two skid resistance test methods was conducted. This review included not only the technical soundness of the test method, but also the equipment availability, ease of the test procedure, and the quality of its performance in previous research. Although textural test methods are simpler in nature than drag test methods, more reliable results can be obtained from drag testing whereby the skid resistance of a pavement surface can be measured directly. The review concluded that the locked-wheel skid test (LWST) and BPT are the most reliable means of measuring the skid resistance of the surface treatment.

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

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

Figure 22 shows the LWST and BPT apparatus.

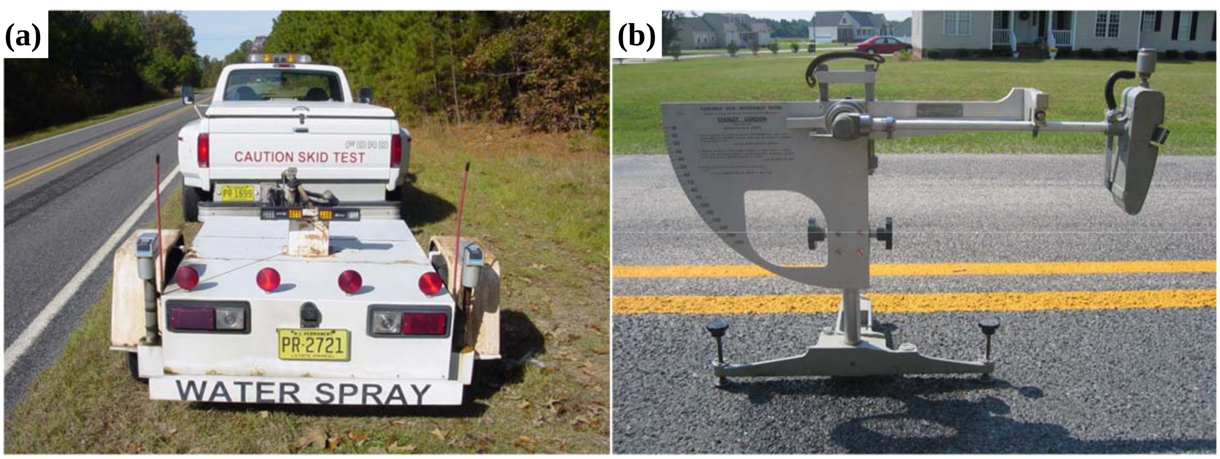


Figure 22 Equipment for the: (a) locked-wheel skid test (LWST) and (b) british pendulum test (BPT)

Because the LWST cannot be performed in the laboratory, the relationship between the SNs obtained from the LWST and the BPNs obtained from the BPT is helpful to know. During the HWY-2004-04 project, Mr. Jerry Blackwelder, with the help of the NCSU research team, conducted BPT and LWST tests for about a dozen surface treatment projects in the fall of 2004. The resultant data were used to develop the relationship between the SN and BPN so that BPNs measured from laboratory experiments could be converted to SNs in the field. This relationship can be seen in Figure 23.

In this research, the BPT is used to determine the skid resistance of fog seals with varying rates of emulsion. In addition, the textural test method, which is based on laser profiling, is used to develop the relationship between the aggregate exposure depth and the skid resistance. The laser profiling method is described in Section 3.4.2.

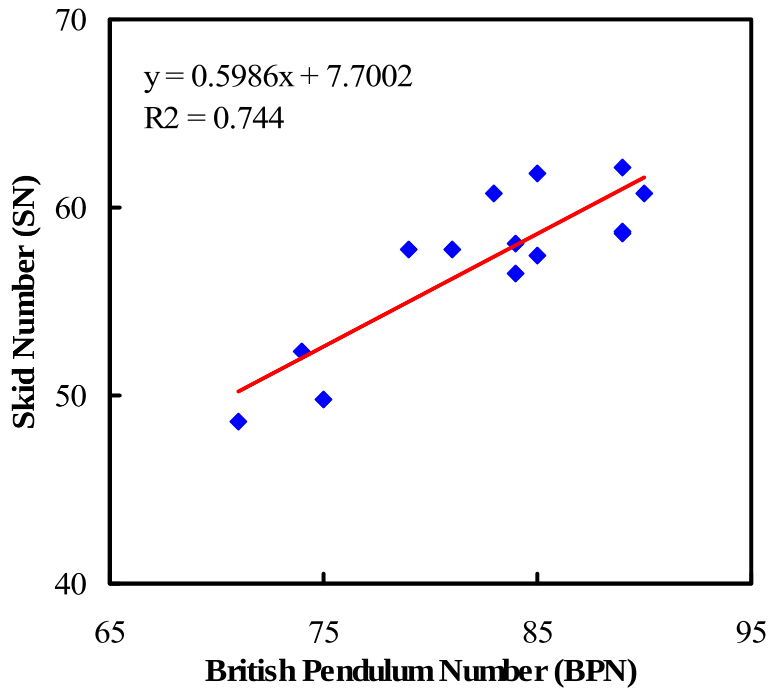


Figure 23 Correlation between average BPN and average SN

4. MATERIALS USED IN THE STUDY

4.1 Emulsion Type

According to the literature, the CSS-1h (cationic slow-setting) and SS-1h (slow-setting) types of emulsions are commonly used in fog seal applications (California DOT 2003). For the granite and lightweight aggregates commonly used in North Carolina, the CSS-1h emulsion best matches the surface charge of these aggregates. From the literature review, the NCSU research team also found that the Minnesota DOT uses PME for its fog seals. Specially-diluted CRS-2Pd (cationic rapid-setting, polymer-modified) emulsion has replaced SS-1h/CSS-1h emulsion as the MnDOT's standard for fog sealing, and essentially serves as their control emulsion. The emulsion is diluted by the manufacturer as 3 parts emulsion to 1 part water for a specified residue content of 51% (King et al. 2007). During the early stages of its research, the NCSU research team considered the use of CRS-2Pd emulsion for fog seal performance testing, but decided against the idea based on information obtained from Mr. Thomas Wood, who is conducting a study of chip seals and fog seals for the MnDOT. He advised the NCSU research team that CSS-1h emulsion typically is used for fog seals because the hard-based asphalt is less sticky than other types of emulsion. The CRS-2Pd emulsion is used only on shoulders, rumble strips, and older recreational trails for fog seals because it stays sticky longer than other types, and live traffic could pull chips out of the fresh chip seal. Some suppliers have tried to dilute CRS-2L (cationic rapid-setting, latex-modified), which is not polymer-modified but latex-modified, but this method has not been successful.

From this information regarding emulsion types, the CSS-1h emulsion is selected as an unmodified emulsion type. The CQS-1h (cationic quick-setting) emulsion also is selected as an unmodified emulsion type to investigate if this emulsion can reduce the curing time. This emulsion has a minimum binder content of 57% and is rarely used for fog seals; it is mainly used as a polymer-modified (latex) version of a slurry seal.

In order to compare unmodified emulsions and PMEs, both Grip-Tight, produced by Hammaker East, Ltd., and Revive*TM*, produced by Road Science, LLC*TM*, have been selected for the fog seal study. The Grip-Tight emulsion is a highly polymerized asphalt emulsion that is specially designed for fog seal and flush coat applications. The best feature of this emulsion is that it allows for a short curing time, i.e., early traffic opening time. According to information provided by the manufacturer, traffic could be back on the road within 15 minutes of application. The Revive*TM* emulsion is a quick-setting fog seal emulsion that is specially designed to break and cure significantly faster than traditional fog seal emulsions. The main advantage of this emulsion is similar to that of Grip-Tight. The emulsion company states that Revive*TM* takes only 30 to 45 minutes to break and cure before the road can be opened to traffic.

4.2 Emulsion Rates

From the literature review it is found that the range of typical application rates for fog seal emulsions, which are diluted with water, is from 0.03 to 0.22 gal/yd^2. In this research, the fog seal EARs are considered when the fog seal is applied on the chip seal surface, which has a rougher surface texture than typical asphalt pavement. A few representative fog seal EARs were selected through the curing time study, and then they were used for the fog seal performance tests. The fog seal EARs were determined and adjusted depending on the test method. Detailed information can be found in Chapter 5.

4.3 Type of Chip Seal

As mentioned before, the ultimate purpose of this research is to create a guideline for the application of fog seals on chip seal pavements commonly used in North Carolina; therefore, representative chip seal samples must be fabricated for fog seal performance testing. In this research, one type of chip seal texture has been created using 0.25 gal/yd^2 of CRS-2L emulsion and 10 lb/yd^2 of lightweight aggregate, as recommended from the HWY-2008-03 research project. It is acknowledged that additional chip seal types should be tested for further research.

5. EVALUATION OF FOG SEAL PERFORMANCE

5.1 Curing Time Study

5.1.1 Emulsion Properties Test

The NCSU research team conducted a simple water compatibility test and residual asphalt content test to better understand the compatibility between water and emulsion and the amount of residual asphalt of the study emulsions.

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

The residual asphalt content tests were conducted based on ASTM D 244. The CSS-1h and CQS-1h emulsions were diluted with water using a dilution rate of 50 percent. The Revive^{TM} emulsion is used in the field with a dilution ratio of 60% emulsion to 40% water, which is recommended by the emulsion manufacturer. The Grip-Tight emulsion is produced for ready use in the field without the diluting process recommended by the emulsion manufacturer. However, once the NCSU research team obtained the Grip-Tight emulsion, it was found that it had been produced with more than typical asphalt residue due to cold weather. So, for the tests, the Grip-Tight emulsion had to be diluted by 45% asphalt residue. Because this research is interested only in each emulsion's properties, the same dilution rates should be applied to each emulsion type. However, because it is more important to find an emulsion that shows better performance when it is used on a typical chip seal surface, the optimized dilution rates recommended by the emulsion manufacturer were applied to each emulsion during this research project.

Three samples were fabricated for each test, and the samples were weighed after complete curing. Table 7 presents the test results for the simple water compatibility test and the residual asphalt content test.

Table 7 Material Properties of Study Emulsions

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

5.1.2 Evaporation Test

The evaporation test is used to help determine the emulsion curing time, and the NCSU research team has conducted this test at several EARs and temperatures. As explained in Section 3.3.1, the evaporation test was conducted at three temperatures, 20°C, 30°C, and 40°C, each of which has eight fog seal EARs, 0.02, 0.06, 0.09, 0.12, 0.16, 0.19, 0.23, and 0.26 gal/yd^2. The test temperatures were determined to range between 20°C and 40°C based on monthly normal high temperatures between March and October for North Carolina cities. The fog seal EARs range from 0.02 to 0.26 gal/yd^2 based on AEMA recommendations and the literature review. For the test, all four study emulsions, CSS-1h, CQS-1h, Revive*TM*, and Grip-Tight, were used, and two replicates were prepared for each condition. The curing time is determined when the percentage of water loss is less than 10% based on the asymptotic trends of all the emulsions.

Figure 24 shows the results of the evaporation tests for the CSS-1h and CQS-1h emulsions with representative EARs of 0.06, 0.12, 0.19, and 0.26 gal/yd^2, and at 20°C, 30°C, and 40°C. From these tests, the NCSU research team has found that two emulsions, CSS-1h and CQS-1h, have similar curing time trends, but the CSS-1h emulsion shows a little shorter curing time than the CQS-1h emulsion. Based on this finding, the CSS-1h emulsion is used as the representative unmodified emulsion type for the evaporation test.

In order to understand the curing time trends of each emulsion for different curing temperatures, Figure 25 shows the results of the evaporation tests for each emulsion at three different temperatures. Figure 26 shows the curing time trends for the different emulsion types.

The NCSU research team has been informed that a few sections in North Carolina have been constructed recently for fog seal application using the Grip-Tight emulsion. For the construction, 0.12 gal/yd^2 of Grip-Tight emulsion was applied in the field, and traffic was opened approximately 1 hour later. Based on this information and the curing time trends for all the emulsions, the evaporation tests for 0.12 gal/yd^2 of fog seal emulsion for all types of emulsions are compared in Figure 27.

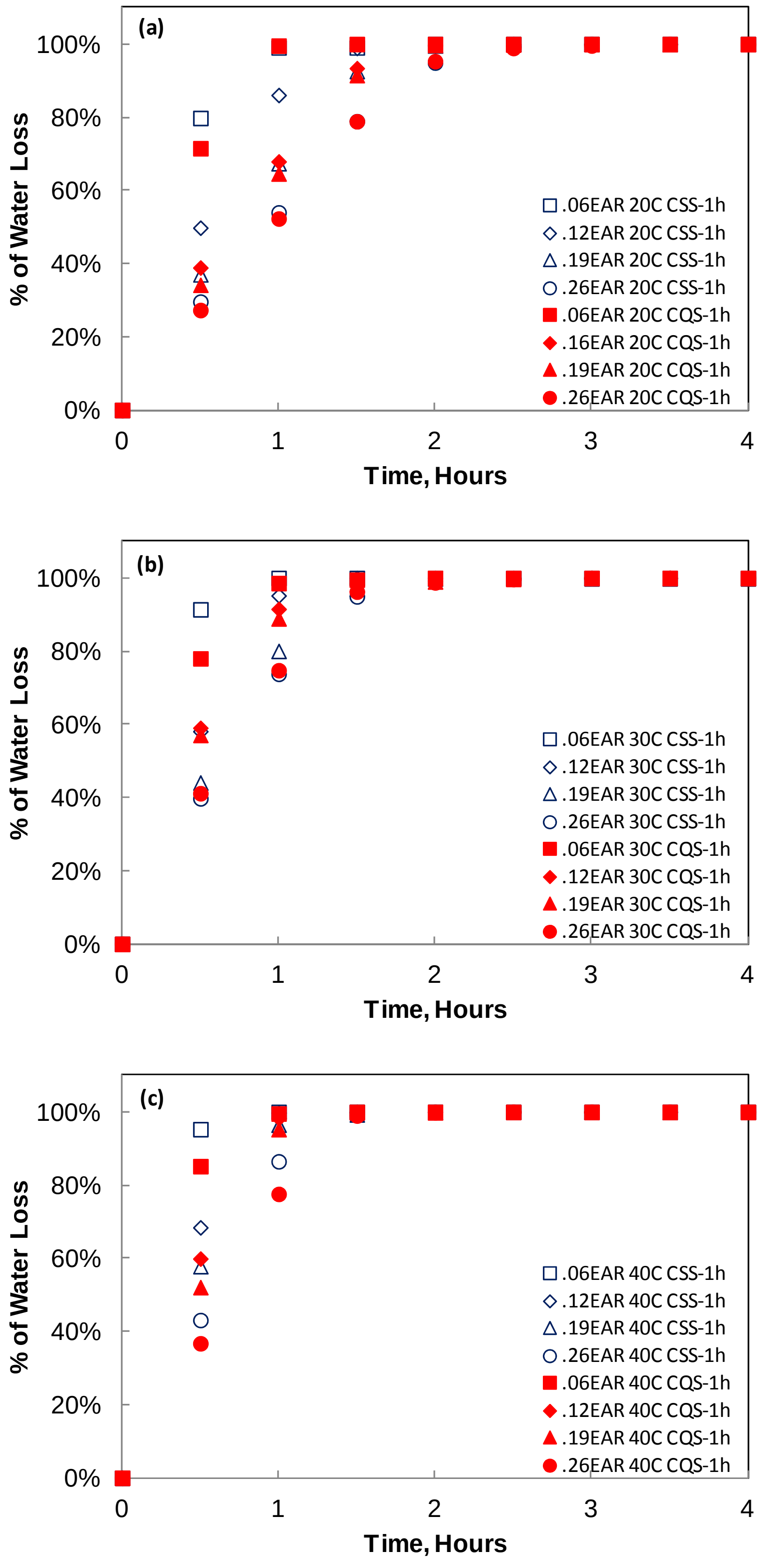


Figure 24 Evaporation test results for CSS-1h and CQS-1h emulsions of 0.06, 0.12, 0.19, and 0.26 gal/yd^2 at: (a) 20°C, (b) 30°C, and (c) 40°C

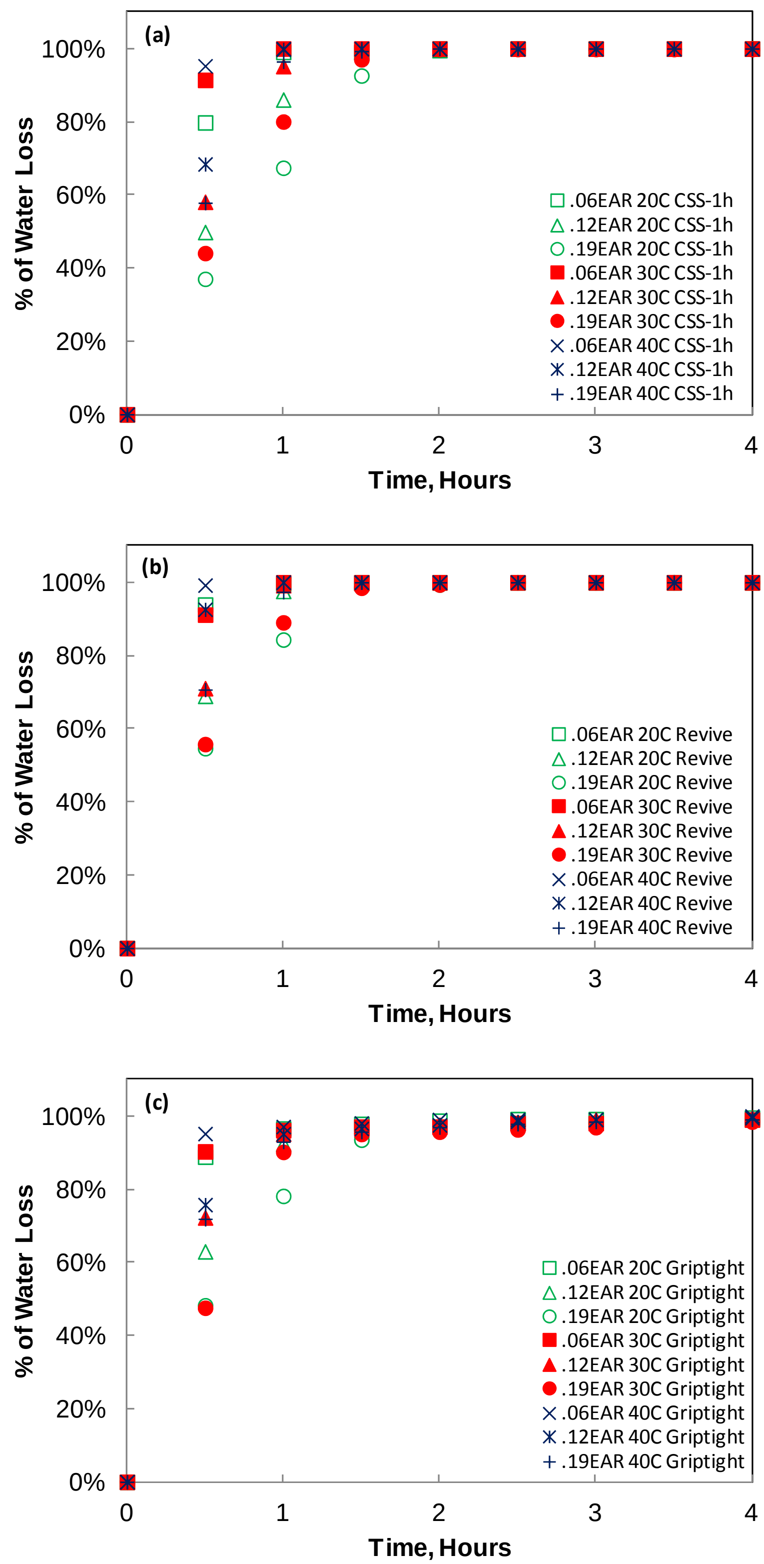


Figure 25 Evaporation test results at all temperatures for 0.06, 0.12, and 0.19 gal/yd^2 of: (a) CSS-1h, (b) Revive^{TM}, and (c) Grip-Tight emulsions

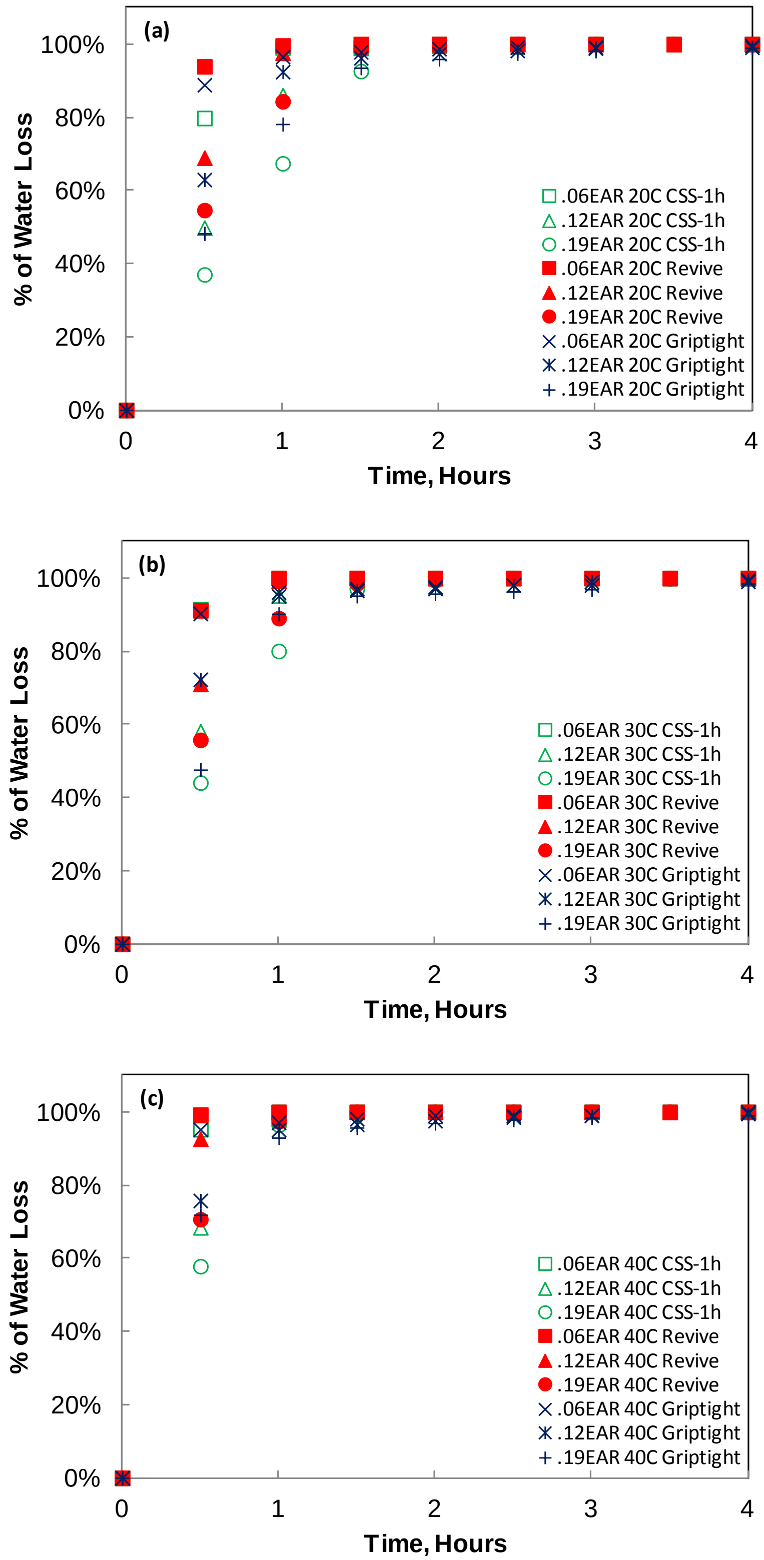


Figure 26 Evaporation test results for CSS-1h, Revive^{TM}, and Grip-Tight emulsions of 0.06, 0.12, and 0.19 gal/yd^2 at: (a) 20°C, (b) 30°C, and (c) 40°C

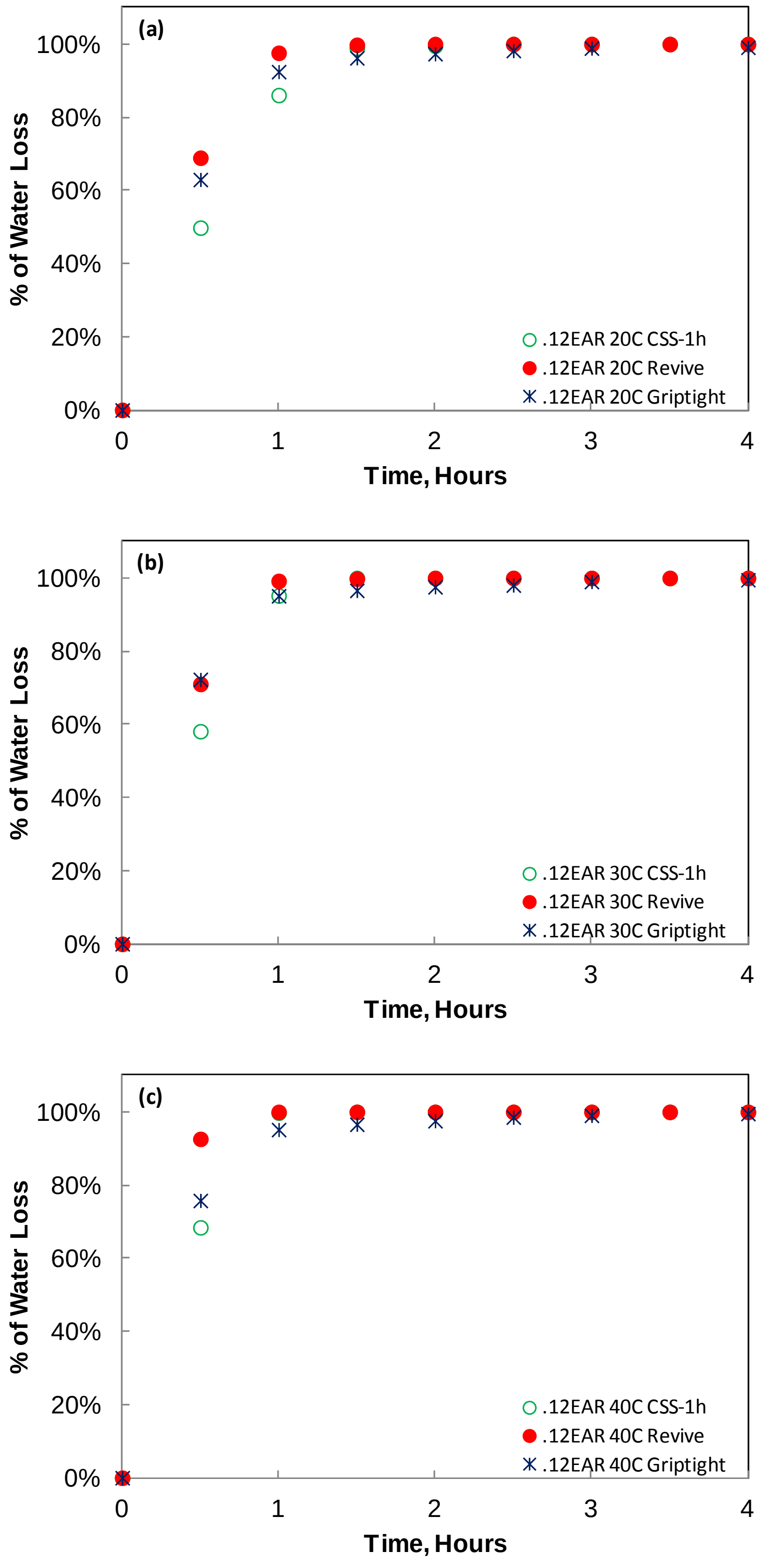


Figure 27 Evaporation test results for CSS-1h, Revive^{TM}, and Grip-Tight emulsions of 0.12 gal/yd^2 at: (a) 20°C, (b) 30°C, and (c) 40°C

Figure 25 indicates that all three types of emulsion show short curing times once the samples are placed at a high temperature. Most samples can reach their asymptotic percentage of water loss within 1.5 hours, except the CSS-1h emulsion samples with a high EAR (0.19 gal/yd^2) tested at 20°C.

Figure 26 shows similar curing time trends for the Revive^{TM} and Grip-Tight emulsions at all three temperatures, but the CSS-1h emulsion shows a little longer curing time. The curing times vary between each emulsion, especially at 20°C.

Figure 27 shows emulsion samples that were tested with an EAR of 0.12 gal/yd^2 at three temperatures. These results show that most samples tested at 30°C and 40°C reach their asymptotic percentage of water loss within one hour. Table 8 presents details regarding curing time values in terms of temperature for each emulsion.

As mentioned before, the curing times for each sample are determined when the percentage of water loss is less than 10% based on the asymptotic trends of all the emulsions. Table 8 presents the determined curing times for all the emulsion types and fog seal EARs.

Table 8 Curing Times for the CSS-1h, CQS-1h, Revive^{TM}, and Grip-Tight Emulsions

Application Rate, gal/yd^2	**Curing Time, Hour**											
	20°C				**30°C**				**40°C**			
	CSS-1h	CQS-1h	Revive^{TM}	Grip-Tight	CSS-1h	CQS-1h	Revive^{TM}	Grip-Tight	CSS-1h	CQS-1h	Revive^{TM}	Grip-Tight
0.02	0.5	1.0	0.5	0.5	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5
0.06	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5	0.5	1.0	0.5	0.5
0.09	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0
0.12	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0
0.16	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.19	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0
0.23	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.0	1.0
0.26	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0

Table 8 also shows that the modified emulsions (Revive^{TM} and Grip-Tight) have shorter curing times than the unmodified emulsions (CSS-1h and CQS-1h). In particular, all the samples are cured within one hour for 0.12 gla/yd^2, except the CSS-1h and CQS-1h emulsions tested at 20°C.

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

Therefore, it is necessary to check the difference in curing times between the recommended and other dilution rates.

The NCSU research team has conducted evaporation tests using the same asphalt residue rate for each emulsion. For this test, the CSS-1h, Revive^{TM}, and Grip-Tight emulsions were selected, and EARs of 0.06, 0.12, and 0.12 gal/yd^2 were applied at 30°C. These three emulsions were diluted prior to testing using the same dilution rate of 33% asphalt residue. Figure 28 and Table 9 present all the test data, and Figure 29 shows the results for an EAR of 0.12 gal/yd^2.

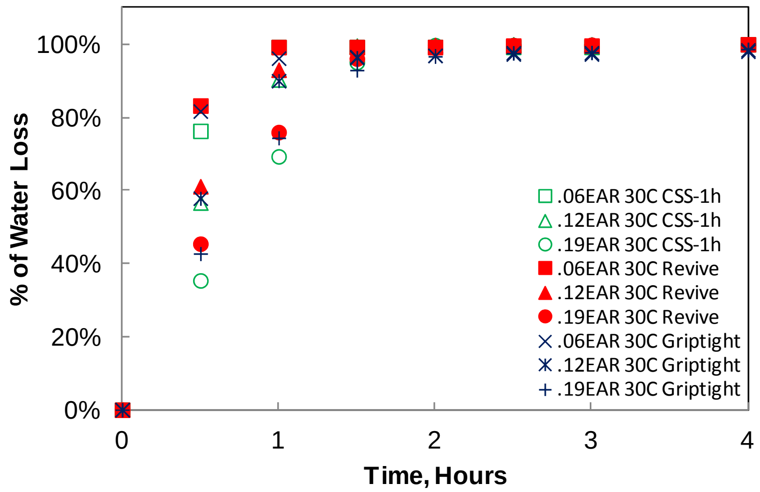


Figure 28 Evaporation test results for CSS-1h, Revive^{TM}, and Grip-Tight emulsions with same asphalt residue

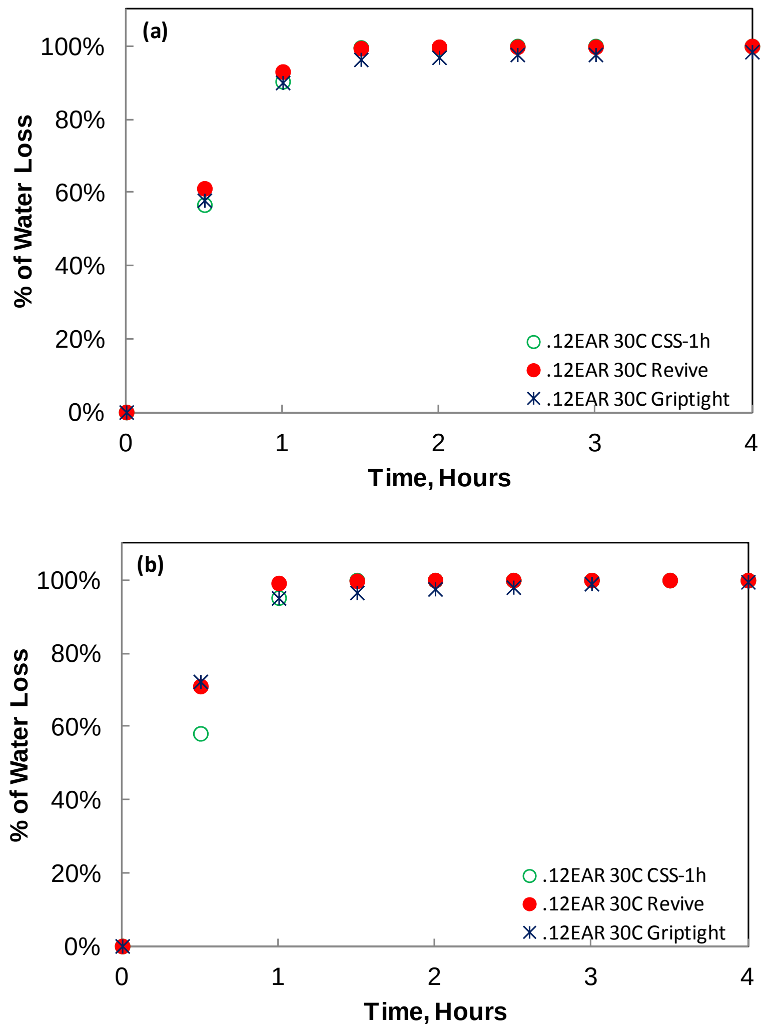


Figure 29 Evaporation test results with 0.12 gal/yd^2 of CSS-1h, Revive^{TM}, and Grip-Tight emulsions for comparison: (a) same asphalt residue and (b) recommended dilution rate

Table 9 Curing Times for the CSS-1h, Revive^{TM}, and Grip-Tight Emulsions at 30°C

Application Rate, gal/yd^2	**Curing Time, Hour**					
	Recommended Dilution Rate			**Same Asphalt Residue**		
	CSS-1h	Revive^{TM}	Grip-Tight	CSS-1h	Revive^{TM}	Grip-Tight
0.02	0.5	0.5	0.5	-	-	-
0.06	0.5	0.5	0.5	1.0	1.0	1.0
0.09	1.0	1.0	1.0	-	-	-
0.12	1.0	1.0	1.0	1.0	1.0	1.0
0.16	1.0	1.0	1.0	-	-	-
0.19	1.5	1.5	1.0	1.5	1.5	1.5
0.23	1.5	1.5	1.5	-	-	-
0.26	1.5	1.5	1.5	-	-	-

Figure 28, Figure 29, and Table 9 indicate that the curing times for a low EAR (0.06 gal/yd^2) of the same asphalt residue samples are lengthened for all emulsion types, but the curing times for high EARs (0.12 and 0.19 gal/yd^2) of the same asphalt residue samples are the same as for the recommended dilution rate samples.

5.1.3 PATTI Test

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

When considering the results of the evaporation tests for the four types of emulsions, the NCSU research team realized that the curing times determined from the evaporation tests may not yield sufficient information to determine the minimum recommended curing times for fog seal emulsions. The evaporation test considers only how fast water evaporates from an emulsion by measuring the weight of the emulsion, so it does not capture the advantages of modified fog seal emulsions, such as higher adhesive strength values than unmodified emulsions. Consequently, the NCSU research team has employed another test method, the PATTI test, to help determine the minimum curing times for fog seal emulsions in addition to the curing times determined from the evaporation tests.

The NCSU research team conducted PATTI tests at different curing times and selected EARs based on the evaporation test results. The PATTI tests were conducted at times of 0.5, 1.0, 1.5, 2.0, 3.0, and 24 hours, at EARs of 0.06, 0.12, 0.19, and 0.25 gal/yd^2, and at temperatures of 25°C, 30°C, and 35°C for the three emulsion types, CSS-1h, CQS-1h, Revive*TM*, and Grip-Tight. However, during the PATTI tests, the team found that the bond strength values at EARs of 0.06 and 0.12 gal/yd^2 were erroneous because the volume of the emulsion was not enough to fill the gap between the pull-stub and the substrate. Thus, only the PATTI data for EARs of 0.19 and 0.25 gal/yd^2 are used for comparison.

Once the PATTI test was performed for the Grip-Tight emulsion, another problem arose. The bond strength values of the Grip-Tight emulsion were much less than those of the other emulsions. Although visual observation of the Grip-Tight emulsion did not indicate that its condition was bad, it was still considered to be broken. Unfortunately, the manufacturer cannot produce more Grip-Tight emulsion due to seasonal issues, but the PATTI test will be conducted as soon as new emulsion is obtained. Figure 30 shows the bond strength values of Grip-Tight versus the other emulsions at 25°C. It shows that the bond strength values of the Grip-Tight emulsion are much lower than those of other emulsions, and also that the bond strength values of the Grip-Tight emulsion do not show any trends as a function of curing time, unlike the other emulsions.

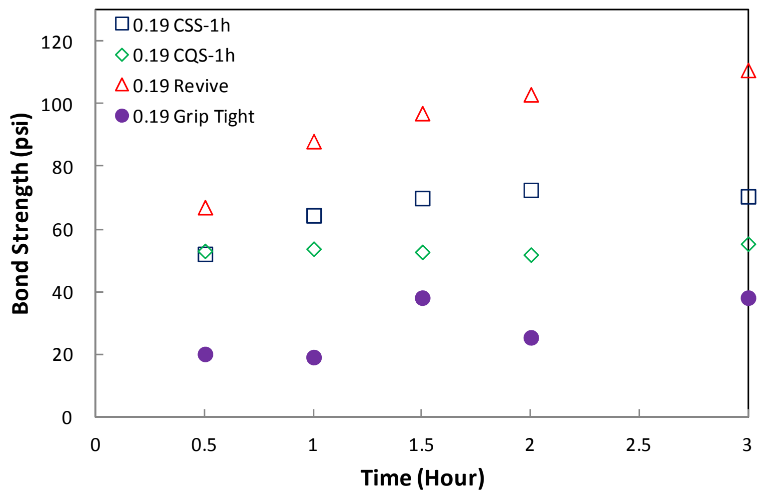
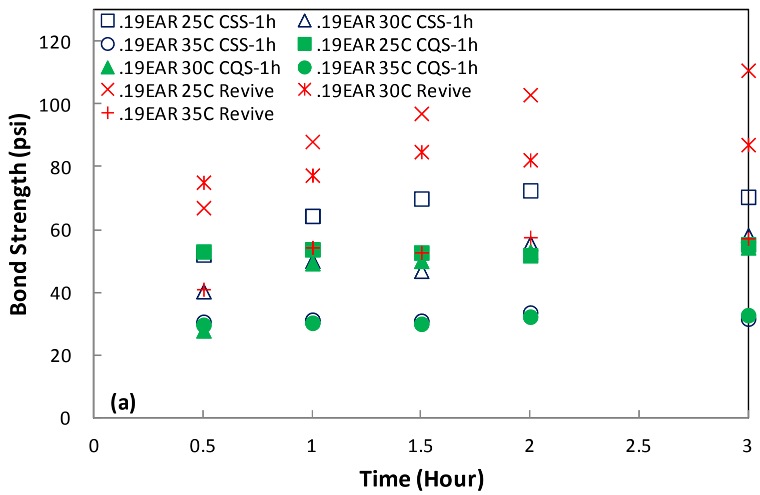


Figure 30 Bond strength value comparison between Grip-Tight and other emulsions at 25°C

Figure 31 and Figure 32 show the results of the PATTI tests at all study temperatures and for all emulsion types for EARs of 0.19 and 0.25 gal/yd^2. Figure 31 lists all the bond strength values according to the study EARs of 0.19 and 0.25 gal/yd^2. Figure 32 presents all the bond strength values at each temperature, 25°C, 30°C, and 35°C.

Table 10 and Table 11 present the bond strength values for all three study emulsions with the two application rates at the three curing times, and also present the percentage of bond strength as determined by dividing the bond strength values at different curing times by the full bond strength, which is determined at 24 hours.



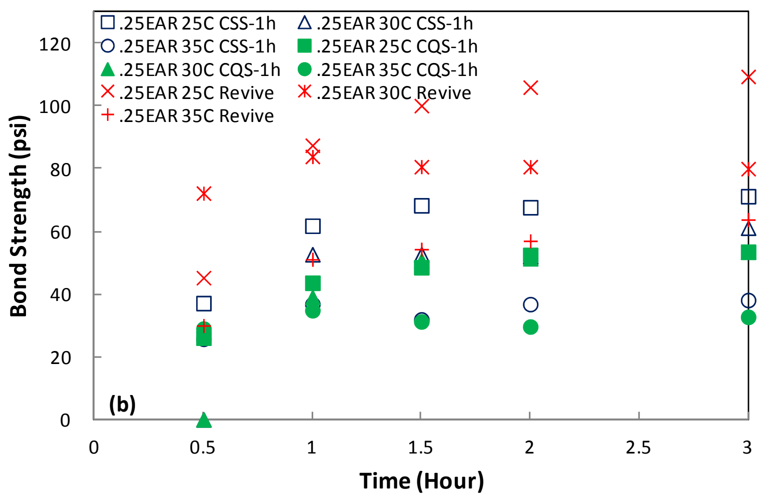


Figure 31 PATTI test results at all temperatures and emulsions for: (a) 0.19 gal/yd^2 and (b) 0.25 gal/yd^2

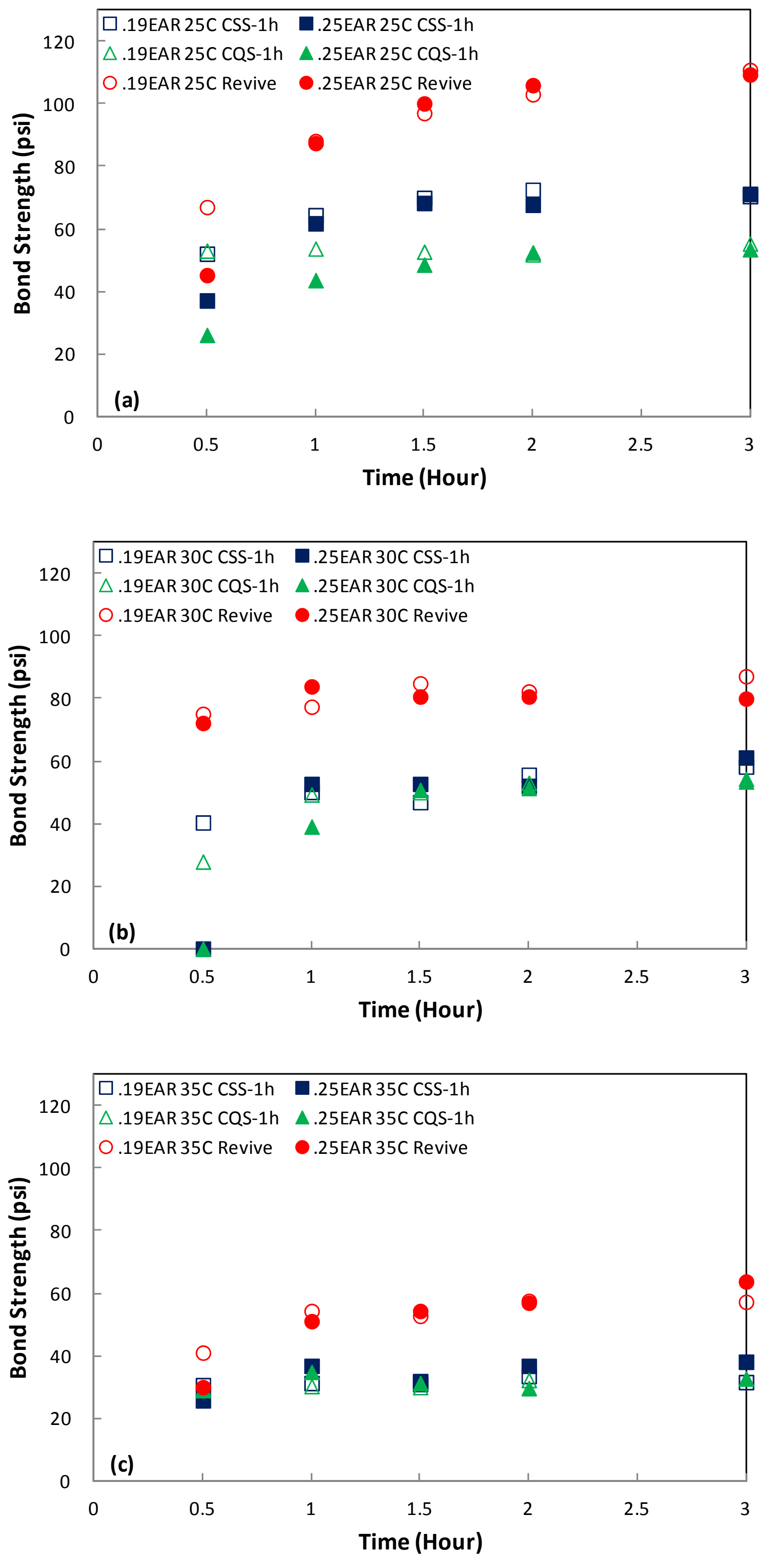


Figure 32 PATTI test results at all EARs and emulsions at: (a) 25°C, (b) 30°C, and (c) 35°C

Table 10 Bond Strength Values for CSS-1h, CQS-1h, and Revive^{TM} Emulsions

Temperature, °C	EARs, gal/yd^2	Emulsion Types	Bond Strength (psi) at Curing Time, Hour					
			0.5 hr	1.0 hr	1.5 hr	2.0 hr	3.0 hr	24 hr
25	0.19	CSS-1h	52.07	64.42	69.94	72.54	70.50	75.79
		CQS-1h	53.05	53.74	52.72	51.85	55.32	55.65
		Revive^{TM}	67.02	88.14	97.08	103.09	110.89	121.28
	0.25	CSS-1h	37.13	61.82	68.32	67.73	71.24	73.13
		CQS-1h	26.08	43.63	48.58	52.48	53.51	56.17
		Revive^{TM}	45.25	87.49	100.16	106.01	109.44	120.63
30	0.19	CSS-1h	40.38	50.12	46.87	55.65	58.25	55.32
		CQS-1h	27.87	49.31	50.06	53.05	54.35	55.65
		Revive^{TM}	75.14	77.42	84.89	82.29	87.17	88.47
	0.25	CSS-1h	0.00	52.72	52.72	52.09	61.17	59.55
		CQS-1h	0.00	39.08	50.77	51.42	53.50	59.22
		Revive^{TM}	72.22	83.92	80.67	80.67	80.02	98.21
35	0.19	CSS-1h	30.63	31.28	30.95	33.55	31.60	30.95
		CQS-1h	29.65	30.30	29.98	32.25	32.74	35.18
		Revive^{TM}	41.03	54.35	52.78	57.60	57.27	64.75
	0.25	CSS-1h	25.75	36.80	31.93	36.80	38.10	39.40
		CQS-1h	29.00	34.85	31.28	29.65	32.74	35.66
		Revive^{TM}	29.98	51.10	54.35	56.98	63.77	64.42

Table 11 Percentages of Full Bond Strength for CSS-1h, CQS-1h, and Revive^{TM} Emulsions

Temperature, °C	EARs, gal/yd^2	Emulsion Types	Percentage Bond Strength at Curing Time, Hour					
			0.5 hr	1.0 hr	1.5 hr	2.0 hr	3.0 hr	24 hr
25	0.19	CSS-1h	69	85	92	96	93	100
		CQS-1h	95	97	95	93	99	100
		Revive^{TM}	55	73	80	85	91	100
	0.25	CSS-1h	51	85	93	93	97	100
		CQS-1h	46	78	86	93	95	100
		Revive^{TM}	38	73	83	88	91	100
30	0.19	CSS-1h	73	91	85	101	105	100
		CQS-1h	50	89	90	95	98	100
		Revive^{TM}	85	88	96	93	99	100
	0.25	CSS-1h	0	89	89	87	103	100
		CQS-1h	0	66	86	87	90	100
		Revive^{TM}	74	85	82	82	81	100
35	0.19	CSS-1h	99	101	100	108	102	100
		CQS-1h	84	86	85	92	93	100
		Revive^{TM}	63	84	82	89	88	100
	0.25	CSS-1h	65	93	81	93	97	100
		CQS-1h	81	98	88	83	92	100
		Revive^{TM}	47	79	84	88	99	100

The following observations can be made from Figure 31, Figure 32, Table 10, and Table 11:

- Figure 31 indicates that differences in EARs do not affect the bond strength of the study emulsions after 1 hour, except for the CQS-1h emulsion, whereas the EAR does affect the bond strength after 1.5 hours.
- The bond strength develops more quickly in the CSS-1h and Revive*TM* emulsions than in the CQS-1h emulsion. After 1 hour, the bond strength of Revive*TM* is greater than that of the CSS-1h and CQS-1h emulsions, indicating the ability of Revive*TM* to gain strength early and quickly.
- Most of the bond strength gain is achieved in the first hour for the CSS-1h and Revive*TM* emulsions and after 1.5 hours for the CQS-1h emulsion.
- The final bond strength values of the CSS-1h and CQS-1h emulsions are similar, except for the 25°C results that show greater bond strength of the CSS-1h emulsion, and that the bond strength of the Revive*TM* emulsion is much greater than that of the other two emulsions.
- The full bond strength of Revive*TM* can be achieved in 1.5 hours. The curing time based on the bond strength is 0.5 hour shorter than that determined from the evaporation test.

5.1.4 Rolling Ball Test

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

Rolling ball tests were conducted at different curing times and selected EARs based on previous testing, i.e., the evaporation test and the PATTI test. The rolling ball tests were conducted at times of 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0 and 24 hours, at EARs of 0.06 and 0.12 gal/yd^2, and at temperatures of 25°C and 30°C for the three emulsion types, CSS-1h, Revive*TM*, and Grip-Tight.

Figure 33 and Table 12 show the rolling ball test results. In Table 12, the shaded cells indicate the curing time of each condition.

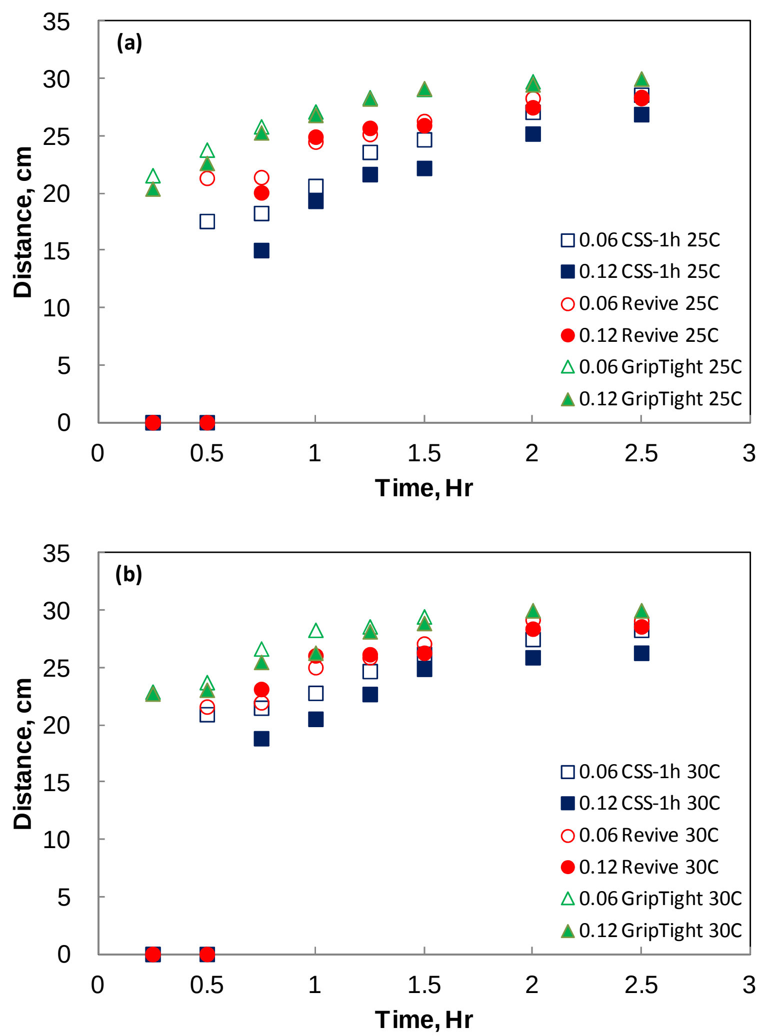


Figure 33 Rolling ball test results for CSS-1h, Revive^{TM}, and Grip-Tight emulsions with 0.06 and 0.12 gal/yd^2 at: (a) 25°C and (b) 30°C

Table 12 Rolling Ball Test Results for CSS-1h, Revive^{TM}, and Grip-Tight Emulsions with EARs of 0.06 and 0.12 gal/yd^2 at 25°C and 30°C

Time, Hour	CSS-1h				Revive^{TM}				Grip-Tight			
	30°C		25°C		30°C		25°C		30°C		25°C	
	0.06 gal/yd^2	0.12 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2
0.25	-	-	-	-	-	-	-	-	22.9	22.7	21.6	20.4
0.5	20.9	-	17.6	-	21.6	-	21.3	-	23.7	23.1	23.8	22.6
0.75	21.5	18.8	18.3	15.0	22.0	23.1	21.4	20.1	26.7	25.5	25.8	25.3
1	22.8	20.5	20.6	19.3	25.0	26.1	24.5	24.9	28.3	26.3	27.1	26.8
1.25	24.7	22.7	23.6	21.7	25.9	26.2	25.2	25.7	28.6	28.2	28.4	28.3
1.5	26.2	24.9	24.7	22.2	27.1	26.3	26.3	25.9	29.5	28.9	29.1	29.2
2	27.5	25.9	27.1	25.2	29.2	28.4	28.3	27.5	30.0	30.0	29.8	29.5
2.5	28.3	26.3	28.6	26.9	29.1	28.6	28.4	28.3	30.0	30.0	30.0	30.0
24	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

The following observations can be made from Figure 33 and Table 12:

- The Grip-Tight emulsion can be tested for 0.25 hour for all conditions, which suggests that the curing rate of the Grip-Tight is faster than that of the other emulsion types.
- At both temperatures, 25°C and 30°C, the Grip-Tight emulsion provides the longest distance in the rolling ball test, and the CSS-1h emulsion shows the shortest distance.
- After 1.5 hours, the Grip-Tight and Revive^{TM} emulsions reach their asymptotic distances.
- When considering all the distances reached by all the samples for each condition, 25 cm can be suggested as a critical distance.
- Based on this critical distance, the Grip-Tight and Revive^{TM} emulsions can be cured within one hour, but the curing times of the CSS-1h emulsion are longer than 1.25 hours. In particular, the CSS-1h emulsion tested at 25°C with an EAR of 0.12 gal/yd^2 can be considered cured after two hours.

5.1.5 Damping Test

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

The damping tests were conducted at different curing times and selected EARs based on previous test results (the evaporation test and PATTI test results). The damping tests were performed at times of 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.5, 3.0, and 24 hours, at EARs of 0.06, 0.12, and 0.19 gal/yd^2, and at 30°C for the four emulsion types, CSS-1h, CQS-1h, Revive^{TM}, and Grip-Tight.

Table 13 shows the percentage of stained pixels after DIP analysis of the damping test results.

Table 13 Percentage of Stained Pixels for Damping Test for All Study Emulsions at 30°C

Time, Hour	Percentage of Stained Pixels											
	CSS-1h			CQS-1h			Revive^{TM}			Grip-Tight		
	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2
0.25	-	-	-	-	-	-	-	-	-	98.9	-	-
0.5	-	-	-	-	-	-	-	-	-	52.2	-	-
0.75	-	-	-	-	-	-	8.7	-	-	0.0	65.1	-
1	33.8	-	-	25.9	-	-	0.1	96.4	-	0.0	0.0	97.3
1.25	1.3	83.5	-	3.2	99.9	-	0.1	10.5	100.0	-	-	30.0
1.5	1.9	4.0	98.2	2.1	65.7	99.6	0.1	0.1	44.1	-	-	0.0
1.75	0.9	3.5	7.1	1.1	3.4	6.5	0.1	0.0	0.1	-	-	-
2	0.5	1.3	0.9	1.6	2.4	1.4	0.1	0.0	0.0	-	-	-
2.5	0.7	0.9	0.9	1.5	0.6	1.3	-	-	-	-	-	-
3	1.7	1.9	1.0	2.1	0.5	0.2	-	-	-	-	-	-
24	1.2	1.6	0.7	0.6	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0

When comparing the data from Table 13 and the digital image samples shown in Figure 14 (Section 3.3), the five percentages of stained pixels can be suggested as a critical value to determine emulsion curing time.

The shaded cells in Table 13 and Table 14 indicate the curing times for each condition. Overall, the Grip-Tight emulsion shows the best results, i.e., a low number of stained pixels, and the Revive^{TM} emulsion performs better than the CSS-1h and CQS-1h emulsions. In order to evaluate the temperature sensitivity of the damping test, the Grip-Tight emulsion was tested at 25°C, and the data were compared against the data obtained from the 30°C test. Table 14 shows the percentage of stained pixels after DIP analysis of the damping test results for the Grip-Tight emulsion at 25°C and 35°C. It shows that the curing time for the Grip-Tight emulsion tested at 25°C is 15 minutes shorter than for the 30°C data, but the Grip-Tight emulsion shows the best results among the four emulsion types even though the other emulsions were tested at 30°C.

Table 14 Percentage of Stained Pixels for Grip-Tight Emulsion at 25°C and 30°C

Time, Hour	Percentage of Stained Pixels					
	Grip-Tight at 30°C			Grip-Tight at 25°C		
	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2	0.06 gal/yd^2	0.12 gal/yd^2	0.19 gal/yd^2
0.25	98.9	-	-	-	-	-
0.5	52.2	-	-	-	-	-
0.75	0.0	65.1	-	86.5	-	-
1	0.0	0.0	97.3	4.2	77.5	-
1.25	-	-	30.0	0.0	0.7	94.3
1.5	-	-	0.0	-	0.0	79.5
1.75	-	-	-	-	-	0.1
2	-	-	-	-	-	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0

5.2 Fog Seal Performance Tests

5.2.1 Aggregate Loss Test

5.2.1.1 Vialit Test

The Vialit test was performed before starting the other tests to verify and select representative fog seal EARs, and was conducted based on the method used in the Estakhri study. The test procedure is that chip seal samples are placed at 77°F for 24 hours for curing and, after fog sealing, the samples are cured at 140°F for 24 hours. EARs of 0.02, 0.06, 0.09, 0.12, 0.16, 0.19, 0.23, and 0.26 gal/yd^2 were used for the CSS-1h and CQS-1h emulsions. In order to fabricate the chip seal samples, the NCSU research team applied an aggregate application rate (AAR) of 10 lb/yd^2 for the lightweight aggregate and an EAR of 0.25 gal/yd^2 for the CRS-2L emulsion. These rates are recommended in the previous chip seal mix design study (Kim and Adams 2011). From these Vialit tests, the NCSU research team found almost 0% aggregate loss for all samples. Table 15 presents the aggregate loss results from the Vialit tests.

Table 15 Aggregate Loss results from the Vialit Tests Using CSS-1h and CQS-1h Emulsions

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

5.2.1.2 MMLS3 Aggregate Loss Performance Test

After the NCSU research team realized that the Vialit test could not properly test aggregate loss for fog seal samples, the MMLS3 aggregate loss test was performed to verify aggregate loss for fog seal samples. Based on the curing time study, the fog seal emulsion types (CSS-1h, Revive^{TM}, and Grip-Tight) and EARs (0.08, 0.12, and 0.16 gal/yd^2) were selected, and chip seal samples were fabricated in accordance with a previous project (HWY-2008-04). For the chip seal samples, 0.25 gal/yd^2 of CRS-2L emulsion and 10 lb/yd^2 of lightweight aggregate were used.

The MMLS3 test procedure is described in Section 3.4.1.3. For aggregate loss testing, the MMLS3 is loaded for 160 minutes at 25°C. Chip seal specimens were fabricated, and then subjected to 10 minutes of MMLS3 loading, which is the time it takes for the MMLS3 to wander across the whole 7-inch width of the specimens. After the fog seal was applied to the loaded chip seal specimens, the specimens again were subjected to MMLS3 loading. Measurements of the specimens were taken for weight, surface texture, and skid resistance at 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15,840 MMLS3 wheel passes). These times can be converted to the number of wheel passes because the MMLS3 applies repeated wheel loads to the specimen surface at a consistent and accelerated rate (990 wheel loads applied every 10 minutes). Figure 34 shows the aggregate loss performance of the fog seal samples.

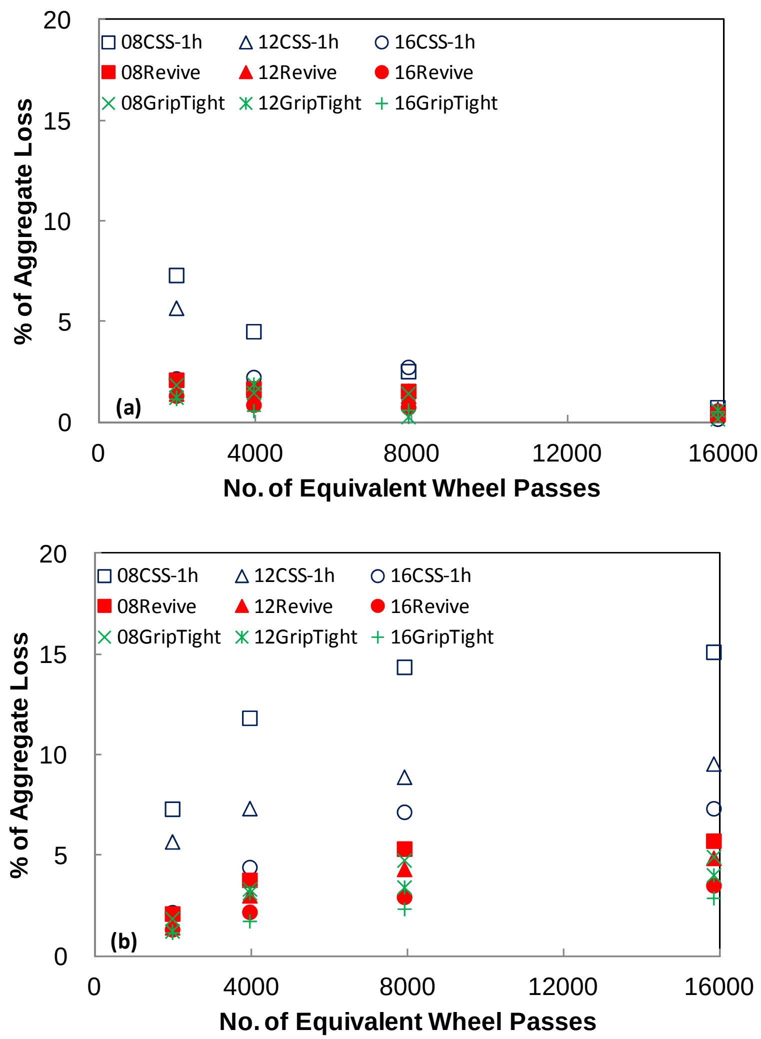


Figure 34 Aggregate loss performance of fog seal specimens: (a) aggregate loss, and (b) cumulative aggregate loss

Figure 34 shows that fog seal samples that contain CSS-1h emulsion perform the worst of all the emulsion types; in particular, the samples with an EAR of 0.08 gal/yd^2 show approximately 15% aggregate loss after MMLS3 loading. However, the samples that are applied with Revive^{TM} and Grip-Tight emulsions show less than 5% aggregate loss. The most aggregate loss occurs during the initial stages of testing, and low EARs induce more aggregate loss for all conditions. Overall, the fog seal samples with Grip-Tight emulsion perform the best in terms of aggregate retention performance.

5.2.2 Mean Profile Depth (MPD) Analysis

The NCSU research team was able to scan the fog seal specimen surfaces at 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15,840 MMLS3 wheel passes) during the MMLS3 aggregate loss performance testing. These laser scan data can be calculated to MPD values, as described in Section 3.4.2.2. Figure 35 and Figure 36 show the MPD values as a function of the number of wheel passes. Table 16 presents all of the MPD values.

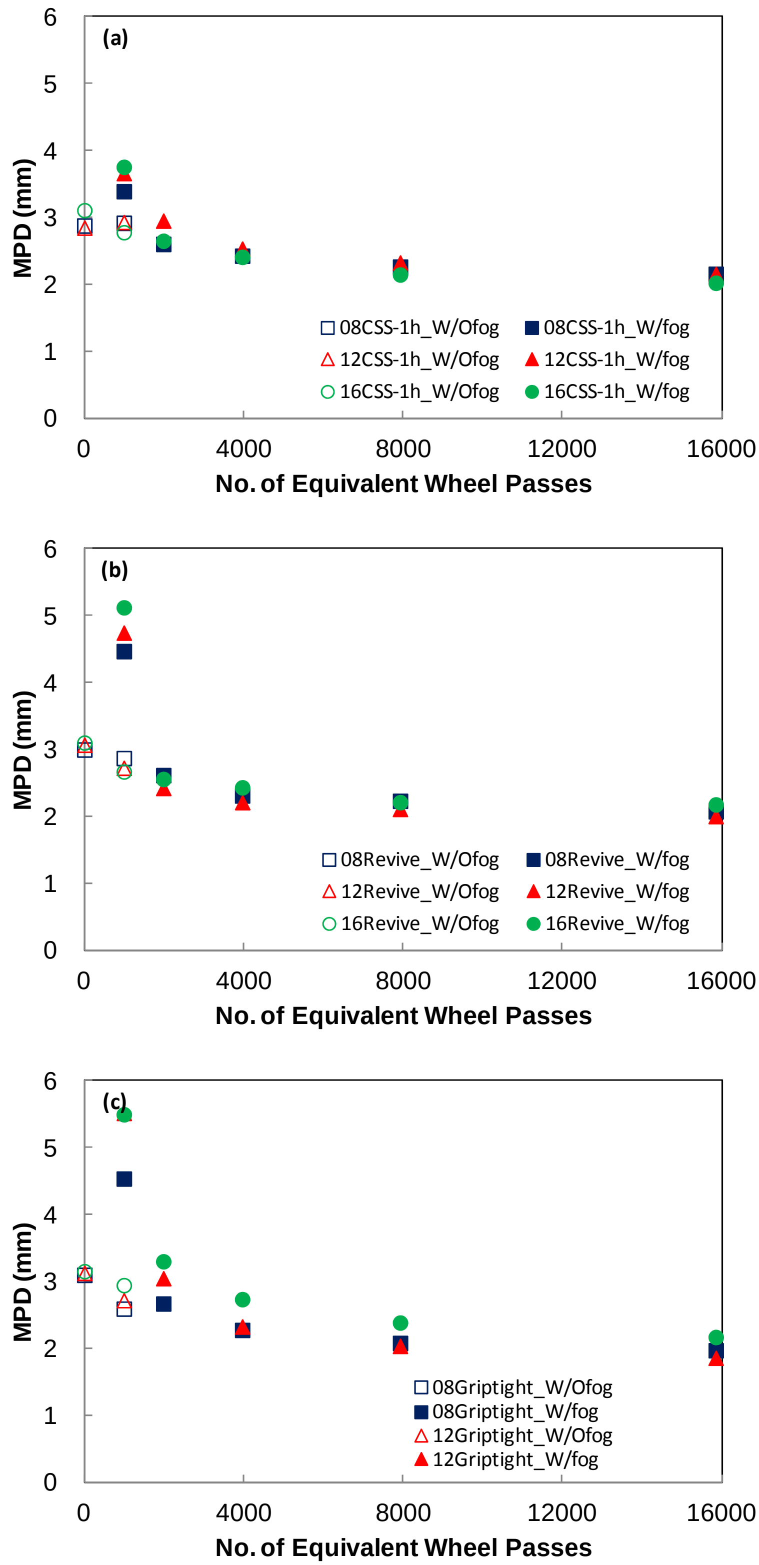


Figure 35 MPD vs. No. of wheel passes for: (a) CSS-1h, (b) Revive^{TM}, and (c) Grip-Tight

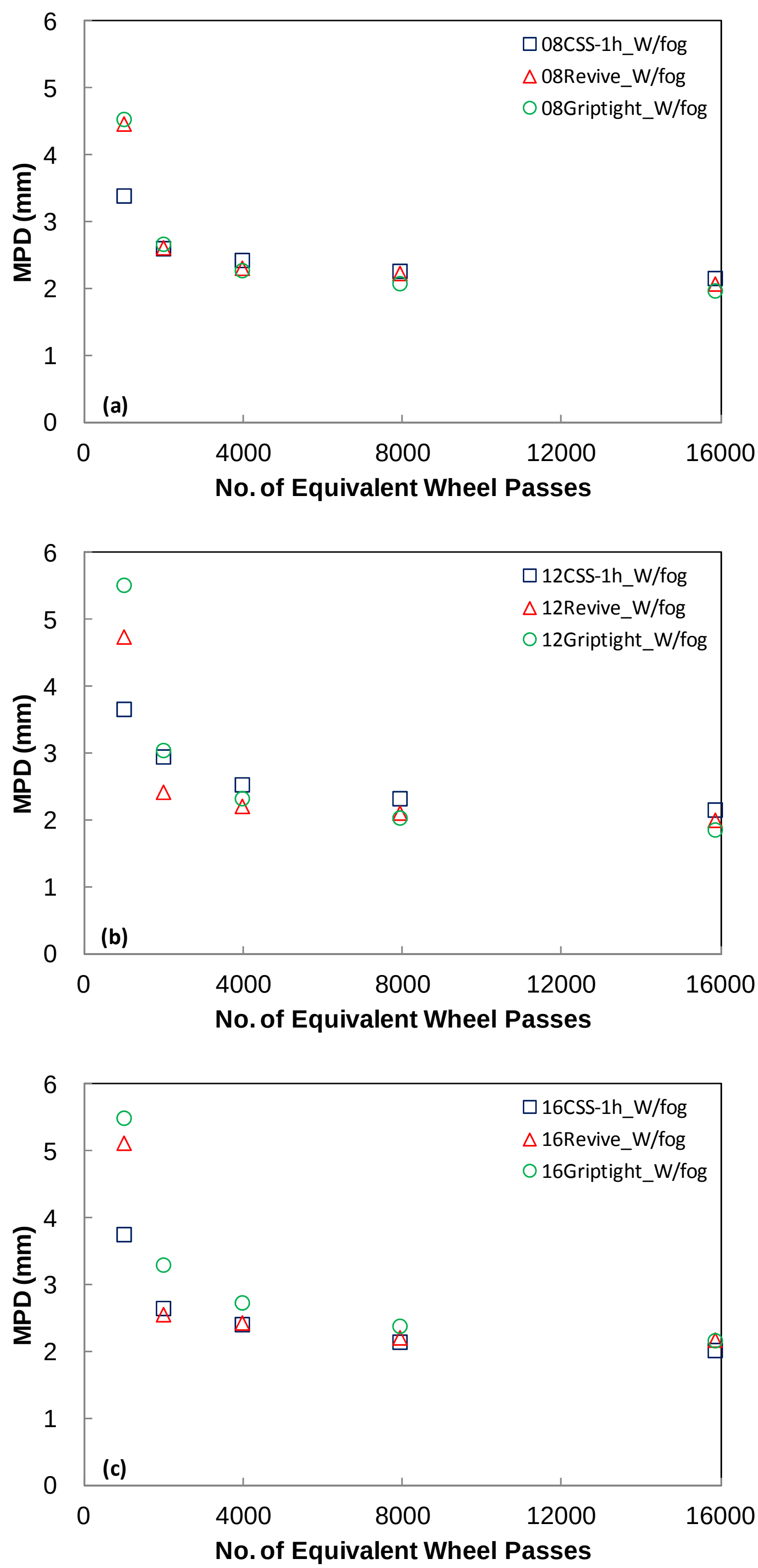


Figure 36 MPD vs. No. of wheel passes for: (a) 0.08, (b) 0.12, and (c) 0.16 gal/yd^2 of EARs

Table 16 Mean Profile Depth Values

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

* The numbers in parenthesis indicate the number of wheel passes.
** The shaded column lists the MPD values obtained from the bleeding test samples.

Figure 35, Figure 36, and Table 16 show that fog sealing increases the MPD values temporarily. However, after traffic loading for 10 minutes, the MPD values decrease to the MPD values of the samples that have not been fog sealed, i.e., the chip seal samples. The reason for this decrease is that applied emulsion can create a rough surface texture once the emulsion is completely cured, but this surface texture can be smoothed easily by traffic loading. Also, the Grip-Tight and Revive*TM* emulsions have more asphalt residue than the CSS-1h emulsion, which suggests that emulsions containing more asphalt residue lead to a rougher surface texture than those that do not contain a high level of asphalt residue. For example, the MPD values of the Grip-Tight and Revive*TM* emulsions are higher than those of the CSS-1h emulsion. When comparing overall MPD values as a function of wheel passes, the MPD values decrease significantly within 40 minutes (3,960 MMLS3 wheel passes), but after that amount of time, the change in MPD values is small. Another finding is that the MPD values of each EAR are similar to each other, although their initial MPD values may differ.

5.2.3 Skid Resistance Test

The NCSU research team ran the BPT on fog seal specimen surfaces for 10, 20, 40, 80, and 160 minutes (990, 1980, 3960, 7920, and 15,840 MMLS3 wheel passes) during the MMLS3 aggregate loss performance testing. The resultant BPN data were converted to SNs, as described in Section 3.4.4. After the aggregate loss performance testing, all of the specimens were subjected to MMLS3 loading for the bleeding test, and the BPT was performed on the bleeding test samples. Table 16 presents all of the SNs acquired from the BPT results, and Figure 37 shows the SNs for the three emulsion types (CSS-1h, Revive*TM*, and Grip-Tight).

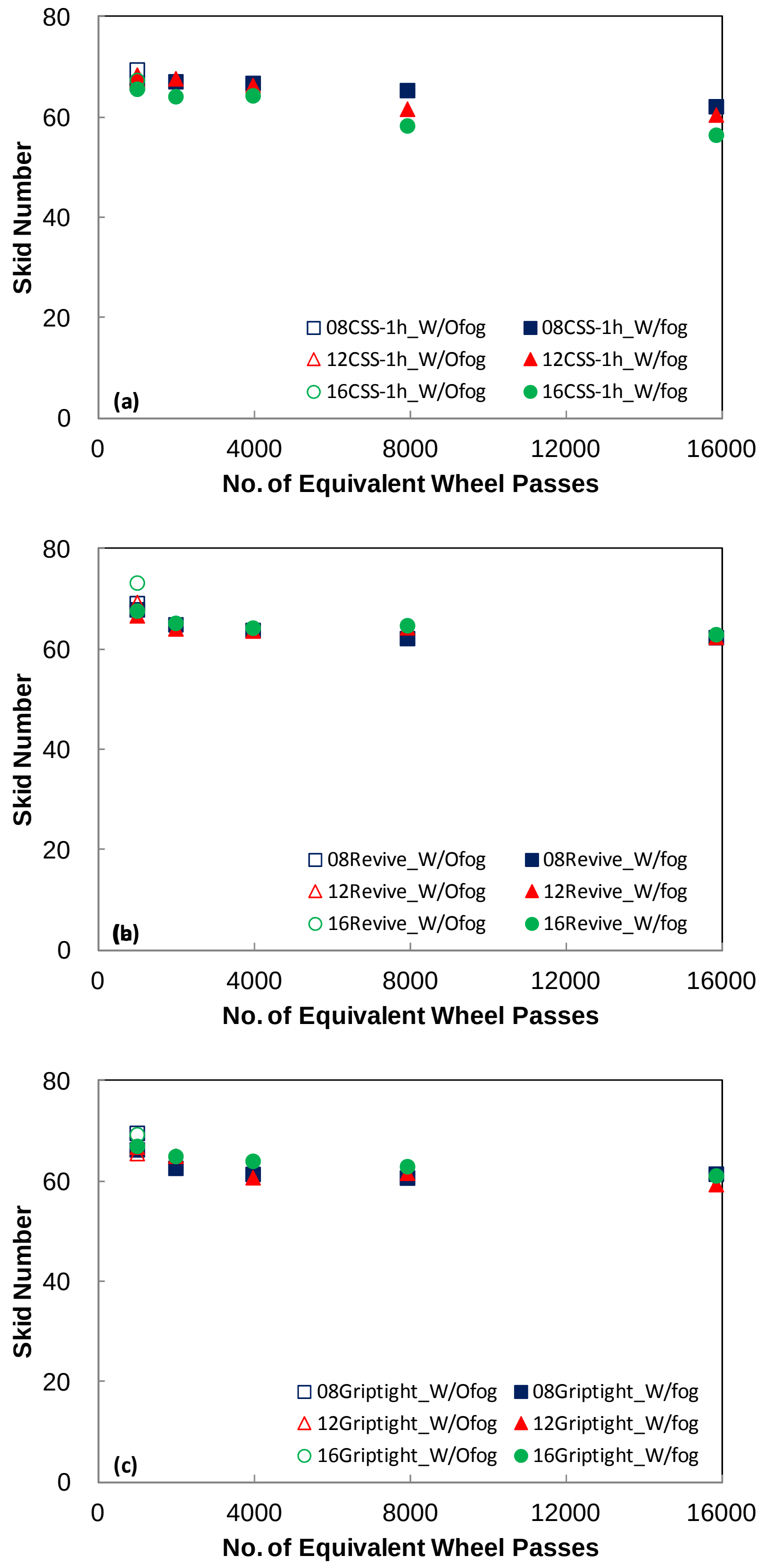


Figure 37 Skid number vs. No. of wheel passes for: (a) CSS-1h, (b) Revive^{TM}, and (c) Grip-Tight emulsions

Table 17 Skid Numbers Obtained from BPT

Specimens	Skid Number						
	10 min. (Chip Seal)	**10 min. (990)**	**20 min. (1,980)**	**40 min. (3,960)**	**80 min. (7,920)**	**160 min. (15,840)**	**400 min. (396,000)**
0.08 CSS-1h	70	67	67	67	65	62	58
0.12 CSS-1h	68	68	68	66	62	61	56
0.16 CSS-1h	67	66	64	64	58	56	38
0.08 Revive^{TM}	69	68	65	64	62	62	58
0.12 Revive^{TM}	69	67	64	64	64	62	56
0.16 Revive^{TM}	73	68	65	64	65	63	54
0.08 GripTight	70	66	63	61	61	61	58
0.12 GripTight	66	67	65	61	62	59	57
0.16 GripTight	69	67	65	64	63	61	53

* The numbers in parentheses indicate the number of wheel passes.
** The shaded column lists the SNs obtained from the bleeding test samples.

From the literature review it is found that the application of a fog seal normally reduces the skid resistance of the pavement surface. However, Figure 37 does not show a significant reduction in skid resistance between the chip seal and fog seal surface. Table 17 indicates that, after the bleeding test, the skid resistance of most samples does not decrease much, except in the one case with a high EAR (0.16 gal/yd^2) for the CSS-1h emulsion. Of course, the skid resistance of fog seal samples is slightly less than that of chip seal samples, but the SNs of the fog seal samples are much higher than the North Carolina requirement for surface skid resistance (SN 37). This finding suggests that the use of chip seals recommended by the chip seal mix design project (HWY-2008-04) for fog seal construction is adequate and does not cause skid resistance problems.

5.2.4 Bleeding Analysis

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

Figure 38 shows the bleeding performance of the CSS-1h, Revive^{TM}, and Grip-Tight emulsions as a function of EARs, i.e., 0.08, 0.12, and 0.16 gal/yd^2.

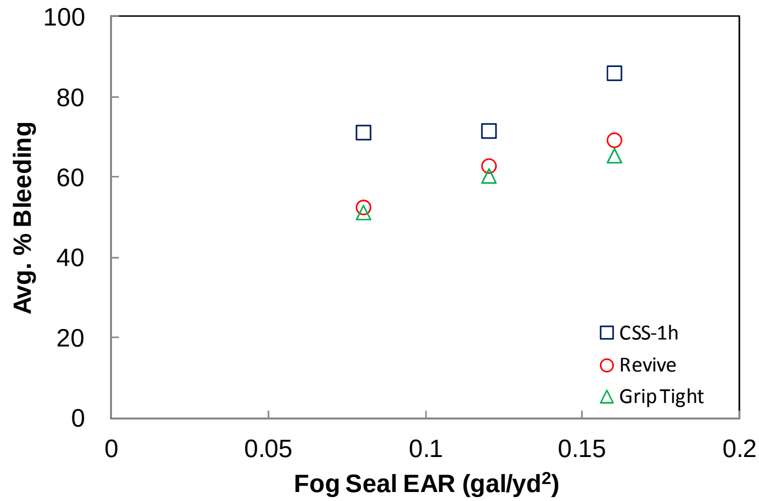


Figure 38 Bleeding test results for CSS-1h, Revive^{TM}, and Grip-Tight emulsions

Figure 38 shows that higher EARs correspond to more bleeding areas for all emulsion types. The Revive^{TM} and Grip-Tight emulsions show a similar bleeding trend to each other, whereas the CSS-1h emulsion presents higher bleeding percentages in every case. In particular, the EAR of 0.16 gal/yd^2 for the CSS-1h emulsion corresponds to the worst performance (least bleeding resistance/most bleeding). This result relates also to the skid resistance results. That is, a high bleeding percentage corresponds to a reduction in skid resistance.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Conclusions

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

Table 18 shows the suggested curing times according to the curing time study results.

Table 18 Suggested Curing Time, Obtained from Emulsion Tests

Test Method	**Curing Time, Hours (30°C, 0.12 gal/yd^2)**			
	CSS-1h	**CQS-1h**	**Revive^{TM}**	**Grip-Tight**
Evaporation Test	1.0	1.0	1.0	1.0
PATTI Test	Approximate 1 Hour			
Rolling Ball Test	1.5	-	1.0	0.75
Damping Test	1.5	1.75	1.5	1.0

* The EAR of 0.19 gal/yd^2 is applied for the PATTI test.

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

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

Tight emulsion cures slightly faster than the Revive^{TM} emulsion, but the difference between them is not significant.
- For field applications, the emulsion diluting process is not necessary for the Grip-Tight emulsion.

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

- The Vialit test is not effective for fog seal performance tests.
- Fog seal samples that are applied with CSS-1h emulsion exhibit the most aggregate loss (i.e., the worst aggregate retention performance), especially at the lowest EAR (0.08 gal/yd^2), showing approximately 15% aggregate loss after MMLS3 loading, whereas the samples applied with the Revive^{TM} and Grip-Tight emulsions show below 5% aggregate loss.
- Overall, the fog seal samples that are applied with the Grip-Tight emulsion exhibit the least aggregate loss (i.e., the best aggregate retention performance).
- Fog sealing increases the MPD values of the samples temporarily, but after traffic loading, the MPD values decrease to those of samples that have not been fog sealed (i.e., chip seal samples).
- When comparing overall MPD values as a function of wheel passes, the MPD values decrease significantly within 40 minutes (3,960 MMLS3 wheel passes), but after that amount of time, the change in MPD values is small.
- The MPD values for each EAR after 40 minutes of loading are similar to each other, although the initial MPD values may differ.
- The skid resistance test results do not indicate a significant reduction in skid resistance between the chip seal and fog seal surfaces.
- After the bleeding test, the skid resistance of most samples does not decrease much, except one case, i.e., the CSS-1h emulsion with a high EAR (0.16 gal/yd^2).
- The skid numbers for fog seal samples are much higher than the North Carolina requirement for surface skid resistance (SN 37). This finding suggests that the use of chip seals recommended by the chip seal mix design project (HWY-2008-04) for fog seal construction does not cause skid resistance problems.
- High EARs lead to more bleeding areas for all the study emulsion types.
- The Revive^{TM} and Grip-Tight emulsions show a similar bleeding trend, whereas the CSS-1h emulsion presents higher bleeding percentages in every case.
- The CSS-1h emulsion with an EAR of 0.16 gal/yd^2 does not resist bleeding well (i.e., exhibits the worst bleeding resistance). The skid resistance results indicate that a high bleeding percentage corresponds to less skid resistance of the surface.

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

6.2 Recommendations for Further Research

It is recommended that the benefits of using fog seals and the findings from this study are verified in the field. The following specific recommendations are made for the future field study:

6.2.1 Emulsion Type

Four types of emulsion were studied and tested for the fog seal research presented in this study. In order to compare properties between modified and unmodified emulsions, the CSS-1h emulsion that is commonly used for fog seals and the CQS-1h emulsion that is normally used for slurry seals were selected to understand unmodified emulsion properties, and the Revive^{TM} and Grip-Tight emulsions were selected as the modified emulsion types. During the early part of this research, no information was available for the field application of the Grip-Tight emulsion, but recently, the NCSU research team was able to identify its field application and would like to apply this information to fog seals in the field.

According to the fog seal emulsion and performance test results, the use of modified emulsions shows advantages, such as shorter curing times and better bond strength, over unmodified emulsions. The CQS-1h emulsion does not have any advantages over even the CSS-1h emulsion. Therefore, for fog seal field applications, the CSS-1h, Revive^{TM}, and Grip-Tight emulsions will be compared for field performance.

6.2.2 Emulsion Rates

The EAR plays an important role in the field performance of fog seals. However, because pavement surfaces in the field are not consistent, it is difficult to suggest one EAR that is suitable for all conditions. Based on the fog seal emulsion and performance test results found from this research, two fog seal EARs that take into account performance properties and traffic opening times can be suggested for chip seal surfaces. For fog seal field applications, 0.08 and 0.12 gal/yd^2 of fog seal EARs will be compared.

6.2.3 Emulsion Curing Time

In order to achieve good fog seal performance, the road should not be opened to traffic until the fog seal emulsion has cured completely. Curing time is affected by weather conditions, surface conditions, emulsion properties, etc. Based on the fog seal emulsion and performance test results, the rolling ball and damping test will be employed to determine appropriate curing times in the field.

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