Technical Report Documentation Page

1. Report No. FHWA/NC/2007-06	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Performance-Based Analysis of Polymer-Modified Emulsions in Asphalt Surface Treatments		5. Report Date October 2009 6. Performing Organization Code
7. Author (s) Y. Richard Kim and Jaejun Lee		8. Performing Organization Report No.
9. Performing Organization Name and Address Campus Box 7908, Dept. of Civil, Construction, & Environmental Engineering, NCSU, Raleigh, NC 27695-7908		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Research and Analysis Group 1 South Wilmington Street Raleigh, NC 27601		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code 2007-06
15. Supplementary Notes		

16. Abstract

Chip seals provide a durable and functional pavement surface and serve as a highly economical highway maintenance option when constructed properly. Data and literature suggest that chip seal sections constructed with polymer-modified emulsions (PMEs) provide better initial and long-term performance and also extend the overall service life of pavements. This project compares the performance of chip seals constructed with PME versus those constructed with unmodified emulsion. The overall performance evaluation is based on aggregate retention performance, bleeding, rutting, and life-cycle cost analysis (LCCA). Three kinds of emulsion (CRS-2, CRS-2P, and CRS-2L) are used to fabricate samples in the laboratory and in the field. Adhesion of the emulsions is examined using the Vialit test with various curing times and temperature conditions in the laboratory. To evaluate the aggregate retention performance of the chip seals, the Vialit test, flip-over test (FOT), and the third-scale Model Mobile Loading Simulator (MMLS3) are employed. Bleeding is measured using a digital image processing method, and rut depth is measured using a profiler at three different testing temperatures (68°F, 104°F, and 129.2°F). The LCCA is estimated using the *RealCost* program, which is recommended by the FHWA.

The results from these tests indicate that the PMEs (CRS-2P and CRS-2L) enhance chip seal performance. In terms of aggregate retention performance, the PMEs significantly improve aggregate retention in the early stages and at low temperatures. This improvement is due specifically to the fast and improved adhesion of PMEs and their ability to enhance the aggregate retention performance at low temperatures. Also, PMEs clearly advance bleeding and rutting resistance based on test results in this project. The LCCA indicates that PMEs are cost-effective if the extended life of PME pavements is two years longer than that of pavements with unmodified emulsions. The performance data obtained from this study, including aggregate loss, bleeding, and rutting, indicate that the use of PMEs can extend the service life of chip seals more than two years, thus justifying the cost effectiveness of using PMEs in chip seals.

17. Key Words Polymer-modified emulsion, asphalt surface treatment, chip seal, aggregate retention, rutting, bleeding, life-cycle cost analysis	18. Distribution Statement		
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 112	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

PERFORMANCE-BASED ANALYSIS OF POLYMER-MODIFIED EMULSIONS IN ASPHALT SURFACE TREATMENTS

FINAL REPORT

(Report No. FHWA/NC/2007-06)

To North Carolina Department of Transportation
(Research Project No. HWY-2007-06)

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October 2009

DISCLAIMER

ACKNOWLEDGMENTS

This research was sponsored by the North Carolina Department of Transportation. The Steering and Implementation Committee consisted of: Emily McGraw, P.E. (Chair); Jennifer Brandenburg; Scott Capps, P.E.; Judith Corley-Lay, Ph.D., P.E.; Jack Cowsert, P.E.; Terry McLaurin; Averette Moore, Christopher Peoples, P.E.; James Phillips, P.E.; Vann Price; Jackson Provost, P.E.; Archie Smith, Jr.; David Spainhour, P.E.; and Todd Whittington, P.E. The Friends of the Committee include: Steve Varnedoe, P.E.; Lacy Love, P.E.; Cecil L. Jones, P.E.; Moy Biswas, Ph.D., P.E.; and Mustan Kadibhai, P.E. These advisors have given invaluable direction and support to the research team throughout the project.

Special thanks go to Dale Register (Division 3), Vann Price (Division 4), Averette Moore (Division 5), Archie Smith (Division 6), and Wayne Spivey (Division 8) for their help in providing equipment, manpower, and advice in the field.

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Chapter 1. INTRODUCTION

1.1 Research Needs and Significance

Chip seals are one of the most common preventive maintenance treatments used in the United States (Gransberg et al. 2005). A chip seal consists of a thin layer of asphalt concrete less than one inch thick formed by the application of emulsified asphalt and aggregate, with the purpose of sealing the existing pavement's surface cracks, improving ride quality, and rejuvenating the surface against aging or oxidation. A chip seal provides a durable and functional pavement surface that serves as a highly economical highway maintenance option when constructed properly. For example, in North Carolina in 2006, approximately 8% of roadway pavement expenditures were spent on surface treatment construction. That percentage constitutes about 50% of the road miles paved in the state. Thus, it is imperative for state highway agencies to optimize the use of these treatments through prolonged service life, decreased life-cycle costs, increased operational efficiency, and enhanced safety. Typical chip seal failure modes include aggregate loss, cracking, bleeding, reduced skid resistance and aging, among others. It must be noted that aggregate loss is a serious concern in chip seal construction because flying aggregate may create windshield damage to a vehicle (Gransberg et al. 2005) or other serious harm. This problem discourages the use of chip seals on high-volume roads (Shuler 1991).

Chip seals constructed with polymer-modified emulsion (PME) provide better initial and long-term performance and extend the overall service life of pavements (Crew 2008). The use of polymer-modified chip seals, which have tougher, more resilient surface characteristics than unmodified chip seals (AEMA 2004), may extend the use of chip seals to roadways that have a higher traffic volume than the low traffic roadways for which unmodified chip seals are typically used.

The enhanced performance and benefits of chip seals constructed with PME can be seen in the following:

- improved aggregate retention, which is evident in a decrease in raveling and cracking due to improved adhesion, cohesion, and elastic properties (Wood 1991, Gransberg 2005);
- decreased bleeding and, hence, greater friction resistance due to the high viscosity of the PME (Kuennen 2004);
- faster construction due to the early break time of the emulsion; this factor is especially advantageous in completing rainy-season work and jobs in remote locations; and
- less frequent maintenance under fast-moving and high volume traffic conditions, with annual average daily traffic (AADT) counts exceeding 2,000, including urban and primary roads (Wade et al. 2001).

However, it must be noted that PME costs typically about 30% more than non-modified emulsion, or unmodified emulsion (Kuennen 2004). Because the decision to adopt a more expensive product, such as PME, depends not only on the performance improvement the product provides but also on its cost, a study using life-cycle cost analysis (LCCA) is warranted. However, limited research and data exist to *quantify* the overall performance of polymer-modified chip seals and their cost effectiveness. The North Carolina Department of Transportation (NCDOT) has embarked on a research project whose objective is to provide a quantitative comparison of the performance of chip seals with non-modified emulsion and those with PME (i.e., unmodified emulsion versus PME) under varying conditions. The results from this project will provide baseline performance information about chip seals with and without PME, which will be most valuable in determining the cost effectiveness of PME and in planning maintenance activities.

The performance characteristics investigated in this study include aggregate loss, bleeding, and rutting. The results from the performance tests and the appropriate LCCA are presented in this report. In this study, samples fabricated in both the laboratory and the field are used to evaluate aggregate loss performance of the chip seals. Two types of chip seal, single and double seals, were fabricated in the field and three types, single, double, and triple seals, were fabricated in the laboratory. The chip seal performance of the field and laboratory samples were evaluated using three aggregate retention tests: the flip-over test (FOT), Vialit test, and the third-scale Model Mobile Loading Simulator (MMLS3). The Vialit test and MMLS3 were also used to evaluate the effects of different variables, such as curing time and temperature conditioning, on the aggregate retention performance of the single seal specimens fabricated in the laboratory.

1.2 Research Objectives

The primary objectives of the proposed research are:

1. to conduct a literature study of chip seal performance, with PMEs as well as unmodified emulsions;
2. to conduct baseline performance tests for unmodified North Carolina chip seals (single, double, and triple seals);
3. to conduct performance tests for polymer-modified chip seals and to compare the results with those from unmodified chip seals (single, double, and triple seals); and
4. to conduct LCCA to evaluate and determine the cost-effective conditions under which PME and unmodified emulsions should be used.

1.3 Report Organization

This report is composed of eight chapters. Chapter 1 presents the research needs and objectives. Chapter 2 summarizes the literature review of PME performance. Chapter 3 describes the physical characteristics of selected materials and experimental test methods employed in this study. Chapter 3 also explains the sample fabrication in both the field and laboratory. In addition, Chapter 3 presents the test protocols for the FOT, Vialit test, and MMLS3 test used in this study to evaluate aggregate retention performance. Chapter 4 describes the evaluation of the aggregate retention performance using the three test methods presented in Chapter 3. Chapter 5 investigates bleeding of the chip seals using samples fabricated with both unmodified emulsion (CRS-2) and PME (CRS-2L). Chapter 6 reports the results of rutting behavior of the triple seals under three different temperature conditions. Chapter 7 presents the field condition survey data. Chapter 8 provides a comparative LCCA of the chip seal pavements constructed using the PME (CRS-2L) versus the unmodified emulsion (CRS-2). Chapter 9 offers conclusions from this research and future research recommendations.

Chapter 2. LITERATURE REVIEW

2.1 General

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

Due to its low-cost maintenance benefits, state highway agencies like to extend the chip seal to higher traffic volume roadways. For high volume roads, PME is used in the design of the chip seal because the polymer modification decreases temperature susceptibility, increases adhesion to reduce aggregate loss, and allows the road to be opened to traffic earlier. Therefore, the use of PMEs in the chip seal industry has increased.

2.2 Emulsion Properties

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

Gransberg (2006) correlated individual chip seal performance ratings with reported construction practices and found a number of strong correlations. The ambient air temperature specification was commonly higher (average of 60°F (15°C)) for those respondents who reported excellent or good chip seal performance. For the best performance of a fresh new chip seal, the newly sealed road must undergo an average wait period of 28 hours prior to allowing full-speed traffic on the new surface.

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

Bolander et al. (1999) summarized the analysis and supporting test information used to determine and evaluate the factors behind the chip seal failure and then discussed the lessons learned. In this research, two types of emulsion were used: HFRS-2 (anionic high float rapid set emulsion) and HFRS-P1 (modified anionic high float rapid set emulsion with polymer). Severe potholes developed where the HFRS-2 was used without a polymer or a low-temperature additive during the first winter. Bolander et al. found that failure resulted from interacting factors, including a dust coating on the chips, an incompatibility of the emulsion and chips, cold and wet weather, and a nearly impervious base course. Five important factors were found from this project to improve bituminous surface treatment (BST) performance: (1) adequate and accurate quality control; (2) a drain in the base courses under a BST; (3) weather and dust on the aggregate; (4) an emulsion’s breaking and curing times; and (5) the compatibility between the asphalt emulsion and the aggregate.

Takamura (2003) presents the properties of modified asphalt emulsion with SBR latex. The SBR latex was designed for asphalt modification to create a polymer film in the presence of residual water, without coagulum formation, thus promoting early strength development. The SBR latex polymer remains in the aqueous phase and naturally changes to the honeycomb structure surrounding asphalt droplets. The finer the polymer structure, the more definitive is the improvement in asphalt rheology. The latex particles in the emulsion spontaneously transform to a continuous polymer film that coats the asphalt particles after water evaporates from the emulsion, as shown in Figure 2-1. Also seen in Figure 2-1, the unmodified residue asphalt would normally fracture through the asphalt/droplet boundaries, but because SBR latex film is highly flexible, the SBR latex films surrounding these droplets reduce excess stresses through elastic deformation without causing permanent deformation to the bulk asphalt phase. This microscopic polymer mechanism is the reason for significantly improved fatigue resistance of the emulsion residue modified by the cationic SBR latex.

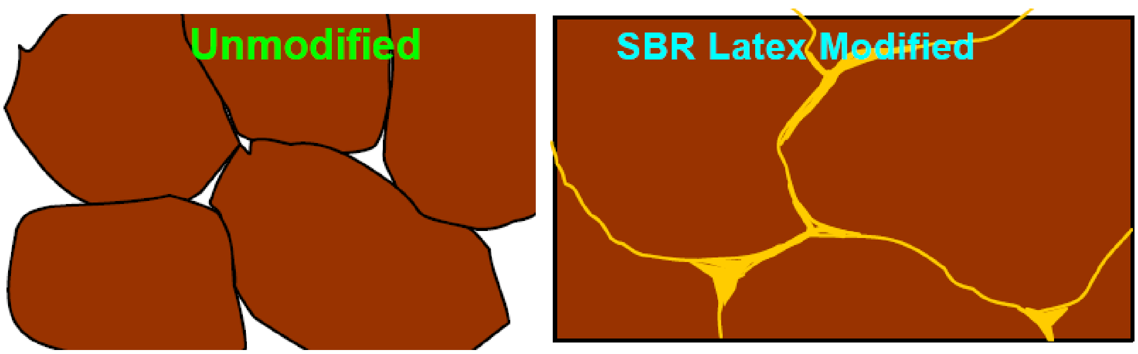


Figure 2-1 Schematic diagram of fully cured unmodified and SBR latex polymer-modified asphalt (Takamura 2003)

James et al. (1997) explain ways that the choice of emulsifier or the use of bitumen additives significantly affects emulsion viscosity and can help correct problems of too high or too low viscosity. For chip seal construction, an adequate emulsion viscosity is necessary to spray emulsion without any construction problems. High viscous emulsions might not distribute well over the surface and, therefore, bleeding or severe aggregate loss could occur. James et al. also found a correlation between the viscosities of emulsions formed using different emulsifiers and the amount of trapped water. So, the differences in viscosity could be related to the tendency of the emulsifier to form multiphase emulsions. Consequently, the right emulsifier is often a more cost-effective approach to satisfying specified viscosities than increasing the binder content.

Vercoe et al. (2006) report that the road pavement industry in New Zealand shifted from the use of cut-back bitumen binder to emulsion for chip seal surfacing pavements. The emulsion produced very good results, particularly in South Island in New Zealand. The use of bitumen emulsions led to long-term and significant agency cost savings, averaging an 11% reduction in savings per year.

2.3 Modified Emulsion Types

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

Through the course of this literature review, it has become clear that the use of emulsions is highly popular because emulsions do not require a hot mix set-up, they have a low sensitivity to temperature changes, and they are not likely to be hazardous to the construction crew. Aside from these benefits, most sources agree that the use of PME binders also provides benefits to the binder after modification. Most scientific sources are also in agreement that the best and most effective concentration of polymers is one that allows for the formation of a continuous polymer, and 3% to 5% is a generally advisable dosage rate for polymers (Voth 2006, Stroup-Gardner et al. 1995). Aside from these benefits that are generally agreed upon, it seems that no real understanding of the best dosage rate or recommended concentration exists for polymer modification. As Voth points out in his preliminary report (2006), there is a considerable amount of information but no real consensus. This dilemma may be due to the fact that the dosage rates are maintained as a kind of ‘secret recipe’ by the companies that manufacture emulsions. The lack of information surrounding PMEs is addressed by the questionnaire that is part of this research, as well as by the rest of the literature review. With the input of industry professionals, the types of polymer that are most often used and the types of test that can benefit those who use PME every day in the field will be much easier to identify. Therefore, the questionnaire must solicit responses not only from DOT employees but from emulsion manufacturers as well.

2.4 Polymer-Modified Emulsion Performance

One of the most prevalent failures of chip seals is aggregate loss by traffic load. One of the benefits of using PME for the chip seal is the mitigation of such loss. Takamura (2003) has compared the aggregate retention performances of unmodified emulsion and PME (3% cationic SBR latex). He used the brush test that was developed to reduce problems associated with loose aggregate in chip seal operations. He conducted the brush test using eight different aggregates after five hours of curing at 95°F (35°C). A comparison of the unmodified emulsion and the PME with SBR latex showed that the SBR latex-modified asphalt emulsion provides faster strength development, with above 80% aggregate retention, than the unmodified emulsion.

Brown et al. (1991) evaluated hot mix asphalt (HMA) to determine potential causes of so-called *fat spots*. Fat spots seemed to occur at the end of truck loads. After time, these fat spots developed into potholes, and the asphalt appeared to be stripped from the aggregate at the bottom of the potholes. The research was conducted by visual inspection of the pavement and obtaining core samples from fat spots, fat spots adjacent to other fat spots, and from random locations throughout the project. Also, rut depth was measured. The cores were used to determine asphalt content, gradation, void content, and slag content. Several of the asphalt mix layers were divided into top and bottom halves, and the asphalt content and gradation of each half were compared. The asphalt cement from various cores was recovered, and the viscosity and penetration were determined. The results of this study indicate that the most likely cause of the fat spots was contamination of the HMA by some solvent (probably diesel fuel) during the placement operation.

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

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

Kuennen (2004) describes the benefits of PME for chip seals. Polymer modifiers generally enhance the bond between aggregate and binder and are commonly used, therefore, as the binder modifiers. The typical price of polymer-modified binders is higher than that of unmodified emulsions by about 30 percent. However, the PMEs reduce bleeding and flushing in warm weather due to enhanced binder stiffness.

Lawson et al. (2007) identified maintenance solutions for bleeding and flushed asphalt pavements surfaced with seal coats or surface treatments. The terms *bleeding* and *flushing* are both used, although the basic mechanism of both terms is the same, referring to the excess asphalt binder that fills the voids between aggregate particles. Figure 2-2 and Figure 2-3 represent the pavement with bleeding and flushed pavement, respectively.

Figure 2-2 Bleeding due to heavy truck traffic and hot weather (Lawson et al. 2007)

Figure 2-3 Flushed pavement (Lawson et al. 2007)

The key factor of bleeding is that the binder is in liquid form. As seen in Figure 2-2, the excess binder (liquid condition) on the pavement surface has risen above the aggregate. Bleeding typically occurs during chip seal construction when the fresh pavement is opened too soon to traffic, before the emulsion has completely cured. On the other hand, the binder in the flushed pavement, as shown in Figure 2-3, has filled the voids in the aggregate; however, this binder is not liquid. Numerous factors converge to create both bleeding and flushed pavements: aggregate issues, binder issues, traffic issues, environmental issues, and construction issues. Bleeding requires immediate maintenance, such as removing the bleeding asphalt and rebuilding the pavement seal. In contrast to bleeding, flushed asphalt pavements are not a maintenance problem. To treat flushed pavement, a new textured surface is required over the flushed pavement. The PME surface has an improved seal coat and surface treatment performance that make bleeding and flushing problems less common.

Serfass et al. (1992) researched the utilization and evaluation of SBS-modified asphalt for aggregate surface treatments. When SBS is added to the emulsion, the emulsion exhibits better cohesion and reduced thermal susceptibility. Thus, less aggregate dislodgement and better resistance to bleeding were found. However, very high SBS rates (up to 5%) indicate some degree of failure in the form of aggregate loss due to early trafficking before the emulsion has formed enough viscosity.

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

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

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

Sebaaly et al. (1995) developed nine flexible pavement maintenance performance models using actual pavement performance data. The maintenance methods included flush seals, sand seals, and chip seals. For the chip seal construction, the binder was usually an emulsion with latex (LMRCRS-2 or LMCRS-2h). In order to produce statistically accurate predictions, performance models for each method were developed separately for each of three districts under the jurisdiction of the Nevada Department of Transportation (NDOT). According to NDOT data, the nine models were tested by comparing the predicted performance to the performance observed at the project sites. Excellent correlations were found between the Pavement Serviceability Index (PSI) values predicted by the models and those observed.

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

2.5 Life-Cycle Cost Analysis

Overby et al. (2007) introduced Otta seal surfacing as an economical and practical alternative to the more traditional BSTs as chip seals and slurry seals. The Otta seal provides a significant cost benefit in terms of life-cycle costs when a single Otta seal is compared to a sand cover seal and the commonly used double chip seal in the order of a 0.6 cost ratio over a twenty-year period. This significant cost benefit is derived as a result of the following three factors, as reported by Overby et al. (2007):

- Lower initial construction cost largely because of greater use of the crushed aggregate or screened gravel (typically 20% less than for a conventional double chip seal);
- Longer service life (typically 10 to 12 years for a single Otta seal with a crusher dust or river sand seal versus 6 to 10 years for a double chip seal); and
- Lower maintenance costs (omission of prime and fog spray; longer reseal and road marking cycles).

Ponniah et al. (1996) investigated performance and cost-effectiveness using polymer-modified asphalt (PMA) pavements in Ontario, Canada. Two trial sections were constructed to monitor field performance, and additional laboratory tests were conducted at temperatures ranging from 0°C to -35°C to evaluate the low temperature cracking resistance of the materials. The results indicate that PMA improves low-temperature performance compared to the control section (non-PMA) asphalt. Based on LCCA, use of PMA suggests a cost-effective benefit in extending the pavement life by two to three years if the cost of polymer modification does not exceed the cost of conventional asphalt by 100 percent.

Romero et al. (2005) compiled performance data on open-graded surface courses (OGSCs) and chip seal courses (CSCs) in an attempt to measure the life of these seal coats and to predict the life of a seal coat for the various materials, environmental conditions, and traffic loadings. The OGSCs had an average life of almost nine years, based on skid resistance, and the CSCs had a significantly longer life on Utah pavements. Among various factors, traffic had the most significant effect on the performance of the treatment. The Utah Department of Transportation (UDOT) generally uses the CSC in highway sections with AADTs below 5,000, and expanded the CSC road to certain roads with AADTs up to 20,000 vehicles. As the CSC was applied up to 20,000 AADT, the UDOT modified existing policies and limited the use of OGSCs where the running speeds are 55 mph or greater and AADTs are in excess of 25,000 vehicles. This project found the results of an initial coat analysis in savings to be over $2 million per year in the maintenance budget.

Chapter 3. EXPERIMENTAL TEST PROGRAM AND METHODS FOR ASPHALT SURFACE TREATMENTS

3.1 Experimental Program

This project focuses on the performance evaluation of PME in chip seals. Limited data and literature are available to suggest that surface treatments constructed with PME provide improved initial and long-term performance as well as extend the overall service life of pavements. Thus, this research is designed to: test the improvements in surface treatment performance that result from modifying the emulsion with polymers; assess the cost-effectiveness; and provide baseline performance information about standard surface treatments that are valuable in planning maintenance activities. In order to accomplish this research, an experimental program has been developed, as presented in Table 3-1.

Phase I is designed to evaluate the aggregate retention performance of the chip seal. Aggregate loss is the most common failure of chip seals. Aggregate retention is examined using three different test methods: the Vialit test, the FOT, and the MMLS3 test. In this phase, granite 78M aggregate and lightweight aggregate, which are the most common aggregates used in chip seal construction in North Carolina, are used for the single and double seals. In order to evaluate the aggregate loss performance at low temperatures, the Vialit test and MMLS3 test are conducted at -4°F and 40°F for the Vialit test and 68°F for the MMLS3 test.

Phase II is designed to compare the bleeding performances of polymer-modified and unmodified chip seals. Bleeding, in addition to aggregate loss, is one of the most common chip seal failures. For this study, single and double seals are tested at 122°F (50°C). The single seal specimens are fabricated using both granite 78M aggregate and lightweight aggregate. Two kinds of double seals are used for this study. One uses granite 78M aggregate for both the bottom and top layers; the other uses granite 78M aggregate and lightweight aggregate for the bottom and top layers, respectively.

Phase III is an investigation of the rutting development of the chip seals in terms of two different emulsion types. For this program, the triple seal is used and composed of granite 78M aggregate, granite 78M aggregate and lightweight aggregate in respective order from the bottom layer to the top layer. Three different testing temperatures are used for this study: 68°F (20°C), 104°F (40°C), and 129.2°F (54°C).

Table 3-1 Experimental Program

Phase	Research Purpose
I	Evaluation of aggregate loss performance • Seal types: single and double seals • Test methods: Vialit, FOT, MMLS3
II	Evaluation of bleeding performance • Single seal • Double seal
III	Evaluation of rutting performance • Specimen type: Triple seal composed of granite78M, granite 78M, and lightweight aggregates, respectively. • Test temperature: 68°F (20°C), 104°F (40°C), 129.2°F (54°C)
IV	Evaluation using LCCA

Phase IV provides a comparative cost analysis of the chip seal pavements constructed using the PME (CRS-2L) versus using unmodified emulsion (CRS-2). PME typically costs about 30% more than PME (AEMA 2004). Chip seals constructed with PME provide better initial and long-term performance and extend the overall service life of pavements. Thus, the LCCA is very important in this research. In this project, *RealCost* software (recommended by the FHWA) is used to perform the LCCA in the case studies of pavement project-level decision making.

3.2 Materials

The choice of aggregate type used for this study is based on the most common usage for chip seal construction in North Carolina. Two types of aggregate were used, lightweight aggregate with a 5/16 in. nominal maximum size of aggregate (NMSA) and a 78M graded granite aggregate. Figure 3-1 shows the gradations for the two aggregate types. Dry sieve analyses were performed on both the aggregate types in accordance with ASTM C 117. Figure 3-1 shows the gradations for the two aggregate types plotted on a 0.45 power chart.

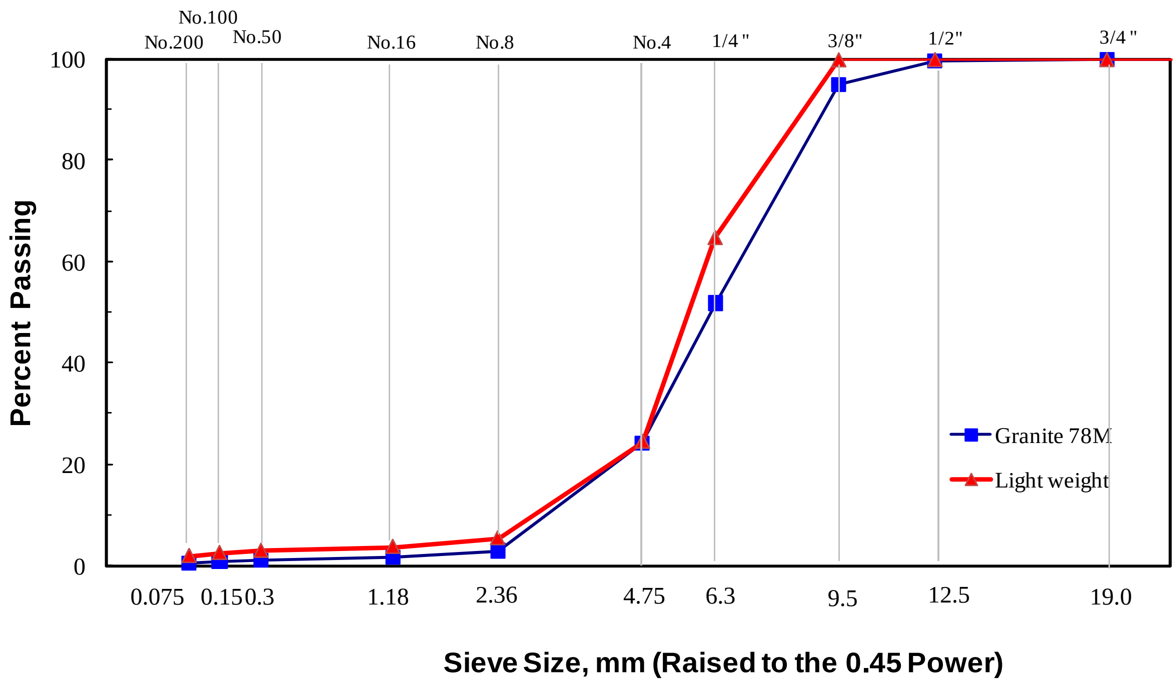


Figure 3-1 Aggregate particle size gradations

Three types of emulsion, a unmodified emulsion (CRS-2) and two PMEs (CRS-2P and CRS-2L), were used in this study. The CRS-2P emulsion, which is SBS-modified, was used for the field construction, and the CRS-2L emulsion, which is latex-modified, was used to fabricate samples in the laboratory.

3.3 Specimen Fabrication

For this project, two types of specimen are used: field fabricated samples and laboratory fabricated samples, described below.

3.3.1 Construction of Field Test Sections and Fabrication of Specimens

Field test sections were constructed on New Sandy Hill Church Road in Wilson County, NC in June (Phase I) and October (Phase II) 2007. These sections were designed to study chip seal samples made from different seal types and emulsions, and therefore were constructed using various aggregate and emulsion combinations. Table 3-2 shows these various aggregate and emulsion combinations used in the field construction. Note, however, that aggregate retention performance testing in the laboratory was conducted for field samples in Phase I only, because huge sample-to-sample variations occurred in the field samples obtained in Phase II. Thus, the field samples fabricated in Phase II are excluded from the laboratory testing.

Table 3-2 Details for the Sections Constructed on New Sandy Hill Church

Phase	Section	Chip Seal Type	Aggregate Type	Emulsion
I	1	Triple Seal	78M/78M/Lightweight	CRS-2
	2			CRS-2P
	3	Double Seal	78M/Lightweight	CRS-2
	4			CRS-2P
	5	Single Seal	78M	CRS-2
	6			CRS-2P
	7		Lightweight	CRS-2
	8			CRS-2P
II	9	Triple Seal	78M/78M/Lightweight	CRS-2
	10			CRS-2P
	11	Double Seal	78M/78M	CRS-2
	12			CRS-2P
	13	Single Seal	Lightweight	CRS-2
	14			CRS-2P

The sections constructed in Phase I include four single seals consisting of granite 78M aggregate and lightweight aggregate for each of the two emulsions, CRS-2P and CRS-2, and two double seals consisting of a bottom layer of 78M aggregate and a top layer of lightweight aggregate for each of the two emulsions, CRS-2P and CRS-2. The aggregate application rates (AARs) and emulsion application rates (EARs) were determined from visual observations made by NCDOT Division Bituminous Supervisors from a trial construction. Table 3-3 summarizes the chip seals used and the AAR and EAR for each. The CRS-2P and CRS-2 emulsions were both used for each of the chip seals shown in this table.

Table 3-3 Application Rates for the Field Construction

Chip Seal Type		**Aggregate**		**Emulsion**
		Type	**Application Rate (lb/yd^2)**	**Application Rate (gal/yd^2)**
Single		Granite 78M	17	0.35
		Lightweight	9	0.35
Double	Bottom Layer	Granite 78M	17	0.25
	Top Layer	Lightweight	9	0.25

A combination of granite 78M aggregate and lightweight aggregate that is used in the double seal was selected for the field construction because this combination is the most popular aggregate combination that is used for double seals in North Carolina. The lightweight aggregate on the top layer reduces windshield damage, and the granite 78M aggregate at the bottom provides a less expensive alternative to using the lightweight aggregate throughout.

Field Sample Fabrication Procedure

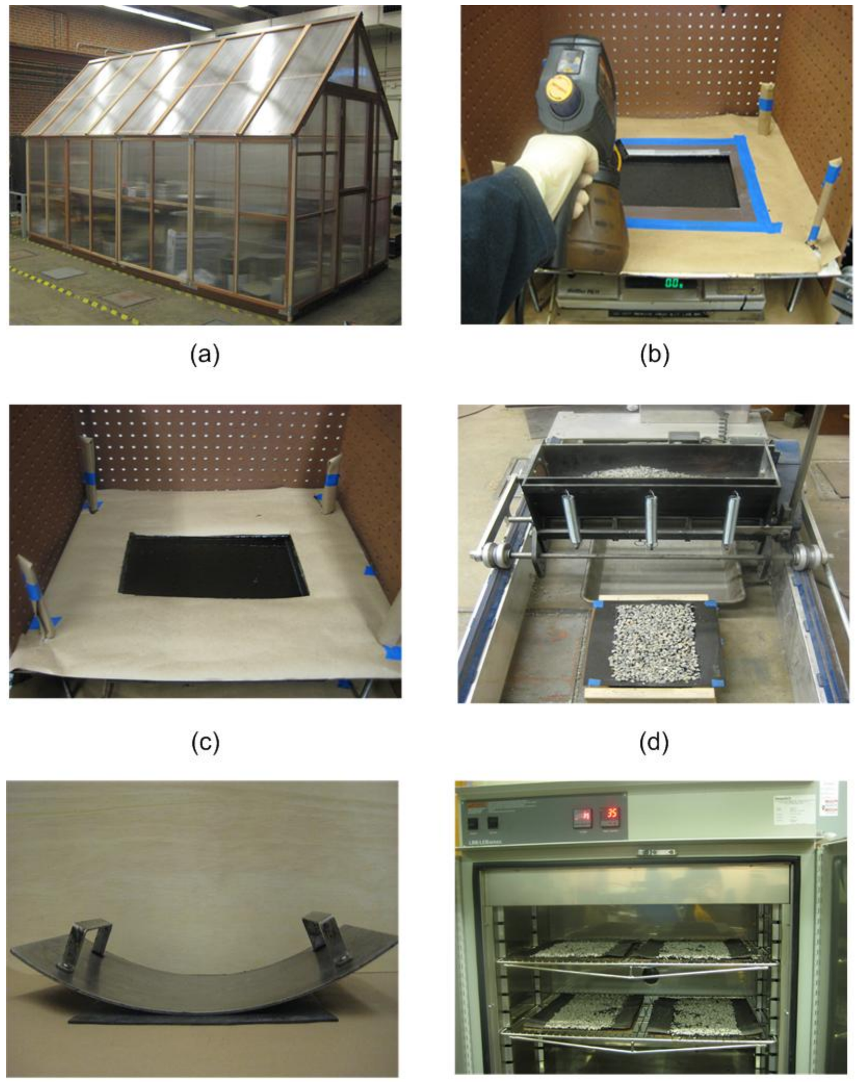
A critical procedure in this research was to obtain field samples that were representative of the actual construction sequence. Thus, establishing the field sampling procedure was fundamental to this project. Figure 3-2 describes the developed sampling procedure designed to meet this goal. Figure 3-2 (a) shows the placement of the templates on the existing pavement. Templates for the FOT, Vialit test and MMLS3 test were affixed in the longitudinal direction to the ground paper that covers the existing pavement. It was observed in a previous NCDOT rolling project (Kim et al. 2008) that segregation across the width of the aggregate spreader could lead to high sample-to-sample variability. Thus, the longitudinal layout helps reduce this sample-to-sample variation. The roller pattern in this study is a parallel pattern that uses two rollers traveling in parallel within a section, as shown in Figure 3-2 (d). Figure 3-2 (e) shows the gathering of the samples for delivery. In order to reduce the disturbance of the aggregates during collection of the samples, the samples were cured for 30 minutes at ambient temperature after completion of the rolling operation. This delay allowed time for an improved mechanical bond between the emulsion and the aggregate and, thus, the samples were more stable when they were handled and transported during the gathering process. Also shown in Figure 3-2 (e), samples were placed on wooden plates to provide rigid support and further minimize disturbance during the delivery. Collected samples on the wooden plates were stored on racks, as shown in Figure 3-2 (f).

3.3.2 Fabrication of Specimens in the Laboratory

Figure 3-3 describes the fabrication procedure of the CRS-2 and CRS-2L emulsions in the laboratory. The procedure was designed for small-scale aggregate retention performance evaluation using the MMLS3 in the laboratory. The two types of emulsions, CRS-2 and CRS-2L, and two sets of testing temperatures, 77°F and 64.4°F, were used for the MMLS3 test. The 78M granite AAR and EAR used in the laboratory are 17 lb/yd^2 and 0.25 gal/yd^2, respectively. These rates are established based on field application rates for double seals and by trial and error to produce repeatable laboratory samples. The aggregate used in the laboratory was completely dried in the oven before fabricating the samples. Also, the temperature must be controlled throughout the entire fabrication 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. A 16 ft. by 8 ft. greenhouse made of wood and polycarbonate glass was used for this purpose. The greenhouse, seen in Figure 3-3 (a), ensures a relatively consistent temperature for the specimens during fabrication.

Figure 3-2 Sample fabrication procedure: (a) affixed felt papers on the existing pavement; (b) spraying emulsion; (c) spreading aggregate; (d) compacting with rollers; (e) gathering samples; (f) delivering samples to laboratory

The chip seal specimen used for the MMLS3 testing has a rectangular shape 7 in. wide and 12 in. long. The width is designed to cover the entire wheel path under wandering MMLS3 loading. A felt disk is placed on the scale, and the template is placed and centered over the felt disk. The emulsion, heated to 158°F, is sprayed with a portable sprayer onto the felt desk resting on the scale so that the EAR can be controlled in the laboratory, as seen in Figure 3-3 (b) and Figure 3-3 (c). Then, the aggregate is immediately spread by the ChipSS aggregate spreader, shown in Figure 3-3 (d). ChipSS was designed to be a scaled-down version of the actual field spreader, so the intent of this device is to mimic the aggregate application in the field as closely as possible. Once the aggregate is spread on the emulsion, a neoprene sheet 3 mm thick is placed on top to prevent crushing the aggregate during compaction. The specimen is then compacted using a half-circle hand kneading compactor for three half-cycles along the wheel path direction of the specimen (Figure 3-3 (e)). The compacted specimen is then cured in a forced mechanical convection oven at 95°F and 30 ± 3% relative humidity (RH) for 24 hours for the aggregate retention test using the MMLS3. It is noted that, in general, this same curing condition is applied to specimens fabricated for the other test methods, but some differences do exist, and these are explained with the appropriate test protocol.



(a) (b) (c) (d) (e) (f)

Figure 3-3 Chip seal specimen fabrication procedure: (a) greenhouse; (b) emulsion application gun; (c) applied CRS-2 on the felt paper; (d) applied aggregate on the emulsion by ChipSS; (e) hand steel compactor with neoprene sheet; (f) sample curing in the oven

3.4 Experimental Test Methods

3.4.1 Vialit Test Procedure

The Vialit test was developed by the French Public Works Research Group and standardized in BS EN 12272-3. This test method is an indicator of aggregate retention of chip seals using the Vialit testing apparatus, as shown in Figure 3-4. A stainless steel ball is dropped three times from a height of 19.7 in. onto inverted chip seal trays. The percentage of aggregate loss after three ball drops is used to evaluate aggregate retention.

The chip seal specimens obtained from the field were cured at 95°F (35°C) for 24 hours. Seven replicates were tested, and Equation (1) was used to calculate the percentage of aggregate loss using the results from the replicated tests.

$$Aggregate\,Loss(\%) = \frac{W_{B,agg} - W_{A,agg}}{W_{B,agg}} \times 100\,, \tag{1}$$

where

$W_{B,agg}$ = weight of aggregate on chip seal specimen before the test, and

$W_{A,agg}$ = weight of aggregate on chip seal specimen after the test.

Figure 3-4 Vialit test apparatus

3.4.2 Flip-Over Test

The flip-over test (FOT) measures the amount of excess aggregate on the specimens and is part of the sweep test procedure (ASTM D 7000). The samples obtained from the test sections were stored at room temperature and were fully cured at 95°F (35°C) for 24 hours before the test. Each specimen was turned vertically, and any loose aggregate was removed by lightly brushing the specimen. Equation (1) was used to calculate the percentage of aggregate loss from the six replicated tests results.

3.4.3 MMLS3 Performance Test Procedure

The MMLS3 is a third-scale unidirectional vehicle load simulator that uses a continuous loop for trafficking. It is comprised of four bogies with only one wheel per bogie. These wheels are pneumatic tires that are 11.8 inches in diameter, approximately one-third the diameter of a standard truck tire. The wheels travel at a speed of about 5,500 wheel applications per hour, which corresponds to a dynamic loading of 3.3 Hz on the pavement surface. This loading consists of a 0.3 second haversine loading time and a rest period of 0.3 second. The dynamic load on the pavement surface by the MMLS3 in motion is measured by a Flexiforce® pressure sensor. The mean value of maximum dynamic loads from the four wheels is approximately 802.6 lbf. The contact area is approximately 5.27 in.^{2} measured from the footprint of one MMLS3 wheel inflated to 101.5 psi, thus resulting in a surface contact stress of approximately 152.1 psi (Lee 2004).

The major steps in the MMLS3 test preparation are shown in Figure 3-5. Figure 3-5 (a) shows the trimmed specimen, 7.1 in. wide and 14 in. long, for the MMLS3. For chip seal testing under the MMLS3, specimens are attached to thin steel plates that are fastened to a steel base plate, as illustrated in Figure 3-5 (c). MMLS3 loading is applied after a 3-hour temperature preconditioning period at 77°F (25°C). The weight of the specimen attached to the steel plate is measured before and after the MMLS3 loading to determine the aggregate loss. The aggregate loss during the initial traffic loading in the field (normally occurring within half a day) is measured after one wandering cycle of the MMLS3 loading. Then, MMLS3 loading is applied, and the weight measurements are taken periodically over a 2-hour period (equivalent to 11,820 wheel loads) to evaluate the aggregate retention performance of the chip seal under traffic (Kim et al. 2005).

The complete MMLS3 test procedure involves the following steps (Kim and Lee 2005):

1) curing the specimens in a forced mechanical convection oven for 24 hours at 95°F (35°C) and 30 ± 3% RH, as specified by ASTM D7000;
2) measuring the initial specimen weight;
3) conditioning specimens at 77°F (25°C) for 3 hours for the aggregate retention test;
4) MMLS3 loading for 10 minutes, which is the time required for the MMLS3 to complete one wandering cycle, and then measuring the specimen weight;
5) MMLS3 loading for 2 hours with periodic measurements of the specimen weight; and measuring the final specimen weight.

MMLS3 Test for Low Temperature Aggregate Loss

It has been postulated that most of the aggregate loss during the first year of service life of a chip seal occurs in late fall when the air temperature drops significantly (Transit New Zealand 2005). To examine whether the use of PME in chip seals improves aggregate retention at low temperatures, a test procedure was developed to evaluate low temperature aggregate loss performance under traffic loading. A comparison was made between the percentage of aggregate loss of the CRS-2 emulsion and the CRS-2L emulsion in the single seal and double seal.

The preliminary procedure developed for the low temperature testing is as follows:

1. Fabricate desired samples and allow them to cure in a 95°F oven for 24 hours.
2. Move samples to a -4°F freezer and store for 24 hours.
3. Allow the MMLS3 chamber to condition to 64.4°F.
4. Measure sample weights.
5. Place samples to be tested in chamber.
6. Run MMLS3 for 10 minutes and measure aggregate loss.
7. Run MMLS3 for an additional 2 hours and measure aggregate loss.

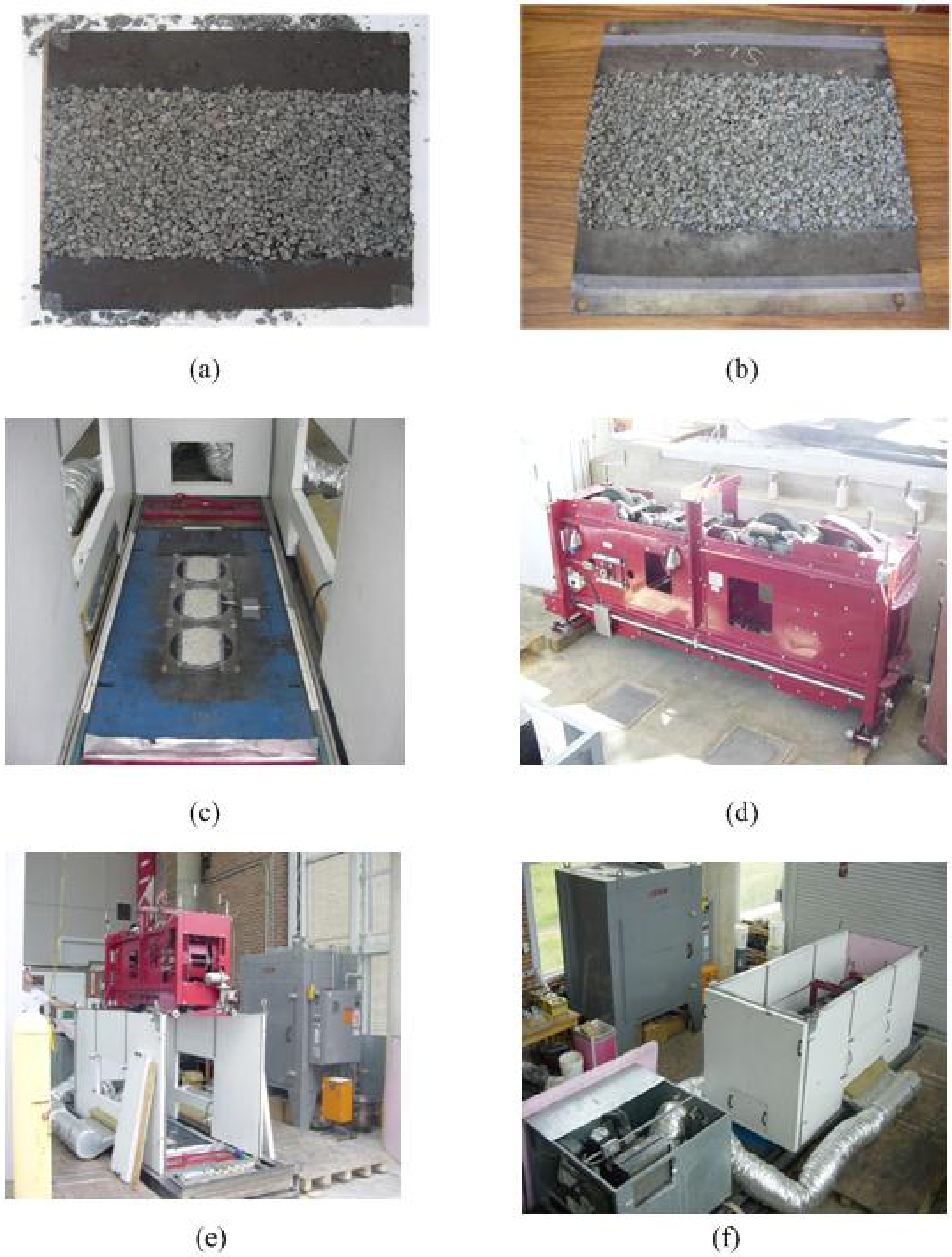


Figure 3-5 MMLS3 test preparation: (a) trimmed specimen; (b) MMLS3 test specimen; (c) installation of specimens on a steel base; (d) side view of MMLS3; (e) positioning MMLS3 in the temperature chamber; (f) complete MMLS3 test setup for chip seal testing

3.4.4 Digital Image Processing for Evaluation of Bleeding Performance of Chip Seal

A bleeding test protocol using digital image processing (DIP), developed at NCSU, was used in this study (Lee 2007) and is described briefly in this section.

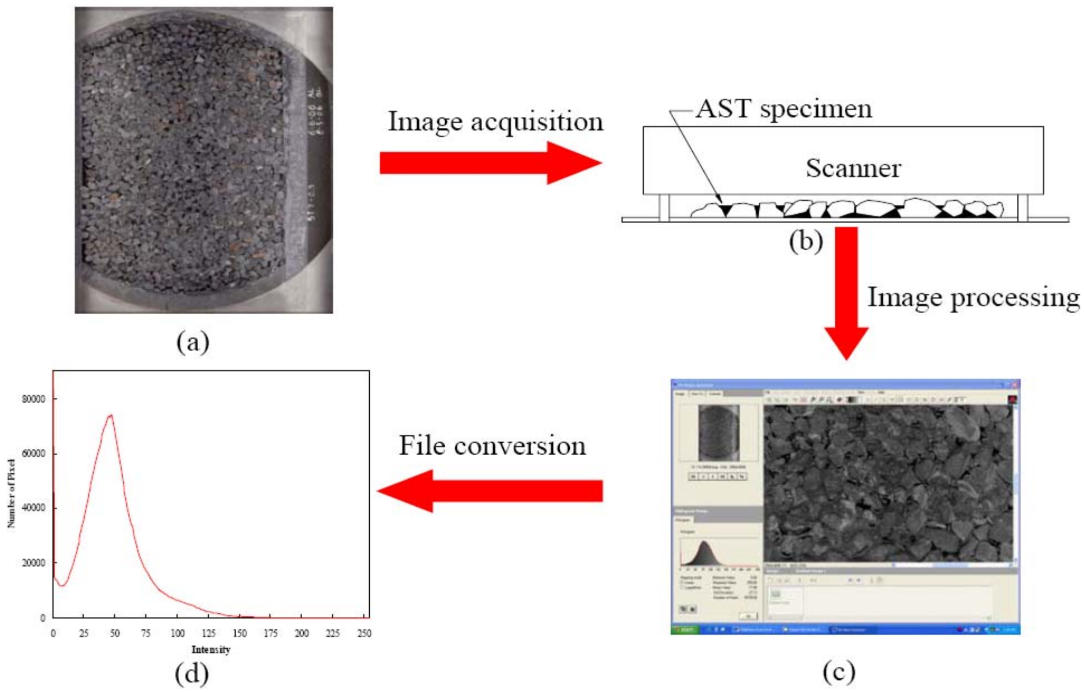


Figure 3-6 Digital image processing procedure of chip seal specimen: (a) actual specimen; (b) image acquisition using scanner (grayscale); (c) image processing; (d) data file (Lee 2007)

Figure 3-6 illustrates the data acquisition procedure used in this project. Before and after the MMLS3 bleeding test, the chip seal specimen surface is scanned into an 8-bit grayscale digital image that consists of a single plane of pixels. Each pixel is encoded using a single number that represents grayscale values from 0 to 225. To scan the specimen surface without disturbing the aggregate, the scanner is turned upside down and held over the specimen instead of turning over the specimen itself, which could potentially dislodge some of the aggregate.

National Instruments Vision Assistant (NIVA) 7.0 is then used for the analysis of the digital image to generate a histogram of grayscale intensity values (GIVs).

The number of pixels with GIVs smaller than the critical bleeding GIV in the GIV histogram is used to quantify bleeding for a given chip seal specimen. The critical bleeding GIV is determined using a special function in NIVA. This function allows the user to define the critical GIV and visually displays the areas that have GIVs lower than the critical value. By comparing the bleeding areas in the actual image of the specimen and the areas suggested by the special function in NIVA, the user can determine the appropriateness of the assigned critical GIV. A trial-and-error method is used to determine the critical GIV for each specimen. The critical GIV was found to be slightly different from sample to sample and between different aggregate samples. The average critical GIV is around 50.

The defined critical bleeding GIV is then applied to the GIV histograms obtained from the chip seal specimen to calculate the percentage of bleeding using the following formula:

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

where

A_{Total} = area of chip seal specimen (total number of pixels); and

$A_{Bleeding}$ = area of bleeding on chip seal specimen (sum of pixels that are smaller than the critical bleeding GIV).

3.4.5 Rutting Test Procedure Using MMLS3 for Asphalt Surface Treatments

The rutting development of chip seals in terms of emulsion type and testing temperature is conducted using the MMLS3. A rutting test protocol that was developed at NCSU (Kim et al. 2005) is utilized for this study.

In order to evaluate the rutting behavior of the chip seals, the triple seal specimen fabricated in the laboratory is used for measuring rut growth. For the triple seal specimen, granite 78M aggregate, granite 78M aggregate, and lightweight aggregate are used for the bottom, middle, and top layers, respectively. The AARs for the triple seal are 17lb/yd^2, 17 lb/yd^2 and 9 lb/yd^2 for the bottom (granite 78M aggregate), middle (granite 78M aggregate), and top (lightweight aggregate) layers, respectively. EARs for both the CRS-2 and CRS-2L emulsions are 0.30 gal/yd^2, 0.25gal/yd^2, and 0.20 gal/yd^2 in order respectively from the bottom layer to the top layer of the triple seal.

The experimental test program, as summarized in Table 3-1, is designed with two different emulsion types and as a function of three different test temperatures. The three test temperatures are selected as 68°F, a LTPP-binder high temperature of 129.2°F, and a mid-range temperature of 104°F that falls between those two temperatures. Three samples are required for the rutting test. The rut depth was measured periodically at the center of each specimen. Figure 3-7 (a) shows the rut depth of the triple seal that meets the failure criteria. Figure 3-7 (b) shows the MMLS3 tire on the triple seal specimen.

Table 3-4 Rutting Test Program

Chip Seal Type	Emulsion Type	Test Temperature, °F
Triple seals	CRS-2	68 (20°C)
		104 (40°C)
		129.2 (54°C)
	CRS-2L	68 (20°C)
		104 (40°C)
		129.2 (54°C)

The transverse profile was measured periodically at the center of each specimen, as seen in Figure 3-7 (c) and Figure 3-7 (d). The profilometer provides a comparison of the initial measurements of the triple seal surface with measurements made at intervals during testing. The Mitutoyo profilometer using RS-232C communication consists of a measurement stand and a vertical reader unit. The stem of the vertical reader slides freely in a slot to obtain the rut depth reading. Transverse profile measurements spaced at 10 mm with a tolerance of ± 2 mm were conducted. The loading histories and the profile measurement periods were kept constant under the various testing conditions.

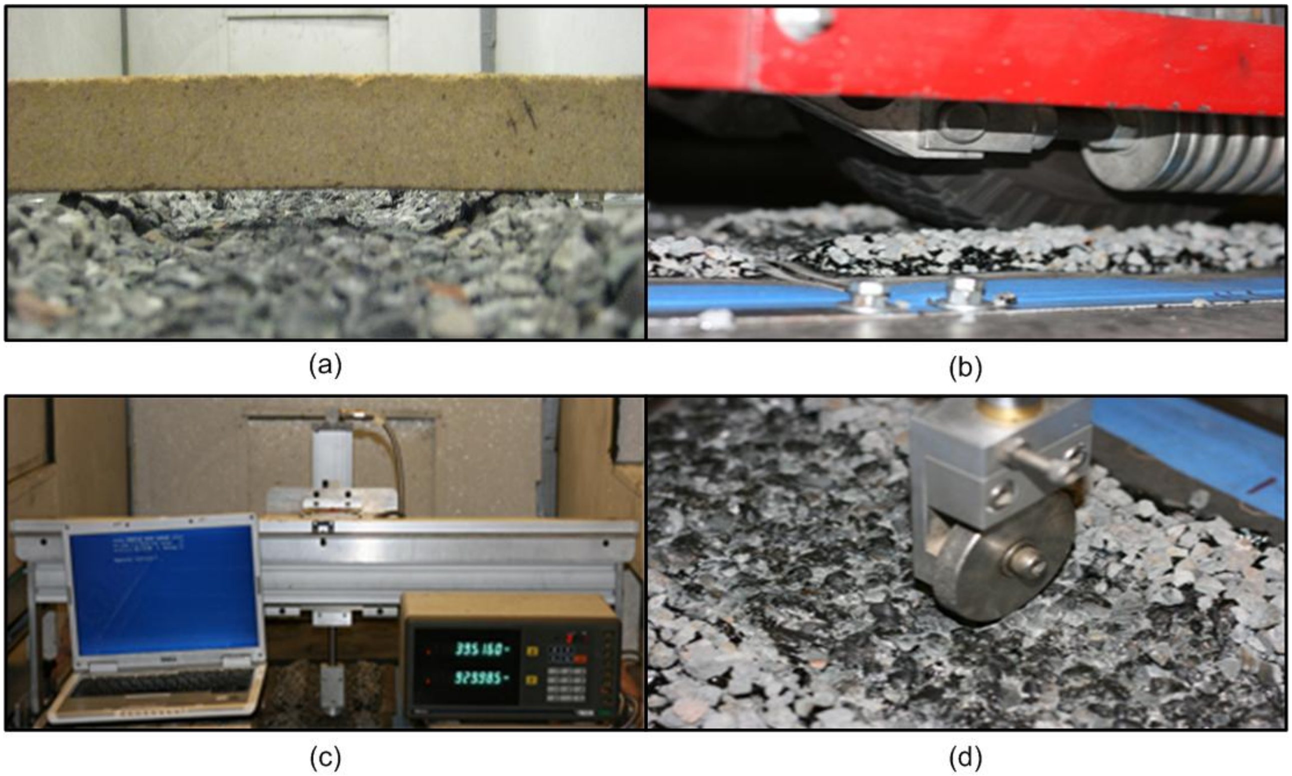


Figure 3-7 Front view of rut depth and profile system: (a) final rut depth of the triple seal after MMLS3 testing; (b) MMLS3 tire on the triple seal; (b) transverse profile measurement using Mitutoyo profilometer; (d) profilometer on the specimen

Chapter 4. EVALUATION OF AGGREGATE RETENTION PERFORMANCE OF ASPHALT SURFACE TREATMENTS

4.1 Experimental Program

Aggregate loss is one of the most critical of the chip seal failure modes. Generally, the most aggregate loss occurs during the initial traffic once a road is newly opened to traffic. Other major causes of aggregate loss include unexpected cold and/or wet weather, excessive aggregate, inadequate traffic control during construction, inadequate embedment of the stone particles in the emulsion, inadequate aggregate characteristics, and dusty or dirty aggregate (Shuler 1998, Gransberg 2005). The aggregate loss due to construction mistakes occurs within a few months, and an chip seal that experiences this type of problem should be repaired rather than resealed because a reseal alone cannot normally last the expected life of the chip seal (Transit New Zealand 2005). The aggregate properties of the chip seal, such as gradation, shape, moisture condition, and dust play a major role in aggregate loss/retention.

For this research, samples were fabricated in two different places, at an actual construction field site and in the laboratory. Initially in this research, the fabrication of the field samples was intended to correspond to the actual construction sequence. However, problems occurred after the first sample fabrication with huge sample weight variations from sample to sample. These substantial variations affected the results from the aggregate retention tests. So, the research team had to change the way of obtaining the samples and decided to fabricate samples in the laboratory. The results from aggregate retention tests in terms of the location of the sample fabrication are described in this chapter.

4.2 Field Sample Evaluation

The aggregate loss results of the three aggregate retention tests (the Vialit test, FOT, and MMLS3 test) using samples taken from the field were calculated and are plotted in Figure 4-1 and Figure 4-2 against the two emulsion types, CRS-2 and CRS-2P. It must be noted that the aggregate loss determined from the field samples using Equation (3) is based on the mixture weight, i.e., the combined weights of the emulsion and aggregate. The use of the mixture weight is necessary because the emulsion weight and the aggregate weight cannot be determined separately from the samples fabricated in the field.

$$Aggregate\,Loss\ (\%) = \frac{W_{B,mixture} - W_{A,mixture}}{W_{B,mixture}} \times 100 \qquad (3)$$

where $W_{B,mixture}$ and $W_{A,mixture}$ are the weights of the emulsion and aggregate on the chip seal specimen before and after the test, respectively.

Figure 4-1 represents test results for the single seal and uses three symbols: a filled symbol, an empty symbol, and a small filled circle symbol. The filled and empty symbols represent the results for the lightweight and granite aggregates, respectively. The small filled circle indicates the average of the data for each emulsion and aggregate type. It is clearly shown in this figure that the aggregate loss of the chip seals with granite 78M aggregate decreases with the CRS-2P emulsion. The results for the lightweight aggregate are less conclusive. Lee et al. (2006) demonstrated that chip seals constructed with lightweight aggregate show a better aggregate retention performance than those made of the granite 78M aggregate, and that this difference is mainly due to the more uniform gradation of the lightweight aggregate compared to the granite 78M aggregate.

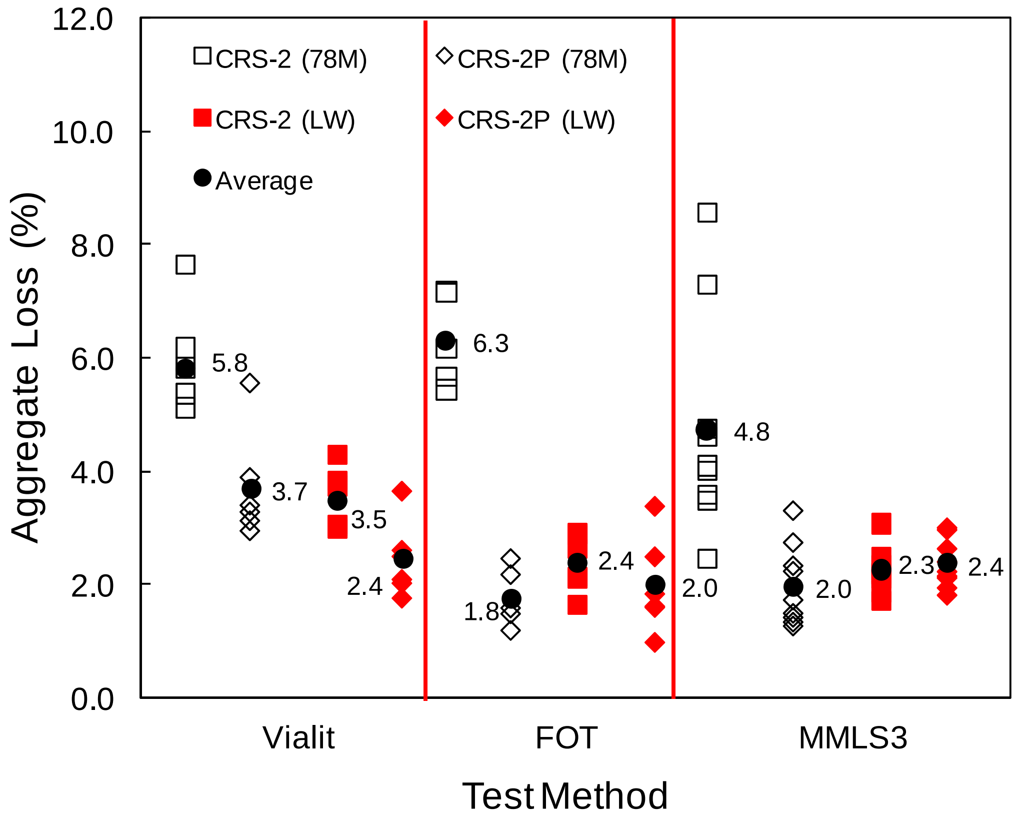


Figure 4-1 Aggregate loss from the single seal field samples

The lack of additional benefits of polymer modification in the chip seals with the lightweight aggregate may be due to the fact that the added benefits of polymer modification are less significant in chip seals made of lightweight aggregate that are already performing well without the modification due to the uniform gradation of the lightweight aggregate and to the additional adhesion from the PME that is not needed to hold the lightweight aggregate under wheel loading.

Results from the double seals are shown in Figure 4-2. In this case, the polymer modification improves the aggregate retention performance of double seals, even though the aggregate in the top layer is the lightweight aggregate, as shown in Figure 4-1. Moreover, it is observed from the test results that the lost aggregates in the double seal are composed of lightweight aggregate from the top layer only. It seems that the uniform gradation of the lightweight aggregate does not contribute to improved aggregate retention performance in the double seals. It is hypothesized that the combined aggregate structure created by the non-uniform granite 78M aggregate in the bottom layer and the uniform lightweight aggregate in the top layer reduces the beneficial effects of the uniform gradation in the lightweight aggregate and, thus, enhances the beneficial effects of polymer modification.

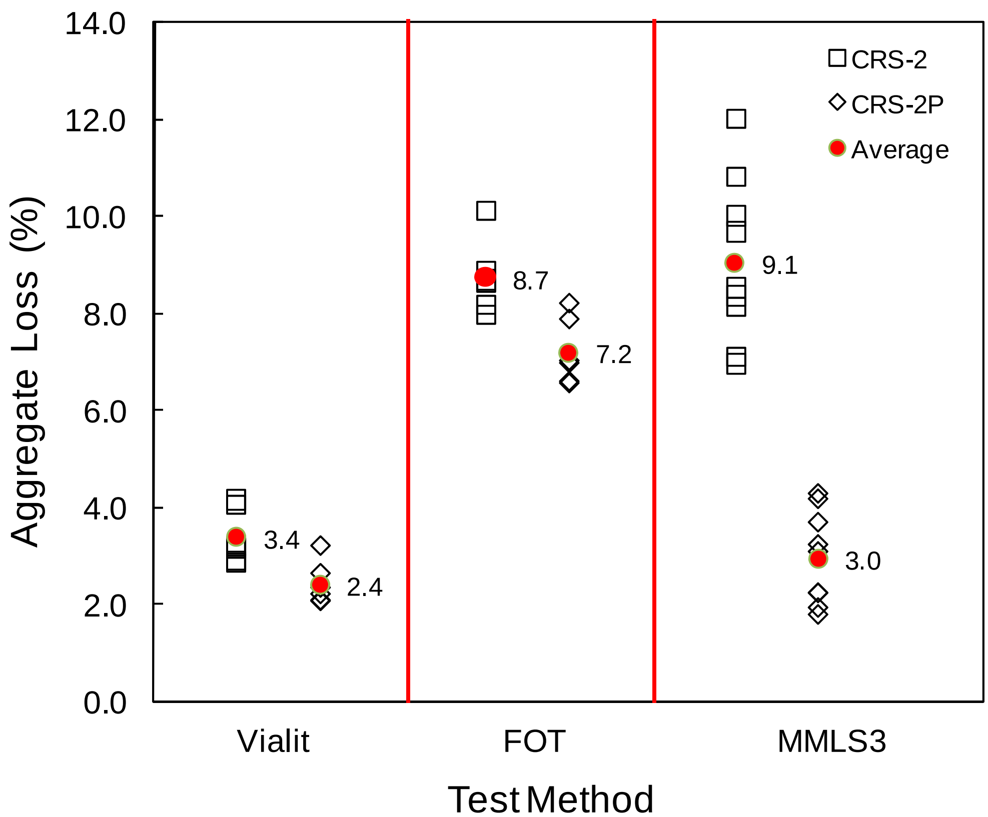


Figure 4-2 Aggregate loss from the double seal using a combination of granite 78M and lightweight aggregate

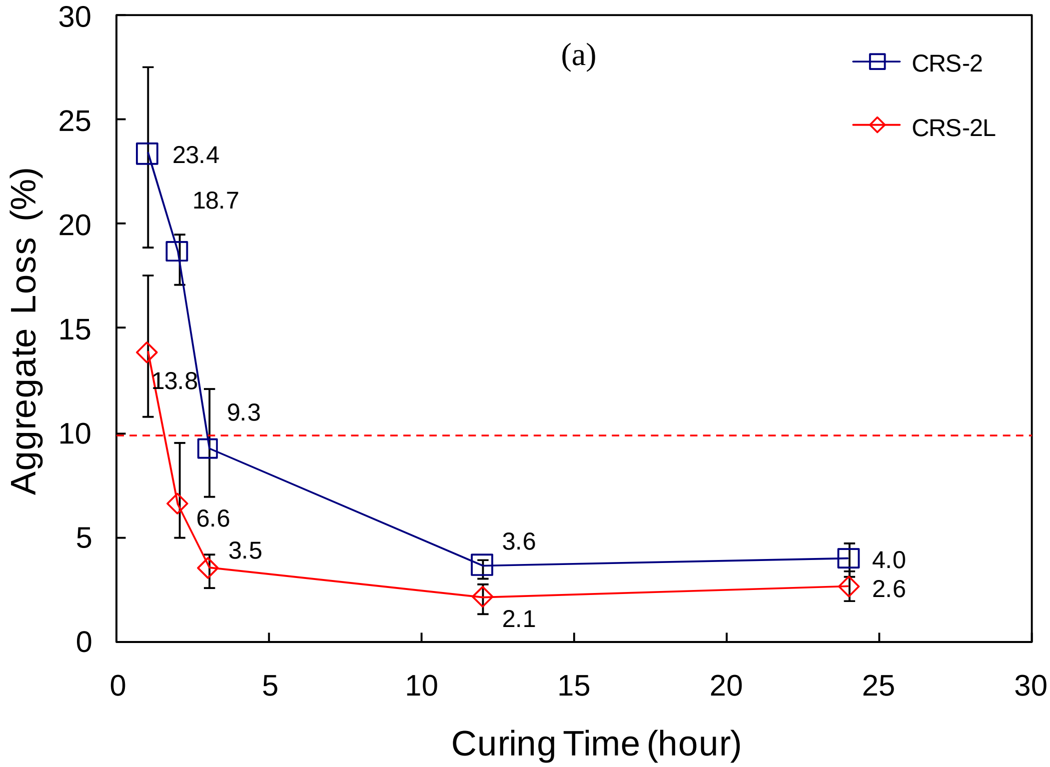
4.3 Laboratory Sample Evaluation

4.3.1 Adhesion Behavior at Different Curing Times

The adhesion development of the CRS-2 and CRS-2L emulsions according to their use with the two aggregate types (granite 78M and lightweight) was investigated as a function of curing time using the Vialit test. The aggregate loss percentages obtained for the two emulsions according to aggregate type are plotted in Figure 4-3. Each data point in this figure represents the average of the seven replicates. Figure 4-3 (a) shows the adhesion behavior of granite 78M aggregate for 1, 2, 3, 12 and 24 hours. In total, seven tests were performed at each curing time for a total of 35 tests. Figure 4-3 (b) shows the adhesion behavior of lightweight aggregate for 1, 2, 3, 6, 12 and 24 hours for a total of 42 tests.

Figure 4-3 (a) and (b) show that aggregate loss decreases as the curing time increases, regardless of emulsion type or aggregate type. Notice that in these plots the error bars are shown to represent the highest and lowest percentage of aggregate loss measured under a particular condition.

In the case of granite 78M aggregate, as seen in Figure 4-3 (a), the average aggregate loss of the CRS-2 emulsion is about 10% greater than that of the CRS-2L emulsion for 1 hour of curing. However, the percentage of aggregate loss for both emulsions is greater than the 10% that is specified in the Alaska chip seal design guide as the maximum allowable aggregate loss (McHattie 2001). This finding implies that 1 hour of curing at 95°F is not enough time for the development of proper adhesion between the aggregate and the binder, whether the emulsion is modified by polymer or not. Another observation from Figure 4-3 (a) can be seen at the 2-hour curing time. The percentage of aggregate loss of the CRS-2L emulsion is less than 10% of the maximum allowable aggregate loss; however, the average aggregate loss of the CRS-2 emulsion is still over 10 percent. This finding indicates that the CRS-2L emulsion achieves proper adhesion within 2 hours, which satisfies the maximum allowable aggregate loss specified in the Alaska chip seal design. However, 2 hours is not enough time for the CRS-2 emulsion to meet the Alaska chip seal criterion. All average aggregate loss values measured for samples that were cured for more than 3 hours (3, 12, and 24 hours) are below 10 percent. Also, the difference between the aggregate loss of the CRS-2L and CRS-2 emulsions is clearly reduced after 3 hours.



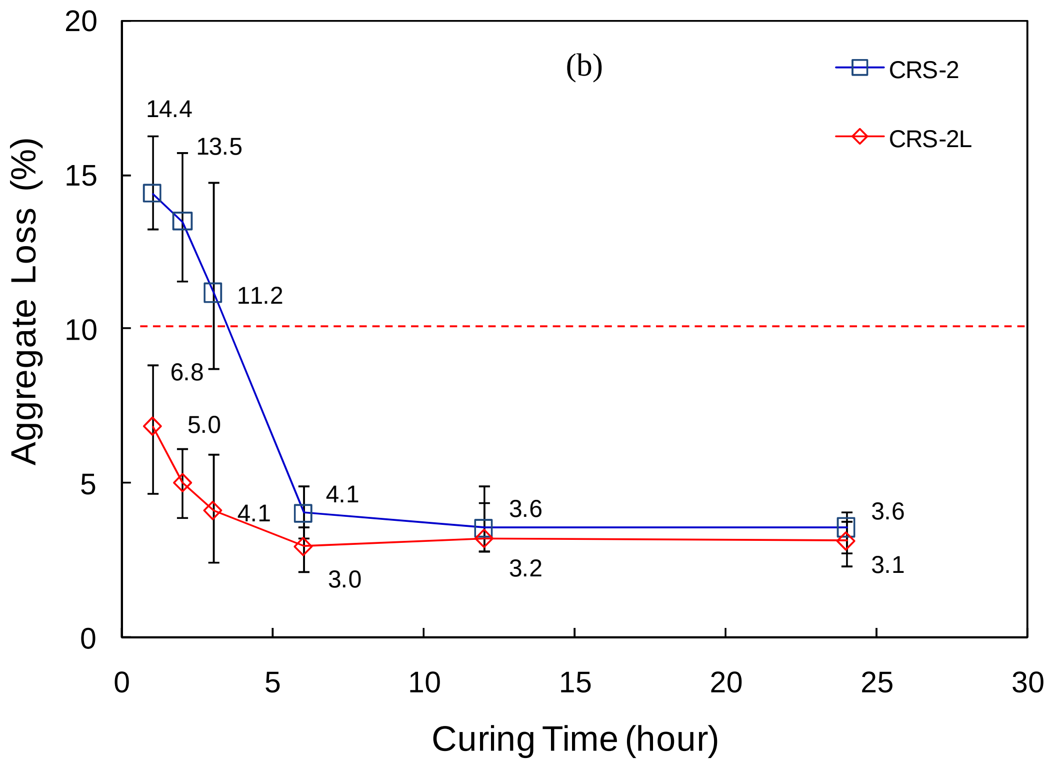


Figure 4-3 Aggregate loss results from the Vialit test as a function of curing time: (a) granite 78M; (b) lightweight

The overall trend, i.e., that the aggregate loss of the CRS-2L emulsion is less than that of the CRS-2 emulsion, as seen in Figure 4-3 (a), indicates that the CRS-2L emulsion enhances the aggregate retention performance, and does so more significantly in the first three hours. The largest difference in aggregate loss between the CRS-2 emulsion and CRS-2L emulsion (i.e., a 12% difference) occurs at 2 hours, as seen in Figure 4-3 (a). Figure 4-3 (b) shows the aggregate loss results using lightweight aggregate as a function of different curing times. Contrary to the behavior of the granite 78M aggregate, the average aggregate loss of the CRS-2L emulsion is below 10% for the 1-hour curing time. However, 3 hours is not enough time for the CRS-2 emulsion to meet the Alaska chip seal criterion.

All average aggregate loss values were measured for samples that were cured for more than 3 hours. After 6 hours, no significant difference in aggregate loss between the CRS-2 and CRS-2L emulsions was evident.

To investigate the early curing behavior of the two emulsions, Figure 4-4 (a) and Figure 4-4 (b) show the data in the first three hours with the 10% maximum allowable aggregate loss according to aggregate type. As shown in Figure 4-4 (a), the CRS-2L emulsion satisfies this criterion after 1 hour 30 minutes, and the CRS-2 emulsion reaches 10% of aggregate loss after 3 hours of curing. In the case of the lightweight aggregate (Figure 4-4 (a)), the CRS-2 emulsion satisfies this criterion after 4 hours 30 minutes. These figures in Figure 4-4 thus indicate that the CRS-2L emulsion exhibits a faster change in adhesion than the CRS-2 emulsion, which reduces the aggregate loss during early curing times. Thus, the benefits of fast and improved adhesion in the CRS-2L emulsion are manifest in: (1) a reduction in the amount of aggregate loss during early curing times; (2) less curing time needed to obtain the desired adhesion between the asphalt and aggregate; and (3) the ability to allow traffic safely on the freshly constructed road sooner.

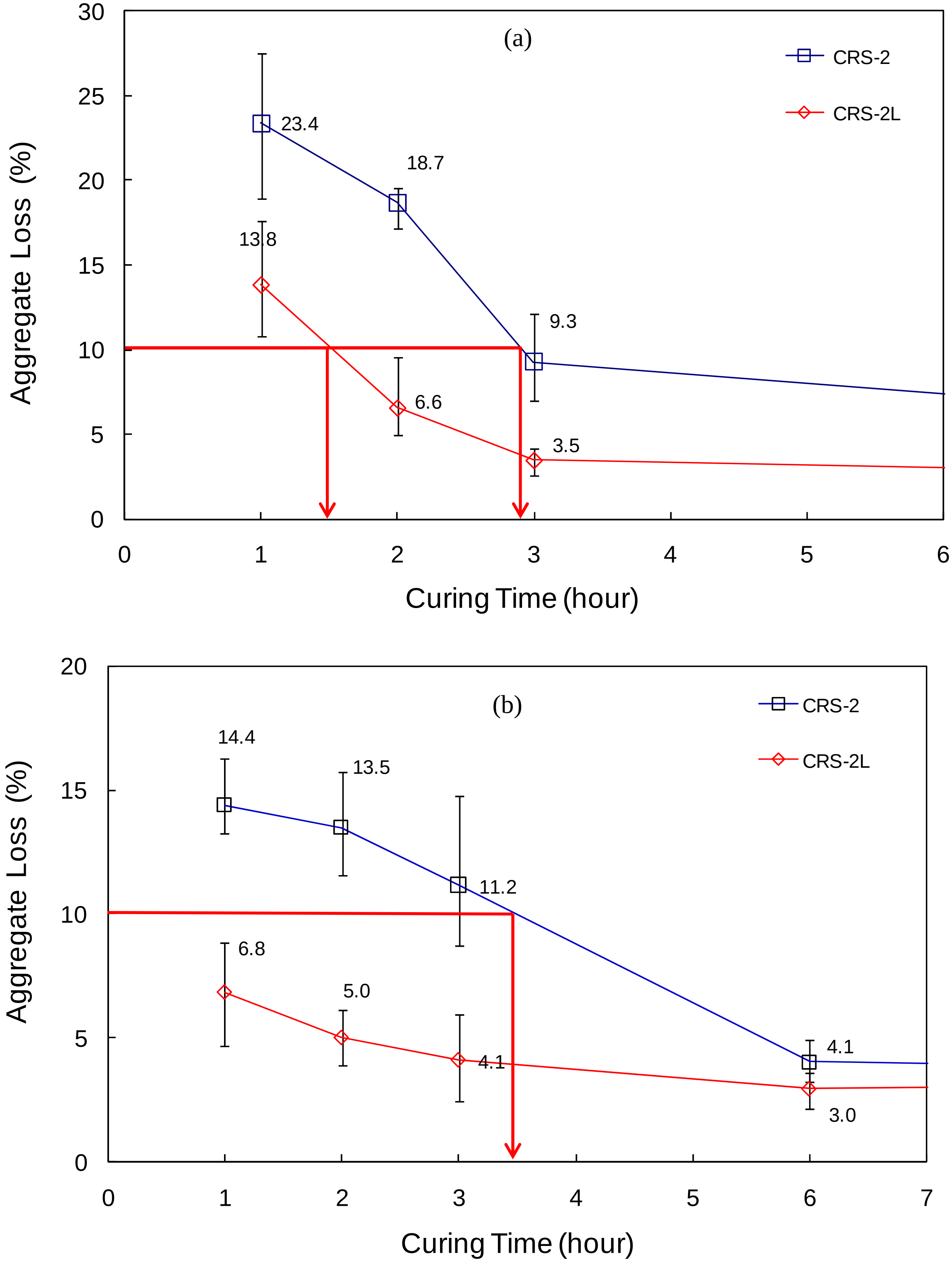


Figure 4-4 Average aggregate loss measured from the Vialit test as a function of curing time (first three hours): (a) granite 78M; (b) lightweight

4.3.2 Adhesion Behavior at Different Curing Temperatures

The aggregate loss percentages obtained for the two emulsions at each of the three curing temperatures (77°, 95°, and 113°F) for two different curing times in terms of two aggregate types are plotted in Figure 4-5 and Figure 4-6. One curing time is 2 hours, which is the time used to estimate the early stage of the adhesion development, as shown in Figure 4-5. Another curing time is 24 hours, which is the time needed to investigate aggregate loss performance for a completely cured sample, as shown in Figure 4-6.

The first observation to be made from these figures (Figure 4-5 and Figure 4-6) is that the CRS-2L emulsion has consistently lower aggregate loss values, as obtained from the average of seven replicates, than the CRS-2 emulsion, regardless of the temperature and curing time. Secondly, the aggregate loss decreases as the curing temperature or the curing time increases. For example, the percentage of aggregate loss of samples cured at 113°F in the oven for 2 hours is similar to that of samples cured at 77°F in the laboratory for 24 hours. It is noted that at 77°F the aggregate loss after the 2-hour curing time is much greater than the 10% threshold, whether the emulsion is modified by polymer or not. This observation suggests that when chip seals are constructed at the ambient temperature of 77°F, traffic should be kept off these pavements for 4 to 5 hours to reduce aggregate whip-off.

The benefit of polymer modification is clearly demonstrated at 95°F. The aggregate loss of the PME chip seal is well within 10% of the maximum allowable aggregate loss after 2 hours of curing, whereas that of the unmodified chip seal is still much greater than the 10% of the maximum allowable aggregate loss. At 113°F, 2 hours of curing time is sufficient for both chip seals. These observations suggest that the adhesive behavior of the emulsion is very sensitive to curing temperature. Thus, special attention should be paid to the rolling operation and brooming time in order to avoid damage caused by loose aggregate during chip seal construction in the field.

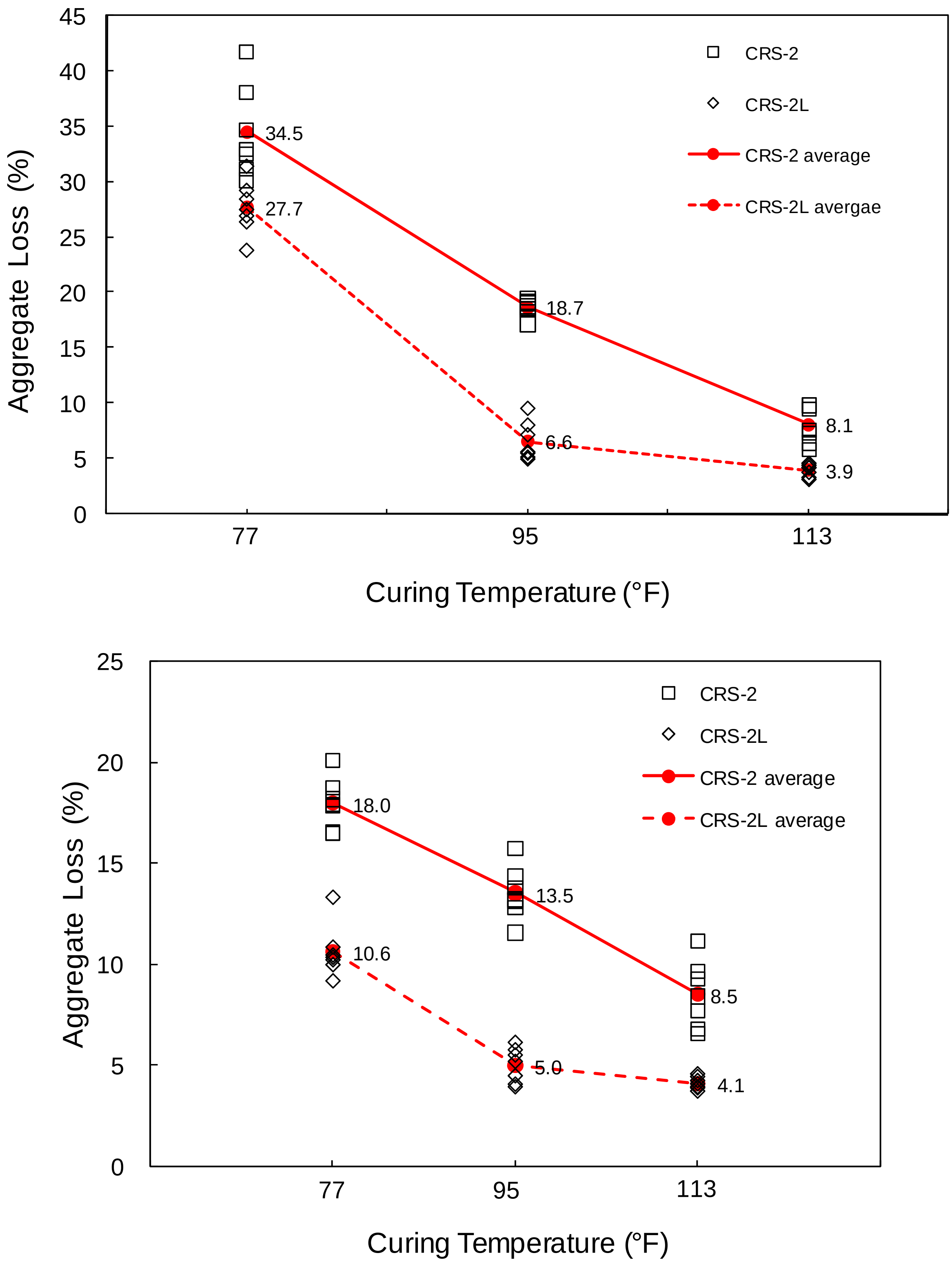


Figure 4-5 Aggregate loss after 2 hours of curing time from the Vialit test at different curing temperatures: (a) granite 78M; (b) lightweight

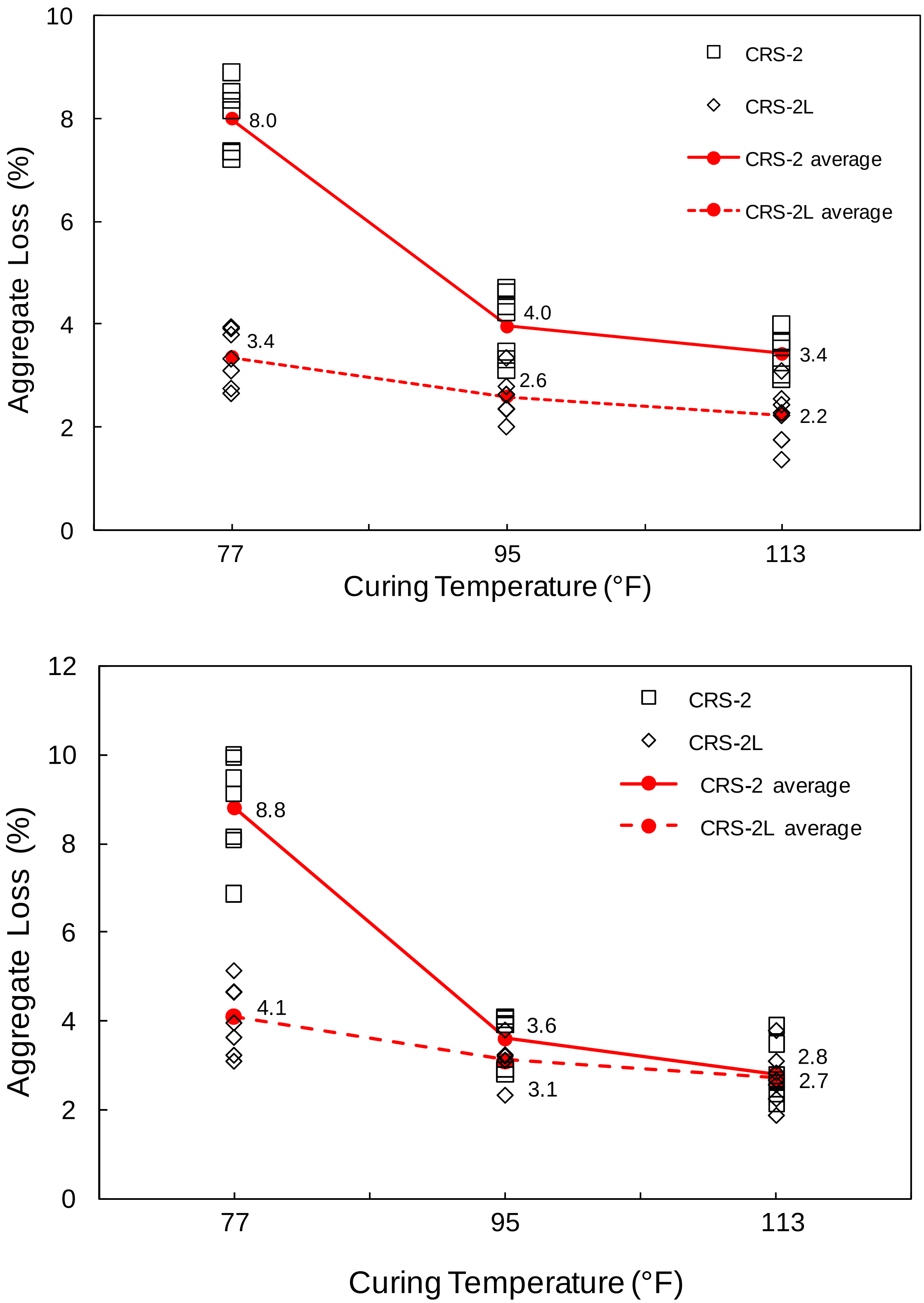


Figure 4-6 Aggregate loss after 24 hours of curing time from the Vialit test at different curing temperatures: (a) granite 78M; (b) lightweight

4.3.3 Adhesion Behavior at Low Temperatures

One of the main failures of chip seals is aggregate loss when the temperature drops during fall and winter (Transit New Zealand 2005). Therefore, this research is designed to study the performance of chip seals at low temperatures. The adhesive behavior of the two emulsions, CRS-2 and CRS-2L, at low temperatures was estimated using the Vialit test. Two sets of Vialit samples were stored at -4°F and -41°F for 24 hours to simulate aggregate retention performance under cold weather conditions. Those samples were completely cured at 95°F in the oven for 24 hours before temperature conditioning. The initial testing of the samples subjected to -4°F revealed that the emulsion became detached from the Vialit steel plate under the shock of impact, as seen in Figure 4-7. Figure 4-7 (b) magnifies the circled area in Figure 4-7 (a), which is one of the areas that became separated between the emulsion and the steel plate.

This detachment between the chip seal and the steel plate could cause an error in interpreting the Vialit test results. Therefore, it was decided to include a delay in the Vialit testing that would take place once the samples were removed from the temperature chamber. To determine the appropriate length of this delay, the Vialit test was conducted using samples that were taken out of the temperature chamber and left at an ambient temperature (77°F) for intervals of 0, 3, and 6 minutes. Visual observation of the Vialit samples clearly showed the different amounts of retained aggregate from the Vialit test as a function of the delayed testing time. The aggregate loss percentages of the two replicates for each interval (elapsed time) were calculated and are plotted in Figure 4-8. As seen in Figure 4-8, the percentage of aggregate loss as a function of delayed testing time shows a clear trend of rapid loss, followed by a gradual reduction. The transition point seems to occur around the 3-minute interval for both emulsion types. Therefore, this elapsed time was adopted to conduct the Vialit test using low temperature samples.

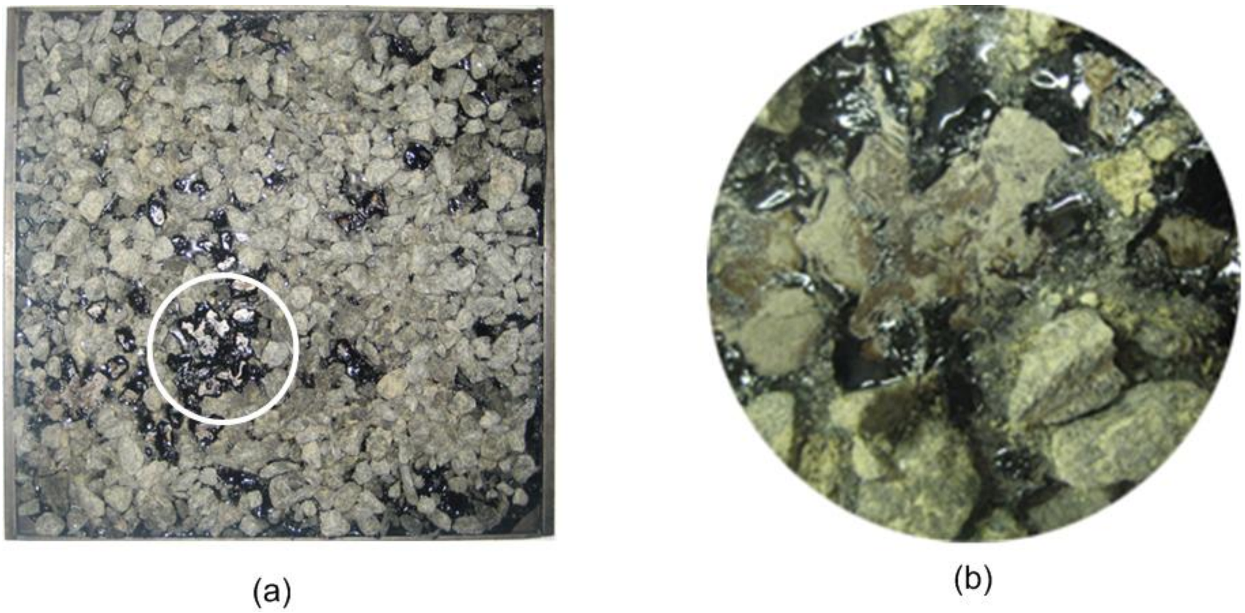


Figure 4-7 Separation of emulsion from the Vialit steel plate when an impact is applied to the sample conditioned at -20°F: (a) after testing the specimen; (b) circle area, magnified

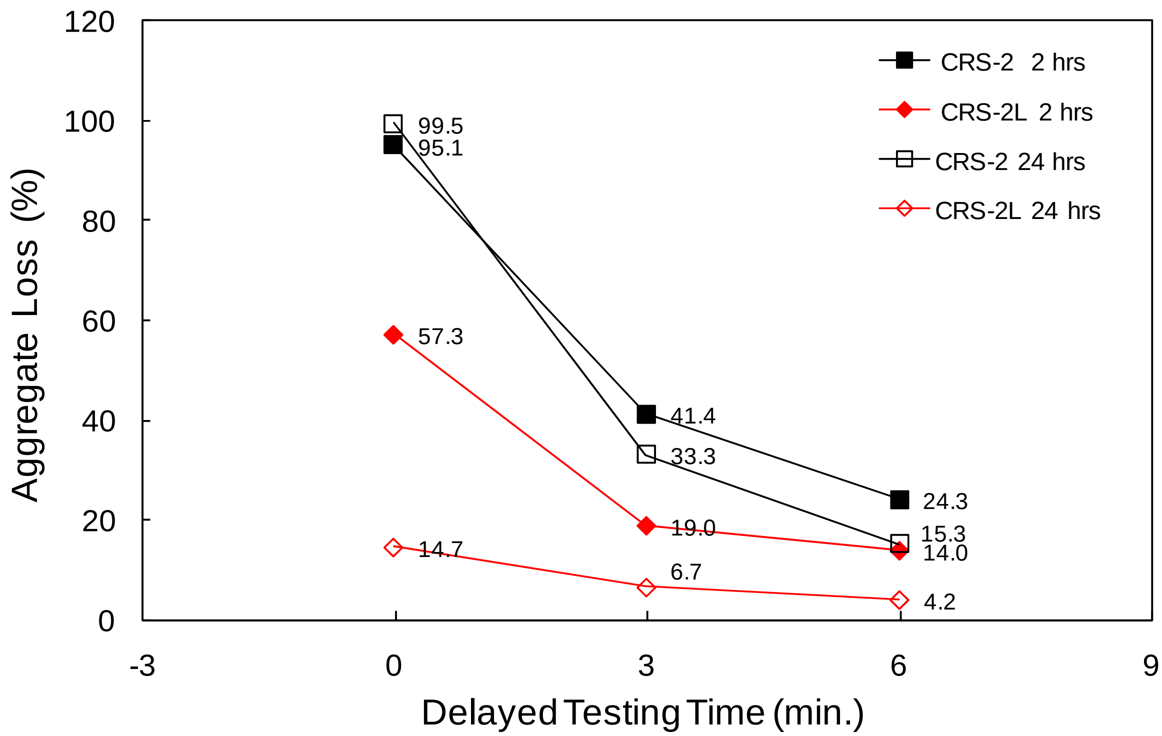


Figure 4-8 Aggregate loss as a function of freeze-thaw times

The aggregate loss was calculated using Equation (1) and is presented in Figure 4-9 for the two types of emulsion. The results from the 77°F testing are also presented in this figure for comparison. It can be seen that the use of PME significantly reduces the aggregate loss at low temperatures (almost three times less aggregate loss than with the non-modified emulsion). The percentages of aggregate loss of the CRS-2 emulsion at 41° and -4°F are over the maximum allowable aggregate loss of 10%, whereas the values for the CRS-2L emulsion are below this maximum allowable aggregate loss. This finding indicates that the CRS-2L emulsion is the most effective in enhancing the aggregate retention performance at low temperatures (below 41°F).

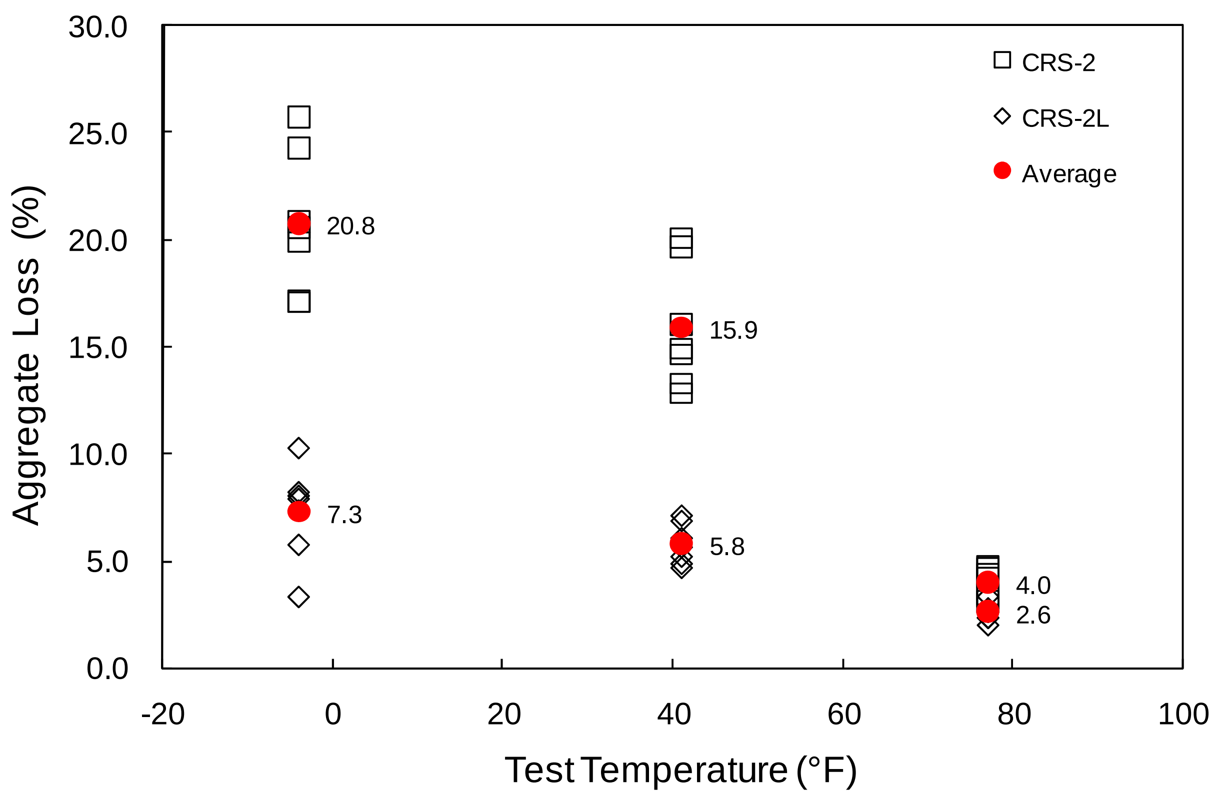


Figure 4-9 Aggregate loss results from the Vialit test on the specimens subjected to low temperatures

4.3.4 Flip-Over Test

The FOT measures the amount of excess aggregate on the specimen. Details regarding specimen curing and FOT procedures are described in Chapter 3 and, therefore, a detailed description is not included here. Figure 4-10 and Figure 4-11 show the percentage of aggregate loss from the FOT of the single seals and double seals in terms of the two different emulsion types (CRS-2 and CRS-2L) with two different aggregate types. The percentages of aggregate loss represented in Figure 4-10 and Figure 4-11 are determined using the weight of the aggregate using Equation (1). A solid circle symbol indicates the average of the data for each emulsion type.

As shown in both Figure 4-10 and Figure 4-11, the percentage of aggregate loss using the CRS-2L emulsion is less than that using the CRS-2 emulsion. However, the range of the percentage of aggregate loss, seen in both Figure 4-10 and Figure 4-11, is over the maximum allowable aggregate loss, 10%, specified in the Alaska chip seal guide.

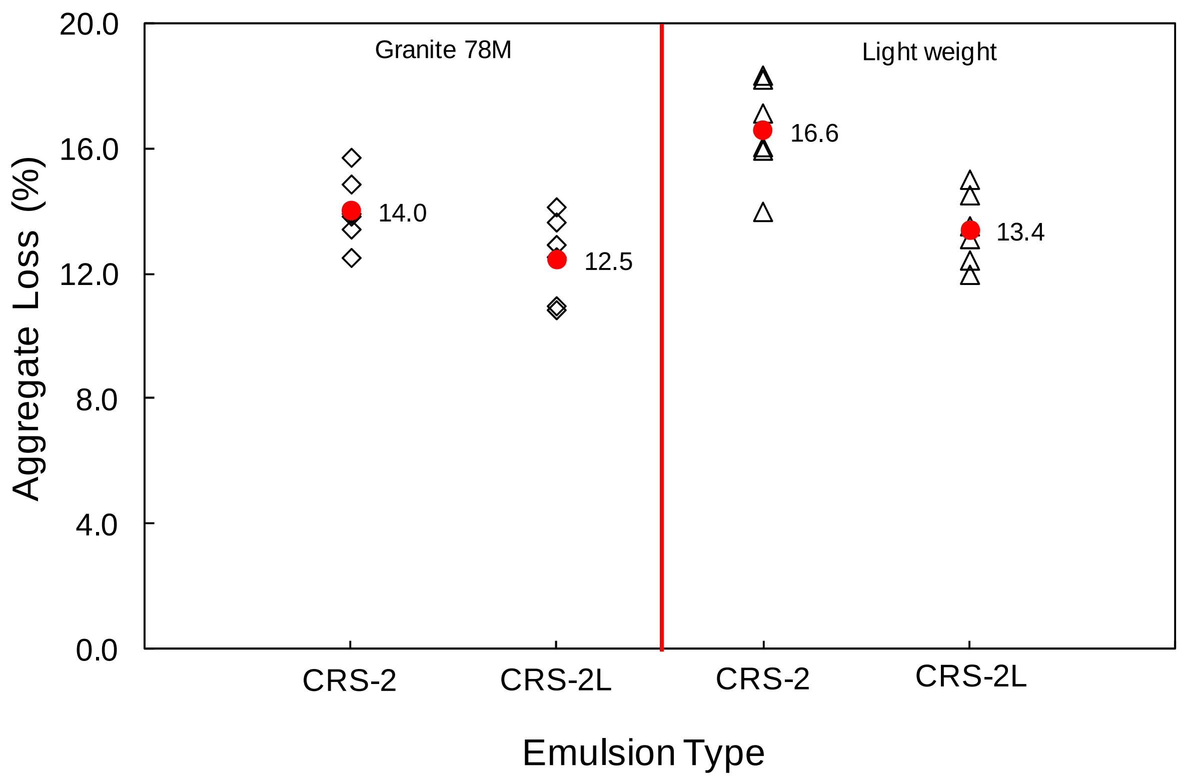


Figure 4-10 Aggregate loss of a single seal

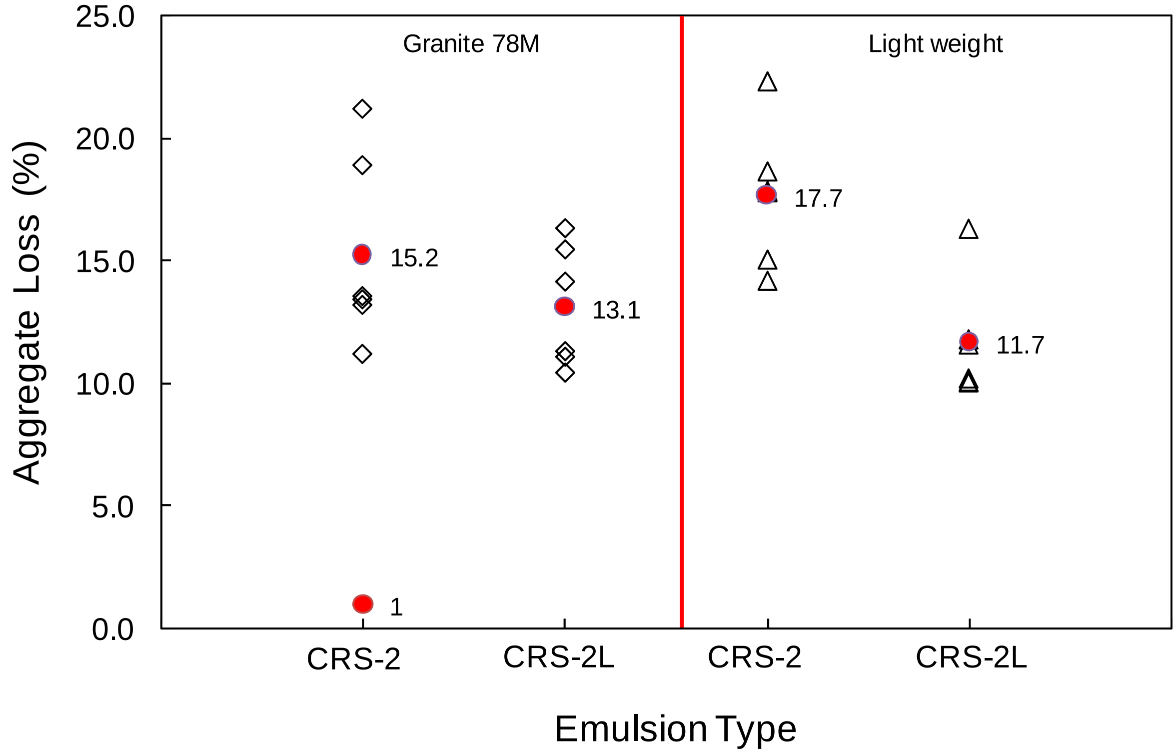


Figure 4-11 Aggregate loss of a double seal

4.3.5 MMLS3 Test

In this section, the aggregate loss performances of both the single and double seals in terms of the two emulsion types (CRS-2 and CRS-2L) with the two aggregate types are measured by the MMLS3 test at two temperatures (64.4° and 77°F), as shown in Figure 4-12 to Figure 4-15.

The purpose of 77°F testing is to evaluate aggregate retention performance at a representative room temperature as a reference point. The 64.4°F testing is designed to evaluate the aggregate loss performance of the different emulsions after a freeze-thaw cycle. This temperature is the lowest possible controllable temperature for MMLS3 testing. In this test, samples were first fully cured at 95°F in the oven for 24 hours. Then, the samples were subjected to -4°F for 24 hours (i.e., one freeze-thaw cycle). Once the frozen samples were removed from the temperature chamber, they were placed on the steel base under the MMLS3 in a temperature-controlled chamber. The samples were conditioned at 64.4°F for 10 minutes, and then the MMLS3 test was conducted.

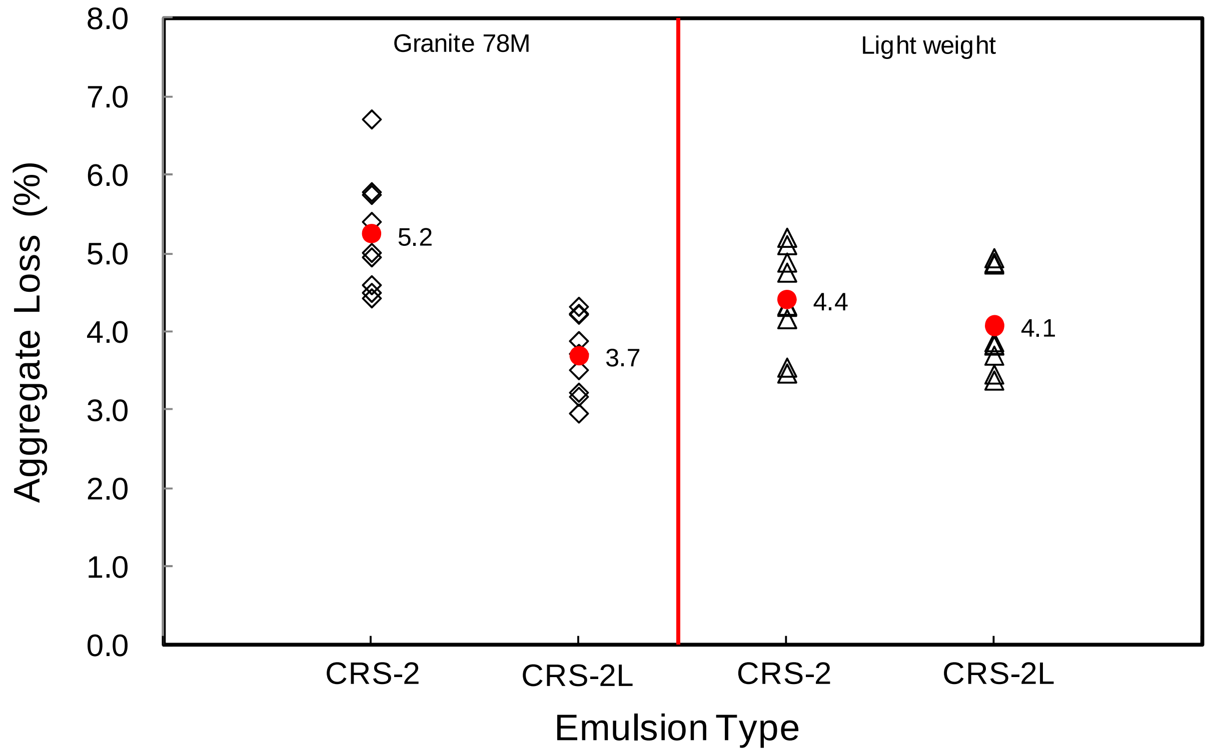


Figure 4-12 Aggregate loss of a single seal at 77°F from MMLS3 samples

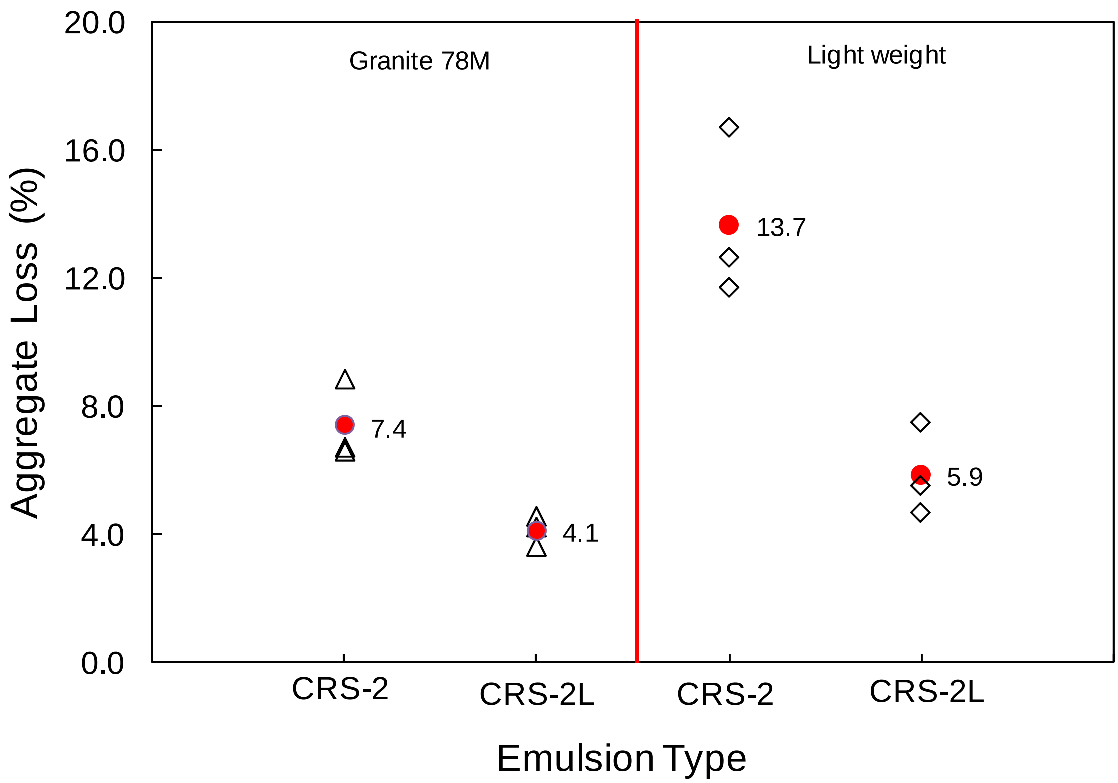


Figure 4-13 Aggregate loss of a double seal at 77°F from MMLS3 samples

For MMLS3 testing, first the percentages of aggregate loss retention for both the single and double seals in terms of the two emulsion types (CRS-2 and CRS-2L) are measured at 77 °F, as shown in Figure 4-12 and Figure 4-13, respectively. The aggregate loss is calculated using the weight of the aggregate and using Equation (1). The red solid circle symbols indicate the average aggregate loss of the nine replicates and three replicates for the single seal and the double seal, respectively. The aggregate types shown in Figure 4-13 indicate that these aggregates are spread at the top layer of the double seal. The research team reduced the number of replicates from nine to three for the double seals because the PME already provides better aggregate retention performance in the single seal. The MMLS3 test results shown in both Figure 4-12 and Figure 4-13 show a significant trend in that the CRS-2L emulsion improves the chip seal performance except in the single seal with lightweight aggregate.

Statistical analysis is required to recognize the significant difference between the two groups (CRS-2 and CRS-2L) in terms of the distribution of the percentage of aggregate loss. The t-test is used to investigate whether differences exist in the means of the two sections in terms of aggregate loss. The t-test with significance levels of 0.05 was performed to investigate whether differences occur in the means of the aggregate loss between the CRS-2 and CRS-2L emulsions for the single seal. The test results of the t-test of the single seal are summarized in Table 4-1.

The p-values from the granite 78M aggregate are less than 0.05, thus indicating that the percentage of aggregate loss performance is significantly different between the CRS-2 and CRS-2L emulsions of the single seal. However, the results from the lightweight aggregate reach a different conclusion from the t-test. These results indicate no significant difference of aggregate retention performance between CRS-2 and CRS-2L emulsions of the single seal, as the p-value is greater than 0.05.

Table 4-1 t-Test Results for Aggregate Retention Test of the Single Seal at 77°F

Aggregate type	Standard Error	DF	T-test	P-value	Conclusion
Granite 78M	0.30	16	5.18	< 0.0001	Reject Ho
Lightweight	0.29	16	1.14	0.2706	Accept Ho

Figure 4-14 and Figure 4-15 show the percentage of aggregate loss in order to evaluate the aggregate retention of the different emulsions after a freeze-thaw cycle in terms of chip seal type, both the single seal and double seal. Equation (1) was used to calculate the aggregate loss performance. A trend similar to that found from the MMLS3 aggregate retention tests at 77°F (Figure 4-12 and Figure 4-13) is observed in both Figure 4-14 and Figure 4-15.

It is clearly shown in Figure 4-14 and Figure 4-15 that the aggregate loss of the chip seals using granite 78M aggregate decreases using CRS-2L emulsion. The results for the lightweight aggregate in the single seal are excluded as same as at 77°F. No significant difference was found in aggregate retention performance in terms of the two emulsion types. Lee et al. (2006) demonstrated that chip seals constructed with lightweight aggregate show a better aggregate retention performance than those made of granite 78M aggregate, and that this difference is mainly due to the more uniform gradation of the lightweight aggregate compared to that of the granite 78M aggregate.

It should be noted that the CRS-2L emulsion improves the chip seal performance regardless of test temperature. The improved performance of the CRS-2L emulsion observed from the freeze-thaw test indicates that the PME may improve the chip seal performance under thermal cycling and thus extend the service life of the chip seal pavement.

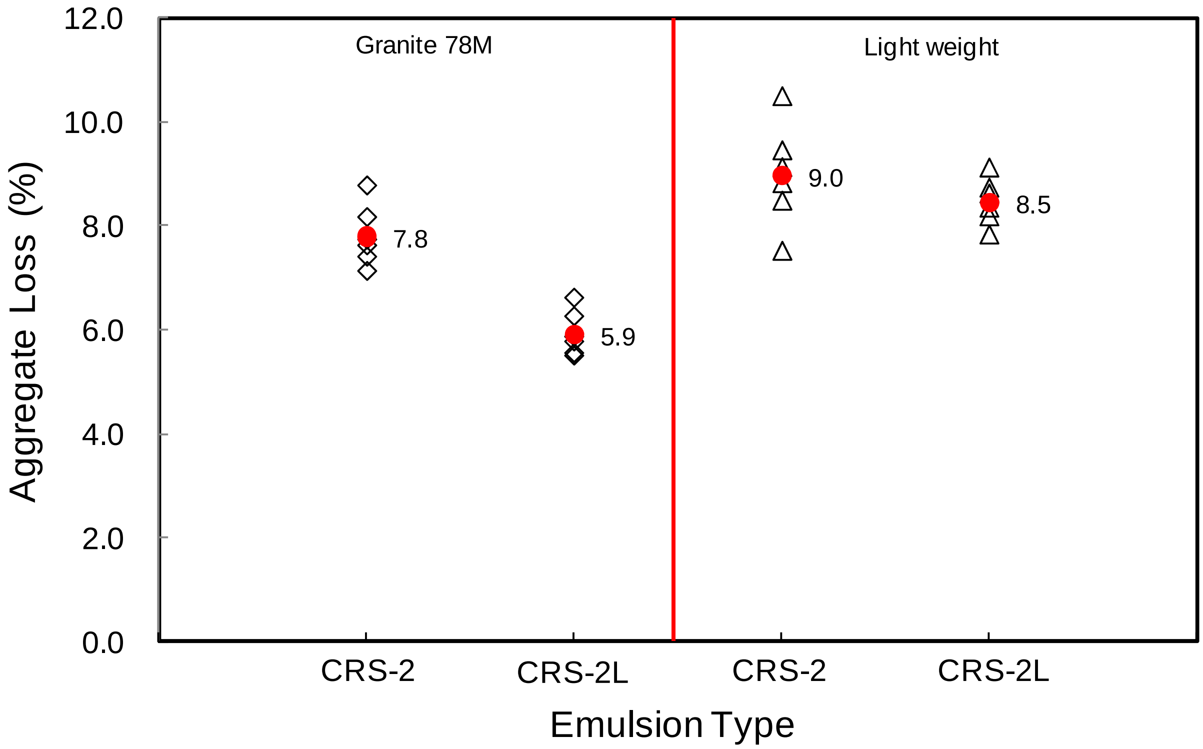


Figure 4-14 Aggregate loss from a single seal at lower temperature

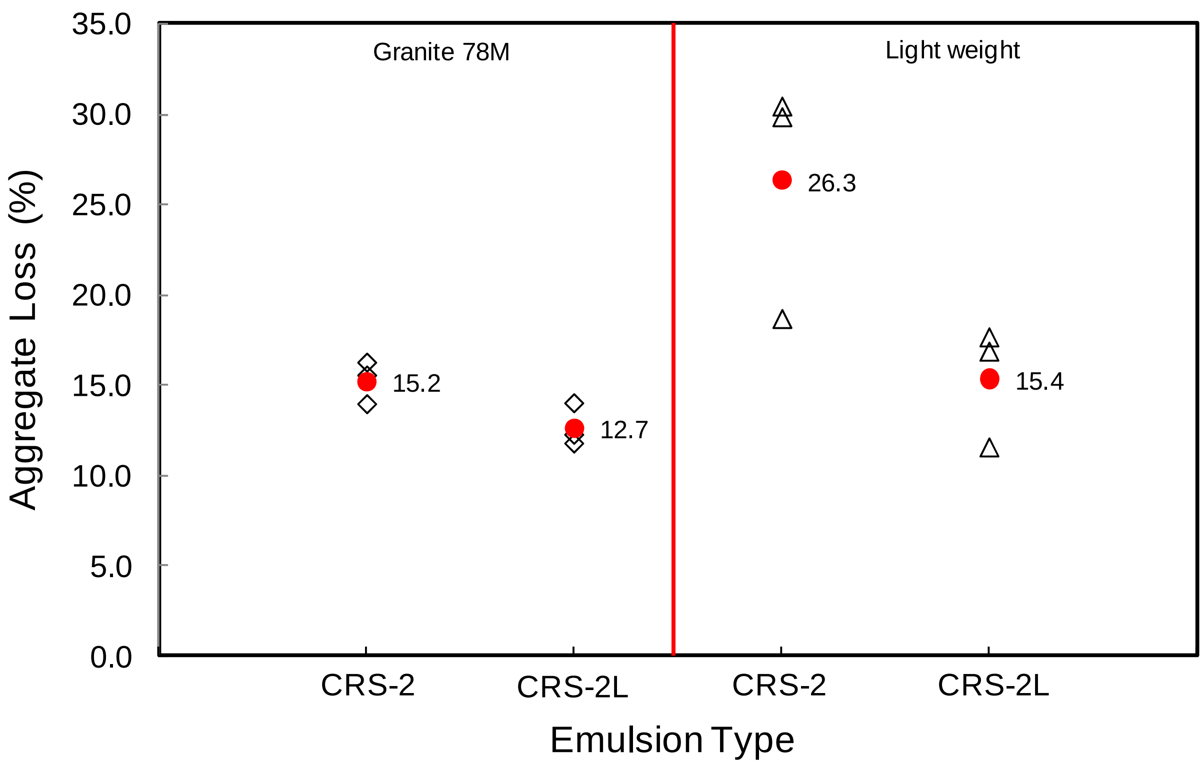


Figure 4-15 Aggregate loss from a double seal at lower temperature

Chapter 5. BLEEDING PERFORMANCE OF ASPHALT SURFACE TREATMENTS

5.1 *Experimental Program*

The chip seal is a cost-effective means to extend the service life of the pavement. Bleeding and raveling are the most common forms of distress in chip seal surfaces, as evident from survey responses and confirmed in the literature review (Gransberg et al. 2005). As such, bleeding (or flushing) is an important factor in determining the service life of the chip seal. Bleeding occurs when excess asphalt binder fills the voids in a chip seal structure and then moves upward to the chip seal pavement surface under traffic.

The bleeding performance is evaluated using the MMLS3 on the two emulsion types, the PME (CRS-2L) and unmodified emulsion (CRS-2). The bleeding test protocol developed at NCSU (Lee 2008) is utilized in this study. The experimental program used to evaluate the bleeding performance of the chip seal includes the following variables:

- Chip seal types: single and double seals
- Emulsion types: PME (CRS-2L) and unmodified emulsion (CRS-2)
- Aggregate types: granite 78M aggregate and lightweight aggregate

Table 5-1 shows the AARs and EARs for this study regardless of emulsion type. The single seal sample is fabricated using both granite 78M and lightweight aggregates. For the single seal, the EAR is 0.25 gal/yd^2, and the AAR for the granite 78M and lightweight aggregates are 17 lb/yd^2 and 9 lb/yd^2, respectively. For the double seal, the same EAR of 0.25 gal/yd^2 as used for the single seal is used for both layers in the double seals, and the AARs are likewise the same as the single seal, 17 lb/yd^2 and 9 lb/yd^2 for the bottom (granite 78M aggregate) and top (lightweight) layers, respectively.

Table 5-1 Application Rates

<table>
<tr><th colspan="2" rowspan="2">Chip Seal Type</th><th colspan="2">Aggregate</th><th>Emulsion</th></tr>
<tr><th>Type</th><th>Application Rate (lb/yd^2)</th><th>Application Rate (gal/yd^2)</th></tr>
<tr><td colspan="2" rowspan="2">Single</td><td>Granite 78 M</td><td>17</td><td>0.25</td></tr>
<tr><td>Lightweight</td><td>9</td><td>0.25</td></tr>
<tr><td rowspan="4">Double</td><td>Top layer</td><td>Granite 78 M</td><td>17</td><td>0.25</td></tr>
<tr><td>Bottom layer</td><td>Granite 78 M</td><td>17</td><td>0.25</td></tr>
<tr><td>Top layer</td><td>Lightweight</td><td>9</td><td>0.25</td></tr>
<tr><td>Bottom layer</td><td>Granite 78 M</td><td>17</td><td>0.25</td></tr>
</table>

A schematic diagram of the MMLS3 bleeding test developed at NCSU, with two different time schedules according to chip seal type, is shown in Figure 5-1. As shown in Figure 5-1, the test temperature of 122°F was used for the bleeding test. For temperature conditioning, specimens that have already undergone the aggregate loss test are placed in the oven at 122°F for 1 hour. The temperature of the specimen reached the testing temperature after being in the oven for 1 hour. After that, the specimen was mounted on the steel base under the MMLS3 for the bleeding test. The MMLS3 then provided traffic loading for 4 hours. The final specimen weight was measured, a visual observation was made, and bleeding was measured using DIP.

During the bleeding test, the research team observed that the MMLS3 tire surface was stained with the emulsion. The emulsion did not come from the bleeding mechanism but rather from aggregate loss or aggregate reorientation. This problem was most noticeable specifically in the case of the double seal with CRS-2 emulsion. Figure 5-1 (a) shows the double seals with CRS-2 emulsion after MMLS3 traffic loading for 40 minutes. The specimen, as shown in Figure 5-2 (a), shows severe bleeding. Figure 5-2 (b) shows the MMLS3 tire after 40 minutes, with aggregate clinging onto the MMLS3 wheel due to aggregate loss from the top layer of the double seal. Bleeding, as shown in Figure 5-2 (a), occurred in the specimen as the aggregate pulled away from the top layer. A similar circumstance is shown in Figure 5-3 which reveals a significant sticky, or adhesive, quality found in the field. This stickiness, or adhesion, picked up both the aggregate and binder, severely ruining the chip seal (Lawson et al. 2007).

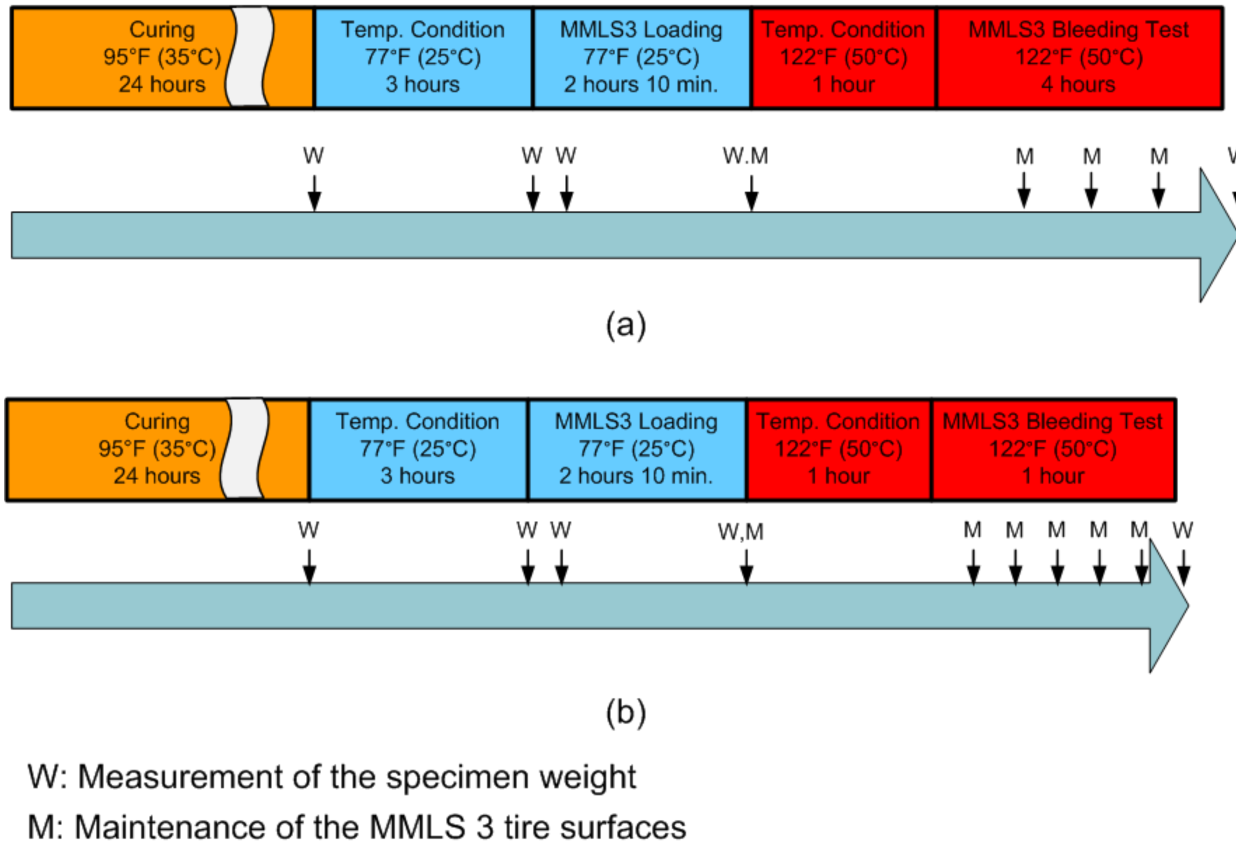


Figure 5-1 Schematic diagram of MMLS3 bleeding test procedure: (a) general bleeding test procedure; (b) the bleeding test procedure for double seals using CRS-2 emulsion

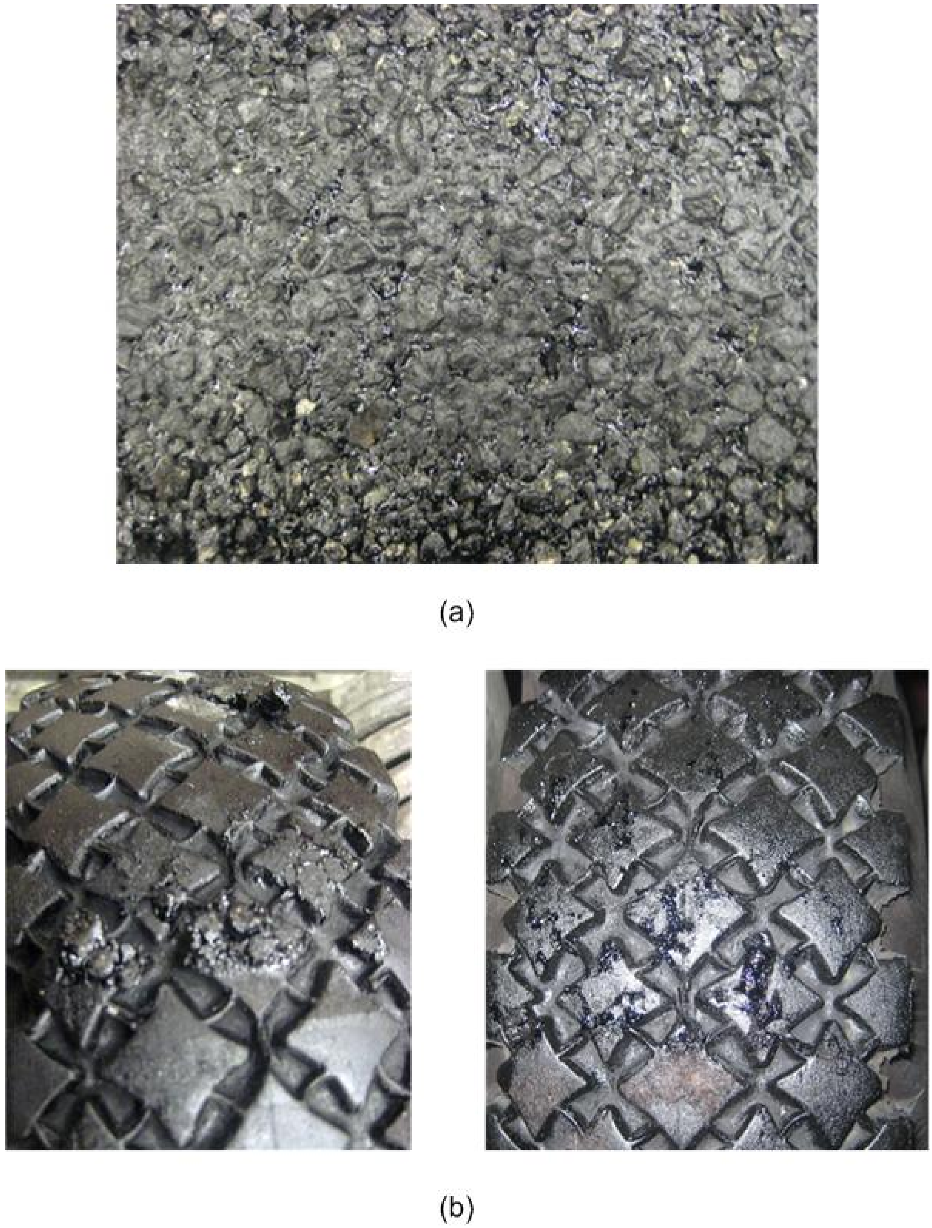


Figure 5-2 Double seal specimen with CRS-2 emulsion and MMLS3 tire after bleeding: (a) double seal specimen using CRS-2 emulsion; (b) tire with aggregate

As part of the bleeding test procedure, the MMLS3 tires were checked to see if the problem of stickiness could be avoided, because when the tire picks up aggregate, it causes black spots on the surface and creates a slicker texture. Therefore, it became necessary to remove the binder from the MMLS3 tires periodically.

A modified bleeding test procedure, as seen in Figure 5-1 (b), was designed specifically for the double seal using CRS-2 emulsion. The modification was made to reduce the testing time from 4 hours to 1 hour, because the research team found that 1 hour is sufficient to create bleeding in the double seals using CRS-2 emulsion. As the residual CRS-2 emulsion became soft at 122°F, severe aggregate loss occurred after 40 minutes. In addition, the MMLS3 tires became coated with emulsion due to aggregate loss from the top layer. Thus, a reduction in MMLS3 running time from 4 hours to 1 hour was adopted, as shown in Figure 5-1 (b). Also, the stickiness of the tire surface of the MMLS3 was checked and maintained every 10 minutes per 1 hour of testing time. Therefore, the bleeding results from the double seal were obtained at different times between 1 and 4 hours as a function of emulsion type.

Figure 5-3 Chip seal damage caused by bleeding (Lawson et al. 2007)

5.2 Single Seal Evaluation

In order to compare the bleeding performance of CRS-2 emulsion with that of CRS-2L emulsion, the two-dimensional DIP procedure, described in Chapter 3, was conducted after MMLS3 traffic loading for 4 hours at 122°F (50°C).

First, single seals using granite 78M and lightweight aggregates were tested, and the surface texture of each single seal was scanned before and after MMLS3 traffic loading. Tests were conducted for four designed chip seal specimen types for each type of aggregate and emulsion using DIP to measure the percent bleeding. Digital images of the seal texture after the bleeding tests are presented in Figure 5-4 and Figure 5-5 for granite 78M and lightweight aggregates, respectively. The percent bleeding was calculated using the critical GIV method described in Chapter 3 and plotted in Figure 5-6 for the four aggregate-emulsion combinations.

Figure 5-6 indicates that the bleeding rates are about the same for all the aggregate-emulsion combinations, except for the much higher rate seen in the lightweight aggregate-CRS-2 combination. To investigate the cause for this behavior, the aggregate loss results from the bleeding tests were plotted and are shown in Figure 5-7. Figure 5-7 shows additional aggregate loss according to the change in aggregate weight before and after the bleeding test. As explained previously, these samples had already been used to measure aggregate loss at 77°F. The amount of additional aggregate loss is about the same and is minimal for all the aggregate-emulsion combinations, except the lightweight-CRS-2 combination. The results shown in Figure 5-6 and Figure 5-7 suggest that the bleeding seen in the lightweight-CRS-2 combination is due to the loss of aggregate during the bleeding test. This aggregate loss occurs in addition to the aggregate loss from the original aggregate loss test, and therefore is due primarily to the aggregate that sticks to the MMLS3 tires. The low viscosity of the CRS-2 emulsion coupled with the lighter weight of the lightweight aggregate seem to be responsible for more aggregate loss in the bleeding test, which, in turn, causes more bleeding. In this test, the general bleeding mechanism, i.e., that the binder moves upward to the surface, does not occur, because the EARs and AARs are close to the optimal rate.

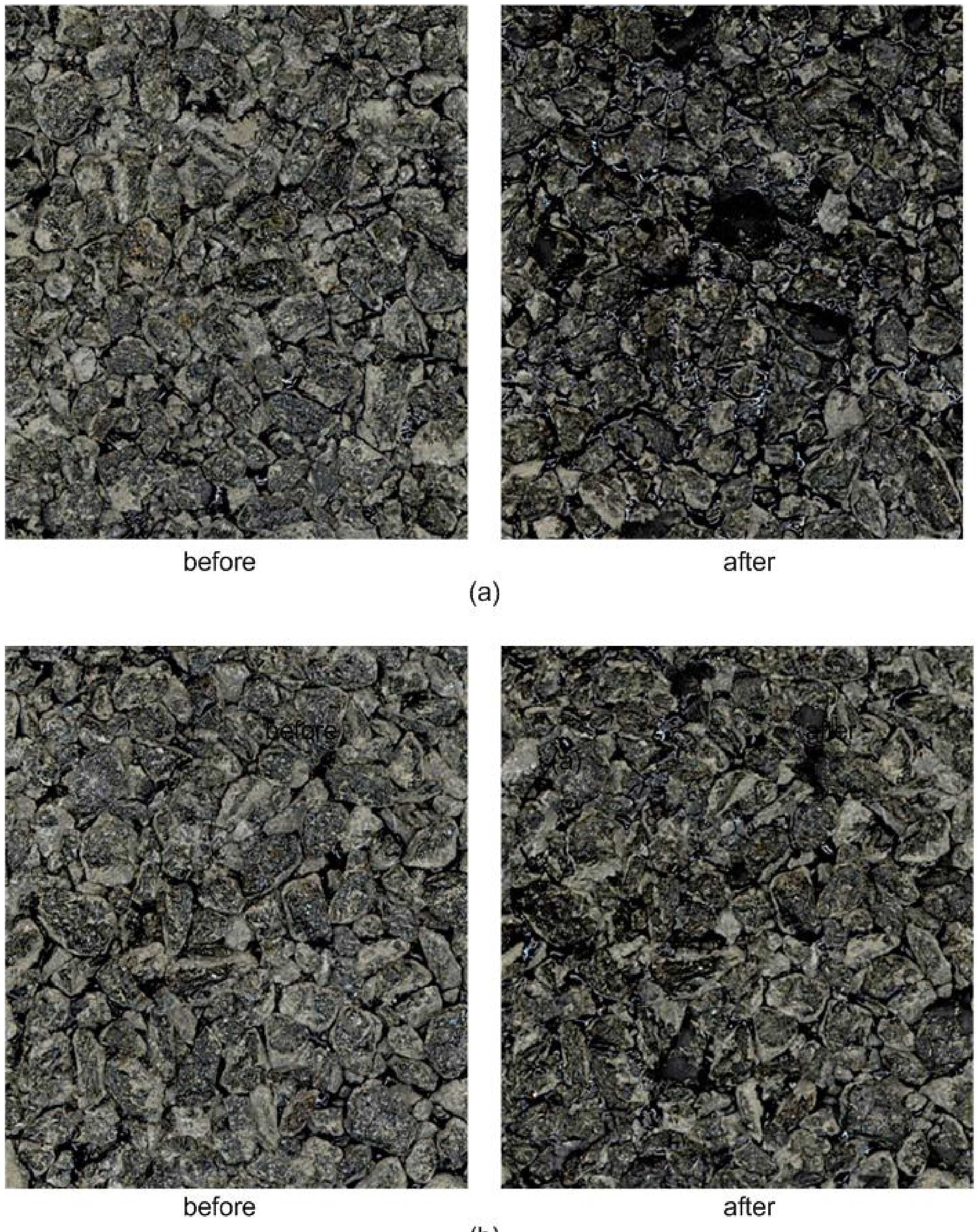


Figure 5-4 Surface texture change after bleeding test of single seal with granite 78M aggregate: (a) using CRS-2 emulsion; (b) using CRS-2L emulsion

Figure 5-5 Surface texture change after bleeding test of single seal with lightweight aggregate: (a) using CRS-2 emulsion; (b) using CRS-2L emulsion

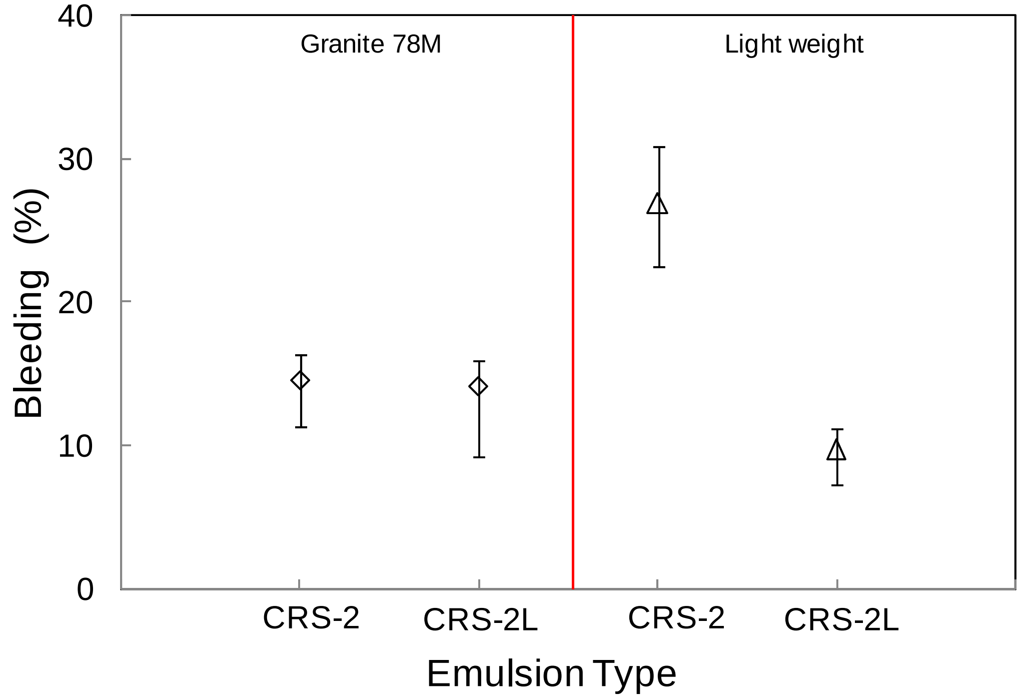


Figure 5-6 Calculated bleeding rates of the single seal

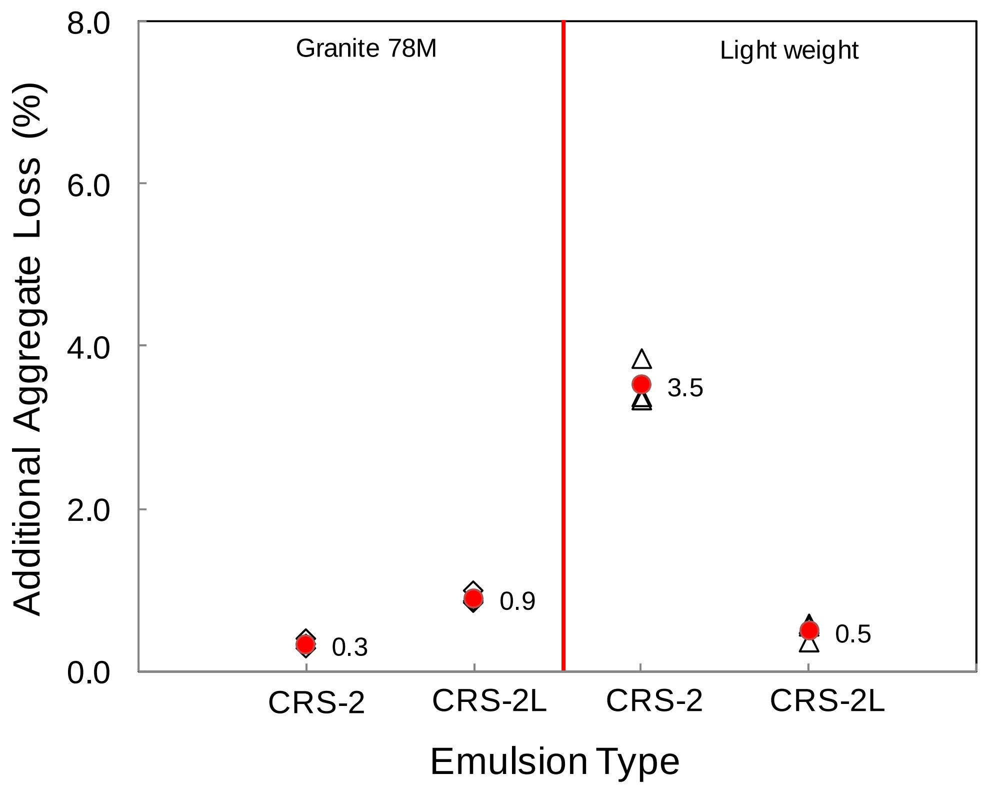


Figure 5-7 Aggregate loss of single seal after the bleeding test

5.3 Double Seal Evaluation

To investigate the bleeding performance of a multiple chip seal, the double seal with two different aggregate combinations and emulsion types was chosen. One combination is granite 78M aggregate for the bottom layer and lightweight aggregate for the top layer. The other combination is granite 78M aggregate for both layers.

In order to measure the bleeding performance of the double seals, the two-dimensional DIP procedure, described in Chapter 3, was conducted after the MMLS3 bleeding test at 122°F (50°C) for 4 hours (CRS-2L emulsion) and 1 hour (CRS-2 emulsion). Theoretically, the major cause of bleeding is excessive emulsion. In a hot temperature (122°F) test, the emulsion between the aggregate particles is soft, which means that the aggregate particles in the emulsion are easily pitched and rolled by MMLS3 trafficking. As shown in Figure 5-1, the MMLS3 trafficking time for the CRS-2 emulsion is much shorter than that for the CRS-2L emulsion due to severe bleeding of the CRS-2 emulsion. Figure 5-8 and Figure 5-9 present the changes in the surface textures of the both the granite 78M aggregate and lightweight aggregate in the top layers before and after the bleeding test in terms of emulsion type. A visual observation of the surface textures, as shown in Figure 5-8 and Figure 5-9, confirms that more bleeding occurs with the CRS-2 emulsion despite less traffic loading. As seen in both figures, the surface texture of the CRS-2 emulsion shows more black areas, although the MMLS3 trafficking time is only 1 hour.

Figure 5-10 provides the calculated percentage of bleeding from the DIP results. Figure 5-10 shows significantly different bleeding characteristics between the CRS-2 and CRS-2L emulsions. The calculated bleeding of the CRS-2 emulsion is four times higher than that of the CRS-2L emulsion. Figure 5-11 shows the results of the aggregate loss of the double seal after the bleeding test. The huge aggregate loss, three times higher, occurred with the CRS-2 emulsion, although the aggregate types in the top layers are different. This finding suggests a strong relationship between aggregate loss and bleeding in the multiple seal. Contrary to the CRS-2 emulsion, the CRS-2L emulsion that was modified with polymer (latex) has enough viscosity to hold the aggregate against MMLS3 traffic loading. Thus, the smaller aggregate loss occurs from using the CRS-2L emulsion.

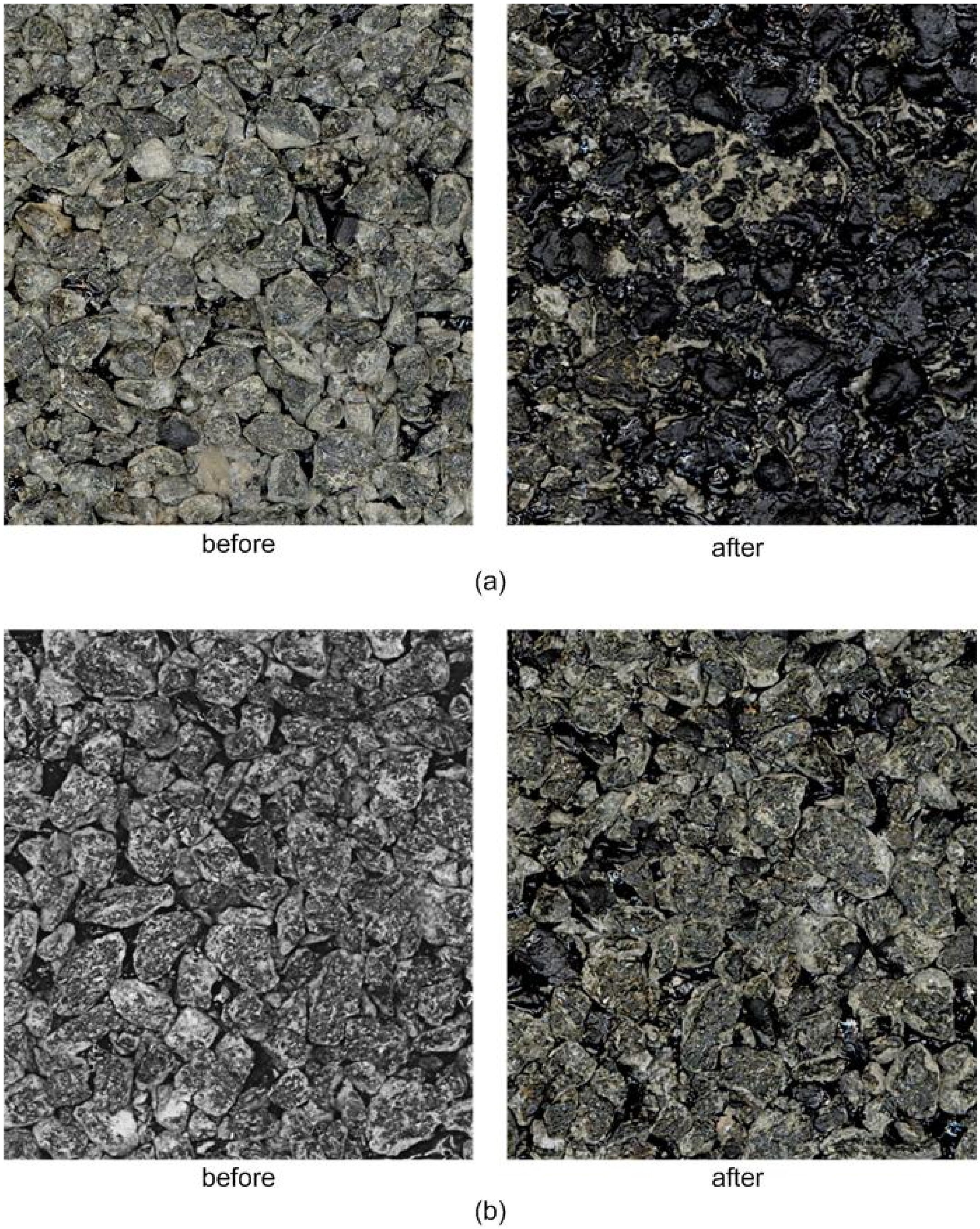


Figure 5-8 Surface texture change after bleeding test of double seal with granite 78M aggregate at the top layer: (a) using CRS-2 emulsion; (b) using CRS-2L emulsion

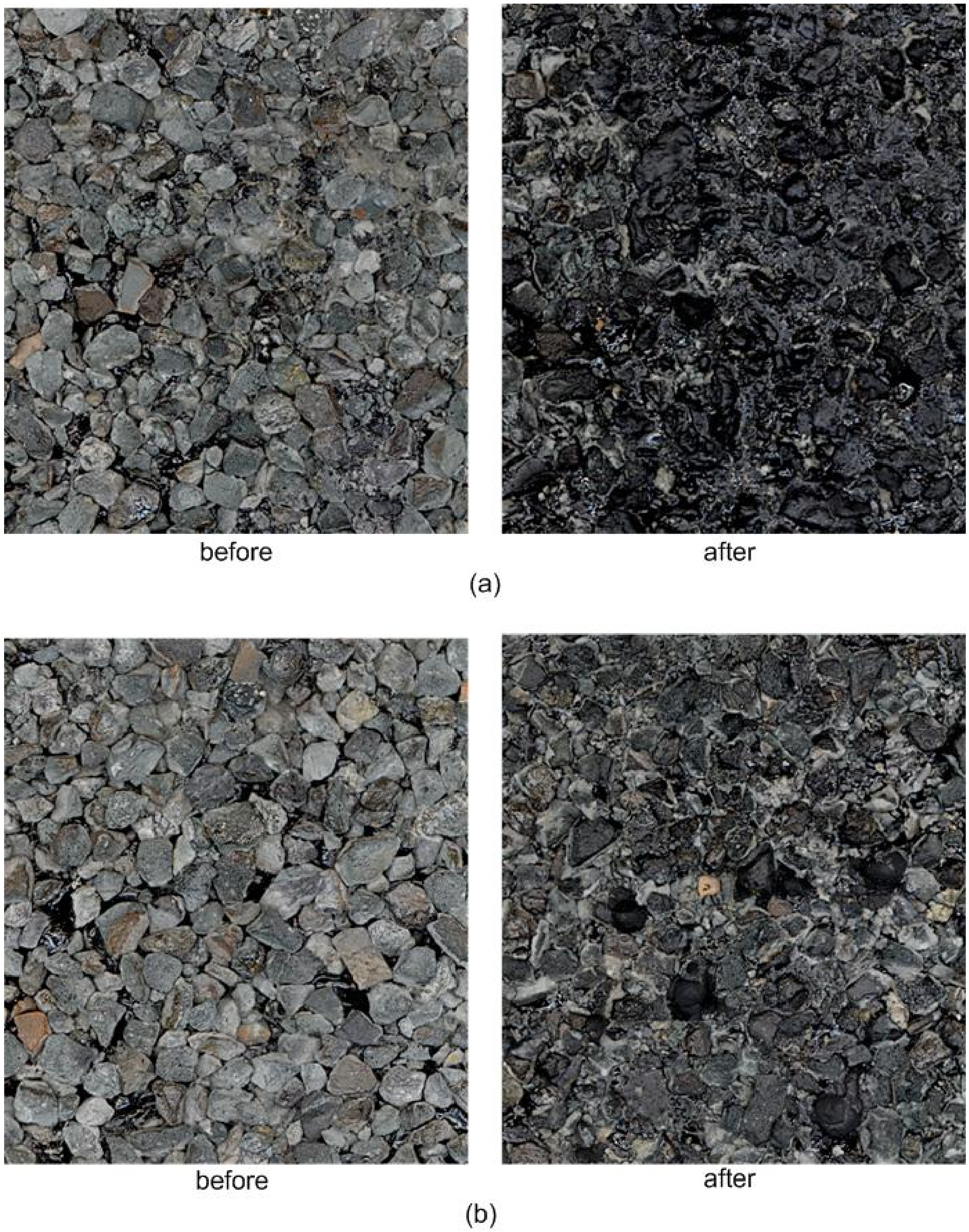


Figure 5-9 Surface texture change after bleeding test of double seal with lightweight aggregate at the top layer: (a) using CRS-2 emulsion; (b) using CRS-2L emulsion

A similar pattern that is seen in the bleeding results shown in Figure 5-10 and the aggregate loss results shown in Figure 5-11 suggests that the same conclusion can be drawn as that from the single seal. That is, the bleeding caused by the MMLS3 test is governed mostly by aggregate loss. When the temperature increases, the viscosity of the residual binder of the chip seal specimen decreases. Thus, the residual binder at the bleeding test temperature (122°F) cannot hold the aggregate during MMLS3 traffic loading. This phenomenon is much more severe with the CRS-2 emulsion than with the CRS-2L.

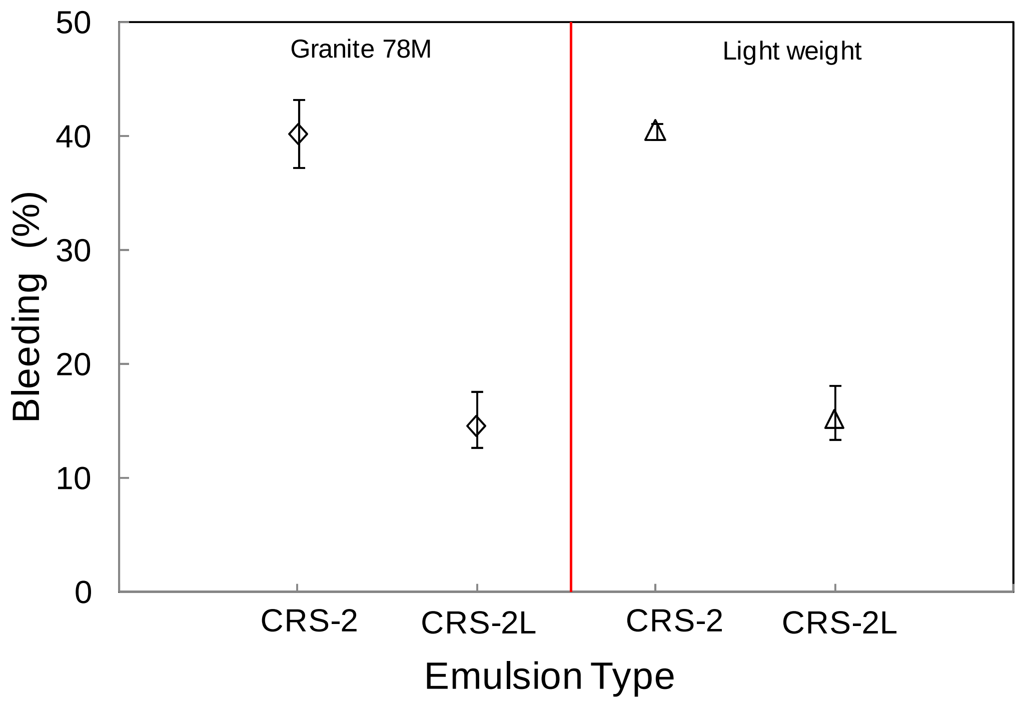


Figure 5-10 Calculated bleeding rates of double seal

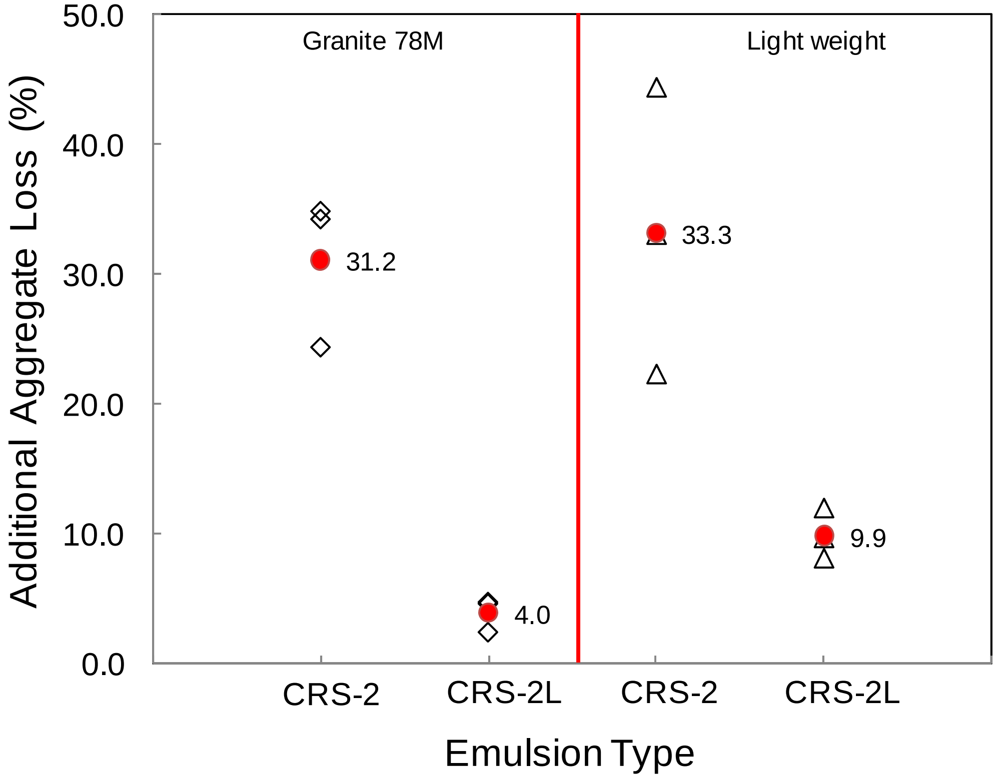


Figure 5-11 Aggregate loss of double seals during bleeding test

Chapter 6. RUTTING PERFORMANCE OF ASPHALT SURFACE TREATMENTS

6.1 Experimental Program

Rutting, also known as permanent deformation can be defined as the accumulation of small amounts of unrecoverable strains as a result of applied loading to a pavement. Rutting occurs when the pavement under traffic loading consolidates and/or there is lateral movement of the asphalt-aggregate mixture. Lateral movement is a shear failure and generally occurs in the upper portion of the pavement surface. As a result of rutting, the pavement service life is reduced. If the rut depth is significant, water may accumulate in the rutted area, which can lead to vehicle hydroplaning.

A multiple chip seal is a chip seal that consists of two or more applications of emulsion and cover aggregate on an existing pavement. The comparatively high quality multiple chip seal should extend the pavement life well beyond that expected with the single seal and may be substituted for more expensive asphalt concrete overlay construction. The multiple chip seal is used increasingly in Texas (Estakhri et al. 1988). Currently, the multiple chip seal is constructed in North Carolina using both PME (CRS-2L) and unmodified emulsion (CRS-2). The objective of this chapter is to evaluate the rut development of the multiple chip seal as a function of two emulsion types (PME and unmodified emulsion). The following factors were varied for the evaluation of rut development:

- Specimen types: a triple seal composed of granite78M aggregate, granite 78M aggregate, and lightweight (Stalite 5/16") aggregate, for each layer, respectively.
- Test temperatures: 68°F (20°C), 104°F (40°C), 129.2°F (54°C)
- Emulsion types: PME (CRS-2L) and unmodified emulsion (CRS-2)

The average rut depth of the triple seal is measured and compared between PME and unmodified emulsion. The rut development of chip seals due to traffic loading is evaluated using the MMLS3. The rutting test protocol is described in Section 3.4.5.

Figure 6-1 Cross-section of the triple seal specimen after MMLS3 loading

The cross-section of a real image obtained from the trafficked MMLS3 specimen is shown in Figure 6-1. This illustration helps explain the rutting mechanism. Theoretically, volume densification and shear flow as the causes for rutting of HMA are well known. Volume densification occurs under MMLS3 traffic loading and is clearly evident in Figure 6-1. The changed volume and shear flow create a rut in the chip seal structure, although the chip seal is thin pavement.

Figure 6-2 shows a typical cross-section of the triple seal before and after the MMLS3 rutting test. Different areas of interest in the transverse direction to traffic are defined. The trafficked area is the wheel path area caused by the MMLS3. The shear flow area represents the area on either side of the rut, where humps normally appear. Humps are created as the material is displaced out from under the wheel load due to the shear flow of the material.

Generally, the HMA surface becomes smooth as traffic loading continues and increases. However, under MMLS3 loading the bottom of the rut is not flat, as shown in Figure 6-2. Thus, the average of the profiles of the trafficked area is calculated to obtain the rut depth. That is, the rut depth is determined by measuring the difference between the highest point on the hump and the average of the profiles of the trafficked area. The rut depth that corresponds to a given number of loading cycles is obtained by subtracting the actual elevation from the reference elevation.

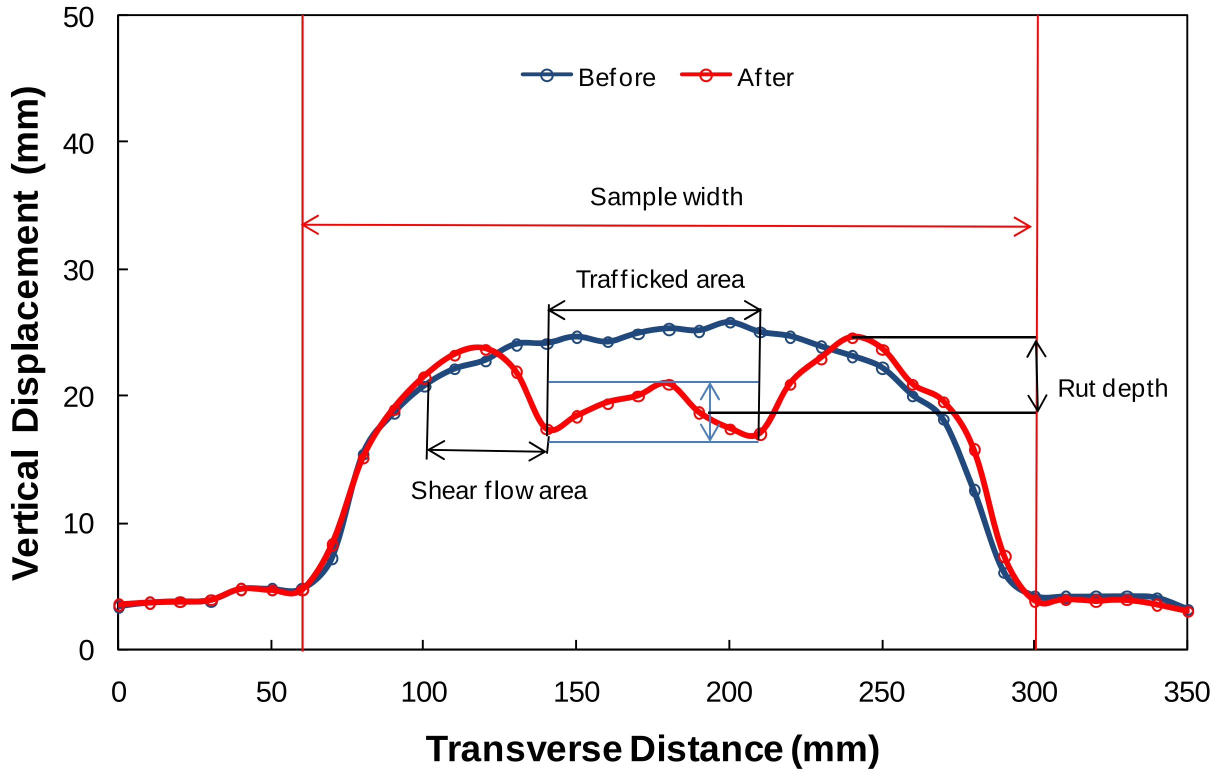


Figure 6-2 Schematic diagram of a typical cross-section of a triple seal

6.2 Test Results

The MMLS3 rutting test has been conducted with triple seals using both CRS-2 emulsion (unmodified emulsion) and CRS-2L emulsion (PME) at 68°F (20°C). The calculated average rut depths of the triple seal are plotted in Figure 6-3 as a function of the number of MMLS3 wheel passes (N). It is noted that the X-axis in Figure 6-3 is in logarithmic scale. The dash line, shown in Figure 6-3, indicates a failure criterion with 8 mm rut depth. The research team used 8 mm for the failure criterion because it is approximately one-third of 1 inch (25.4 mm), which is the common failure criterion for HMA pavements, and thereby reflects that the MMLS3 is a third scale down. Significantly different rutting behavior is evident between the use of the CRS-2 and CRS-2L emulsions. Two different rut growth times may be identified in Figure 6-3. With the CRS-2 emulsion, two distinct states of rut development are observed: a huge rut depth at the beginning of the test at 990 wheel passes, and a rapid growth at the beginning of the test followed by a gradual rate of growth.

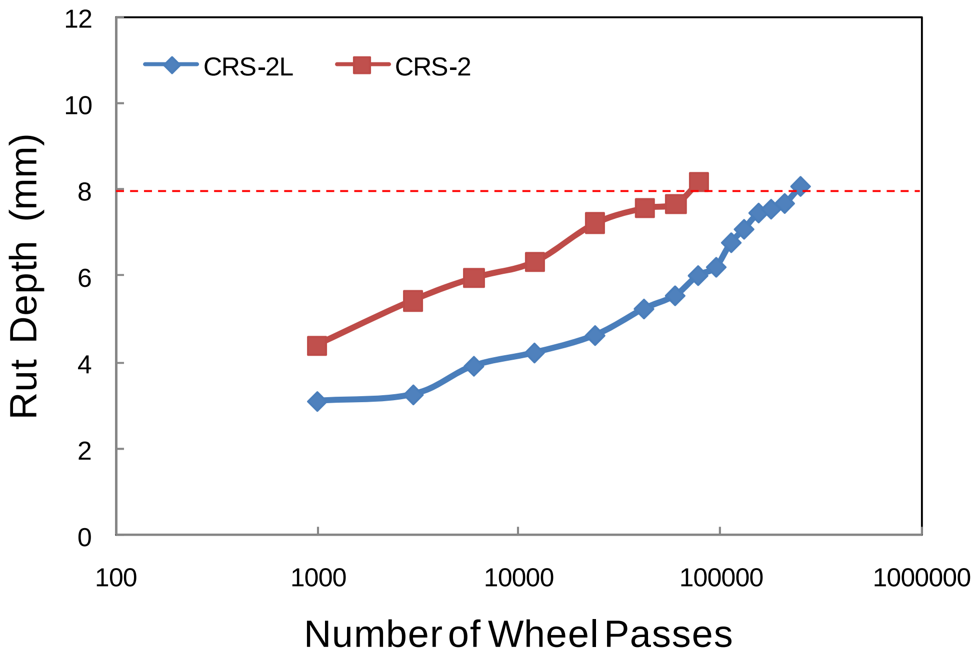


Figure 6-3 Comparison of rut depth growth at 68°F (20°C)

However, for the CRS-2L emulsion, rutting develops slowly at the beginning of the trafficking and slowly approaches the failure criterion. A comparison of the rut depth growth, as presented in Figure 6-3, clearly illustrates that the CRS-2L emulsion has more advantages in reducing rut depth than the CRS-2 emulsion.

Also, the CRS-2 emulsion shows the higher initial rut depth after 1000 wheel passes than that of the CRS-2L emulsion. Contrary to the CRS-2 emulsion, the rut depth growth of the CRS-2L emulsion starts more gradually in the beginning until around 3,000 cycles. After that point, the rut depth growth of the two emulsion types is similar, as shown in Figure 6-3. Finally, the CRS-2 emulsion reaches the failure criterion in fewer wheel passes. Therefore, the CRS-2L emulsion (PME) extends the service life of the pavement against rutting failure.

Secondly, the rutting performance of the triple seals using CRS-2 and CRS-2L is evaluated at 104°F (40°C) and plotted in Figure 6-4. Clearly, different rut depth behavior is evident between the CRS-2 emulsion and CRS-2L emulsion at this temperature.

The rut depth growth at 104°F, as shown in Figure 6-4, definitely illustrates that the CRS-2 emulsion shows poor permanent deformation behavior. As seen in Figure 6-3, the CRS-2 emulsion shows a higher rut depth and faster rut depth growth than seen in Figure 6-4. Figure 6-5 presents the visual observation of the tested specimen surface textures at 104°F.

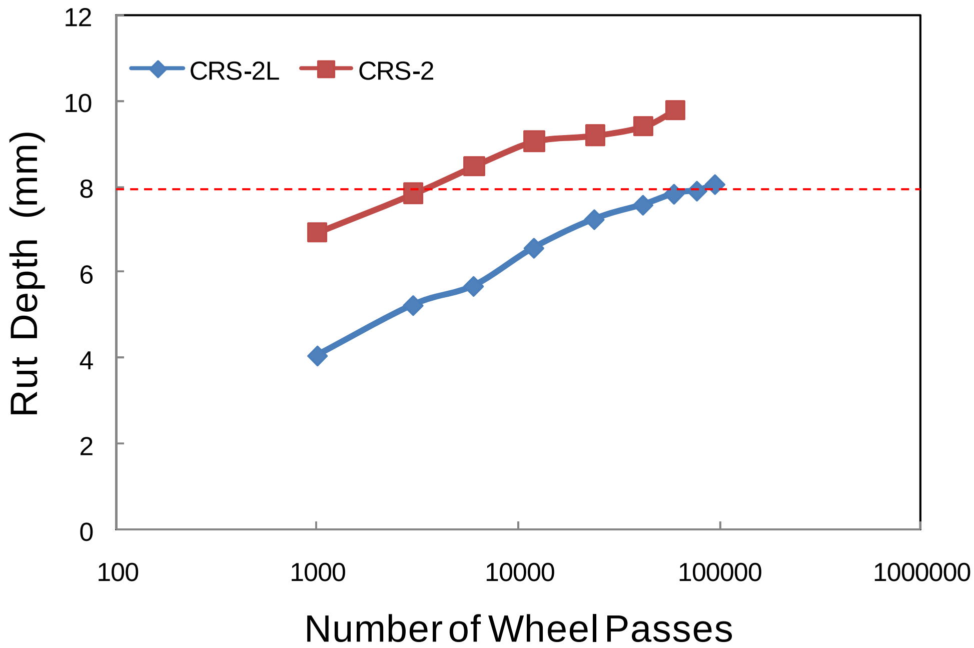


Figure 6-4 Comparison of rut depth growth at 104°F (40°C)

As compared with the surface texture of the CRS-2L specimen, the CRS-2 specimen shows more black spots, as marked with circles on the MMLS3 path area in Figure 6-5. The black spots are due to aggregate loss from the top layer. As the test temperature increases, the residual binder of the CRS-2 emulsion specimen becomes soft. Thus, resistance to traffic loading is weaker than at a low temperature (66°F). Consequently, the CRS-2 emulsion shows the higher initial rut depth and faster rut depth growth with aggregate loss than the CRS-2L emulsion.

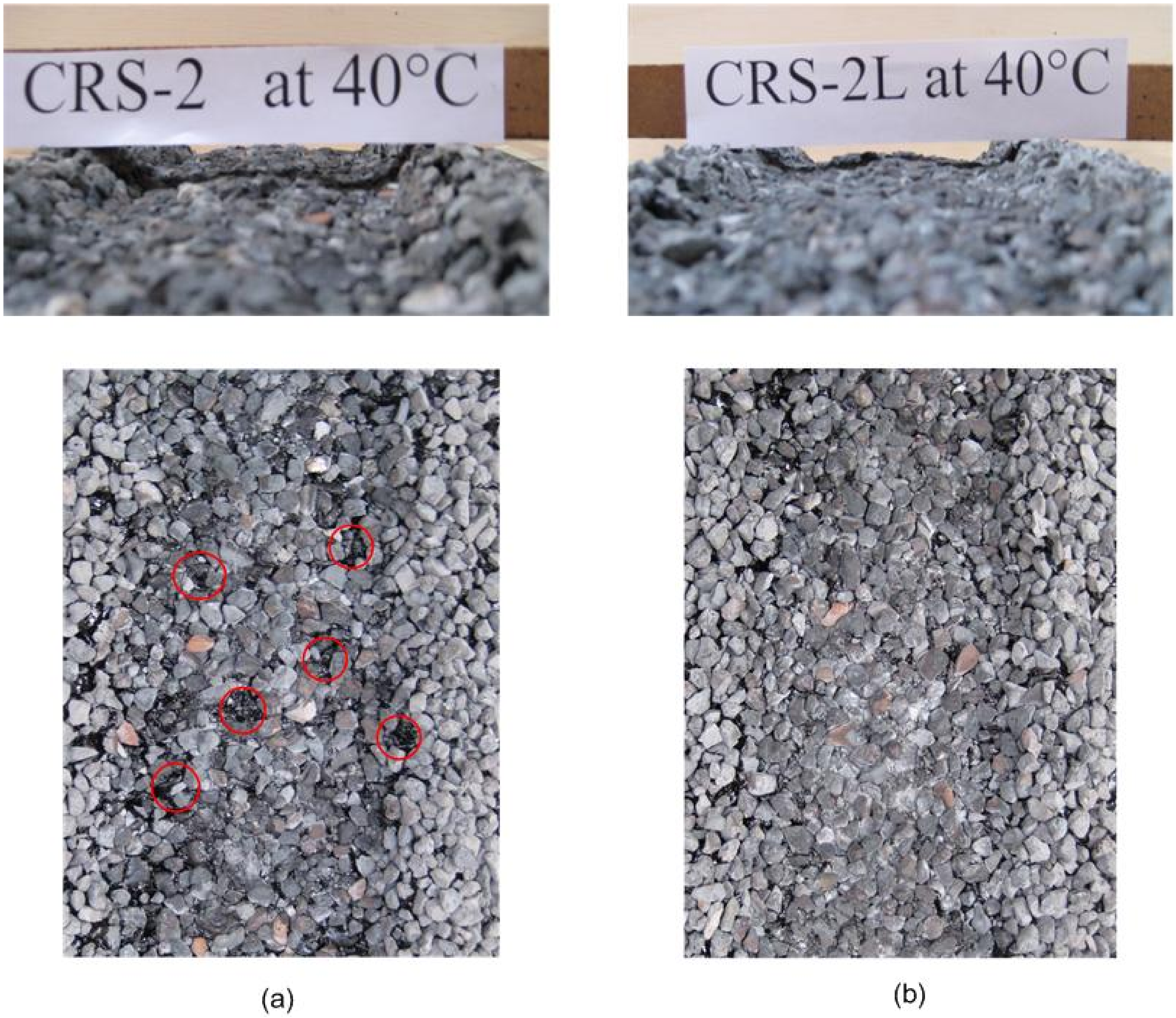


Figure 6-5 Rut depth and surface texture of test specimen at 104°F (40°C): (a) CRS-2; (b) CRS-2L

Finally, the rut depth growth found in the triple seals using both the CRS-2 emulsion and CRS-2L emulsion is evaluated at 129.2°F (54°C) and plotted in Figure 6-6. This test temperature of 129.2°F (54°C) was selected in order to evaluate rutting performance at a high temperature. Unlike previous rut depth graphs (as seen in Figure 6-3 and Figure 6-4), Figure 6-6 has only one rut depth growth line. The reason for this difference in graphs is that the rutting performance test cannot be run for CRS-2 emulsion samples after 990 wheel passes due to severe aggregate loss in the wheel path area, as shown in Figure 6-7. The black color indicates that the emulsion sprayed over the second layer became detached from the aggregate in the top layer.

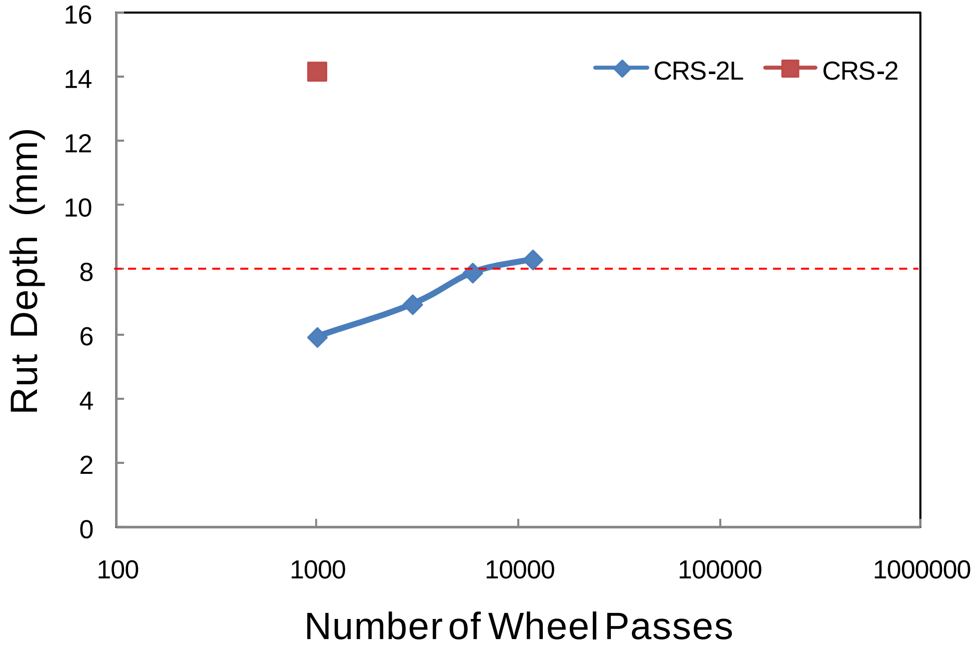


Figure 6-6 Comparison of rut depth growth at 129.2°F (54°C)

Compared with Figure 6-7 (b), Figure 6-7 (a) shows a thinner layer under the trafficked area; that is, most of the aggregate from both the middle and top layers has been lost. At this high temperature (129.2°F), the residual binder is so soft that it cannot hold the aggregate under MMLS3 traffic loading. Figure 6-7 clearly shows the black wheel path area where the aggregate has disappeared. Contrary to the wheel path area when CRS-2 emulsion is used, the wheel path area for the CRS-2L emulsion is not as dark because of less aggregate loss. Figure 6-7 thus indicates that the CRS-2L emulsion has a higher viscosity than the CRS-2 emulsion at the high temperature of 129.2°F. So, the CRS-2L emulsion provides an improved rutting resistance and thereby enhances the aggregate retention performance in the triple seals. Consequently, this finding suggests that PME is particularly suitable for high volume roads.

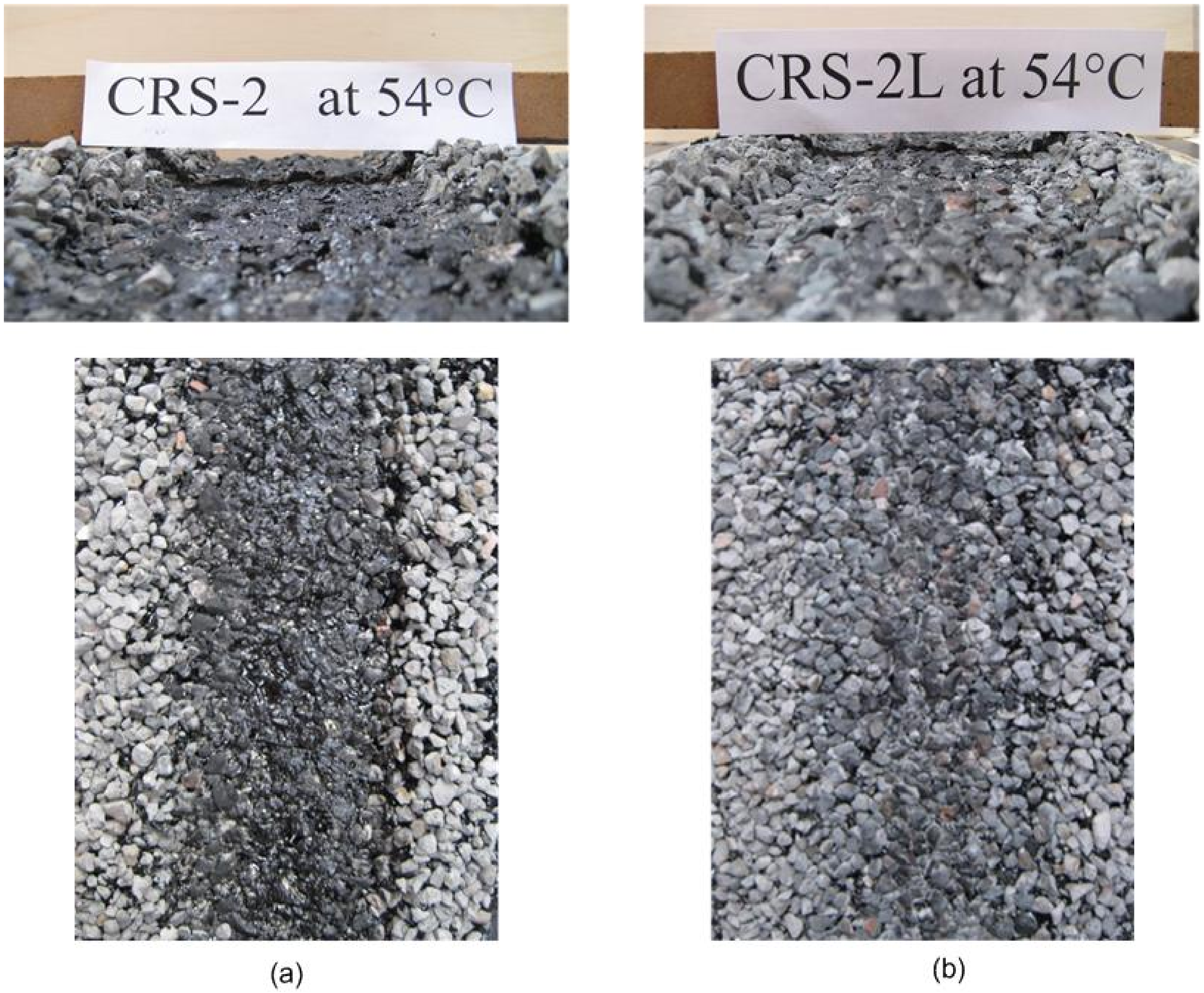


Figure 6-7 Rut depth and surface texture of test specimen at 129.2°F (54°C): (a) CRS-2; (b) CRS-2L

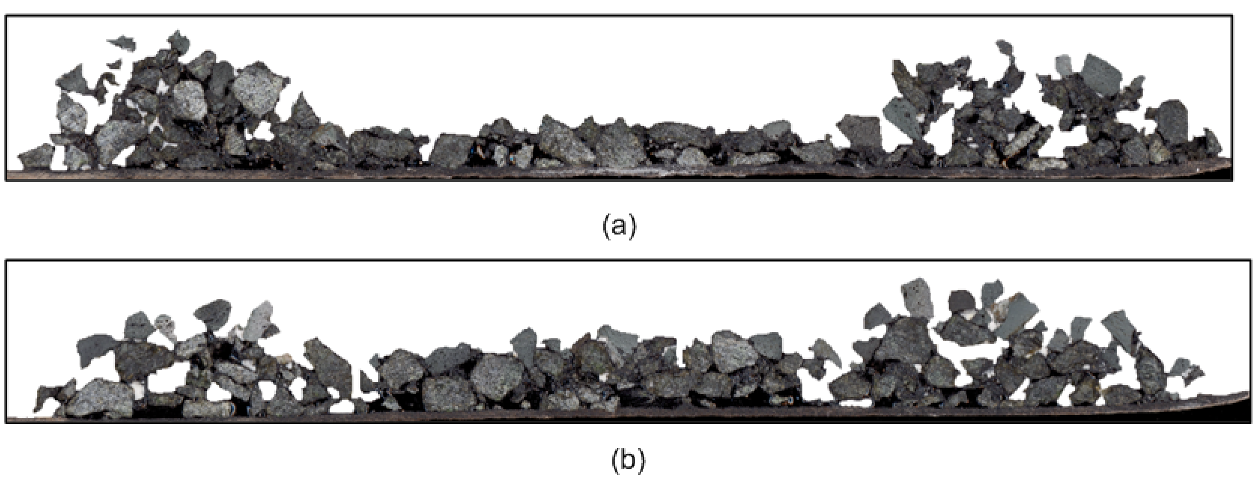


Figure 6-8 Cross-section of rutting samples at 129.2°F: (a) CRS-2; (b) CRS-2L

Figure 6-8 shows the cross-section of the specimens after the rutting test; Figure 6-8 (a) presents the cross-section of the CRS-2 emulsion specimen after 990 wheel passes of traffic loading, whereas Figure 6-8 (b) presents that of the CRS-2L specimen after 11,880 cycles. Two important observations can be made from Figure 6-8. First, the void reduction due to vehicular traffic can be clearly explained in this figure regardless of emulsion type. The white gaps in the aggregate structure indicate the voids in the chip seal pavement. A significantly different distribution between the trafficked area and non-trafficked area can be seen; that is, almost no voids are evident in the wheel path. The second observation from Figure 6-8 is that the aggregate orientation of the chip seal structure is caused by and reflects the traffic loading. Aggregate orientation is an important feature of the chip seal structure. When the aggregate shape is flat and elongated, traffic causes any flat aggregate in the wheel path to orient itself horizontally on its flat side. This orientation of the aggregate results in a thinner chip seal in the trafficked area than is in the non-wheel path area, as evident in Figure 6-8. Bleeding occurs when the aggregate is oriented flat-wise, especially if too much binder is applied in the wheel paths.

Figure 6-9 provides the rut depth measured after 990 wheel passes (i.e., initial traffic) as a function of testing temperature to compare the PME (CRS-2L) with unmodified emulsion (CRS-2). The figure clearly explains that rutting behavior is especially sensitive to temperature and the CRS-2 emulsion. A comparison of data presented in Figure 6-9 clearly explains the beneficial effects of PME in resisting rut development, regardless of temperature. The rut depth with the CRS-2 emulsion is twice as deep as that of the CRS-2L emulsion at 129.2°F.

Table 6-1 summarizes the number of wheel passes that meets the 8 mm failure criteria at each of the three testing temperatures. The CRS-2L emulsion (PME) shows significantly better rutting resistance against traffic loading than the CRS-2 emulsion. Comparing Figure 6-3, Figure 6-4, Figure 6-6, it is evident that the PME provides this benefit especially at high temperatures.

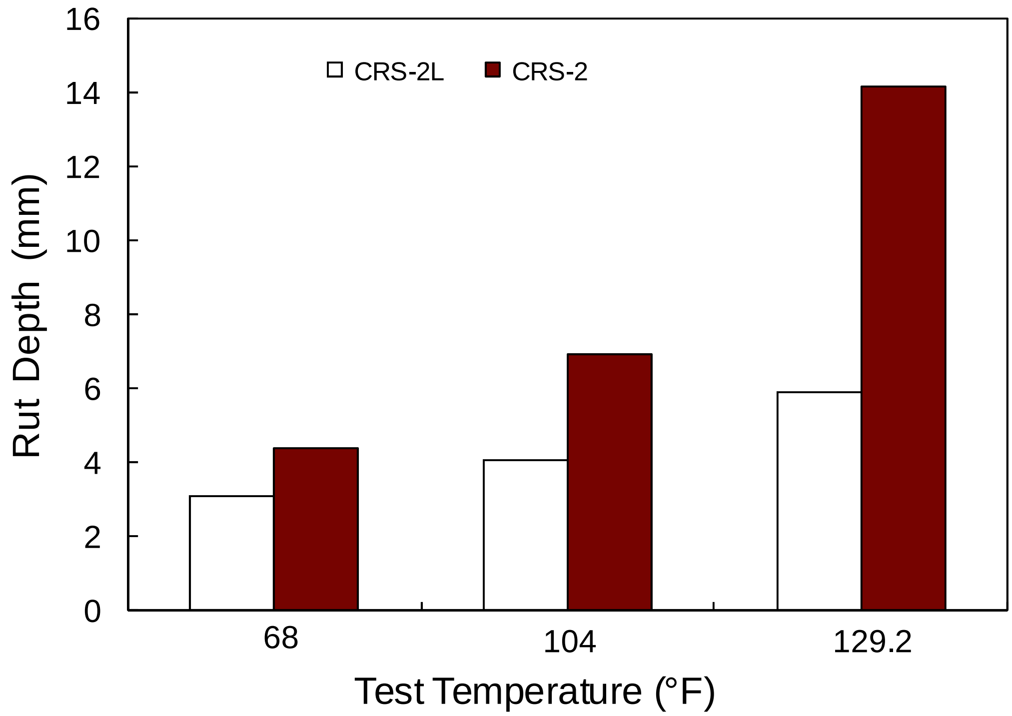


Figure 6-9 Comparison of initial rut depth growth after 990 wheel passes

Table 6-1 Allowed Number of Wheel Passes to Reach the Rutting Failure Criteria

Temperature (°F)	Number of Wheel Passes	
	CRS-2	CRS-2L
68	77,220	249,480
104	5,940	95,040
129.2	990*	5,940

Note: *At 129.2°F, the rut depth reached to 14.16 mm at the first reading at 990 wheel passes.

Chapter 7. EVALUATION OF FIELD SECTIONS

As described in Section 3.3.1, field test sections were constructed on New Sandy Hill Church Road in Wilson County, NC in June (Phase I) and October (Phase II) 2007. Although the laboratory testing was performed only for the sections constructed in Phase I because of the large sample-to-sample variations in the Phase II sections, the sections from both Phases I and II could be used for the field condition visual survey.

In March 2009 the research team evaluated the condition of each section using a visual condition survey and rut depth measurements of the triple seals. The field survey results are summarized in Table 7-1. It is noted that the sections with odd numbers were constructed using the unmodified emulsion and those with even numbers using the CRS-2P. The most prevalent distress was aggregate loss, regardless of chip seal type and emulsion type. Some flushing was also observed. The overall trends are the same as those found from the laboratory tests; that is, the PME (CRS-2P) shows better performance in terms of aggregate loss, rut depth, and flushing.

Figure 7-1 and Figure 7-2 show the flushed surface textures of the single and double seals constructed with CRS-2 emulsion. The flushing distress appears only in the sections with CRS-2 emulsion. Figure 7-3 shows the surface textures of the triple seals with CRS-2 and CRS-2P. The triple seals shown in Figure 7-3 were composed of granite 78M, granite 78M, and lightweight aggregate from the bottom to the top layer, respectively. It can be seen in this figure that the surface texture of the unmodified seal is much rougher than that of the polymer-modified seal due to the loss of aggregate particles.

Table 7-1 Field Survey Summary

Phase	Section	Rut Depth (inch)	Condition
I	1	1/4	• Good condition • A few spots of aggregate loss • Slight flushing in a few spots
	2	1/8	• Good condition
	3	3/16	• Good condition • A few spots of aggregate loss • Slight flushing in a few spots
	4	1/8	• Good condition
	5	-	• Maintenance required due to mechanical damage • Flushing in a few spots • A few spots of aggregate loss
	6	-	• Aggregate loss due to some mechanical damage • Otherwise, good condition
	7	-	• Good condition • Maintenance required due to mechanical damage • Slight flushing in a few spots
	8	-	• Good condition
II	9	3/8	• A few spots of aggregate loss • Poor condition
	10	3/16	• A few spots of aggregate loss • Maintenance required due to mechanical damage • Poor condition
	11	1/2	• Severe aggregate loss • Rough road surface due to excessive aggregate loss
	12	1/4	• A few spots of aggregate loss • Otherwise, good condition
	13	-	• Good condition
	14	-	• Good condition

Figure 7-1 Flushed surface texture of single seal in Section 5 with granite 78M and CRS-2 emulsion

Figure 7-2 Flushed surface texture of double seal (78M/Lightweight) in Section 3 with CRS-2 emulsion

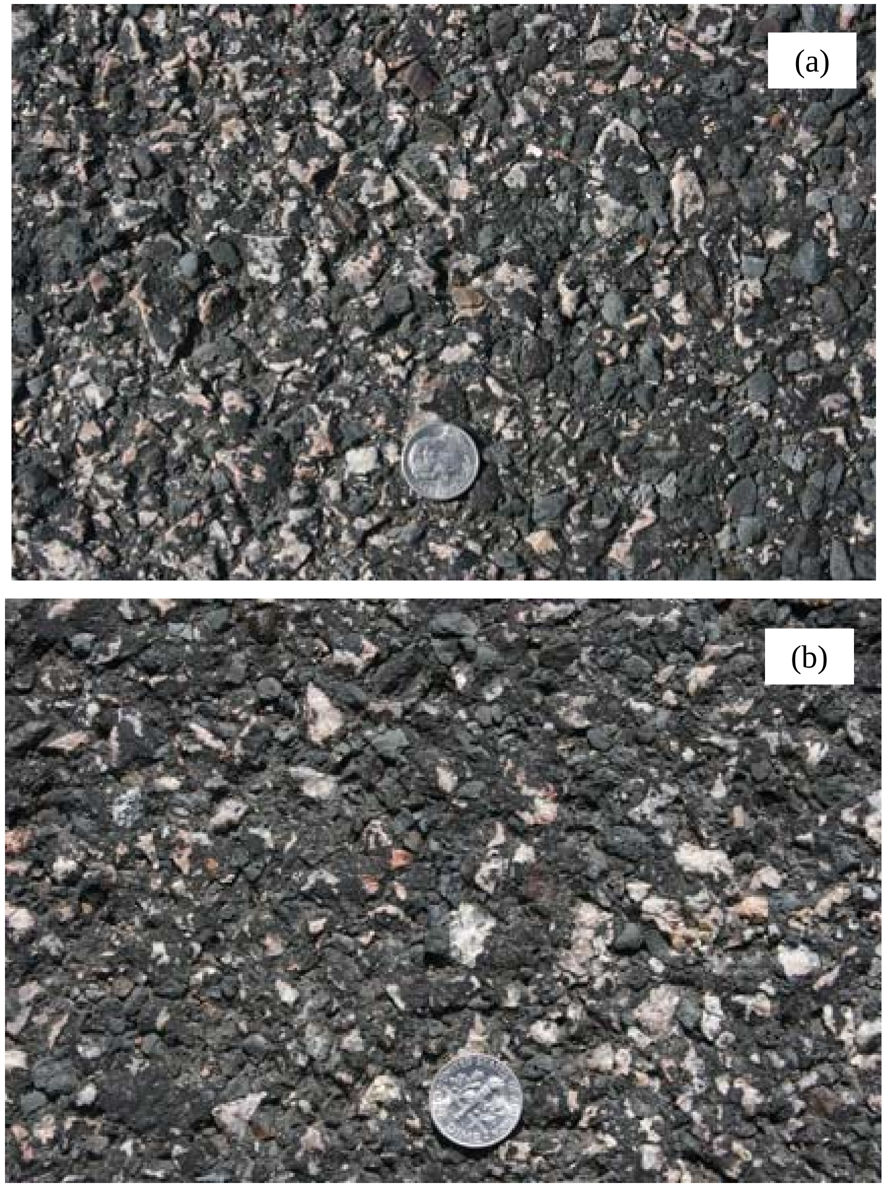


Figure 7-3 Surface texture of triple seal with aggregate loss at the top layer: (a) Section 1 with CRS-2; (b) Section 2 with CRS-2P

Another observation was made by comparing the field survey results between Phase I and Phase II sections. The same emulsion and aggregate application rates and construction sequences were used in the Phase I and Phase II construction. However, the overall trend shows that the condition of the Phase II sections was worse than that of the corresponding Phase I sections regardless of the emulsion type. Figure 7-4 shows surface textures of the triple seal sections in Phase I and Phase II. The triple seal was composed of 78M, 78M, and lightweight aggregate from the bottom layer to the top layer. The Phase II sections (Figure 7-4 (b) and (Figure 7-4 (d)) show more aggregate loss from the top layer than the Phase I sections in Figure 7-4 (a) and Figure 7-4 (c) even though the Phase I sections have been in service longer. It implies that the construction environment has a significant effect on the chip seal performance. The main difference between Phase I and Phase II was the ambient temperature. From the weather record, it was found that the range of the ambient temperature in Bailey, Wilson County in June 2007 was between 64° and 87°F whereas in October 2007 it was between 48° and 73°F. The Phase II sections could have been exposed to a rapid temperature drop after the construction. This temperature drop can interrupt the proper formation of bonding between the aggregate and the binder, and therefore more aggregate loss.

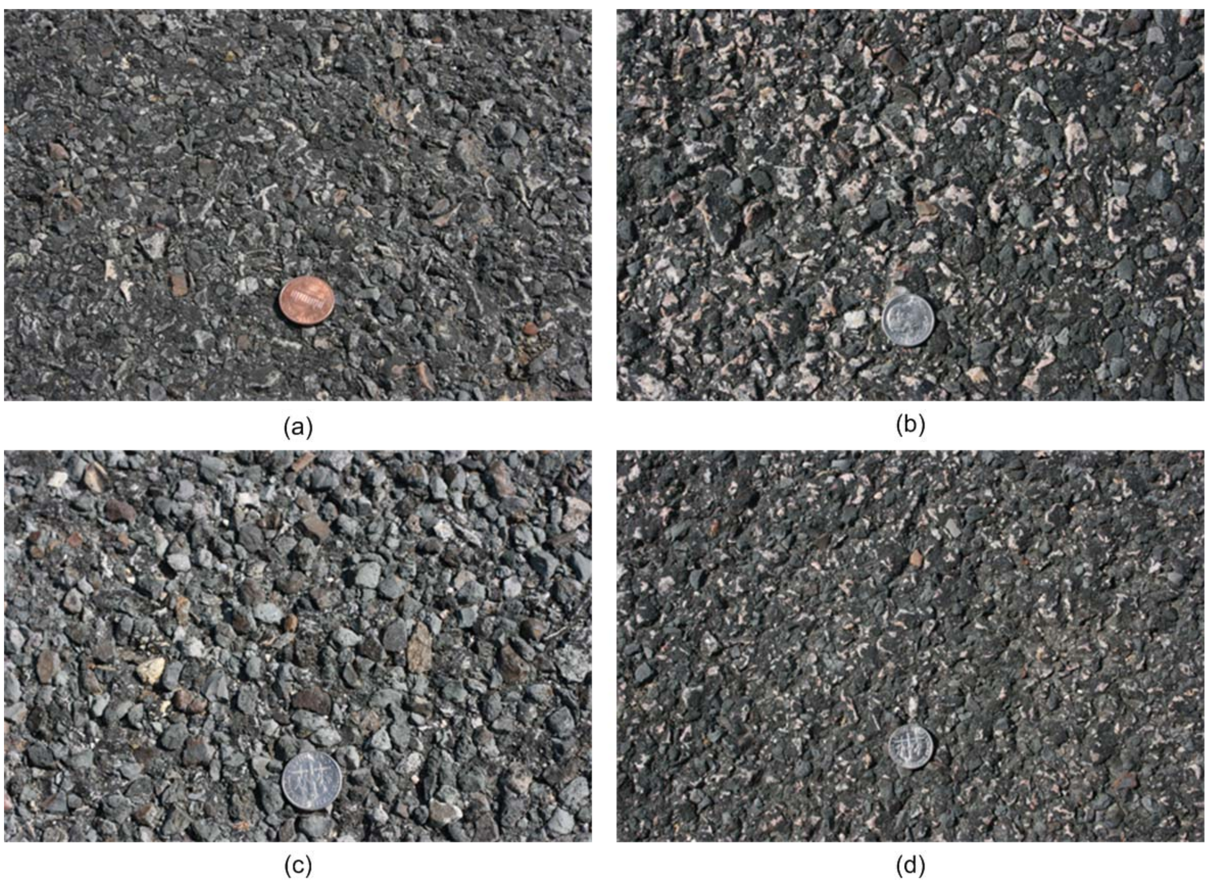


Figure 7-4 Surface texture of the triple seal for comparison between Phase I and Phase II construction programs: (a) CRS-2 in Phase I; (b) CRS-2 in Phase II; (c) CRS-2P in Phase I; (d) CRS-2P in Phase II

Chapter 8. LIFE-CYCLE COST ANALYSIS (LCCA) OF ASPHALT SURFACE TREATMENTS

8.1 Experimental Program

LCCA is an economic analysis in which alternative methods are evaluated using measurements of costs and benefits or effectiveness. The effectiveness in this project is determined based on a comparison of the life-cycle cost benefits of an extended pavement service life due to the use (or non-use) of PME in chip seals.

The objective of this chapter is to provide a comparative cost analysis of the chip seal pavements constructed using PME (CRS-2L) versus using unmodified emulsion (CRS-2). PME typically costs about 30% more than unmodified emulsion (AEMA 2004); however, the chip seals constructed with PME provide better initial and long-term performance and extend the overall service life of pavements. Thus, it is important to evaluate the effectiveness of PME in life cycle costs.

In this project, *RealCost* software, recommended by the FHWA, is used to perform the LCCA in the case study for a project-level decision making process. Table 8-1 provides the average cost information for chip seal construction in North Carolina for 2008 that is provided by the State Road Maintenance Unity at NCDOT. This cost information is input to the *RealCost* software to provide a LCCA comparison of the use of PME versus unmodified emulsion.

Table 8-1 Chip Seal Construction Costs

Seal Type	Chip Seal Cost ($/yd^2)		Difference (%)
	CRS-2 Emulsion	CRS-2L Emulsion	
Single	$ 1.30	$ 1.38	6.44
Double	$ 1.56	$ 1.99	27.56
Triple	$ 2.58	$ 3.19	23.64

8.2 *Life-Cycle Cost Analysis Process*

The objective of this study is to provide a comparative chip seal construction cost analysis of the use of PME (CRS-2L) versus unmodified emulsion (CRS-2) in North Carolina, based on parallel life cycles and performance. LCCA is an evaluation technique applicable to the consideration of certain transportation investment decisions (FHWA 2004). It incorporates both the transportation agency's institutional knowledge and the application of sound economic analysis techniques (FHWA 2004).

Many factors affect an agency's decisions and the LCCA. First, the initial agency costs constitute the main factor because they determine and control most of the total costs. Second, user costs, which consider travel delays, vehicle costs, and safety impacts for the public, must be acknowledged. The third influential factor is preservation activity. While the first two factors affect the performance of the software and the results, preservation activity affects the strategy of selecting alternatives. Preservation strategies are different from traditional maintenance and rehabilitation because such activities are performed before distress occurs. Lastly, an agency's stewardship (in the hands of its officials) is responsible for explaining ways that its funds are spent (Smith et al. 2006, FHWA 2004, Caltrans 2007).

The process of performing the LCCA is as follows. The first step is to establish design alternatives. At least two alternatives should be determined before the process begins. Also as part of this first step, the analysis period must be set. The second step is to determine activity timing, which is related to the service life of each activity. The third step is to estimate costs, including both agency costs and user costs. Agency costs include initial costs, maintenance costs, and salvage value; the latter emerges at the end of the analysis period. User costs include vehicle operating costs, travel time costs, and crash costs. The fourth step is to compute life-cycle costs. (Caltrans 2007, FHWA 2004)

The FHWA recommends a present value (PV) approach, which considers the present value of each activity in the future. Also, when computing life-cycle costs, two approaches, deterministic and probabilistic, may be taken. The deterministic approach uses a fixed value, and the probabilistic approach uses a frequency distribution. The final step is to analyze the results, which should provide answers as to the lowest cost alternative and best decisions (FHWA 2004).

8.3 Development of Life-Cycle Cost Models

Life-cycle cost models reflect the type and sequence of maintenance and rehabilitation activities that can be expected to occur for a particular original pavement structure over a chosen analysis period (Smith et al. 2006). Two different scenarios are developed for the LCCA analysis.

The first scenario assumes that the chip seal is applied to an existing HMA pavement, as shown in Figure 8-1. The chip seal is constructed to rehabilitate a HMA pavement that has been in service for 12 years. It is assumed that the life span of the chip seal using unmodified emulsion is 5 years, and the same treatment is repeated, as necessary, within the 40-year analysis period. The 5-year life of unmodified chip seals is found typical in various literatures. For the polymer-modified chip seals, six different strategies are assumed with the rehabilitation life cycle of the PME chip seal increasing from 5 years to 10 years at one year increment. The life-cycle costs of these strategies are estimated using *RealCost* software.

Figure 8-2 illustrates that the second scenario follows the same process, except that the chip seal is used as the surface treatment in a newly constructed road. Also, the life span of one design alternative has been changed from 40 years to 30 years.

For this LCCA program study, the research team assumes that the construction road is a 2-lane rural road with 10 ft. travel lanes, which is typical of a North Carolina rural road. Such a road has an AADT of 1,700 (1-way) of approximately 2,000 vehicles/day, and 3.0% of trucks on this facility yield an estimated 140 trucks per day (1-way, designed lane).

For probabilistic LCCA purposes, the chip seal treatment was repeated, as necessary, within the 40-year analysis period. The cost estimates were determined for each activity based on unit costs assembled as part of this study.

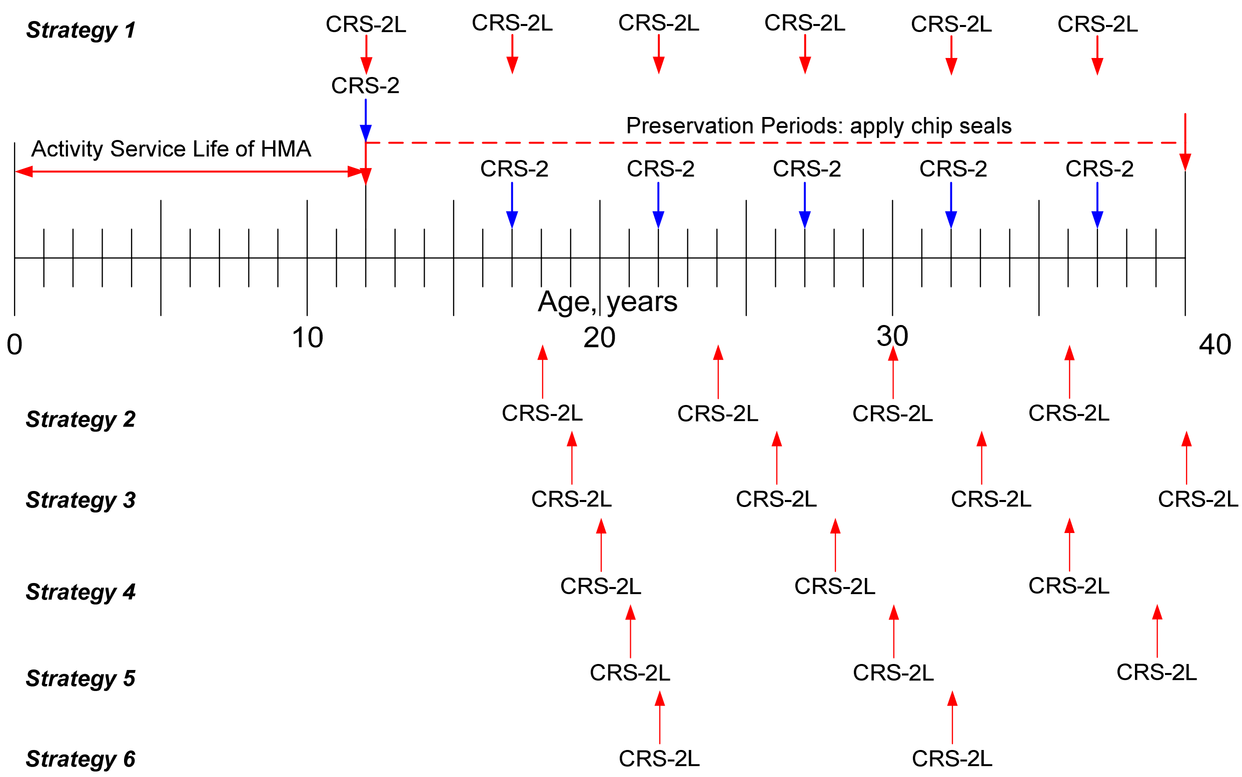


Figure 8-1 Conceptual illustration of the first alternative LCCA program

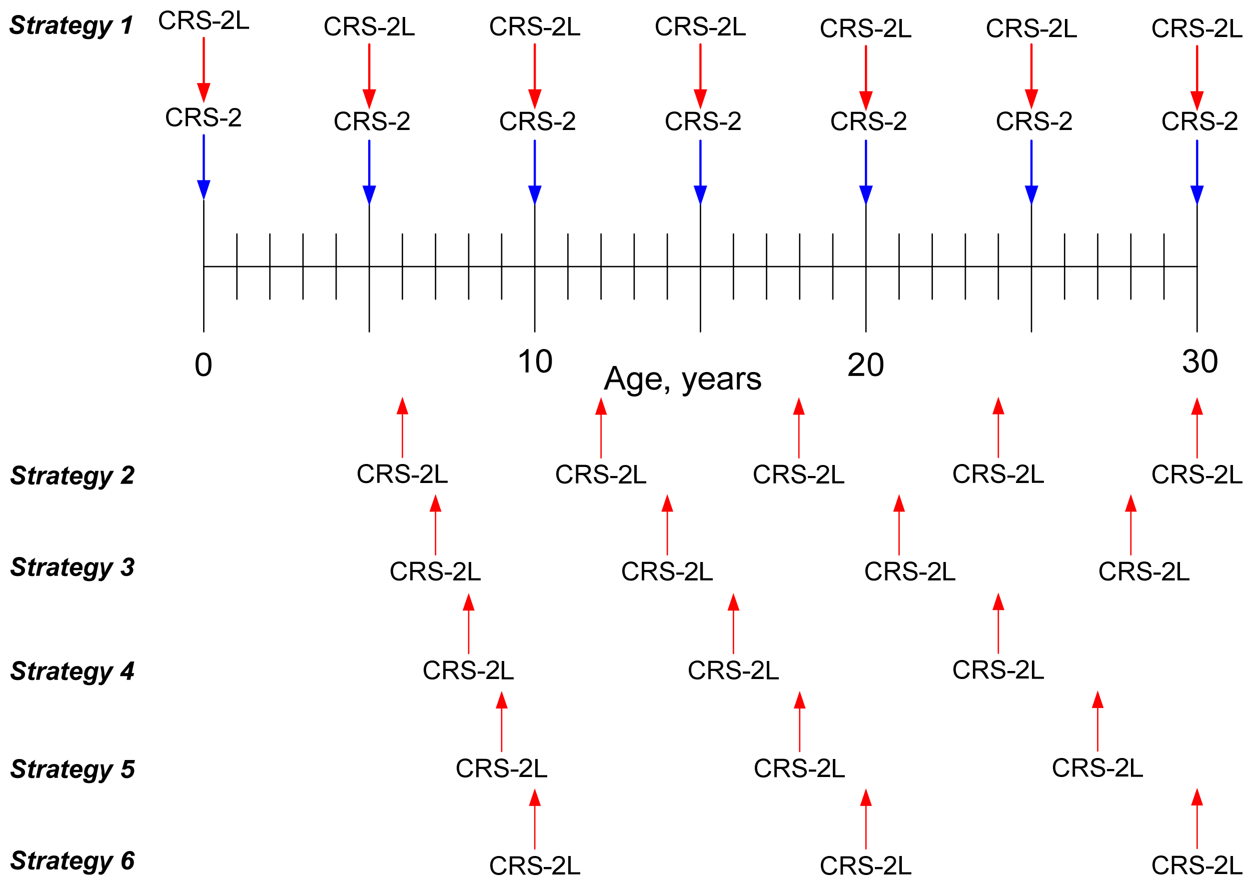


Figure 8-2 Conceptual illustration of the second alternative LCCA program

8.4 Life-Cycle Cost Analysis

8.4.1 LCCA Program Selection

In order to investigate the life-cycle cost benefits between using PME and unmodified emulsion in the chip seal construction, the program used for analysis is the FHWA's LCCA spreadsheet program, *RealCost Version 2.2 2*. This software investigates the effects of cost, service life, and economic inputs of the life-cycle costs. *RealCost* calculates life-cycle values for both agency and user costs that are associated with construction and rehabilitation. The software can perform both deterministic and probabilistic modeling of pavement LCCA problems. Outputs are provided in tabular and graphic formats. Additionally, *RealCost* supports deterministic sensitivity analyses and probabilistic risk analyses (FHWA 2004).

8.4.2 LCCA Inputs

Figure 8-3 shows the so-called *switchboard* panel that appears immediately after the worksheet is opened. The layout shows the various functions and inputs of the program and the inputs required for analysis. The switchboard consists of five sections, as shown in Figure 8-3. A summary of the functions and inputs are as follows (FHWA 2004, Caltrans 2007):

- Project-level inputs—Inputs common to both alternatives under consideration, such as traffic, project details, analysis options, and so on. (Note that for this study user costs are not considered in the LCCA).
- Alternative-level inputs—Inputs specific to a given design alternative (i.e., HMA and stone matrix asphalt (SMA) design alternatives). The information required includes initial construction costs, subsequent maintenance and rehabilitation activities costs, reconstruction costs, service life data, and anticipated maintenance costs and frequency.
- Input warnings—Warnings triggered by possible errors in the input data.
- Simulations and outputs—Inputs for the actual running of the LCCA, such as the number of simulations, etc., and reported results.
- Administrative functions

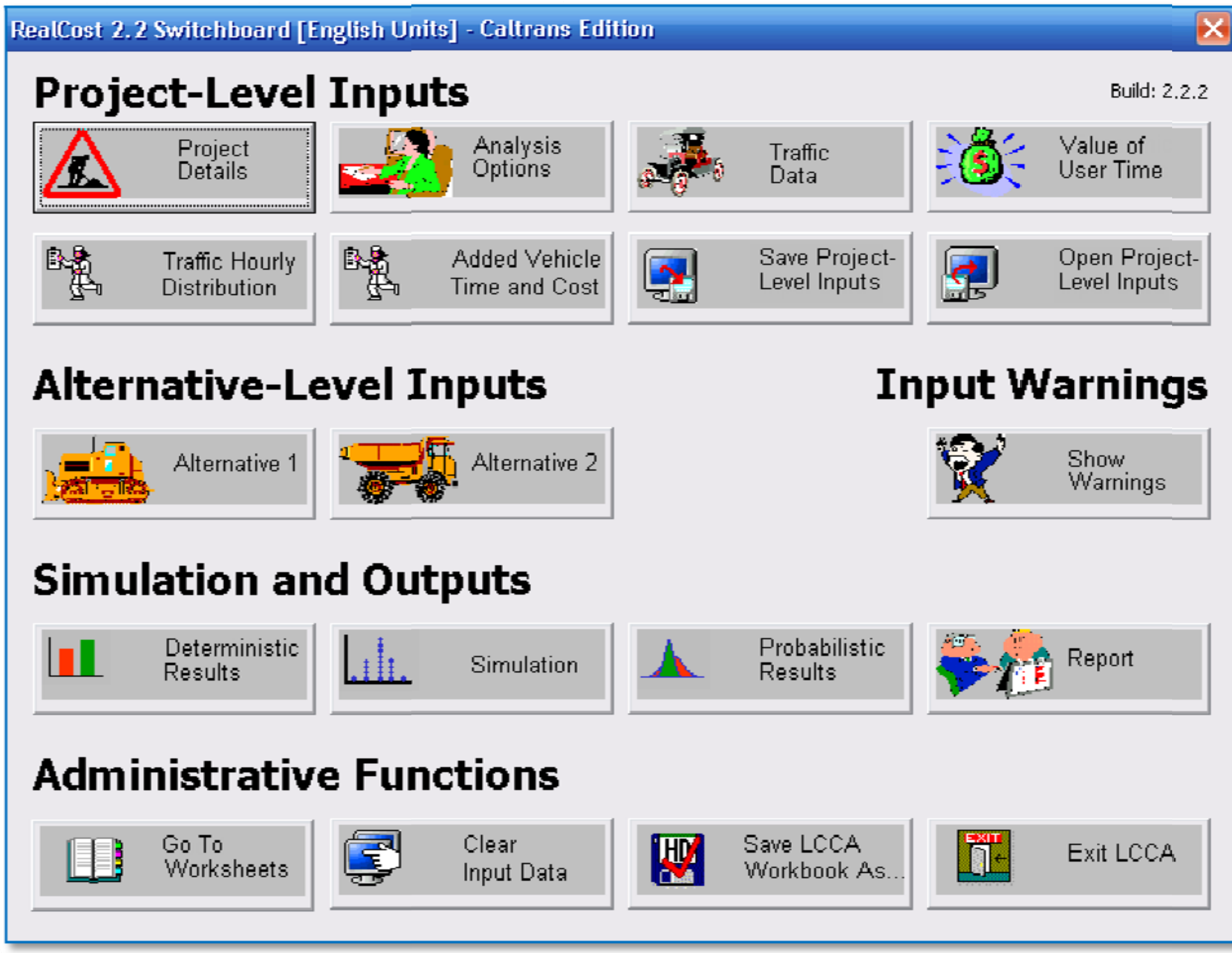


Figure 8-3 *RealCost* switchboard

Two levels of information are required in *RealCost*: project-level input and alternative-level input. Project-level inputs are used to enter the detailed project information. The information entered here is necessary to differentiate between projects. The alternative-level input is used to input information for the project alternatives that are being analyzed. A total of six rehabilitation activities can be included after the initial construction, as shown in Figure 8-4 (Caltrans 2007).

Figure 8-5 shows the information for the analysis assumptions that are applied in this analysis (e.g., an analysis period of 40 years and a discount rate of 4%). Figure 8-6 shows the traffic data panel that is used to enter traffic data for analysis. Figure 8-7 presents examples of default inputs, such as analysis period, traffic capacity, and traffic hourly distribution (obtained from *RealCost* and to represent hourly traffic distribution for rural environments) that are used for analysis.

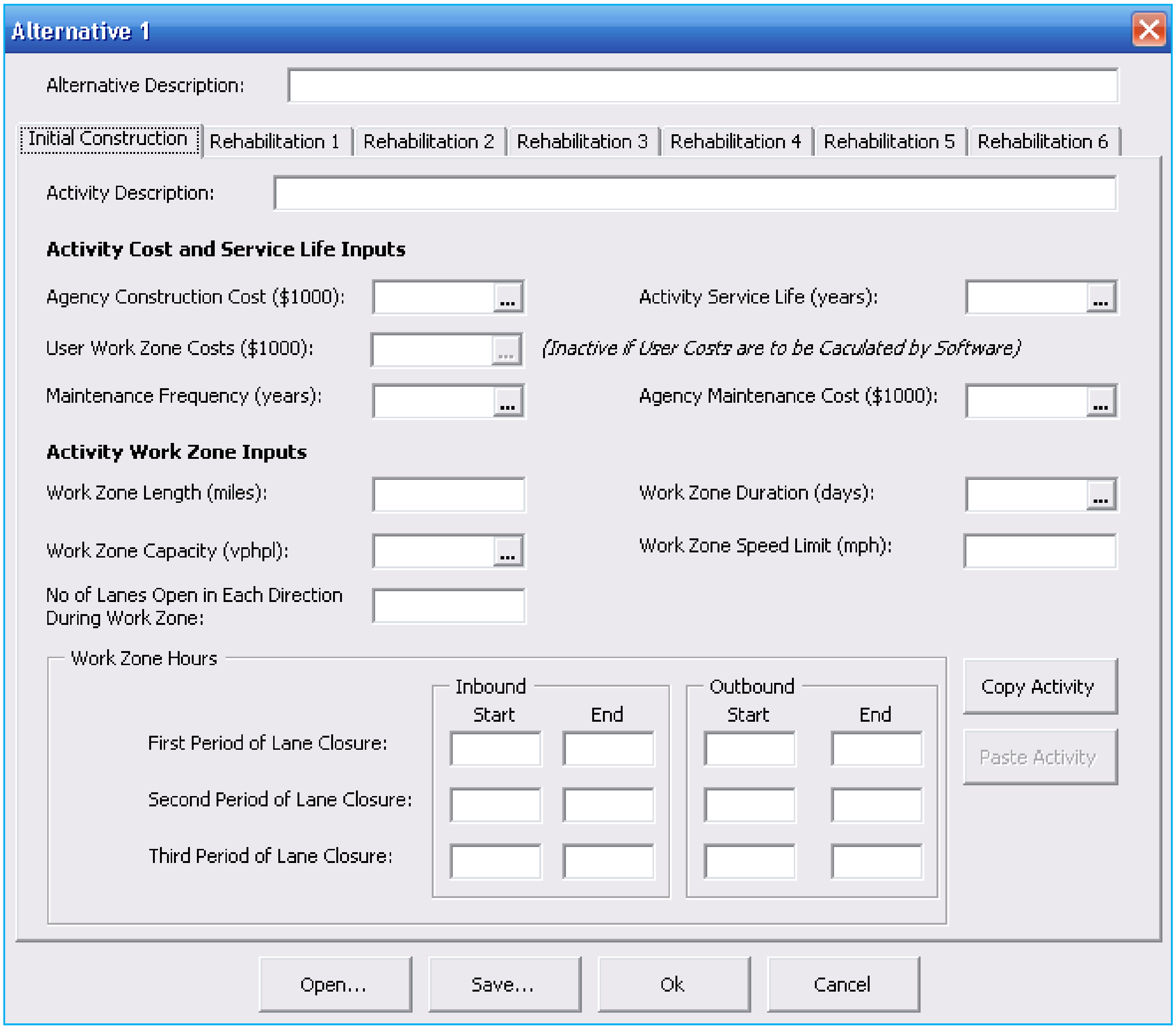


Figure 8-4 Typical alternative panel (Alternative 1)

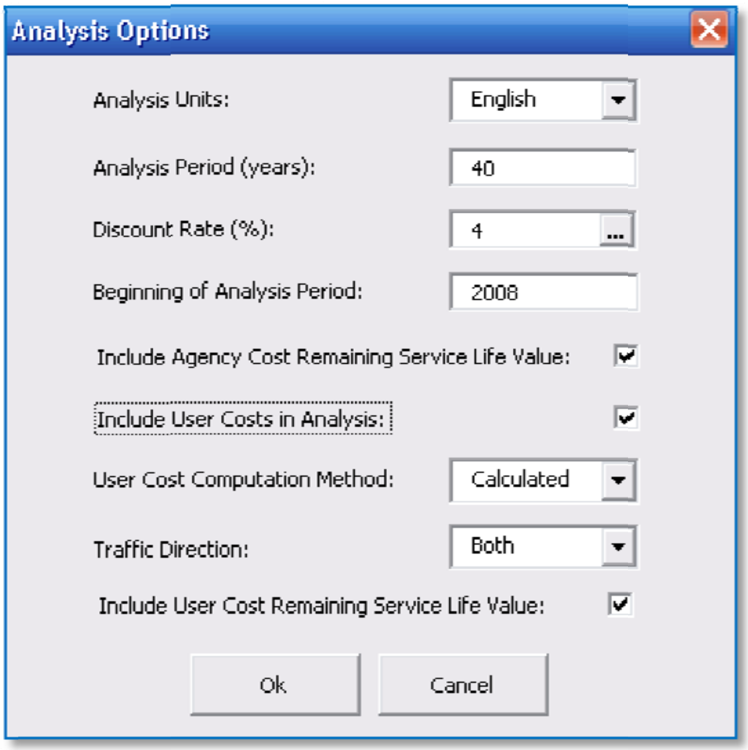


Figure 8-5 *RealCost* analysis options applied and used for computing life-cycle costs

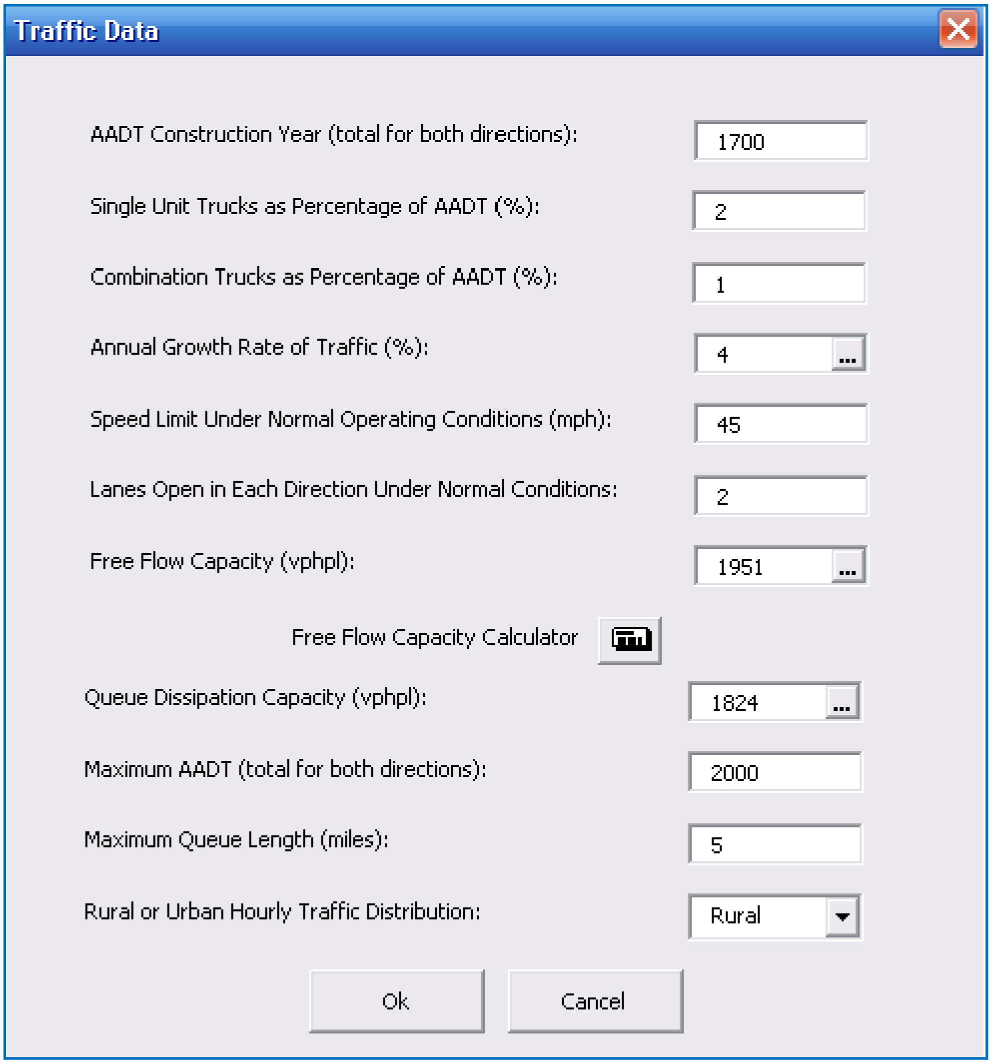


Figure 8-6 Traffic data used for analysis

Traffic Hourly Distribution

Hour	AADT Rural (%)	Inbound Rural (%)	Outbound Rural (%)	AADT Urban (%)	Inbound Urban (%)	Outbound Urban (%)
0 - 1	1.62	48.82	51.18	0.92	48.03	51.97
1 - 2	1.3	52.07	47.93	0.62	49.51	50.49
2 - 3	1.31	53.49	46.51	0.58	51.88	48.12
3 - 4	1.52	59.27	40.73	0.78	56.79	43.21
4 - 5	2.14	62.1	37.9	1.59	61.32	38.68
5 - 6	3.43	59.81	40.19	3.11	60.31	39.69
6 - 7	4.79	58.49	41.51	5.01	58.39	41.61
7 - 8	5.3	57.83	42.17	6.04	57.59	42.41
8 - 9	5.12	55.96	44.04	5.8	55.89	44.11
9 - 10	5.1	54.28	45.72	5.46	53.9	46.1
10 - 11	5.24	52.51	47.49	5.44	51.45	48.55
11 - 12	5.44	51.21	48.79	5.78	50.12	49.88
12 - 13	5.63	50.94	49.06	6.03	49.1	50.9
13 - 14	5.74	51.23	48.77	6.11	48.39	51.61
14 - 15	6.11	50.3	49.7	6.52	46.33	53.67
15 - 16	6.57	48.84	51.16	7.03	44.6	55.4
16 - 17	6.73	47.45	52.55	7	43.39	56.61
17 - 18	6.4	45.23	54.77	6.54	43.37	56.63
18 - 19	5.32	45.61	54.39	5.35	44.39	55.61
19 - 20	4.31	44.55	55.45	4.22	44.85	55.15
20 - 21	3.57	45.62	54.38	3.54	45.39	54.61
21 - 22	3.03	46.01	53.99	2.95	45.88	54.12
22 - 23	2.4	47.06	52.94	2.18	47.23	52.77
23 - 24	1.88	47.11	52.89	1.4	45.12	54.88
Total	100			100		

Restore Defaults | Ok

Figure 8-7 Hourly traffic distribution (default) used for analysis

8.5 LCCA Results

Life-cycle cost analyses of the six strategies in each of the two scenarios were performed using the *RealCost* program to compare the cost-effectiveness of chip seals using PME as compared to those using unmodified emulsion. The LCCA results for unmodified (5-year cycle) chip seals are compared with the LCCA results of six cycle periods (5, 6, 7, 8, 9, 10 years). The *RealCost* program provided deterministic life-cycle costs and probabilistic life-cycle costs. Thus, this chapter shows both simulated deterministic and probabilistic results.

The deterministic results are presented in Figure 8-8 to Figure 8-9 for each of the two scenarios as a function of emulsion type. Both figures use two symbols, a filled symbol and an empty symbol. The empty symbol indicates the calculated data for the use of CRS-2 (unmodified emulsion) for a 5-year life cycle. The calculated data for the use of CRS-2L (PME), represented by the filled symbol, are determined based on the change in service life from 5 years to 10 years.

The calculated LCCA involves a direct comparison of the total life-cycle costs for each alternative. The PV approach that brings initial and future costs to a single point in time is recommended by the FHWA (Caltrans 2007) and is adopted in this study. The results from Figure 8-8 and Figure 8-9 indicate that the PV of the PME becomes lower than that of the unmodified emulsion when the PME pavement has at least a 7-year rehabilitation cycle. That is, the deterministic results for each LCCA program suggest that the PME chip seal is more cost-effective than the unmodified chip seal if the extended service life of the PME chip seal is two years longer than that of the unmodified chip seal, regardless of seal type.

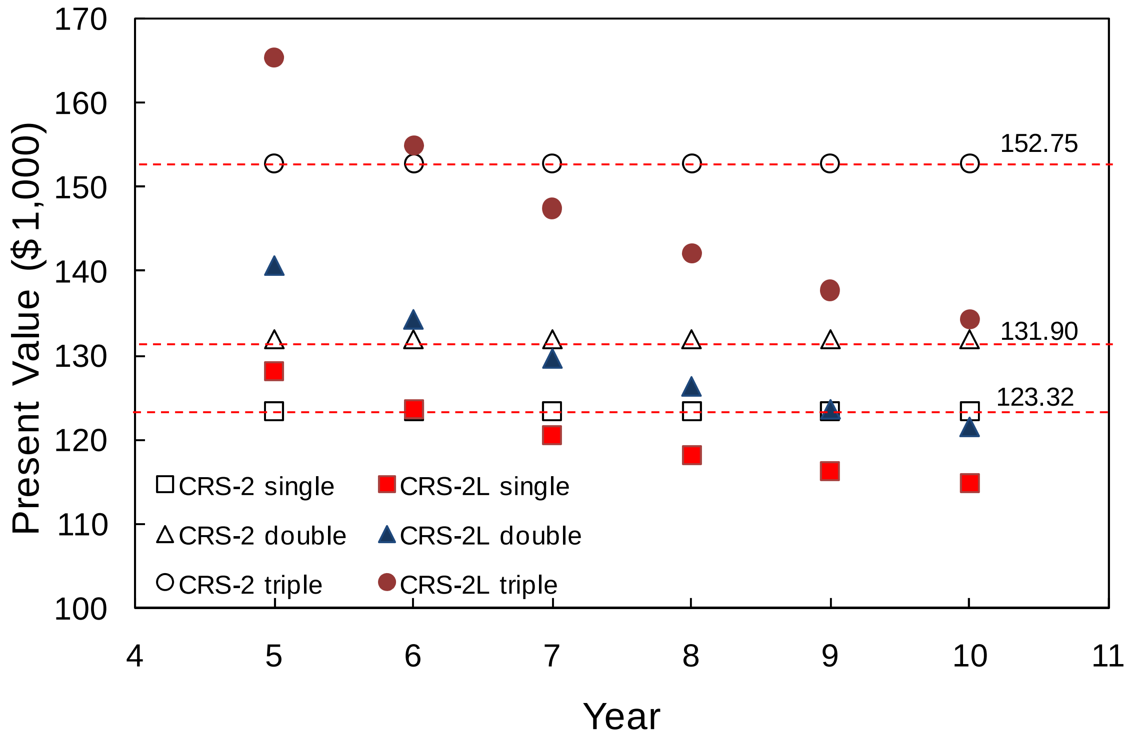


Figure 8-8 Results of deterministic life-cycle costs for HMA pavements

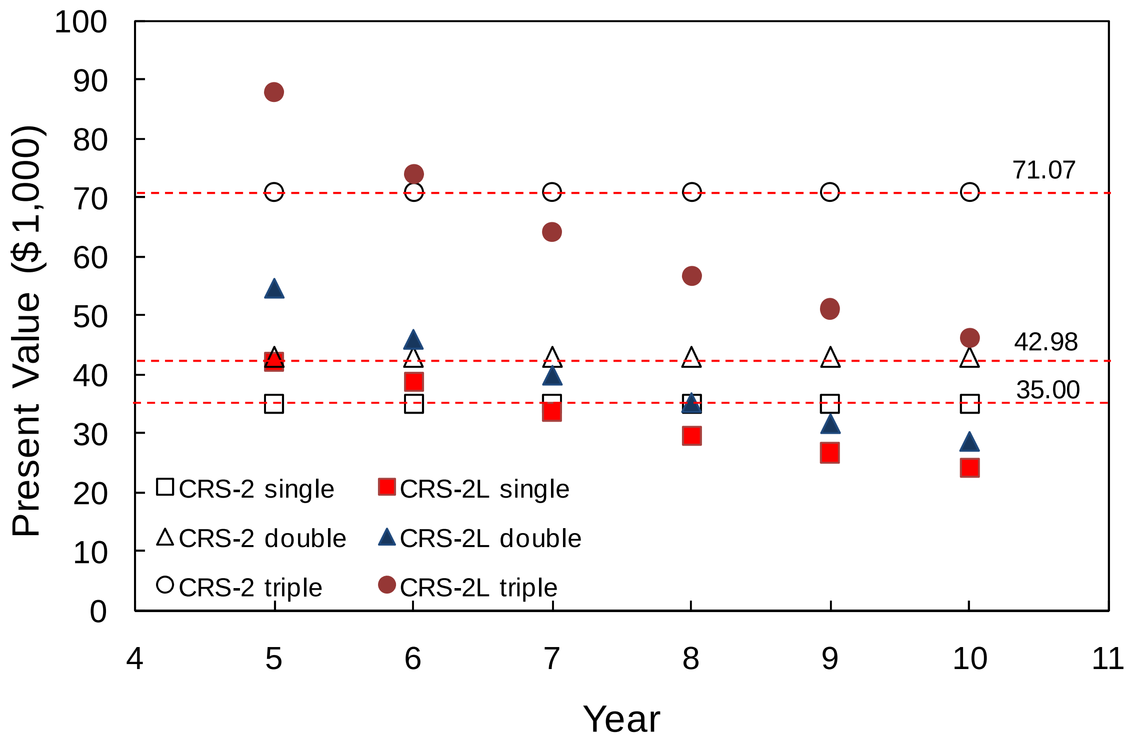


Figure 8-9 Computed deterministic life-cycle costs for chip seal pavements

Also, *RealCost* reported the full range of possible PV outcomes based on the probabilistic LCCA model. The analysis recognizes that each project alternative is reflected in the PV output results according to this information. This analysis provides important statistical information to help the decision maker (FHWA 2004).

Simulations of probability life-cycle costs are also performed and are provided in Table 8-2 to Table 8-4. These results show the same trends as the deterministic results. The PME chip seal is cost-effective according to LCCA on condition that the PME chip seal service life is two years longer than that of an unmodified chip seal.

Table 8-2 Computed Probabilistic Life-Cycle Costs of Single Seal

Scenario Type		Emulsion Type and Life Cycle						
		CRS-2 5 years	CRS-2L 5 years	CRS-2L 6 years	CRS-2L 7 years	CRS-2L 8 years	CRS-2L 9 years	CRS-2L 10 years
		Total Cost (Present Value $1,000)						
1	Mean	$124.09	$129.07	$124.45	$121.11	$118.70	$116.74	$115.23
	Standard Deviation	$5.65	$6.82	$5.61	$4.75	$4.09	$3.59	$3.18
	Minimum	$115.66	$118.90	$116.06	$113.99	$112.54	$111.32	$110.41
	Maximum	$135.72	$143.10	$135.95	$130.84	$127.02	$124.04	$121.66
2	Mean	$35.56	$42.91	$39.65	$34.31	$30.26	$27.22	$24.66
	Standard Deviation	$4.91	$5.92	$6.06	$5.06	$4.33	$3.73	$3.28
	Minimum	$28.03	$33.81	$30.50	$26.64	$23.71	$21.54	$19.68
	Maximum	$45.41	$54.79	$51.98	$44.60	$39.06	$34.77	$31.31

Table 8-3 Computed Probabilistic Life-Cycle Costs of Double Seal

Scenario Type		Emulsion Type and Life Cycle						
		CRS-2 5 years	CRS-2L 5 years	CRS-2L 6 years	CRS-2L 7 years	CRS-2L 8 years	CRS-2L 9 years	CRS-2L 10 years
		Total Cost (Present Value $ 1,000)						
1	Mean	$132.96	$142.05	$135.37	$130.53	$127.05	$124.21	$122.02
	Standard Deviation	$7.73	$9.86	$8.11	$6.87	$5.91	$5.19	$4.60
	Minimum	$121.43	$127.33	$123.23	$120.23	$118.13	$116.37	$115.05
	Maximum	$148.87	$162.33	$152.00	$144.60	$139.09	$134.77	$131.33
2	Mean	$43.49	$55.47	$46.67	$40.46	$35.76	$32.12	$29.08
	Standard Deviation	$5.09	$6.49	$5.22	$4.29	$3.61	$3.07	$2.67
	Minimum	$35.52	$45.31	$38.48	$33.70	$30.07	$27.26	$24.87
	Maximum	$53.51	$68.26	$56.94	$48.87	$42.80	$38.09	$34.30

Table 8-4 Computed Probabilistic Life-Cycle Costs of Triple Seal

Scenario Type		Emulsion Type and Life Cycle						
		CRS-2 5 years	CRS-2L 5 years	CRS-2L 6 years	CRS-2L 7 years	CRS-2L 8 years	CRS-2L 9 years	CRS-2L 10 years
		Total Cost (Present Value $ 1,000)						
1	Mean	$154.51	$167.40	$156.70	$148.95	$143.36	$138.82	$135.31
	Standard Deviation	$12.79	$15.81	$13.00	$11.01	$9.48	$8.32	$7.37
	Minimum	$135.44	$143.82	$137.24	$132.43	$129.06	$126.24	$124.13
	Maximum	$180.81	$199.92	$183.36	$171.50	$162.66	$155.74	$150.23
2	Mean	$71.92	$88.92	$74.81	$64.87	$57.32	$51.49	$46.62
	Standard Deviation	$8.41	$10.40	$8.37	$6.88	$5.78	$4.92	$4.28
	Minimum	$58.74	$72.63	$61.68	$54.03	$48.20	$43.71	$39.86
	Maximum	$88.49	$109.42	$91.27	$78.34	$68.62	$61.07	$54.98

The LCCA results indicate that the polymer modification of the emulsion needs to extend the service life of a chip seal at least two years in order for it to be cost-effective. The results presented in this report seem to indicate that this amount of life extension is possible with the PME. Evidence includes the following observations from this study:

1. Although it is not easy to translate a decrease in aggregate loss to an increase in service life, the use of PME nonetheless shows a decrease in aggregate loss that is 50% of that of the unmodified chip seal under many of the conditions tested in this study. For the low temperature testing, the aggregate loss decreases to around 30% of that of the unmodified seals when PME is used.
2. The use of PME reduces the amount of bleeding by about 70% for the single seal with lightweight aggregate and the double seals.
3. The MMLS3 rutting data shown in Table 6-1 suggest that the use of PME can extend the service life of chip seals by 3 to 10 times.
4. The visual survey data from the two-year-old field sections indicate that some signs of distress are evident in the unmodified seals, whereas the modified chip seals show no distress.

Chapter 9. CONCLUSIONS AND FUTURE RESEARCH RECOMMENDATIONS

In order to compare the aggregate retention performance of unmodified emulsion (CRS-2) and PME (CRS-2L and CRS-2P), the MMLS3 test, FOT, Vialit test, bleeding test, and rutting test were performed on both laboratory and field fabricated samples under different temperature conditions. Based on the test data obtained from this study, the following conclusions are drawn to support the benefits of using PME in chip seal construction:

1. The CRS-2L emulsion exhibits benefits of fast and improved adhesion in terms of: (1) a reduction in the amount of aggregate loss during early curing times; (2) less curing time needed to obtain the desired adhesion between the asphalt and aggregate; and (3) the ability to allow traffic on the newly constructed road safely and quickly.
2. The CRS-2L emulsion improves aggregate retention performance at low temperatures, such as experienced in winter. The CRS-2L emulsion meets the criterion of 10% maximum allowable excess aggregate loss, as specified by the Alaska specifications, at -4° and 41°F.
3. The adhesion development of each emulsion is very sensitive to the curing temperature. Emulsion, especially CRS-2, at low temperatures requires more curing time to minimize early aggregate loss, which is a major failure in newly-constructed chip seals.
4. Based on the limited data presented in this report, the benefits of polymer modification in chip seals diminish with the use of lightweight aggregate. This observation may be due to the fact that the added benefits of polymer modification are less significant in chip seals made of lightweight aggregate because they are already performing well without the modification due to the uniform gradation of the lightweight aggregate, and because the additional adhesion provided by PME is not needed to hold the lightweight aggregate under wheel loading.

5. However, polymer modification improves the aggregate retention performance of double seals, even though the aggregate in the top layer is the lightweight aggregate. It seems that the uniform gradation of the lightweight aggregate does not contribute to improved aggregate retention performance in the double seals because the combined aggregate structure created by the non-uniform granite 78M aggregate in the bottom layer and the uniform lightweight aggregate in the top layer reduces the beneficial effects of the uniform gradation in the lightweight aggregate and, thus, enhances the beneficial effects of polymer modification.
6. Based on the results from bleeding performance tests and visual observation, PME is recommended to improve bleeding resistance regardless of chip seal type. The bleeding caused by excess binder does not occur, regardless of chip seal type, in this study because the EAR used in this study is close to the optimal rate. The bleeding performance of the double seal is significantly different because the unmodified emulsion in the double seals shows evidence of bleeding due to aggregate loss, thus indicating a significant relationship between aggregate loss and bleeding. Nonetheless, the PME chip seal does not exhibit bleeding after four hours.
7. Polymer modification enhances both resistance to rutting development and aggregate retention performance. PME shows significant rutting resistance against traffic loading. Specifically, PME provides rutting resistance at high temperatures.
8. LCCA shows PME to be cost effective on condition that the service life of the PME is two years longer than that of an unmodified chip seal, despite the fact that PME typically costs about 30% more than unmodified emulsion. The performance data obtained from this study, including aggregate loss, bleeding, and rutting, indicate that the use of PMEs can extend the service life of chip seals more than two years, thus justifying the cost effectiveness of using PMEs in chip seals.

The main recommendation for future research is to optimize the construction procedure (including the rolling pattern and traffic closure time) for polymer-modified chip seals to maximize the benefits of using PME. This report clearly demonstrates that polymer-modified chip seals behave quite differently than unmodified chip seals. Therefore, the construction procedure used for unmodified chip seals will not yield the best performance if applied to polymer-modified chip seals. The findings from this project and the previous NCDOT project on the rolling of chip seals (HWY-2006-06) will serve as an excellent foundation to optimize the construction procedure for polymer-modified chip seals.

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