TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
   Evaluation of Asphalt Rubber and Reclaimed Tire Rubber in Chip Seal Applications

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   P.O. Box 94245
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5. Report No.
   FHWA/LA.17/660

6. Report Date
   April 2022

7. Performing Organization Code
   LTRC Project Number: 18-5B
   SIO Number: DOTLT1000244

8. Type of Report and Period Covered
   Final Report
   05/2018 – 12/2021

9. No. of Pages
   162

10. Supplementary Notes
    Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

11. Distribution Statement
    Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161

12. Key Words
    Chip seal; crumb rubber; asphalt emulsion; pavement maintenance

13. Abstract
Chip sealing is a commonly used pavement maintenance technique that aims to delay pavement deterioration by reducing water infiltration and restoring skid resistance. The aim of this study was to characterize the chemical, molecular, and rheological properties of different asphalt emulsions, evaluate their laboratory performance, short-term field performance, and cost-effectiveness in chip seals prepared with different application rates and aggregate blends. The effect of rubber aggregate was also evaluated as a partial replacement for light-weight aggregate (LWA). A newly introduced tire rubber modified asphalt emulsion was evaluated that allows chip seal installation at the same temperature of a standard emulsion. Types of emulsion included a newly introduced tire rubber modified asphalt emulsion (CRS-2TR), two polymer-modified emulsion (CRS-2P and CHFRS-2P), a conventional unmodified emulsion (CRS-2), and an asphalt rubber binder (AC20-5TR). Based on laboratory and field findings of this study, tire rubber modified asphalt emulsion provided promising results and is expected to provide equivalent or superior performance in the field. However,

incorporation of rubber as aggregate in chip sealing increased the loss of aggregate in laboratory testing indicating poor adhesion between the emulsion and the rubber aggregate.

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Evaluation of Asphalt Rubber and Reclaimed Tire Rubber in Chip Seal Applications

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LTRC Project No. 18-5B
SIO No. DOTLT1000244

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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April 2022

Abstract

Chip sealing is a commonly used pavement maintenance technique that aims to delay pavement deterioration by reducing water infiltration and restoring skid resistance. The aim of this study was to characterize the chemical, molecular, and rheological properties of different asphalt emulsions, evaluate their laboratory performance, short-term field performance, and cost-effectiveness in chip seals prepared with different application rates, and aggregate blends. A newly introduced tire rubber modified asphalt emulsion was evaluated that allows chip seal installation at the same temperature of a standard emulsion. Types of emulsion included a newly introduced tire rubber modified asphalt emulsion (CRS-2TR), a polymer-modified emulsion (CRS-2P), high float polymer modified emulsion (CHFRS-2P), a conventional unmodified emulsion (CRS-2), and an asphalt rubber binder (AC20-5TR). Application rates were selected based on the Louisiana Department of Transportation and Development (DOTD) specifications, the Texas Department of Transportation (TxDOT) specifications as well as from the chip seal design method recommended in NCHRP Report 680. Partial replacement of lightweight aggregate (LWA) and granite aggregate (GA) with rubber aggregate (RA) was also investigated.

The loss of aggregate was measured using two laboratory performance tests: the sweep test (ASTM D 7000) and the Pennsylvania Aggregate Retention Test (PART). Superpave Performance Grade (PG), Surface Performance Grade (SPG), and the Multiple Stress Creep Recovery (MSCR) tests were conducted to evaluate the rheological properties of the binder residues. Evaluation of the differences in functional groups, molecular weight distribution, and chemical composition of the asphalt binder residues was conducted using Fourier Transform Infrared Spectroscopy (FTIR), High-Pressure Gel Permeation Chromatography (HP-GPC), and Saturates, Aromatics, Resins and Asphaltenes (SARA) fractionation, respectively.

Based on the results of the experimental program, it was found that aggregate retention properties of polymer-modified and tire rubber emulsions were superior to the unmodified emulsion. While CHFRS-2P and AC20-5TR were the best performer in terms of aggregate loss, CRS-2P and CRS-2TR performed similarly followed by the unmodified emulsion. Results of the Bitumen Bond Strength (BBS) test showed a similar rank for the bond strength of the emulsions. It was also observed that the loss of aggregate in chip seal decreased with the increase in application rate. However,

incorporation of rubber as aggregate in chip sealing increased the loss of aggregate in the specimens indicating poor adhesion between the emulsions and the rubber aggregate. Chemical and molecular characterization test results indicated that the tire rubber modified emulsion had lower carbonyl indices and colloidal instability indices as compared to the other conventional emulsions, indicating higher resistance to aging. On the other hand, rheological test results showed that the performance of CRS-2TR was comparable to CRS-2P and was expected to perform better than CRS-2.

In the field study, seven chip seal sections were successfully constructed and were regularly monitored over an 18-month period as part of the short-term field performance evaluation. In the northbound lane, the chip seal section constructed with CRS-2TR (0.37 gsy) was the best performer statistically. In the southbound lane, the chip seal sections constructed with CRS-2TR and CRS-2P (0.31 gsy) performed similarly. Furthermore, the maximum Service Life Extension (SLE) was predicted for the CRS-2TR (0.31 gsy) chip seal sections; whereas, the chip seal sections constructed with CRS-2 was expected to exhibit the minimum SLE. In addition, the most cost-effective chip seal section was achieved by the application of CRS-2TR emulsion at the DOTD recommended emulsion application rate.

Overall, the tire rubber modified asphalt emulsion provided promising results in the laboratory and in the field experiments and is expected to provide equivalent or superior performance in chip seal applications. Based on the results of this study, incorporation of the tire rubber modified asphalt emulsion is recommended in the Louisiana specifications.

Acknowledgments

The study was financially supported by the Louisiana Transportation Research Center (LTRC). The authors would like to acknowledge the staff at LTRC for their assistance including Samuel Cooper, Corey Mayeux, and Jeremy Icenogle. The assistance of Paragon Technical Services in this research project is greatly appreciated. In addition, the assistance of Ted Flanigan of Wright Asphalt Products and Ken Free and Derek Parker of District 58 (LA) was of great benefit to the authors and is greatly appreciated.

Implementation Statement

Based on the findings of this project, incorporation of the tire rubber modified asphalt emulsion in the Louisiana specifications is recommended. The tire rubber modified asphalt emulsion provided promising results in the laboratory and in the field experiments and is expected to provide equivalent or superior performance in chip seal applications. Furthermore, the tire rubber modified asphalt emulsion is installed at the same temperature of a standard emulsion, which is typically between 60 and 71°C. Additionally, the current asphalt emulsion and aggregate application rates in the Louisiana specifications for chip sealing are adequate and should be maintained.

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Introduction

Pavement maintenance and rehabilitation activities have received increased interest in recent years as compared to the design and construction of new pavements. A growing number of agencies including the Louisiana Department of Transportation and Development (DOTD) focuses more on their preservation programs as these timely maintenance activities arrest initial deteriorations, reduce the deterioration rate, and defer costly rehabilitation activities [1]. Historically, thin overlays and resurfacing have been the most common preventive maintenance activities, which are applied to pavements exhibiting age-related distresses [2] [3]. Chip seals are also widely used as preventive maintenance treatments due to their low initial costs and convenient construction process when the structural capacity of the existing pavement is adequate to support future traffic loads [4] [5]. Chip seal is popular in the United States as its cost is approximately one-fifth of the cost of a regular Asphalt Concrete (AC) overlay.

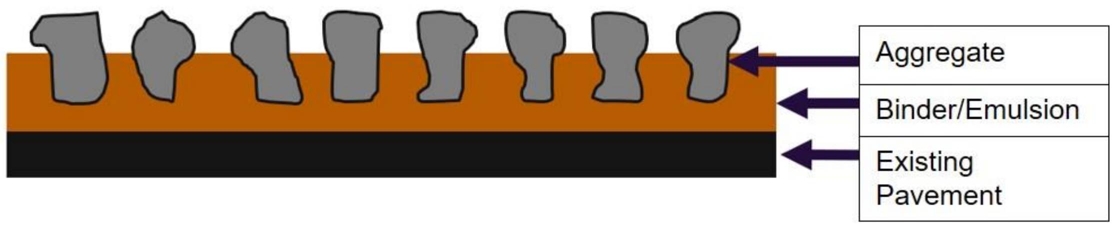
Chip sealing, also referred to as Asphalt Surface Treatment (AST) in Louisiana, is carried out by spraying asphalt emulsion or hot bitumen on the existing roadway surface, followed by the application of a layer of crushed aggregate [6] [7]. Chip seals are typically favored on relatively low traffic roadways with the aim to reduce the permeability of the pavement surface, improve skid resistance, eliminate raveling, and retard oxidation [2]. Bleeding and early loss of aggregate are the most commonly observed distresses associated with chip seal [4] [8]. High surface roughness and increased traffic noise are also functional limitations of this treatment method.

Highway agencies in a number of states including California, Florida, and Arizona have adopted the hot application of asphalt rubber in chip sealing [9]. Incorporation of crumb rubber in asphalt cement was observed to be effective in improving its performance. The crumb rubber absorption has been reported to improve the rheological and physical properties of asphalt rubber and showed improved resistance against reflective cracking, permanent deformation, and increased durability [10] [11] [12]. However, the application temperature requirement of hot applied asphalt rubber binder is high (160-170°C), which is an issue for the workers' safety in several states including Louisiana and Mississippi. Hence, the use of a newly introduced tire rubber modified asphalt emulsion may be considered as a promising alternative given its installment at a temperature that is similar to that of a standard emulsion, ranging between 60 and 70°C. The use of crumb rubber as part of the aggregate layer can also improve the treatment durability and reduce traffic noise. However, these benefits have not been validated in the literature especially for the operating conditions pertinent to hot and wet climate.

Literature Review

Chip sealing, a type of AST, is applied to provide a new wearing surface and is typically applied on low volume roadways. The aim of chip sealing is to reduce water intrusion, retard oxidation, eliminate raveling, improve skid resistance, and thus, defer the need for costly rehabilitation activities [13] [14] [15]. The asphalt binder is used to provide adequate bonding between the aggregate and the existing pavement surface and to produce a waterproof seal [16]. The aggregate in chip sealing is used to provide good skid resistance for the vehicles [8]. The number of chip seal layers applied on roadways varies to account for specific distress modes or traffic volume conditions [17].

Figure 1. Single chip seal application



Several factors such as the increased need of maintenance, and low-cost application of chip sealing have contributed to the popularity of chip seals in the US [18]. Currently, more than 100,000 miles of roadways in the US has been treated with chip seal [19]. The cost of chip seal is two to five times lower compared to that of a conventional thin asphalt overlay [20]. The application of chip sealing was found successful due to its good skid resistance and lower waiting period to open to traffic [21]. In the US, chip sealing is not typically favored on high traffic volume roads because of possible vehicle damage due to flying aggregate chips, high traffic noise, high roughness, and relatively shorter life expectancy [22]. However, it was reported that chip seal may be considered for roads with high traffic volumes when rutting is not a concern [20].

Types of Chip Seal

Several types of chip sealing are available to account for different pavement conditions. The different types of chip seal are based on their design methodologies, construction process, number of courses applied, aggregate size, and the type of binder used [8]. They include the types discussed in the sections below.

Single Layer Chip Seal

A very common type of chip sealing, which involves applying a single layer of aggregate over sprayed asphalt binder. These seals are used for flexible pavements where the pavement does not require any special consideration [23]. Single chip seals are useful to address raveling and minor cracks [17].

Double or Multiple Layer Chip Seal

Double chip seal is used in areas where the traffic volume and stress are relatively higher. It provides less traffic noise, better waterproofing, smoother surface, and better resistance to snowplow damage compared to single chip sealing [24] [25]. The construction process of double chip seal is similar to that of the single chip seal except that two separate single chip seals are applied; one on top of the other where the aggregate size of the top layer is half the size of the bottom layer. The first layer is cured before the application of the second layer. The thickness of the surface layer is determined by the aggregate size of the first layer [26].

Inverted Seal

Inverted seals are a special type of double chip seal where the larger sized aggregate is placed over the smaller sized aggregate. Bleeding due to low and high traffic levels and the variation in transverse surface texture can be corrected by applying an inverted seal.

Racked-In Seal

Racked-in seal is a special type of chip seal, which involves applying choke stone over a single course chip seal to prevent aggregate loss. The choke stone provides improved interlock between the aggregate, and therefore, reduces the chance of aggregate dislodging before the water breaks out from the emulsion. Racked-in seal is used in areas that experience a large amount of stopping and turning movements [23].

Cape Seal

Cape seal is a surface treatment, which is a combination of a conventional chip seal and a slurry seal. The benefits of using slurry cover over the chip seal is that it reduces traffic noise and eliminates the problem with loose aggregate, which makes it very suitable for high-traffic volume roads. Cape seal provides good shear resistance and achieves a dense and waterproof pavement surface [27]. Cape seal originated in South Africa where a larger sized aggregate (up to ¾ in.) was used; however, North American countries elected to use smaller-sized aggregate in cape sealing.

Geotextile-Reinforced Seal

This type of chip seal is effective in case of extremely oxidized or thermally cracked surfaces where the cost for rehabilitation or reconstruction is high. A tack coat is applied over the cracked surface, followed by a geotextile and then a single chip seal is placed on the surface. Geotextile-reinforced seal acts as a stress-absorbing membrane interlayer (SAMI) system and provides improved resistance against reflective cracking.

Sandwich Seal

A type of chip sealing where the asphalt emulsion is sprayed once over a 9.5 mm or 4.75 mm one-sized aggregate followed by the application of a 2.36 mm to 4.75 mm one-sized aggregate. Compared to conventional chip seal, the emulsion application rate in sandwich sealing is 1.2 to 1.5 times higher. Sandwich sealing is used in raveled surfaces to reestablish its surface texture.

Asphalt Rubber Chip Seal

Asphalt rubber chip seal, also known as stress absorbing membrane (SAM), is a type of single chip seal in which the asphalt emulsion is replaced with a crumb rubber-modified asphalt binder, i.e., an asphalt rubber, to achieve improved adhesion. The aggregate layer is usually pre-coated and hot applied in the construction of an asphalt rubber chip seal [17]. In addition, the binder application rate is higher compared to that of a conventional chip sealing. Asphalt rubber chip sealing had shown enhanced performance in mitigating reflective cracking, reducing aggregate loss, and traffic noise.

Stress-Absorbing Membrane Interlayer (SAMI)

It involves the application of an asphalt rubber chip sealing followed by the application of an AC overlay. SAMI is used to reduce the rate of reflective cracking in an AC overlay constructed of a cracked or jointed concrete pavement.

Components of Chip Seal

Asphalt Binders

Factors such as climate conditions, traffic level, pavement surface temperature, and aggregate compatibility govern the selection of an asphalt binder in chip sealing [28] [29]. An asphalt binder or emulsion are selected to achieve good adhesion properties in order to maintain the aggregate attached to the pavement surface. Chip seal binders are also required to have enough fluidity so that it may be sprayed uniformly to cover the pavement surface; in addition, it should be viscous enough to maintain a uniform layer, and it should not cause any bleeding or stripping under changing climatic conditions and traffic levels [30].

Although the majority of chip seal projects in the U.S. were constructed using an unmodified asphalt emulsion or asphalt cement in the past, modified asphalt binders such as asphalt rubber binder, polymer-modified binder, and high float emulsion have been increasingly used by state agencies in recent years [31]. An asphalt emulsion is produced using an emulsifying agent, which disperses the asphalt as droplets in water. The emulsifying agent used in asphalt emulsion imparts electrical charges to asphalt elements, which may be positive or negative charges based on the type of emulsifying agent used.

Compared to asphalt emulsion, an asphalt cement requires more rolling energy, higher application temperatures, and shows higher sensitivity to the moisture in the aggregate [8]. Asphalt cements such as AC 10, AC 20, AC 15-P, and AC 15-5TR are typically used in hot applied chip seals. However, asphalt emulsions have many advantages such as early aggregate retention, low application temperature, low application cost, and safer environment for the field personnel [16]. The breaking time of emulsion is defined by the time it takes for the water to evaporate leaving only the asphalt cement holding the aggregate. The aggregate layer is applied over the sprayed emulsion before it starts to break [18]. Factors that influence the breaking time of emulsion include aggregate type, cleanliness of aggregate, composition of the emulsion, moisture content of the aggregate, compatibility of aggregate and emulsion charges, and the temperature during the construction of chip sealing [32]. Aggregate with higher absorption rate tend to have shorter breaking time. However, aggregate should not be pre-coated when an asphalt emulsion is used in the construction of chip sealing since it may prevent absorption and bonding of the aggregate with the emulsion.

Researchers have reported that cationic emulsions are less sensitive to climatic conditions, less susceptible to stripping, provide better performance than anionic emulsions, and have greater compatibility with the aggregate [33]. Cationic emulsions can break faster and set more quickly than anionic emulsions in humid conditions, whereas anionic emulsions take more time to cure and tend to work well in low humidity or dry weather conditions [19]. It has also been reported that a binder with the same charge as the aggregate does not achieve adequate bond with the aggregate and can be more susceptible to raveling.

Lee and Kim reported that polymer-modified asphalt emulsions are less vulnerable to temperature, provide quicker application to the existing pavement surface, prevent early aggregate loss, and increase durability [34]. CRS-2P (a polymer-modified emulsion) is a commonly used emulsion in chip seal applications [35]. Polymer modified emulsions are usually applied at a rate ranging from 0.25 to 0.40 gsy [7] [17]. DOTD commonly uses CRS-2P in the construction of chip sealing. Table 1 and Table 2 lists the binder requirements for chip seals as per the Louisiana Standard Specifications for Roads and Bridges section 507 for cold and hot applications, respectively [7].

Table 1. DOTD binder requirements for chip seal (cold application) [7]

	Course No.	**Asphalt Surface Treatment (AST)**				
		TYPE A	**TYPE B**	**TYPE C**	**TYPE D**	**TYPE E (Int. layer)**
Aggregate		Lightweight, Crushed Stone	Lightweight, Crushed Stone	Lightweight, Crushed Stone	Lightweight, Crushed Stone, Crushed Gravel	Crushed Stone, Crushed Gravel

	Course No.	Asphalt Surface Treatment (AST)								
		TYPE A		**TYPE B**		**TYPE C**	**TYPE D**			**TYPE E (Int. layer)**
Aggregate Friction Rating		I, II		I, II, III		I, II, III	I, II, III, IV			I, II, III, IV
Asphalt Emulsion		CRS-2P		CRS-2P		CRS-2P	CRS-2P			CRS-2P
Application Temp. Minimum Maximum		160°F 175°F		160°F 175°F		160°F 175°F	160°F 175°F			160°F 175°F
Number of Applications		2	1	2	1	1	3	2	1	2
Asphalt Emulsion Application Rates Per Course	1 2 3	0.39 0.29 —	0.41 — —	0.39 0.29 —	0.31 — —	0.41 — —	0.46 0.36 0.26	0.39 0.29 —	0.31 — —	0.39 0.29 —
Aggregate size and Application Rates Per Course	1 2 3	S2-0.0111 S3-0.0075 —	S2-0.0111 — —	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 — —	S1-0.0200 S2-0.0111 S3-0.0075	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 S3-0.0075 —

Table 2. DOTD binder requirements for chip seal (hot application) [7]

	Course No.	Asphalt Surface Treatment (AST)								
		TYPE A		**TYPE B**		**TYPE C**	**TYPE D**			**TYPE E (Int. layer)**
Aggregate		Lightweight, Crushed Stone		Lightweight, Crushed Stone		Lightweight, Crushed Stone	Lightweight, Crushed Stone, Crushed Gravel			Crushed Stone, Crushed Gravel
Aggregate Friction Rating		I, II		I, II, III		I, II, III	I, II, III, IV			I, II, III, IV
Asphalt Cement		PAC-15		PAC-15		PAC-15	PAC-15			PAC-15
Application Temp. Minimum Maximum		300°F 360°F		300°F 360°F		300°F 360°F	300°F 360°F			300°F 360°F
Number of Applications		2	1	2	1	1	3	2	1	2
Asphalt Cement Application Rates Per Course	1 2 3	0.30 0.23 —	0.31 — —	0.30 0.23 —	0.24 — —	0.31 — —	0.36 0.28 0.20	0.30 0.23 —	0.24 — —	0.30 0.23 —
Aggregate size and Application Rates Per Course	1 2 3	S2-0.0111 S3-0.0075 —	S2-0.0111 — —	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 — —	S1-0.0200 S2-0.0111 S3-0.0075	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 S3-0.0075 —

Another type of binder commonly used in chip seal is asphalt rubber binder, which is obtained by the blending of asphalt and crumb rubber, which acts as an elastomer in the blend. Asphalt rubber has been successfully used as a stress-absorbing membrane (SAM) in surface treatments [36]. It is applied at high temperature and requires hot pre-coated aggregate. State agencies including Arizona, California, and Texas commonly use asphalt rubber in surface treatments and in structural and non-structural overlays [36]

[37]. It has been reported that asphalt rubber reduces reflective cracking and traffic noise, and prevent aggregate loss [24].

Aggregate

The type and quality of the aggregate ensure the successful application of chip sealing. The type of chip seal, binder grade, and construction procedures in a chip seal project depend on the aggregate selected. The charge of the aggregate should be compatible with that of the emulsion to be applied to ensure adequate bonding after the application of chip seal [8] [17]. The selection of the type aggregate for chip sealing depends upon various factors including the existing pavement conditions, traffic volume, climatic conditions, cost, and the availability of the aggregate [17]. According to the California Department of Transportation (Caltrans), the aggregate selected for chip sealing should be clean and dust free, one-sized, cubical shaped, compatible with the selected binder type, and must be dry when used with hot binders and damp when used with emulsion.

The gradation of the aggregate should be selected as part of the design process in order to achieve good performance [38]. Typically, one-sized aggregate is the most desirable and the ideal type of aggregate for the construction of chip seal [25]. Uniformly-graded aggregate has been reported to yield improved performance in terms of aggregate retention, surface friction, and drainage capabilities of chip seal as it achieves a consistent aggregate embedment [33]. Lee and Kim introduced a performance uniformity coefficient (PUC) to estimate the allowable limit for particle size in order to achieve adequate resistance against bleeding and aggregate loss [34]. The PUC is calculated as follows:

$$\mathrm{PUC} = \mathrm{P_{EM}} \,/\, \mathrm{P_{2EM}} \qquad (1)$$

Where, P_{EM} = percent passing at a given embedment depth in a sieve analysis curve, which indicates bleeding potential of chip seal, and P_{2EM} = percent passing of the aggregate at twice the embedment depth in a sieve analysis curve, which represents the raveling potential of chip seal.

As the PUC value approaches zero, the aggregate becomes more uniformly graded. It is important to use a uniformly-graded aggregate to ensure that each aggregate is contributing to the chip seal performance. The application of well-graded aggregate in chip seal may save in cost; however, it may result in poor aggregate retention and a shorter service life. A coefficient of uniformity (C_u) value less than 4.0 is recommended by NCHRP for uniformly graded aggregate [38]. According to DOTD, chip seal projects should comply with the aggregate gradation presented in Table 3.

Table 3. Aggregate gradation for chip seal projects [7]

Sieve		Size 1		Size 1A	Size 2	Size 3
U. S.	Metric	Slag or Stone Aggregate (Size No. 5)	Crushed Gravel or Lightweight Aggregate	Slag or Stone Aggregate	All Aggregate	All Aggregate
1 1/2 inch	37.5 mm	100	100	100	—	—
1 inch	25.0 mm	90-100	95-100	100	—	—
3/4 inch	19.0 mm	20-55	60-90	85-100	100	—
1/2 inch	12.5 mm	0-10	—	25-40	95-100	100
3/8 inch	9.5 mm	0-5	0-15	5-15	60- 80	95-100
No. 4	4.75 mm	—	0-5	—	0-5	20-50
No. 8	2.36 mm	—	—	—	0-2	0-2
No. 200	75 µm	0-1	0-1	0-1	—	—

The binder application rate varies with the size of the aggregate. It was reported that using large-sized aggregate increases the thickness of the binder layer, which in turn enhances the performance of chip seal. Although the use of large-sized aggregate increases durability and lessens the sensitivity to small variations in binder application rate compared to smaller aggregate, it may cause insufficient aggregate embedment, which would increase traffic noise due to tire-pavement interaction and vehicle damage due to aggregate dislodgment from the pavement [25]. Chip seal with small-sized aggregate is susceptible to bleeding [34]. Aggregate size is selected based on traffic volume, surface conditions, and the type of chip sealing. Most agencies use 3/8 in. (10 mm) sized aggregate in single-layer chip seal and ½ in. (12.5 mm) aggregate are used in the application of double-layered chip seal. Dusty aggregate surface has been reported to prevent the binder from bonding with the aggregate and causes aggregate dislodgment from the chip sealing when opened for traffic [7]. The percentage of fine materials that passes through the No. 200 sieve is defined as dust. NCHRP recommends that the percentage of dust content should be 1% or less; however, many state agencies allow a maximum of 2% dust content.

The angularity of the aggregate determines the aggregate shape and the degree of interlocking achieved in chip seal. Angular particles possess greater interlocking and offer more resistance to aggregate dislodgment. The higher the angularity, the more the level of interlock because since there are many available contact points. The resistance to dislodgement of particles, vehicle damage, and flushing increase with the level of interlocking of the chip seal aggregate [38].

Cubical-shaped aggregate is desirable in the application of chip sealing and other types of surface treatments as they are more stable, have good interlocking, provide better long-term retention, and retain orientation under heavy traffic [39]. Cubical aggregate also reduces the potential of bleeding in chip seals. Round aggregate has low percent-fracture and are more susceptible to rolling and displacement by traffic compared to angular aggregate. In the case of high traffic volume road, a greater percentage of mechanically-fractured particles are required. Australian chip sealing projects require 75% of the aggregate to have at least two fractured faces [24].

Flakiness index test is used to determine the amount of flat aggregate [16]. A high flakiness index indicates a flaky or elongated shape whereas a lower flakiness index indicates a cubical shape. Aggregate with high flakiness index change their orientation on the flat side and increases the aggregate embedment under heavy traffic, which results in flushing or bleeding along the wheel paths [38].

The aggregate used in the construction of chip seal should be able to resist abrasion, degradation, and polishing such that the chip seal remains functional throughout its service life. The aggregate particles may cause windshield damage and bleeding if they become dislodged as a result of continuous traffic [16]. Historically, the most popular measure of abrasion resistance is the Los Angeles Abrasion test (AASHTO T 96, ASTM C131). However, another test known as the Micro-Deval test (AASHTO T 327) has been recently introduced to measure the abrasion resistance property of the aggregate. In a study conducted by Shuler et al., it was suggested that the Los Angeles Abrasion test should not be considered an appropriate measure of toughness for lightweight aggregate [40]. The percentage of abrasion loss depends on the traffic level. Several state agencies have developed their abrasion specifications as shown in Table 4.

It is also important for the aggregate in chip sealing to be able to resist polishing, which is commonly measured by the British Wheel test (AASHTO T279, ASTM D3319). Polishing of aggregate due to traffic leads to reduced friction and skid resistance in chip seal. The test results predict the polishing of aggregate in term of the polished stone value. Utah DOT recommends a limit of 31, whereas in Australia, a polished stone value in the range of 44 to 48 is recommended [24].

Freeze-thaw degradation and resistance to weathering is usually measured by the magnesium sulfate loss (AASHTO T104). Sodium sulfate loss (ASTM C88) is also used to determine the freeze-thaw degradation and resistance to weathering. While they are not common performance criteria for chip-seal aggregate, a limit of 10% loss is considered appropriate [38].

The absorption of binder into the cover aggregate should also be considered in the selection of chip seal aggregate. Gravel is a less absorptive aggregate compared to limestone and lightweight aggregate. The adhesion between the binder and the aggregate increases when an aggregate with high absorption capacity is used. Extra precautions are recommended for an aggregate source, which shows a lower affinity for asphalt with respect to cleanliness and dryness of the aggregate [16].

The type of aggregate and their cost-effectiveness are also important factors in the selection of aggregate for chip seal. State agencies are expected to select the aggregate source based on availability and cost effectiveness. Limestone, granite, and natural gravels are widely used in North America. Using lightweight synthetic aggregate in chip seal may provide a superior skid resistance ability and reduce windshield vehicular damage. However, the availability and cost-effectiveness of lightweight aggregate should be considered before selecting.

Table 4. Los Angeles abrasion and Micro-Deval loss requirements for different traffic conditions [38]

Traffic Volume (veh/day/lane)	Loss Angeles Abrasion Loss (% max)	Micro-Deval Loss (% max)
<500	40	15
500-1500	35	13
>1500	30	12

Overview of Asphalt Emulsion

Low viscosity of asphalt emulsion allows it to be used at low temperature, reduces total energy consumption and emissions, minimizes cost, and makes it more environmentally-friendly and less hazardous compared to hot applied asphalt binder. The application of emulsion reduces the energy consumption by half compared to hot-mix asphalt (HMA) and when used in chip seal, it was found to be more environmentally-friendly than thin

AC overlay [41] [42]. The primary components of an emulsion include asphalt cement (40-75% in concentration and 0.1-20 micron in droplets diameter), emulsifier (0.1-2.5%), and water (25-60%) [43]. The viscosity of the emulsion depends on the percentage of asphalt cement; the higher the percentage of asphalt cement, the higher is the viscosity [44]. The emulsions can be of three types; O/W (oil-in-water), W/O (water-in-oil), or W/O/W (water-in-oil-in-water), which contains smaller water droplets within them. However, asphalt emulsions are typically O/W type of emulsions; asphalt droplets are dispersed in an aqueous phase to produce the emulsion [45].

Importance of Particle Size

Viscosity, storage stability, and the performance of the emulsion are greatly affected by the size of the particles and their distribution in the continuous phase. Low emulsion viscosity is observed in case of large particle size and wide-ranged distribution, whereas improved performance is observed in case of smaller particle sizes [46] [47]. Smaller particles are more shear-resistant due to the Brownian or osmotic pressure effect and decreased deformity. The surface area of the particles varies with their sizes, and is greatly affected by the flocculation system in the emulsion and thus affects its viscosity. The role of particle size in the phase separation or sedimentation of the emulsion can be expressed by the following equation [48]:

$$\vartheta_0 = \frac{2r^2(\Delta\rho)}{9n} \qquad (2)$$

Where, ϑ_0 = rate of sedimentation of a single asphalt droplet, r = droplet radius, $\Delta\rho$ = difference between the density of external and internal phases; and n = shear viscosity.

The milling shear rate, milling time, percentage of asphalt cement, and nature of the emulsion mainly control the particle size [49] [50]. Smaller particles are produced by high shear rate, which requires a large amount of energy and due to large surface area, smaller particles flocculate and coagulate faster, which increases the surface energy. The free energy of the emulsion formation is given by the following equation:

$$\Delta G_{formation} = \Delta A \gamma_{tension} - T\Delta S \qquad (3)$$

Where, ΔA = change in area when asphalt droplet in emulsion breaks up, $\gamma_{tension}$ = interfacial tension amongst water and asphalt, and $T\Delta S$ = entropy growth.

Emulsions become unstable when the total free energy ($\Delta G_{formation}$) is positive due to higher surface area of the droplets, which increases the $\Delta A\gamma_{tension}$ value more than $T\Delta S$. As smaller particles have higher surface area, the lack of emulsifiers may lead to coagulation. The emulsifier stabilizes the emulsion by reducing the surface energy of the particles and $\Delta G_{formation}$.

Emulsion Stability

The presence of water within the asphalt droplets has strong influence over the viscosity of the emulsion during storage [51]. Emulsion properties are greatly influenced by the type of emulsifier or surfactants used for stabilization. As stated earlier, emulsifiers or surfactants reduce the surface free energy during the emulsification process and allows the asphalt droplets to be in suspension by creating an energy barrier between the droplets and water and therefore, increases emulsion stability by preventing coagulation. The double diffused layers created from the absorption of emulsifiers on the surface of asphalt particles repel each other due to the same surface charge [52] [53]. The concentration of electrolytes and salts present in the continuous phase of an emulsion also affects the stability of the emulsion; lower concentration of electrolytes and salts offer higher stability, whereas the stability of emulsion may be negatively impacted if the concentration of salts rises above 1% by weight [45] [52].

The pH of the soap plays an important role in terms of the stability of emulsions. Zeta potential measures the sign and charge of the asphalt droplets and is greatly dependent on the pH; rising of pH leads the charge of the asphalt droplets towards negative and decreases the zeta potential value [44] [54]. In contrast, the emulsions stability increases with the increase in zeta potential value [44] [54].

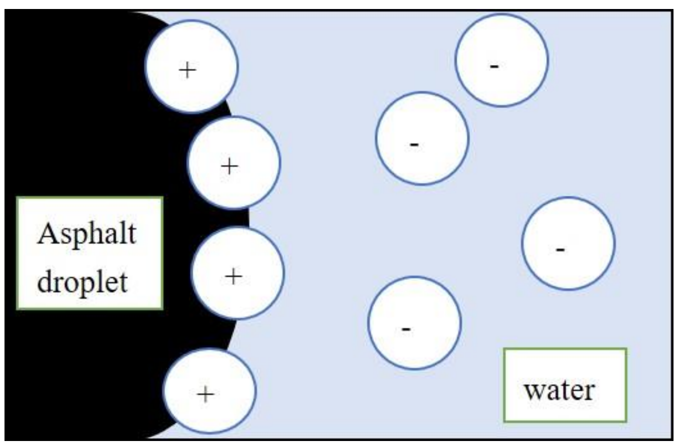
Rheology and emulsion stability are related to each other and the changes in rheology over time can be used to measure the stability of the emulsion. Several researchers have studied the effects of rheology on the stability of the emulsion [55] [56]. Zhai et al. evaluated the phase changes in asphalt emulsion by observing the changes in complex loss and storage modulus and found that the rheological properties vary with the interaction type (i.e., cationic, anionic, or electrostatic) in asphalt emulsion [55]. Legrand et al. studied the changes in viscosity of the emulsion under a constant shear rate in the presence of silica particles. The viscosity was observed to increase rapidly from its constant state in the presence of silica particles and constant shear rate. The authors also identified the factors that influence this rapid increase, which include the size and concentration of the silica particles, size of the asphalt droplets, and the rate of shear [56].

Emulsion breakdown mechanisms including creaming and sedimentation, flocculation, coalescence, Ostwald ripening, and phase inversion also affect the storage stability [50]. Flocculation is a faster process while coalescence is slower. The viscosity of asphalt and temperature at the time of application control the rate of coalescence; faster coalescence is observed in low viscosity asphalt [57]. Skin formation can occur due to early occurrence of coalescence [58] [59].

Significance of Emulsifiers

Emulsions can be cationic or anionic depending on the charge of surface-active agents (emulsifiers), their concentration, and the charge of the asphalt itself. As shown in Figure 2, the emulsifier positions itself at the water and asphalt interface, while the counterions impart negative charges into water leading the asphalt droplets to be positively charged.

Figure 2. Sources of charge on emulsion [43]



Emulsifiers have a hydrophilic (water-loving) “head group,” which is either positively or negatively charged when linked with water and controls the charge of the asphalt droplets and a nonpolar lipophilic (oil-loving) “tail group” derived from wood resin, lignin, or natural fats, which is neutral. Table 5 presents the head group of the most common emulsifiers and their charge.

Table 5. Asphalt emulsifier's head group and their charge [43]

Oil Loving portion	Water-loving "head" group	Counterion	Charge of the water-loving "Head" group, pH2	Charge of the water-loving "Head" group, pH11
Tallowalkyl-	$[-NH_2CH_2CH_2CH_2NH_3]2+$	2 Cl–	Positive	Neutral
Nonylphenyl-	$[–O(CH_2CH_2O)100H$	None	Neutral	Nonionic
Tall oil-	[–COO]-	Na+	Neutral	Negative
Tallowalkyl-	$[–N (CH_3)3]+$	Cl–	Positive	Positive
Alkylbenzene	$[–SO_3]-$	Na+	Negative	Negative

Breaking of Emulsions

In order to act as a binding material, emulsified asphalt needs to break by the flocculation and coalescence processes. The rate at which the emulsion "breaks" by separating from water, leaving only the asphalt cement holding the aggregate is defined as the "breaking" time [16]. The speed of curing or breaking process depends on the chemical compensation and emulsifier used, reaction of the emulsion with aggregate, and several other environmental factors such as temperature, wind speed, and humidity at the time of application [8]. The aggregate must be applied over the sprayed emulsion before the water breaks out [18]. Aggregate with higher absorption rate tends to have faster breaking time [16]. When an aggregate is applied over the sprayed emulsion, its surface turns into somewhat lipophilic by absorbing some of the oppositely charged free emulsifiers present in the emulsion. Then, flocculation of the emulsion and coalescence processes start due to neutralization of the acids by the minerals and loss of charge on the asphalt droplets. Finally, absorption and evaporation of water lead asphalt film to spread over the aggregate surface. However, aggregate should never be pre-coated when used with asphalt emulsion because it can prevent absorption and bonding of the aggregate with the emulsion after breaking of water [16]. Emulsions having the same charge as the aggregate will not have a solid bond with the aggregate and may lead to raveling and aggregate loss [8].

Type of Emulsions

Asphalt emulsions as specified in ASTM D977 and ASTM D2397 are classified according to the charge on the asphalt droplets and their reactivity. Emulsions with positive charges are denoted by C (cationic) and based on their setting behavior they are denoted by CRS (cationic rapid setting), CMS (cationic medium setting), and CSS (cationic slow setting). Anionic emulsions with rapid setting, medium setting, and slow setting behavior are denoted as RS, MS, and SS, respectively. They can be further classified based on their viscosity and residue properties such as SS-1H, where number "1" indicates low viscosity and "H" indicates hard residue. Similarly, CRS-2, where number "2" indicates high viscosity. Cationic emulsions can break faster and set more quickly in humid conditions, show less susceptibility to stripping, show better performance, and are more compatible with the aggregate, whereas anionic emulsions take more time to cure and tend to work well in low humidity or dry weather conditions [16] [33] [38]. Additionally, letters and terms such QS (quick setting), CQS (cationic quick setting), LM (latex modified), P (polymer modified), S (high solvent content), ERA (recycling agent emulsion), AEM (asphalt emulsion prime), and PEP (penetrating emulsion prime) are commonly used to indicate other types of emulsions that are available in the market.

Modified Emulsions

Depending on the requirement of the project, asphalt emulsions can be modified with adhesive agents, polymers, and solvents [8]. Studies show that chip seals constructed with polymer-modified emulsions such as CRS-2P show less vulnerability to temperature. In addition, polymer-modified emulsions minimize bleeding, provide improved and faster adhesion to the existing pavement surface, prevent early aggregate loss, and enhance its overall performance [34].

Im and Kim evaluated the curing and adhesive behavior of polymer-modified emulsions in high volume roads using the Bitumen Bond Strength (BBS) test, evaporation test, and vialit test [60]. They observed that polymer modification improves the curing and adhesive characteristics of chip seal. Kim and Lee compared the performance of a latex modified emulsion (CRS-2L) to an unmodified emulsion (CRS-2). Results suggested that polymer-modified emulsion improves resistance against bleeding and enhances chip seal performance [61]. Serfass et al. evaluated SBS-modified asphalt emulsions in chip seal applications; they reported that the emulsion showed better resistance against aging and increased cohesion when modified with SBS [62]. Yet, compared to unmodified emulsions, the cost of polymer-modified emulsions is about 30% higher [61].

Emulsion Testing

Emulsion testing needs to be conducted on both the fresh emulsion and its residue in order to better characterize its properties. Properties such as storage stability, sprayability, and drainout should be evaluated to measure the constructability of emulsion. The ability of an emulsion to resist any change without significantly altering its properties is termed as its storage stability [43]. Problems associated with unstable emulsion include difficulty in spraying/flow, distribution, skin formation, etc. [43].

Emulsion storage stability can be measured according to the test method specified in ASTM D 6930. Electrokinetic test methods can also be used to measure emulsion stability [45]. Sprayability and drainout are the two other most important parameters for evaluating the constructability of emulsion for chip seals. Sprayability is the ability of an emulsion to be sprayed over the surface of an existing pavement uniformly [63]. If used, highly viscous emulsions may cause loss of aggregate, spot bleeding, and improper aggregate wetting. Drainout is the ability of an emulsion to resist flow under gravity. Early aggregate loss due to insufficient embedment of aggregate is the primary problem associated with drainout. Sprayability and drainout of emulsions can be assessed from their viscosity. Viscosity testing provides more insight regarding the emulsion tested. Saybolt furol second (SFS) viscometer (ASTM D 7496), paddle viscometer (ASTM D 7226), and rotational viscometer (ASTM D 4402 and AASHTO TP 48) are some of the test methods that are available for measuring the viscosity of emulsions. Performance Grade (PG) testing utilizes the Rotational Viscometer (RV) to evaluate the apparent viscosity of asphalt binder and emulsion residue. Tests such as the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) may also be used to evaluate the performance grade of the emulsion residue and compare them with the properties of other binders having the same performance grade (PG). Table 6 and Table 7 present the standard requirements of DOTD and TxDOT for the emulsions CRS-2P and CRS-2TR, when tested according to the test methods described in AASHTO and ASTM.

Table 6. Standard specifications for CRS-2P by DOTD [7]

Property	**Test Procedure**	**CRS-2P**	
		Min	**Max**
Viscosity, Saybolt Furol	T 59		
50°C, s		100	400

Property	Test Procedure	CRS-2P	
		Min	Max
25°C, s			
Storage Stability, 1 day, %	T 59	-	1
Settlement, 5-day, %	T 59	-	5.0
Identification test	T 59	Pass	
Particle Charge	T 59	Positive	
Distillation test	T 59		
Residue by Distillation, % by wt.		65	-
Oil Distillate, % by volume of emulsion		-	3.0
Sieve Test, %	T 59	-	0.1
Tests on Residue from Distillation:			
Penetration, 25°C, 100g, 5 sec., dmm	T 49	100	200
Solubility, %	T 44	97.5	-
Softening Point (Ring and Ball), °C	T 53	38	-
Ductility, 25°C, 5 cm/min, cm	T 51	-	-
Tests on Residue by Evaporation:	T 51	50	-
Force Ductility Ratio, (f2/f1, 4°C, 5 cm/min, f2 at second peak)	T 300	0.30	-
Elastic recovery, 10°C@ 20cm elongation, %	T 301	58	-

Table 7. Standard specifications for CRS-2TR by TxDOT [64]

Property	Test Procedure	CRS-2TR	
		Min	Max
Viscosity, Saybolt Furol	T 72		
77°F, Sec.		-	-
122°F, Sec.		150	500
Sieve Test %	T 59	-	0.1
Demulsibility, 35 ml of 0.8% sodium dioctyl sulfosuccinate, %	T 59	40	-

Property	Test Procedure	CRS-2TR	
		Min	Max
Storage Stability, 1 day, %	T 59	-	1
Breaking Index, g	Tex-542-C	-	-
Particle Charge	T 59	Positive	
Distillation test	T 59		
Residue by Distillation, % by wt.		65	-
Oil Distillate, % by volume of emulsion		-	3
Tests on Residue from Distillation:	T 59		
Modifier Type	T 59	Tire rubber	
Modifier Content, wt % (solids basis)	T 59	5.0	-
Penetration, 77°F, 100g, 5 sec.	T 49	90	150
Viscosity, 140°F, poise	T 202	1000	-
Solubility in Trichloroethylene, %	T 44	98	-
Softening Point, °F	T 53	-	-
Ductility, 77°F, 5 cm/min, cm	T 51	40	-
Ductility, 39.2°F, 5 cm/min, cm	T 51	-	-
Elastic recovery, 50°F, %	Tex-539-C	-	-

Specifications for Chip Seal Binders and Emulsions

One of the most noteworthy outcomes of the Strategic Highway Research Program (SHRP) undertaken in 1987 was the development of a performance-based asphalt binder specification known as the Superior Performing Asphalt Pavements (Superpave) or Performance-Graded (PG) binder specification, which was correlated to field performance [65]. PG is used to select binders to meet certain aging considerations and weather conditions of the chip seal project with a certain degree of consistency [17]. Binders are characterized at three different aging temperatures (low, intermediate, and high). The PG specification system was able to eliminate the shortcomings of the previous penetration or viscosity graded specification system including the absence of long-term aging of the binders and low temperature characterization, inability to grade modified binders, and the empirical nature of the test methods. New test equipment such as the dynamic shear rheometer and the bending beam rheometer were introduced to measure the binder resistance against rutting, fatigue cracking, and low-temperature thermal cracking at different climatic conditions. The Rolling Thin-Film Oven (RTFO) and the Pressure Aging Vessel (PAV) were also introduced to simulate short-term aging and long-term aging in the specifications [65]. The test method and the limiting value remain the same for every binder and area; however, the testing temperature vary. The temperature range in which the criteria are met is considered the PG of that binder.

The PG system was primarily intended to be used as a selection tool for asphalt binders, which did not consider the aging of the emulsion residues. Hence, the specification system may not be suitable for chip seal binder residues in terms of their ability to simulate field performance. Consequently, the distress exhibited by chip seal, their construction method, and exposure to environmental conditions are different from hot-mix asphalt.

Table 8. Performance graded specification (AASHTO M 320)

Performance Grade	**PG 58**					**PG 64**						**PG 70**					
	16	22	28	34	40	10	16	22	28	34	40	10	16	22	28	34	40
Average 7-day max pavement design temp, °C	<58					<64						<70					
Min pavement design temperature, °C	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
Original Binder																	
Flash point temp, T 48, min °C	230																
Viscosity, T 316; max 3 Pa·s, test temp, °C	135																
Dynamic shear, T 315; G*/sinδ, minimum 1.00 kPa test temp @ 10 rad/s, °C	58					64						70					

Performance Grade	**PG 58**					**PG 64**						**PG 70**					
RTFO Aged Residue																	
Mass change, maximum, percent	1.00																
Dynamic shear, T 315; G*/sinδ, minimum 2.20 kPa test temp @ 10 rad/s, °C	58					64						70					
RTFO+PAV aged Residue																	
PAV aging temperature, °C	100					100						100 (110)					
Dynamic shear, T 315; G* sinδ, maximum 5000 kPa test temp @ 10 rad/s, °C	25	22	19	16	13	31	28	25	22	19	16	34	31	28	25	22	19
Creep stiffness, T 313; S, maximum 300 MPa m-value, minimum 0.300 test temp @ 60 s, °C	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct tension, T 314; Failure strain, minimum 1.0% test temp @ 1.0 mm/min, °C	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

Epps et al. (2001) developed a specification system for asphalt emulsions and binders used in chip seals. The Surface treatment Performance Grading (SPG) system was developed to address the distress and conditioning differences between HMA and chip seals during construction and service [66]. Both high and low temperature grade in the SPG specifications are offset 3°C from the grade used in the PG specifications. It eliminated the use of RTFO for asphalt emulsions and removed the intermediate grading temperature [66] [67]. This specification was further validated and refined by other researchers based on the differences between laboratory and field performance. Table 9 presents the latest SPG specification published by Texas DOT for implementation in 2017.

The current SPG and PG specifications are different on the following aspects:

- Both high and low temperatures are obtained at the pavement surface for SPG specifications;
- Both high and low temperature grade in the SPG specifications are offset 3°C from the grade used in the PG specifications;
- Unlike PG specifications, time-temperature shift is not considered in the SPG specifications;
- Use of RTFO device is eliminated and no tests are required at the intermediate temperature;
- The m-value is dropped from the SPG specifications and only the creep stiffness value at 8s is considered;
- A limit on phase angle is incorporated for emulsions or binders in the SPG specifications.

Table 9. Surface performance grade (SPG) specification for emulsified asphalt residues and hot-poured asphalt cements [66]

Specification	**SPG 67**				**SPG 73**			
	-13	-19	-25	-31	-13	-19	-25	-31
Average 7-day max pavement design temp, °C	<67				<73			
Minimum pavement surface design temperature, °C	>-13	>-19	>-25	>-31	>-13	>-19	>-25	>-31
Original Binder								
Flash point temperature, T 48, min °C	230							
Viscosity, T 316; maximum 0.15 Pa·s, test temp, °C	205							
Performance properties for original binder/emulsified asphalt residues								
Dynamic shear, T 315; $G^*/\sin\delta$, minimum 0.65 kPa test temp @ 10 rad/s, °C	67				73			

Specification	SPG 67				SPG 73			
Maximum Phase angle (δ), @temp. where G*/sinδ=0.65 kPa	Na	80	80	80	80	80	80	80
PAV aged residue (AASHTO R 28)								
PAV aging temperature, °C	100				100			
Creep stiffness, T 313; S, max 500 MPa test temp @8 s, °C	-13	-19	-25	-31	-13	-19	-25	-31

Adams (2014) developed a performance-related specification for chip seal surface treatments, see Table 10 [68]. Different limiting values of bitumen bond strength (BBS) test results were proposed for different traffic levels at intermediate temperatures to characterize the resistance of chip seal to early raveling, dry raveling, and wet raveling. The maximum value of non-recoverable creep compliance, i.e. J_{nr}, at different traffic levels were also proposed to address the performance to flushing and bleeding at high temperature. Additionally, the author proposed thermal cracking performance parameters. However, the fresh emulsion properties for chip seal were not included in the specifications.

Table 10. Performance related specification for chip seal [68]

Performance Grade for Chip seal Binders	PG 58				PG 64			
	-22	-28	-34	-40	-22	-28	-34	-40
Average 7-day max pavement design temp, °C	<58				<64			
Minimum pavement surface design temperature, °C	>-22	>-28	>-34	>-40	>-22	>-28	>-34	>-40
Original Binder								
Test method proposed for chip seal binders	Testing conditions							

<table>
<tr><th>Performance Grade for Chip seal Binders</th><th colspan="4">PG 58</th><th colspan="4">PG 64</th></tr>
<tr><td>Resistance to Early Raveling
BBS test (TP91-11), POTS
4 hours Curing time @temp. (°C)
Minimum dry bond strength for low traffic: 200 kPa
Minimum dry bond strength for medium traffic: 250 kPa
Minimum dry bond strength for high traffic: 300 kPa</td><td>22</td><td>19</td><td>16</td><td>13</td><td>25</td><td>22</td><td>19</td><td>16</td></tr>
<tr><td>Resistance to Dry Raveling
BBS test (TP91-11);
21 hours dry Curing time @temp. (°C)
Minimum dry bond strength for low traffic: 400 kPa
Minimum dry bond strength for medium traffic: 600 kPa
Minimum dry bond strength for high traffic: 800 kPa</td><td>22</td><td>19</td><td>16</td><td>13</td><td>25</td><td>22</td><td>19</td><td>16</td></tr>
<tr><td>Resistance to Wet Raveling
BBS test (TP91-11);
4 hours dry and 16 hours wet Curing time; wet curing @40°C, test @temp. (°C)
Minimum wet bond strength for low traffic: 4200 kPa
Minimum dry bond strength for medium traffic: 325 kPa
Minimum dry bond strength for high traffic: 450 kPa</td><td>22</td><td>19</td><td>16</td><td>13</td><td>25</td><td>22</td><td>19</td><td>16</td></tr>
<tr><td colspan="9">Tests on residue recovered by ASTM D7497- Method B</td></tr>
<tr><td>Resistance to Flushing and Bleeding
Measured response: non-recoverable creep compliance, J_{nr} @ Testing temperature, °C; MSCR (AASHTO TP70)
Maximum J_{nr} @3.2 kPa, 8 kPa−1 (low traffic)
Maximum J_{nr} @3.2 kPa, 5.25 kPa−1 (medium traffic)
Maximum J_{nr} @3.2 kPa, 3.25 kPa−1 (high traffic)</td><td colspan="4">58</td><td colspan="4">64</td></tr>
</table>

Performance Grade for Chip seal Binders	PG 58				PG 64			
Tests on PAV aged residue								
Thermal Cracking S (60) and m (60) estimated from DSR frequency Sweep test@°C Maximum S (60) =300Mpa; Minimum m (60) =0.300	-12	-18	-24	-30	-12	-18	-24	-30

The properties of emulsions are critical for chip seal performance. According to a survey conducted by Johnston and King, most of the pavement practitioners supported the need for having a performance-related grading system for asphalt emulsions used in chip seals [69]. Adams et al. (2017) developed a new specification named "Emulsion performance-grade (EPG) specification" for the emulsions used in chip seal surface treatment and to eliminate the risk of premature chip seal failure in the field [70], see Table 11.

Table 11. EPG specifications for chip seals [70]

Specification	**EPG 67**				**EPG 73**			
	-13	-19	-25	-31	-13	-19	-25	-31
Average 7-day max pavement design temp, °C	<67				<73			
Minimum pavement surface design temperature, °C	>-13	>-19	>-25	>-31	>-13	>-19	>-25	>-31
Recovered residue by AASHTO R 78 Method B								
Resistance to rutting and bleeding Testing temperature, °C; Measured response: non-recoverable creep compliance, J_{nr} MSCR, AASHTO T 350 Maximum J_{nr} @3.2 kPa, 8 kPa−1 (low traffic) Maximum J_{nr} @3.2 kPa, 5.5 kPa−1 (medium traffic) Maximum J_{nr} @3.2 kPa, 3.5 kPa−1 (high traffic)	67				73			
Resistance to low temperature raveling DSR temperature frequency sweep Measured response: |G*| at critical phase angle, δc Max. |G*| @ δc: 30 MPa (low traffic) Max. |G*| @ δc: 20 MPa (medium traffic) Max. |G*| @ δc: 12 MPa (high traffic)	5°C and 15°C Critical phase angle, δc (°)							
	51	48	45	42	51	48	45	42

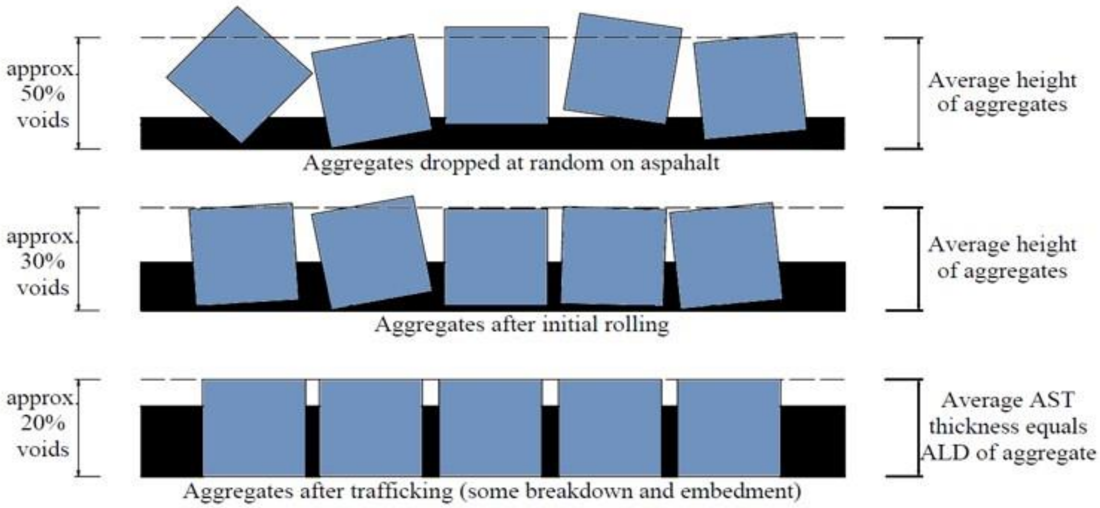
Design of Chip Seals

The application rates for emulsion and aggregate are two major components in the design of chip seal. Several theoretical procedures are available for designing chip seal and state agencies follow different design procedures for chip seal. DOTD standard design specifications for chip seals require that a fixed application rate of 0.31 gsy be used for the emulsion and 0.0075 cy/sq. yd. for the lightweight aggregate. A number of procedures involve mathematical calculations along with some laboratory testing to determine the binder and aggregate application rates. However, chip-seal design methods originally proposed by Hanson (1934–1935) and by Kearby (1953) provided the basis for current chip seal design methods [71] [72]. The Kearby method was later improved and adopted by TxDOT [73] [74]. Other methods available for chip seal design include the McLeod method, Road Note 39, Austroads Provisional Sprayed Seal Design Method (2001), and TRH3 [24] [28] [75].

Hanson Method

Hanson developed a design procedure for chip seal in 1935 for liquid asphalt, specifically for cutback asphalt based on the average least dimension (ALD) of the selected aggregate. The voids between aggregate particles after spreading them into the binder layer was observed to be 50% right after construction, which decreased to 30% after compaction by rolling, and to 20% when the traffic was allowed on the newly constructed chip seal, see Figure 3. The aggregate embedment depth was not considered as a design criterion; however, it was suggested that the void area of 60% to 75% should be filled by the residual asphalt to yield an embedment depth between 60% and 75%.

Figure 3. Embedment scenario of asphalt surface treatment [76]



Modified Kearby Method

The modified Kearby method requires dry loose unit weight, bulk specific gravity, and a board test to be conducted before designing chip seal. The board test is used to find the amount of aggregate needed to cover one half square yard area on a board with one stone depth in thickness. The following equation is used to calculate the amount of aggregate needed to cover one square yard of roadway in terms of volume:

$$S = \frac{27W}{Q} \tag{4}$$

Where, S = required amount of aggregate (yd^2/ yd^3), W = dry loos unit weight of the aggregate (lbs./ft^3), and Q = aggregate quantity determined from the board test (lbs./ yd^2).

The asphalt binder application rate can be obtained from the following equation:

$$A = 5.61E(1 - W / 62.4G)T + V \tag{5}$$

Where, A = binder application rate (gal/sq. yd.) in 60°C, E = embedment depth, G = dry bulk Specific Gravity of the aggregate, T = correction factor for traffic volume, and V = adjustment factor for the existing pavement condition.

$$E = e * d \tag{6}$$

Where, d = average mat depth in inches, as calculated from Equation (7), and e = percent embedment expressed as a decimal.

$$d = 1.33 * {}^{Q}/_{W} \tag{7}$$

Where, Q = aggregate quantity determined from the board test in lbs./sy, and W = dry loose unit weight in lbs./ft^3.

The final application rate for the emulsion is calculated from the following equation:

$$A_{recommended} = A + k(A_{theoretical} - A) \tag{8}$$

Where, A = asphalt application rate from Equation (5), K = seasonal adjustment factor; $A_{theoretical}$ = Theoretical quantity of emulsified asphalt = A/R, R = percent residual asphalt in the emulsion expressed as decimal.

McLeod Design Method

The design method proposed by McLeod is widely accepted and was recommended by the Asphalt Institute and the Asphalt Emulsion Manufacturers Association [8]. In this method, the shape of aggregate, gradation of aggregate, specific gravity, and a wastage factor governs the aggregate application rate. The binder application rate is governed by the gradation, absorption and shape of the aggregate, volume of traffic, surface condition, and type of asphalt binder. McLeod design method was primarily developed for emulsions and established the aggregate embedment depth of 70% under moderate traffic [28]. McLeod design method uses the following equations to calculate the aggregate and binder application rates:

$$\mathrm{C} = 46.8\ (1 - 0.4\mathrm{V})HGE \tag{9}$$

Where, C = rate of aggregate application, lbs./sy, V = voids present in the loose aggregate; H = average least dimension, in., G = aggregate's bulk specific gravity, and E = traffic whip-off factor.

$$B = \frac{2.244HTV + S + A}{R} \tag{10}$$

Where, B = rate of Binder application, gsy, H = average least dimension, in., T = correction Factor for different traffic condition, V = voids in loose aggregate, S =

correction factor for surface condition, gsy, A = absorption factor for aggregate, gsy, R = residual asphalt in the emulsion (%), R = 1 for asphalt cement.

NCHRP Recommended Austroads Design Method

NCHRP report 680 recommended the Austroads design method for the construction of chip seals in the US [38]. The Austroads design method is valid when heavy traffic volume is less than 10% for the whole design period. It assumes an aggregate embedment depth of 50 to 65% after 2 years of construction. The design requires the use of one-sized aggregate with a flakiness index of 15 to 25% and the application should be such that the aggregate is one stone layer thick. The percentage of voids in mineral aggregate (VMA), traffic volume and type, and the percentage of voids filled with asphalt (VFA) are the parameters necessary to determine the basic emulsion application rate. The parameters such as the texture of existing surface, aggregate embedment, binder absorption into the aggregate, and substrate are also required to determine the design emulsion application rate. In addition, aggregate size, shape of the aggregate, loose unit weight of the aggregate, and traffic level are required to determine the aggregate application rate. The aggregate application rate is reported in the unit m^2/m^3 in the Austroads design method whereas NCHRP report 680 uses lbs./yd^2. The following equations are used as per the Austroads design method to determine the aggregate application rate and the binder application rate:

Emulsion application rate:

$$B_d = \{[V_f + V_a + V_t) * ALD] * EF * PF\} + A_s + A_e + A_{as} + A_{aa} \quad (11)$$

Where, Bd = design binder application rate, gsy (L/m^2), EF = emulsion factor; PF = polymer factor (for polymer modified emulsions only), A_s, A_e, A_{as}, A_{aa} = adjustments for substrate texture, embedment, absorption into substrate, and absorption into cover aggregate, gsy (L/m^2), V_f = basic voids factor, V_a = aggregate shape adjustment factor, and V_t = traffic effects adjustment factor.

Aggregate application rate:

For less than 200 vehicles/day/lane, aggregate spread rate, lbs./yd^2:

$$\frac{[ALD, in. * W]}{27.08} \quad (12)$$

For more than 200 vehicles/day/lane, aggregate spread rate, lbs./yd^2:

$$\frac{[ALD, in. * W]}{25.27} \quad (13)$$

Where, ALD = average least dimension; and W = loose unit weight, lb./yd³.

Performance Measures of Chip Seals

Chip Seal Performance Test Methods

There are several standard test methods, which can measure aggregate loss, rutting, and adhesion in chip sealing. Researchers have utilized these standard test methods to evaluate the performance of chip sealing [77] [78] [79] [80] [81]. Table 12 illustrates the most common standard test methods for evaluation of chip seal performance and the properties evaluated.

Table 12. Laboratory performance test methods for chip seal [82]

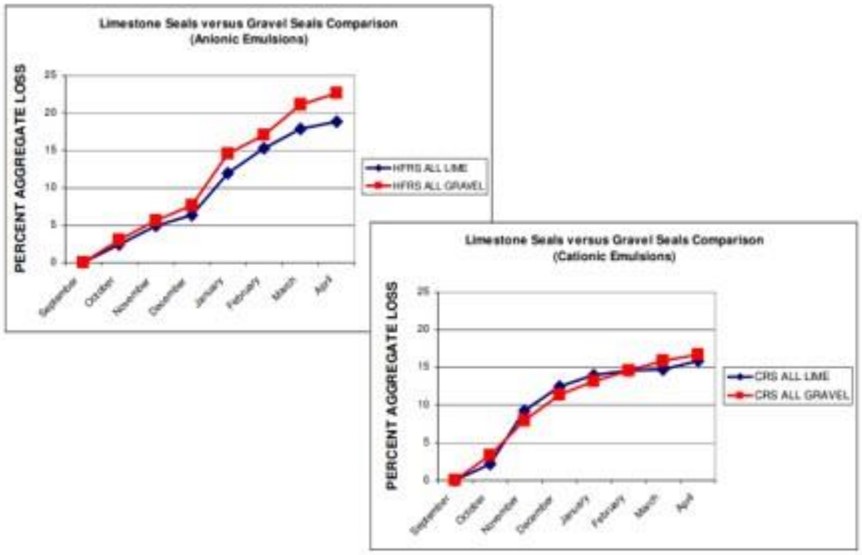
Test methods	***Property measured***
Tex-216-F Aggregate retention test	Aggregate loss
ASTM D7000 Sweep Test	Aggregate loss
Vialit Adhesion Test	Aggregate loss
Flip Over Test	Aggregate loss
Hamburg Wheel Tracker test	Rutting
Frosted Marble Test	Aggregate loss
Australian Aggregate Pull-out Test	Pull-out force required to separate aggregate from binder
Pennsylvania Aggregate Retention Test (PART)	Aggregate loss
British Pendulum Test	Skid Resistance (British Pendulum Number)
Third Scale Model Mobile Loading Simulator (MMLS3)	Rutting, Aggregate loss, Bleeding
Pneumatic Adhesion Tension Test	Pull-off adhesion strength achieved at failure
Bitumen Bond Strength Test	Pull-off strength

Studies on Chip Seal Performance

Ozdemir et al. evaluated the effects of aggregate and binder application rates on the percent embedment using laboratory fabricated samples [82]. Sweep tests were also performed to investigate the effect of percent embedment and to evaluate the performance of laboratory and field chip seal samples. The aggregate application rate was observed to have negligible effect on the percent embedment depth when compared to the binder application rate. The authors also observed that both percent embedment depth and aggregate surface coverage increased with the increase in binder application rate.

Wielinski et al. (2011) used image analysis to evaluate the performance of chip seal prepared with different types of aggregate, emulsions, and their combinations in terms of aggregate retention during the winter period [83]. The authors evaluated different combinations of aggregate and emulsions to determine an optimum combination that performs best during the winter season in Michigan, i.e., when the probability of snowplows on chip sealing is higher. The emulsions considered in the analysis include unmodified emulsions and emulsions modified with low oil additives (1.0% #2 fuel oil), latex modified emulsions (SBR), and SBS modified emulsions. The aggregate considered included limestone and crushed gravel aggregate, see Figure 4. Colored images captured for each month at the same spot were first converted to black and white binary images. The loss of aggregate was then calculated by measuring the change in aggregate coverages in the images. The addition of fuel oil (1.0% #2 fuel oil) to an anionic emulsion was observed to improve the chip seal performance in terms of aggregate retention compared to the unmodified emulsion. The limestone chip seals outperformed gravel chip seals within the anionic group; the gravel chip seals exhibited an overall 4% greater aggregate loss. The limestone and gravel chip seals exhibited similar performance when a cationic emulsion was used. The latex modified limestone chip sealing performed better compared to the SBS modified limestone chip sealing; however, the performance of gravel chip sealing prepared with latex modified asphalt emulsion was similar to that of the gravel chip sealing prepared with SBS modified asphalt emulsion.

Figure 4. Comparison of limestone chip seal versus gravel chip seal in terms of percent average aggregate loss measured by imaging analysis technique [83]



Johannes et al. (2011) evaluated the effects of emulsion application rates and aggregate gradation on the performance of chip seal [80]. The performance of chip seal samples was determined in terms of aggregate loss by conducting sweep test according to ASTM D 7000 standard specification. The investigation was conducted with two types of aggregate (limestone and granite), two gradations (fine and coarse), three types of emulsion (CRS-2, HFRS-2L, and HFRS-2), three emulsion application rates (low, medium, and high), and two curing periods (2 h and 6 h). Statistical analysis of the results revealed that the sweep test method was not sensitive to the emulsion application rate required to fill 35 to 70% of the voids in the aggregate. It was observed that chip seal specimens prepared with fine-graded aggregate had lower aggregate loss compared to that of the chip seal specimens prepared with coarse-graded aggregate; see Figures 5 and 6. Loss of aggregate varied with the type of emulsion and aggregate used, indicating that the sweep test was sensitive to the type of emulsion used, aggregate mineralogy, and gradation of the aggregate. The aggregate investigated performed well with the cationic emulsion at different curing periods compared to the high float emulsions. However, 2 h curing time resulted in more loss of aggregate (>10%) compared to 6 h curing time. The study concluded that the current sweep test protocol should be modified for better correlation with field conditions, to evaluate the performance of different aggregate-emulsion combinations, and to estimate the optimum curing time.

Figure 5. Sensitivity of sweep test to aggregate gradation (a) granite aggregate and (b) limestone aggregate [80]

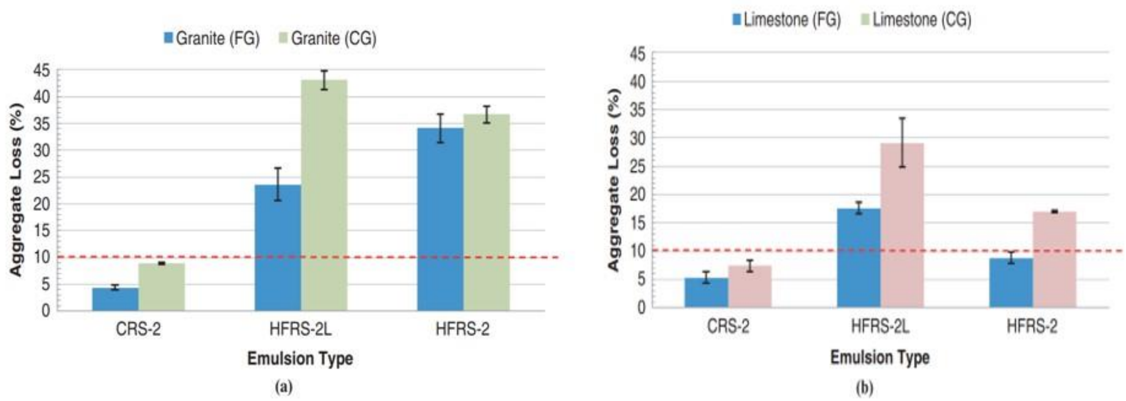
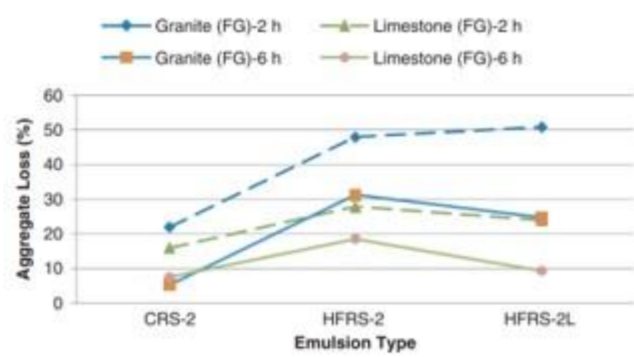
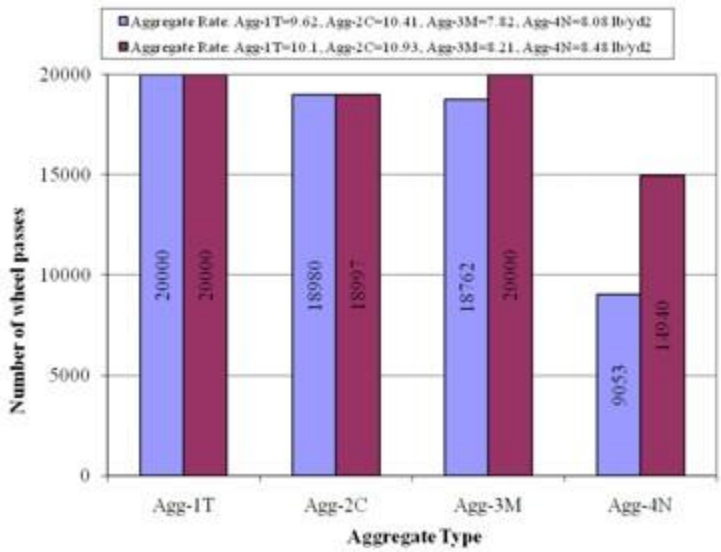


Figure 6. Effects of type of emulsion and aggregate on aggregate loss for fine-graded chip seals [80]



Islam and Hossain (2011) used lightweight aggregate from four sources with two types of polymer-modified asphalt emulsion (CRS-1HP and CRS-2P) to determine the optimum aggregate and emulsion application rates in order to achieve 70% aggregate embedment depth and to reduce aggregate loss. The study also evaluated the effect of moisture content and electrical charge on aggregate loss [84]. Four different tests including modified sand circle test, Hamburg wheel tracking test (LWT), sweep test, and modified sweep test were conducted to evaluate the embedment depth and rutting and aggregate retention properties of the chip seal specimen; see Figure 7. Statistical analysis of the results indicated that the charge of the emulsion and the aggregate influenced the aggregate retention in chip seal specimens. The loss of aggregate was observed to be lower when aggregate-emulsion combinations of opposite electric charges were used as indicated by the sweep test. Therefore, it was concluded that the aggregate should be compatible with the asphalt emulsion in order to reduce the loss of aggregate. The interaction between emulsion and aggregate was observed to influence the aggregate embedment depth and the aggregate retention in chip seal specimens, whereas the source of aggregate influenced the rutting performance of chip seal [84].

Figure 7. Number of wheels passes for different aggregate and application rates according to the criteria set for rutting test [84]



Montoya et al. (2017) presented a novel, rapid, non-destructive, and portable approach based on electrical resistance measurements to determine the optimal curing period for brooming and opening to unrestricted traffic for a newly-applied chip seal [85]. A handheld electronic device with a two-point probe resistance measurement was used to monitor the increase in electrical resistance under different field conditions. The test was conducted until a sufficient adhesive strength was gained by the asphalt emulsion residue to hold the aggregate in place. Sweep test according to ASTM D 7000 standard specification was also conducted to compare field and laboratory results. Based on the results obtained from laboratory and field tests, it was established that the water evaporation rate (WER) and aggregate mass loss (AML) correlated with the electrical resistance of chip seals (Figures 8 to 11). It was concluded that the electrical resistance may be used to evaluate the curing characteristics of a newly applied chip seal and a chip sealing may be confirmed sufficiently cured when its normalized resistances index (NRI) value exceeds 10.

Figure 8. Changes of electrical resistance measurement with different curing time [85]

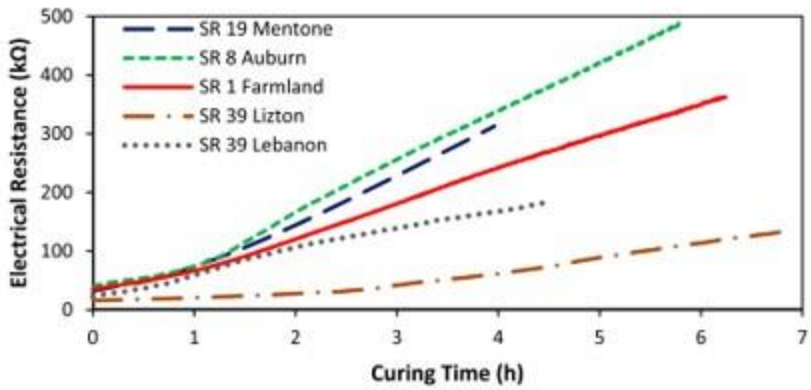


Figure 9. Changes of normalized resistances index (NRI) value with different curing time [85]

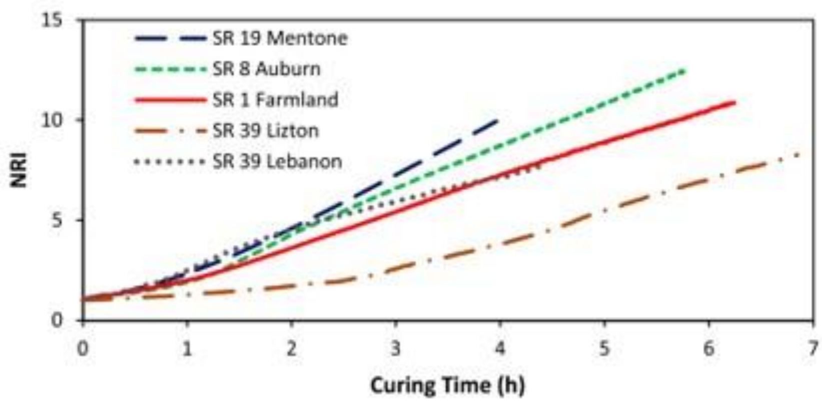


Figure 10. Correlation of NRI with WER [85]

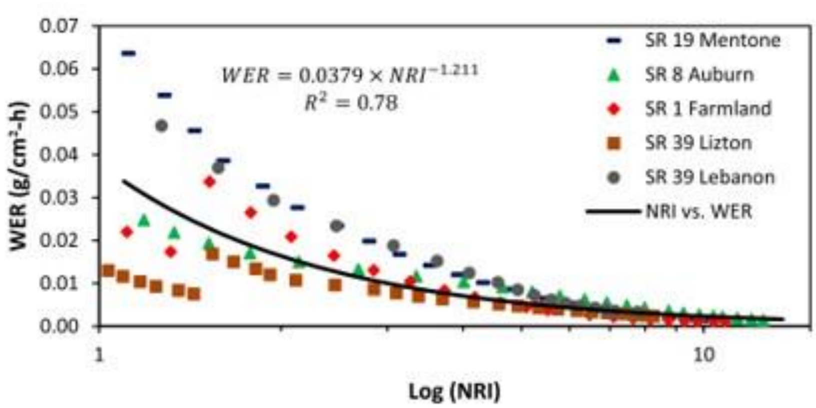
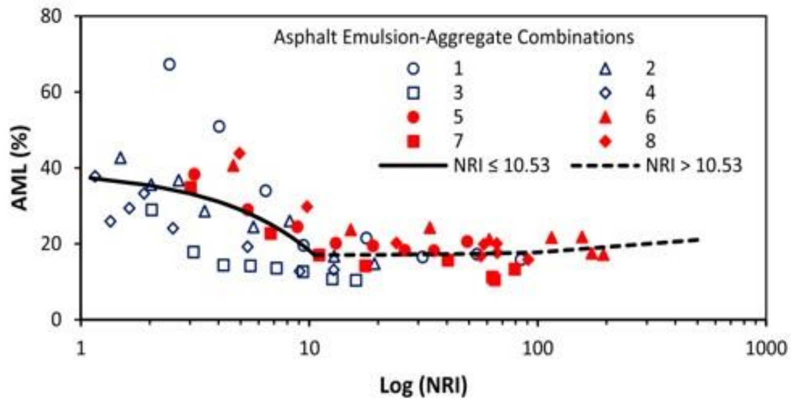
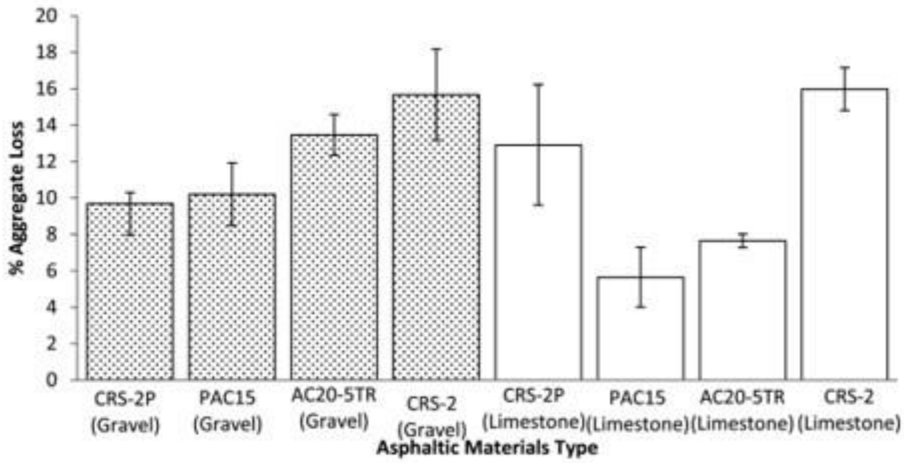


Figure 11. Aggregate mass loss (AML) as a function of NRI [85]



Wasiuddin et al. evaluated the influence of the aggregate and binder types, aggregate moisture content, precoating of the aggregate, and binder application rates on the sensitivity of the sweep test [79]. The types of binder investigated included CRS-2, CRS-2P, PAC-15, and AC20-5TR and the types of aggregate investigated included gravel, limestone (crushed), granite (crushed), expanded clay lightweight, and uncoated and precoated expanded shale lightweight aggregate; see Figure 12. The gravel aggregate and CRS-2 emulsion were excluded from the test factorial in the field experiment. A visual distress rating in terms of aggregate loss and bleeding were conducted on the field sections after 2 years of construction and the results were compared with the laboratory measured chip seal performance. The sweep test was conducted at a curing time of 48 h and a temperature of 28°C as recommended by NCHRP report 680. The laboratory measured chip seal performance varied with the emulsion and aggregate types, binder application rates, and aggregate moisture condition. The laboratory and field test results indicated an improved performance of pre-coated expanded shale aggregate compared to the crushed aggregate and expanded clay aggregate. The PAC-15 performed better than AC20-5TR binder for both gravel and limestone. While the percentage of aggregate loss increased with the increase of moisture content in oven dry, air dry, and SSD (saturated surface dry) aggregate, some moisture in aggregate was observed to be needed for adequate performance of emulsions. Increasing the application rates of both emulsion and hot asphalt by 33% significantly reduced the aggregate loss in chip seals. The distress survey matched closely with the sweep test results indicating the effectiveness of the sweep test to evaluate and predict chip seal field performance.

Figure 12. Effect of binder types on loss of aggregate in chip seals [79]



Kim et al. evaluated the performance of polymer modified emulsion in chip sealing in terms of rutting, bleeding, and aggregate retention [86]. The authors investigated one conventional unmodified emulsion (CRS-2) and two polymer modified emulsions (CRS-2P and CRS-2L) in both laboratory and field conditions at different test temperatures using the vialit test, flip-over test (FOT), third-scale model mobile loading simulator (MMLS3), image processing, and rutting test. The fast and enhanced bonding characteristics of polymer-modified emulsion (CRS-2P and CRS-2L) significantly improved the aggregate retention in chip sealing in the initial stage of its service life. Test results also indicated that the polymer modified emulsions are more resistant to bleeding and rutting compared to the unmodified emulsions, thus improving chip seal performance [86].

Howard et al. studied the correlation between moisture loss and strength gain in chip seal using ASTM D 7000, a modified sweep test, and the frosted marble test (FMT) [87]. The aggregate retention was observed to strongly correlate with the curing time and torque (adhesive strength gain indicator). The moisture loss, torque, and aggregate retention increased with the increase in curing period in all cases. The results indicated that the strength gain increased significantly when the moisture loss approached 80% and a substantially higher strength was achieved when the moisture loss was above 90%. The ASTM D7000 and modified sweep test method were observed to be more effective in predicting the performance of chip seals although FMT was considered as an effective test method to evaluate the curing rate and asphalt binder characteristics.

Kucharek et al. (2006) evaluated early aggregate retention of chip seal samples using FMT and sweep test. Ten different emulsions (both anionic and cationic) and three types of aggregate (granite, limestone, and trap rock) with less than 1% fines content were evaluated at different curing temperatures (22°C and 25°C) and curing periods (2,4,6, and 24 hour) [88]. The total aggregate loss starting from sample preparation to the completion of sweep test was monitored to plot cure time vs. total aggregate loss. It was reported that the chemical compatibility between the aggregate and the residual binder was a very important factor for the emulsion residue to gain strength. In addition, the curing rate of the anionic emulsions in chip sealing was observed to be slower compared to that of the cationic emulsions.

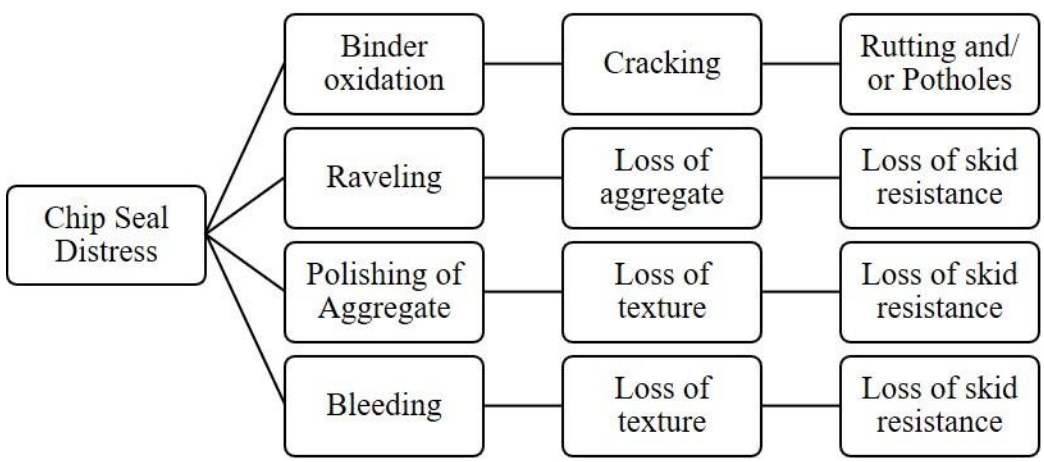
Kandhal and Motter (1991) evaluated the adhesion of precoated aggregate and developed the Pennsylvania Aggregate Retention Test (PART). The effect of precoating on the performance of chip sealing was investigated for five types of aggregate and two different gradations (3/8 in. single sized and ½ in.) in terms of aggregate loss [77]. The aggregate was precoated with MC-70 cutback asphalt and CRS-2 asphalt emulsion was used to prepare the control chip seal specimen. The study also evaluated uncoated aggregate with 0 to 5% dust content. Results indicated that the increase in the percentage of dust content in uncoated aggregate increased aggregate loss in chip seals. The loss of aggregate increased significantly when the dust content was more than 3%. In addition, aggregate loss decreased with the increase in percentage precoating. Precoating of the aggregate with 90% or greater resulted in reduced loss of aggregate up to 80% for both 3/8 in. single-sized and ½ in. aggregate. However, ½ in. aggregate resulted in more aggregate loss than 3/8 in. single-sized aggregate. Visual inspection of the precoated aggregate samples also indicated that 90% aggregate precoating was optimum in order to achieve adequate adhesion between the cover aggregate and the asphalt binder.

Gheni et. al. studied the performance of chip seal incorporating crumb rubber as aggregate [31]. A total of 222 chip seal specimens were prepared to evaluate the performance of chip sealing in terms of aggregate retention, micro texture, macrotexture, and skid resistance under ambient conditions and high temperature. The study investigated two types of mineral aggregate (trap rock and creek gravel), one synthetic aggregate (crumb rubber obtained from recycled tire), two types of emulsions (CHFRS-2P and CRS-2P), and two types of asphalt cement (PG 64-28 and PG 70-28). The performance of chip seal prepared with crumb rubber aggregate and the conventional chip seal were evaluated and compared in terms of aggregate retention using standard sweep test, modified sweep test, vialit test, modified vialit test, and the Pennsylvania aggregate retention test (PART). The performance of the chip seal prepared with crumb rubber was observed to be satisfactory; the low unit weight of the crumb rubber and the rough surface increased the adhesion of the crumb rubber aggregate with the asphalt emulsion and asphalt cement, which resulted in good aggregate retention. The study concluded that partial or full replacement of the mineral aggregate with crumb rubber aggregate may be considered in the construction of chip seal. Chip seals prepared with crumb rubber aggregate outperformed the chip seals prepared with mineral aggregate in terms of aggregate retention as indicated by the vialit and the PART test methods. High-resolution 3D microscope, image processing, and a volumetric method results suggested that replacing mineral aggregate with crumb rubber significantly improved the macrotexture and micro texture of chip seal. Additionally, chip seal resisted high temperature without significant loss in frictional resistance due to the low thermal conductivity of crumb rubber.

Distresses Observed in Chip Seal

The loss of aggregate and bleeding are the two major distresses in chip seal [8]. A study reported the results from a survey where 81% of the respondents selected bleeding as a common chip seal distress and 67% selected loss of aggregate as a common distress; see Figure 13 [8]. The most common distresses associated with chip sealing are discussed below.

Figure 13. Chip seal distress model [8]



Aggregate loss. Aggregate loss, also known as raveling, is the dislodgement of aggregate due to adhesion failure between aggregate and binder. Aggregate loss is considered one of the most critical chip seal distresses since it is directly related to the surface texture of the treated pavement. It reduces the skid resistance of the pavement and results in bleeding [18]. Typically, early aggregate loss occurs when traffic is allowed on a pavement freshly treated with chip sealing before the curing period is completed. Early aggregate loss in chip seals is significantly affected by the type of emulsion used while the construction and design also affect the early aggregate loss of chip seals [76]. Inadequate embedment of the aggregate due to insufficient binder application rate and aging of binder, excessive aggregate application rate, type of aggregate, aggregate gradation, shape of aggregate, moisture condition, dust content, and poor traffic control after construction are the main causes of aggregate loss in chip seals [40]. Researchers have also identified aggregate loss due to low temperature as another major chip seal distress [89]. The binder layer becomes brittle due to the drop in pavement temperature, which results in aggregate loss at low temperature. A brittle binder becomes less adhered to the aggregate surface causing dislodgment of aggregate under traffic leaving them in a loose state. In addition, stripping or wet raveling can cause the loss of the cover aggregate. The moisture present in the porous aggregate and trapped moisture in the chip seal air voids causes the loss of adhesion between the binder and the aggregate, which results in the loss of cover aggregate causing the binder to migrate to the surface reducing the frictional characteristics of chip seal. Aggregate loss usually occurs just outside of the wheel paths where the embedment of the aggregate into the binder layer is the lowest [90].

Bleeding. Bleeding is sometimes referred as flushing since it appears as black patches on top of the chip sealed surface. Excessive binder application rate, high traffic volume, aggregate gradation, size and shape of aggregate, aggregate toughness, types of binder used, and the condition of the existing pavement surface are the main factors that affect the susceptibility of chip seals to bleeding [91] [92]. Aggregate undergoes repetitive stresses resulting in a higher degree of embedment exceeding the design embedment depth in the pavement wheel paths resulting in bleeding [8]. The selection of the suitable type of binder is an important factor to reduce bleeding in chip seal; for example, modified binders show better bleeding performance compared to other binders. A performance related specification has been introduced recently in order to select a suitable asphalt emulsion [38].

Cost Effectiveness of Chip Seals

Cost-Benefit Analysis Methodologies

The cost-effectiveness of pavement maintenance activities was evaluated using several approaches. Table 13 presents the most common methods that are used in estimating the economic benefits of a treatment method. The equivalent annual cost method is the most straightforward approach while the life-cycle cost analysis method is used to obtain more detailed results.

Table 13. Common approaches used in cost-benefit analysis [93]

Method	***Input***	***Output***
Life-Cycle Cost Analysis	Interest rates Inflation Analysis period Unit cost for treatment Estimated life of treatment	Present Value (PV) or Equivalent Uniform Annual Cost (EUAC) for each proposed treatment
Equivalent Annual Cost	Unit cost for treatment Estimated life of treatment	Unit performance life of treatment per cost
Cost-Effectiveness Analysis	Pavement performance curve	Area under the pavement performance curve is equivalent to effectiveness
Longevity Cost Index	Treatment unit cost Present value of unit cost over life of treatment Traffic loading Life of treatment	Relates present value of cost of treatment to life and traffic

Life-Cycle Cost Analysis

Hicks et al. defined life cycle costs as "an economic assessment of an item, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars" [9] [37]. Highway maintenance agencies use this tool to comprehensively assess the long-term costs associated with a proposed treatment activity, to compare among several feasible treatments, and to allocate available funds optimally.

Chip Sealing Cost-Effectiveness

A cost-effectiveness analysis was conducted to assess the cost-benefits of chip seal [93]. The performance of chip seal applied at a level before reaching the threshold was compared with the performance of the existing pavement without any maintenance activity, i.e., with the "do nothing" baseline approach. The following equations were used to estimate the equivalent uniform annual costs (EUAC) for the different cases [93]:

$$EUAC_{do\ nothing} = IC \times \left[\frac{(1+i)^{SL_{pre}}}{(1+i)^{SL_{pre}}-1}\right] \tag{14}$$

$$NPV_{treatment} = IC + PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \tag{15}$$

$$EUAC_{treatment} = NPV_{treatment} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}}-1}\right] \tag{16}$$

$$NPV_{ST} = PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \tag{17}$$

$$EUAC_{ST} = NPV_{ST} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}}-1}\right] \tag{18}$$

Where, IC = initial cost; i = discount rate; t_i = year of expenditure; PMC_{t_i} = surface treatment cost at year t_i; SL_{pre}= service life without treatment; and SL_{post}= service life with treatment.

The benefit of the treatment activities was determined as the monetary savings due to the treatment activity as follows:

$$\Delta EUAC = EUAC_{do\ nothing} - EUAC_{treatment} \tag{19}$$

The benefit-cost ratios for the projects were calculated according to the following equation:

$$\frac{B}{C} = \frac{\Delta EUAC}{EUAC_{ST}} \tag{20}$$

Where, $\Delta EUAC$ = monetary savings due to the treatment activity; and $EUAC_{ST}$ = equivalent uniform annual costs for the surface treatment activity.

Past Studies on Cost-Effectiveness of Chip Seals

Tarefder et al. investigated the cost-effectiveness of milling over virgin chips in terms of benefit area, EUAC, B-C ratio, and Effectiveness Index [94]. For all the cases, chip seal with milling was observed to have greater economic benefits than chip seals without milling. The benefit-cost ratios for the sections with chip seals with virgin chips ranged from 0.51 to 0.89; whereas, the benefits cost ratios for the projects with milling ranged from 0.66 to 1.35. Other economic measures indicated similar outcomes.

A study by Mamlouk et al. calculated the benefit-cost ratios based on the surface conditions of chip seal applied in four different climatic zones [95]. Smooth pavements were observed to have the highest benefit-cost ratios across all four climatic zones, and benefit-cost ratios for these pavements ranged from 8 to 15. Results also indicated that chip seals are more cost-effective in dry freeze and wet non-freeze zones as compared to the wet freeze and dry no-freeze zones.

The Pennsylvania Department of Transportation conducted a study to assess the benefits and costs associated with microsurfacing and other similar pavement treatment strategies [93]. The study discussed several approaches in assessing the economic aspects of these treatment activities and reported that the adopted approach may result in slight differences in the outcome; however, the relative ranking of the treatments remained the same. Statewide survey results indicated that typical cost for microsurfacing and chip seal ranged from \$2-4/SY and \$1-2/SY, respectively. The study also identified several other potential cost-effective treatments and compared the equivalent annual cost (EAC) of these treatments with respect to the EAC's of thin AC overlay. The findings of the study are summarized in Table 14, which showed that crack sealing, fog seal, and chip seal were the most cost-effective maintenance treatment methods. Another study by Hicks et al. reported similar unit costs and expected life of the treated pavements, see Table 15.

Table 14. EAC based on the survey of state highway agencies [93]

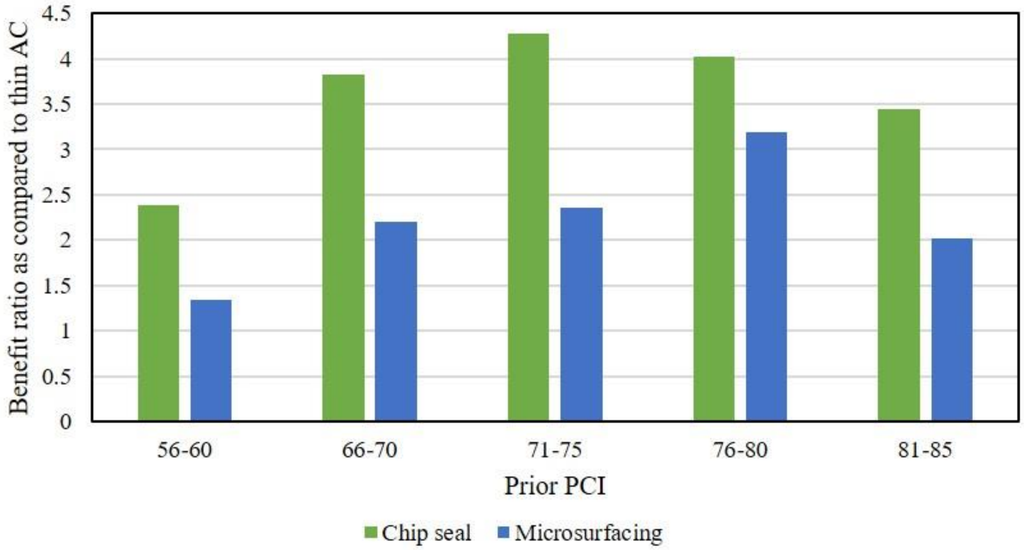
Treatment type	Cost ($/yd^2)		Performance life (year)		EAC ($/yd^2/year)			Cost ratio
	Low	High	Max	Min	Low	High	Ave	
Thin Overlay	2.55	5.50	12	7	0.21	0.79	0.50	1.00
Micro-surfacing	2.00	4.00	12	5	0.17	0.80	0.48	0.97
Crack Sealing	0.32	0.40	5	2	0.06	0.20	0.13	0.26
Chip Seal	0.90	1.78	8	4	0.11	0.45	0.28	0.56
NovaChip®	4.50	6.50	15	8	0.30	0.81	0.56	1.11
Fog Seal	0.25	0.60	5	2	0.05	0.30	0.18	0.35
Slurry Seal	1.50	3.00	6	4	0.25	0.75	0.50	1.00

Table 15. Typical unit costs and expected life of the preventive maintenance treatments [37]

Treatment	Cost/m^2	Cost/yd^2	Expected life of treatment		
			Min.	Average	Max
Crack Treatment	$0.60	$0.50	2	3	5
Fog Seals	$0.54	$0.45	2	3	4
Slurry Seals	$1.08	$0.90	3	5	7
Microsurfacing	$1.50	$1.25	3	7	9
Chip Seals	$1.02	$0.85	3	5	7
Thin Hot-Mix Overlay	$2.09	$1.75	2	7	12
Thin Cold-Mix Overlay	$1.50	$1.25	2	5	10

Rajagopal evaluated the cost-effectiveness of 225 chip seal and 214 microsurfacing projects [2]. Results showed that chip seals are more economically beneficial than microsurfacing. Chip seals were observed to be more beneficial when applied to the pavements having a prior PCI of 71-75. The results of the study are presented in Figure 14.

Figure 14. Relative benefit ratios for chip seal and microsurfacing [2]



Objective

The objective of this study was threefold. First, the rheological and molecular properties of tire rubber modified asphalt emulsion and other conventional emulsions were evaluated in the laboratory. Second, the laboratory performance of chip seal specimens prepared with tire rubber modified asphalt emulsion was investigated in terms of aggregate loss and the results were compared to that of the chip seal specimens prepared with conventional and polymer-modified asphalt emulsions. The effect of Rubber Aggregate (RA) as a partial replacement to Light-weight Aggregate (LWA) and Granite Aggregate (GA) in chip seals was also evaluated as a part of this study. For this purpose, a partial experimental factorial was developed where several test factors including the types of emulsion, and application rates of emulsions were investigated. Finally, an experimental factorial was developed to assess the short-term field performance of chip seal sections constructed with tire rubber modified asphalt emulsion and the results were compared to that of the chip seal sections constructed with conventional emulsions.

Scope

Chip seal specimens were prepared in the laboratory with different types of emulsion, different application rates as specified by DOTD, Texas Department of Transportation (TxDOT), and the National Cooperative Highway Research Program (NCHRP) Report 680; and different aggregate blends. Laboratory testing evaluated the loss of aggregate, adhesion bond between the emulsion and the aggregate, and the rutting performance of field extracted specimens using the Sweep Test, Pennsylvania Aggregate Retention Test (PART), the Bitumen Bond Strength (BBS) test, and the Hamburg Loaded-Wheel Tester (LWT), respectively.

The chemical compositions and rheological properties of the asphalt binder residues were evaluated using High-Pressure Gel Permeation Chromatography (HP-GPC), and Saturate, Aromatic, Resin and Asphaltene (SARA) analysis tests, while Fourier Transform Infrared Spectroscopy (FTIR) was used to detect and measure the indices of various functional groups present in the binder residues at different aging conditions. Furthermore, the quantification and comparison of the rheological properties of the asphalt binder residues were evaluated using the Superpave Performance Grading (PG) and the Surface Performance Grade (SPG). The Multiple Stress Creep Recovery (MSCR) test was also conducted to assess the resistance of the binder residues against rutting at high temperature. The analysis of the test results was conducted to evaluate the potential benefits of using tire rubber modified emulsion in not only chip seal applications but also in other pavement preservation activities.

A manual distress survey was conducted on the chip seal field sections after three, six, twelve, and eighteen months of construction. Field distresses associated with chip seals such as bleeding, rutting, longitudinal cracking, and transverse cracking were monitored, and the Pavement Condition Index (PCI) for each test section was calculated.

Methodology

To achieve the objective of this study, an experimental test factorial was developed and conducted to evaluate the rheological, chemical, and molecular properties of asphalt emulsions and to measure the laboratory performance of chip seals prepared with different asphalt emulsions, aggregate blends, and application rates. Based on the test results of the laboratory experiment, a field-testing program was executed to investigate the short-term performance of chip seals constructed with conventional and tire rubber modified asphalt emulsions and at different application rates. Chip seal sections were constructed on project LA 128, a 2.9-mile control section located in Tensas parish with an Average Daily Traffic (ADT) of 470 vehicle/lane/day, and performance data were collected regularly during the field monitoring period.

Test Materials

Asphalt Emulsions and Asphalt Binder

Table 16 presents the types of emulsion investigated in this study, which included a tire rubber modified asphalt emulsion (CRS-2TR), two conventional emulsions (CRS-2 and CRS-2P), a high float polymer modified emulsion (CHFRS-2P), and an asphalt rubber (AC20-5TR), which is designed to be used in hot chip seal application.

Table 16. Asphalt emulsion application rates

Types of binder	Total Application Rates in gsy (Residual Application Rates)			
	ASTM D 7000	DOTD	TxDOT	NCHRP
CRS-2	0.30 (0.20*)	0.31 (0.20)	0.37 (0.24)	-
CRS-2P	0.30 (0.20)	0.31 (0.21)	0.37 (0.25)	0.58 (0.39)
CRS-2TR	0.30 (0.20)	0.31 (0.20)	0.37 (0.24)	0.60 (0.39)
CHFRS-2P	0.30 (0.20)	0.31 (0.21)	0.37 (0.25)	-
AC20-5TR	-	0.31	-	-

* Residual application rates

Production Process of the Tire Rubber Modified Asphalt Emulsion

Scraped tires are collected and ground until minus 30 mesh size is achieved to produce crumb rubber, which is then used to produce tire rubber modified asphalt emulsion. The metal and fibers present in the scrap tires are removed through a screening process. The production of CRS-2TR starts with manufacturing a Tire Rubber Modified Asphalt Cement (TRMAC) with a crumb rubber concentration of 25%. A base asphalt cement is mixed with the ground (either by cryogenic or ambient process) crumb rubber particles by utilizing an absorption process under specific pressure, time, temperature (approximately 260°C), and agitation conditions. The agitation process is continued until all the crumb rubber particles become fully digested and dispersed into the asphalt cement and the product meets the solubility requirement (ASTM D 2042) of 99.0%. If the produced binder passes the solubility test, it is added with additional base asphalt cement to dilute to adjust the concentration of crumb rubber to 5% and to create a tire rubber emulsion base. Afterward, the Tire Rubber Emulsion Base (TREB) is emulsified using water and emulsifiers to create the tire rubber modified cationic rapid set emulsion (CRS-2TR). Typical application temperature for CRS-2TR ranges between 60 and 70°C in the field. It is worth noting that the asphalt rubber (AC20-5TR) is produced by further modifying the 5% concentration asphalt base with SBS co-block polymer, making it suitable to sustain high traffic volume.

Residue Recovery of the Emulsions and Aging

A low-temperature evaporative method described in AASHTO PP 72 (Method A) was used for residue recovering from the emulsions. This procedure requires the emulsion sample to be placed and spread over a silicone mat to create an emulsion film thickness of 2 mm. The poured sample was then kept in an oven and was subjected to curing for 48 hours (at 25°C for the first 24 hours and at 60°C for the second 24 hours) in order to remove the water present in the emulsion. After recovering the residue, the sample was collected in a quart can and was kept in an oven at 135°C for an adequate amount of time to render it liquid enough to pour into small tins for further testing. Simulation of aging in the short-term and in the long-term was accomplished in accordance with AASHTO R28 using the Rolling Thin Film Oven (RTFO) and the Pressure Aging Vessel (PAV) devices.

Aggregate Types

The coarse aggregate investigated in this study included lightweight aggregate (LWA), granite aggregate (GA), and rubber aggregate (RA). The physical properties of the coarse aggregate are summarized in Table 17. Size 3 gradation was selected for LWA according to DOTD standard specifications for chip seal and a 90-10 blend of LWA-RA was also prepared by replacing 10% of the particles retained in the 6.35 mm sieve in the Size 3 LWA gradation with crumb rubber aggregate. For the granite aggregate, two aggregate blends were prepared by replacing 10% and 20% of the particles, respectively.

Table 17. Physical properties of aggregate investigated

Type of Aggregate	Bulk specific gravity in SSD condition	Absorption capacity (%)	Unit weight (Kg/m^3)
Light weight aggregate (LWA)	1.51	15.63	595
Granite aggregate (GA)	2.61	1.36	1561.8
Rubber aggregate (RA)	1.15	2.55	460

Design of Chip Seals

The two main components in the design of chip seal are the total application rate for emulsion and the application rate for the aggregate. As previously discussed, state agencies follow different design procedures for the design of chip seal. The emulsion application rates were evaluated based on ASTM D 7000 (fixed application rate of 0.3 gsy), DOTD, TxDOT, and NCHRP Report 680 for the different types of emulsion investigated in this study. DOTD standard design specifications for chip seals require that a fixed application rate of 0.31 gsy be used for the emulsion and 0.0075 cy/sy for the aggregate, as shown in Table 1. TxDOT uses the modified-Kearby method and the McLeod method for the design of chip seal [16]. In this study, the modified Kearby method was used to design the chip seal, which employs the following equation to calculate the application rate for the emulsion:

$$A = 5.61E\left(1 - \frac{W}{62.4G}\right)T + V \tag{21}$$

Where, A = asphalt emulsion application rate in gsy at 60°C; E = embedment depth calculated using Equation (22); G = dry bulk specific gravity of the aggregate; T = traffic correction factor obtained from Table 18; and V = correction for surface condition obtained from Table 19.

$$E = e * d \tag{22}$$

Where, d = average mat depth in inches, as calculated from Equation (23); and e = percent embedment expressed as a decimal, as determined from Figure 15.

$$d = 1.33 * {}^{Q}/_{W} \tag{23}$$

Where, Q = aggregate quantity determined from the board test in lbs./sy; and W = dry loose unit weight in lbs./ft^3.

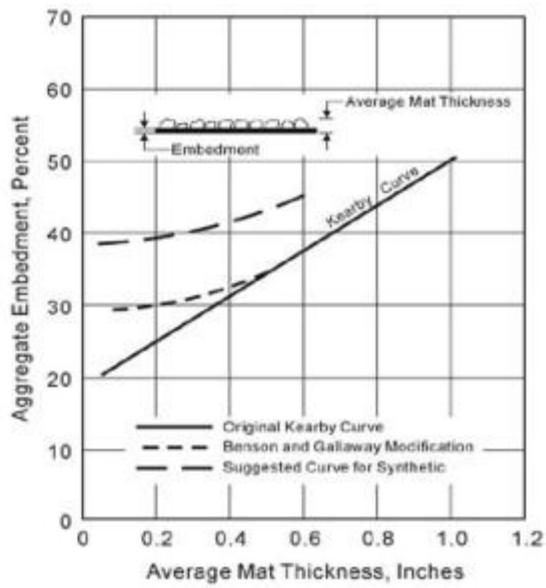
Table 18. Asphalt application rate correction for traffic [16]

	Traffic – Vehicles per day per lane				
	>1000	500-1000	250-500	100-250	<100
Traffic Correction Factor (T)	1.00	1.05	1.10	1.15	1.20

Table 19. Application rate correction for existing pavement condition [16]

Description of Existing Surface	**Correction, gsy**
Flushing, slightly bleeding surface	-0.06
Smooth, nonporous surface	-0.03
Slightly porous, slightly oxidized surface	0.00
Slightly pocked, porous, oxidized surface	+0.03
Badly pocked, porous, oxidized surface	+0.06

Figure 15. Relation of percent embedment to mat thickness [74]



The final application rate for emulsion is calculated from the following equation:

$$A_{recommended} = A + k(A_{theoretical} - A) \quad (24)$$

Where, A = asphalt application rate from Equation (21); $A_{theoretical}$ = Theoretical quantity of emulsified asphalt = A/R; R = percent residual asphalt in the emulsion expressed as decimal; and K = seasonal adjustment factor obtained from Table 20.

Table 20. Adjustment factor K based on the season of construction [16]

Construction season	Seasonal adjustment factor, K
Spring	0.60
Summer	0.40
Fall	0.70
Winter	0.90

NCHRP Report 680 recommends the following equations to determine the design application rate for emulsions in chip seal [38]:

$$B_d = [B_b * EF * PF] + A_s + A_e + A_{as} + A_{aa} \quad (25)$$

Where, B_d = design binder application rate, gsy, B_b = basic binder application rate, gsy, EF = emulsion factor = 1.0 for emulsions with < 67% residue and 1.1 – 1.2 for emulsions with > 67% residue; PF = polymer factor (for polymer-modified emulsions) obtained from Table 21; and A_s , A_e , A_{as} , A_{aa}= adjustments for substrate texture, embedment, absorption into substrate, absorption into cover aggregate, gsy.

Where,

$$B_b = VF * ALD \quad (26)$$

Where, VF = design voids factor, gsy/in, ALD = average least dimension of cover aggregate.

Where,

$$\mathrm{VF} = \mathrm{Vf} + \mathrm{Va} + \mathrm{Vt} \quad (27)$$

Where, Vf = basic voids factor, as determined from Figure 16, Va = aggregate shape adjustment factor obtained from Table 22, and Vt = traffic effects adjustment factor for absence of an average mix of light and heavy vehicle in free flow condition.

Figure 16. Basic void factor versus traffic [38]

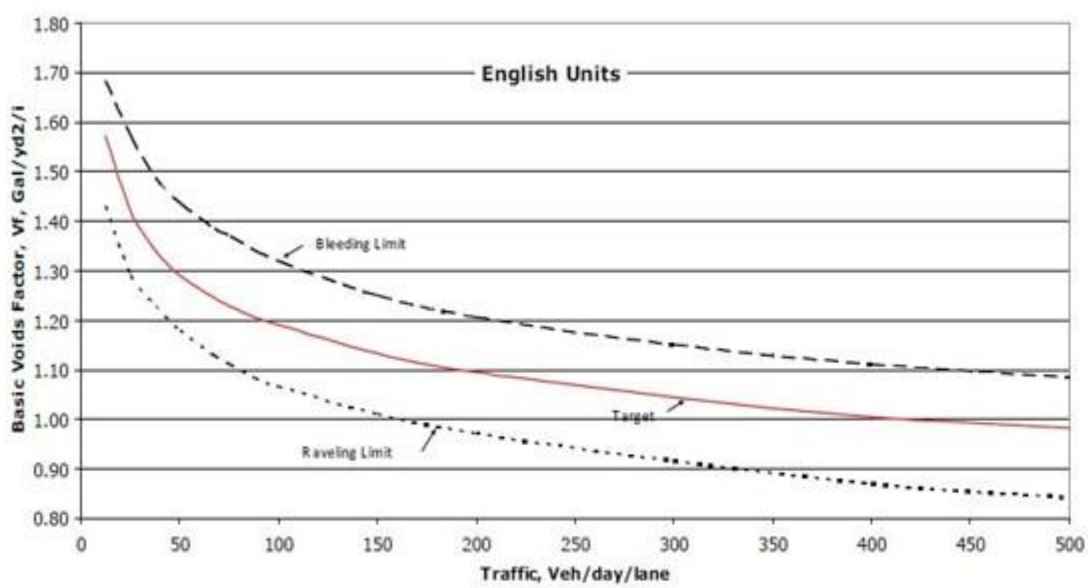


Table 21. Polymer modified emulsion factor [38]

Traffic (veh/day/lane)	PF
< 500	1.0
500 – 2500	1.1
> 2500	1.2

Table 22. Suggested adjustment for aggregate shape, Va [38]

Aggregate Type	Aggregate Shape	Flakiness Index, FI, %	Va, gsy/in
Crushed	Very flaky	>35	Too flaky, not recommended
	Flaky	26 – 35	0 to -0.056
	Angular	15 – 25	0
	Cubic	<15	+0.056
	Rounded	-	0 to +0.056
Uncrushed	Rounded	-	+0.056

The aforementioned design procedures were used to calculate the emulsion application rates based on ASTM D 7000 (fixed application rate of 0.3 gsy), DOTD, TxDOT, and NCHRP Report 680 for the different types of emulsion investigated in this study. As shown in Table 23, the application rates recommended by NCHRP Report 680 were almost double the application rates recommended by the other design methods. It is noted that practical experiences in Louisiana indicate that an application rate greater than 0.42 gsy would result in a failing installation due to an aggregate embedment depth of 100%, causing a frictionless surface for the traveling vehicles. Therefore, the NCHRP-recommended application rate was adjusted in the field-testing experiment.

Table 23. Asphalt Emulsion Application Rates

Types of binder	Application Rates (gsy)			
	ASTM D 7000	**DOTD**	**TxDOT**	**NCHRP**
CRS-2	0.30	0.31	0.37	-
CRS-2P	0.30	0.31	0.37	0.58
CRS-2TR	0.30	0.31	0.37	0.60
AC20-5TR	-	0.31	-	-

Experimental Factorial

An experimental design was developed to analyze the effects of the variables to be investigated and their interaction. Although a full factorial experiment design can account for all the possible interactions among the variables, it was not feasible due to the time and resource constraints of the study. In this study, three factors were investigated, which were the application rates, types of emulsion, and aggregate blends, at the corresponding number of levels of 4, 4, and 2, respectively, yielding a total number of 16*2=32 cases for lightweight aggregate. In addition, considering three replicates for each case, the total number of cases was 96. To keep the number of cases within a manageable size, a partial test factorial was developed neglecting the higher order interactions, where a total number of 16 cases were considered allowing for drawing direct comparisons for the variables investigated. To investigate the applications rates at four levels, the types of emulsion and aggregate blends were kept constant at the number of levels 2 and 1, respectively. Similarly, the type of emulsion was investigated at four levels by keeping both the application rates and aggregate blends at level 1. Finally, the aggregate blend was investigated at two levels; whereas, the types of emulsion and application rates were kept constant at levels 2 and 1, respectively. Similarly, 34 (22+12) cases were investigated for granite aggregate. A summary of the test factorial is presented in Table 24 and Table 25.

Table 24. Details of the experimental test factorial (for lightweight aggregate)

Test	Primary Factors	Levels	Corresponding Factors	Levels	Corresponding Factors	Levels
Sweep and PART	**Application rates**	DOTD	**Types of emulsion**	CRS-2P	**Aggregate blends**	LWA
		TxDOT				
		ASTM D 7000		CRS-2TR		
		NCHRP 680				
	Types of emulsion	CRS-2P	**Application rates**	DOTD	**Aggregate blends**	LWA
		CRS-2TR				
		CRS-2				
		AC20-5TR				
	Aggregate blends	LWA	**Application rates**	DOTD	**Types of emulsion**	CRS-2P
		90-10 blend of LWA and RA				CRS-2TR

Table 25. Details of the experimental test factorial (for granite aggregate)

Test	Primary Factors	Levels	Corresponding Factors	Levels	Corresponding Factors	Levels
Sweep test	**Application rates**	DOTD	**Types of emulsion**	CRS-2P	**Aggregate blends**	Granite
		TxDOT		CRS-2TR		
		ASTM D 7000		CHFRS-2P		
	Types of emulsion	CRS-2	**Application rates**	DOTD	**Aggregate blends**	Granite
		CRS-2P				
		CRS-2TR				
		CHFRS-2P				
	Aggregate blends	Granite	**Application rates**	DOTD	**Types of emulsion**	CRS-2P
		90-10 blend of granite and RA				CRS-2TR
		80-20 blend of granite and RA				CHFRS-2P
PART	**Types of emulsion**	CRS-2P	**Application rates**	DOTD	**Aggregate blends**	Granite
		CRS-2TR				
		CHFRS-2P				
	Aggregate blends	Granite	**Application rates**	DOTD	**Types of emulsion**	CRS-2P
		90-10 blend of granite and RA				CRS-2TR
		80-20 blend of granite and RA				CHFRS-2P

Rheological, Molecular, and Chemical Characterization

Performance Grade and Surface Performance Grade Test

The viscous and elastic behaviors of the emulsion residues and binder at intermediate to high temperatures were characterized by conducting the Dynamic Shear Rheometer (DSR) test according to AASHTO T 315. A DSR test was conducted on both unaged, RTFO-aged, and PAV-aged samples to evaluate the rutting and fatigue resistances of the binder residues, see Figure 17. Binder's resistance to rutting or permanent deformation and fatigue cracking is related to $G^*/\sin\delta$ and $G^*\sin\delta$, respectively, where G^* is the complex modulus of the binders and δ is the time lag between the applied stress and the resulting strain. Low temperature performance was characterized by the Bending Beam Rheometer (BBR) test according to AASHTO T 313 (See Figure 18). Creep stiffness, S(t) and the m-value as measured from the BBR test were the performance parameters of interest at low temperature. Additionally, the Performance Grade (PG) for the binders was obtained following the specification provided in AASHTO M 320. The number of replicates was three for all cases and the average Coefficient of Variation (COV) obtained from the test results was 1.2%, which validates the repeatability of the test results.

Figure 17. Dynamic Shear Rheometer (DSR) test; (a) sample trimming (b) DSR machine

(a) (b)

Figure 18. Bending Beam Rheometer (BBR) test; (a) mold preparation before testing (b) BBR machine

(a) (b)

Surface Performance Grade (SPG) tests were also conducted to evaluate the susceptibility of the binders to bleeding and aggregate loss for chip seal application. SPG specification was originally developed to account for the shortcomings of the current PG specification in evaluating chip seal binders as it was developed primarily for HMA binders [66].

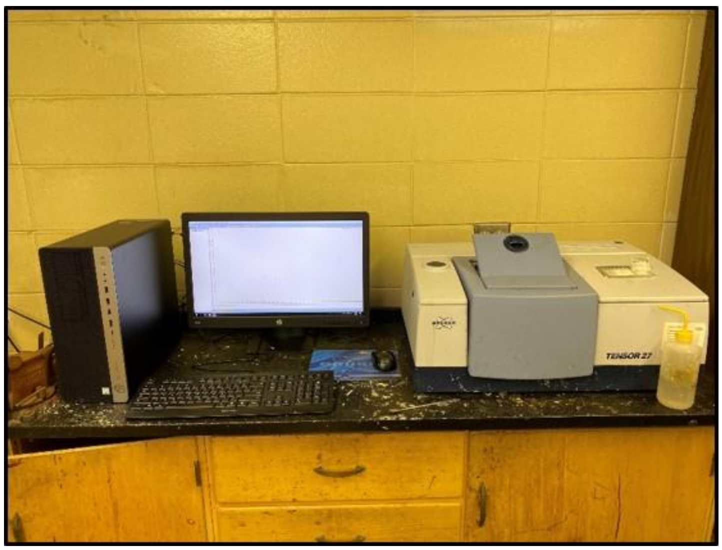
Multiple Stress Creep Recovery Test

The rutting and permanent deformation potential and the effect of modifications on the binder's resistance at high temperatures were evaluated by conducting the Multiple Stress Creep Recovery (MSCR) test. This test was conducted according to the loading scheme and number of cycles specified in AASHTO TP 70. The concept of applying a cyclic load (creep) and then a recovery period (subjecting a creep load for one second and allowing it to recover for 9 seconds) is used in the test to evaluate the potential for permanent deformation. A DSR was used to perform the MSCR test on RTFO-aged samples by subjecting the specimen to 10 repeated stress and relaxation levels at 0.1 kPa and 3.2 kPa. The measured performance parameters were the recovery percentage and the non-recoverable creep compliance (J_{nr}), which were used in the analysis and the interpretation of the measurements.

Fourier Transform Infrared Spectroscopy (FTIR) test

Infrared spectroscopy provides useful information about the different functional groups present in asphalt binder. However, the identification of each functional group in asphalt binder can be challenging due to the complex structure of the material. Therefore, the FTIR test was performed only to quantitatively evaluate the changes in highly polar and oxygen containing groups such as carbonyl (C=O) and sulfoxide (S=O) and to compare the resistance of the binder residues to aging. Table 26 presents the equations used to calculate these indices [96].

Figure 19. FTIR testing using Bruker Alpha FTIR spectrometer



Absorption band regions of carbonyl and sulfoxide group vibrations are located around the wave number of 1,700 cm^{-1} and 1,030 cm^{-1}, respectively. A Bruker Alpha FTIR spectrometer was used to characterize the FTIR spectra of the binder residue samples using an attenuated total reflectance (ATR) mode with a diamond crystal. Each sample was scanned 64 times with a spectral wavelength range of 600 to 4,000 cm^{-1} and a resolution of 4 cm^{-1} for the data collection. The spectra were collected and analyzed using the OPUS 7.2 software. The relative degree of concentration changes of the different functional groups present in the asphalt binder residues under RTFO-aged and PAV-aged conditions were the focus of the FTIR analysis.

Table 26. Definitions of FTIR-based indices [97]

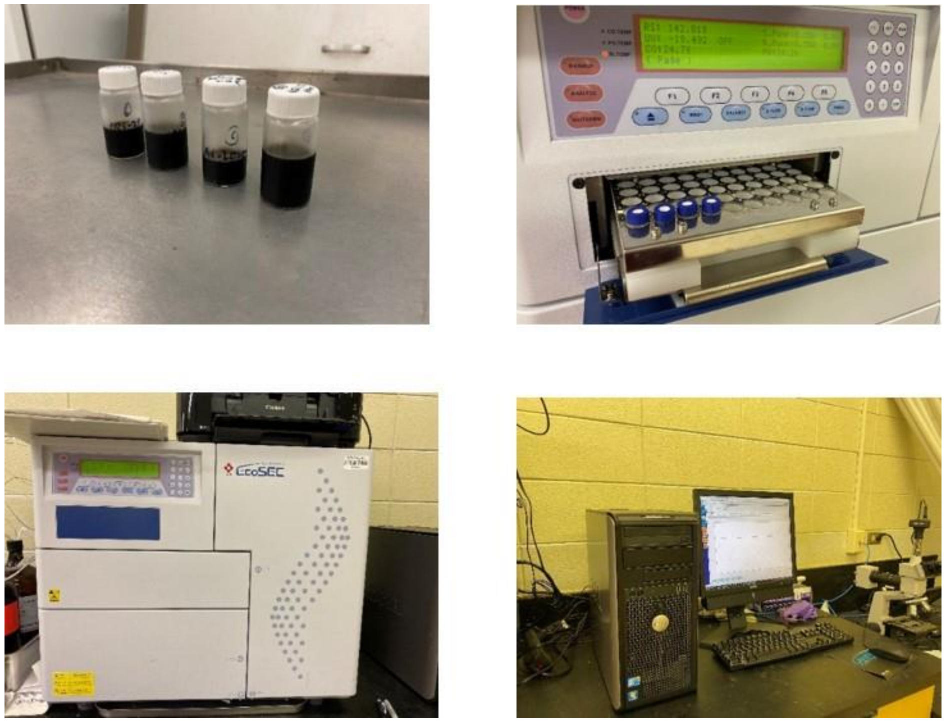
Group	Name of Index	Equations	Equation Number
Functional Group	Carbonyl Index (IC=O)	$\frac{A_{1700}}{(A_{1460}+A_{1375})}$	(1)
	Sulfoxide Index (IS=O)	$\frac{A_{1030}}{(A_{1460}+A_{1375})}$	(2)

High Pressure Gel Permeation Chromatography (HP-GPC) test

In order to study the effects of aging on the distribution of the molecular components in the different binder residues, HP-GPC test was conducted for aged and unaged samples using an EcoSEC HLC-8320GPC containing an auto injector, along with DRI and UV detectors. The microstyragel columns with pore sizes of 30 Å, 75 Å (2 columns), and 200 Å, were used for the separation of the molecular components. Pre-weighted calibration standards, Tosoh PStQuick series (B, E, and F) containing different polystyrene standard mixtures inside each vial, were used to calibrate the GPC columns.

The distribution of molecular components was divided into two groups based on their molecular weights; the first is a low molecular weight group containing the molecular components, which weigh less than 3,000 Daltons and the second is a high molecular weight group containing molecular components with a weight of 3,000 Daltons or higher. The curves obtained from the HP-GPC tests were integrated and normalized over the total area for analysis. An error of 0.2% or less in the measured molecular fractions can be expected from the test results. Each binder residue was tested with two replicates and the average value was used in the analysis.

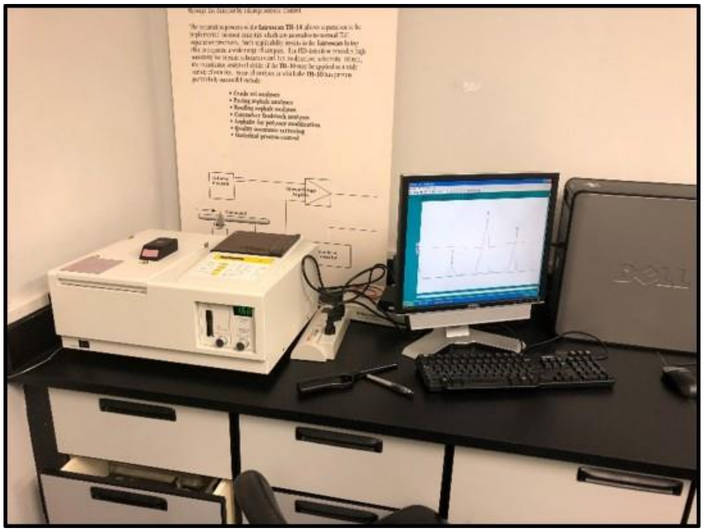
Figure 20. HP-GPC testing using EcoSEC HLC-8320GPC



SARA Analysis

SARA analysis was used to determine the chemical compositions of asphalt binder, which is considered a colloidal system of four fractions (saturates, asphaltenes, resins, and aromatics) distinguished by their polarity. Among the four constituents, asphaltenes and resins are considered as polar fractions; whereas, saturates and aromatics are considered as nonpolar or less polar fractions [98]. Each binder and residual asphalt were fractionated to produce maltenes and asphaltenes (As) using ASTM Method D 3279. The composition of saturates (S), aromatics (Ar), and resins (R) were then obtained from further fractionation of the maltene using an Iatroscan Hydrocarbon Analyzer, see Figure 21.

Figure 21. SARA analysis using Latroscan Hydrocarbon Analyzer



Binder properties are greatly related to the composition of these fractions and their polarity [99]. Higher asphaltenes have been linked to higher stiffness, aging, and brittleness [100]. Due to the formation of ketones with aging of asphalt binders, the concentration of asphaltene component also increases, creating a stiffer structure [99]. The creep stiffness modulus and the m-value were also found to be affected negatively by the increase in asphaltene content [101]. The current study evaluated the asphaltene fraction obtained from the SARA analysis to assess its effects on asphalt binder aging. Colloidal stability of the asphalt binders depends on the solubility of asphaltenes into maltenes and is represented by the colloidal instability index, CII. The colloidal instability index was calculated using Equation (30) [102]. The colloidal stability decreases with the increase in colloidal index and becomes unstable when the index value is from 0.5 to 2.7 [103].

$$CII=\frac{\text{Saturates}+\text{Asphaltenes}}{\text{Resins}+\text{Aromatics}} \quad (30)$$

Chip Seal Laboratory Performance Tests

Sweep Test

As shown in Figure 22, chip seal specimens were prepared and subjected to a brooming action simulated in the laboratory to determine the %Aggregate Loss. First, asphalt felt disks of 300 mm diameter were cut and placed in a forced draft oven at 50°C for 48 hours followed by 24 hours of cooling at room temperature to flatten prior to testing. Then, the disks were glued to circular wooden disks of similar diameter to keep the specimens flat during the sweep test. The sample disks were weighed and placed inside a strike-off template. The emulsion, preheated at 60°C, was then applied to the sample disks. A strike-off trowel was used to spread the emulsion evenly over the asphalt felt disk and remove the excess.

Figure 22. Preparation of chip seal specimen

The pre-weighed aggregate was then applied immediately onto the emulsion and compacted using a cylindrical roller compactor having an average diameter of 165 mm. The compactor was rolled three half cycles in one direction and three half cycles in the perpendicular direction to set the aggregate. The samples were conditioned at 35°C for 4 hours before testing [87] [104]. After 4 hours, the specimens were taken out and gently brushed to remove any loose aggregate on the specimens. The specimen weights were then recorded as the initial weight.

The sweep test was performed on the resulting chip seal specimen according to ASTM D 7000 to assess the performance of chip sealing against aggregate loss, see Figure 23(a). The specimens were placed in the sweep test apparatus (A 120 Hobart Mixer) with a modified brush holder equipped with a nylon brush as shown in Figure 23(a). The mixer was calibrated to facilitate sweeping at a rate of 0.83 gyrations per second and abraded the test specimens for 60 sec. to simulate the sweeping action of a broom in the field. The specimens were then taken out and gently brushed to remove the loose aggregate. Then, the specimens were weighed again, which was recorded as the final specimen weight. The % Aggregate Loss was determined for each sample using the following equation:

$$\%\ Aggregate\ Loss=\left(\frac{A\text{-}B}{A\text{-}C}\right)*100 \tag{31}$$

Where, A = initial specimen weight; B = final specimen weight; and C = asphalt disk weight.

Three replicates were tested for each case and the average value was considered in the analysis. The average coefficient of variation (COV) in the sweep test results was 10.7%, which was deemed acceptable.

Figure 23. Laboratory testing of chip sealing

(a) Sweep Test

(b) Pennsylvania Aggregate Retention Test (PART)

(c) Bitumen Bond Strength (BBS)

(d) Loaded Wheel-Tracking Tester (LWT)

Pennsylvania Aggregate Retention Test (PART)

The Pennsylvania aggregate retention test (PART), developed by Kandhal et al., was also conducted to assess aggregate loss in chip seal and to confirm the results obtained from the sweep test [77]. To conduct the test, a sieve was modified by drilling three screws from the sides to the inward direction. Four 12.5-mm standard sieves of 200 mm diameter and 50 mm height were assembled with a pan and placed in a Mary Ann laboratory sieve shaker. The modified sieve was placed on top of the assembly. As shown in Figure 23(b), the chip seal specimen was placed in the modified sieve in an upside-down position where the screw extensions inside provided support for the resting specimen. The sieve shaker was inclined at an angle of 60° and run for 10 minutes. The bottom pan was then removed from the assembly, which collected the aggregate that dropped from the specimen due to the shaking and the tapping action of the shaker. The aggregate was weighed and recorded as the knock-off weight. The percent knock-off loss was determined for each sample using the following equation:

$$\%\ Knockoff\ loss = \left(\frac{C}{A-B}\right) * 100 \tag{32}$$

Where, A = weight of total aggregate applied to the specimen; B = weight of initial loss of aggregate by hand sweep; and C = weight of knock-off aggregate.

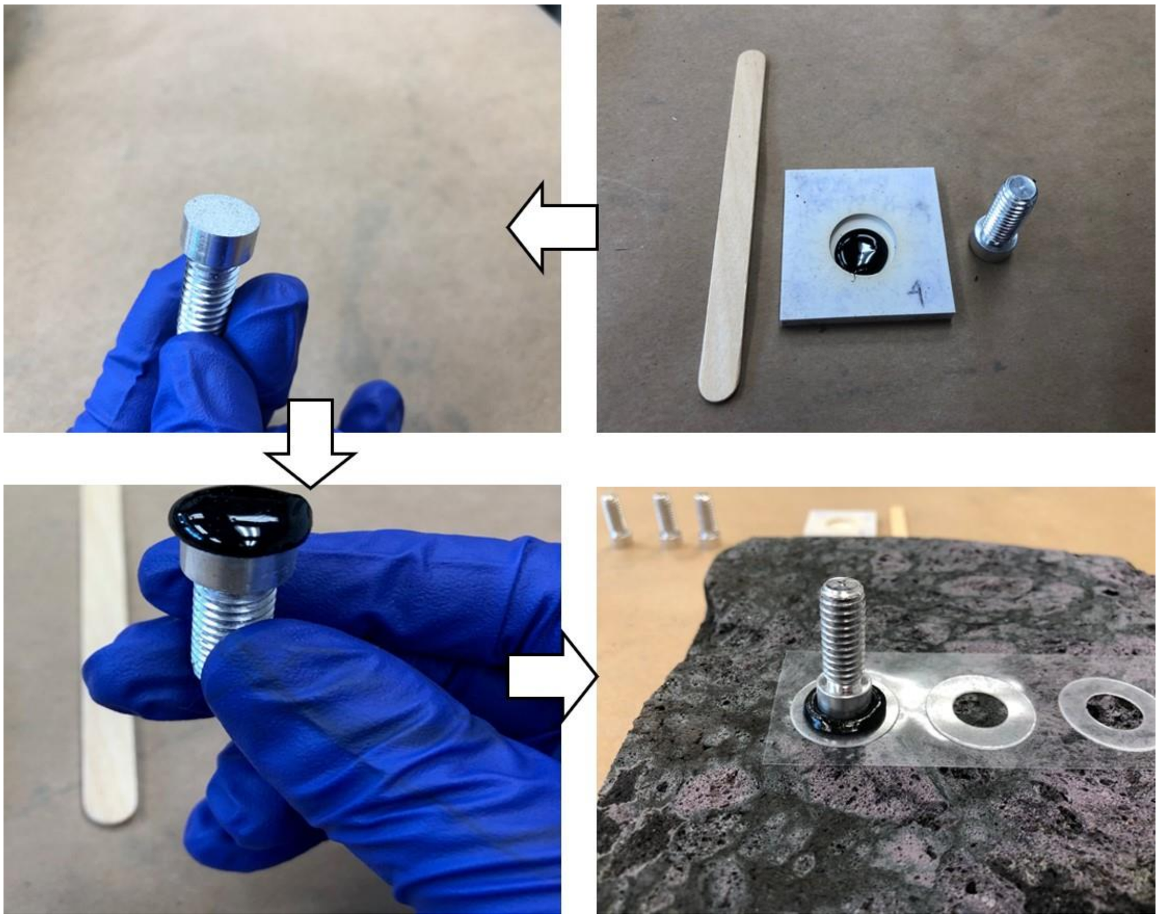
Three replicates were tested for each case and the average value was considered in the analysis. The average coefficient of variation in the PART test results was 3.8%, which validates the repeatability of this test.

Bitumen Bond Strength (BBS) Test

To evaluate the effect of emulsion type on the adhesion bond strength between the emulsion and the aggregate, a pull-out test was conducted in accordance with ASTM D 4541 by using a portable adhesion tester. The tester consists of a control module, a loading fixture or pull-off stub, a piston, and a pressurized air source. For this study, a Type IV self-aligning portable adhesion tester equipped with an F-2 piston (load range 100 psi – 1250 psi) was used as shown in Figure 23(c). Self-contained miniature CO_2 cylinders were used as the pressurized air source. Pull-off stubs of ½-in. diameter were used to test the adhesion bond between LWA and the emulsions being investigated.

The sample preparation for BBS test is presented in Figure 24. The aggregate blocks of 6 in. x 6 in. x 1.5 in. dimension were first cut from large rocks extracted from the supplying quarry. To ensure uniform roughness, the aggregate samples were cleaned with de-ionized water and were then placed in the oven at 60°C for 1 hour to remove the absorbed water from the surface. The pull-off stubs were degreased with acetone to remove dust. The residues were prepared from the emulsions according to AASHTO PP 72. The binder samples were prepared by pouring 0.40 ± 0.05 g of residue into an 8-mm diameter silicone mold. The binder specimen was removed from the mold and was carefully placed onto the pull-off stub as it reached a stable consistency. The pull-off stub was then pressed vertically against the aggregate surface without any torsion to avoid the entrapment of air bubbles. The stub-aggregate system was cured at room temperature (25°C) for 24 hours before testing.

Figure 24. Preparation of bond strength test specimen



The adhesion tester measured the bond strength by pulling the stub at a constant rate of 100 psi/sec. The burst pressure at which debonding between the pull-off stub and the aggregate plate occurs, was recorded. Three replicates were tested for each type of emulsion and the average value was used in the analysis. The average COV in the BBS test results was 1.8%, which demonstrates the repeatability of this test. The pull-off tensile strength was calculated using the following equation:

$$POTS = \frac{(BP \text{ x } Ag) - C}{Aps} \quad (33)$$

Where, POTS = pull-off tensile strength in psi; BP = burst pressure in psi; Ag = contact area between gasket and piston plate = 2.009 in^2 for F-2 piston; C = piston Constant =

0.1775 lbs ± 1.5% for F-2 piston; and Aps = area of pull stub = 0.1963 in^2 for ½-in. diameter pull-stub.

Loaded Wheel Tracking (LWT) Test

Rutting performance of chip seal was assessed using a Hamburg-type Loaded Wheel Tester (LWT), manufactured by PMW, Inc. of Salina, Kansas. The test was conducted in accordance with ASTM D 6372, "Standard Practice for Design, Testing, and Construction of Microsurfacing." First, the loaded wheel tracking machine was prepared by installing a suitable load cell and calibrating it to ensure that 125 lbs. of load was being applied by the wheels. The specification also requires that a soft rubber wheel is used for the testing, which was achieved by gluing neoprene rubber pads on the surface of the LWT wheels. A field trial was conducted with different type of emulsions and application rates obtained from the DOTD and TxDOT standard specifications. Cores samples were extracted from these sections and were used in the LWT test. After extraction, the core samples were placed into the oven at 60°C for 18 h to achieve a constant weight. The cores were weighed and were measured prior to testing. The cores were then mounted in the loaded wheel tester machine and were subjected to 1,000 passes at 44 passes a minute, as shown in Figure 23(d). The test was performed under dry condition at 22°C. After testing, the core samples were weighed again and were measured. The rut depth at 1,000 cycles was measured and was used in the analysis. The average COV in the LWT test results was 1.3%, which validates the repeatability of the measurements.

Field Testing Program

Overview of Test Project

The LA 128 project is located near Tensas Parish; Figure 25 shows an aerial view of the project location with the control section (036–05) marked in red. The road section had a traffic flow of 470 vehicle/lane/day indicating a low traffic volume. The DOTD Pavement Management System (PMS) was reviewed for construction history of the control section. It was observed that the control section (036-05) had two construction events: the first one was in 2002, which consisted of an asphalt surface treatment (AST) and the latest construction event was in 2009, which consisted of base stabilization and construction of an AC overlay.

Figure 25. Aerial view of project LA 128

The surface texture measurements were conducted to assess the existing surface conditions before the chip seals were placed. Distributor-truck application rate measurements were also carried out during construction of chip seals, followed by conducting surface texture measurement and manual distress survey at the chip seal sections after three, six, twelve, and eighteen months of construction.

Experimental Field Factorial

Figure 26 shows the project layout illustrating the types of emulsion and their application rates used in each test section. As shown in Figure 26, the project control section, a 2.9-mile long road section beginning from log mile 2.13 and ending at log mile 5.03, was divided into seven test sections on both the northbound lane and the southbound lane. The types of emulsion evaluated included a tire rubber modified asphalt emulsion (CRS-2TR) and two conventional emulsions (CRS-2 and CRS-2P). Asphalt rubber was not evaluated since the district does not use it regularly and does not have the expertise or the means to construct it in the field. Size 3 lightweight aggregate (LWA) was selected as the coarse aggregate according to DOTD standard specifications for chip seal.

There are two main components in the design of chip seal, which are the application rate for emulsion and the application rate for aggregate. In this project, the application rates of the emulsions were based on three approaches: DOTD specified rate, TxDOT design specification, and NCHRP 680 recommended rate; see Table 27. The DOTD specified application rate is 0.31 gsy, the TxDOT design procedure yields an application rate of

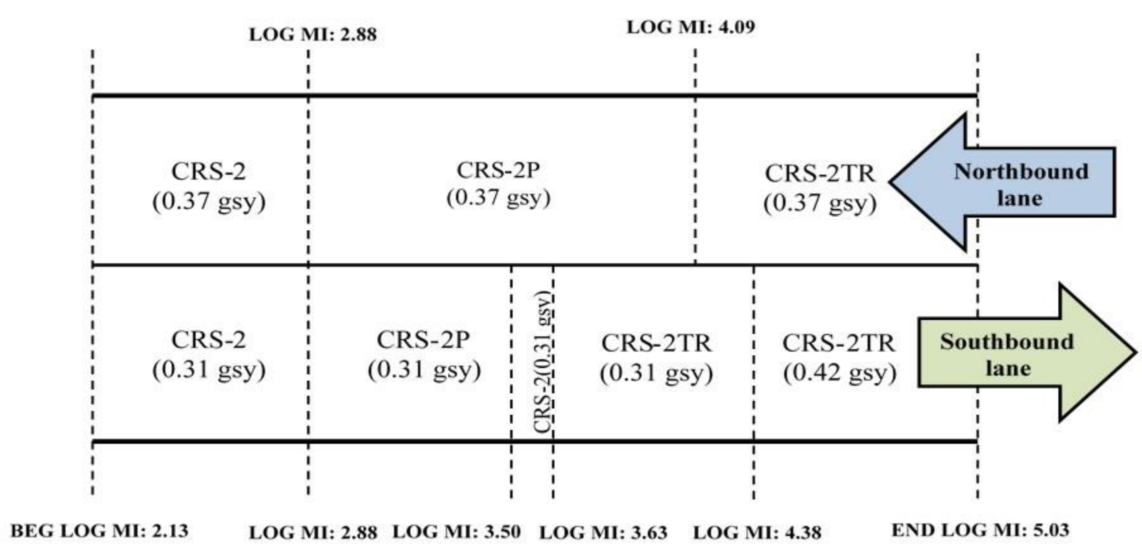
0.37 gsy, and the NCHRP recommended-application rate was 0.60 gsy. As previously noted, practical experience in Louisiana indicates that an application rate greater than 0.42 gsy would result in a failing installation due to an aggregate embedment depth of 100% causing a frictionless surface for the traveling vehicles. Therefore, the NCHRP application rate was reduced to 0.42 gsy for constructability reasons and this application rate was only used in the construction of a chip seal section with CRS-2TR emulsion. A fixed application rate of 0.0075 cy/sy for the lightweight aggregate was adopted as specified by DOTD standard specifications for chip seal.

Table 27. Experimental factorial for project LA 128

Section No.	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**
Type of emulsion	CRS-2	CRS-2P	CRS-2TR	CRS-2	CRS-2P	CRS-2TR	CRS-2TR
Application rate	TxDOT	TxDOT	TxDOT	DOTD	DOTD	DOTD	NCHRP[1]
Length, mile	0.75	1.21	0.94	0.75	0.62	0.75	0.65

[1] The application rate was reduced from 0.60 to 0.42 gsy for constructability reasons.

Figure 26. Project layout for the road section in LA 128



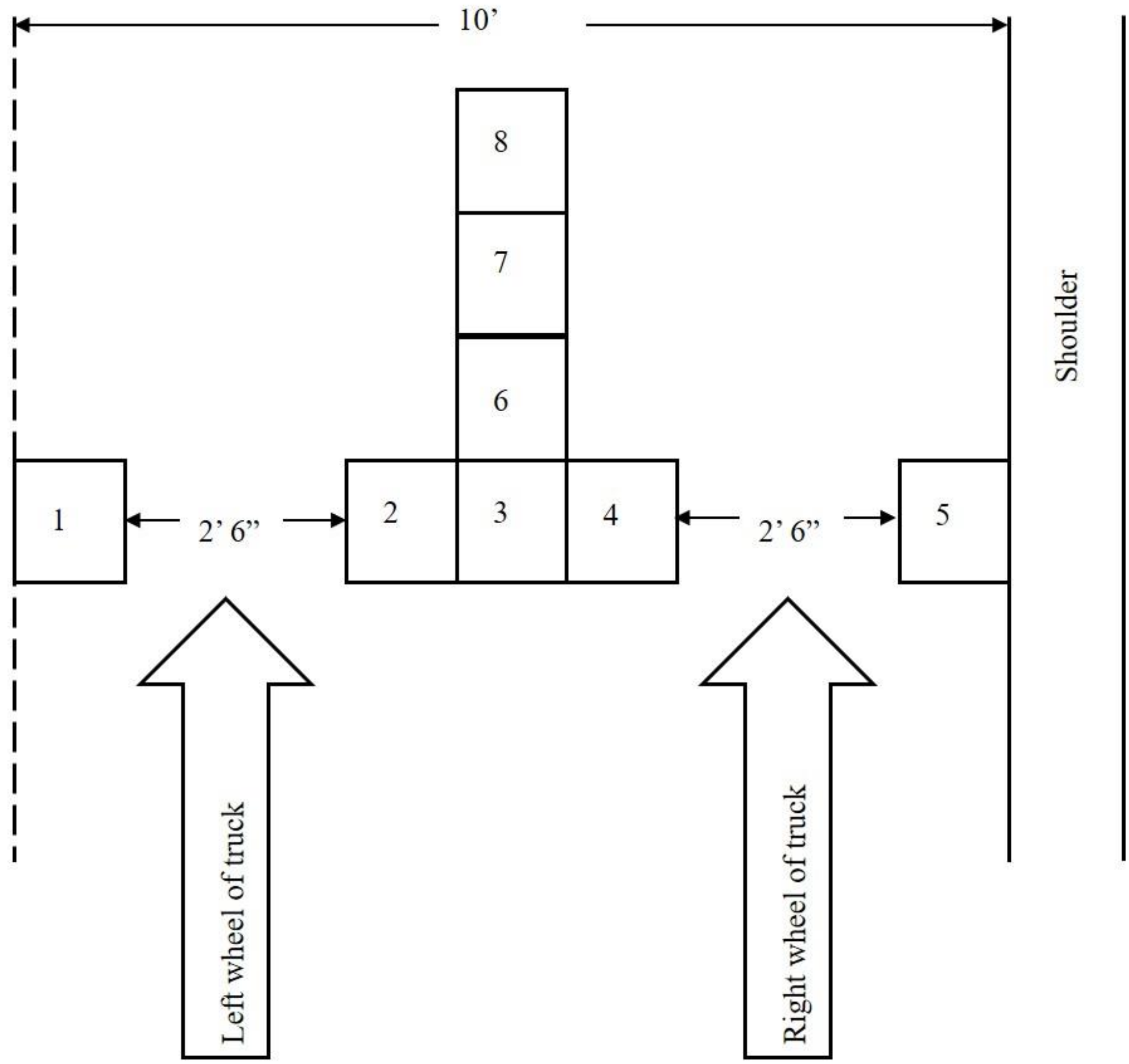
Construction of Chip Seals

Mean Texture Depth. Prior to the construction of chip seals, the surface macrotexture of each test section was measured according to ASTM E 965, "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique." First, a dry and homogenous area on the pavement surface was selected avoiding the presence of cracks and depressions. Then, the surface area was thoroughly cleaned by a soft bristle brush to remove any residue. A cylindrical container marked with volumetric scale was filled to the 25 ml line with Ottawa sand. The measured volume of Ottawa sand was poured on the cleaned pavement surface. The sand was evenly spread on the pavement to create flat surface by moving a standard ice hockey puck of 75 mm diameter in a circular motion. The hockey puck was used to spread the beads to the edges as much as possible. The diameter of the circular flat surface of the sand was measured at four equally spaced locations from edge to edge around the perimeter, and the average diameter was determined as shown in Figure 27. Three measurements were performed within each test section and the average value was used in the analysis.

Figure 27. Sand patch test locations in CRS-2TR (0.37 gsy) and CRS-2TR (0.42 gsy)

Application Rate Measurement during Construction. The LA 128 project was constructed on May 30, 2019, by Wright Asphalt and DOTD in District 58. During field application of the emulsions, the application rate was measured according to ASTM D 2995, "Standard Practice for Estimating Application Rate of Bituminous Distributors." Two BearCat BC-502 emulsion distributor trucks were used by the contractors in this project. The second distributor truck was used for the tire rubber modified emulsion in order to avoid contamination of the emulsions within the same distributor truck. The width of the test section varied between 10 and 11 ft. depending on the accessibility between the two lanes. Eight pre-weighed geotextile pads (12 in. by 12 in.) were placed across the width and along the length of the test section, as shown in Figure 28.

Figure 28. Pad layout for distributor truck application rate measurements



The distributor truck with the tire rubber modified emulsion, CRS-2TR, was first used to apply the emulsion on the test section CRS-2TR (0.31 gsy) starting from log mile 3.63 to log mile 4.38 at a target application rate of 0.31 gsy. It then continued to spray the emulsion to the next section, CRS-2TR (0.42 gsy), at a target application rate of 0.42 gsy from log mile 4.38 to log mile 5.03. A stop was scheduled during this operation to refill the distributor truck. The truck was turned around and started spraying on the test section CRS-2TR (0.37 gsy) at a target rate of 0.37 gsy from log mile 5.03 to log mile 4.09.

The second distributor truck then started spraying the CRS-2P emulsion on the section with a target application rate of 0.37 gsy starting from log mile 4.09 to log mile 2.88. The distributor truck was refilled and started spraying emulsion on the test section with a target application rate of 0.31 gsy from log mile 2.88 to log mile 3.50. At that point, the contractor had run out of the CRS-2P emulsion type. Therefore, from log mile 3.50 to log mile 3.63, the distributor truck sprayed CRS-2 emulsion on the remaining of the test section as shown in Figure 26.

The distributor truck was then moved to log mile 2.88 to start spraying CRS-2 emulsion on the test section at a target application rate of 0.37 gsy and continued to spray until it reached log mile 2.13. A stop was scheduled during the operation to refill the distributor truck. A DOTD distributor truck was used to transport CRS-2 emulsion from the district storage tank for refilling purpose. After refilling, the truck was then turned around and started spraying emulsion on the test section from log mile 2.13 to log mile 2.88 at a target application rate of 0.31 gsy.

The geotextile pads were set up before the distributor truck started spraying emulsion on the test sections as shown in Figure 29. The pads were removed right after the application of the emulsion and were weighed immediately as shown in Figure 30. A DOTD truck was used to transport rock from the district stockpile to the job site and loaded into the aggregate spreader truck, which then applied the aggregate on the test sections at a fixed application rate of 0.0075 cy/sy as specified in the DOTD specifications for the construction of chip seals.

Figure 29. Geotextile pads placement on the test sections

Figure 30. Geotextile pads after application of emulsion

Distress Survey

To assess the short-term field performance, manual distress survey was conducted on the chip seal sections after three, six, twelve, and eighteen months of construction. The distresses including bleeding, rutting, cracking, and potholes were considered to monitor the pavement deterioration. Measurement and quantification of the distresses observed in the chip seal sections was carried out according to the "Distress Identification Manual for the Long-Term Pavement Performance Program” published by the Federal Highway Administration (FHWA).

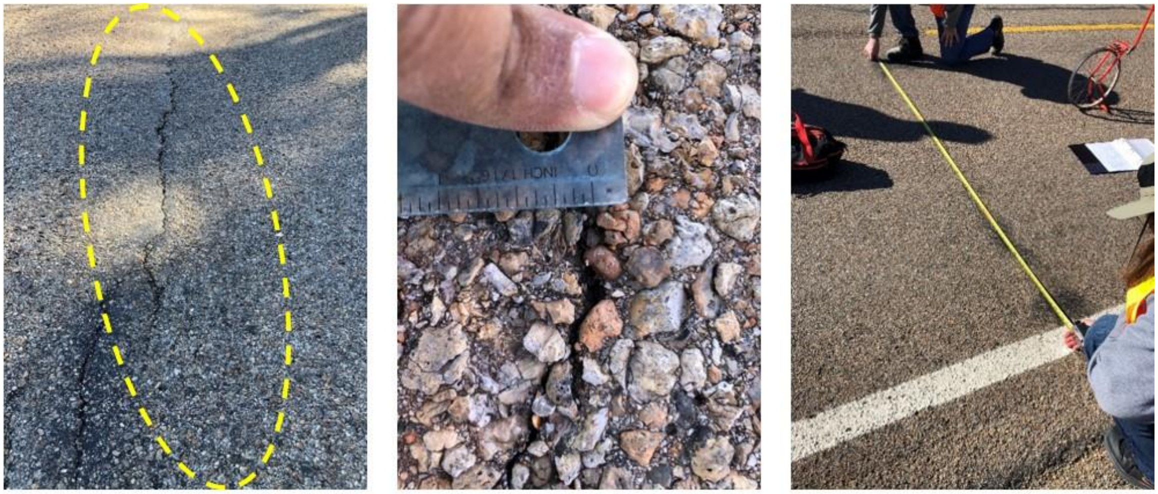
Bleeding. Chip seal sections were thoroughly inspected for bleeding. Any occurrence of bleeding along the wheel path was noted and the precise locations were recorded for any localized bleeding observed in the chip seal sections.

Rutting. Rut measurements were conducted every 400 ft. in each chip seal section. As shown in Figure 31, a triangular rut scale was used to measure the rut depths along the wheel paths and the average value was used in the analysis.

Figure 31. Rutting measurement along the wheel path

Cracks and Potholes. Each chip seal section was inspected for cracks and potholes prior and after chip seal installation. The types of crack included longitudinal cracks, transverse cracks, fatigue cracks, and edge cracks. As shown in Figure 32, the length and the width of each type of crack was recorded in addition to its precise location in each chip seal sections.

Figure 32. Identification and measurement of cracks in test sections



Longitudinal crack   Crack width measurement   Transverse crack

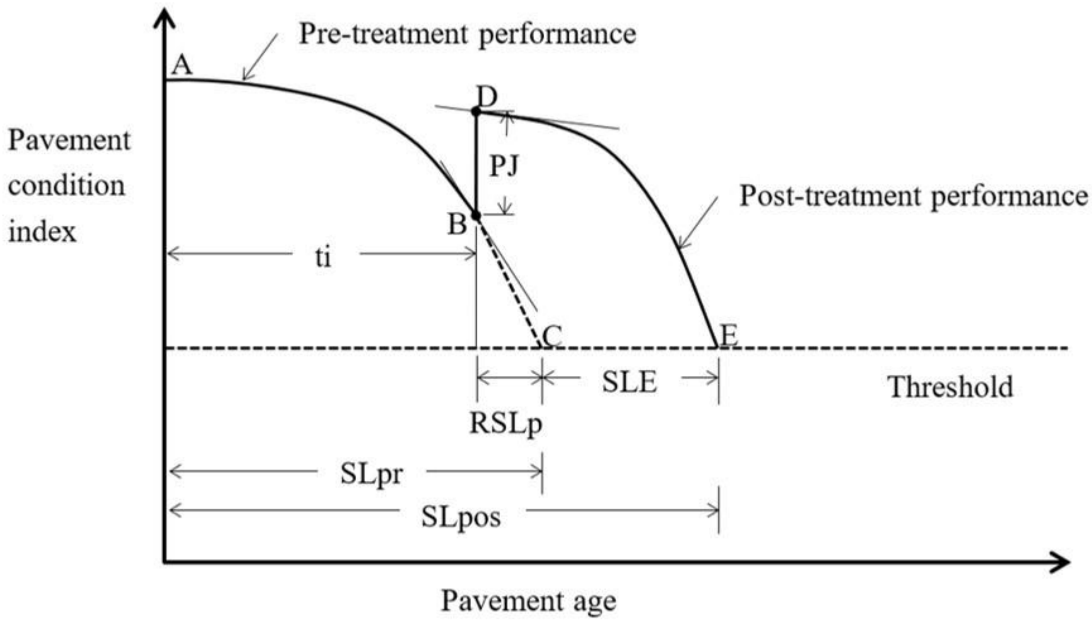
Pavement Condition Modeling

The pavement condition was modeled as a function of time, see Figure 33. Many researchers have successfully used polynomial functions to model the condition of a pavement [16]. The following equations were used to model the pavement condition before and after the application of chip seals:

$$f_{pre}(t) = a_1 t^2 + b_1 t + c_1 \tag{34}$$

$$f_{post}(t) = a_2 t^2 + b_2 t + c_2 \tag{35}$$

Figure 33. Pavement performance curves before and after the application of chip seals



Where, a_1, b_1, c_1, a_2, b_2 and c_2 = parameters representing the pavement condition and deterioration rates over time for pre and post-treatment performance models; and t = time in years.

As shown in Figure 33, the pre-treatment performance curve (AC) refers to the deterioration of the untreated pavement condition with time in terms of pavement condition index (PCI). When chip seal is applied at time ti, the PCI will increase from point B to point D. The sudden increase in PCI after the treatment activity is known as performance jump. The pavement condition will continue to deteriorate following curve DE after the performance jump. The post-treatment performance curve is modelled by setting the time equal to zero at point D.

It can be observed that the pre- and post-treatment curves will reach the threshold PCI value at different time periods. The following equations were used to predict the pavement age before and after application of chip seal:

$$SL_{pre} = \frac{-b_1 - \sqrt{-b_1^2 - 4a_1(c_1 - T)}}{2a_1} \quad (36)$$

$$SL_{post} = \frac{-b_2 - \sqrt{-b_2^2 - 4a_2(c_2 - T)}}{2a_2} + t_i \quad (37)$$

Where, SL_{pre} = age of untreated pavement to a threshold; SL_{post} = age of treated pavement to a threshold; T = threshold value for pavement condition index; and t_i = time of the treatment activity in years.

Service life extension of a pavement as a result of chip seal application was estimated as follows:

$$SLE = SL_{post} - SL_{pre} \quad (38)$$

Where, SLE = service life extension in years.

The following equations were used to predict the pavement condition just before and after the application of chip seal:

$$f_{pre}(t_i) = a_1 t_i^2 + b_1 t_i + c_1 \quad (39)$$

$$f_{post}(0) = c_2 \quad (40)$$

Performance jump (PJ) is calculated by subtracting equation (39) from equation (40):

$$PJ = c_2 - (a_1 t_i^2 + b_1 t_i + c_1) \quad (41)$$

Cost-Benefit Analysis

Life-Cycle Cost Analysis (LCCA). In this study, the Benefit-Cost ratio (B/C) of the chip seal sections were predicted and were compared for the different test sections. The performance of the test sections before the application of chip sealing was compared to that of the test sections after chip sealing [93]. The following equation was used to determine B/C as follows:

$$\frac{\mathrm{B}}{\mathrm{C}} = \frac{\Delta\mathrm{EUAC}}{\mathrm{EUAC_{pvc}}} = \frac{\mathrm{EUAC_{do\ nothing}} - \mathrm{EUAC_{treatment}}}{\mathrm{EUAC_{pvc}}} \quad (42)$$

where, ΔEUAC= net benefit of chip sealing; EUAC do nothing = EUAC of the original AC overlay due to “do nothing”; EUAC treatment = EUAC with application of a treatment; and EUAC pvc = EUAC due to the cost of preservation.

The equations used to calculate EUAC do nothing, EUAC treatment, and EUAC preservation are as follows:

$$EUAC_{do\ nothing} = IC \times \left[\frac{(1+i)^{SL_{pre}}}{(1+i)^{SL_{pre}-1}}\right] \tag{43}$$

$$NPV_{treatment} = IC + PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \tag{44}$$

$$EUAC_{treatment} = NPV_{treatment} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}-1}}\right] \tag{45}$$

$$NPV_{chip\ seal} = PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \tag{46}$$

$$EUAC_{chip\ seal} = NPV_{chip\ seal} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}-1}}\right] \tag{47}$$

Where, IC = initial cost, i = discount rate, t_i = year of expenditure, PMC_{t_i} = chip seal treatment cost at year t_i, SL_{pre}= service life without treatment, and SL_{post} = service life with treatment.

The benefit was determined as the monetary savings as a result of chip seal application:

$$\Delta EUAC = EUAC_{do\ nothing} - EUAC_{treatment} \tag{48}$$

The benefit-cost ratios for the chip seal sections were estimated using the following equation:

$$\frac{B}{C} = \frac{\Delta EUAC}{EUAC_{chip\ seal}} \tag{49}$$

Where, $\Delta EUAC$ = monetary savings due to the treatment activity, and $EUAC_{chip\ seal}$ = equivalent uniform annual costs for the chip seal treatment.

As summarized in Table 28, the unit cost/lane-mile for each chip seal section was calculated using the cost of the materials. An initial cost of $200,000 of construction per lane-mile and a discount rate of 6% was used based on past studies [13].

Table 28. Unit cost of the materials investigated

Material description	Unit cost
CRS-2	\$2.35/gallon
CRS-2P	\$2.65/gallon
CRS-2TR	\$2.50/gallon
LWA	\$58.36/yd^3

Cost-Effectiveness (CE) Analysis. The CE of each chip seal section was calculated as the ratio of the Treatment Net Benefit (TNB) to the unit cost per lane-mile as follows [93]:

$$CE = \frac{TNB}{\text{Unit cost of the treatment (\$/lane-mile)}} \quad (50)$$

The TNB of chip sealing is determined by subtracting the residual performance area of the existing pavement from the performance area of the chip sealing (ABCD). The following equations were used to determine the TNB; see Figure 34:

$$TNB = A2 - A1 \quad (51)$$

$$A1 = \int_{Y}^{PSL_1} |TV - (a_1x^2 + b_1x + c_1)| dx$$

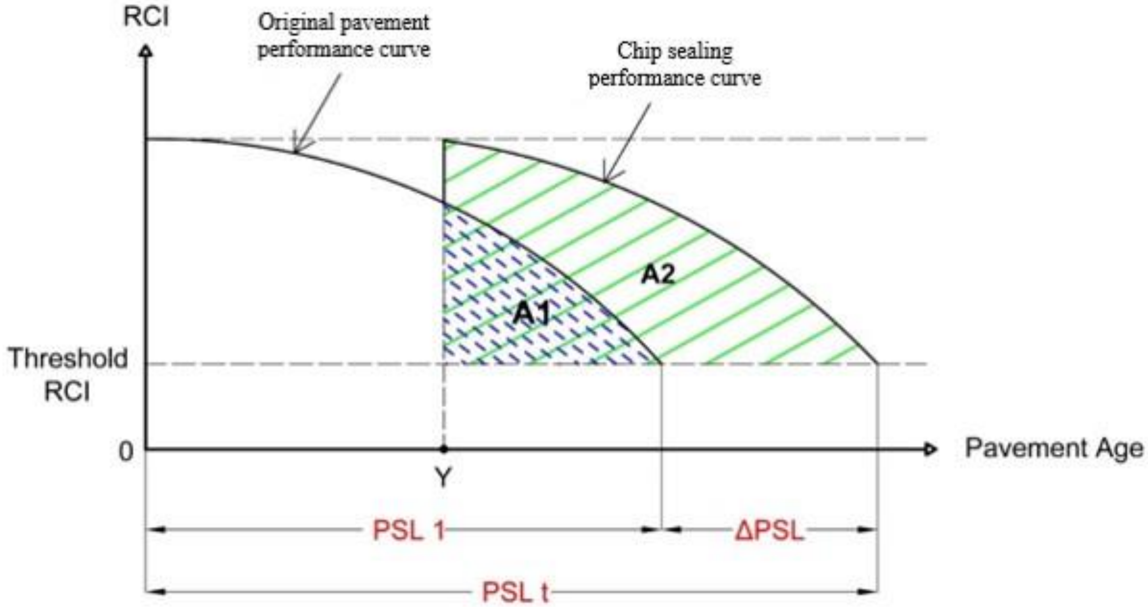
$$= \left[\frac{a_1 PSL_1{}^3}{3} + \frac{b_1 PSL_1{}^2}{2} + (PSL_1\{C_1 - TV\})\right] - \left[\frac{a_1Y^3}{3} + \frac{b_1Y^2}{2} + (Y\{C_1 - TV\})\right] \quad (3)$$

$$A2 = \int_{Y}^{PSL_t} |TV - (a_2x^2 + b_2x + c_2)| dx$$

$$= \left[\frac{a_2 PSL_t{}^3}{3} + \frac{b_2 PSL_t{}^2}{2} + (PSL_t\{C_2 - TV\})\right] - \left[\frac{a_2Y^3}{3} + \frac{b_2Y^2}{2} + (Y\{C_2 - TV\})\right] \quad (4)$$

Where, A2 = area enclosed between chip sealing performance curve and threshold value; A1 = area enclosed between original pavement performance curve, threshold value, and the date of chip sealing; PSLt = PSL 1+ΔPSL; Y = pavement age at the date of chip sealing; TV = threshold Pavement Condition Index (PCI), assumed 60 as per road classification; and a_1, b_1, c_1, a_2, b_2, and c_2 = parameters representing the pavement condition over time for the original pavement and chip sealing performance polynomial curves.

Figure 34. Determining TNB from pavement performance curve



Discussion of Results

Rheological, Molecular, and Chemical Characterization Test Results

Performance Grade and Surface Performance Grade Test

The rheological properties of the binders and emulsion residues were characterized according to AASHTO M320-09. The rheological properties of CRS-2, CRS-2P, CRS-2TR, AC20-5TR, and CHFRS-2P were investigated and their final PG grades were determined based on the laboratory tests, see Table 29(a). According to the test results, CHFRS-2P had the highest (92.69) Useful Temperature Interval (UTI) followed by AC20-5TR, CRS-2P, CRS-2TR, and CRS-2. The interval between the high and low limiting temperatures in which an asphalt binder is anticipated to show adequate resistance to fatigue cracking, permanent deformation, and low temperature cracking is known as the UTI. The UTIs for AC20-5TR and CRS-2P were almost the same (88.8 and 87.8, respectively). Although CRS-2TR showed the same PG grade at high temperature as CRS-2, it is expected to perform better than CRS-2 as it had a higher UTI (UTI of CRS-2TR was 82.6 as compared to 76.7 for CRS-2).

At high temperature, $G^*/\sin(\delta)$ is an important parameter used to evaluate the resistance of the binders to permanent deformation. Binders having higher $G^*/\sin(\delta)$ are expected to exhibit improved resistance to permanent deformation. Comparing the results at high temperature, CHFRS-2P and AC20-5TR are expected to exhibit better performance against permanent deformation than the other binder residues. As previously noted, the asphalt rubber (AC20-5TR) material is modified with 5% SBS co-block polymer, hence, making it suitable to sustain high traffic volume and high temperature. Additionally, BBR test results indicated that both polymers modified emulsions, CRS-2P and CHFRS-2P, had higher negative temperature limiting value followed by AC20-5TR, CRS-2TR, and CRS-2. CRS-2 exhibited the lowest m-value and the highest creep stiffness compared to the other binders with a low temperature limit of -16°C, which indicates greater susceptibility to thermal cracking. A lower creep stiffness value indicates greater resistance to thermal stress and a higher m-value indicates greater rate of stress relaxation. Therefore, CRS-2P and CHFRS-2P are more likely to show better performance against thermal cracking as compared to the other binder residues. This may be attributed to the complex polymer network present in these binder residues. Nevertheless, the low temperature PG grade of CRS-2TR, CRS-2P, CHFRS-2P, and

AC20-5TR was found to be the same (-28°C) and their relaxation slope, m-value, was quite similar.

As shown in Table 29(b), CRS-2P showed the highest UTI in the Surface Performance Grade (SPG) specification system followed by AC20-5TR, CRS-2TR, and CRS-2. Both CRS-2P and AC20-5TR had the same SPG grade, whereas CRS-2TR had higher high temperature limit as compared to CRS-2.

Table 29. (a) Performance Grade (PG) and (b) Surface Performance Grade (SPG) test results

(a)

Test	Specification	Temp.	CRS-2	CRS-2P	CRS-2TR	CHFRS-2P	AC20-5TR
Original							
DSR G*/Sin(δ), kPa	>1.0 kPa	58°C	1.48	-	-	-	-
DSR G*/Sin(δ), kPa	>1.0 kPa	64°C	0.670	1.38	1.09	-	1.56
DSR G*/Sin(δ), kPa	>1.0 kPa	70°C	-	0.724	0.547	1.06	0.846
DSR G*/Sin(δ), kPa	>1.0 kPa	76°C	-	-	-	0.626	-
RTFO							
DSR G*/Sin(δ), kPa	>2.20 kPa	58°C	3.25	-	4.26	-	-
DSR G*/Sin(δ), kPa	>2.20 kPa	64°C	1.43	2.57	2.03	-	3.49
DSR G*/Sin(δ), kPa	>2.20 kPa	70°C	-	1.36	-	2.26	1.85
DSR G*/Sin(δ), kPa	>2.20 kPa	76°C	-	-	-	1.3	-
PAV							
DSR G*Sin(δ), kPa	<5000 kPa	10°C	-	5990	-	-	-
DSR G*Sin(δ), kPa	<5000 kPa	13°C	6080	4220	-	5315	6930
DSR G*Sin(δ), kPa	<5000 kPa	16°C	4540	-	5695	3610	4810
DSR G*Sin(δ), kPa	<5000 kPa	19°C	-	-	3955	-	-
BBR, S, MPa	<300 MPa	-12°C	77	58.5	-	-	-
BBR, S, MPa	<300 MPa	-18°C	196	148	207	158	199
BBR, S, MPa	<300 MPa	-24°C	-	278	396	386	359
BBR, m-value	>0.300	-12°C	0.32	0.372	-	-	-
BBR, m-value	>0.300	-18°C	0.29	0.324	0.31	0.342	0.316
BBR, m-value	>0.300	-24°C	-	0.287	0.266	0.277	0.28
PG Grading			**58-22**	**64-28**	**58-28**	**70-28**	**64-28**
Continuous PG grade			**60.7-16.0**	**65.7-22.1**	**63.3-19.3**	**70.82-21.9**	**68.3-20.5**
Useful temperature interval (UTI)			**76.7**	**87.8**	**82.6**	**92.7**	**88.8**

(b)

Item Description	CRS-2	CRS-2P	CRS-2TR	CHFRS-2P	AC20-5TR
SPG Grading	61-19	73-19	67-19	-	73-19
Continuous SPG grade	64.4-22.9	73.2-24.1	69.1-21.5	-	75.0-21.9
Useful temperature interval (UTI)	87.3	97.3	90.6	-	96.9
Phase angle (δ), max at G*/Sin(δ)=0.65kPa	86.5	79.1	85.5	-	77.7

Multiple Stress Creep Recovery (MSCR) Test

Rutting susceptibility of the binder residues was evaluated by conducting the MSCR test at 58°C. Table 30 presents the non-recoverable creep compliance (J_{nr}) and percent recovery as measured using the MSCR test. The ratio of non-recoverable strain to the applied creep stress is defined as the non-recoverable creep compliance (J_{nr}). J_{nr} value is linked to the binder's resistance to rutting, bleeding, and flow. Lower J_{nr} indicates higher resistance to rutting and bleeding. Results indicated that binder modification led to an improved performance against accumulated strain as all the modified binder residues including CRS-2TR showed lower J_{nr} compared to the unmodified binder, CRS-2. Results also suggested that AC20-5TR exhibit the lowest non-recoverable creep compliance followed by CRS-2P, CRS-2TR, and CRS-2 at 3.2 kPa stress level, indicating improved rutting resistance compared to the unmodified emulsion; this result may be attributed to the higher shock absorbing capacity of the rubber particles. However, CRS-2P exhibited higher percent recovery than the other binders, which may be due to the improved elasticity of the polymer network present in the binder residue [105]. These results indicate that CRS-2P is likely to accumulate less permanent deformation. As expected, the unmodified asphalt emulsion CRS-2 showed the lowest percent recovery demonstrating the superior performance of polymer and rubber-modified binder residues due to their improved elastic response at high temperature.

Table 30. MSCR test results for binders at 58°C

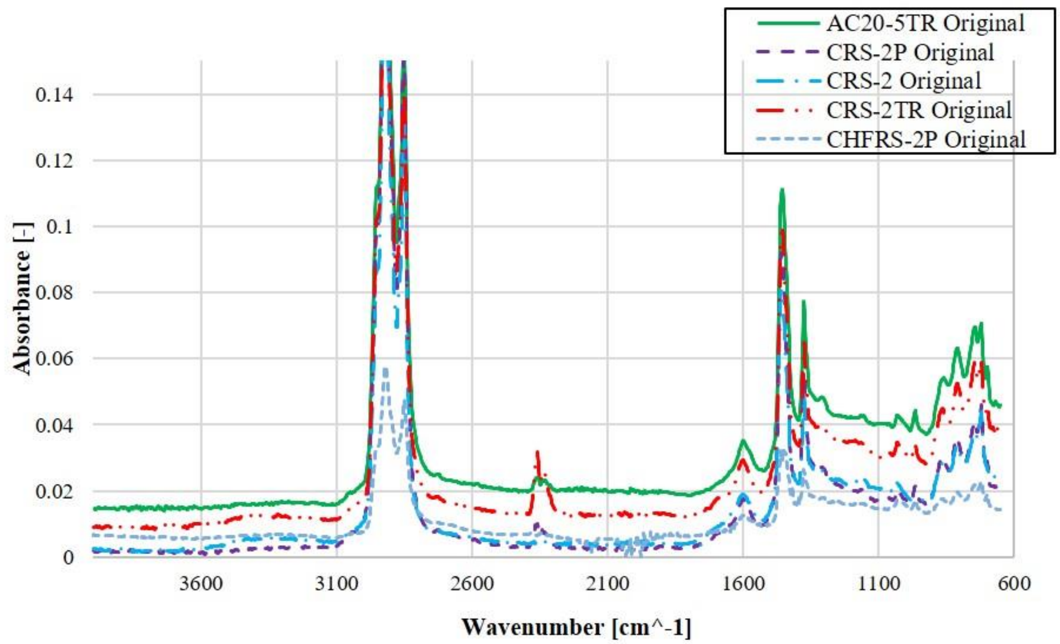
Binder Type	Temperature	% Recovery		J_{nr} (1/kPa)	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
CRS-2	58	11.476	2.208	2.210	2.630
CRS-2P		64.800	44.889	0.3492	0.604
CRS-2TR		18.562	8.580	1.757	2.170
AC 20-5TR		57.84	43.391	0.400	0.579

Fourier Transform Infrared Spectroscopy (FTIR) Test

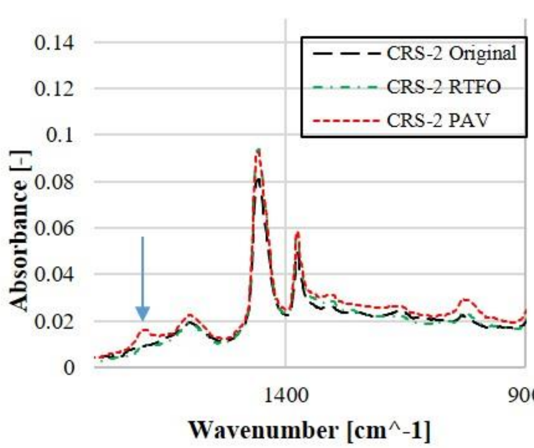
The spectrum of the investigated unaged binder residues from FTIR test are shown in Figure 35(a) in the wavenumber range of 4000 cm^{-1} to 600 cm^{-1}. To evaluate qualitative differences between the binder residues, the spectra were grouped in the same figure. As observed in Figure 35(a), binder residues were observed to have different peaks, which can be correlated to the various functional groups present in the different binder residues. AC20-5TR showed different peaks in the region around wavenumber 699cm^{-1}, which is the aromatic C-H bending and a characteristic peak for SBS. A valley-to-valley band area method was used to calculate the indices and to evaluate the changes in the different functional groups with aging.

Qualitative differences among the binder residues spectra under different aging conditions are presented in Figure 35(b to f). Each diagram shows the FTIR spectra of the asphalt binder residues at different aging conditions: original, RTFO-aged, and PAV-aged. The aging effects on the different binder residues were also evaluated quantitatively by calculating the indices of carbonyl and sulfoxide groups at different aging conditions (see Table 31). In addition, a statistical analysis consisting of an Analysis of Variance (ANOVA) and a Tukey's Honest Significant Difference (HSD) tests were conducted at a 95% confidence level to assess if the differences in carbonyl and sulfoxide indices growth amongst the binder residues were statistically different. As expected, variations with aging in the carbonyl and sulfoxide indices were noted. The carbon chain of asphalt breaks with aging, and then reacts with oxygen to produce carbonyl, and the sulfur turns into sulfoxide by reacting with oxygen in the presence of heat. Hence, aging characterization of the binders was accomplished by evaluating the changes in the carbonyl and sulfoxide indices [106]. As illustrated in Figure 35, the formation of a carbonyl group led to the presence of an absorption band near the 1700 cm^{-1} peak, shown by an arrow in the chart.

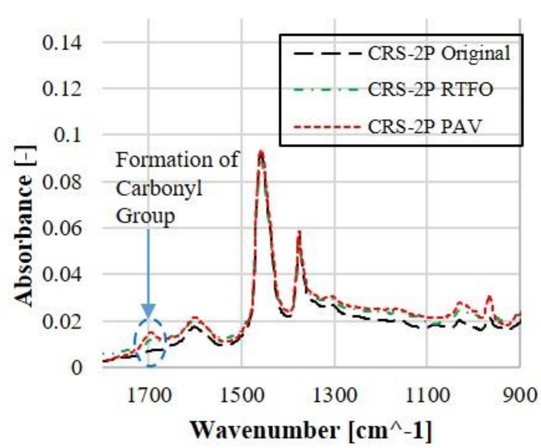
Figure 35. FTIR spectra of all the binders under unaged/original, RTFO-aged, and PAV-aged condition; (a) All unaged binders, (b) CRS-2, (c) CRS-2P, (d) CRS-2TR, (e) AC20-5TR, and (f) CHFRS-2P



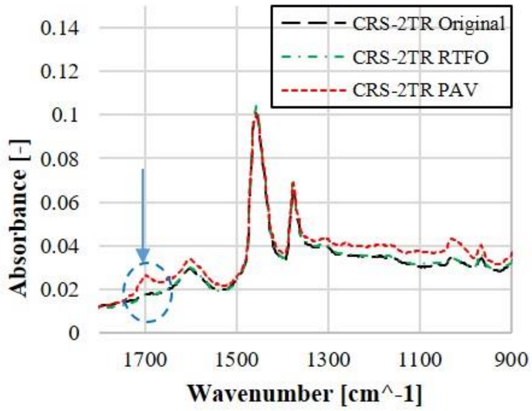
(a)



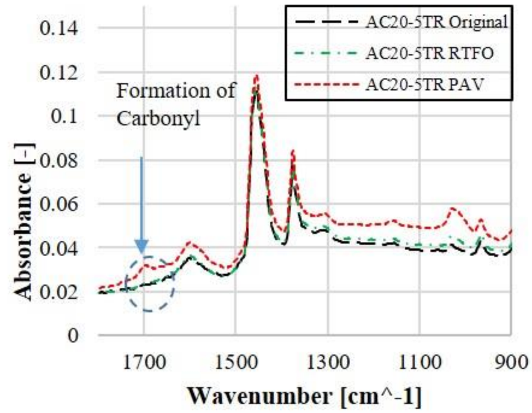
(b)



(c)



(d)



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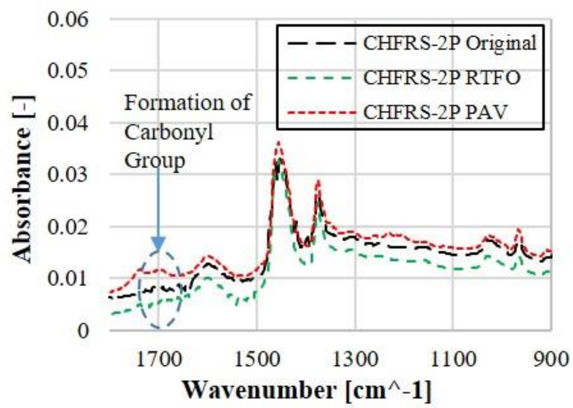


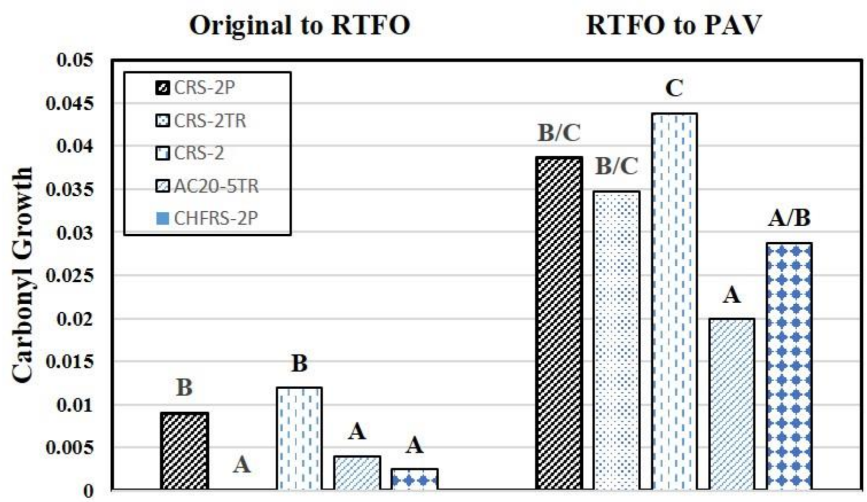
(f)

Table 31. Functional indices of the evaluated binders under different aging conditions

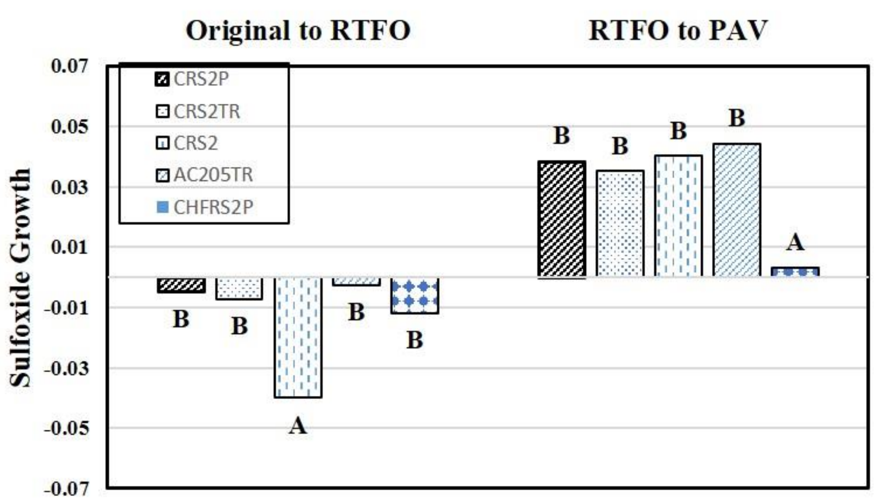
Binder type	Carbonyl Index (Ic=o)			Sulfoxide Index (Is=o)		
	Original	RTFO-aged	PAV-aged	Original	RTFO-aged	PAV-aged
CRS-2P	0.0040	0.0130	0.0516	0.0231	0.0181	0.0564
CRS-2TR	0.0080	0.0081	0.0428	0.0327	0.0256	0.0607
CRS-2	0.0006	0.0124	0.0562	0.0819	0.0419	0.0821
CHFRS-2P	0.0349	0.0374	0.0661	0.0917	0.0799	0.0830
AC20-5TR	0.0002	0.0042	0.0241	0.0312	0.0285	0.0727

The peak areas were observed to be more substantial with the gradual aging of the binder residues. Therefore, the difference in carbonyl indices between the aged and unaged binders were used to evaluate the extent of aging. The growths of the carbonyl and sulfoxide indices of the tested binders from original to RTFO and from RTFO to PAV are presented in Figure 36.

Figure 36. Growth of carbonyl and sulfoxide index for the studied binders



(a)



(b)

As shown in Figure 36 and as compared to the carbonyl index of the binders in the unaged condition, RTFO or short-term aging did not cause a significant increase in this index; whereas, PAV-aged samples showed a significant increase in the carbonyl index growth. Among the binder residues, CRS-2TR was observed to have the lowest carbonyl index increase in the RTFO-aged state as compared to CRS-2P, CRS-2, AC20-5TR, and CHFRS-2P indicating that CRS-2TR to be more resistant to short-term aging than the other emulsions. Binder stiffness also increases with the increase in carbonyl and sulfoxide indices as the reaction between oxygen compound and perhydro aromatic ring of the binder intensifies [106]. The statistical analysis of the results shows that the growth of carbonyl index in CRS-2TR from original to RTFO aged condition was significantly lower (p-value of $0.0006 < 0.05$) as compared to the other binders. The improved short-term aging resistance of tire rubber modified asphalt emulsion as compared to the crumb rubber modified asphalt binder can possibly be attributed to the high initial Carbonyl Index in the unaged condition. This may be explained by the nature of the tire rubber modified emulsion itself, from the source asphalt, or from the high processing temperature during the production stage. The formation of the carbonyl group occurs in two stages [107]. The first stage is relatively rapid as compared to the second one, where the carbonyl formation occurs at a constant rate for a long period. It can be assumed that CRS-2TR reached the constant rate stage prior to AC20-5TR as it experienced the growth of the carbonyl group during the production stage, which can be compared to the rapid stage. In PAV-aged condition, AC20-5TR showed the lowest carbonyl index growth followed by CHFRS-2P, CRS-2TR, CRS-2P, and CRS-2. The low carbonyl index growth of CHFRS-2P can also be attributed to its higher initial carbonyl index in the unaged stage. Both CRS-2TR and AC20-5TR yielded lower growth in the carbonyl area than CRS-2 and CRS-2P in both RTFO-aged and PAV-aged conditions, which indicates that the absorption of tire rubber components in the binder phase improved its resistance to aging. The growth of the carbonyl area in CRS-2 was highest for both RTFO-aged and PAV-aged samples; statistical test results also indicate significant differences. However, both CRS-2TR and CRS-2P were placed in the same statistical group by the Tukey test results (p-value of $0.0025 < 0.05$), indicating that both binder residues may show the same level of resistance to aging in the long-term.

Results also suggested the absorbance in the sulfoxide group band region in the unaged condition. CRS-2 and CHFRS-2P showed the lowest sulfoxide index jump after short-term and long-term aging, respectively (p-value of 0.0035 and 0.0007, respectively). The sulfoxide growth area of CRS-2TR was less than for CRS-2P in both RTFO and PAV-aged conditions. Nonetheless, CRS-2P, CRS-2TR, CRS-2, and AC20-5TR were placed in the same statistical group by the Tukey test results of the sulfoxide index growth from RTFO to PAV aged condition (p-value of $0.0007 < 0.05$), indicating that they may show the same level of resistance to aging in the long-term.

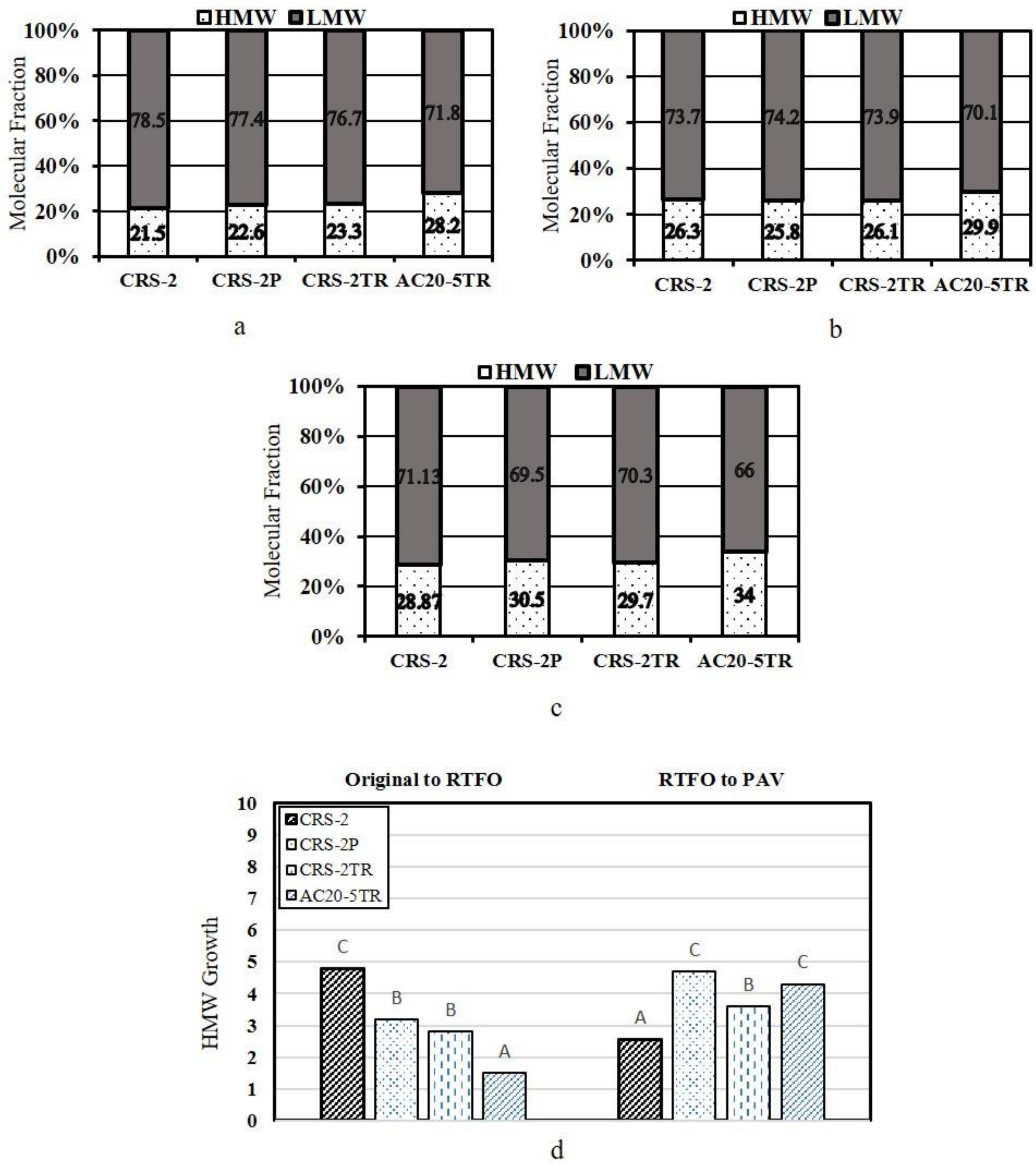
Based on these results, CRS-2TR is expected to show improved resistance to aging as compared to conventional emulsions. The presence of carbon black, antiozonant, and antioxidant in the crumb rubber particles could be a reason behind the improved aging resistance performance of both tire rubber modified asphalt emulsion and crumb rubber modified asphalt binder. It can also be interpreted from the results that PAV aging or long-term aging is more critical for the carbonyl index and sulfoxide index growth in the binders than RTFO aging.

High-Pressure Gel Permeation Chromatography (HP-GPC) Test

HP-GPC test was conducted on the original, RTFO, and PAV-aged binder residues to evaluate their molecular size distribution and its change with aging, as shown in Figure 37. As previously noted, the distribution of the molecular components was divided into two groups, i.e., the high molecular weight group (HMW) and the low molecular weight (LMW) group. These groups were reported to correlate with pavement performance since the HMW content is positively corelated to the brittleness of the binder [108]. An ANOVA test was also conducted followed by a Tukey HSD test at a confidence level of 95% to assess if the growth of the HMW content was significantly different amongst the binders (see Figure 37(d)).

As shown in Figure 37, a decrease in the low molecular weight content of the binder residues was observed with the increase in high molecular weight content in the short term and long-term aging conditions. Therefore, it may be concluded that the loss of LMW occurs due to oxidation of the binder residues. Furthermore, a higher HMW content was observed for AC20-5TR compared to all the emulsions. A possible reason could be due to the crumb rubber content present in AC20-5TR since the molecular weight of rubber is between 100,000 and 1,000,000 Daltons. However, HMW content observed for CRS-2TR and other conventional emulsions were similar. This may be due to better digestion of the crumb rubber particles into the base binder of CRS-2TR because of the high processing temperature. All the binders were observed with a noteworthy increase in the HMW content with aging. The authors past research results had shown that at intermediate and low temperatures, the binders’ elongation properties were significantly improved with the increase in the LMW content [109].

Figure 37. Molecular fractional distribution for different Original, RTFO-aged, and PAV-aged binders; (a) Original and (b) RTFO-aged binders (C) PAV aged binders (d) HMW growth



SARA Analysis

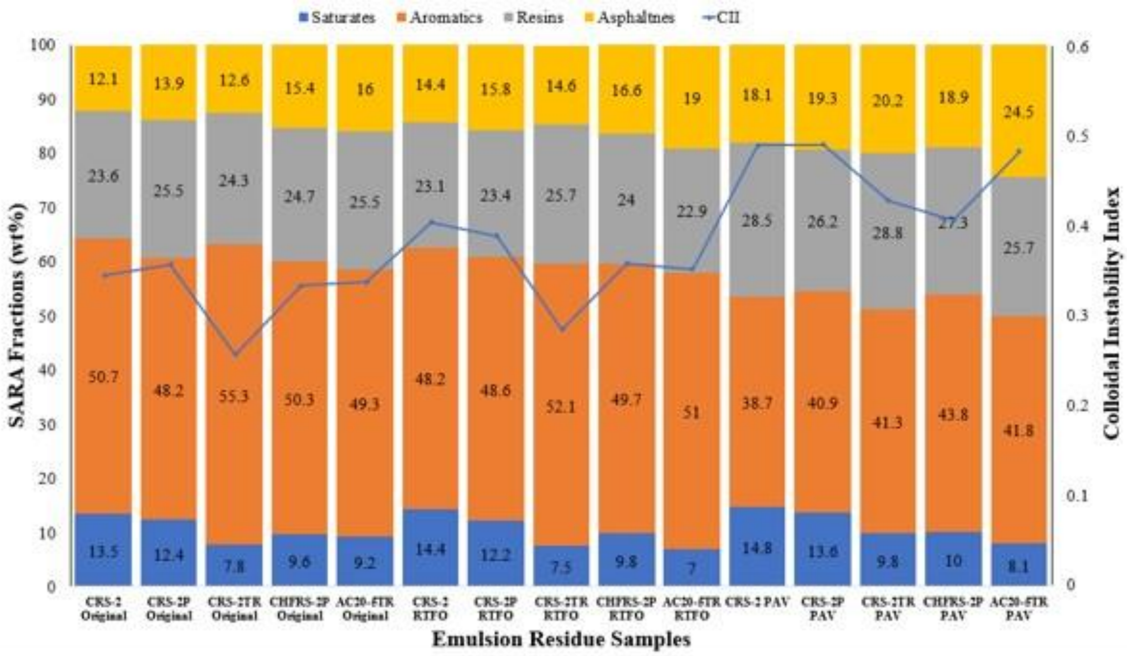
A thin film chromatography was used in an Iatroscan analyzer to evaluate the effects of crumb rubber incorporation on the different saturates, aromatics, resins, and asphaltenes components of the binder residues. Table 32 presents the SARA fractional compositions for the binders in the original, RTFO-aged, and PAV aged conditions, where with aging, a growth in asphaltene and resins and a reduction in aromatics were observed. As presented in Table 32, CRS-2 had the lowest percentage of asphaltene component in the unaged/original state and AC20-5TR had the highest. This is because of the composition of carbon black and assorted fillers within the tire rubber composition, which remain insoluble in n-heptane and are counted as asphaltene in the SARA analysis. With aging, the percentage of asphaltene components increased in all the binders. The results show that CHFRS-2P had the lowest asphaltene component growth in both RTFO-aged and PAV-aged condition (1.2% and 2.3%, respectively) compared to the other binders. AC20-5TR showed a high asphaltene component growth in both RTFO and PAV-aged conditions (3% and 5.5%, respectively), indicating that AC20-5TR may lose its elongation characteristics faster than the other binder residues. The polymer-modified asphalt emulsion, CRS-2P and CHFRS-2P, showed lower asphaltene growth in both RTFO-aged and PAV-aged conditions, indicating higher resistance to aging. However, both CRS-2 and CRS-2TR were also expected to perform well against short-term aging as they showed the least amount of asphaltene content in the original and RTFO-aged conditions. Asphaltenes are the heaviest components in the SARA fractions; therefore, they can be compared with the HMW content in the binders obtained from the HP-GPC analysis. Yet, researchers have reported that some of the asphaltenes might remain in the resin fraction resulting in a lower count of asphaltenes from SARA analysis by precipitation [110].

The study also analyzed the changes in the colloidal instability indices (CII) with aging. The colloidal system is more stable as the indices value for the emulsion residue is lower. Binders tend to become more colloidally unstable with aging as the asphaltenes contents tend to increase. Figure 38 illustrates the change in the colloidal instability of the binders under different aging conditions. According to the results presented in Figure 38, CRS-2TR showed the lowest colloidal instability index (CII) value in both original (unaged) and RTFO (short-term aged) conditions (0.256 and 0.284, respectively), while CHFRS-2P had the lowest CII value (0.406) in PAV (long-term aged) condition, indicating that CRS-2TR may perform well against short-term aging. However, for all the emulsion residues, the CII values were less than the limit (0.5) demonstrating the presence of stable colloidal system in the residues. Overall, the CII showed an increasing trend with aging.

Table 32. Iatroscan SARA fraction analysis of the asphalt binders

Binder Residue	Components (%)			
	Asphaltenes	Resins	Aromatics	Saturates
Unaged				
CRS-2	12.1	23.6	50.7	13.5
CRS-2P	13.9	25.5	48.2	12.4
CRS-2TR	12.6	24.3	55.3	7.8
CHFRS-2P	15.4	24.7	50.3	9.6
AC20-5TR	16.0	25.5	49.3	9.2
RTFO-aged				
CRS-2	14.4	23.1	48.2	14.4
CRS-2P	15.8	23.4	48.6	12.2
CRS-2TR	14.6	25.7	52.1	7.5
CHFRS-2P	16.6	24	49.7	9.8
AC20-5TR	19.0	22.9	51.0	7.0
PAV-aged				
CRS-2	18.1	28.5	38.7	14.8
CRS-2P	19.3	26.2	40.9	13.6
CRS-2TR	20.2	28.8	41.3	9.8
CHFRS-2P	18.9	27.3	43.8	10
AC20-5TR	24.5	25.7	41.8	8.1

Figure 38. Colloidal instability of asphalt binders with aging



Chip Seal Laboratory Performance Test Results

Aggregate Retention Performance

Effect of the Types of Emulsion. Figure 39 and Figure 40 present the percentage aggregate loss (%Aggregate Loss) calculated from the sweep test and the Pennsylvania Aggregate Retention Test (PART) and illustrate the effect of different types of emulsion on chip seal performance. As shown in the Figure 39, the performance of the emulsions with lightweight aggregate can be ordered as CRS-2 > CRS-2P > CRS-2TR > AC20-5TR with the asphalt rubber providing the best performance in terms of %Aggregate Loss. The chip seal specimens prepared with asphalt rubber were observed to have the lowest aggregate loss. Figure 41 presents the bond strength between the aggregate and the different types of emulsion. The AC20-5TR was observed to have the highest bond strength; this was expected since the asphalt rubber is installed at high temperature and is designed to be used in high volume roads and sustain heavy traffic. The performance of asphalt emulsions investigated with granite aggregate can be ordered as CRS-2 > CRS-2P > CRS-2TR > CHFRS-2P. The chip seal specimens prepared with CHFRS-2P were observed to have the lowest aggregate loss due to its high float base. On the other hand, chip seal specimens prepared with CRS-2P and CRS-2TR yielded lower loss of aggregate compared to that of CRS-2 for all the cases (lightweight aggregate and granite aggregate). CRS-2P and CRS-2TR also had higher bond strength compared to that of CRS-2. Therefore, the results indicated the correlation between the effects of the different types of emulsion on aggregate' loss and the bond strength between the emulsion and the aggregate.

Figure 39. Effects of types of emulsions (with lightweight aggregate)

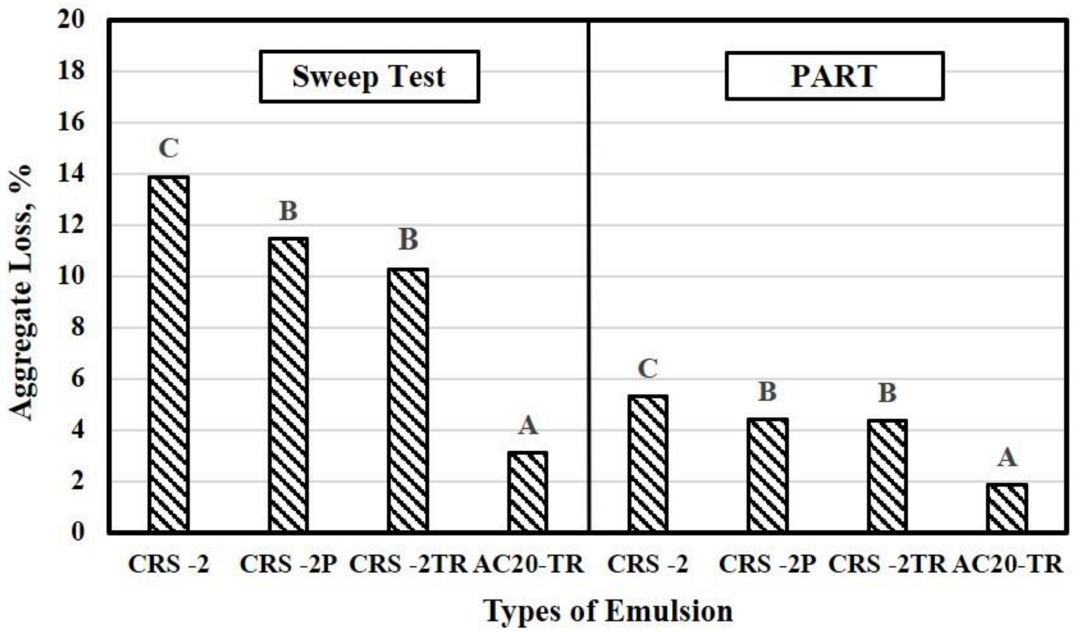


Figure 40. Effects of types of emulsions (with granite aggregate)

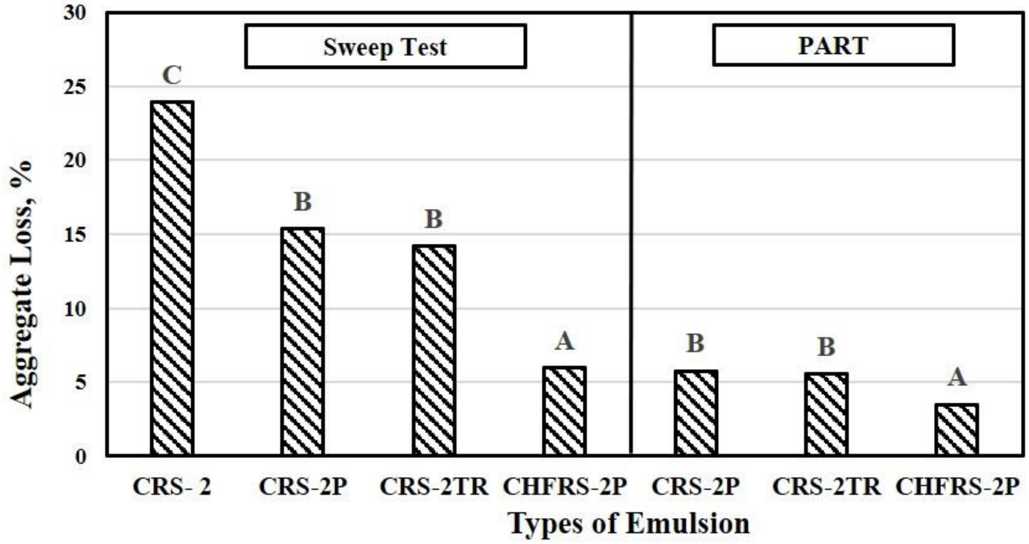
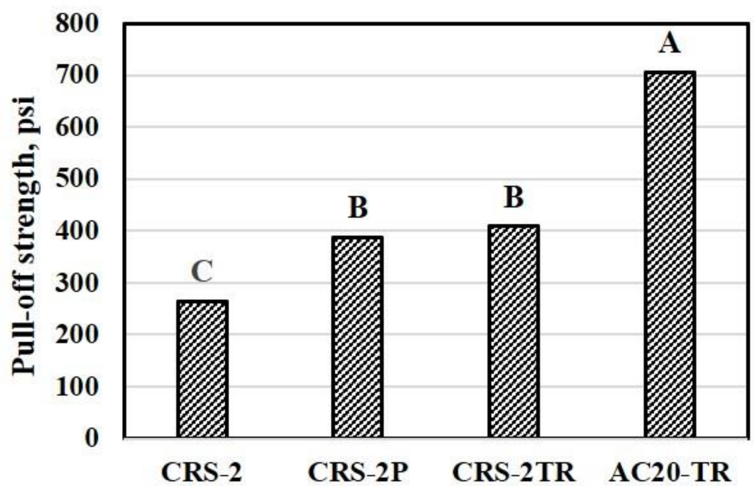


Figure 41. Bond strength of different emulsions and asphalt rubber binder



An ANOVA was conducted at 95% confidence level (α=0.05) followed by the Tukey's HSD test to evaluate if the %Aggregate Loss obtained for the different types of emulsion was statistically significant. Table 33 and Table 34 summarize the results of ANOVA where the F-statistics and the P-value were used to assess the statistical significance of the factors investigated in the study. As shown in Figures 39 and 40, the %Aggregate Loss values obtained for the different types of emulsion were assigned letters, which represent the statistical grouping based on performance and significance. From Figure

39, it can be observed that AC20-5TR is the best performer in terms of loss of aggregate (lightweight); hence, it was assigned a letter "A." CRS-2P and CRS-2TR performed better than CRS-2 but their %Aggregate Loss values were not significantly different; therefore, both CRS-2P and CRS-2TR were assigned a letter "B." Similarly, CRS-2 was assigned a "C" due to its poor performance. From these results, while AC20-5TR was the best performer, the application of this material at an elevated temperature of 160-170°C is a safety concern for many states and limits its use in states such as Louisiana and Mississippi.

The high float polymer modified emulsion (CHFRS-2P) was observed to provide better performance in terms of loss of aggregate (granite); therefore, it was assigned a letter "A," see Figure 40. On the other hand, it was observed that the difference in aggregate loss in chip seal specimens prepared with CRS-2TR and CRS-2P were not statistically significant; hence, they were assigned the same letter "B" as they fall into the same statistical group. Finally, the unmodified asphalt emulsion (CRS-2) was the worst performer; therefore, it was assigned a letter "C."

Table 33. Analysis of variance of the factors investigated (with lightweight aggregate)

Primary Factors	**Secondary Levels**	**Sweep Test**				**PART**			
		Sum of Square	**Mean Square**	**F-value**	**P-value**	**Sum of Square**	**Mean Square**	**F-value**	**P-value**
Application rates	CRS-2P and LWA	26.98	8.99	59.62	<.0001	25.75	8.58	25.31	<.0001
	CRS-2TR and LWA	33.25	11.084	49.59	<.0001	23.66	7.89	25.29	<.0001

Primary Factors	Secondary Levels	Sweep Test				PART			
		Sum of Square	Mean Square	F-value	P-value	Sum of Square	Mean Square	F-value	P-value
Types of emulsion	DOTD and LWA	192.65	64.22	1314.5	<.0001	30.24	10.08	32.50	<.0001
Aggregate blends	DOTD and CRS-2P	4.753	4.753	37.07	0.6037	0.049	0.049	0.12	0.7447
	DOTD and CRS-2TR	59.72	59.724	331.2	<.0001	4.133	4.133	12.41	<.0001

Table 34. Analysis of variance of the factors investigated (with granite aggregate)

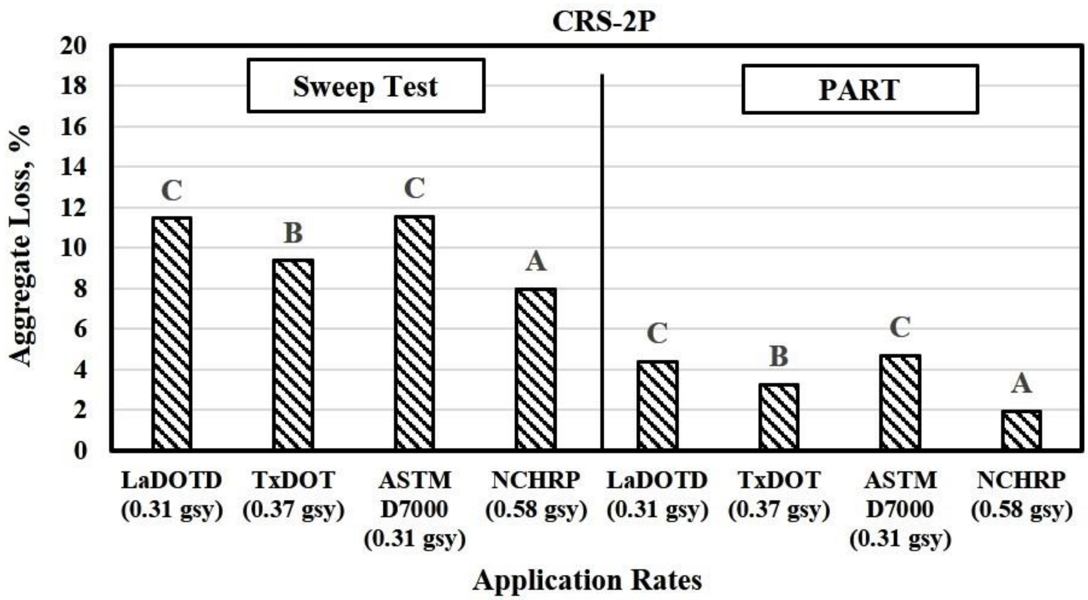
Primary Factors	Secondary Levels	Sweep Test				PART			
		Sum of Square	Mean Square	F-value	P-value	Sum of Square	Mean Square	F-value	P-value
Application rates	CRS-2P and Granite	24.45	12.22	6.94	0.0275	N/A	N/A	N/A	N/A
	CRS-2TR and Granite	106.60	53.30	50.06	0.0002	N/A	N/A	N/A	N/A
	CHFRS-2P and Granite	17.98	8.99	63.06	<0.0001	N/A	N/A	N/A	N/A

Primary Factors	Secondary Levels	Sweep Test				PART			
		Sum of Square	Mean Square	F-value	P-value	Sum of Square	Mean Square	F-value	P-value
Types of emulsion	DOTD and Granite	485.55	161.85	97.65	<0.0001	9.42	4.71	21.45	0.0018
Aggregate blends	DOTD and CRS-2P	14.83	7.41	11.16	0.0095	6.44	3.22	9.52	0.0138
	DOTD and CRS-2TR	78.25	39.12	44.18	0.0003	16.93	8.47	17.91	0.0030
	DOTD and CHFRS-2P	10.23	5.11	19.50	0.0024	2.22	1.11	5.27	0.0477

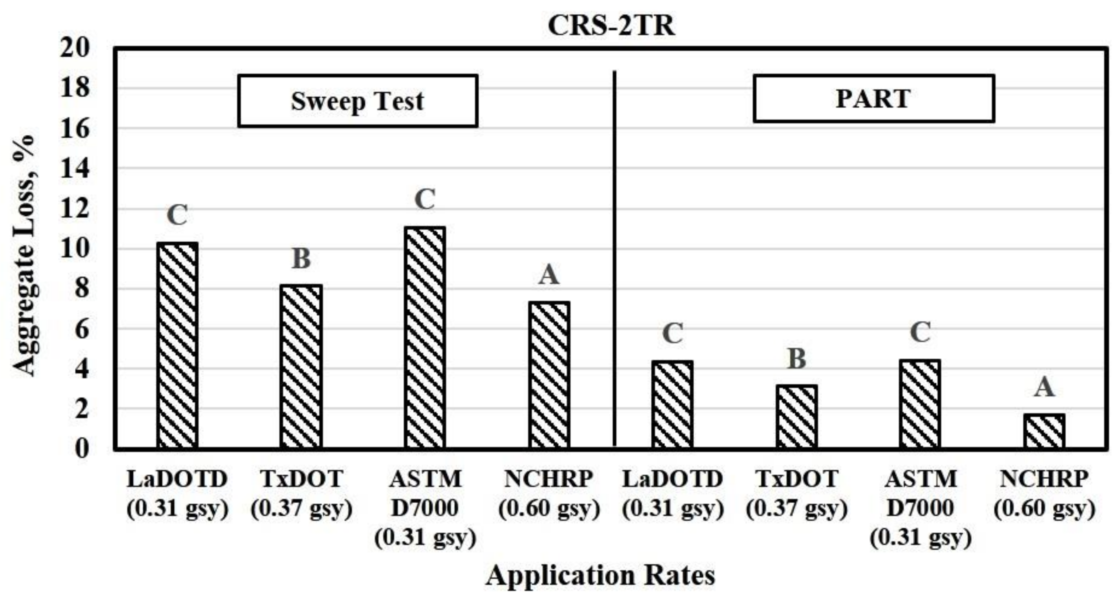
Effect of Application Rates. Figure 42 presents the effect of application rates on the %Aggregate Loss in chip seal specimens prepared with lightweight aggregate and CRS-2P and CRS-2TR from two performance tests, i.e., the sweep test and the Pennsylvania Aggregate Retention Test (PART). As shown in this figure, with respect to %Aggregate Loss, the application rates investigated in this study can be ordered as DOTD > ASTM D 7000 > TxDOT > NCHRP with the NCHRP application rate providing the best performance. The chip seal specimens prepared with the NCHRP application rate were observed to have the lowest aggregate loss; this was expected since it had the highest application rate. Due to higher application rate, more emulsions were applied onto the chip seal specimens leading to an increased adhesion, therefore, a decreased loss of aggregate. Chip seal specimens made with TxDOT yielded lower loss of aggregate compared to that of chip seal specimens prepared with DOTD and ASTM D 7000. This is because the TxDOT application rate was higher compared to the DOTD and ASTM D 7000 application rates.

An ANOVA was conducted followed by the Tukey's HSD test to evaluate if the %Aggregate Loss obtained for the different application rates was significant. As shown in Figure 42, the %Aggregate Loss obtained for different application rates are alphabetically lettered in terms of their performance and significance. It can be observed that among the application rates investigated, NCHRP was the best performer in terms of loss of aggregate; hence, it was assigned a letter “A.” TxDOT performed better compared to DOTD and ASTM D 7000; hence, it was assigned a letter “B.” Both DOTD and ASTM D 7000 are assigned a letter “C” as the %Aggregate Loss were not significantly different, and they had the lowest performance. While the NCHRP application rate performed well, practical experiences in Louisiana indicate that an application rate greater than 0.42 gsy would result in a failing installation due to 100% aggregate embedment depth, causing skid resistance issues at the surface.

Figure 42. Effect of application rates (a) CRS-2P (b) CRS-2TR (with lightweight aggregate)



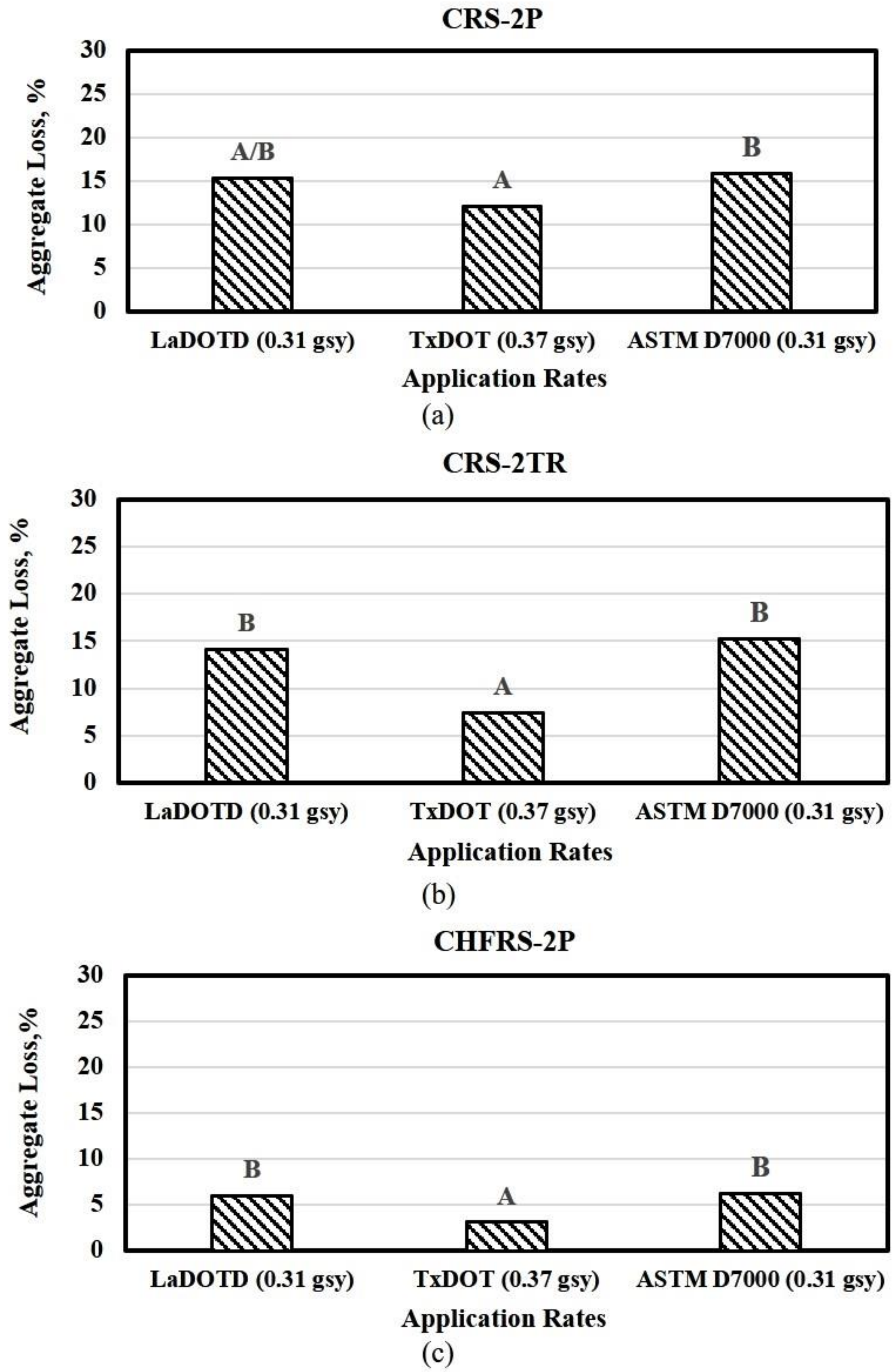
(a)



(b)

The chip seal specimens prepared with granite aggregate and different emulsions provided similar results as the specimens with lightweight aggregate. Figure 43 represents the effect of the emulsion application rates on the aggregate retention performance of chip seal specimens that are prepared with granite aggregate. Lower percentage of aggregate loss was measured for the specimens prepared with the TxDOT application rate (0.37 gsy) as compared to DOTD (0.31 gsy) and ASTM D7000 (0.31 gsy) application rates, indicating that with the increase in emulsion application rate, the percentage of aggregate loss decreased. Statistical analysis of the sweep test results also indicated that the emulsion application rate was a significant factor affecting the percentage of aggregate loss (P-value less than 0.05 at a confidence level of 95%).

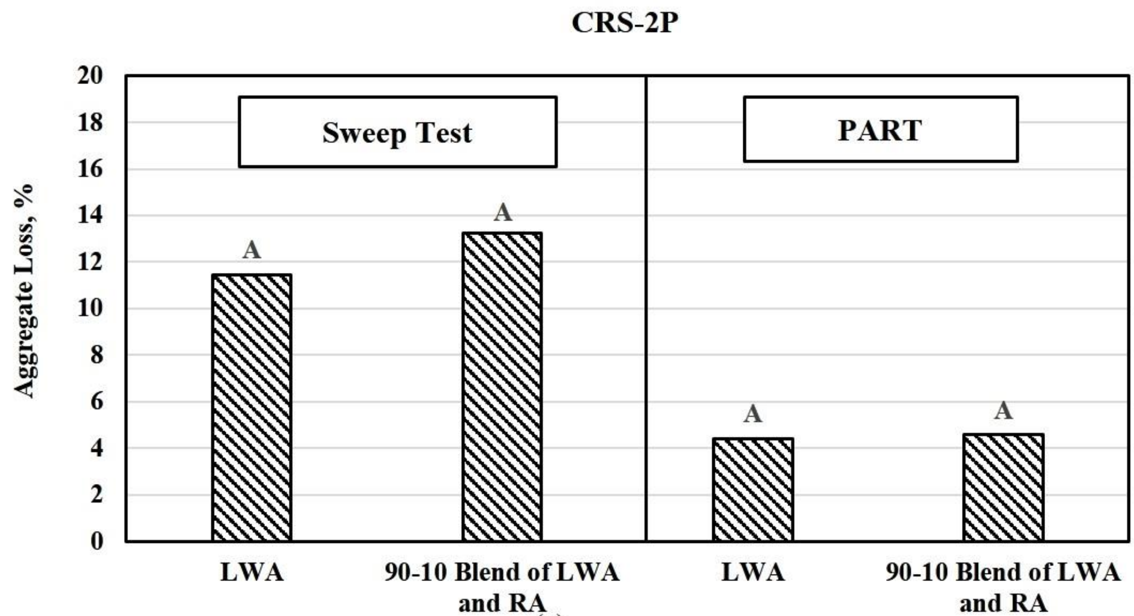
Figure 43. Effect of application rates (a) CRS-2P (b) CRS-2TR (b) CHFRS-2P (with granite aggregate)



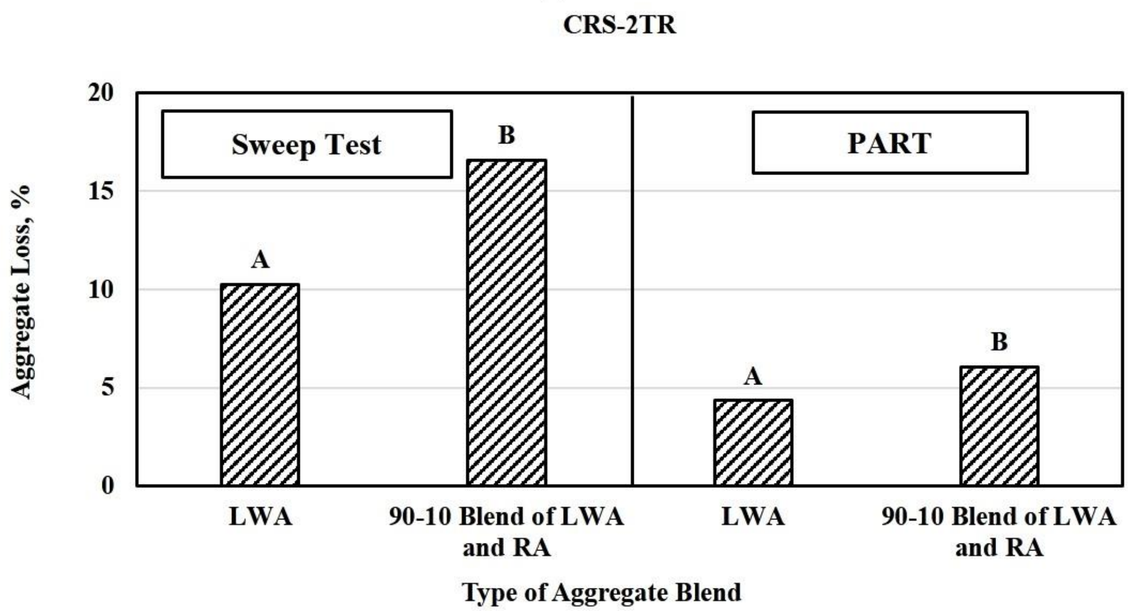
Effect of Aggregate Blends. Figure 44 and 45 present the effect of aggregate blends (lightweight- rubber and granite – rubber respectively) on %Aggregate Loss in chip seal specimens prepared with CRS-2P, CRS-2TR, and CHFRS-2P from two performance tests, the sweep test and the Pennsylvania Aggregate Retention Test (PART). As shown in Figure 44, with respect to %Aggregate Loss, the aggregate blends investigated in this study can be ordered as 90-10 blend of LWA and RA > LWA. It can be observed that irrespective of the type of emulsion used, chip seal specimens prepared with LWA had lower aggregate loss compared to chip seal specimens prepared with 90-10 blend. In case of chip seal specimens prepared with CRS-2TR, a significant difference was observed between the %Aggregate Loss in chip seal specimens made with LWA and 90-10 blend. These results indicate that the adhesion bond between the emulsion and the rubber aggregate was lower compared to the bond between the emulsion and LWA. Since chip seal specimens prepared with CRS-2P did not show a significant difference in performance, it indicates that a difference in emulsion-aggregate compatibility exists between CRS-2P and CRS-2TR.

Three types of aggregate blend were evaluated with the granite aggregate: 100% granite, 90-10 blend of granite and crumb rubber, and 80-20 blend of granite and crumb rubber. As shown in Figure 45, aggregate blends had a significant effect on the performance of chip seal specimens. The statistical analysis of the sweep test results also supports this finding as the P-values obtained were all less than 0.05 at a confidence level of 95%; see Table 34. As illustrated, among the three aggregate blends, granite performed the best regardless of the emulsion type used in the specimens. The percentage of aggregate loss increased when crumb rubber aggregate was used. However, for the 90-10 blend of the granite and crumb rubber, aggregate loss did not increase significantly as they were statistically in the same group as the 100% granite aggregate blend; with the exemption of the CRS-2TR sample (sweep test). This indicates that a small percentage of crumb rubber may be used in chip seal without significantly affecting its performance. Interestingly, CHFRS-2P showed improved aggregate retention in all the cases as compared to CRS-2P and CRS-2TR, which indicates that CHFRS-2P may be more compatible with rubber aggregate than the other emulsions. On the other hand, the percentage loss of aggregate increased significantly in chip seal specimen prepared with CRS-2TR emulsion and granite-rubber blend as compared to the other emulsions, indicating that an aggregate-emulsion incompatibility issue may exist between CRS-2TR and crumb rubber aggregate. The Pennsylvania aggregate retention test also showed similar trend as the sweep test (see Table 34). However, further investigation is necessary to understand the interaction and compatibility between the emulsions and the rubber aggregate.

Figure 44. Effect of aggregate blends (a) CRS-2P (b) CRS-2TR (lightweight aggregate)

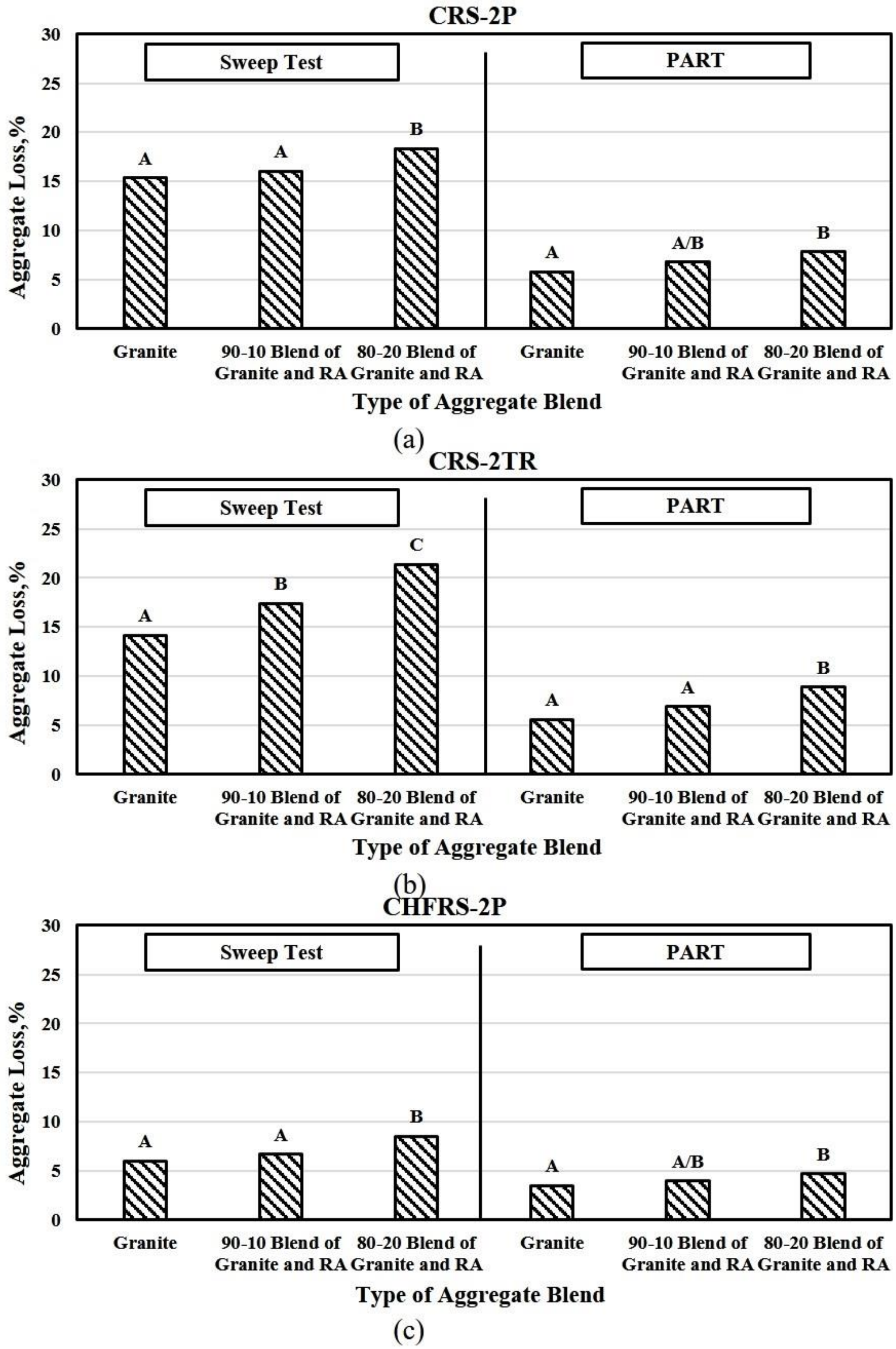


(a)



(b)

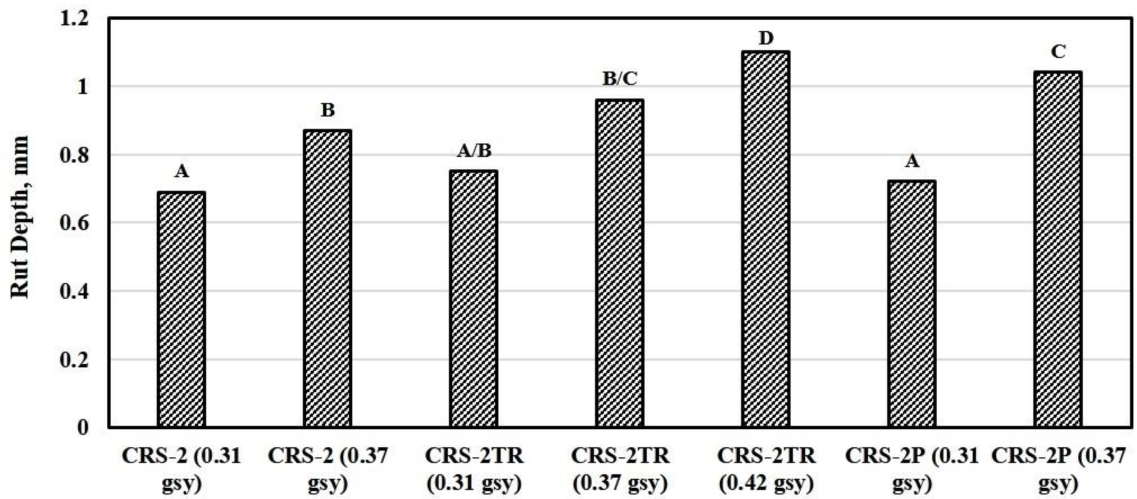
Figure 45. Effect of aggregate blends (a) CRS-2P (b) CRS-2TR (c) CHFRS-2P (with granite aggregate)



Rutting Performance

Figure 46 presents the final rut depths for the different types of emulsion and their application rates as measured by the Hamburg Wheel Loaded Tracking Test based on the specifications for microsurfacing, ASTM D 6372. As shown in the figure, irrespective of the type of emulsion used in the field, the rut depth increased with the increase in application rate. The figure also illustrates the ranking of the emulsions determined by the ANOVA analysis. The letter "A" was assigned to the best performer followed by the other letters in order of their performance and significance. A double letter designation, such as A/B, indicates that the statistical difference is not conclusive; hence, the results could fall in either category. The best rutting performance was observed for CRS-2, CRS-2P, and CRS-2TR at the DOTD application rate of 0.31 gsy. CRS-2P and CRS-2TR had comparable rutting performance at the same application rate among the emulsions investigated in this study.

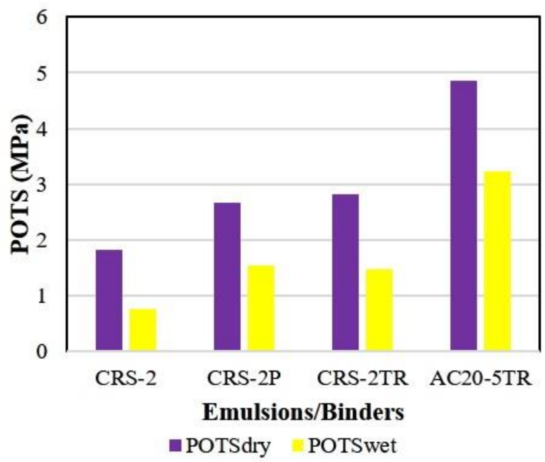
Figure 46. Loaded wheel test results



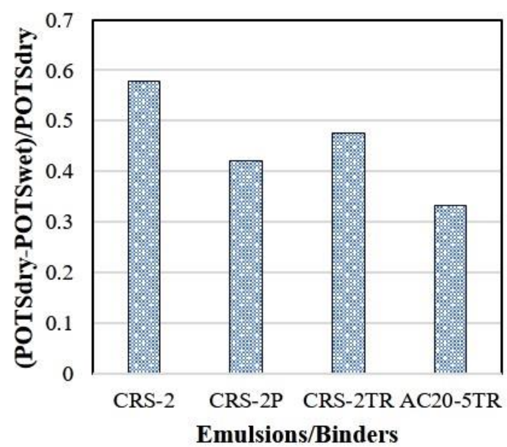
Moisture Resistance

The BBS test was conducted with three replicates for each sample at 24 hours curing time and the average value was considered as the final POTS value. Figure 47(a) presents the average pull off tensile strength (POTS) for each binder residue under dry and wet conditions. A statistical analysis consisting of an ANOVA and a Tukey's HSD test were conducted at a 95% confidence level to assess if the differences in performance were statistically significant. According to the test results, AC20-5TR had the highest bond strength values in both dry and wet conditions, whereas CRS-2 exhibited the lowest. The statistical analysis results showed that the performance of CRS-2 was significantly different from AC20-5TR. The loss of bond strength is possibly related to the modification in the emulsion, interactive effects between substrate and emulsion, type of aggregate, and conditioning time.

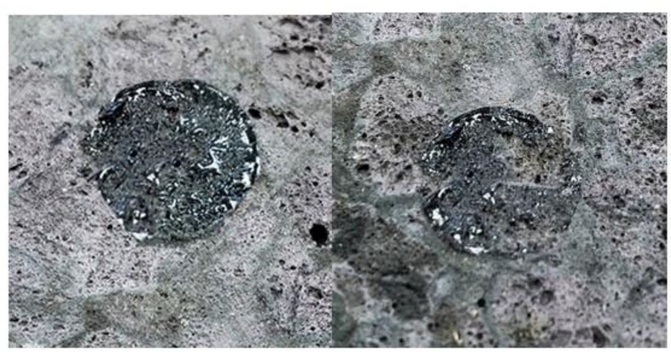
Figure 47. Pull-off tensile strength test results; (a) POTS under dry and wet conditions (b) loss of bond strength expressed by ratio (POTSdry-POTSwet)/POTSdry (c) failure mechanism



(a)



(b)



(c)

As shown in Figure 47, CRS-2TR and CRS-2P resulted in comparable POTS values in dry conditions (2.81 MPa and 2.67 psi, respectively). In addition, the presence of water in the asphalt-aggregate matrix reduced the bond strength of the binders. As anticipated, all the binders showed reduced POTS after wet conditioning (see Figure 47(a)). Compared to the initial dry bond strength of the evaluated binders, all the binder residues lost more than 40% of their bond strength after 24 h of moisture conditioning, except for AC20-5TR (See Figure 47(b)). However, a higher dry bond strength ($POTS_{dry}$) and a higher wet strength ($POTS_{wet}$) do not necessarily mean that the binder is highly resistant to moisture damage, which also depends on the ratio of ($POTS_{dry} - POTS_{wet}$)/$POTS_{dry}$. Results indicated that AC20-5TR had the highest bond strength in the dry and wet conditions and lost 33.4% of its bond strength with moisture conditioning. In contrast, CRS-2 had the worst performance as it lost 57.8% of its bond strength with moisture conditioning. Furthermore, the performance of CRS-2TR was statistically equivalent (p-value <0.0001 for both cases) to CRS-2P under both dry and wet conditions.

The mechanism of failure was also visually observed and captured after each test. Cohesive failure was observed for the unconditioned (dry) samples, which mean that the adhesive strength of the binder-aggregate interface was stronger than the cohesive strength of the binder. In contrast, adhesive failure (i.e., within the binder-aggregate interface) was observed for the wet conditioned samples of CRS-2 (see Figure 47(c)). The change in the failure mode can be attributed to the penetration of water from the sides of the asphalt film and through the aggregate pores, decreasing the adhesive strength of the binder-aggregate interface under wet conditions.

Short-term Field Performance

Mean Texture Depth

Figure 48 presents the mean texture depth of the test sections before construction, three months, six months, twelve, and eighteen months after construction. It is observed that the mean texture depths of the test sections increased after the construction of chip seals. This was expected since the aggregate in the chip seal sections should have lower embedment depth compared to that of AC. As shown in the figure, MTD decreased with time after the test sections were opened to traffic. This is due to the traffic actions, which reduced the surface texture in chip seals. Test section CRS-2P (0.31 gsy) had the highest MTD after the construction of chip sealing, indicating better friction characteristics and skid resistance. However, high MTD values are also associated with high surface roughness and increased traffic noise. It was also observed that CRS-2TR (0.42 gsy), CRS-2TR (0.37 gsy), and CRS-2P (0.37 gsy) chip seal sections had lower MTD values possibly due to the higher application rates of emulsion in these sections. Table 35 presents the aggregate percent embedment depths in the chip seal sections at different time periods after construction. It is observed that the percent embedment depth of the aggregate increased in the short-term; therefore, decreasing the MTD in the chip seal sections. The increase in percent embedment depth is due to the reorientation of the aggregate to lie on its flat side as a result of traffic action. It is also observed that the chip seal sections constructed at higher application rates such as 0.37 gsy and 0.42 gsy, had higher aggregate percent embedment depths indicating more susceptibility to bleeding.

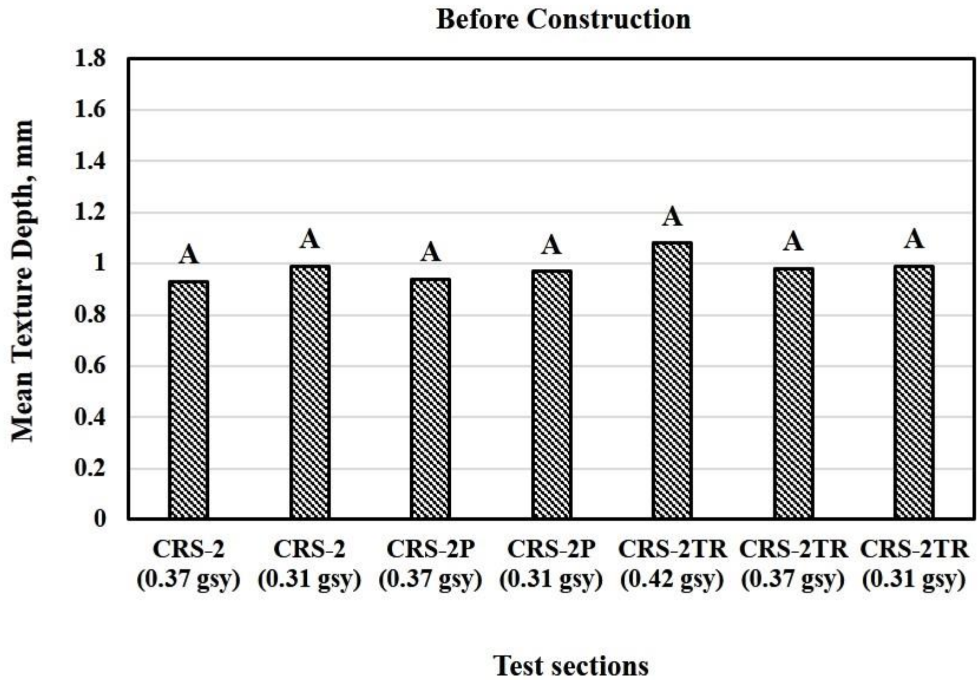
An ANOVA was conducted at 95% confidence level (α=0.05) followed by the Tukey's HSD test to evaluate the statistical significance of the average MTD in the test sections before and after construction of chip seals. The average MTD values in the chip seal sections were assigned letters indicating a statistical grouping based on their significance to each other. As shown in Figure 48(a), before construction of chip seals, the test sections had statistically similar MTD; hence, all test sections were assigned a letter "A." As shown in Figure 48(b), it was observed that after construction of chip seals, MTD in the test sections constructed with CRS-2, CRS-2P, and CRS-2TR at an application rate of 0.31 gsy were statistically higher compared to that of rest of the chip seal sections; hence, they were assigned a letter "A." MTD in the chip seal sections constructed with CRS-2, CRS-2P, and CRS-2TR at an application rate of 0.37 gsy was found statistically higher compared to the chip seal section constructed with CRS-2TR at an application rate of

0.42 gsy; hence, it was assigned a letter "B." Since the chip seal section constructed with CRS-2TR at 0.42 gsy application rate had the lowest MTD, it received a letter "C."

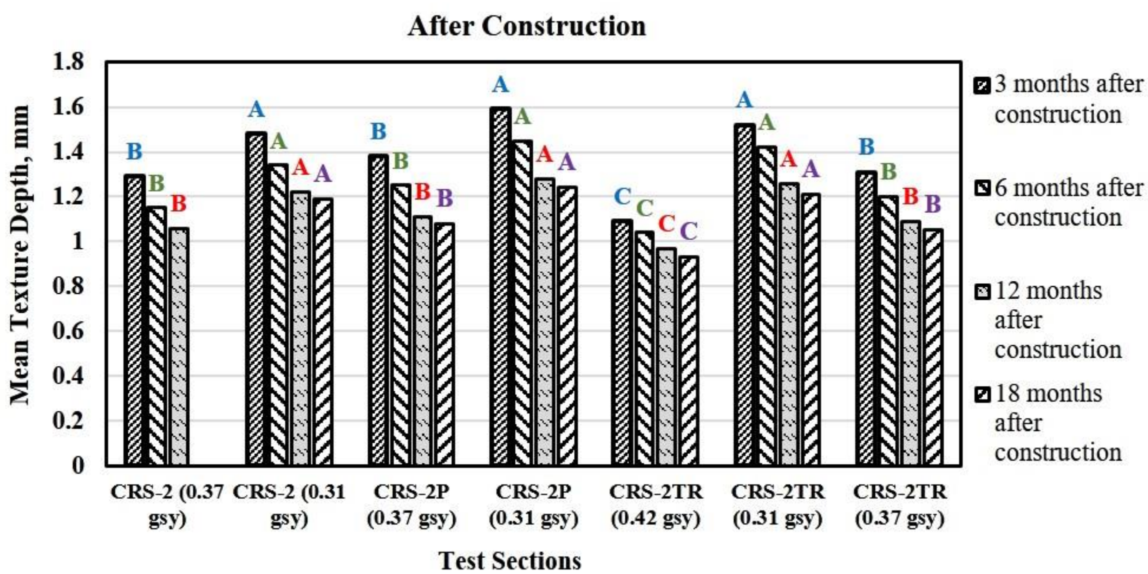
Table 35. Percent embedment depths of aggregate in chip seal sections

Chip seal section	Percent embedment depth			
	After 3 months of construction	After 6 months of construction	After 12 months of construction	After 18 months of construction
CRS-2 (0.37 gsy)	53.41	60.86	66.52	N/A
CRS-2 (0.31 gsy)	48.00	54.05	56.63	N/A
CRS-2P (0.37 gsy)	49.06	58.00	63.67	N/A
CRS-2P (0.31 gsy)	42.35	48.58	51.53	N/A
CRS-2TR (0.42 gsy)	69.72	76.88	79.72	N/A
CRS-2TR (0.31 gsy)	45.71	50.28	53.82	N/A
CRS-2TR (0.37 gsy)	51.22	57.16	60.72	N/A

Figure 48. MTD in test sections (a) before construction and (b) after construction



(a)



(b)

Measurement of Application Rates

Table 36 shows the measured application rates in each geotextile pad during construction, their average, standard deviation, and coefficient of variation (COV). However, the measurements from the CRS-2P (0.37 gsy) chip seal section could not be retrieved due to time constraints. It can be observed from the table that the measured application rates of the distributor trucks were very close to the target application rate. Low standard deviation values and COV (%) were observed when computing the measured application rates indicating adequate accuracy of the results obtained.

Table 36. Application rate measurements during construction

Types of emulsion	DOTD application rate, gsy			TxDOT application rate, gsy			Field adjusted application rate, gsy		
	Target	Measured		Target	Measured		Target	Measured	
CRS-2	0.31	AVG	0.29	0.37	AVG	0.34	N/A	N/A	N/A
		STD	0.02		STD	0.04			
		COV (%)	7.11		COV (%)	11.25			
CRS-2P	0.31	AVG	0.25	0.37	AVG	N/A			
		STD	0.01		STD				
		COV (%)	4.16		COV (%)				
CRS-2TR	0.31	AVG	0.27	0.37	AVG	0.38	0.42	AVG	0.41
		STD	0.02		STD	0.01		STD	0.04
		COV (%)	8.70		COV (%)	3.57		COV (%)	9.57

Rutting

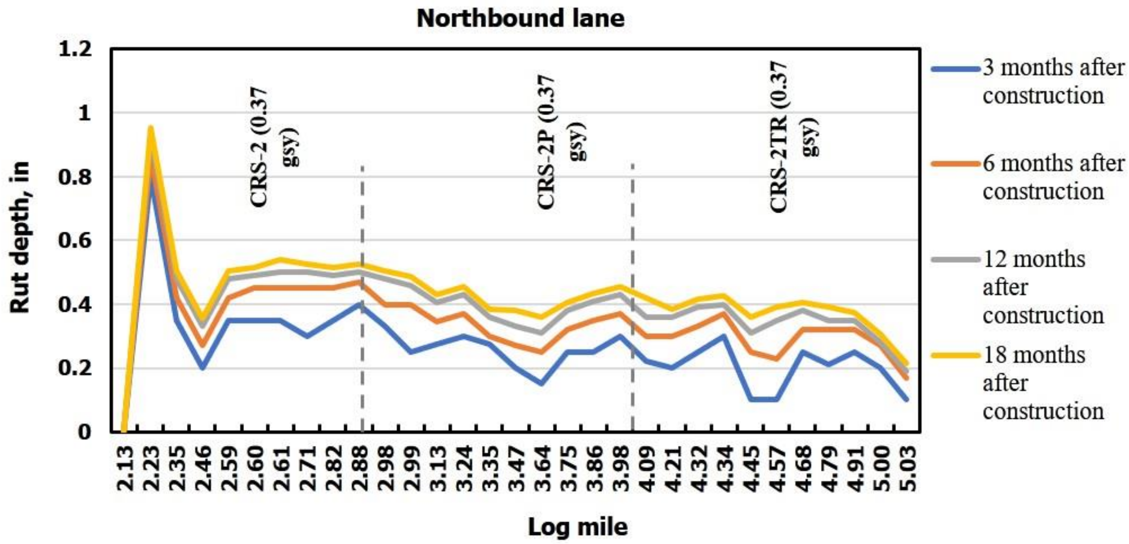
Table 37 presents the average rut depth of the test sections before construction. It is observed that most test sections had similar rut depths prior to construction. Rut measurements were conducted to evaluate the rut depth in different test sections right after construction. The measurements were obtained for every 400 ft. at each test section.

As shown in Figure 49, the average rut depths for both the northbound and southbound lanes were consistent throughout the test sections. However, the presence of high rut depth was detected for the CRS-2 test sections in both lanes. Relatively lower rut depths were observed in the CRS-2TR test sections. The measured rut depths may not be related to the chip seals and may have been present prior to the construction of chip seals in the test sections.

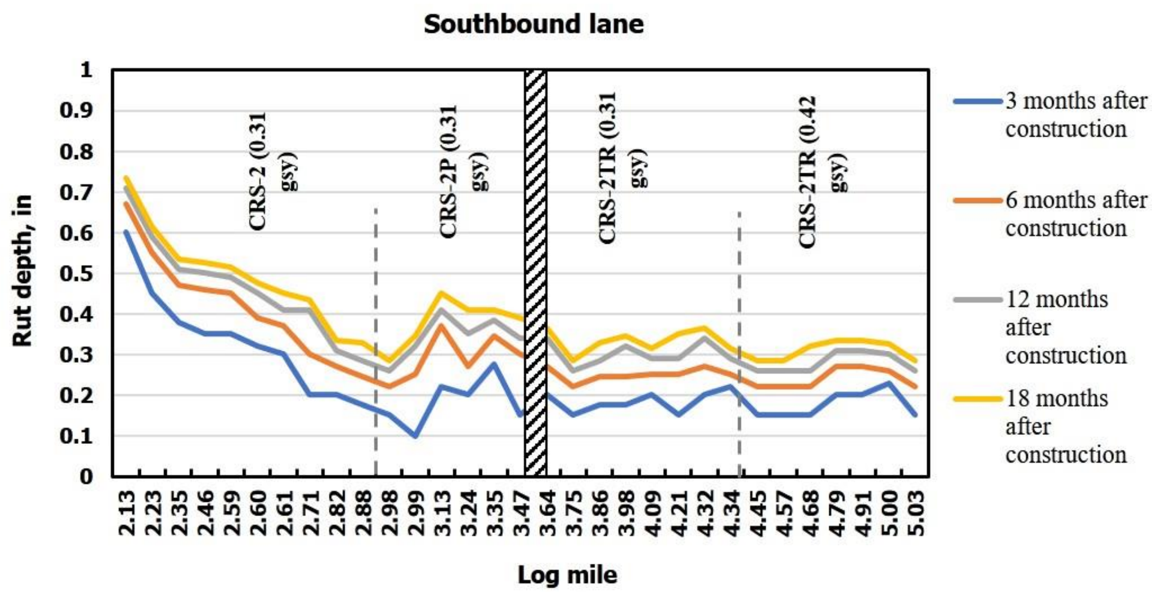
Table 37. Average rut depth of the test sections prior to chip seal construction

Northbound Lane			**Southbound Lane**		
Log Mile	**Section**	**Avg. Rut Depth (in.)**	**Log Mile**	**Section**	**Avg. Rut Depth (in.)**
2.13 – 2.88	CRS-2 (0.37 gsy)	0.22	2.13 – 2.88	CRS-2 (0.31 gsy)	0.18
2.88 – 4.09	CRS-2P (0.37 gsy)	0.21	2.88 – 3.50	CRS-2P (0.31 gsy)	0.14
4.09 – 5.03	CRS-2TR (0.37 gsy)	0.31	3.63 – 4.38	CRS-2TR (0.31 gsy)	0.20
N/A			4.38 – 5.03	CRS-2TR (0.42 gsy)	0.22

Figure 49. Average rut depth in (a) northbound lane and (b) southbound lane



(a)



(b)

Bleeding

Each test section was thoroughly inspected for bleeding, and a few occurrences were observed in the test sections where CRS-2TR was applied at a high application rate. As shown in Figure 50, bleeding along the wheel path was observed in the test sections where CRS-2TR was constructed with the TxDOT application rate of 0.37 gsy and the modified NCHRP application rate of 0.42 gsy. As discussed in the previous section, lower MTD values were observed in these test sections possibly due to bleeding. While low MTD values are positively related to the surface roughness of the pavement; the presence of bleeding along the wheel path reduces pavement friction and skid resistance, therefore, reducing the functional conditions of the pavement.

Figure 50. Bleeding in chip seal test sections

CRS-2 (0.37 gsy)

CRS-2P (0.37 gsy)

CRS-2TR (0.37 gsy)

CRS-2 (0.31 gsy)

CRS-2P (0.31 gsy)

CRS-2TR (0.31 gsy)

CRS-2TR (0.42 gsy)

Cracking and Potholes

Each test section was inspected for the presence of pavement cracking, such as fatigue cracking, longitudinal cracking, and transverse cracking. The distress survey conducted after three months of the construction of chip sealing indicated no noticeable cracks and potholes. However, a few longitudinal cracks along the wheel path were recorded in the chip seal section constructed with CRS-2 (0.31 gsy) in the subsequent survey cycles. A few transverse cracks and edge cracks also developed in the CRS-2 (0.31 gsy) test section. The presence of cracks greatly reduces the structural capacity of the pavement by allowing moisture into the underlying pavement structure. Few cracks were also observed in the test sections, which were too small to consider by the time of the surveys; hence, only their presence and precise location were recorded for future reference.

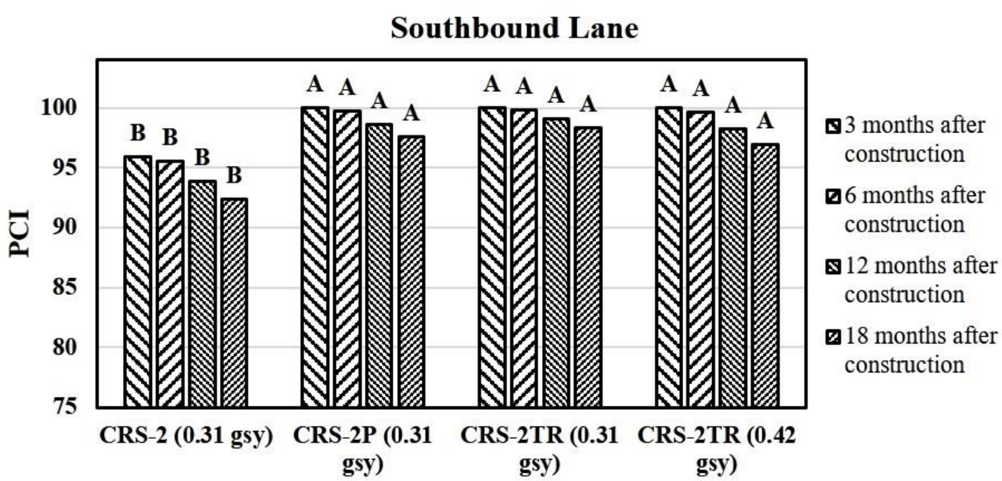
Pavement Condition Index (PCI)

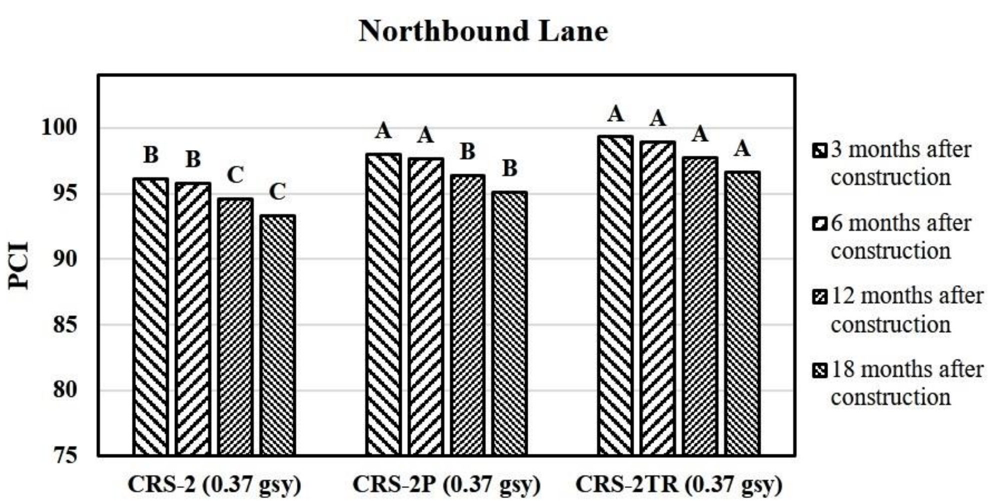
The Pavement Condition Index (PCI) was calculated based on the data collected by conducting distress surveys at different time periods. As shown in Figure 51, PCI varied for the test sections surveyed on both the northbound and the southbound lanes. All chip seal test sections had overall high PCI values; however, the test sections constructed with CRS-2 had the lowest PCI values. The PCI values determined after three months of construction were higher compared to the PCI values measured after six months and 12 months from the construction. This was expected since the test sections are less likely to have high intensity distresses present after three months of their construction and are expected to deteriorate over time.

Figure 51 presents the average PCI values for the respective test sections on both the northbound and southbound lanes at different time periods. In terms of PCI, the chip seal sections on the northbound lane can be ordered as CRS-2TR (0.37 gsy) > CRS-2P (0.37 gsy) > CRS-2 (0.37 gsy), and the test sections on the southbound lane can be ordered as CRS-2TR (0.31 gsy), CRS-2TR (0.42 gsy), CRS-2P (0.31 gsy) > CRS-2 (0.31 gsy). It can be concluded from the figure that the chip seal sections constructed with CRS-2 had the lowest PCI values indicating the presence of higher level of distresses.

An ANOVA was conducted at 95% confidence level (α=0.05) followed by the Tukey's HSD test to evaluate the statistical significance of the PCI values obtained for the chip seal test sections. As shown in Figure 51, the average PCI values obtained for the chip seals constructed with different types of emulsion were assigned letters indicating a statistical grouping based on their performance and significance to each other. It was observed that in the northbound lane, three months after construction, chip seal sections constructed with CRS-2P and CRS-2TR had the best performance in terms of PCI; hence, they are assigned the letter "A." Although CRS-2TR had retained its performance throughout the monitoring period, the performance of CRS-2P degraded over time; hence, it is assigned the letter "B" after 12 months. CRS-2 had the poorest performance amongst the types of emulsions investigated; hence it received the letter "C" after 12 months. In the southbound lane, chip seals constructed with CRS-2P and CRS-2TR performed similarly; hence, they were assigned the letter "A." The poorest performance was observed for chip seals constructed with CRS-2; hence, it was assigned the letter "B."

Figure 51. Performance of chip seal test sections



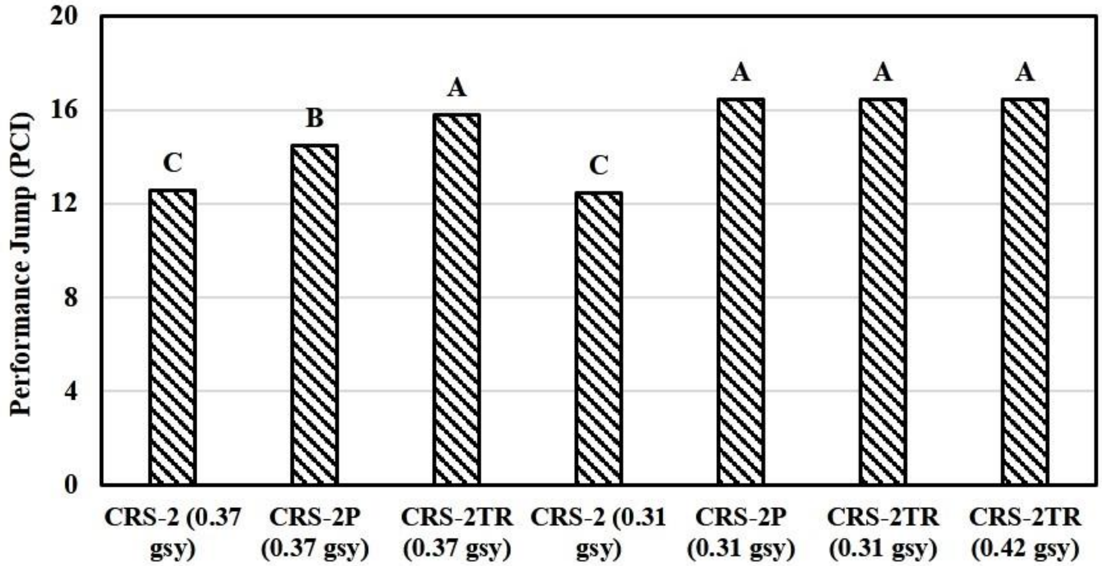


Performance Jump (PJ)

The performance jump for different test sections due to application of chip sealing was calculated, as shown in Figure 52. It can be observed that chip seal sections constructed with CRS-2P and CRS-2TR emulsions exhibited the highest performance jump. This was expected since the condition of the test sections are likely to improve just after chip seal application. However, the chip seal sections constructed with CRS-2 emulsion exhibited a low performance jump, indicating that pavement condition was not completely restored after chip sealing. As previously mentioned, CRS-2 (0.31 gsy) and CRS-2 (0.37 gsy) chip seal sections had pre-existing rutting, which may have contributed towards the observed low performance jump.

An ANOVA was conducted at 95% confidence level (α=0.05) followed by the Tukey's HSD test to evaluate the statistical significance of the performance jump observed in different chip seal sections. As shown in Figure 52, the average performance jumps observed in the chip seal sections were assigned letters indicating statistical grouping based on their performance and significance to each other. It can be observed that except for CRS-2P (0.37 gsy) test section, all the chip seal sections constructed with CRS-2P and CRS-2TR had the best performance; hence, they were assigned the letter "A." The average performance jump of CRS-2P (0.37 gsy) chip seal section was not statistically equivalent to the CRS-2TR test sections but had better performance compared to the chip seal sections constructed with CRS-2; hence it was assigned the letter "B." The poorest performance was observed in the chip seal sections constructed with CRS-2; hence, they received the letter "C."

Figure 52. Performance jump observed in the chip seal sections

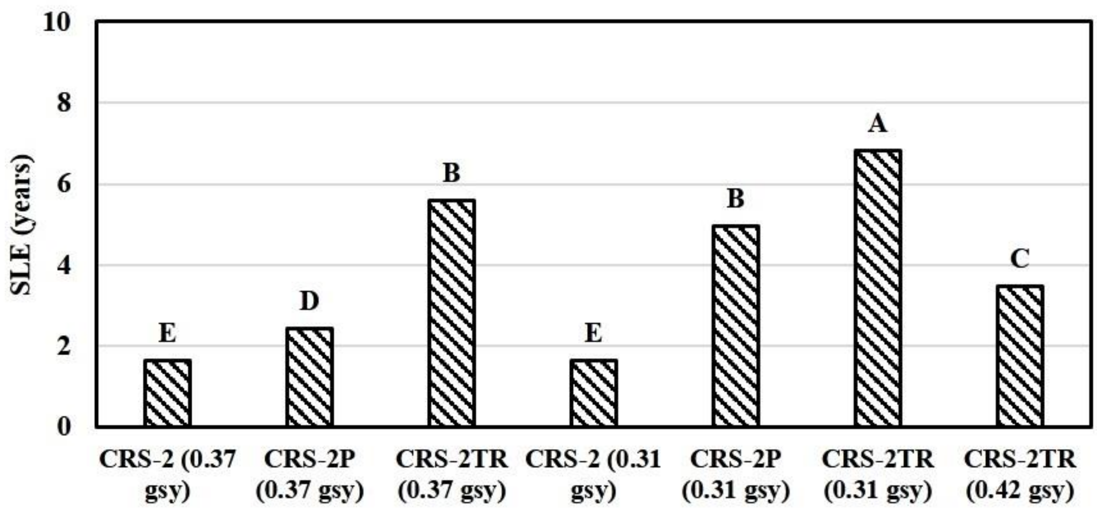


Service Life Extension (SLE)

Figure 53 presents the estimated service life extension of the test sections after application of chip sealing. It can be observed that the chip seal section constructed with CRS-2TR at an application rate of 0.31 gsy had the highest SLE of 6.5 years. In terms of SLE, the chip seal sections can be ordered as CRS-2TR (0.31 gsy) > CRS-2TR (0.37 gsy), CRS-2P (0.31 gsy) > CRS-2TR (0.42 gsy) > CRS-2P (0.37 gsy) > CRS-2 (0.37 gsy), CRS-2 (0.31 gsy). Therefore, it can be concluded that the maximum increase in the pavement service life would be achieved by applying CRS-2TR at the DOTD recommended emulsion application rate.

To determine which chip sealing had the most significant effect in increasing the service life of the pavement, an ANOVA was conducted at 95% confidence level ($\alpha = 0.05$) followed by the Tukey's HSD test to evaluate the statistical significance of SLE obtained for the different chip seal sections. As shown in Figure 53, the average SLE values obtained for the chip seal sections were assigned letters indicating statistical grouping based on performance and significance related to each other. It can be observed that the CRS-2TR (0.31 gsy) chip seal section had the best performance in terms of SLE; hence, it was assigned the letter "A." The performance of CRS-2TR (0.37 gsy) and CRS-2P (0.31 gsy) chip seal sections was superior compared to that of CRS-2TR (0.42 gsy) chip seal section and their performance was not significantly different; hence, they were assigned the letter “B.” CRS-2TR (0.42 gsy) chip seal section performed better compared to CRS-2P (0.37 gsy) chip seal section; hence, it was assigned the letter “C.” CRS-2P (0.37 gsy) section had better performance compared to the CRS-2 chip seal sections; hence, it was assigned the letter “D.” Lastly, the chip seal sections constructed with CRS-2 were observed with the poorest performance; hence, they received the letter “E.”

Figure 53. Estimated SLE for different chip seal sections



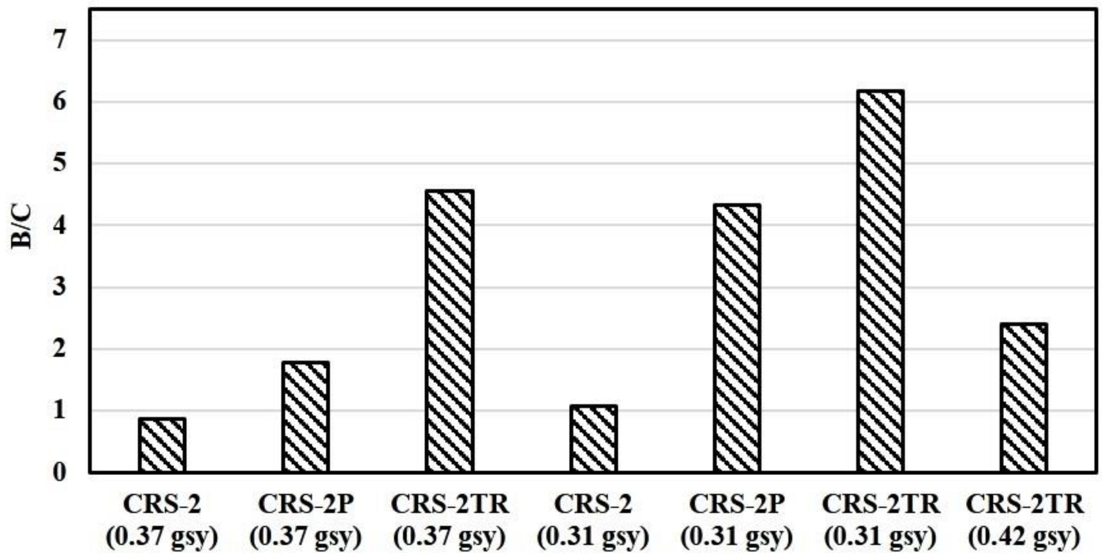
Cost-Benefit Analysis

Life-Cycle Cost Analysis (LCCA)

As shown in Figure 54, the LCCA analysis was conducted by estimating the Benefit-Cost (B/C) ratio for each chip seal section. It can be observed that the highest B/C was achieved for the CRS-2TR (0.31 gsy) chip seal section indicating that constructing a chip seal with CRS-2TR at an application rate of 0.31 gsy would result in the most cost-effective chip seal section. In addition, almost no net benefit was provided by the chip seal section constructed with CRS-2.

In terms of B/C, the chip seal sections can be ordered as CRS-2TR (0.31 gsy) > CRS-2TR (0.37 gsy) > CRS-2P (0.31 gsy) > CRS-2TR (0.42 gsy) > CRS-2P (0.37 gsy) > CRS-2 (0.31 gsy) > CRS-2 (0.37 gsy). Therefore, it is inferred that the most cost-effective chip seal section can be constructed with CRS-2TR applied at the DOTD recommended emulsion application rate.

Figure 54. B/C for different chip seal sections

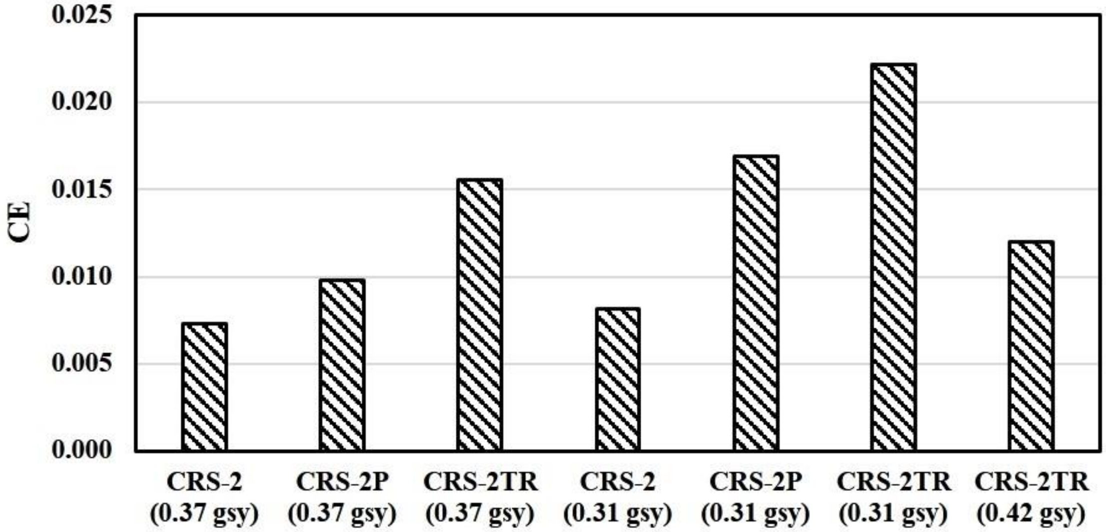


Cost-Effectiveness (CE) Analysis

Cost-effectiveness (CE) of each chip seal section was calculated to identify the most cost-effective chip seal section, as shown in Figure 55. It can be observed that the CRS-2TR (0.31 gsy) chip seal section achieved the highest cost-effectiveness indicating that the application of CRS-2TR at an application rate of 0.31 gsy would result in the most cost-effective chip seal application. It was also observed that the chip seal sections constructed with CRS-2 emulsion had the minimum cost-effectiveness.

In terms of CE, the chip seal sections can be ordered as CRS-2TR (0.31 gsy) > CRS-2P (0.31 gsy) > CRS-2TR (0.37 gsy) > CRS-2TR (0.42 gsy) > CRS-2P (0.37 gsy) > CRS-2 (0.31 gsy) > CRS-2 (0.37 gsy). Therefore, it can be concluded that a chip seal section with the best cost-effectiveness can be achieved by the application of CRS-2TR emulsion at the DOTD recommended emulsion application rate.

Figure 55. Cost-effectiveness for different chip seal sections



Conclusions

The objective of this study was to investigate the rheological and molecular properties of different asphalt emulsions and evaluate their laboratory and short-term field performance in chip seals prepared with different application rates, and aggregate blends. A newly introduced tire rubber modified asphalt emulsion was evaluated that allows chip seal installation at the same temperature of a standard emulsion. Conclusions drawn from the results are summarized as follows:

Rheological, Molecular, and Chemical characterization results of Tire Rubber Modified Asphalt Emulsion

- Rheological properties indicated that CHFRS-2P had the highest useful temperature interval (UTI) value of 92.7 followed by AC20-5TR (88.8), CRS-2P (87.8), CRS-2TR (82.6), and CRS-2 (76.7). Comparing the permanent deformation parameter ($G^*/\sin\delta$), fatigue resistance parameter ($G^*\sin\delta$), creep stiffness and m-value as measured from the PG grading test, CRS-2TR is expected to perform better than CRS-2 at both high and low temperatures.
- FTIR results showed that both CRS-2TR and AC20-5TR had the lowest carbonyl index growth in RTFO-aged and PAV-aged conditions, respectively, indicating that incorporating crumb rubber improved the binder's resistance to aging. Overall, CRS-2TR was expected to perform better against aging-related distresses as compared to other conventional emulsions (CRS-2 and CRS-2P).
- Moisture susceptibility characterization by the BBS test indicated that AC20-5TR had the highest bond strength values in both dry and wet conditions whereas CRS-2 exhibited the lowest. Furthermore, CRS-2TR and CRS-2P both yielded statistically equivalent pull off tensile strength in the wet and dry conditions.

Laboratory Performance of Tire Rubber Modified Asphalt Emulsion

- The laboratory performance of tire rubber modified asphalt emulsion was statistically comparable to that of the conventional polymer modified emulsion. In terms of aggregate loss in chip seals, the emulsions investigated in this study can be ordered as

CRS-2 > CRS-2P > CRS-2TR > AC20-5TR for lightweight aggregate and CRS-2 > CRS-2P> CRS-2TR > CHFRS-2P for granite aggregate.

- The investigation of the different application rates showed that the loss of aggregate in chip seal is reduced at high application rates. Although the NCHRP application rate performed well, a high application rate may not be practically feasible since it may result in a failing installation due to an aggregate embedment depth of 100%, causing a frictionless surface for the traveling vehicles.
- ANOVA test results indicated that, emulsion type, emulsion application rates, and aggregate blends are all significant factors influencing aggregate retention performance of chip seal.
- Incorporation of rubber as aggregate in the LWA gradation increased the loss of aggregate in chip seal specimens. These results indicate a poor adhesion between the emulsion and the rubber aggregate. However, a small percentage of crumb rubber (10% or less) may be used in chip seal without significantly affecting its performance. Further investigation is necessary to understand the emulsion-aggregate compatibility with crumb rubber aggregate.
- The loss of aggregate determined from both the sweep test and PART had a similar trend indicating the high correlation between these two tests.

Short-term Field Performance and Cost-effectiveness of Tire Rubber Modified Asphalt Emulsion

- Pavement macrotexture depth increased as a result of chip sealing, which indicates improved friction characteristics and skid resistance. However, chip seal sections constructed with CRS-2TR at high application rates of 0.37 gsy and 0.42 gsy resulted in relatively lower macrotexture depths. While a decrease in macrotexture depth reduces pavement surface friction, it improves surface roughness and reduces traffic noise.
- Chip seal sections constructed with the unmodified conventional emulsion, CRS-2, were the worst performer and had more susceptibility to cracking compared to the chip seal sections constructed with CRS-2P and CRS-2TR.

- In the northbound lane, the chip seal section constructed with CRS-2TR (0.37 gsy) was the best performer statistically. In the southbound lane, the chip seal sections constructed with CRS-2TR and CRS-2P (0.31 gsy) performed similarly.
- Chip seal section constructed with CRS-2TR (0.31 gsy) had the highest performance jump, whereas chip seal sections constructed with the unmodified conventional emulsion, CRS-2, had the lowest performance jump indicating an inferior restoration of pavement conditions after chip sealing.
- The maximum SLE was observed for the CRS-2TR (0.31 gsy) chip seal sections, whereas the chip seal sections constructed with CRS-2 had the lowest SLE.
- The most cost-effective chip seal section was achieved by the application of CRS-2TR emulsion at the DOTD recommended emulsion application rate.

Based on the results of this study, tire rubber modified asphalt emulsion provided promising results and is expected to provide adequate performance in the field. While hot-applied asphalt rubber showed superior performance and bond strength capabilities, the application of this material at an elevated temperature of 160-170°C is a safety concern for many states, which limit its use in states such as Louisiana and Mississippi. Therefore, the use of a newly introduced tire rubber modified asphalt emulsion may be considered as a promising alternative since it is installed at the same temperature of a standard emulsion, which is typically between 60 and 71°C.

Recommendations

The findings of this study should be adopted by DOTD in setting guidelines and specifications for the construction of chip seals with tire rubber modified asphalt emulsion. The following recommendations should also be considered in future research to optimize the use of the tire rubber modified asphalt emulsion:

- Investigate the compatibility of tire rubber modified emulsion with different type of aggregate used in chip seals.
- Investigate the use of crumb rubber aggregate in reducing traffic noise in chip seal applications.
- Add tire rubber modified emulsion to the specifications for use in chip seal in Louisiana.
- Investigate long-term field performance and cost effectiveness in future studies.

Acronyms, Abbreviations, and Symbols

Term	Description
AC	Asphalt Concrete
AST	Asphalt Surface Treatment
SAM	Stress Absorbing Membrane
SAMI	Stress Absorbing Membrane Interlayer
PUC	Performance Uniformity Coefficient
HMA	Hot-Mix Asphalt
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
ADT	Average Daily Traffic
ALD	Average Least Dimension
VMA	Void Between Aggregate
VFA	Void Between Aggregate Filled with Asphalt
ANOVA	Analysis of Variance
ARAN	Automatic Road Analyzer
LWT	Hamburg Wheel Tracking Test
B/C	Benefit Cost
BBR	Bending Beam Rheometer
CE	Cost Effectiveness
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation
TxDOT	Texas Department of Transportation
RV	Rotational Viscometer
DSR	Dynamic Shear Rheometer
BBS	Bitumen Bond Strength
EUAC	Equivalent Uniform Annual Cost
LCCA	Life-Cycle Cost Analysis
LTRC	Louisiana Transportation Research Center
NCHRP	National Cooperative Highway Research Program
NPV	Net Present Value
PAV	Pressure Aging Vessel
PCI	Pavement Condition Index or Composite Index
PG	Performance Grade

SPG	Surface Treatment Performance Grading
PJ	Performance Jump
MTD	Mean Texture Depth
POTS	Pull-off Tensile Strength
CII	Colloidal Instability Indices
SLE	Service Life Extension
HSD	Honest Significant Difference
COV	Coefficient of Variation
TNB	Treatment Net Benefit
ATR	Attenuated Total Reflectance
FI	Flakiness Index
MSCR	Multiple Stress Creep Recovery
PV	Present Value
PART	Pennsylvania Aggregate Retention Test
SSD	Saturated Surface Dry
AML	Aggregate Mass Loss
NRI	Normalized Resistances Index
PMS	Pavement Management System
PSL	Pavement Service Life
RTFO	Rolling Thin Film Oven
SHRP	Strategic Highway Research Program
HP-GPC	High-Pressure Gel Permeation Chromatography
SARA	Saturate, Aromatic, Resin and Asphaltene
FTIR	Fourier Transform Infrared Spectroscopy
EPG	Emulsion Performance-Grade

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