

**The Monroe Michigan Chip Seal Case Study: An Evaluation of Multiple Chip Seals'
Cold Weather Field Performance.**

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ABSTRACT

The purpose of the Monroe Chip Seal Case Study was to evaluate chip seal performance for multiple test sections comprised with different asphalt emulsion – aggregate type combinations with emphasis on aggregate retention, especially during winter months. Different emulsions and aggregates were desired to be evaluated to determine if there was an optimum combination for performance in this climate over the course of one winter. Specific comparisons of interest in this project included:

- 1.) Neat (non-oil) emulsions versus emulsions with low oil additives
- 2.) Modified emulsions with latex (SBR) versus modified emulsions with SBS
- 3.) Limestone aggregate retention versus crushed gravel aggregate retention.

Aggregate retention was measured through imaging analysis. Photographs were taken at identical locations monthly between September 2009 and April 2010. The change in aggregate coverage was measured over time by converting the photographs into black and white binary images. The binary images allowed for the calculation of aggregate coverage.

Major findings of the research include that adding 1.0% #2 fuel oil to an anionic high float emulsion improved performance (aggregate retention) over emulsions without oil. Anionic limestone chip seals outperformed anionic gravel chip seals. No appreciable difference between limestone and gravel cationic chip seals was observed. There was no significant difference between latex modified and SBS modified chip seals for gravel seals. Limestone seals with latex modified emulsion performed slightly better than SBS modified chip seals.

INTRODUCTION

Chip seals are a pavement preservation technique that consists of a layer of asphalt covered by aggregates that are embedded in the asphalt layer. Chip seals serve two key purposes on the roadway. The first purpose, accomplished by the asphalt layer, is to provide an impermeable layer of asphalt that protects the underlying layers of base and subgrade from moisture intrusion and reduces the amount of oxidation experienced in underlying layers similar to built up roofing systems on flat roofs. The second key purpose, performed by the embedded aggregate, of a chip seal is to provide a skid resistant layer for vehicles. The aggregate also reduce ultra violet (UV) damage to the asphalt layer. Together, the aggregate and asphalt assist each other in accomplishing both tasks. The aggregate on the surface protects the asphalt layer from any damage. In turn, the asphalt serves as a bonding agent that holds onto the aggregate and underlying pavement which permits the surface to maintain its skid resistant quality over time.

Chip seals continue to be the most frequently used method of pavement preservation not only in the United States but also around the world, especially in South Africa, Australia and New Zealand. This can be attributed to chip seals proving to be economically beneficial to extend the life of pavements that are structurally sound to withstand existing loads due to their lower initial costs compared to thin lift overlays (1). As funding for road construction and agency budgets continue to decrease, the role of pavement preservation significantly increases. These trends coupled with the already advantageous ability of chip seals to delay major rehabilitation or reconstruction of HMA pavements lead to the conclusion that chip seals will continue to be, or may play a larger role, in America's transportation network.

BACKGROUND

Chip seals, like other types of construction materials, can experience major distress that results in poor performance or premature failure. One main distress that occurs in chip seals is aggregate loss (2). Aggregate loss causes a decrease in surface macro texture which results in an overall reduction in skid resistance yielding safety concerns. Aggregate polishing, resulting in texture loss, also results in loss of skid resistance. Loss of aggregate distress occurs generally when the adhesive bond between asphalt and aggregate fails or if too little asphalt is applied during construction. Other distresses include bleeding and oxidation of binder. Bleeding is sometimes distinguished by black patches of excess binder appearing on the surface of the chip seal (3) and are typically found in the wheelpaths where trafficking further embeds the aggregate into the asphalt layer. Excessive oxidation of binder results in a binder that is more susceptible to cracking.

Many laboratory test methods including the sweep test (ASTM D7000), the Vialit test (4) and the aggregate retention test (5) have been developed to predict chip seal performance and/or aggregate emulsion compatibility. However, these tests have been considered to be limited due to their ability to measure only aggregate retention and use different forms of energy in simulating the effect of traffic. Lee and Kim developed a comprehensive chip seal performance test using a small sized accelerated pavement testing device (APT) called the Model Mobile Loading Simulator (MMLS3) (2). The MMLS3 would better simulate traffic behavior on chip seals than the previously

mentioned testing methods. However, the MMLS3 is limited based on the availability and accessibility.

Chip seal performance measured in the field can involve the following; performing windshield surveys, quantifying skid resistance or surface texture, and by indirectly measuring aggregate coverage with imaging techniques. During a windshield survey, the assessor observes and records the type and amount of distress present on the pavement surface. From this data, a pavement condition index value can be assigned which is related to overall performance.

Methods to quantify surface texture include the sand patch method and the dynamic friction tester. The sand patch method (ASTM E 965) consists of taking a volume of silica sand, placing it on the surface and spreading it in a circular formation. Once the sand is level with the pavement profile, the diameter is recorded and the mean surface profile depth is calculated. As stone loss occurs surface profile depth would decrease, resulting in lower skid resistance. The dynamic friction tester (ASTM E 303) is a mechanical measure of frictional force which correlates to skid resistance. As aggregate loss would occur, the frictional force would decrease resulting in lower skid resistance.

Imaging techniques to quantify aggregate coverage have been discussed by Carter and Stroup-Gardiner (6) as well by Lee and Kim (2). Carter showed that digital imaging using Scion Image software could quantify the aggregate coverage area. Scion Image for Windows is an image processing and analysis program capable of image processing functions including contrast enhancement, density profiling, smoothing and edge detection (7) The process to determine aggregate coverage is as follows:

- 1.) A photograph is taken of the area desired to be analyzed
- 2.) The photograph is converted to a black and white, where the black area represents asphalt binder and the white area is represented by the cover aggregate.
- 3.) This black and white image is then converted to a binary file, where each pixel, either black or white, is assigned a value (0 or 255)
- 4.) The black area (or binder) than can be calculated based on the mean pixel value.

Lee and Kim used a similar process in analyzing their asphalt surface treatment specimens before and after their testing to quantify bleeding. They used scanned images instead of photographs as well as different imaging software (National Instruments Vision Assistant 7.0). Nonetheless, essentially the same steps were completed to quantify binder area.

OBJECTIVES

The major objective of this research was to evaluate chip seal performance for multiple test sections comprised with various emulsion – aggregate combinations with emphasis on aggregate retention especially during winter months. Winter months (November – March) were of particular importance due to the presence of snow plows on chip seals in Michigan. Different emulsions and aggregates were desired to be evaluated to determine which performed best in this climate over the course of one winter. Specific comparisons of interest in this project included:

- 1.) Neat (non-oil) emulsions versus emulsions with oil

- 2.) Modified emulsions with latex (Styrene-Butadiene Rubber or SBR) versus modified emulsions with SBS (Styrene-Butadiene Styrene)
- 3.) Limestone aggregate retention versus crushed gravel aggregate retention.

PROJECT SCOPE

A section of North Dixie Highway near Monroe, MI was selected to serve as the project site for this research. A total of nine emulsions were selected to be included in the project. Four of these emulsions were anionic rapid set emulsions while the other five were cationic rapid set emulsions. Two types of aggregate were planned to be used in the project resulting in 18 different chip seals to be compared in the field. Construction occurred over a two day period. The first day consisted of placing the four anionic emulsions and the second day consisted of placing the five cationic emulsions.

Samples of aggregate and emulsion were collected to perform standard quality control emulsion and aggregate testing. Field monitoring of the chip seal sections comprised of two parts. Aggregate retention was monitored by randomly selecting three locations in each chip seal section. These three locations were photographed in both wheel paths. These locations were adequately marked so that the same location could be photographed over time. The change in aggregate coverage could be calculated for each monitored section over time which in turn was used as an indicator of chip seal performance.

MATERIAL SELECTION

It was desired to include multiple aggregates and emulsions in this study to determine if performance would differ between materials and combinations thereof. Two aggregates were selected to be incorporated in the study. The first was a crushed limestone (featured on the left of Figure 1) and the other was partially crushed gravel (right on Figure 1). Both of these aggregates are commonly used in this region as chip seal cover aggregates with similar gradations. The limestone aggregate came from the Stoneco Newport Quarry and the gravel originated from the Stoneco Moscow Quarry.



Figure 1. Aggregates Used in Monroe Chip Seal Case Study.

A total of four anionic and five cationic emulsions were selected to be used in the study. Each emulsion was to be covered with limestone and gravel resulting in 18 different chip seal aggregate emulsion combinations for the study. This number was reduced to 17 as the gravel was not placed on the final cationic emulsion. The emulsions studied were:

Anionic High Float Rapid Set Emulsions:

- HFRS-2 Neat (no oil or modifier)
- HFRS-2 with 1.0% #2 Fuel Oil
- HFRS-2L Modified with SBR and 1.0% #2 Fuel Oil
- HFRS-2M Modified with SBS and 1.0% #2 Fuel Oil

Cationic Rapid Set Emulsions:

- CRS-2 Neat (no oil or modifier)
- CRS-2 with 1.0% #2 Fuel Oil
- CRS-2L modified with SBR and 1.0% #2 Fuel Oil
- CRS-2M modified with SBS and 1.0% #2 Fuel Oil
- CRS-2Mm modified with both SBR and SBS and 1.0% #2 Fuel Oil

The emulsions were produced at Asphalt Materials Inc. Orgeon, Ohio location.

PROJECT LOCATION

The test sections were selected to be placed on a section of North Dixie Highway near the intersection of US Turnpike in Newport, MI near Monroe. This section of Dixie Highway is a two lane HMA pavement that serves as a rural collector. The pavement had no preventive maintenance treatment other than cold mix patching and some crack filling prior to placement of the chip seal test sections.

This section of Dixie Highway did possess some pavement distress prior to chip seal placement. The northbound lane did have more localized fatigue cracking and transverse cracking than the southbound section. Some minor rutting in the wheelpaths was also present. The distresses were consistent within each lane for the length of the project. The traffic on Dixie Highway was not equal between the north and southbound sections. The northbound section carries loaded aggregate trucks which return southbound Dixie Highway unloaded. This along with the difference in pavement distress prevented direct comparison of chip seals placed in the different lanes.

CONSTRUCTION OF TEST SECTIONS

Construction of the chip seal sections occurred on September 1st and 2nd, 2009. Figure 2 is a schematic of the section layout. The chip seals with anionic, or the High Float, emulsions were placed first on September 1st, 2009, beginning with the HFRS-2 Neat Limestone section at the Southern terminus of the project on the northbound lane. The HFRS-2M Latex with #2 fuel oil emulsion with limestone aggregate was the final section placed on September 1st, 2009. The following day, the cationic emulsions were placed starting at the northernmost section (CRS-2 Neat with limestone aggregate) working south ending with the CRS-2Mm with limestone section at the intersection of Dixie Hwy and US Turnpike. Due to a limited availability of gravel, the CRS-2Mm was not covered with gravel.

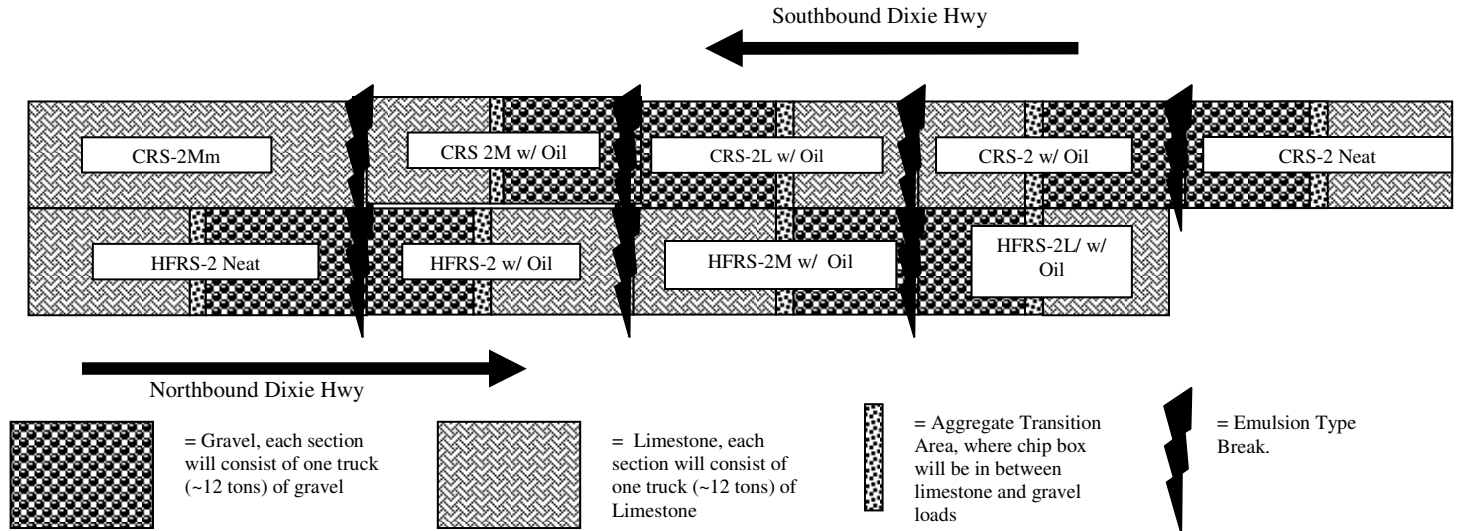


Figure 2. Layout of Chip Seal Sections on Dixie Hwy.

Each chip seal section was targeted to be around 1,000 feet in length. This translated into roughly one truckload of aggregate per section. To facilitate aggregate hauling logistics, it was decided to alternate aggregate type without jettisoning any remaining aggregate from the previous section as one chip box was available for placement. This caused aggregate transition sections roughly 25 to 50 feet in length consisting of a blend of limestone and gravel aggregates. Once the aggregate transition was visibly over, the next section was marked and located. Both the gravel and limestone were applied at a rate of 22 lbs/ yd². This rate was verified by ASTM D5624.

The emulsions were placed at a rate of 0.40 gal/ yd². Each distributor's application rate was verified by ASTM D2995. The application rates were selected to be used by the contractor based on experience with both aggregates as well as many of the emulsions used in the study. The shot rates for both the binder and aggregates were not altered in order to reduce variables for analysis.

Two rubber wheel rollers performed rolling on the chip seal sections. The established rolling pattern for this project was three coverages by each roller. This pattern was established during the first section and maintained throughout the project to minimize any construction variability between sections.

Weather on both days was also very similar with sunny conditions. Ambient air temperature was at least 60°F and rising in shaded areas prior to placement of the first chip seals of each day. Maximum temperatures reached between 70°F and 75°F around noon on both days and remained around these temperatures until 7 PM. The nightly low temperature for both nights was around 50°F. Relative humidity on each day was 75% and 78% respectively. Winds remained calm with maximum wind speeds of 8 mph on both days.

Construction and site selection for this project was performed with the reduction of variables as a high priority. This project permitted the construction of multiple chip seal sections placed by the same crew and equipment. The same manufacturing

procedure was used for all of the emulsions. The single site also eliminates weather as a contributing factor to overall performance. One variable, however, that could not be completely eliminated was traffic. Traffic was clearly higher on the anionic emulsion than the cationic emulsions. However, within the sections (cationic or anionic) the traffic levels are consistent. The effect of differing traffic levels, compounded with different pavement conditions, makes direct comparison of the cationic and anionic sections impractical.

FIELD PERFORMANCE TESTING METHODOLOGY

Field performance of the chip seals was quantified by aggregate retention measured through image analysis. Figure 3 is a visual aid explaining the steps taken to determine the field performance of the chip seal test sections. Each step is explained in detail.

1. Three random stations were identified in each chip seal section. At each station, the wheel path locations were painted for future reference and identified with GPS. Each location was then photographed. These pictures were then catalogued and prepared for imaging analysis.
2. Each photograph was then converted to a black and white image using Microsoft Office Picture Manager tools. The brightness, contrast and midtones were adjusted to convert the image into a black and white. The black and white images were then saved as 16 color bitmap image.
3. The bitmap image was imported into the Scion Image software program. This file was then converted into a binary file where all black or dark pixels were assigned a pixel value of 255 and all white or lighter pixels were assigned a value of 0. The program then assigned an average pixel value for the entire image. The average pixel value along with the number of pixels (or area) was then used to calculate the average area of aggregate coverage.
4. The aggregate coverage for each chip seal was then averaged and converted into a percent of aggregate loss calculation. Equation 1 shows the calculation of percent aggregate loss.

$$\text{Percent Aggregate Loss}_x = \left(1 - \frac{\text{Avg. Agg Coverage in Month}_x}{\text{Initial Agg Coverage}} \right) * 100 \quad (1.)$$

These values were then plotted monthly starting in September and ending in April.

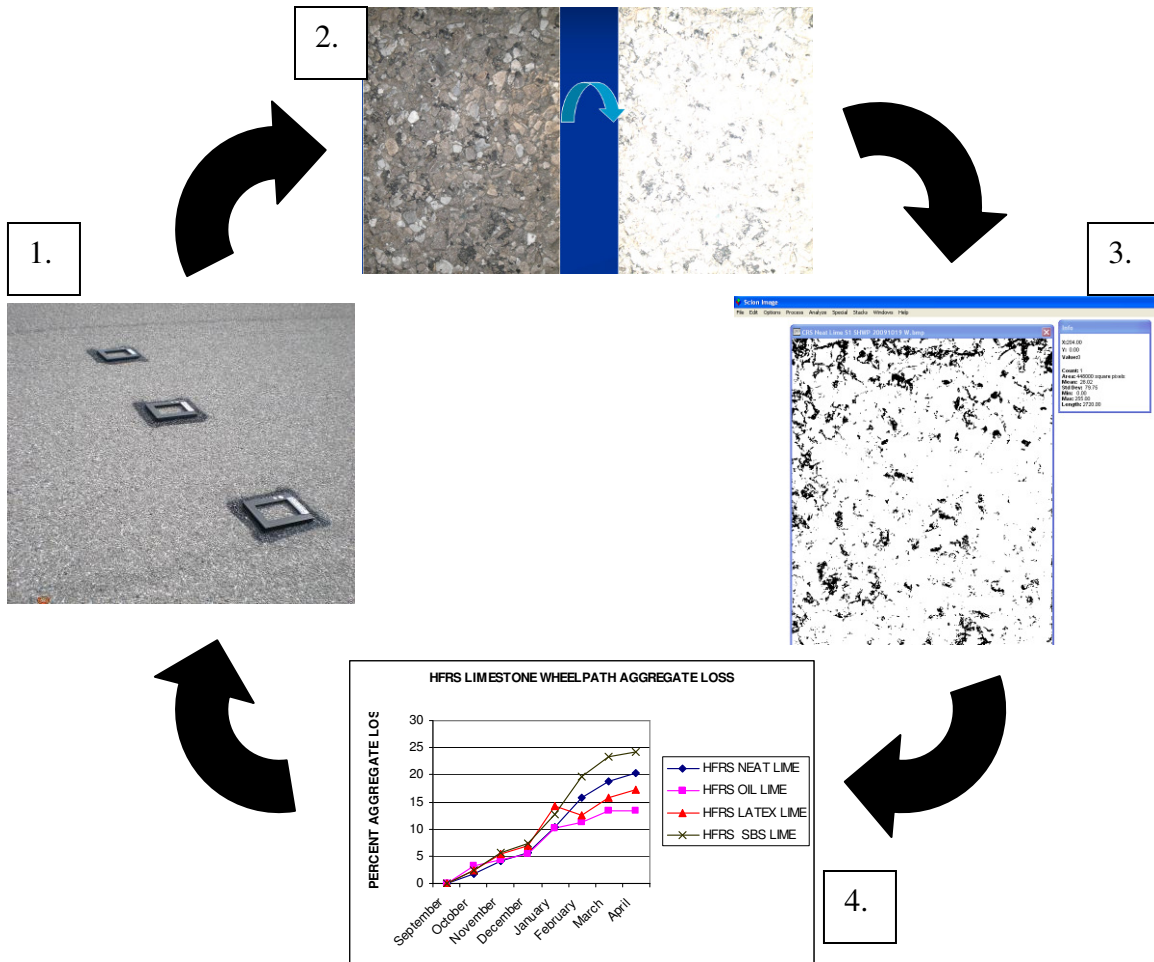


Figure 3. Field Performance Testing Methodology.

Image Analysis Issues

The process of quantifying aggregate cover and loss thereof as described in this research does have some challenges to obtain accurate and repeatable data. The first issue is the subjectivity of processing the photographs. When converting the color file into a black and white image, the operator must be very repeatable in converting areas that represent binder are depicting as binder areas in the binary file. An example of one of these challenges is shown in Figure 4.

In some areas where coarse aggregate loss had occurred, dust covers the binder and does not show as black when the color photograph is converted to a binary file. To combat this false coarse aggregate coverage, every color photograph was visually inspected and areas that show aggregate loss were manually colored black in Microsoft Paint program. These pictures were then converted to black and white images and the aggregate coverage analysis was performed.

For this study, one operator performed all of the conversion of photographs, therefore the data is considered to be repeatable and comparable. If multiple operators would have performed the processing and analysis, then issues with multi-operator repeatable may have been an issue of concern.

Another shortfall of this technique is that it cannot distinguish the difference between aggregate loss and asphalt bleeding. For this study, bleeding was not observed in the sections due to when the investigations were performed (temperatures were not high enough to induce bleeding in the sections). For other studies using a similar technique, the operator ought to be aware and determine a method to distinguish the difference between aggregate loss and bleeding.

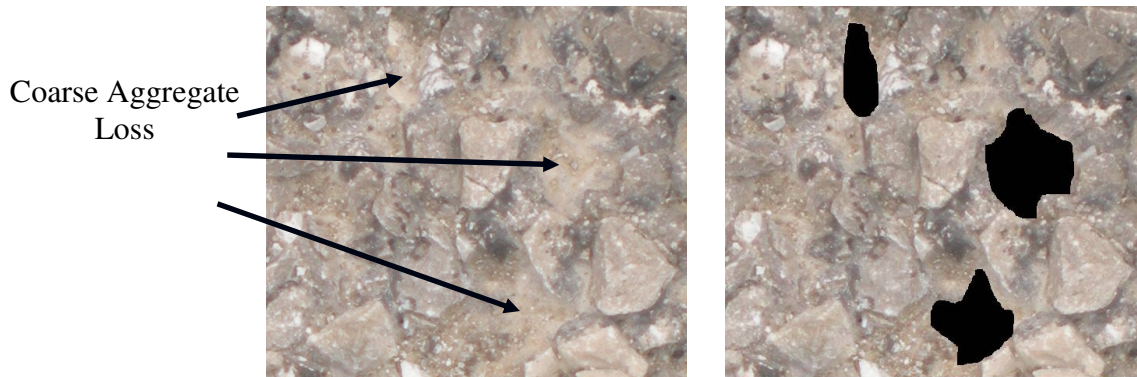


Figure 4. Accounting for Aggregate Loss Manually.

TEST RESULTS

Material Testing Results

Aggregate Testing Results

Table 1 shows the results of the aggregate testing. Both the limestone and gravel were fairly single sized, which is a particularly desirable characteristic for ideal chip seal cover aggregate. Nearly 92% of the gravel sized between the 9.5mm and 4.75mm sieve. The limestone was a little less one sized with 82% of the aggregate sized between the 9.5mm and 4.75 mm sieves. Both aggregates also had a very small amount passing the 0.075mm sieve (Limestone = 0.2%; Gravel 0.1%). It is beneficial to have cover aggregates with low dust so that adhesion occurs between the asphalt and aggregate. Other typical aggregate testing results are shown including Los Angeles Abrasion, fractured face count, flat/elongated particles and specific gravity.

Table 1. Aggregate Testing Results.

Parameter		Material	
Sieve		Newport Limestone	Moscow Gravel
Percent Passing	12.0mm	100	100
	9.5 mm	95.7	97.3
	4.75mm	13.6	5.6
	2.36mm	0.6	0.4
	1.18mm	0.3	0.3
	0.60mm	0.3	0.3
	0.30mm	0.2	0.3

	0.150mm	0.2	0.2
	0.075mm	0.2	0.1
Los Angeles Abrasion (% Loss)		31	22
Flat/ Elongated Particles	5 to 1 (%)	0	0
	3 to 1 (%)	9	2
Fractured Particles (%)		100	95
Bulk Specific Gravity		2.561	2.599

Emulsion Testing Results

Table 2 shows the typical QC emulsion testing results for all of the products evaluated in this study.

Table 2. Emulsion Testing Results.

Anionic Emulsion Test Results					
Test Method	HFRS-2	HFRS-2 w/ #2	HFRS-2L w/ #2	HFRS-2M w/ #2	
Residue By Distillation @ 500°F	69.5	69.5	-	-	
Residue By Distillation @ 350°F	-	-	68.9	67.9	
Oil Distillate	0.5	1.5	1.0	1.0	
Sieve, %	0	0	0	0	
Demulsibility, 0.02N, 35mL CaCl ₂ , %	49.2	31.8	52.3	54.9	
Viscosity, Saybolt Furol, 50°C, sec*	2103.0	3143	2101	2914	
Residue					
Float Test, 60°C, sec	1200+	1200+	1200+	1200+	
Penetration, 25°C, dmm	120	131	65	96	
Elastic Recovery, %, 10°C, cm	-	-	74	73	
Cationic Emulsion Test Results					
Test Method	CRS-2	CRS-2 #2	CRS-2L w/ #2	CRS-2M w/ #2	CRS2Mm w/ #2
Residue By Distillation @ 500°F	67.8	67.7	-	-	-
Residue By Distillation @ 350°F	-	-	68.1	69.2	68.7
Oil Distillate	0.5	1.0	1.5	1.0	0.5
Sieve, %	0	0	0	0	0
Demulsibility, 8% DSS, 35mL	100	100	85	98.8	99.1
Viscosity, Saybolt Furol, 50°C, sec*	2025	3120	2095	590	725
Residue					
Penetration, 25°C, dmm	148	153	136	112	117
Elastic Recovery, %, 10°C, cm	-	-	85	88	86

*Viscosity values were above desired levels, however these materials were placed directly after production at 175°F – 180°F. High viscosity tends to cause drilling on the seal coat. This was only observed in a few localized locations.

Aggregate Field Retention Results

Figure 5 shows the cumulative average aggregate loss for each of the anionic high float chip seal sections in the study. The results show that the best performing section was the HFRS with oil and limestone aggregates (around 13% loss through April 2010). The poorest performing anionic chip seal was the HFRS 2 Neat with gravel (around 32% loss through April 2010). Except for the neat chip seal, the HFRS 2 chip seals with gravel all performed relatively the same (all around 20% loss). The results were more varied for the anionic limestone chip seals. As previously mentioned, the HFRS 2 with oil performed best (around 13% loss) followed by the latex modified (around 16% loss), the HFRS 2 neat (20% loss) and finally the HFRS 2 modified with SBS (24% loss).

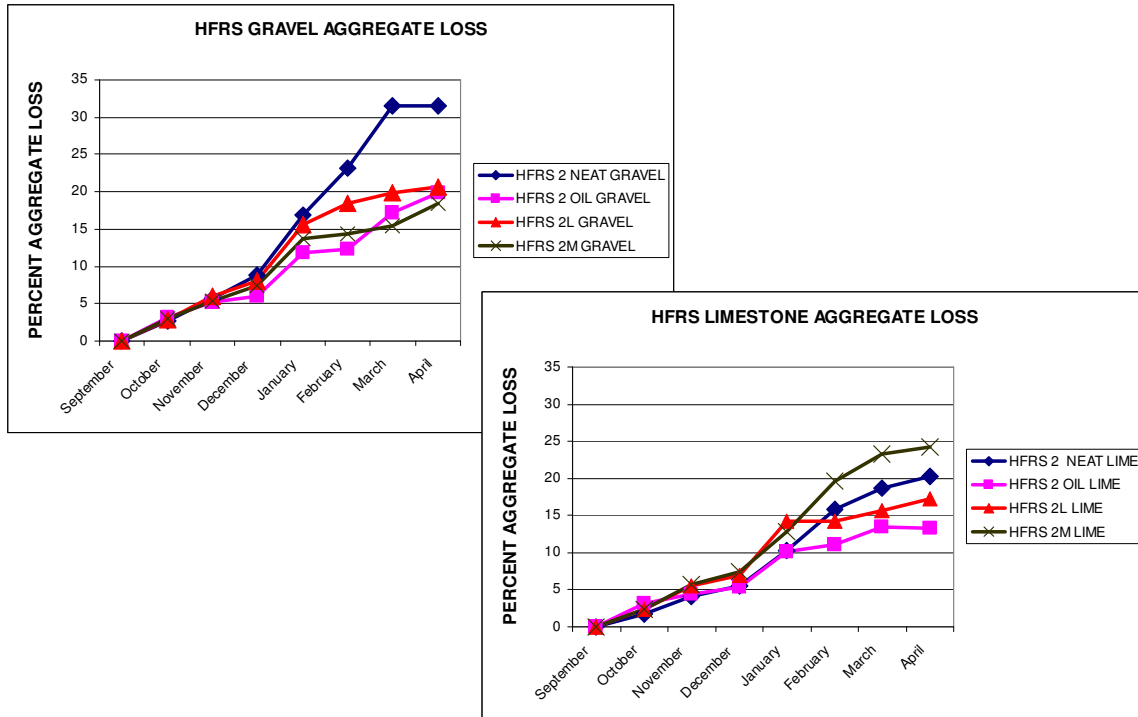


Figure 5. Anionic Chip Seal Cumulative Average Aggregate Loss.

Figure 6 shows the monthly average cumulative aggregate loss charts for the cationic emulsion chip seals. For the gravel cationic chip seals, the unmodified (neat and neat w/ #2 oil) outperformed the modified emulsion chip seals (both latex and SBS). There was nearly no difference between the neat and oil gravel sections after April (around 14% loss). There was also little difference between the latex and SBS modified gravel seals with both having around 19% aggregate loss through April.

The cationic limestone chip seals all performed relatively equal, with the latex modified section performing slightly better. The cationic latex modified limestone

overall was the best performing section with an average loss of 11%. The other four cationic limestone section all had around 15% loss by the end of the study.

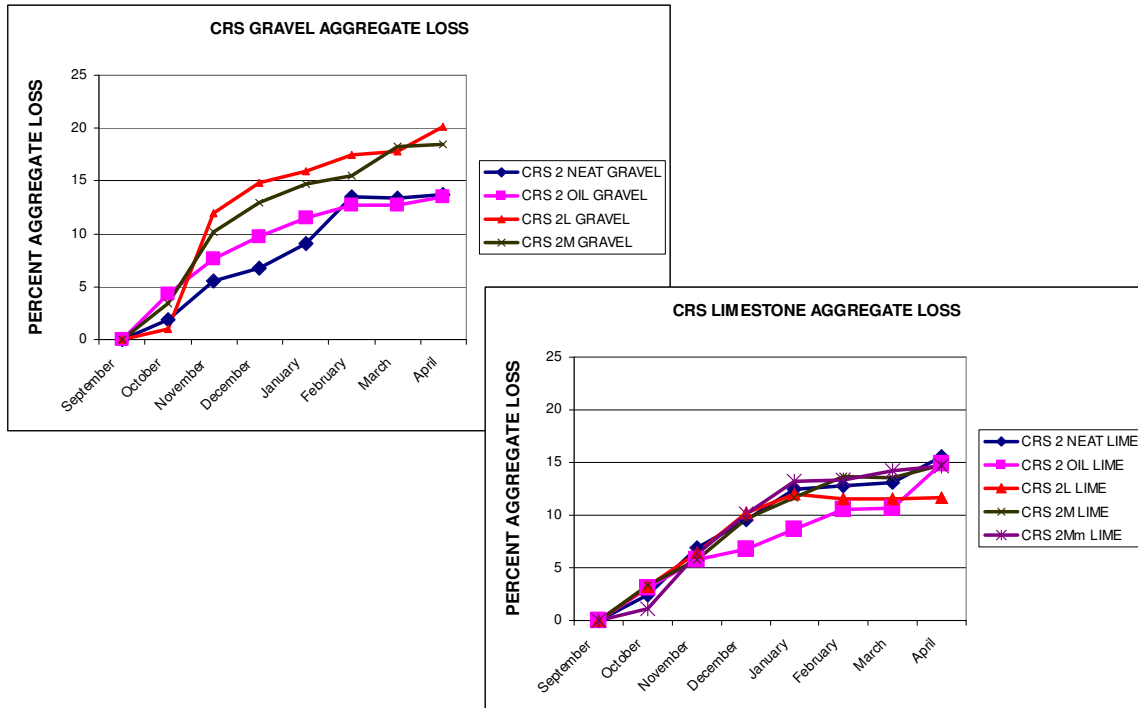


Figure 6. Cationic Chip Seal Cumulative Average Aggregate Loss.

Figure 7 shows the effect of adding 1.0% #2 fuel oil to a neat emulsion for both anionic and cationic emulsions for both limestone and gravel seals. According to the results, adding fuel oil to the anionic high float emulsions results in a significant improvement in terms of aggregate retention. Significant differences became evident after January and became more significant throughout the remainder of the study. The cationic emulsions with both limestone and gravel cover aggregate did not exhibit similar response to the anionic seals by adding fuel oil. Even though there was a slight improvement of oil versus neat in February and March, the final data points show essentially equal performance.

The performance graphs comparing latex and SBS modification are shown in Figure 8. The anionic chip seals with latex modified emulsions exhibit similar performance to those seals with SBS modification. The anionic latex modified seals (19% loss) performed slightly better than the anionic SBS modified seals (21% loss). The cationic modified emulsion all performed relatively similar. The hybrid emulsion (CRS 2Mm w/ 2% Oil) with latex and SBS performed best, however no gravel was placed with this emulsion so direct comparisons cannot be made with the others. No significant difference was observed between the SBS and latex modified emulsions throughout the study.

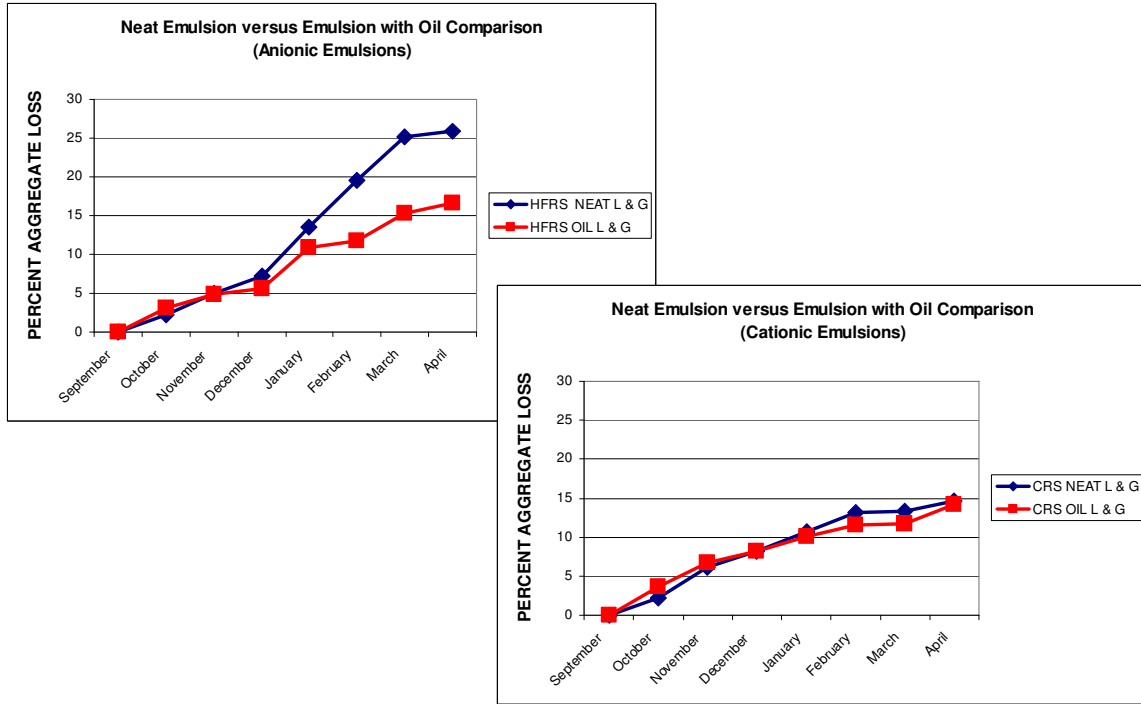


Figure 7. Neat Emulsion versus Emulsion with Oil Cumulative Average Aggregate Loss Comparison. (L & G = Limestone and Gravel)

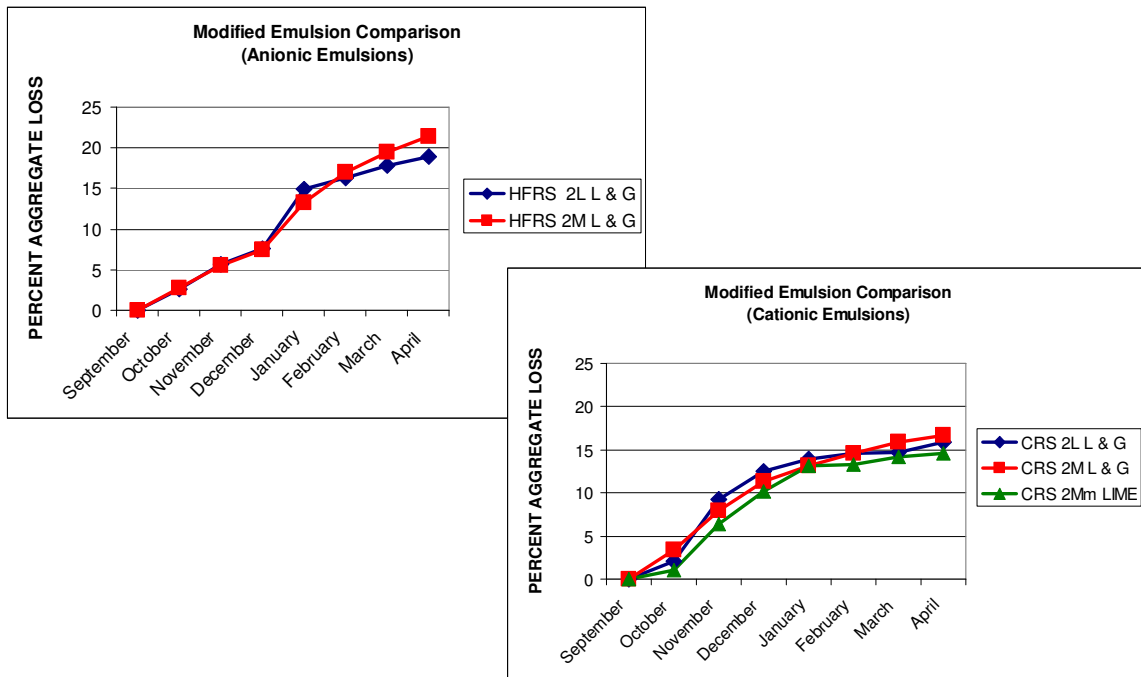


Figure 8. Latex Modified versus SBS Modified Average Aggregate Loss Comparison.

The performance of gravel and limestone chip seals is displayed in Figure 9. The data shows that for anionic emulsions, the limestone outperformed the gravel with evident differences beginning to show in January resulting in a difference of 4% in April. The cationic emulsions showed little variation in performance between limestone and gravel seals. This also shows that anionic emulsions are more sensitive to aggregate type than cationic emulsions.

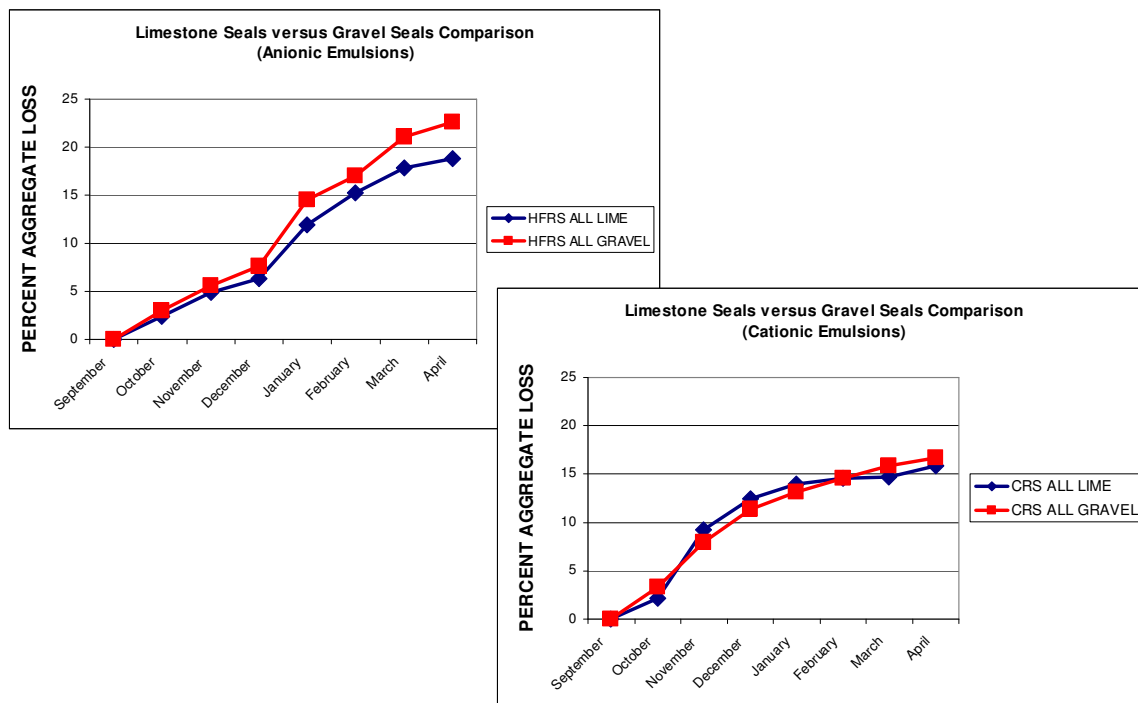


Figure 9. Limestone versus Gravel Average Aggregate Loss Comparison.

DISCUSSION OF RESULTS AND CONCLUSIONS

Based on the results of the study, the following discussion and conclusions were made:

- 1.) The effort to conduct a field chip seal study with as little variability in construction, production and climate was achieved resulting in a long term case study that adequately measured performance of chip seals by measuring aggregate coverage over time. The process of measuring aggregate coverage by use of image analysis posed challenges that were adroitly managed resulting in accurate and representative data used for comparative purposes. These efforts successfully met the objectives of the research.
- 2.) Many comparisons can be made between seals of the same emulsion charge type. Considering the difference in pavement condition and traffic between the Northbound and Southbound lanes, cationic performance and anionic performance cannot be directly compared.
- 3.) Comparisons of chip seals comprised of similar emulsion charge types can be made. The first main comparison of interest was between neat emulsions and

emulsions with 1.0% #2 fuel oil. Adding fuel oil to the anionic emulsions improved chip seal performance considerably. The anionic gravel seals were most beneficial with the inclusion of oil in the emulsion (nearly a 10% reduction in aggregate loss). The oil may have an effect on the wetting of the emulsion and aggregate creating a better adhesive bond than a neat high float emulsion. The effect of oil on the cationic emulsions showed some improvement during the course of the study, but ultimately ended with similar aggregate loss numbers.

- 4.) Performance comparison of latex modified emulsions and SBS modified emulsion showed conflicting results. For the anionic gravel sections, there was no appreciable difference between latex and SBS modified seals. The limestone anionic emulsions had better performance with latex than SBS. The cationic emulsion seals as a whole (grouping limestone and gravel) also showed little to no difference in performance between the latex, SBS and the latex/SBS hybrid emulsions. Further investigation shows that the cationic gravel latex and SBS seals performed quite similar throughout the study. The latex modified seal outperformed all other cationic limestone seals by the conclusion of the investigation. Interestingly, the latex modified limestone chip seals were both the best performing sections in both the anionic and cationic groups.
- 5.) Limestone chip seals outperformed gravel chip seals within the anionic group. Overall, the limestone seals had roughly 4% less aggregate loss than the gravel seals. Gravel's siliceous nature and the chemistry of high float emulsion may play a role in the adhering of asphalt molecules onto the aggregate. On the other hand, the cationic limestone and gravel sections compared as a group showed similar performance, leading to the conclusion that adhering capabilities of cationic emulsified asphalt to limestone and gravel are similar. It is also surprising the gravel performed similar to limestone due to its geometry. Round or semi-round particles tend to roll in traffic and loose bonding. Considering that this gravel was partially crushed (91% with one fractured face) the geometry more than likely did not play a role.

RECOMMENDATIONS and FUTURE WORK

The findings in this case study help raise more questions about the field performance of chip seals using multiple products. Further investigation of bond strength and bond dynamics would be of particular interest. Repeatability of this case study would also be interesting to see if similar performance trends would exist. Investigating the potential role of bleeding within these test sections has also been discussed.

ACKNOWLEDGMENTS

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