Quality Assurance for Chip Seals using Mean Profile Depth

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

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September 20, 2024
Blacksburg, Virginia

Keywords: Quality Assurance, Quality Control, Chip Seals, Macrotexture

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ABSTRACT

Chip sealing has numerous benefits as a pavement preservation treatment. The quality of the chip seal is assessed through various parameters, including texture depth, skid resistance, and visual evaluation. Current practice reveals that transportation agencies conduct quality assurance after construction, while contractors are typically responsible for chip seal placement and quality control. However, existing quality assurance procedures predominantly depend on visual inspection, and lack well-established methodologies. This study used Mean Profile Depth (MPD) as a macrotexture metric for the quality assurance of chip seals. Field data were collected using state-of-the-art equipment from the Virginia Department of Transportation (VDOT) area. Considering both qualitative (visual assessment) and quantitative (MPD analysis) approaches, this study delineates definitive categories representative of chip seal quality. These categories included good quality chip seals, with minimal to no signs of flushing and aggregate loss and MPD values ranging from 1 to 1.2 mm. Fair-quality seals had MPD values between 0.6 and 1 mm, while poor-quality seals were identified with MPD values below 0.6 mm. This structured classification enhances preventive maintenance strategies, improving chip seal pavements' overall sustainability and longevity.

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GENERAL AUDIENCE ABSTRACT

This thesis examines the quality of chip seals, an important aspect of road surface treatment that involves the application of one or more layers of specific aggregates and asphalt binders. The quality of chip seals was examined using macrotexture which is the larger-scale texture of the pavement. Macrotexture is one of the key properties of safety that significantly influences tire-road interactions especially when there is water presence on the pavement. Consistent and less varied macrotexture values on chip seals offer a reliable metric for evaluating pavement quality.

By focusing on macrotexture measurement and visual inspection, this thesis effectively differentiates between good and poor-quality chip seals, fostering a nuanced understanding of potential construction and practice-related issues. This insight aims to inspire improvements in chip seal applications, promoting enhanced road safety and performance for all users.

ACKNOWLEDGEMENTS

I extend my sincere gratitude to my advisor, Dr. Gerardo W. Flintsch, for his unconditional support, generous sharing of knowledge, and profound wisdom throughout my master's degree journey. His expertise in pavement engineering has been instrumental, and his encouragement has fueled my desire to learn even more.

I would also like to express my sincere appreciation to Dr. Edgar de leon Izeppi for his thoughtfulness and support during my thesis study, particularly in the realm of pavement safety knowledge.

A special thank you goes to Dr. Antonio Trani, my committee member, for delivering high-quality airport courses and imparting invaluable knowledge to me.

I am truly grateful for the guidance and mentorship received from each of you, which has significantly enriched my academic experience.

I also want to convey my profound gratitude to my husband, Batmunkh, for his consistent support in my pursuit of becoming a better version of myself. To my daughter Luna, I am grateful for staying with her grandparents to support my study. Lastly, thank you to my parents, Bold-Enkh and Tsogt-Ochir for always being there for me.

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CHAPTER 1. INTRODUCTION

Chip seal and similar surface treatment applications have been utilized as wearing courses on flexible pavements for low-volume roads since 1930. Over the past 75 years, their application has evolved to include surface treatments that have demonstrated effective for both high-volume and low-volume traffic roads (Gransberg and James 2005).

A chip seal is an application of asphalt binder covered by uniformly sized aggregates and it is one of the most used preventive maintenance treatments in the United States. In recent years, the expected service life of chip seals is 5 to 10 years. The thickness of the chip seal varies between 3/8 to 3/2 inches depending on the number of layers (Raza 1994).

Other frequently used preventive maintenance treatments besides chip seals include crack seal, slurry seal, cape seal, microsurfacing, thin and ultra-thin hot mix asphalt overlay, and ultra-thin friction course (de Leon Izeppi et al. 2015). Chip sealing has numerous benefits as a preventive maintenance. The asphalt binder provides a thin waterproofing layer to the underlying existing pavement base and subbase that prevents potential cracking, while the chip aggregates enhance macrotexture and provide surface friction for vehicles. According to the Long-term Pavement Performance Specific Study (SPS)-3, chip seals are more effective than slurry and crack seals in terms of mitigating fatigue cracking. Moreover, the chip seal outperformed the other treatments when the existing section had minor cracking before placing any treatments (Wiser 2011). The literature review highlights the necessity for enhancing the quality of chip seal end products by utilizing state-of-the-art practices and accurate performance measures. Chip seal performance is assessed through different parameters, including texture depth, skid resistance, visual evaluation, and visible distress.(Gransberg and James 2005).

Quality assurance (QA) for chip seals involves planned and systematic activities that are designated to provide confidence that a chip seal will perform satisfactorily in service (Burati et al. 2003; Halstead 1979). Current practice reveals that transportation agencies conduct quality assurance during construction, while contractors are typically responsible for chip seal placement and quality control. Agencies have forms or checklists to ensure compliance with quality standards, and field inspectors carry out visual inspections on-site. Depending on the agency, a visual inspection as a quality assurance may occur after a month to twelve months post-construction, or it may not be conducted.

Problem Statement

The quality of the chip seal depends on various factors, such as the pavement condition before the application of the chip seal, pavement surface temperature during application, aggregate and equipment quality, aggregate and binder application rate, and construction practices (Davis 2005; Gransberg and James 2005). AASHTO and ASTM provide recommendations for conducting quality control tests on aggregates and binders before their use in chip seal construction. However, post-construction quality assurance or acceptance is typically carried out by field inspectors, with the timing of visual inspection ranging from one month to a year, depending on the agency. The inspection heavily relies on personnel experience and training, which may raise concerns regarding reliability and validity (Zhao et al. 2018).

To address these concerns, a comprehensive chip seal quality assurance program should consider both the judgment of qualified personnel and quantitative engineering analysis based on scientific tests and principles to ensure its performance (Gransberg and James 2005) . This thesis proposes a quality assurance procedure based on quantitative analysis using a macrotexture characterization parameter, the Mean Profile Depth (MPD), to ensure that the chip seal construction meets the expected performance.

Objective

The main objective of this thesis is to propose a post-construction quality assurance method for chip seal projects using a macrotexture metric, aiming to assist in the development and implementation of a chip seal quality control and assurance program. This is achieved by measuring and analyzing the MPD on the chip-sealed surface. The proposed method involves the following steps:

- Assessing the variability of macrotexture across different projects and establishing threshold values for macrotextures based on descriptive statistics of measured macrotexture that ensure chip seal quality. This analysis will be based on data collected from chip seal in Virginia.
- Introducing a preliminary rating scale for chip seal quality assurance, incorporating the MPD parameter.

CHAPTER 2. LITERATURE REVIEW

Surface Treatments and Chip Seal Types

Surface treatments are pavement preservation treatments that extend the service life of pavements without structural deterioration, and, if applied properly, allow to improve the safety and condition of the road. Pavement preservation methods save money in the long term for both low-volume and high-volume roads. Depending on the pavement preservation type, preservation treatments can delay the expansion of existing distresses or prevent new distresses, restore surface properties, and enhance the serviceability. The main benefits of the chip seal are cost-effectiveness, ease of application, improved performance, and prolonged service life of pavement. In addition, preservation treatments are considered sustainable as they produce less greenhouse gas emissions and energy consumption compared to reconstruction and rehabilitation activities (Chan et al. 2011).

There are numerous pavement preservation treatments including chip seal, microsurfacing, slurry seal, fog seal, surface rejuvenation, and thin overlays. The choice of a preservation type and the correct timing to apply treatment must be based on the condition of the pavement and the desired goals. Chip seals are one of the most common pavement treatments in the US, New Zealand, Australia, and Canada. A “chip” refers to the single-sized crushed aggregate used in asphalt surface treatments. The bituminous material can be asphalt emulsion, cutback asphalt, polymer-modified asphalt emulsion, asphalt cement, or rubberized asphalt (Jalali and Vargas-Nordcbeck 2021; Merritt et al. 2015). Transportation agencies can fully leverage the benefits of chip seals by selecting the appropriate timing for application and considering the pavement condition. Chip seals need to be applied in the warmest seasons especially from May to September due to its curing time to the bond aggregate with emulsion. The appropriate candidate for chip seals is the road with low or moderate severity cracks, up to 1/8 inches wide and rutting of less than 3/8 inches (Shuler 2011).

Single-Coat Chip Seal

A single-coat chip seal is an application of emulsion followed by single-sized aggregates on a prepared pavement surface (Figure 1). Single coat chip seal can provide:

- Adequate macrotexture to the pavement surface
- Prevention of water intrusion into the base course by sealing minor cracks.

Using single-sized aggregates for single-layer chip seals can lead to better performance as they provide a more uniform height on the pavement surface. This ensures proper embedding of the aggregates in the binder and helps prevent chip loss. However, it is important to note that this type of chip seal should never be applied with chips that are the same size as the existing surface chip (TNZ 2005). The expected performance life for conventional single-chip seals is between 2 and 4 years and for polymer-modified single-chip seals ranges between 3 to 7 years (de Leon Izeppi et al. 2015).

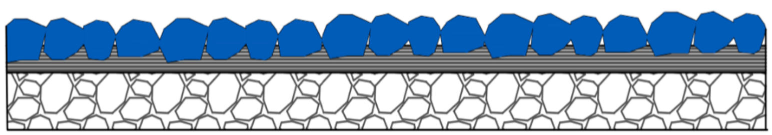


Figure 1. Single Coat Chip Seal

Double-Coat Chip Seal

Double-coat chip seal is a two-layer application chip seal. One application of binder and larger aggregate is followed by another application of binder and smaller aggregate with little or no time delay (Figure 2. Double Coat Chip Seal. Double chip seals are long-lasting and durable due to the chip interlock between the two layers and can withstand more traffic volume than any other chip seal type (Gundersen 2008).

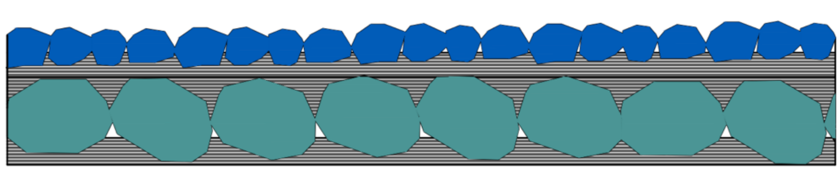


Figure 2. Double Coat Chip Seal.

Sandwich Seal

A sandwich seal is an application of a binder on top of the spread of large chips followed by an application of smaller chips. Large chips are placed directly on the existing pavement surface without the binder material underneath it. Sandwich refers to the binder material in between chips. Sandwich seals are effective on flushed or bleeding surfaces and minimize minor irregularities on a pavement surface. The excessive binder on the existing pavement acts as a binder for the sandwich seal aggregate layer (Marjerison et al. 2011). This type of chip seal can help restore skid resistance and macrotexture properties.

Geotextile Reinforced Seal

Geotextile reinforced seal is an application of asphalt covered by a layer of geotextile and the second spray of bitumen, followed by aggregate. Polymer-modified or other types of specialized binder cost more than the regular binder. Therefore, geotextile reinforced seals cost more than the single, and multiple layers of chip seals and have higher effectiveness than the other types of spray seals (Rebbechi and Alderson 2019).

Designs of Chip Seals

Chip seal designs aim to enhance the scientific, uniform, and systematic nature of chip seals. Internationally, the most widely adopted chip seal designs are those developed by Hanson, Kearby, and McLeod.

- Hanson introduced a chip seal design approach in 1935 that relied on the concept of void percentages and assumed the void percentage decrease for each activity such as after construction, rolling, and traffic compaction.
- Kearby devised a nomograph in 1953 that considered factors such as percent embedment depth, average aggregate size, and void percentages between aggregates. McLeod subsequently investigated aggregate and binder application rate techniques for chip seal construction.
- McLeod demonstrated the equations of the asphalt and binder application rate to design the single and multiple chip seals. An appropriate asphalt binder can be seen, and 70 percent of the aggregate height should be embedded in the binder.

According to (McLeod et al. 1969), the quantity of graded cover aggregate can be calculated using the equation (Eq. 2-1).

$$C = 46.8\,(1 - 0.4V)HGE \qquad \textit{Eq. 2-1}$$

where:
C = Cover aggregates (lbs/yrd^2)
H = Average Least Dimension of aggregates (inches)
G = Bulk specific gravity, ASTM
E = wastage factor due to the whip-off (E varies between 1.01 to 1.2, depending on the percentage of wastage)

Quantity of asphalt binder:

$$B = \frac{2.244HTV + S + A}{R} \qquad \textit{Eq. 2-2}$$

where:
B = asphalt binder per square yard
T = traffic factor (ranges from 0.6 to 0.85 depending on the traffic count)
V = voids fraction
S = surface texture correction
A = absorption correction

R = fraction of residual asphalt

Pavement Macrotexture

Macrotexture is a deviation of a pavement surface from a true planar surface with texture wavelengths in a range between 0.5 to 50 mm (Wambold et al. 1995). Macrotexture influences many pavement surface properties, including friction at high speeds, rolling resistance, tire-pavement noise, and splash and spray (Mogrovejo et al. 2016). The influence of a macrotexture on skid resistance is crucial as vehicle speeds because of its water drainage ability from the pavement's surface. Adequate drainage provides better interaction between the tire and pavement and leads to a safer driving experience.

Macrotexture Measurements

Macrotexture can be measured by static or dynamic methods. Dynamic methods employ high-speed laser profilers that measure macrotexture at traffic speeds (Flintsch et al. 2005). Furthermore, the textures measured using laser-based equipment are the most closely aligned with practical applications for detecting segregation, ensuring quality assurance (McGhee et al. 2003). Static methods include volumetric techniques, outflow meters, and portable laser-based macrotexture measuring devices. The volumetric technique involves spreading glass beads or sand on the pavement surface and is used for project-level analysis. Dynamic methods are less time-consuming, more accurate, and cause fewer disruptions to traffic compared to static methods.

The mean profile depth (MPD) is one of the parameters that provide an accurate assessment of the surface texture of the chip seal (Adams and Richard Kim 2014). MPD is the average mean segment depth of all segments within the measured profile (Figure 3). Each segment has a length of 100 mm, is further divided into two 50 mm subsegments, and the highest peak height in each half-segment is determined. The mean segment depth (MSD) is obtained by averaging these two peak heights. For a road segment, MPD is calculated following ASTM E 1845-15 in Equation (Eq.2-3):

$$MPD = \frac{1}{N}\sum_{i=1}^{N} MSD_i \qquad \textit{Eq. 2-3}$$

where:
N = the total number of 100-mm long segments in the test section
MSD = Mean Segment Depth of a 100 mm texture profile

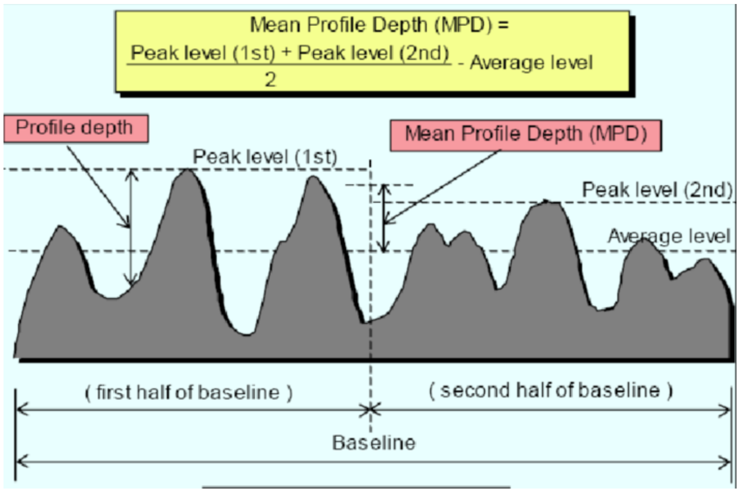


Figure 3. Mean Profile Depth (ISO 1997)

Advancements in technology enable the use of various experimental characterization procedures. Some studies suggest utilizing the root mean square value in pavement texture to distinguish the negative and positive textures (Zuniga-Garcia and Prozzi 2019). The texture depth generally can reflect common distress like chip seal bleeding and aggregate loss, making it an ideal parameter for QA/QC procedure (Bao et al. 2023).

Macrotexture as a performance measure

Macrotexture is one of the most crucial indicators of chip seal performance (Aktaş et al. 2013). Based on detailed measurements spanning 13 months, including texture depth, skid number, visual examination, stereo photos, and geotextile analysis, the macrotexture depth (Figure 4) was found to be the most effective parameter for chip seal performance (Roque et al. 1991). According to the findings of this study, MPD values were observed to be lower in areas affected by bleeding. In contrast, MPD values were found to be higher in areas where there was a loss of aggregates. Measuring the MPD can help in identifying common distresses associated with chip seals such as chip loss, bleeding, and cracking. Therefore, macrotexture measurements encouraged to detect and quantify segregation for quality assurance procedure (Flintsch et al. 2003). MPD for asphalt surfaces usually ranges from 0.4 to 2.5 mm. As the maximum aggregate size increases, raveling becomes more prominent, leading to increased tire pavement noise on chip-sealed pavement or dry asphalt (Rada et al. 2013). Performance measurement after 12 months from the placement of the chip seal is a recommended practice in New Zealand, Australia, and the UK. By evaluating the performance of chip seal surfaces, transportation authorities, and road maintenance agencies can make informed decisions regarding maintenance strategies and the quality of chip seals.

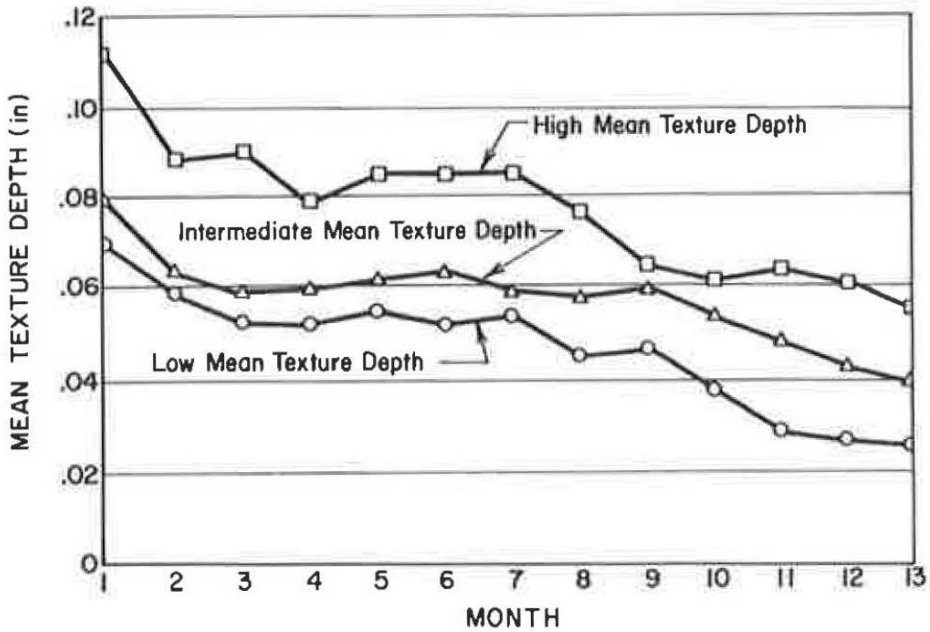


Figure 4. Mean Texture Depth for low, intermediate, and high MTD sections (Roque et al. 1991)

Performance requirements for chip sealing

The performance of pavement preservation is influenced by several variables: pavement condition before placing chip seals, the weather conditions during its application, and the volume of traffic they accommodate. The Strategic Highway Research Program 2 (SHRP2) quantifies high traffic volume as an of 5,000 vehicles daily for rural roads and 10,000 for urban roads. For such high-traffic roads, the adoption of a modified binder is advocated to ensure prolonged macrotexture durability (Bellanger et al. 1992). In a survey involving 28 state highway agencies regarding performance assurance methods, between 65-75% reported their reliance on method-based specifications for upholding quality and performance. Notably, most respondents highlighted an existing void in their quality assurance and quality control practices in pavement preservation, with no forthcoming plans to adopt such frameworks.

To gain deeper insights, a detailed literature review on the current practice of quality control and assurance program of chip seal treatment is essential, emphasizing the existing quality assurance practices in the USA, New Zealand, Australia and other countries. The following table offers an extract from various literatures, capturing the quality metrics associated with the quality and performance of chip seal projects.

Table 1. Literature summary table for quality measures

Author	Purpose	Quality Measures	Source	Summary of Findings
Gransberg and James 2005	Identify the benefits of using technologically innovative and advanced chip seal	Quantitatively - Skid Resistance, Texture Depth	Book	The quality of chip seal is affected by a numerious factors related to materials, design, and construction. An approved method to measure the chip seal macrotexture can furnish an objectively measured chip seal performance indicator. The use of the chip seal deterioration model expressed in the New Zealanf P17 Specification will furnish an objective definition of chip seal performance based on engineering measurements. Visual distress rating performed by an experienced personnel can support the above methods.
Kutay et al. 2016	Develop a standard test procedure to directly evaluate the aggregate embedment into the asphalt binder using digital image analysis.	Percent embedment (PE), Percent Within Limits	Report	Three image analysis algorithms, the surface coverage area method, peak valley method, and each aggregate method were developed. The peak and valley method showed similar results as sand-patch test. Needs to be identified the appropriate limits of percent embedment parameter. The percent within limits sensitivy to variability gives an advantage to contractors with lower variability in their production.
Haider et al. 2021	Develop empirical relationship between acceptance quality characteristics (PE) and chip seal performance (aggregate loss and bleeding).	Percent embedment, Percent Within Limits	Journal Article	Equations developed to show the relationship for bleeding and aggregate loss as a function of PE for chip seals with natural aggregates. Chip seal pay factors were estimated based on the bleeding and aggregate loss. A lower limit of 58 and an upper limit of 70 was set for PE based on aggregate loss and bleeding performance, respectively.
Zhao et al. 2018	Validate the concept of using macrotexture measurements to provide a cost-effective solution to assuring the quality of chip seal construction.	Friction Number, Mean Profile Depth (MPD), Visual inspection (Meanline Seal Coat Quality Assurance Evaluation).	Report	Field visual inspection reveals that bleeding and tracking are commonly found in the wheel paths, either in one wheel path or both wheel paths. MPD found to be the best macrotexture to assess the surface friction and therefore, the quality of chip seal.
Kebede and Pierce 2015	Evaluate chip seals performance indicators to develop these trigger values , end of service life and the pavement condition indices for resurfacing.	Pavement Structural Condition (PSC) that based on alligator, longitudinal, and transverse cracking	Report	Implementation of the proposed chip seal performance measure requires the identification of in-service performance measurement and currently available data that accurately identifies the appropriate timing for maintenance. In this study, a number of chip seal performance prediction models were identified. However, non of them addressed raveling which has been identified as one of the leading chip seal distress type.

Chip Seal Distresses

In discussing the performance and quality of chip seals, it is imperative to address the prevalent distresses and their impact on performance. The most common distresses in surface treatments are flushing or bleeding, chip loss, and striking of chips. Flushing refers to an excess of solid or semi-solid binder appearing on the surface, while bleeding pertains to a liquid and sticky form of binder (Lawson and Senadheera 2009). Aggregate loss, typically associated to the deterioration of the bond between binder and aggregate, contributing further to the occurrence of bleeding (Kim et al. 2017).

Quality control and assurance procedure for chip seals

Construction practices, material and equipment quality, aggregate and emulsion application rates, and road surface preparation significantly impact the chip seal quality and performance. The contractor bears responsibility for the material quality and construction processes, including handling and transportation of aggregates and other materials, equipment calibration and maintenance, field placement procedures, and sampling. Conversely, the transportation agency oversees product quality and adherence to specified standards during construction (Joslin et al. 2019).

Indications of premature chip seal failure include loose chips on the pavement and bleeding. These problems are linked to weather conditions, aggregate application rate, binder application rate, as well as inadequate rolling compaction. Chip loss commonly occurs during the initial settling period and persists over time due to insufficient chip embedding in the binder (TNZ 2005).

The literature review revealed that the post-construction quality assurance is typically conducted by the agency itself within a timeframe of one to twelve months, heavily relying on the field inspector’s experience and perspective. The primary distresses observed on chip seal pavements often attributed to lack of proper quality control, construction practices, and weather-related factors.

Quality control for Materials

The performance of a chip seal is directly associated with the materials being used (Shuler et al. 2011). The quality control program for materials includes field and laboratory testing. Laboratory testing for quarry products ensures the desired criteria for aggregate strength, crushing, and weathering resistance, size, and shape are met.

There is a quality control concern with field sampling tests of aggregate and binder. Binders can be contaminated by foreign substances during transport (Gransberg and James 2005).

The aggregate gradation changes during the transportation and stockpiling and increases the finer material which can affect the quality of the chip seal. Since the samples can only represent the minor proportions of a stockpile, test results are only an estimation of the true average (Gundersen et al. 2008).

Quality Control for Equipment

Construction equipment and its proper calibration leads to a successful chip seal project. The equipment utilized for the application of chip seals is a bitumen distributor, aggregate spreader, roller, motorized broom, and trucks. The literature review shows several practices related to the equipment and construction to achieve the anticipated quality.

1. Ensuring the surface is clean and dry constitutes the initial and most critical phase in the successful execution of chip seal projects.
2. Aggregate and application rate, speed of the trucks, and calibration of the equipment should be monitored throughout the process of applying the chip seal.
3. In the pre-construction period, a contractor determines the design voids factor and binder application rate based on the average least dimension.

Asphalt/bitumen distributor (Figure 5) is a vital piece of equipment requiring technician control. It must be monitored to prevent clogs during binder spray and ensure consistent application rates, with adjustments as needed for specific areas. To achieve a uniform application of the binder, it is essential for a technician to calibrate the equipment before start and consistently monitor the binder application rate during its spray application onto the surface.

Figure 5. Asphalt Distributor

Delayed time of aggregate application causes the emulsion to break and reduces the effectiveness of the rollers in achieving the expected embedment depth. Therefore, aggregate must apply right after the application of emulsion (Gransberg and James 2005).

Equipment that are required for chip sealing are showed in Figure 6, Figure 7, and Figure 8.

Figure 6. Chip Spreader

Figure 7.Chip Spreader following asphalt distributor

Figure 8. Roller

Quality Acceptance for Chip Seals

In chip seal construction, quality acceptance stands as a crucial component of the quality control process. It acts as the ultimate confirmation that the project aligns with the established standards and specifications. This important step includes evaluation or testing to confirm the integrity and performance of the finished chip seal surface (Bao et al. 2023).

According to the New Zealand Specification, quality is accepted when the texture depth is reached 0.9 mm or above after a year of chip seal construction.
As per UK specifications, contractors are obligated to maintain the surface macrotexture requirement for two years following the construction of chip seals. For quality acceptance purposes, the macrotexture depths are assessed between the 11^{th} and 13^{th} months, additional measurements are conducted after 22^{nd} months and before 24 months (Money and Hodgson 1992). The targeted retained macrotexture value is either 1.2 or 1.5 mm as per design (Bateman 2016).

National and International Chip Sealing Practices

Virginia Department of Transportation

Within the VDOT, chip seal is referred to as asphalt surface treatment and includes seal treatment, modified single seal, and modified double seal. Seal treatment involves one application of binder and one application of aggregates. Modified single seal comprises two applications of asphalt and one application of binder. Modified double seal consists of three applications of asphalt and two applications of aggregates.

Pavement selection for chip seal treatment

Decision matrices and Critical Condition Index (CCI) values assist determining the appropriate category of maintenance for the road section under consideration. These matrices evaluate each maintenance type based on the severity level of alligator cracking, transverse cracking, patching, and rutting as well as their density or area.

VDOT has implemented five categories for their pavement maintenance activities:

- Do Nothing (DN)
- Preventive Maintenance (PM)
- Corrective Maintenance (CM)
- Restorative Maintenance (RM)
- Rehabilitation or Reconstruction (RC)

The category of preventive maintenance incorporates chip seal, slurry seal, thin hot-mix asphalt, latex, and Novachip. In Virginia, chip seal treatments are specifically applied to secondary roads, targeting potential chip seal candidates with a CCI ranging from 66 to 85.

The pavement conditions are classified based on CCI value as follows:

- Excellent: Pavements with a CCI of 90 or above
- Good: Pavements within the CCI range of 70-89
- Fair: Pavements with a CCI between 60 and 69
- Poor: Pavements characterized by a CCI of 50- 59
- Very Poor: Pavements with a CCI of 49 and below.

In Virginia, pavement sections with an Average Annual Daily Traffic (AADT) of 3,500 or more are classified as high-volume traffic, while those with an AADT of less than 3,500 are categorized as low volume traffic (Prezioso 2022). The percentage of each pavement condition along with their high and low AADT presented in the (Figure 9. **Pavement Condition of Secondary Roads in Virginia**).

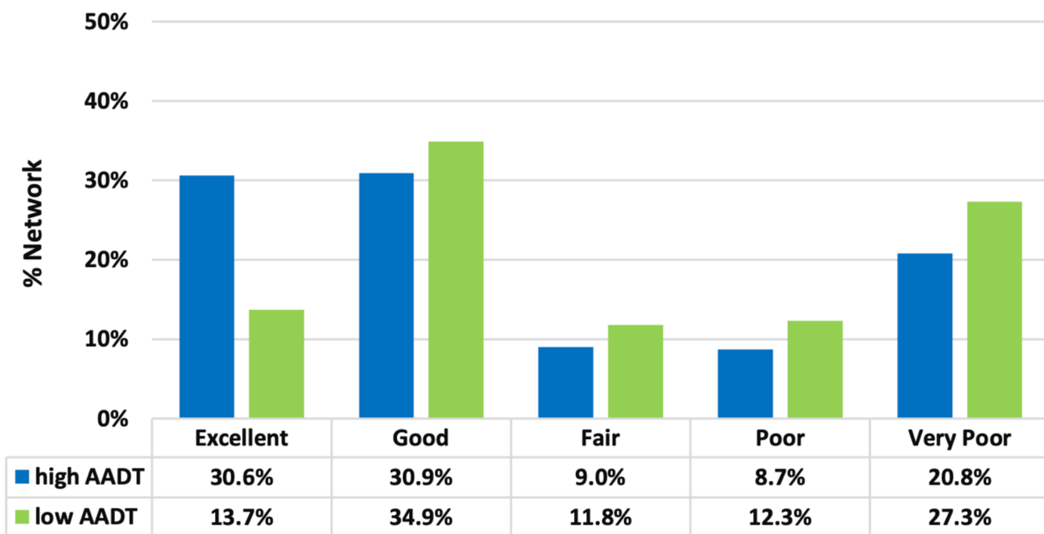


Figure 9. Pavement Condition of Secondary Roads in Virginia (Prezioso 2022)

Therefore, in Virginia, it is evident that pavements classified as fair, and often in good condition, are recommended for chip seal or surface treatment.

Surface Treatment Design

VDOT uses a modified version of the Asphalt Institute chip seal design procedure, based on the McLeod method, with specific adjustment to sieve analysis and flakiness index as outlined in Virginia Test Method VTM-66. A sieve analysis (Table 2) is conducted in adherence to VDOT specifications, the percentages passing are as follows:

Table 2. Sieve Analysis

Sieve Size	Percent Passing
1/24	100
3/8	75-100
No.4	10-40
No.8	Max.5

VDOT's aggregate and asphalt application rate for the modified single and modified double seal listed in the Table 3 and Table 4.

Table 3. Modified Single Seal Application Rate

Application	Aggregate Size	Aggregate Spreader Rate, lbs./sq.yd.	Asphalt Distributor Rate, gal./sq.yd.
1	8P	15	0.17
2	9	12	0.15

Table 4. Modified Double Seal Application Rate

Application	Aggregate Size	Aggregate Spreader Rate, lbs./sq.yd.	Asphalt Distributor Rate, gal./sq.yd.
1	8P	15	0.17
2	8P	15	0.17
3	9	12	0.15

Asphalt materials for surface treatments in Virginia include cationic rapid setting emulsified asphalt CRS-2, CRS-2h, CRS-2M, and RC-250.

Material Specifications

According to the VDOT Special Provision for Asphalt Surface Treatment – SP314-000100-00, the materials used in the surface treatment, modified single and double treatments, should be assessed and tested in accordance with the standards and methodologies outlined in the Table 5.

Table 5. Material Testing List for Asphalt Surface Treatments in Virginia

Testing	Standard
Compatibility of asphalt emulsion and cover aggregate	VTM-65
CRS-2 (Cationic rapid setting asphalt emulsion)	AASHTO T59
CRS-2M	AASHTO M316
CRS-2L	AASHTO T301
Aggregates	VDOT Sieve Analysis

The evaluation process involves the compatibility test of aggregate and asphalt for surface treatments. The procedure, conducted per Virginia Test Methods, is instrumental in determining the susceptibility of emulsified asphalt to stripping from the aggregate. The method involves the combination of 200 grams of saturated surface-dried aggregate with 30 grams of emulsion. For a sample to be deemed satisfactory and pass the compatibility test, it must exhibit a glossy and tacky black surface post-application on roofing felt and subsequent water sprinkling.

VDOT also utilizes a 1 by 1 inch plate to ensure the uniform application of binder for quality control purposes.

Washington Department of Transportation

Chip seal knowns as bituminous surface treatments in Washington state, is divided into new construction of surface treatments, seal coats that apply on the existing bituminous surface.

Pavement selection for chip seal treatment

Project selection is based on the Average Annual Daily Traffic (AADT) and pavement condition before placing any bituminous surface treatments.

Chip Seal Design

WSDOT does not have a formal design method for chip sealing activities; however, some agencies use modified McLeod or Asphalt Institute methods.

According to Special Provision 5-02.3 (WSDOT 2024), the application of emulsified asphalt and aggregates determined in Table 6Table 7.

Table 6. Application Rates for Surface Treatments

Application	Aggregate Size	Aggregate Spreader Rate, lbs./sq.yd.	Asphalt Distributor Rate, gal./sq.yd.
1	½ inch – No.4 or ¾ inch – ½ inch	25-45	0.35-0.65
2	½ inch – No.4	25-40	0.35-0.6
Choke Stone	No.4 - 0	4-6	N/A

Cationic Emulsified Asphalt is used for the bituminous surface treatments and the temperature range at the time of the application of binder must recommended by the manufacturer, otherwise the following:

Table 7. Asphalt Distributor Temperature

Type of Emulsified Asphalt	Min distributor temperature, ^{0}F	Max distributor temperature, ^{0}F
CRS-1, CRS-2, CRS-2P	125	195
CMS-2, CMS-2S, CMS-2h	125	185

Performance of chip seals

Washington Department of Transportation (WSDOT) measures the performance of chip seals by qualitative and engineering-based performance indicators. Engineering-based performance parameters are friction numbers and texture depths. Friction numbers are measured using locked-wheel friction trailer and texture depths (MPD and Mean Texture Depth (MTD)) are measured by sand circle test (Pierce and Kebede 2015). WSDOT developed a performance prediction model based on the percentages of fatigue, longitudinal, and transverse cracking measured by a profiler. These distress percentages are then used to determine the structural condition of the pavement. Equation (2-4) represents the calculation of Pavement Structural Condition (PSC).

$$PSC = 100 - 15.8\,x\,(EC)0.5; \quad \text{Eq. 1-4}$$

Where:
EC = equivalent alligator, longitudinal, and transverse cracking

WSDOT ensures to do the following for a better quality of chip seals:

- to place the second application of surface treatments the next day
- maintain a one-minute interval between applying the binder and spreading the aggregate.
- provide a minimum 1,000-foot binder shots to initiate uniform distribution of emulsified asphalt (Mahoney et al. 2014; WSDOT 2024).

Texas Department of Transportation Chip Seal Practice

In Texas Department of Transportation (TxDOT) preventive maintenance program, a seal coat is applied to an existing pavement surface, while surface treatment is used on prepared bases.

Pavement selection for chip seal treatment

TxDOT selects pavements with minor surface deficiencies for chip seal treatment. These deficiencies include cracking up to 1/8 inch (or wider if cracks sealed), low severity raveling, bleeding, and reduced speed resistance.

Surface Treatment Design

Since 1981, Texas Department of Transportation (TxDOT) has utilized the modified Kearby design method to determine the aggregate spread rate and asphalt application rate. Aggregate application rate is determined using board test method, where a single layer of aggregate is applied to a ½ square yard area (Kim and Adams 2012).

Aggregate application rate is calculated by the following equation:

$$S = \frac{27W}{Q} \quad \textit{Eq. 2-4}$$

Where:
S = Quantity of aggregate (yard^2/yard^3)
W = Dry loose unit weight (lb/ft^3)

Q = Aggregate quantity determined from the board test (lb/yard^2)

Asphalt application rate:

$$A = 5.61E\left(1 - \frac{W}{62.4G}\right)T + V \qquad \textit{Eq. 2-5}$$

Where:

A = Asphalt rate (gal/sq.yards) at 60^0F
E = Embedment depth calculated using Eq.7
G = Dry bulk specific gravity of the aggregate
T = Traffic correction factor
V = Correction for surface condition

$$E = e * d \qquad \textit{Eq. 2-6}$$

d = average mat depth (inches) in Eq.8
e = percent embedment determined from Figure

$$d = 1.33\frac{Q}{W} \qquad \textit{Eq. 2-7}$$

Material Specifications

Quality of aggregate and binder is essential for successful chip seals. Therefore, stockpiled aggregates undergo three laboratory tests:

- Dry loose unit weight,
- Bulk specific gravity,
- Board test that determines the aggregate quantity using a board with size of one-half square yard.

TxDOT aims to use single-sized stone and achieve an embedment depth of 40 to 50%. Grades 3 and 4 are used for the seal coat activities. Grade 4 aggregates are commonly used for seal coat due to their cost-effectiveness, although chip seals with Grade 3 aggregates have a longer lifespan. Grade 3 lightweight aggregates, which offer favorable frictional properties and reduced weight, are the primary type specified by TxDOT for seal coat applications (Estakhri and Sendheera 2017).

TxDOT utilizes rapid and medium curing cutback asphalt. Surface treatment mainly employ rapid curing cutbacks:

- RC-30
- RC-70
- RC-250
- RC-800.

The use of cationic emulsions enables chip seal projects to be opened to traffic sooner due to their quicker break nature. TxDOT employs AC-20-%TR asphalt containing 5% tire rubber and AC-20 XP polymer-modified asphalt cements. The chip seal emulsion comprises 30-35% water and is compatible with damp aggregates, providing an initial high embedment depth. Hot-applied asphalt concrete is the most used asphalt cement for seal coat construction.

Transit New Zealand

Pavement selection for chip seal treatment

New Zealand provides a wide range of sealing options including single and double coat chip seals. The selection of the sealing type and chip size depends on the traffic levels and surface conditions, including low skid resistance, inadequate macrotexture, and the presence of cracks and stresses.

Chip Seal Design

Chip seal design in New Zealand first introduced by Hanson in 1935, based on the concept of air voids in aggregates. Hanson proposed that these voids would decrease during roller compaction and under the influence of traffic. Since then, modifications were made in 1960s and 1990s to accommodate changes in traffic volume and to adjust the binder application rate accordingly. Building on previous work, a performance-based chip seal design algorithm was developed in 2004. The specification requires that 35% of the voids must be filled before winter (TNZ 2005).

$$V_v = ALD(0.83 - 0.07\log(T \cdot 100)) \qquad \textit{Eq. 2-8}$$

$$V_b = 0.35V_V \qquad \textit{Eq 2-9}$$

Where:
V_v = volume of voids
ALD = average least dimension (mm)
T = traffic volume (elv per lane per day)
elv = 2*VLD

Chip Spread Rate

$$S = \frac{750}{ALD} \qquad \textit{Eq. 2-10}$$

Where:
S = Spread rate
ALD = Average Least Dimension in range between 5.5 to 12.0 mm according to the TNZ M/6:2019 specification.

Binder Application Rate

$$V_b = (ALD + 0.7T_d)(0.291 - 0.025\log(200VLD)) \qquad \textit{Eq. 2-11}$$

Where:
VLD = Number of vehicles per lane per day
Vb = Volume of binder

Material Specifications

Chip sealing uses single-sized crushed or uncrushed aggregates in Grades 2,3,4,5 and 6. These aggregates must meet the minimum cleanness value (Table 8) and undergo tests for polished stone value, weathering quality index, and crushing resistance, as specified by Transit New Zealand in TNZ M/06. Quality control requires sampling and testing one sample for every 10,000 m^3 of aggregates produced.

Table 8. TNZ Specification for chips

Grade	Average Least Dimension (mm)	Minimum Cleanness Value
2	9.5-12	89
3	7.5-10	87
4	5.5-8.0	85
5	-	-
6	-	-

For two-coat chip seal application, Transit New Zealand uses Grade 3 for the lower layer and Grade 5 for the upper layer of chip seal. Single coat chip seals with Grade 3 aggregates lasts longer than the Grade 4 and 5. However, two-coat chip seal with Grade 2 for the first layer and Grade 4 for the second layer has a longer average service life.

Emulsion and asphalt cements should require TNZ P/3: 1995 Specification for first coat sealing and TNZ M/1:2022 Specification for Bitumen. 130/150 penetration grade for bitumen is used in warmer areas, while the 180/200 is applied in other regions (Gundersen 2008).

Performance of chip seals

Performance of chip seals is divided into short and long-term performance in New Zealand. Short-term performance or chip seal performance after the construction period depends on factors like aggregate and binder application rate, traffic impact, effect of rolling and temperature, and binder properties. In contrast, long-term performance of chip seal or in-service performance mostly relies on binder properties, compaction quality, and application rates of asphalt binder and chip (TNZ 2005).
Texture loss is one of the main indications of chip seal failure. New Zealand Transportation Agency defined flushed chip seal treatment when texture depth is less than 0.7 mm for the roads with speed limits of over 70 km/h (43.5mph) or texture depth is less than 0.9 mm for those roads with posted speed limit under 70 km/h (Herrington et al. 2015).

According to the New Zealand Transport Agency NZTA T10 Specification (Table 9), minimum MPD values established for the investigatory and threshold levels are 1.0 and 0.7, respectively. The investigatory level of macrotexture defines the point at which treatment consideration commences, while the threshold level of macrotexture represents the trigger level of MPD that needs to be treated first.

Table 9. NZTA T10 Specification - Minimum Macrotexture Requirements

Minimum macrotexture (MPD, mm)						
Permanent Speed Limit	**Chip Seal**		**Asphaltic Concrete (ESC≥0.4)**		**Asphaltic Concrete (ESC<0.4)**	
	ILM	TLM	ILM	TLM	ILM	TLM
50 km/h (31mph) and less	1.0	0.7	0.4	0.3	0.5	0.5
Less than or equal to 70 km/h (43 mph) but >50 km/h	1.0	0.7	0.4	0.3	0.7	0.5
Greater than 70 km/h	1.0	0.7	0.9	0.7	0.9	0.7

Transit New Zealand uses TNZ T/3: 1981 Standard test procedure for measurement of texture by the sand circle method to determine the average texture depth and is calculated by the following equation (Eq.2-12):

$$T_d = \frac{57300}{D^2} \qquad \textit{Eq. 2-12}$$

Where:
T_d = Average texture depth, mm
D = Sand circle diameter, mm.

Australia

Sprayed seals in Australia, used effectively on roads that carry several thousand vehicles per day.

Pavement selection for sprayed seals

The selection of sprayed seal types is influenced by existing surface distresses, severity, texture depth, traffic volume, and skid resistance. The most common types of sprayed seals are single and double seals, as well as reseals. Reseals are applied over existing bituminous surfaces to restore surface conditions.

Chip Seal Design

Design procedure for sprayed seals was adopted from Hanson method. ALD, traffic volume, and percentage of voids after rolling and trafficking are important parameters when designing sprayed seals. Design traffic volume is determined by adding all light and heavy vehicles in a lane. ALD used to calculate the aggregate spread rate and binder application rate (Patrick 2019). Aggregate spread rate for single and double seals is determined in Table 10 depending on the binder types that use for specific pavement application. Basic and design binder application is determined using Equations 2-2 and 2-3.

Table 10. Aggregate Spread Rate Calculations (Patrick 2019)

	Aggregate Spread Rate (m²/m³)	
Binder	**Single Seals**	**Double Seals**
C170, C240, C320, PMB, and multigrade bitumen,	900/ALD	950/ALD
Emulsion, cutback binders	800/ALD	850/ALD

Average Least Dimension (ALD) is the parameter that used to calculate the design binder and aggregate application rate. Chip seal design input parameters are basic void factor, the parameter that bases on the traffic volume, and design void parameter which determined the by equation.

$$VF = V_f + V_a + V_t \qquad \textit{Eq. 2-13}$$

where:

Vf = basic voids factor

Va = adjustment for aggregate shape

Vt = adjustment for traffic effects

Basic binder application rate

$$B_b = VF \times ALD \qquad \textit{Eq. 2-14}$$

Where:
B_b = basic binder application (l/m^2)
VF = design void factor
ALD = average least dimension of aggregate

Modified basic binder application rate

$$B_{bm} = B_b \times BF \qquad \textit{Eq. 2-15}$$

Where:
BF = binder factor (BF = 1.0 for binder type C170, C240, and C320)

Design binder application rate

$$B_d = B_{bm} + allowances. \quad \textit{Eq. 2-16}$$

Where:
B_d = design binder application

Allowances = applicable allowances in Section 6.2.2 (Patrick 2019).

Performance of chip seals

In terms of performance, traffic has a significant effect on whether the aggregate particles would achieve their average least dimension. Heavy traffic aids aggregate to lie on their wide side, and light traffic which is less than 200 vehicles a day has less effect on aggregate arrangement. Selection of seal treatment requires consideration of traffic volume, speed, turning movements, existing surface condition such as cracking severity and type, and texture depth variation, equipment and material availability and expertise.
Austroads performance requirement for seal coats are surface texture, skid resistance, noise, brightness of pavement markings, spray and water characteristics, and appearance (Patrick 2019). Performance expectation is higher in the high-stress areas, and it can be obtained by using multiple layers of application and binder. Compaction and uniform surface finish of granular materials are critical element for successful seals. Aggregate embedment is complicated to achieve when placing a chip seal over flushed or bleeding surface. In Australia, nominal size of aggregate is considered up to 20 mm and up to 14 mm used for single chip seals. Aggregate size for high traffic volume roads is between 10 and 14 mm, and for lower traffic volume is 7 to 10 mm (Rebbechi and Alderson 2019).

The adhesion between binder and aggregate develops well if the sealing is performed in warm weather and expected to be reduced in cool weather. Therefore, choosing appropriate dry, warm weather condition to commence spray sealing reduce the risk of unbonded materials and extended caring time to open to traffic. Chip seal service life is influenced by:

- Seasonal temperature variation
- Moisture changes in pavement materials
- Binder oxidation in high temperature

Key Findings of the Literature Review

- Transportation agencies select roads with low-severity cracks and minor surface wear as suitable candidates for chip seals.
- Surface texture measurements can serve as a performance measure or acceptance quality characteristics for chip seals. By analyzing surface texture parameters such as MTD or MPD, agencies can determine whether a chip seal has been constructed with quality or if maintenance is required.
- Rigorous quality control of materials, equipment and application process contributes the production of higher quality chip seals.
- The uniform application of aggregates and binder is essential for chip seal performance. Monitoring the proper spread of application serve as a part of quality control and may prevent bleeding issues later in the chip seal’s lifespan.

CHAPTER 3. METHODOLOGY

The thesis includes several tasks: data collection, data processing and analysis, and visual and quantitative assessments to perform quality assurance for chip seals. The chip seal projects evaluated included a main set of projects selected by different districts and used to define the methodology, and a supplementary set of projects in Franklin County to fine tune it and enhancing our understanding of the relationship between visual assessment and macrotexture measurements.

Data Collection

Macrotexture and friction data were obtained from 8 chip seal projects of the Virginia Department of Transportation (VDOT) in Richmond, Hampton Roads, Fredericksburg, Lynchburg, and Salem districts as shown in Table 11. Out of the eight routes evaluated, seven are treated with modified single seal and one route treated with a seal treatment that incorporates a singular layer of asphalt ang aggregates. The measurement lengths differ from route to route and all routes are divided into the same length sections or analysis units. Each section of the route consists of 0.1 miles (160 meters).

Data was collected by using high-speed macrotexture machine called Sideway-Force Coefficient Routine Investigation Machine (SCRIM). SCRIM measures MPD using 64 kHz single spot laser on the left wheel path in 1 and 10 m averages. It also measures a friction force using a smooth tire with a fixed 20 degree slip angle (de León Izeppi et al. 2019) Additional data including aggregate and binder application rate, pre-application pavement condition, age, and chip size for each route will be obtained from VDOT. Furthermore, images of three chip seal projects in Salem District area were acquired to investigate the correlation between image analysis and macrotexture deviations. Collected data are then analyzed, allowing for a comprehensive evaluation of chip seal performance.

Table 11. Chip seal projects' description

Route	County, District	Measurement Length	Chip Seal Type	AADT
VA 609	Mecklenburg, Richmond	MP 11.2 – 12.9	Modified Single Seal	252
VA 730	Southampton, Hampton Roads	MP 2.64 – 8.47	Seal Treatment	100-249
VA 660	Brunswick, Richmond	MP 1.7 – 2.85	Modified Single Seal	406
VA 633 Caroline	Caroline, Fredericksburg	MP 7.12 – 8.2	Modified Single Seal	170
VA 647	Appomattox, Lynchburg	MP 5.85 – 9.15	Modified Single Seal	422
VA 628	Cumberland, Lynchburg	MP 0.17 – 3.25	Modified Single Seal	150
VA 633 Salem	Botetourt, Salem	MP 2.2 – 4.5	Modified Single Seal	400-749
VA 623	Prince George, Richmond	MP 0.37 – 3.25	Modified Single Seal	359
SC 914	Franklin, Salem	MP 0-0.1	Modified Single Seal	1382
SC 704		MP 0-1.02	Modified Single Seal	239
SC 705		MP 3.61-5.46	Modified Single Seal	316
SC 668-B		MP 0.77-2.29	Modified Single Seal	2049
SC 936		MP 0-0.79	Modified Single Seal	248
SC 702		MP 0-2.25	Modified Single Seal	293
SC 815		MP 0-1.52	Modified Single Seal	214
SC 668-A		MP 0-0.77	Modified Single Seal	427

In addition, to ascertain the proximity between the visual evaluations conducted by experienced personnel and the quantitively measured macrotexture results, supplementary data were gathered from several secondary roads SC 914, SC 936, SC 702, SC 815, SC 704, SC 705, and SC 668 in Franklin County area. All the routes were treated with modified single seals in 2022. These projects were assessed visually by an experienced engineer in VDOT, and macrotextures measured by SCRIM.

Consequently, these respective routes were subsequently categorized into good, fair, and poor quality based on visual assessment.

Data Processing and Analysis

The data processing step involves removing the outliers and spikes from the collected data. Macrotexture measurements on bridge deck surface was excluded due to a different pavement type - rigid pavement. MPD and Global Positioning System (GPS) data were collected at every 10 meters along the route from SCRIM measurements and mileposts (MP) were obtained from using iVision for correlated GPS data points.

For the main analysis, macrotexture data was examined using standard deviation, boxplots, and mean values. Standard deviation assessed the variability along each route, boxplots illustrated the central tendency of each segment, and mean values were used for route comparisons.
Additionally, data for 8 routes were compared and analyzed using the following descriptive statistics: Root mean square (RMS), Coefficient of Variation (COV), and the percentages fall between the expected range of macrotexture. The results are detailed in the results section.
Figure 10 and Figure 11 show plots of macrotexture and friction data to visualize variability within VA 609 and VA 660, respectively.

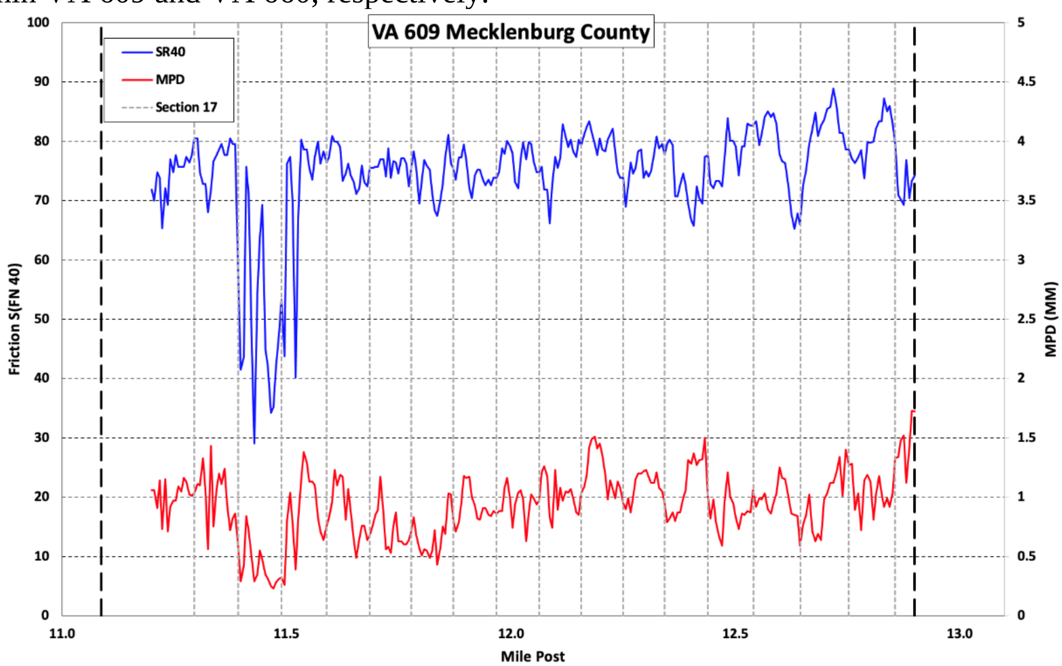


Figure 10. MPD and Friction Measurements on the VA 660 test section.

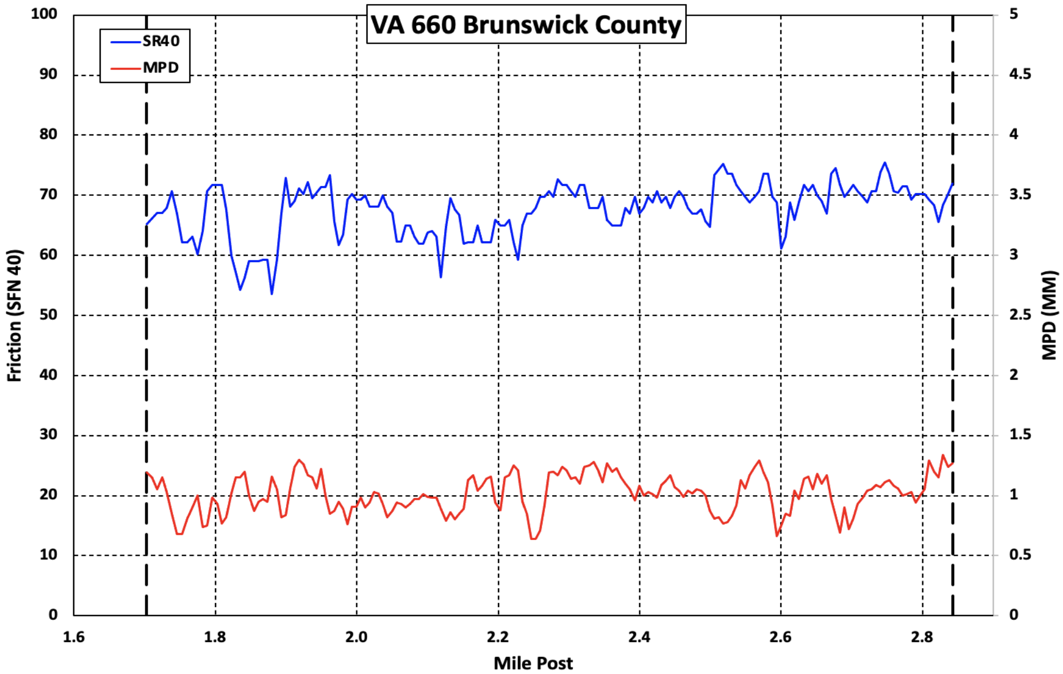


Figure 11. MPD and Friction measurements on the SC 936 test section

Additional data collection for the routes SC 914, SC 936, SC 702, SC 815, SC 704, SC 705, and SC 668 underwent the same analysis and processing procedures as the primary chip seal projects. MPD and Friction plots for two routes are provided in the Figure 12 and Figure 13.

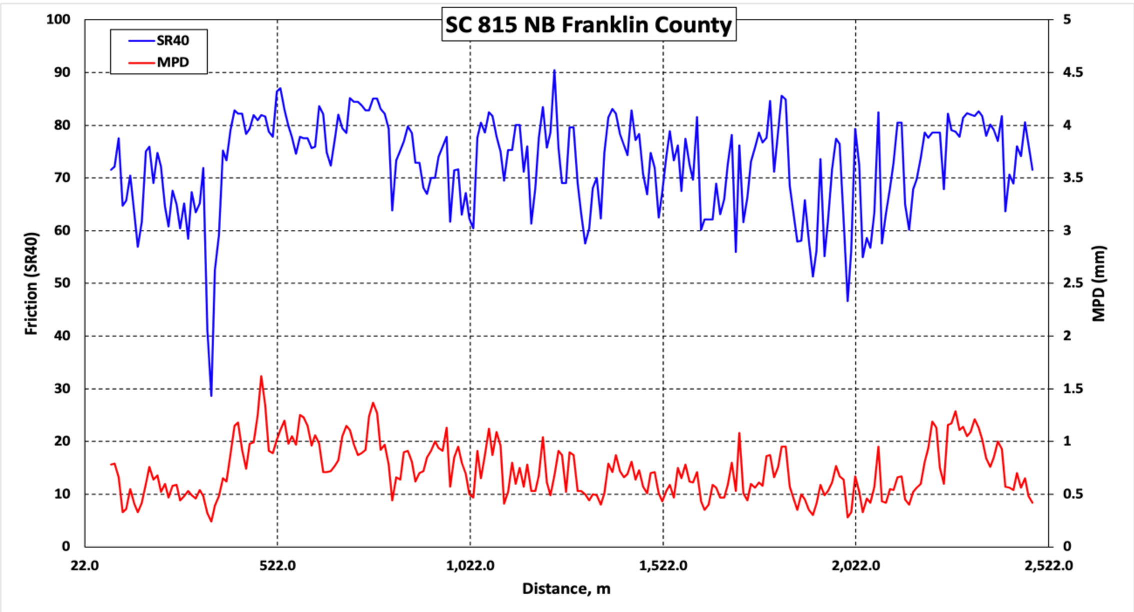


Figure 12. MPD and Friction measurements on the SC 815 test section

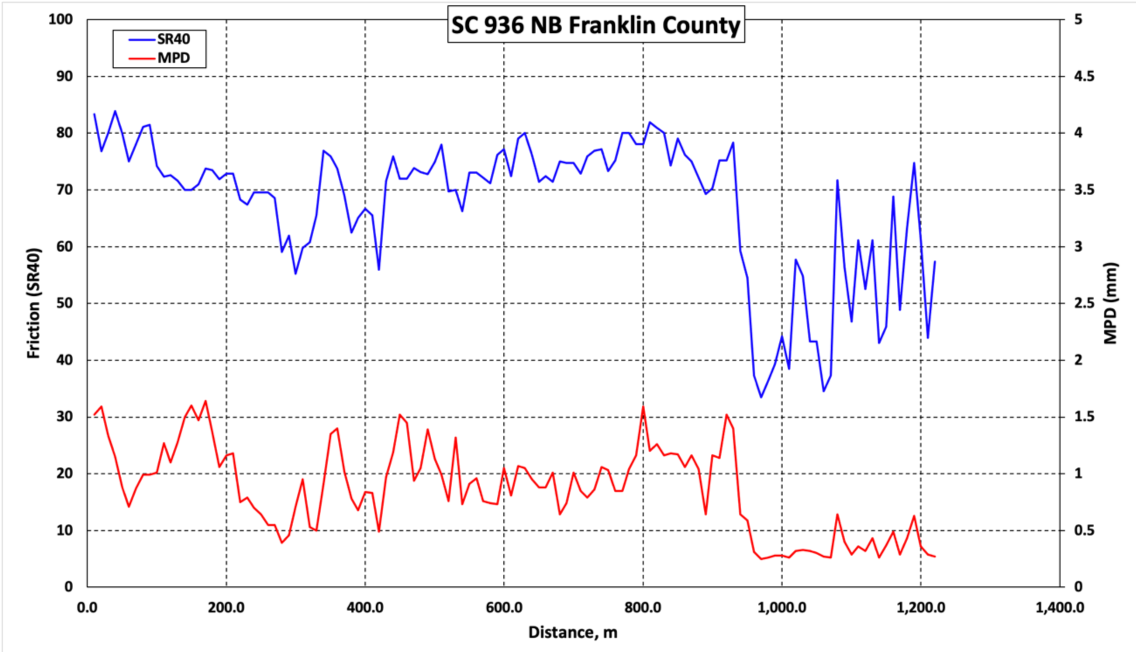


Figure 13. MPD and Friction measurements on the SC 936 test section

Visual assessment involved visiting project sites to identify pavement defects or distresses present on the surface. Then, the pavement distresses were categorized as either good, fair, or poor based on the severity of the distress observed. VA 628, VA 647, and VA 633S were visually assessed approximately a year after the chip seals were placed to investigate the correlation between descriptive statistics and visual evaluation.

CHAPTER 4. RESULTS

The results of a visual assessment and quantitative analysis are presented in this section.

Quantitative Analysis

Chip seal projects analyzing for this thesis were compared and analyzed based on the macrotexture standard deviation, average, RMS, boxplots, COV, and the percentages fall between the expected range of macrotexture.

Table 12 represents the results of the descriptive statistics. The proposed macrotexture threshold values of 0.6 mm and 1.2 mm were used to calculate the percentages of MPD within these limits, less than 0.6 mm and higher than 1.2 mm. These values were selected based on the New Zealand and the United Kingdom's specifications on chip sealing and our analyzed data (Money and Hodgson, 1992).

Table 12. A summary of descriptive statistics

Route	Average MPD	SD	RMS	COV	% MPD within limits	% MPD less than 0.6 mm	% MPD over 1.2 mm
VA 660	1.011	0.158	1.023	0.156	88.64	0	11.36
VA 628	0.631	0.189	0.658	0.299	54.81	45.19	0
VA 647	0.901	0.219	0.927	0.243	83.47	7.26	9.27
VA 623	0.905	0.229	0.933	0.253	81.85	11.31	6.85
VA 633 Salem	1.262	0.264	1.289	0.209	41.41	1.0	57.55
VA 609	0.973	0.276	0.977	0.294	73.90	11.76	14.34
VA 633 Caroline	1.048	0.297	1.090	0.283	66.88	2.50	30.63
VA 730	0.862	0.349	0.930	0.405	57.11	24.14	18.75

The summary shows that VA 730 exhibited the highest SD value across all routes, while VA 660 had a less varied SD. SDs are presented in ascending order.

Regarding macrotexture percentages between 0.6 and 1.2-mm limits, most measured MPD values for VA 660, VA 623, and VA 647 fell within these bounds. VA 633 Salem had the highest macrotexture across the entire project, whereas VA 628 recorded the lowest, with no MPD values exceeding the given limit. As an example, Figure 14 compares the macrotexture along these sections.

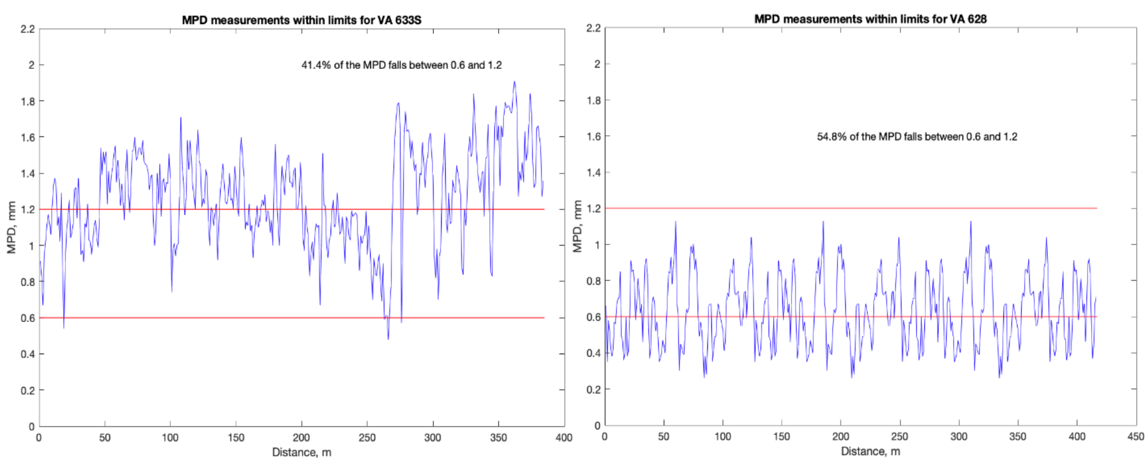


Figure 14. Macrotexture measurements within the expected limits

Figure 15 compares the macrotexture along another six sections. The figure shows that VA 730 exhibited the highest data variability with 58 sections, while VA 660 demonstrated the least with 11 sections. Noticeably, all routes presented taller box heights in the central measurement area, suggesting elevated macrotexture variability, attributable to application practices or surface wear. VA 660 and VA 628 demonstrated the most consistent chip seal application, as evidenced by their closely aligned median values.

As outlined, the sections were analyzed also segmented into 0.1-mile analysis units and the numbers of units per section are compared in the
Table 13.

Table 13. Chip seals projects section

Route	Measurement Length	Number of Sections
VA 609	MP 11.2 – 12.9	17
VA 730	MP 2.64 – 8.47	58
VA 660	MP 1.7 – 2.85	11
VA 633 Caroline	MP 7.12 – 8.2	10
VA 647	MP 5.85 – 9.15	31
VA 628	MP 0.17 – 3.25	26
VA 633 Salem	MP 2.2 – 4.5	24
VA 623	MP 0.37 – 3.25	21

Typically, the initial and final segments of the chip seal application revealed inconsistencies (Figure 16), displaying either higher or lower levels than the remaining sections, implicating irregular aggregate and/or binder application in these project areas.

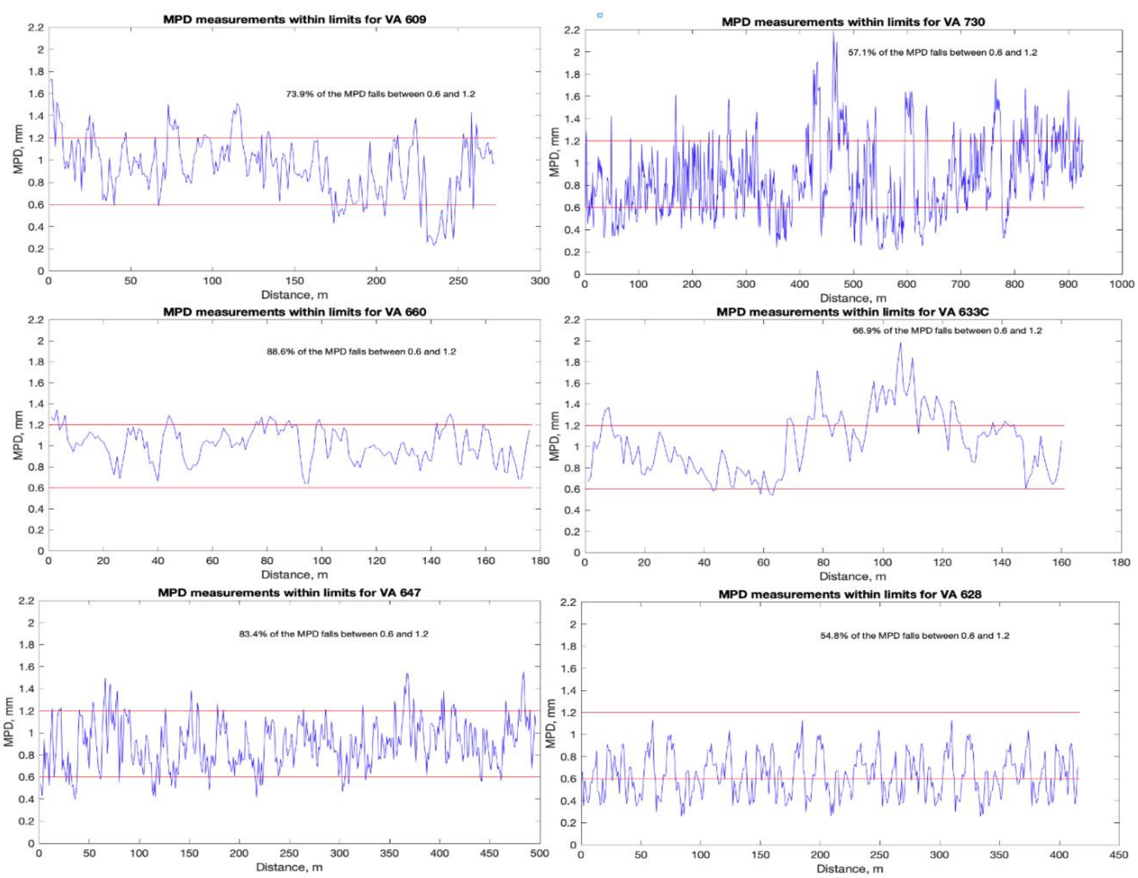


Figure 15. Macrotexture measurements within the expected limits

The analysis of boxplot trends reveals some patterns in the MPD median values across different road sections. Specifically, a consistent decline is observed in the median values of macrotexture in the third section across all routes. In contrast, there is an increase in the median value when examining the fifth section. This trend could potentially be linked to variations in the uniformity of the binder and variations in aggregate applications over time.

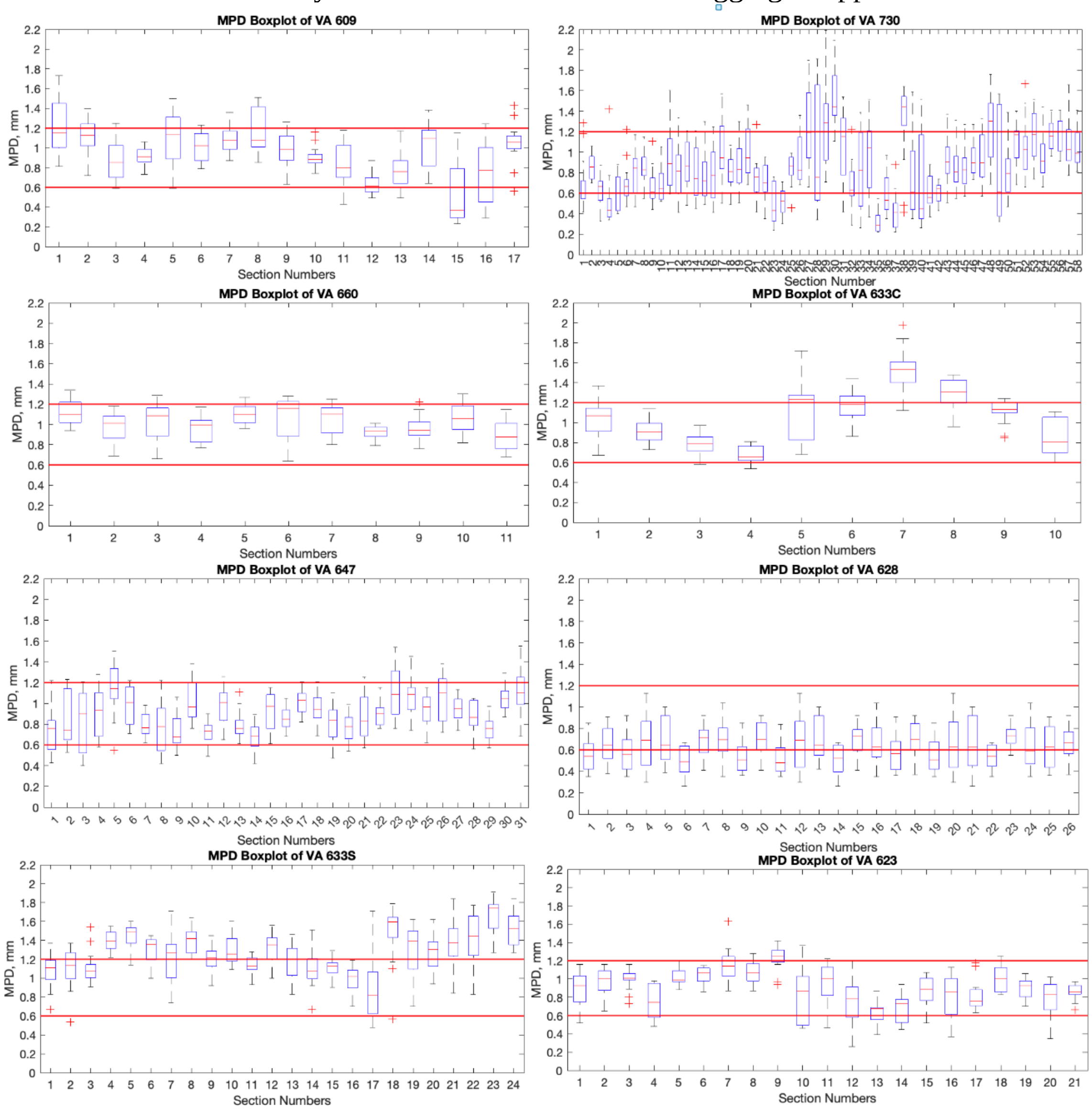


Figure 16. Boxplots of macrotexture for selected routes

To conduct a comparative analysis of the presented chip seal projects, acknowledging the different lengths of roads presented a challenge. Consequently, to establish a standardized basis for evaluation, the initial 10 sections of each project were selected as focal points for the comparative and analytical evaluation as shown in Figure 17. Table 14 presents the average MPD for each section of the project, along with the overall average and standard deviation for comparison across the 8 projects. VA 633 Salem and VA 609 had the highest average MPD of 1.1 and 1.116 mm, respectively, while VA 628 had the lowest average MPD at 0.646 mm based on the first 10 sections.

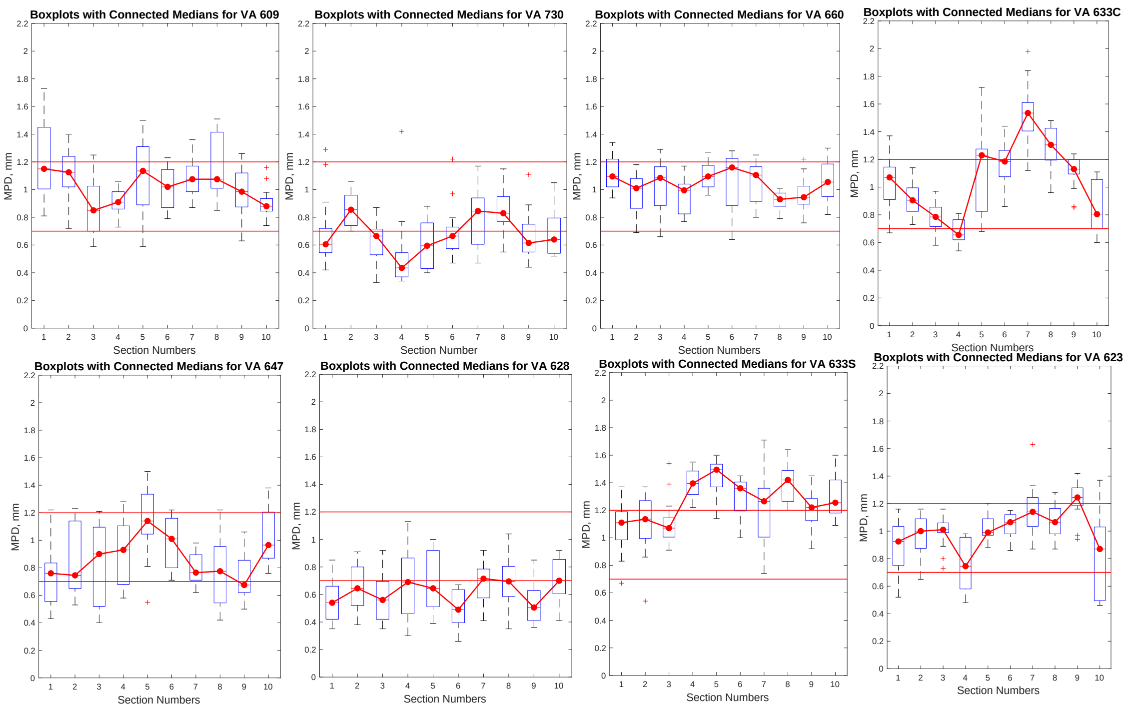


Figure 17. Boxplots comparison for the initial 10 sections

Table 14. Average and Standard Deviation of MPD for the initial 10 sections

Route	Average MPD for										Average MPD	SD
	Sec #1	Sec #2	Sec #3	Sec #4	Sec #5	Sec #6	Sect #7	Sec #8	Sec #9	Sec #10		
VA 660	1.12	0.97	1.03	0.95	1.10	1.06	1.05	0.92	0.97	1.06	0.974	0.173
VA 628	0.54	0.65	0.59	0.69	0.70	0.49	0.69	0.70	0.53	0.71	0.646	0.172
VA 647	0.74	0.84	0.83	0.91	1.15	0.99	0.80	0.77	0.73	1.02	0.839	0.255
VA 623	0.89	0.97	1.00	0.75	1.02	1.04	1.16	1.08	1.23	0.83	0.966	0.146
VA 633 Salem	1.09	1.10	1.11	1.39	1.44	1.30	1.22	1.40	1.21	1.30	1.100	0.212
VA 609	1.22	1.12	0.88	0.92	1.09	1.01	1.08	1.16	0.99	0.90	1.116	0.173
VA 633 Caroline	1.04	0.91	0.78	0.68	1.12	1.16	1.54	1.28	1.11	0.86	0.910	0.119
VA 730	0.68	0.86	0.62	0.52	0.60	0.70	0.80	0.84	0.66	0.67	0.857	0.120

Visual Assessment

This section illustrates a series of typical three of the investigated surface treatments in service and the most common distresses observed in these sections.

<u>VA 628 in Cumberland, Lynchburg:</u>

Alligator/Fatigue cracking were visibly apparent at both the edge and center of the road during visual observations, resulting from the stress of heavy vehicle traffic (Figure 19 and Figure 19). Chip seal and surface treatments, especially in Virginia's rural areas, are typically not designed to accommodate heavy vehicular loads. As a result, this type of distress adversely affected the road’s texture and quality.

Figure 18. Fatigue cracking at the edge of the road

Figure 19. Fatigue cracking in the center of the road

<u>VA 647 in Appomattox, Lynchburg:</u>

Flushing and chip loss were predominant distresses observed in this chip seal project (Figure 21 and Figure 21). Flushing was present in the wheel paths and certain areas extended beyond them. Conversely, chip loss is particularly evident at the route’s end, resulting in a rough surface.

Figure 20. Flushing at the end of the route

Figure 21. Chip loss at the end of the route

<u>VA 633S in Salem, Botetourt:</u>
The road's texture and aggregate distribution appeared uniform upon visual assessment, though irregularities in horizontal alignment or minor rutting were noted.

Figure 22. Irregularities/Rutting along the route

Supplementary Analysis

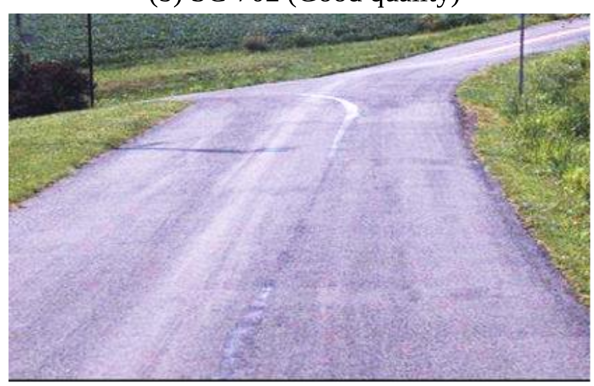
Secondary routes SC 914, SC 936, SC 702, SC 815, SC 704, SC 705, and SC 668 were evaluated into three categories by an experienced engineer, based on the perceived quality of their chip seals a year after treatment: good quality, fair quality, and poor-quality chip seals.

The categorization criteria are as follows: chip seals classified as "good quality" exhibit minimal to no deficiencies upon visual inspection (Figure 23(a) and (b)). "fair quality" chip seals are identified by the presence of some flushing or loss of cover aggregate (Figure 23 (c) and (d)). Conversely, chip seals deemed to be of "poor quality" display more extensive flushing and additional loss of cover aggregate. SC 914 was designated as being of poor quality based on the evaluation criteria (Figure 23 (e)).

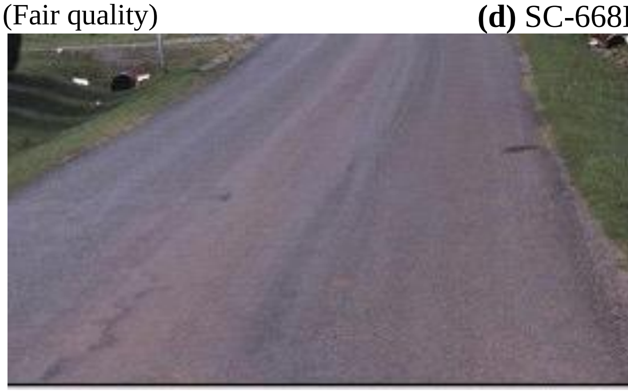
(a) SC-936 (Good Quality)

(b) SC-702 (Good quality)

(c) SC-704 (Fair quality)



(d) SC-668B (Fair Quality)



(e) SC-914 (Poor quality)

Figure 23.Comparison of surface treatments in good, fair, and poor condition

Quantitative Analysis

Given that these chip seal projects were located within Franklin County, the aggregate and binder application rates, as well as the materials utilized, adhered to the same requirements and techniques across all projects. Average MPD values ranged from 0.5 to 1.17, serving as a reflection of the quality of chip seals. Macrotexture values of fair quality chip seals were found to range between 0.68 to 0.97, while the good quality displayed a range from 0.72 to 1.17 (Table 14). Furthermore, a plot was created to examine the correlation between macrotexture and traffic volume (Figure 24). Quality rate uses a color code to represent various levels: red for poor, orange for fair, and green for good.

Table 15. Average and Standard Deviation of MPD for Secondary Roads

Quality Rate	Route	Measurement Length, miles	Average MPD	SD
Poor	**SC 914**	0.1	0.5	0.21
Fair	**SC 704**	1.02	0.68	0.35
	SC 705	1.85	0.7	0.32
	SC 668-B	1.52	0.97	0.34
Good	**SC 936**	0.79	0.86	0.38
	SC 702	2.25	0.73	0.37
	SC 815	1.52	0.72	0.26
	SC 668-A	0.77	1.17	0.39

The relationship between the Annual Average Daily Traffic and the average Mean Profile Depth values illustrates various significant patterns pertaining to the quality of chip seals on different routes. The route SC 914, highlighted in red, exhibits poor quality chip seals, its MPD is notably lower when correlated with higher AADT values.

Conversely, the routes with fair and some good quality chip seals manifest MPD values from 0.6 to 0.9 that predominantly converge around the mid-range. Particularly notable is route SC 668, which demonstrates good-quality chip seals and distinctly stands apart by exhibiting a considerably higher average to the others.

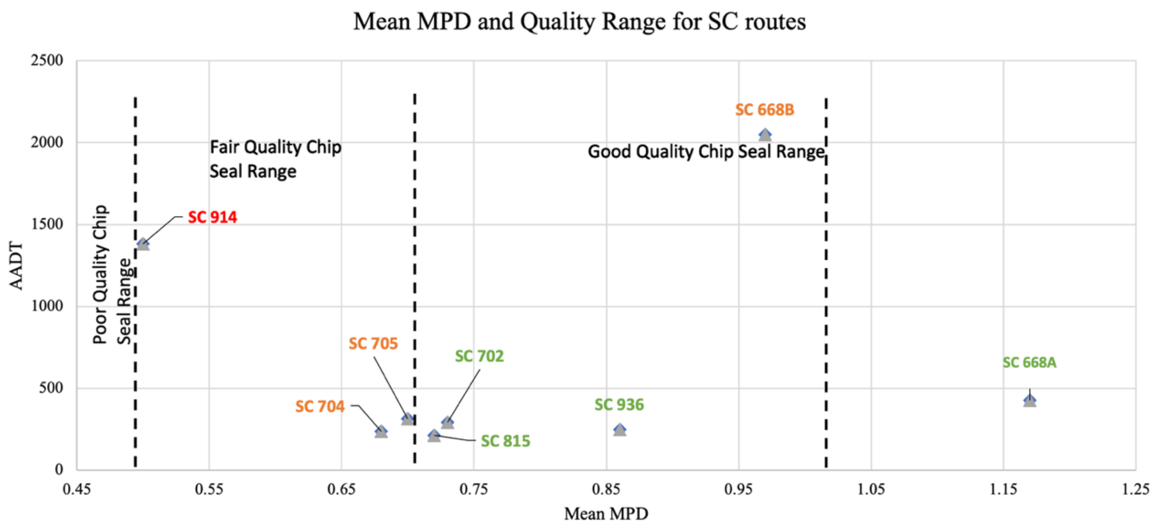


Figure 24. Relation between Average Mean Profile and Average Annual Daily Traffic

Additionally, descriptive statistics for selected secondary roads were listed in Table 16 and the percentage of MPD within 0.6 and 1.2 mm, less than 0.6 mm, and over 1.2 mm were determined for each project. Subsequently, these average values were categorized based on proposed quality 'good', 'fair', and 'poor'.

Table 16. Percentages for good, fair, and poor-quality chip seals

Route	Average MPD	SD	RMS	COV	% MPD within limits	% MPD less than 0.6 mm	% MPD over 1.2 mm
SC 914	0.5	0.21	0.54	0.42	80	16	4
SC 704	0.68	0.35	0.76	0.51	36.25	52.50	11.25
SC 705	0.7	0.32	0.77	0.45	50	43.06	6.94
SC 668-B	0.97	0.34	1.02	0.35	51.48	20.68	27.85
SC 936	0.86	0.38	0.94	0.45	56.56	27.05	16.39
SC 702	0.73	0.37	0.82	0.51	38.84	48.70	12.46
SC 815	0.72	0.26	0.77	0.36	57.50	38.33	4.17
SC 668-A	1.17	0.39	1.21	0.25	40.32	3.23	56.45

The calculated percentages of these quality categories illustrate the dominant classification of macrotexture values in each segment, providing an overview of the surface quality distribution.

CHAPTER 5. FINDINGS, CONLUSIONS AND RECOMMENDATIONS

Findings

The results suggest that there is a relationship between what is visually observed and the macrotexture measurements. However, using only the macrotexture measurements and their deviation can provide a detailed understanding of a project's quality, eliminating the need for a direct visual inspection.

Using two primary approaches: 1) macrotexture standard deviation for variability and 2) average values can enhance the understanding of chip seal quality by observing both consistency across the route and the overall performance of the chip seal.

The data from various chip sealing projects has been analyzed to evaluate the quality of the chip seals based on their MPD. The findings suggest that MPD of 0.6 to 1.0 is indicative of satisfactory chip seal quality. MPD value less than 0.6 mm represents poor quality, whereas MPD value between 1.0 and 1.2 mm suggests good quality (Figure 25)**.** A categorization has been proposed based on the literature review, visual assessment, and data analysis of collected macrotexture measurements.

Figure 25. Chip Seal Quality Categories and Range

The following comments summarize further observations from the analysis:

- A particular project (VA 730), with seal treatment, exhibited notable variability in macrotexture values, reflecting a deviation in uniformity and consistency across the project.
- A correlation has been found between the Average Annual Daily Traffic and the macrotexture, as per supplementary data analysis.
- Boxplot analysis of ten initial sections revealed a tendency for the median MPD values to increase centrally within the sections, providing a nuanced understanding of texture and variation over project segments.
- MPD values are generally lower at route turns compared to other areas, which influences overall chip seal quality. This discrepancy needs further analysis.

Conclusions

In conclusion, this study has examined the quality assurance procedures of chip sealing projects, emphasizing the MPD metric and the integration of both quantitative and qualitative analytical methods. Key discoveries were articulated through quality rating scales, derived from descriptive statistics and visual assessment of chip seal performance.

Chip sealing emerges as a cost-effective strategy with the potential for longevity, contingent on rigorous quality control mechanisms. The identified variability and patterns in the MPD values provide a foundation for enhanced analysis and optimization for chip sealing projects. The conventional practice of post-construction quality assurance predominantly reliant on visual observations is underscored as a limitation, advocating for a combination of quantitative and qualitative assessments to foster a more holistic and accurate evaluation.

Furthermore, the study illuminates the critical influence of various distresses primarily flushing and aggregate loss on the overall quality of chip seals. Quality control encompassing equipment, material, and operational facets, such as the calibration and consistent application of aggregates and binders, emerges as instrumental in mitigating these distresses.

Ultimately, the study provided quality assurance scales, categorizing chip seals into good, fair, and poor quality. The categorization aimed to serve as practical tools for road authorities and contractors, facilitating quality assessments and driving the enhancement of chip seal projects' quality nationwide.

Recommendations

- This study primarily focuses on modified single chip seals. For a more comprehensive understanding, it is recommended to expand the research to include several types of chip seals, as macrotexture characteristics may vary across several types.
- Macrotexture values are influenced by several factors such as chip seal type, weather conditions, and Average Annual Daily Traffic. A deeper analysis considering these variables is essential to understand their collective impact on chip seal performance.
- Combining macrotexture standard deviation and average values can enhance the evaluation of the end-product.
- Instances where macrotexture values exceed 1.2 mm warrant a detailed investigation. Identifying the causative factors contributing to these elevated values is crucial for enhancing chip seal quality.
- A discussion and analysis are recommended concerning whether to exclude lower macrotexture values on turns. Such evaluation is necessary to establish comprehensive quality and performance assessment criteria.
- It is advisable to measure macrotexture one month post construction and maintain continuous monitoring thereafter. This practice will foster a more detailed understanding of chip seal deterioration trends, particularly concerning macrotexture and skid resistance.

References

Adams, J. M., and Richard Kim, Y. (2014). "Mean profile depth analysis of field and laboratory traffic-loaded chip seal surface treatments." *International Journal of Pavement Engineering*, 15(7), 645-656.

Aktaş, B., Karaşahin, M., and Tiğdemir, M. (2013). "Developing a macrotexture prediction model for chip seals." *Construction and Building Materials*, 41, 784-789.

Bao, J., Adcock, J., Li, S., and Jiang, Y. (2023). "Enhancing Quality Control of Chip Seal Construction through Machine Learning-Based Analysis of Surface Macrotexture Metrics." *Lubricants*, 11(9), 409.

Bateman, D. (2016). *Design Guide for Road Surface Dressing*, Transport Research Laboratory.

Bellanger, J., Brosseaud, Y., and Gourdon, J. (1992). "Thinner and thinner asphalt layers for maintenance of French roads." *Transportation research record*(1334).

Burati, J., Weed, R., Hughes, C., and Hill, H. (2003). *Optimal procedures for quality assurance specifications.* Turner-Fairbank Highway Research Center.

Chan, S., Lane, B., Kazmierowski, T., and Lee, W. (2011). "Pavement preservation: A solution for sustainability." *Transportation Research Record*, 2235(1), 36-42.

Davis, L. (2005). "Quality control and quality assurance on chip seal projects." *Roadway Pavement Preservation*, 54.

de León Izeppi, E., Flintsch, G., Katicha, S., McCarthy, R., and McGhee, K. (2019). "Locked-Wheel and Sideway-Force CFME Friction Testing Equipment Comparison and Evaluation Report." United States. Federal Highway Administration.

de Leon Izeppi, E., Morrison, A., Flintsch, G. W., McGhee, K. K., Virginia Center for Transportation Innovation and Research, and United States Federal Highway Administration. (2015). *Best practices and performance assessment for preventive maintenance treatments for Virginia pavements.* Virginia Center for Transportation Innovation and Research, Charlottesville, VA.

Estakhri, C. K., and Sendheera, S. (2017). "Guidelines for TxDOT in selecting seal coat materials." Texas A&M Transportation Institute.

Flintsch, G. W., De León, E., McGhee, K. K., and AI-Qadi, I. L. (2003). "Pavement surface macrotexture measurement and applications." *Transportation research record*, 1860(1), 168-177.

Flintsch, G. W., Huang, M., and McGhee, K. (2005). *Harmonization of macrotexture measuring devices,* ASTM International.

Gransberg, D. D., and James, D. M. (2005). *Chip seal best practices*, Transportation Research Board.

Gundersen, B. (2008). "Chipsealing practice in New Zealand." *Proceedings of the International Conference on Road and Pavement Engineering,* Gundersen Consulting Ltd, New Zealand.

Gundersen, B., Hart, G., and Muir, P. (2008). "Development and use of performance-based chipsealing contracts in New Zealand." *Proc., International Sprayed Sealing Conference, 1st,* Adelaide, South Australia, Australia.

Halstead, W. (1979). *NCHRP synthesis 65: Quality assurance.*

Herrington, P., Kodippily, S., and Henning, T. (2015). "Flushing in chipseals September 2015." Wellington.

Jalali, F., and Vargas-Nordcbeck, A. (2021). "Life-extending benefit of chip sealing for pavement preservation." *Transportation Research Record*, 2675(6), 104-116.

Joslin, K., Lopez, E., Cheng, D., and Hicks, G. (2019). "Literature review on performance, best practices, and training needs for chip seals, slurry surfacing, and cape seals." *San Jose: Mineta Transportation Institute*.

Kim, Y. R., Adams, J., Castorena, C., Ilias, M., Im, J. H., Bahia, H., Chaturabong, P., Hanz, A., and Johannes, P. T. (2017). *Performance-related specifications for emulsified asphaltic binders used in preservation surface treatments*.

Kim, Y. R., and Adams, J. M. (2012). *Development of a New Chip Seal Mix Design Method*. Final Report No. FHWA/NC/2008-04, North Carolina Department of Transportation, Research and Analysis Group, Raleigh, NC.

Lawson, W. D., and Senadheera, S. (2009). "Chip seal maintenance: solutions for bleeding and flushed pavement surfaces." *Transportation research record*, 2108(1), 61-68.

Mahoney, J. P., Slater, M., Keifenheim, C., Uhlmeyer, J., Moomaw, T., and Willoughby, K. (2014). "WSDOT chip seals: optimal timing, design and construction considerations."

Marjerison, B., Anthony, A., Croteau, J.-M., Gareau, M., and Dechkoff, C. "The evaluation of a fibre-reinforced sandwich chip seal in Saskatchewan." *Proc., CTAA Annual Conference Proceedings-Canadian Technical Asphalt Association,* 369.

McGhee, K. K., Flintsch, G. W., and de Leon Izeppi, E. (2003). "Using high-speed texture measurements to improve the uniformity of hot-mix asphalt." Virginia Center for Transportation Innovation and Research.

McLeod, N. W., Chaffin, C., Holberg, A., Parker, C., Obrcian, V., Edwards, J., Campen, W., and Kari, W. "A general method of design for seal coats and surface treatments." *Proc., Proceedings of the Association of Asphalt Paving Technologists*, 537-630.

Merritt, D. K., Lyon, C., and Persaud, B. (2015). *Evaluation of pavement safety performance.* United States Federal Highway Administration.

Mogrovejo, D. E., Flintsch, G. W., Katicha, S. W., de León Izeppi, E. D., and McGhee, K. K. (2016). "Enhancing pavement surface macrotexture characterization by using the effective area for water evacuation." *Transportation Research Record*, 2591(1), 80-93.

Money, B., and Hodgson, G. J. (1992). *Manual of contract documents for highway works*, Telford.

Patrick, S. (2019). *Guide to Pavement Technology Part 4K: Selection and Design of Sprayed Seals.* Austroads Ltd., Sydney, NSW, Australia. ISBN 978-1-925854-70-1. Austroads Project No. TT1850. Austroads Publication No. AGPT04K-18.

Pierce, L. M., and Kebede, N. (2015). "Chip seal performance measures: best practices."

Prezioso, R.E. (2022). State of the pavement 2022. Virginia Department of Transportation, Richmond, VA.

Rada, G. R., Jones, D. J., Harvey, J. T., Senn, K. A., and Thomas, M. (2013). "Guide for Conducting Forensic Investigations of Highway Pavements." *National Cooperative Highway Research Program*.

Raza, H. (1994). An Overview of Surface Rehabilitation Techniques for Asphalt Pavement: Instructor's Guide.

Rebbechi, J., and Alderson, A. (2019). *Guide to Pavement Technology Part 4K: Selection and design of sprayed seals.*Austroads Ltd., Sydney, NSW.

Roque, R., Anderson, D., and Thompson, M. (1991). "Effect of material, design, and construction variables on seal-coat performance." *Transportation research record*, 1300, 108-115.

Shuler, S. (2011). *Manual for emulsion-based chip seals for pavement preservation.* Transportation Research Board.

TNZ. (2005). *Chip sealing in New Zealand.* Road Controlling Authorities, Wellington, New Zealand.

Transit New Zealand. (1995). *TNZ P/3: Specification for first coat sealing.*

Transit New Zealand. (2022). *TNZ M/1: Specification for bitumen.*

Wambold, J. C., Antle, C. E., Henry, J., and Rado, Z. (1995). *International PIARC experiment to compare and harmonize texture and skid resistance measurements*, PIARC.

Wiser, L. (2011). *Results of long-term pavement performance SPS-3 analysis: Preventive maintenance of flexible pavements.*

WSDOT (2024). "Standard specifications for road, bridge, and municipal construction." WSDOT Olympia, WA.

Zhao, G., Li, S., Jiang, Y., and Lee, J. (2018). *Quality assurance procedures for chip seal operations using macrotexture metrics.* Purdue University, Joint Transportation Research Program.

Zuniga-Garcia, N., and Prozzi, J. A. (2019). "High-definition field texture measurements for predicting pavement friction." *Transportation Research Record*, 2673(1), 246-260.